

Soil Pulverization and Lime Migration in Soil-Lime Stabilization

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• THIS INVESTIGATION was initiated to study the effect on soil-lime stabilization of one important variable, the degree of pulverization before compaction. For soil-lime stabilization it is generally recommended that 60 to 70 percent of all material, exclusive of gravel and stones, should pass the No. 4 sieve, and 100 percent of this material should pass the 1-in. sieve (1). Some specifications have called for as much as 100 percent of all material, exclusive of gravel and stone, to pass the No. 4 sieve (2). Soils with greater than 20 to 30 percent clay and with a plasticity index (P.I.) greater than 20 percent, however, are sometimes difficult or even impossible to pulverize (3). Curing of partially mixed soil and lime before final mixing improves pulverization, but this procedure has been found to be detrimental to the lime-soil reaction due to exposure to air containing carbon dioxide (2).

Field observations by the authors and others (4) of stabilized unmixed soil lumps within cured soil-lime and soil-cement indicated that free lime may migrate into and stabilize these lumps. The goal of the present study was to evaluate the effects and effectiveness of such lime migration, with the eventual possibility of a relaxation of soil-lime pulverization requirements.

DIFFUSION PHENOMENA

Diffusion in solids is similar to that in liquids except for certain complications due to mechanical defects and grain boundary interfaces through which diffusion can occur. Therefore, diffusion in a solid may take place either homogeneously through the crystal lattice, or as grain boundary or interface diffusion process. Diffusion of these two types will occur at very different rates (5).

Because of the interactions between clay and exchangeable ions and between clay and water, the diffusion process in clay-water systems is very complex; these two interactions could affect each other. Different diffusion mechanisms with different diffusion coefficients and activation energies can be operating in a clay-water system at the same time (6). Diffusing cations have been found to move by at least two different mechanisms. Cation migration in an oven-dry soil is evidence for diffusion by movement along the exchange sites on a clay particle surface and by jumping from the exchange sites on one particle to exchange sites on an adjacent particle. Diffusion of cations occurs at a faster rate through the pores of a clay-water system.

The diffusion of anions through a bentonite-water system was found to take place exclusively within the pores or "channels" (6). In accordance with this conclusion, anion diffusion did not occur in an oven-dry bentonite. Significantly, in a clay-water system containing free water, anions will diffuse faster than cations if the concentration gradient is small, and cations and anions can diffuse separately. Barber has concluded that calcium ion movement in soil is due primarily to water movement but, if a concentration gradient exists, diffusion is possible (7).

That the diffusion of lime in soil is possible and even probable has been shown as early as 1939 and perhaps even earlier. The movements of ions in gels and soils have been divided into four groups according to mechanism (8): (a) free diffusion of ion pairs in the intermicellar pores and channels, (b) adsorption of ions by colloidal particles

which themselves diffuse as a result of Brownian movement or with the aid of some transporting agent, (c) exchange of ions between surfaces and intermicellar liquids, and (d) surface migration and contact exchange, independent of the nature of the intermicellar liquid.

By the use of radioactive tracer techniques the apparent self-diffusion coefficients of calcium ions added as a chloride were found by Lai and Mortland (6) to be 2.36 ± 0.07 , 1.95 ± 0.06 , and 1.75 ± 0.05 (10^6 sq cm/sec) for bentonite-water systems containing 17.9, 23.9 and 28.0 percent by weight of bentonite. Gast (9) determined the self-diffusion coefficients of calcium ions through a bentonite-water system containing 3 percent bentonite by weight to be 0.607 ± 0.045 and 2.14 ± 0.25 (10^6 sq cm/sec) for calcium ions added as hydroxide and as chloride, respectively. In both investigations Ca-saturated bentonite was used so that cation exchange would not interfere with diffusion.

In interpreting diffusion coefficient determination data both authors (6, 9) attached considerable significance to viscosity of water adjacent to clay particles. Lai and Mortland refer to Low's work (10) in their interpretation, and Gast refers to Kemper's work (11). Both Low and Kemper measured viscosity of water in a clay-water system indirectly, but the influence of all possible variables was not investigated. Definite conclusions about viscosity of water in a clay-water system on the basis of these two investigations would require considerable speculation. Although viscosity undoubtedly has an important influence on the diffusion of ions in a clay-water system, speculation about the manner and magnitude of influence is impractical without further investigation.

Investigators thus far have succeeded only in determining the apparent diffusion coefficients of cations in a soil-water system. It has been generally concluded that cations in these systems have at least two different diffusion mechanisms and, therefore, two different diffusion coefficients. Determination of these two coefficients has not yet been achieved.

Anions may have a different diffusion coefficient than cations (6). Electrolyte concentrations high enough to cause chemical reaction and cation exchange would affect diffusion through soil-water systems. Consideration of all these factors would require a very theoretical and detailed expression for the rate of diffusion of lime through soil. The validity of applying one of the solutions given for the diffusion equation by Barrer (12) is questionable. Until more is known of all the factors influencing ion migration through a clay-water system a more general approach, as presented below, is justifiable.

Lime Diffusion, a Boundary Process

The development of a reaction product layer at the boundary of lime and soil is the result of a series of processes which may be classified as boundary processes of solid-state reactions. These boundary processes may include (a) the transfer of lime into the soil, (b) a chemical reaction between the two, (c) formation of nuclei and growth of the reaction product, and (d) further diffusion of lime into the soil through the reaction product layer. The first three of these processes are generally referred to as phase boundary processes, and the last as a diffusion process (13). The reaction rate may then be expressed as

$$\frac{dn}{dt} = c \frac{\Delta\mu}{W_R + W_D} \quad (1)$$

where W_R is the reaction resistance defined as the reciprocal of the velocity of all phase boundary processes, W_D is the diffusion resistance, and $\Delta\mu$ is the free energy change involved in the reaction.

When only one of the reactants is able to move, two different rate-determining conditions may control the reaction rate. One of the possible rate-determining conditions exists when the diffusion resistance is much larger than the reaction resistance ($W_D \gg W_R$), and diffusion is occurring at a much slower rate than is the boundary reaction. In this case the reaction rate can be written:

$$\frac{dn}{dt} = c \frac{\Delta\mu}{WD} = c \frac{\Delta\mu}{1/D \int_{\text{Phase Boundary I}}^{\text{Phase Boundary II}} dl/A} \quad (2)$$

where D is the diffusion coefficient defined by Frick's law, l is the thickness of diffusion layer, and A is the cross-sectional area of diffusion layer. Assuming a constant cross-section and constant D, this equation when integrated gives the following expression for the rate of growth of the product layer:

$$l^2 = k't \quad (3)$$

where k' is a constant, and t is time. The other controlling condition exists if the reaction resistance is much larger than the diffusion resistance ($W_R \gg WD$) and the reaction is taking place at a much slower rate than is diffusion. If this is true, a general expression for the reaction rate cannot be formulated due to the complex nature of the phase boundary processes. Expressions must be formulated for each particular reaction involved.

These two conditions are extreme cases and often both the diffusion rate and the phase boundary reaction rate must be considered in the overall reaction rate (13). If the total free energy change is separated into parts due to diffusion and to phase boundary processes, the general expression for the reaction rate can be resolved into:

$$bl + l^2 = kt \quad (4)$$

Eqs. 3 and 4 relate the thickness of the reaction product layer with time. The application and solution of an appropriate expression of this type to a soil-lime system is of significant importance to an investigation of the effect of pulverization on soil-lime stabilization. The applicability of Eq. 3 has been verified for the reaction between calcium carbonate and mullite (14).

METHODS OF INVESTIGATION

Materials

The soil used in this investigation was a Sharpsburg series plastic loess from Clarke County, Iowa. A sample was taken from the B horizon at a depth between 12 and 46 in. The physical and chemical properties of this soil are given in Table 1.

Commercially available calcitic hydrated lime (Kemikal, U.S. Gypsum Co.) was used.

Soil Preparation

Soil samples were brought into the laboratory in two large metal containers. One of the containers had been sealed in the field with plastic wrapping and cellophane tape so the field moisture content of this soil could be maintained. The other can was merely covered with a metal lid. The sealed container was placed in a humidity room where the relative humidity is maintained at 95 ± 5 percent, and the contents of the other can were spread and allowed to air dry for several days.

The soil sample which had been stored at its field moisture content in the humidity room was pulverized by hand to pass a 1-in. sieve and be retained on a No. 4 sieve. All material from this sample passing the No.

TABLE 1
SOIL PROPERTIES

Property	Value
Textural composition, AASHO (% by wt.)	
Sand, 2.0 to 0.074 mm	3.1
Silt, 0.074 to 0.005 mm	53.6
Clay (5 μ), <0.005 mm	43.3
Clay (2 μ), <0.002 mm	35.0
AASHO classification	A-7-6(12)
Textural classification	Clay
L.L. (%)	41.2
P.L. (%)	21.0
P.I.	20.2
Predominant clay mineral	Ca-montmorillonite
pH	7.0

4 sieve was discarded. The material passing the 1-in. sieve and retained on the No. 4 sieve (lump sample) was again placed in a metal container, sealed with plastic wrap and cellophane tape, and replaced in the humidity room until used. Lumps were kept at the field moisture content of about 16 percent to minimize density drops during compaction of specimens. The size distribution by weight of the soil lumps was as follows:

Percent passing 1-in. sieve, 100.0;
 Percent passing $\frac{3}{4}$ -in. sieve, 55.6;
 Percent passing $\frac{1}{2}$ -in. sieve, 35.8;
 Percent passing $\frac{3}{8}$ -in. sieve, 24.9; and
 Percent passing No. 4 sieve, 0.0.

The air-dry soil was then crushed in a jaw crusher to pass a No. 4 sieve and stored in a metal container until used. Representative samples for mechanical analysis and for determination of Atterberg limits were obtained from this air-dried sample.

Moisture-Density Relationship

The percentage of lime used was chosen arbitrarily. Since in Iowa 6 percent lime is a frequently used amount for soil-lime stabilization, this amount, based on the oven-dry weight of the soil, was added to a representative sample of air-dried soil (100 percent pulverized) for the density-moisture relationship study. The ingredients were placed in a metal mixing bowl and given a thorough hand mixing. Then the soil-lime mixture was mixed with a Hobart kitchen mixer, Model C-100, at low speed for 1 min. Further stirring by hand insured mixing of material in the bottom of the bowl. The mixing bowl was again placed on the mixer and water was added from a graduated cylinder while mixing proceeded for 1 min. Scraping of the sides of the bowl and an additional 1 min on the kitchen mixer completed the mixing process. A damp cloth was placed over the bowl to prevent evaporation during molding.

Specimens 2 in. in diameter by 2 ± 0.05 in. high were molded with a compaction apparatus developed at the Iowa Engineering Experiment Station (15) to give approximate standard AASHO T99-57 density. With the exception of dry-mixing, the mixing and molding procedure was repeated for increasing moisture contents of the soil-lime mixture to obtain the density-moisture relationship.

The optimum moisture content for maximum AASHO density of 100 percent pulverized plastic loess soil containing 6 percent of hydrated calcitic lime was determined to be 23.2 percent. Although the unconfined compressive strength specimens were prepared with soil samples containing various percentages of lumps using the Rainhart Co. compaction apparatus, the optimum moisture content was, for convenience, determined with 100 percent pulverized soil using the Iowa State compaction apparatus. The difference between the density obtained at 23.2 percent moisture for the two methods was about 1 pcf, an insignificant amount.

Unconfined Compressive Strength Specimens

The primary purpose of the unconfined compressive strength study was to secure comparative data which would indicate the effect of pulverization on soil-lime stabilization. For this purpose unconfined compressive strength specimens containing 100, 80, 60, 40 and 20 percent lumps were prepared.

The necessary amounts of soil passing the No. 4 sieve, corrected for hygroscopic moisture, and the necessary amount of soil lumps passing the 1-in. sieve and retained on the No. 4 sieve, corrected for their moisture content, were weighed to the nearest gram, placed in a metal mixing bowl, and given a short-period preliminary hand mixing with a large metal spoon. The desired amount of lime was then weighed to the nearest gram and added to the mixing bowl. Further hand mixing was initiated to insure a relatively intimate mixture of soil and lime before water was added to bring the moisture content of the mixture to the optimum moisture content determined for 100 percent pulverized soil. Then the mixture was hand mixed with a spoon for $6\frac{1}{2}$ min. Following this, the bowl was covered with a damp cloth to prevent evaporation, and moisture samples were taken.

Proctor specimens 4 in. in diameter and 4.6 in. high were molded using a Rainhart Co. compaction apparatus, Model 662. The motor-driven rammer of this apparatus is calibrated to deliver the same compactive effort as the standard AASHTO T 99-57 rammer. After being molded and extruded, the specimen was weighed, marked, and sealed in plastic wrap with cellophane tape to limit carbonation of the lime by carbon dioxide from the air and to limit moisture loss. After each group of three specimens were molded, moisture samples were taken; the wrapped samples were placed in the curing room in which the relative humidity was maintained at 95 ± 5 percent and the temperature at 70 ± 5 F. The specimens were cured for periods from 7 to 270 days.

At the end of the selected curing periods, the specimens were removed from the curing room and tested to failure using a Universal hydraulic testing machine. The rate of strain applied to the specimens was held constant at about 0.1 in./min. The ultimate load in pounds was recorded for each specimen; the load was read to the nearest 5 lb for specimens tested with the low range of the machine (up to 6,000 lb) and to the nearest 20 lb for samples tested with the medium range (up to 24,000 lb).

Pressed fiber pads, trimmed to approximately the same diameter as the samples, were used on the top and bottom of the samples during load testing to insure uniform load application.

Lime Migration Study Specimens

Soil and water to bring the moisture content to optimum were mixed using the same soil, equipment, and procedure used for mixing the materials for determination of the moisture-density relationship, except that no lime was used and, therefore, dry mixing was unnecessary.

Molding of specimens was accomplished using the Iowa State compaction apparatus mentioned previously. The procedure and equipment used were the same as those used for the moisture-density relationship study except that a 6-in. high and 2-in. diameter Plexiglas mold was used instead of the regular metal one. After being molded, the specimens were positioned in the Plexiglas molds so that one face was flush with the end of the mold. The specimens were then weighed and their heights were measured.

A lime slurry containing 7 parts water to 5 parts lime, by weight, was poured to a depth of $1\frac{1}{2}$ in. on the top of the specimens contained in the Plexiglas molds. These molds were then sealed at both ends with plastic wrap and cellophane tape to prevent moisture loss and carbonation from carbon dioxide in the air and were placed in an upright position in the curing room. The samples remained in the curing room at 95 ± 5 percent RH and a temperature of 70 ± 5 F until testing.

At specified intervals of time, two of the specimens were removed from the curing room for testing. The plastic wrap was removed from the ends of each mold, a sample was taken of the lime slurry, and the remainder of the slurry was removed from the surface of the sample and discarded. After measurement of the sample height, the sample was extruded in eight small increments and sliced even with the edge of the mold, using a wire cheese cutter. All of the slices were $\frac{1}{4} \pm 1\frac{1}{32}$ in. thick with the exception of the first slice, which was taken from the end opposite the one placed in contact with the lime slurry and was usually less than $\frac{1}{4}$ in. thick due to shrinkage and variation from 2 in. in the molded height of the specimen. The slices and lime slurry samples were placed in small airtight jars to prevent carbonation.

Partial drying of the slices and lime slurry specimens was accomplished by placing the uncapped jars containing the samples into a vacuum desiccator containing calcium chloride for moisture absorption and Askarite (NaOH and asbestos) for prevention of carbonation. The desiccator was then evacuated and sealed, and the samples were vacuum dried for 36 to 48 hr.

After being dried, the samples were removed from the desiccator, ground with a mortar and pestle, and replaced in capped, airtight jars. All procedures were carried out with the knowledge that more than a minimum amount of exposure to air could cause undesirable carbonation of the samples.

Two-gram portions of each of the slices and lime slurry samples along with a sample of untreated soil were weighed into 50-ml Erlenmeyer flasks, and water was added to the flasks to bring the volume of the soil-water and soil-lime mixtures to 45 ± 5 ml.

After each flask was sealed with a cork stopper, the mixtures were mechanically agitated for $\frac{1}{2}$ hr. The suspensions were then allowed to settle for about 4 hr before the supernatant liquid was poured from the flasks into smaller beakers, and the pH of this supernatant was measured. The pH measurements were taken with a Beckman pH meter. To minimize interference of suspended soil particles with the pH measurement, the beaker was gently agitated by hand while the measurement was being taken.

A 3-g portion of each partially dried and ground slice sample was weighed into a 60-ml Buchner funnel equipped with a coarse fritted glass filter. The samples in the funnels were covered with filter paper and were then leached with successive 100-ml quantities of 1N potassium chloride solution until less than 1 meg of cation per 100 g of oven-dry samples was being leached from the sample by 100 ml of the solution. After being leached with potassium chloride solution, the samples were leached with 0.1N hydrochloric acid in two successive 100-ml quantities.

The amounts of cation removed from the soil by leaching with the two solutions were determined by titrating to the nearest 0.05 ml with standard EDTA in the presence of pH 10.5 ammonium hydroxide-ammonium chloride buffer. Erchromeschwartz I was used as the indicator. In the case of the hydrochloric acid leachate, adjustment of the pH to a level between 6 and 8 with sodium hydroxide was necessary before addition of the indicator and buffer.

X-Ray Diffraction

X-ray diffraction studies were performed on representative samples of the original soil and on samples taken from unconfined compressive strength specimens and from the lime migration study specimens. The samples were either air dried or dried in a desiccator containing calcium chloride. Samples were pulverized with a mortar and pestle and mounted in a brass ring or on a glass slide. All lump samples taken from the unconfined compressive strength specimens were carefully scraped to insure removal of all adherent matrix material.

A General Electric Co. Model XRD-5 diffraction unit with copper $K\alpha$ radiation was used. The diffractometer settings used for all studies were a 1° or 3° beam slit, medium resolution soller slits, 0.2° detector slit, a $2^\circ/\text{min}$ scan rate and a 3-sec time constant.

STRENGTH STUDY

Unconfined Compressive Strength

The results of the unconfined compressive strength tests (Figs. 1 and 2, Table 2) show that the presence of soil lumps in a compacted soil-lime mixture decreases the strength of the mixture. After 14 days of humid curing the average difference between the strength of the specimens containing 0 percent soil lumps and those containing 80 percent soil lumps was 26 psi, or about 20 percent of the strength with no lumps. The strength difference between these two extremes of percentage of soil lumps after 90 days of curing was about 35 psi, or about 13 percent.

The strength differences of the intermediate specimens containing 20, 40 and 60 percent of soil lumps was relatively small at all curing periods. The strength differences after 14-days curing between the specimens containing 20 percent soil lumps and those containing 40 and 60 percent soil lumps were only 7 and 9 psi, respectively. These differences after 90 days of curing were 7 and 13 psi. Figure 1 indicates that at a curing time of about 150 days, the strengths yielded by these three mixtures were about equal and only about 20 psi less than those of specimens containing no soil lumps. All four groups of specimens showed strengths above 300 psi.

The rate of strength gain was relatively constant for all specimens tested at curing times up to about 150 days; after this the rate slowed. This change was slower for specimens with no lumps, indicating that the strength differences increase after 200 days until strength equilibrium is reached.

Soil lumps were clearly visible in the specimens tested after curing periods up to 190 days. The lumps were darker in color than the matrix of the specimens. The color difference between the soil lumps and the matrix surrounding the lumps became less pronounced after 190 days.

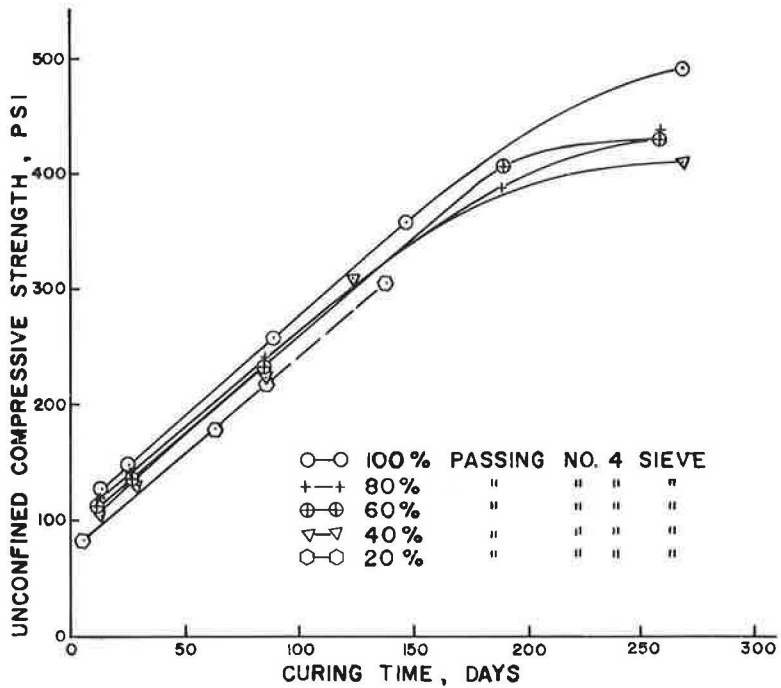


Figure 1. Effect of curing on unconfined compressive strength of specimens containing various percentages of soil lumps.

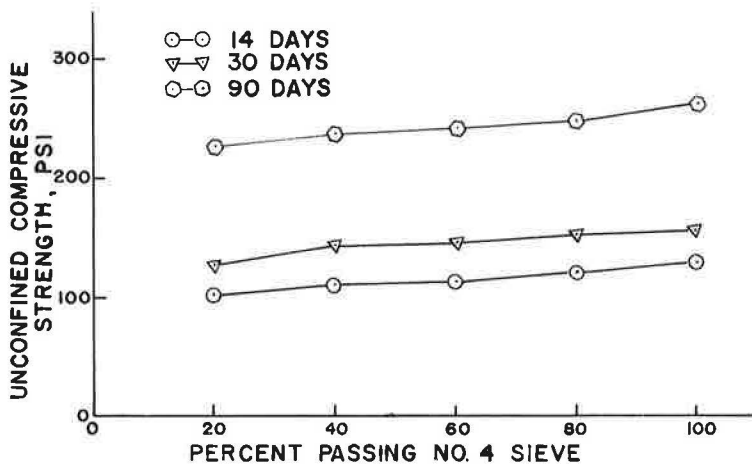


Figure 2. Effect of lump percentage on unconfined compressive strength of specimens cured for various lengths of time.

The lumps were quite easily separated from the matrix of specimens cured from 30 to 190 days. Oddly enough, the lumps appeared to be even stronger than the matrix surrounding them, and it was possible to crumble away the surrounding matrix and leave the lumps intact. Although some of the larger lumps appeared to have soft centers after 30 days of curing, even the largest lumps appeared to be uniform in hardness after 90 days of curing.

TABLE 2
UNCONFINED COMPRESSIVE STRENGTHS OF
SPECIMENS CONTAINING VARIOUS
PERCENTAGES OF SOIL LUMPS

Percent Passing No. 4 Sieve	Avg. Moisture Content (%)	Avg. Dry Density (pcf) ^a	Curing Period (days)	Avg. Unconfined Compressive Strength (psi) ^a
100	23.2	98.4	14	128
	23.2	98.1	30	156
	23.3	98.1	90	260
	23.1	97.7	147	359
80	23.1	98.1	270	494
	23.1	97.5	14	119
	23.2	96.6	30	151
	23.4	97.1	90	247
60	23.1	97.4	190	389
	22.9	97.4	260	432
	23.1	97.2	14	112
	23.1	97.0	30	145
40	22.9	97.3	90	240
	23.0	98.0	190	410
	23.1	97.5	260	431
	23.0	97.8	14	110
20	23.2	98.1	30	143
	23.4	97.6	90	234
	23.3	97.9	128	318
	23.1	97.3	270	411
20	23.0	97.6	7	86
	23.4	97.2	14	102
	23.6	97.3	30	126
	22.9	97.0	65	178
	23.1	97.2	90	225

^aResults average from three specimens tested.

After 190 days of curing, the strength of the lumps and the matrix of the specimens became more uniform; crumbling away the matrix surrounding the lumps was difficult. The matrix strength and the bonding between the lumps and the matrix had increased.

Lumps removed from specimens containing 60 percent lumps at the time of compaction and cured for 90 days were immersed in water for 48 hr. Although the natural soil slaked quite rapidly, these lumps did not slake, and no loss of strength was apparent.

X-Ray Diffraction

The results of X-ray diffraction studies are summarized in Table 3. A lump sample from the specimen containing 60 percent lumps and cured for 190 days was pulverized and dispersed in water with an ultrasonic dispersion apparatus for 10 min. X-ray diffraction of a glass slide prepared with the dispersed liquid showed a strong calcium carbonate peak at a d-spacing of 3.03 Å. X-ray diffraction of an undispersed lump sample from the same specimens showed only a very weak calcium carbonate peak, suggesting carbonation during testing. Another glass slide was prepared from the dispersed lump sample, and precautions were taken to prevent exposure of the slide

TABLE 3
X-RAY DATA SUMMARY

Sample	Treatment	Reduced Peak Spacings (Å)	New Peak Spacings (Å)	Remarks
190-days cured specimens containing 60% lumps:	Pulverized and dispersed in distilled water, then deposited on glass slide.		3.03, strong	Calcium carbonate.
	Pulverized and dispersed in CO ₂ -free distilled water, then deposited on glass slide with precautions to prevent exposure to CO ₂ .		3.03, strong	Calcium carbonate.
	Pulverized and dispersed in benzene, then deposited on glass slide.		3.03, very weak	Trace amount of calcium carbonate.
14-days cured specimens containing 80% lumps:	6-days additional storage in airtight containers.	Matrix	15 (montmorillonite)	8.1, 7.6, 3.9 Calcium aluminate hydrate (16).
		Lumps	15 (montmorillonite)	4.9, 3.9, 2.6 8.1, 7.6, 3.9, 2.66 Calcium hydroxide. Calcium aluminate hydrate, no calcium hydroxide.
270-days cured specimens containing 60% lumps: matrix and lumps	None		8.1, 7.6, 3.9, very weak. Halo between 2.88 and 3.13	Calcium aluminate hydrate. Calcium silicate hydrate (?)
128-days cured specimens containing 60% lumps: matrix and lumps	Autoclaved at 126 C for 7 days	15 (montmorillonite)	7.96, very strong	Calcium aluminate hydrate.
128-days cured specimens containing 60% lumps: matrix and lumps	Autoclaved at 126 C for 14 days	15 (montmorillonite)	6.4, 4.7, 2.8, 2.7, 2.15 Halo between 2.88 and 3.13	Afwillite (17). Calcium silicate hydrate (?)

to carbon dioxide in the air. In spite of these precautions X-ray diffraction of this slide also showed a strong calcium carbonate peak. When sodium oxalate was added to the supernatant of the lump dispersion, a calcium oxalate precipitate was formed. This formation of the calcium oxalate precipitate was evidence that dissociated calcium ions were in the supernatant and indicated that precautions taken to prevent carbonation of the glass slide X-ray diffraction sample were unsuccessful.

Another lump sample, taken from the specimen containing 60 percent lumps and cured 190 days, was dispersed in benzene for 15 min with the ultrasonic dispersion apparatus. X-ray diffraction of a glass slide prepared from the lump dispersion produced a very weak calcium carbonate peak. Addition of water to the slide and exposure to air containing carbon dioxide increased the intensity of the calcium carbonate.

X-ray diffraction patterns from the natural soil and from matrix and lump samples were examined in an effort to detect the presence of pozzolanic reaction products and to detect differences between lump and matrix samples. A general trend observed in lump and matrix samples was the decrease in montmorillonite peak.

Calcium aluminate was identified on diffraction patterns from samples taken from unconfined compressive strength specimens which had contained 80 percent of soil as lumps and has been cured 14 days. The samples had been stored an additional 6 days in airtight jars before they were X-rayed, bringing the actual curing time to 20 days. New peaks were observed at 8.1, 7.6, 4.9, 3.9 and 2.6 Å in the diffraction pattern from the matrix sample. Glenn (16) has identified the 8.1, 7.6 and 3.9 Å peaks as calcium aluminate hydrate. The 4.9, 3.9 and 2.6 Å peaks were from calcium hydroxide in the matrix material. Diffraction patterns from the lump sample failed to produce any calcium hydroxide peaks, but peaks at 8.1, 7.6, 3.9 and 2.86 Å showed the presence of calcium aluminate hydrate in the samples.

X-rayed samples from specimens containing less than 80 percent of soil as lumps failed to produce strong pozzolanic reaction product peaks in their diffraction patterns. This was true of both matrix and lump samples. After 270 days of curing, the X-ray diffraction patterns of lump and matrix samples taken from specimens containing 60 percent of soil as lumps showed only very weak peaks at the d-spacing given for calcium aluminate hydrates. The most definite evidence of a pozzolanic reaction was the presence of a diffraction halo between 3.13 and 2.88 Å. This halo appeared on the diffraction patterns of both the lump and matrix samples, and is an indication of calcium silicate hydrate.

In an attempt to crystallize any pozzolanic reaction products present in a specimen containing 60 percent soil as lumps and cured 128 days, both lump and matrix samples of these materials were placed in an autoclave maintained at 126 C for 7 days. Diffraction patterns from both materials yielded one strong new peak at 7.96 Å, identified as calcium aluminate hydrate. When the two samples were autoclaved for 14 days this peak disappeared, and most of the strong intensity peaks listed by Glenn and Handy (17) for afwillite, a calcium silicate hydrate, appeared. A halo between 2.88 and 3.13 Å on the two diffraction patterns suggested the presence of other phases of calcium silicate hydrate.

Discussion

Three stabilization mechanisms may be suggested for a compacted soil-lime-water mixture containing some of the soil as lumps, with the percentage of lime in the matrix in excess of the lime retention point (18, 19) and therefore available for a pozzolanic reaction. The lumps may be surrounded by a waterproof skeletal matrix of soil and lime-soil reaction products. In this case, the lumps add almost no strength to the compacted mixture but are prevented from undergoing moisture and volume changes which might disrupt the matrix. The matrix development becomes the strength-determining factor of the compacted mixture.

The other two possible mechanisms involve the assumption that lime will migrate into the lumps of the compacted soil-water-lime mixture. First, the amount of lime migrating into the lumps may only be sufficient to cause a thin reaction product crust on the surface of the lumps and flocculation of soil within the crust. In this case the

lumps will have considerable strength, depending on the crust thickness. Second, it may be that enough lime will migrate into the lumps to cause a pozzolanic reaction throughout the lumps and not just in a thin crust at the lump surface. The strongest mixture would result from this mechanism.

Strength results, X-ray diffraction studies, and slaking resistance of lumps removed from tested unconfined compressive strength specimens demonstrated not only that lime movement takes place in a soil-lime-water mixture, but that lime movement occurs in sufficient quantities to cause a pozzolanic reaction in soil lumps within the mixture.

Since the rate of strength gain was nearly the same for the five different soil-lime-water mixtures tested after curing periods up to 150 days, it is logical to assume that the early strength differences among the compacted mixtures were due to differences in a reaction occurring during the early stages of curing. The first phase of a soil-lime reaction is flocculation, but before flocculation can occur within soil lumps, lime movement is necessary. Initial flocculation of lumps is confined primarily to the surfaces, but initial flocculation of the matrix soil is quite extensive because of closer contact with lime. A larger percentage of rapidly flocculated soil in the specimens containing fewer lumps produces an almost immediate strength difference, and larger percentages of lumps will produce lower initial strength.

Increasing the percentage of soil lumps increases the lime content of the matrix material. This increase in lime content will produce more soil-lime contacts and increase initial flocculation of the matrix and lump surfaces. The increase of initial flocculation in the matrix and on the lump surfaces will partially compensate for the unreacted soil within the lumps. The degree of compensation will depend on the gradation or distribution of soil lumps and lime-matrix material.

Similarity in the strengths of specimens containing 20, 40 and 60 percent lumps showed that the amounts of initial flocculation in these specimens were nearly equal. The decreased strength of the sample containing 80 percent lumps indicated a decrease in initial flocculation because of an inferior distribution of soil lump and lime-matrix material.

The relatively equal rates of strength gain for all specimens tested after curing periods of up to 150 days were due to a constant rate of lime-soil reaction rate.

Increased differences between the unconfined compressive strengths of specimens cured over 150 days were due to differences in the distribution of pozzolanic reaction products. Since 6 percent hydrated calcium lime was mixed with the portion of soil passing the No. 4 sieve during the preparation of unconfined compressive strength specimens, the amount of lime in the matrix material at molding varied from 7.5 to 30 percent as the amount of soil as lumps in the specimens varied from 20 percent to 80 percent. Specimens containing a smaller percentage of soil lumps had a better distribution of reaction products and, thus, a higher ultimate strength. A pozzolanic reaction within the soil lumps depended on lime movement, and the quantity of lime movement depended on the distance from a lime source. Since the distance from a lime source in the matrix soil was much less than in the lump soil, more pozzolanic reaction occurred in the matrix soil. The difference in the amount of pozzolanic reaction occurring in the lumps and the matrix increased with the percentage of lumps.

Uniformity of pozzolanic reaction products in a soil-lime-water system containing some soil as lumps would be impossible unless sufficient lime for a reaction with all the clay minerals and other reactants in the system was available. Even then, attainment of uniformity would require a long time.

In verification of this, the percentage of lime (30 percent) present in the matrix material of specimens containing 80 percent of soil lumps before molding was responsible for the formation of calcium aluminate hydrate in a concentration large enough to be detected on X-ray diffraction charts after only 20 days of curing. Increased lime in proximity with soil lump surfaces also resulted in the formation of an X-ray-detectable concentration of calcium aluminate hydrate within the lumps of these samples. X-ray diffraction charts from samples of strength specimens containing a smaller percentage of lime in the matrix material failed to show the presence of calcium aluminate hydrate until after 270 days of curing.

Although calcium silicate hydrate was evidenced only by a halo on X-ray diffraction charts for specimens cured at room temperature, this lime-soil reaction product was undoubtedly formed at the same time as calcium aluminate hydrate. Poor crystallinity prevented a positive identification of this reaction product from X-ray charts.

RATE STUDY

The purpose of the lime migration study was to determine the rate and extent of the penetration of lime into the soil; this was accomplished by pH and calcium ion content determinations described previously.

pH Changes

The results of pH measurements are given in Table 4. To plot the distribution of hydroxyl ions with distance, the pH scale should first be changed to a logarithmic or extended linear scale, since the average distance of fairly thick slices from the lime source does not correspond to the average pH value. Such a transformation, however, magnifies the hydroxyl ion concentration scale out of proportion to the distance scale and makes the distribution curve uncertain in the critical range. To obtain a satisfactory distribution curve, thinner slice samples should have been taken; this, however, was practically impossible.

Table 4 does show a significant change in the hydroxyl ion concentration within soil specimens as the distance away from the lime source increased. The departure from the pH of the natural soil becomes even more evident as the time allowed for diffusion to take place is increased.

The pH appeared to have reached equilibrium in the first $\frac{1}{4}$ in. of soil away from the lime source at some time between 28 and 42 days. This phenomenon may have been due to the buffering action of clay present in the liquid poured from the top of soil water mixture prepared for pH determination. The apparent pH equilibrium may also have been due to movement of hydroxyl ions out of the first $\frac{1}{4}$ in. of soil as fast as they were moving in. This would indicate equilibrium of the flocculation reaction and possibly even the pozzolanic reaction in the first $\frac{1}{4}$ in. of soil.

Calcium Ion Migration

Calcium ion content determinations from slices of the diffusion study samples taken at increasing distances from the calcitic lime source are presented in Figure 3 and Table 5. Results of this determination were plotted in Figure 3 as a bar graph. Lines imposed on the bar graph balance the areas above and below the bars plotted for each slice taken after different times allowed for diffusion. For example, on Figure 3, area a is equal to area b. Theoretically, these lines gave a reasonable indication of the dis-

TABLE 4
RESULTS OF pH MEASUREMENTS AT INCREASING DISTANCES AWAY FROM
SOURCE OF LIME^a

Distance from Lime (in.)	pH						
	0 Days	3 Days	7 Days	14 Days	28 Days	42 Days	63 Days
0- $\frac{1}{4}$	7.00	10.80	11.00	11.15	11.25	11.45	11.45
$\frac{1}{4}$ - $\frac{1}{2}$	7.00	7.30	7.55	8.60	9.75	10.45	10.85
$\frac{1}{2}$ - $\frac{3}{4}$	7.00	7.15	7.25	7.30	7.55	7.75	8.80
$\frac{3}{4}$ -1	7.00	7.00	7.10	7.15	7.45	7.55	8.00
1- $1\frac{1}{4}$	7.00	7.00	7.20	7.15	7.30	7.50	7.85
$1\frac{1}{4}$ - $1\frac{1}{2}$	7.00	7.05	7.20	7.10	7.30	7.45	7.85
$1\frac{1}{2}$ - $1\frac{3}{4}$	7.00	7.00	7.10	7.10	7.30	7.45	7.80

^aResults average from two slice samples.

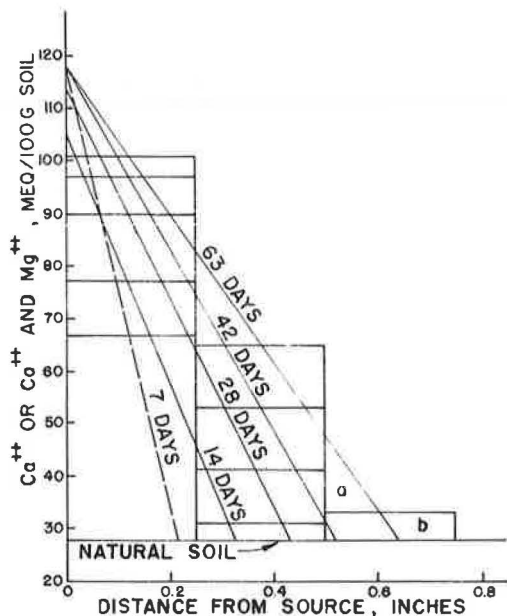


Figure 3. Ca^{++} or Ca^{++} and Mg^{++} ions present in $\frac{1}{4}$ -in. slices taken at increasing distances from hydrated calcitic lime source.

tribution of calcium ions within the diffusion samples. The intersection between these imposed lines and the natural soil line was the maximum penetration of a significant amount of lime.

The calcium penetration distance, determined by the intersection of the lines imposed on the bar graph in Figure 3 and the natural soil base line, was plotted vs the square root of time in days (Fig. 4). A straight line through the origin fitted the points quite well and verified the validity of Eq. 3 for the rate of a diffusion-controlled solid-state reaction. The slope of the straight line in Figure 4 was equal to the constant k' . The rate at which lime penetrated this particular soil-water system is defined by the expression

$$l = 0.081 t^{1/2} \quad (5)$$

where l equals the lime penetration distance in inches and t equals the time in days.

The application of this rate equation to many other soil-lime water systems is probably valid providing the constant is adjusted. Differences in clay content, clay minerals, density, adsorbed cations, and

TABLE 5
 Ca^{++} PENETRATION

Distance from Lime (in.)	Leaching Solution	Leached Cations (meq/100 g dry soil) ^a					
		3 Days	7 Days	14 Days	28 Days	42 Days	63 Days
0- $\frac{1}{4}$	KCl	43.73	48.30	56.53	64.41	72.69	60.25
	HCl	18.86	18.74	21.20	25.78	24.97	41.23
	Total	62.59	67.04	77.73	90.19	97.66	101.48
$\frac{1}{4}$ - $\frac{1}{2}$	KCl	23.36	23.13	25.62	29.80	34.42	40.17
	HCl	5.15	5.70	5.50	11.70	19.01	25.13
	Total	28.51	28.83	31.12	41.50	53.43	65.30
$\frac{1}{2}$ - $\frac{3}{4}$	KCl	23.51	23.48	23.21	22.85	23.22	28.87
	HCl	5.02	5.70	3.99	5.20	3.44	4.47
	Total	28.53	29.18	27.20	28.05	26.66	33.34
$\frac{3}{4}$ -1	KCl	22.95	24.47	23.48	23.02	22.73	23.17
	HCl	5.01	4.66	4.70	5.02	3.59	4.12
	Total	27.96	29.13	28.18	28.04	26.32	27.29
1- $\frac{1}{4}$	KCl	23.42	23.64	23.76	23.28	23.33	23.02
	HCl	5.21	4.83	4.52	4.32	3.60	4.12
	Total	28.63	28.47	28.28	27.60	26.93	27.14
$\frac{1}{4}$ - $\frac{1}{2}$	KCl	23.41	24.16	24.94	23.26	23.24	23.02
	HCl	4.83	5.01	4.68	4.86	3.93	3.95
	Total	28.24	29.17	29.62	28.12	27.17	26.97
$\frac{1}{2}$ - $\frac{3}{4}$	KCl	23.80	23.83	24.16	23.54	23.35	23.29
	HCl	4.83	4.49	5.00	4.33	4.09	4.31
	Total	28.63	28.32	29.16	27.87	27.44	27.60

^aAverage results from two slice samples; results for natural soil: KCl, 24.06; HCl, 3.96; total, 28.02.

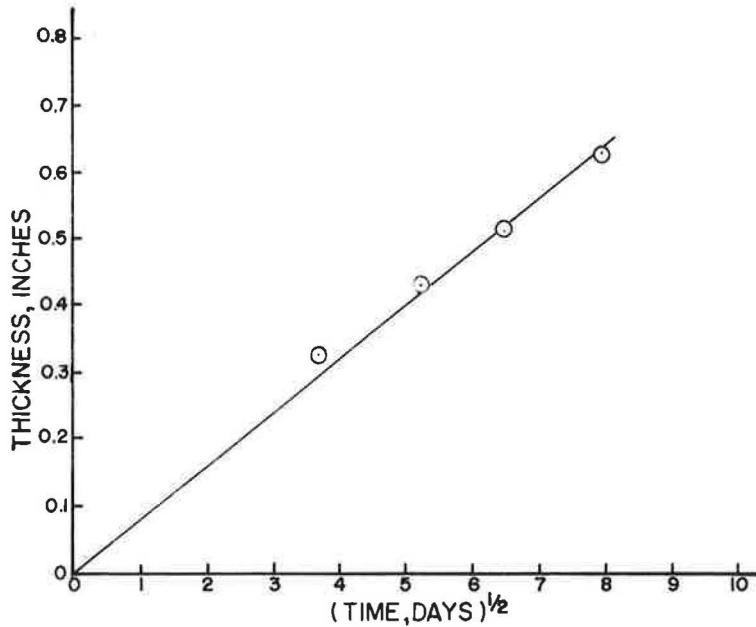


Figure 4. Thickness of lime penetration layer in lime migration study specimens vs square root of time.

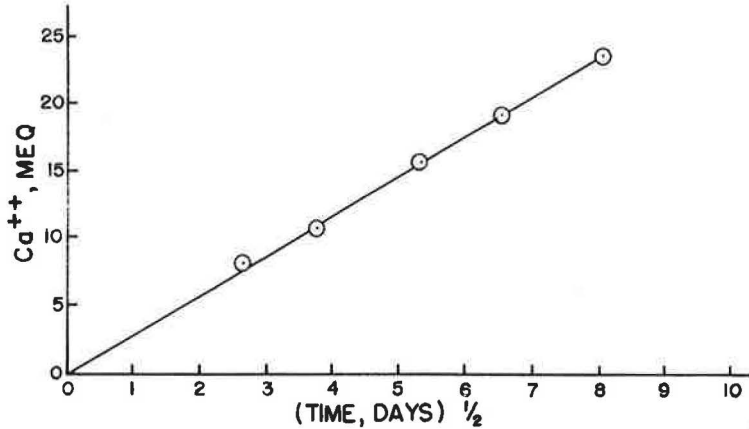


Figure 5. Total amount of calcium moving into 2-in. diameter lime migration study specimens vs square root of time.

temperature will affect the diffusion coefficient involved in the soil-lime reaction rate and will change the value of the constant.

The expression for the rate of lime penetration into a lime-soil water system will apply as long as there is solid lime available for the lime-soil reaction. Only after all lime enters into solution will there be a deviation from this relationship. The amount of lime penetration and pozzolanic reaction occurring after all lime enters into solution, however, will be insignificant, because lime solubility in water is quite low.

Agreement between the rate of lime migration into the specimens used in this investigation and an accepted solid-state reaction rate equation proves that water movement

into the specimens was negligible. A small hydraulic head resulting from placement of the lime slurry on top of the compacted soil specimens and a slightly less than 100 percent saturation condition present in the specimens apparently caused no significant water movement.

Figure 5 shows the relation between the total amount of calcium ions which diffused into the migration study specimens with time. The amount of calcium was calculated from the areas under the bars in Figure 3 and the density and dimensions of the specimens. A linear relationship between the total amount of lime diffusing and the square root of time is shown by this plot.

The diffusion coefficient for the particular soil-water system investigated could not be determined from data taken in this investigation. The constant in the rate equation formulated is a function of the change in free energy of the reaction, the diffusion coefficient, the cross-sectional area of the diffusion layer, and a constant. A diffusion coefficient determination would require an investigation of the temperature dependence of the equation.

Plastic Limit Changes

P.L. tests were performed on slice samples from specimens into which migration of lime had occurred for periods of 28, 42, and 63 days. The results shown in Figure 6 are evidence of lime movement in an amount sufficient to increase the P.L. of soil contained in the migration study samples. Although large slice samples made the actual P.L. distribution impossible to determine and the 28-day results are erratic, the P.L. results are generally consistent with the calcium ion determination data. At 63 days there was a significant increase in the P.L. of the soil located at $\frac{1}{2}$ to $\frac{3}{4}$ in. away from the lime source. The lime penetration distance calculated from calcium ion determination data demonstrated that the lime had diffused approximately 0.64 in. in 63 days.

Pozzolanic Reaction Products

X-ray diffraction patterns of $\frac{1}{4}$ -in slice samples taken from the portions of the lime migration specimens immediately adjacent to the lime sources showed the presence of

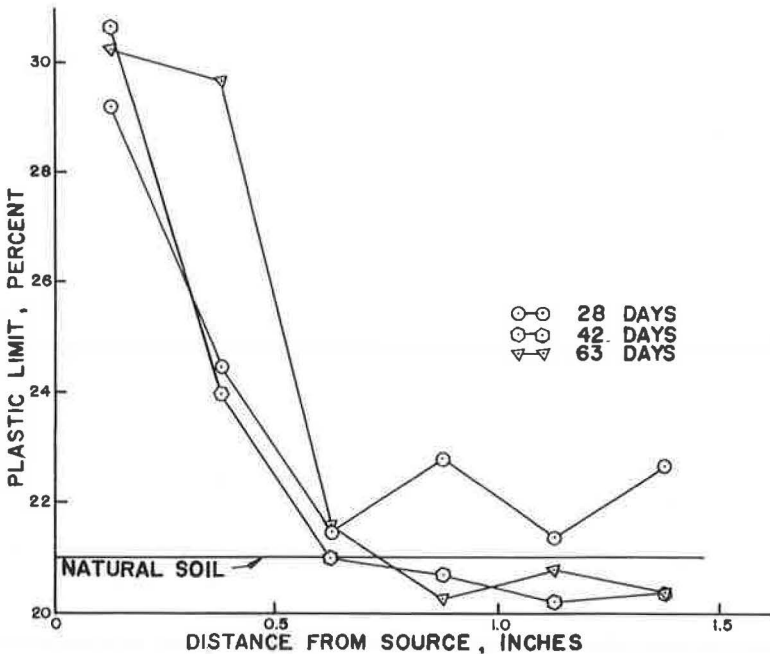


Figure 6. Plastic limit of slice samples taken from lime migration study specimens after various times vs distance from lime source.

calcium aluminate hydrate. All calcium aluminate hydrate peaks at d-spacing of 8.1, 7.6 and 3.9 Å were present on the diffraction charts of two samples studied. One of the samples was from 14-day diffusion specimens and the other was from 63-day specimens.

A $\frac{1}{4}$ -in. slice sample from the 63-day diffusion specimens taken $\frac{1}{4}$ to $\frac{1}{2}$ in. away also gave weak X-ray diffraction peaks at d-spacing of 8.1 and 7.6 Å. A sample from this pattern of the other diffusion specimens failed to produce these peaks. The actual extent of the pozzolanic reaction product layer in the 63-day specimens was impossible to determine from the X-ray diffraction study, but it is obvious that the layer boundary was somewhere between $\frac{1}{4}$ and $\frac{1}{2}$ in. away from the lime source.

X-ray diffraction findings and the results of the calcium ion determinations in Table 5 indicate that when the secondary leaching solution of hydrochloric acid removed an amount of calcium ions over 5 to 6 meq/100 g of dry soil from the diffusion study samples, a pozzolanic reaction had taken place. Although a small amount of reaction products was probably dissolved and removed by leaching with potassium chloride, increased calcium ions in the hydrochloric acid leachate is the most logical indication of a pozzolanic reaction. Results of this investigation show that a pozzolanic reaction can be detected by changes in the calcium ion concentration in a secondary hydrochloric acid leachate from a lime-soil mixture which has been previously leached with a potassium chloride solution to remove all dissociated calcium ions.

Increased calcium ions were detected in the hydrochloric acid leachate from the slice samples taken $\frac{1}{4}$ to $\frac{1}{2}$ in. away from the lime source of the 28-day lime migration specimens. The average pH of these slice samples was 9.75; the average pH of the slice samples nearest the lime source was 11.25. This indicated that a minimum pH of approximately 10.5 was necessary for a pozzolanic reaction, which agrees with previous work by Ho and Handy (19).

CONCLUSIONS

1. Although soil lumps lower the strength of a compacted soil-hydrated calcitic lime-water mixture, the effect diminishes with time as the lumps are stabilized as a result of lime movement in the system. The degree of lump stabilization depends on time and the size of the lumps.
2. The rate of hydrated calcitic lime penetration by diffusion into the particular soil-water system investigated is given by Eq. 5. This expression relating lime penetration and time will hold as long as solid lime is available to the soil-water system. Although an adjustment may be needed in the constant, this expression should be applicable to any similar soil-water-lime systems.
3. Water movement may assist the movement of lime within a soil-water system but is essential only because it provides a medium for lime diffusion.
4. Lime diffusion can occur in sufficient amounts to cause both flocculation and pozzolanic reactions in the soil-water system. The amount of reaction depends on time and the availability of lime. A minimum pH of approximately 10.5 is necessary for pozzolanic reaction.
5. Calcium aluminate hydrates crystallize in a montmorillonitic soil-lime-water system after less than 20 days of curing at room temperature. Calcium silicate hydrates probably are formed at the same time as the calcium aluminate hydrates, but poor crystallinity prevents absolute detection by X-ray diffraction after such a short curing time.
6. Providing no carbonate is present, pozzolanic reactions may be detected from a change in the calcium ion content of the hydrochloric acid leachate from soil-lime-water previously leached free of dissociable calcium ions with a potassium chloride solution.
7. Some soils posing a pulverization problem may be more effectively and economically stabilized with lime if pulverization requirements are relaxed. Rather than specifying a minimum percent passing any given sieve, a specification might indicate a maximum lump size, which could relate to time allowable for complete stabilization.

ACKNOWLEDGMENTS

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Discussion

ROBERT M. NADY, Consulting Engineer and Associate Professor, Iowa State University. — The following deals with an application of coarse soil pulverization for soil-lime stabilization. Early in 1964, a problem arose during the design of the pavement for the Mount Pleasant, Iowa, airport. Preliminary design estimates indicated that a soil-lime subbase would be the logical selection. The existing technology of lime stabilization in

Iowa seemed to be largely based on the techniques employed for portland cement stabilization. Prevalent specifications required that 60 to 80 percent of the pulverized material pass the No. 4 sieve, exclusive of any gravel-sized particles present in the mass.

The problem centered around soil pulverization. The soils in the Mount Pleasant region are montmorillonitic with clay-sized fractions in the 25 to 35 percent range. Pulverizing such plastic soils finer than about 1-in. lumps is expensive and time consuming, especially if the soil moisture is high. Therefore, the use of lime as a stabilizer depended on modification of the usual requirements for soil pulverization.

Design

In February 1964, I was retained by a consulting engineering firm to participate in the design of the airport pavement. Several soil samples secured from the site on Feb. 28, 1964, were tested in the laboratory. Though extensive sampling was done, two samples of materials were from sources which would lie in the subbase or upper subgrade of the pavement structure. Properties of these soil materials are given in Table 6.

Based on these subgrade soil properties, a design wheel load of 10,000 lb, and the availability of construction materials in the vicinity of the site, the pavement cross-section was selected as follows:

- 2 in. asphaltic concrete surface,
- 4 in. asphaltic concrete base,
- 6 in. subbase, and
- Prepared subgrade.

Lime Tests, Laboratory

Standard subbase construction makes use of the existing soils improved by the addition of granular material. It was felt that a greater degree of improvement than normally realized from granular treatment would be desirable for this project. Experience with granular-stabilized montmorillonitic soils showed that shrinkage and frost susceptibility were modified but not eliminated.

The benefits derived from lime treatment of heavy Iowa soils has been established on several highway projects in the state. The improvement in quality of subgrade soils by the use of lime for both airports and highways has been well documented in other states. Because of the nature of the construction materials in the vicinity of the airport site, it was assumed that lime stabilization of the subgrade

TABLE 6
PROPERTIES OF SUBBASE SOILS

Property	Sample	
	1	2
Color	Dark gray	Dark yellow brown
Depth (ft)	0-2	2-4 $\frac{1}{2}$
FAA classification	E-10	E-10
% sand, No. 10-270	3.5	5.0
% silt, No. 270-5 μ	64.4	67.0
% clay, < 5 μ	32.1	28.0
Atterberg limits		
L. L. (%)	67.0	60.1
P. I. (%)	39.8	34.9
CBR, 4-day soaked,		
0.1-in. pene.	2.8	3.3
Expansion (%)	4.7	3.3
Moisture increase (% dry wt.)	5.1	3.0

TABLE 7
IMPROVEMENT OF LIME-TREATED SOIL NO. 1

Property	Soil Values	
	Untreated ^a	Treated ^b
CBR, 4-day soaked, 0.1 in.	2.8	45.4
Expansion (%)	4.7	1.9
Moisture increase (% dry wt.)	5.1	3.0

^aStandard pulverization.

^b3 percent lime, 1-in. lumps, approximately 20 percent passing No. 4 sieve.

soil, rather than granular improvement or total replacement, would provide an economical subbase having the desired properties. A detailed cost estimate proved this assumption to be correct, and soil-lime was selected for further study.

As noted earlier, pulverization of heavy clay soils has proved to be a difficult requirement. Current practice on state highway projects requires that from 60 to 80 percent of the processed mixture, exclusive of gravel-sized material, pass the No. 4 sieve. Contractor experience shows that this requirement is sometimes impossible to achieve, even with lime pretreatment of the soil, and it is time consuming and expensive. Therefore, lime appeared to be the logical stabilizing agent. But for construction purposes, a different concept of the degree of pulverization of the mass was necessary.

About this time, preliminary data from the work of Davidson, Demirel and Handy became available. The data indicated good results with lime-soil stabilization with the soil pulverized to a much lesser degree than required by current practice. The migratory effect of the lime reaction was under study, and the early results were positive. The trade literature also contained articles dealing with drill-lime stabilization of soft subbases under existing pavements. Although all the information pointed to favorable results with soil-lime in which a large proportion of soil lumps remained undivided, a laboratory test of the soil from this project site was conducted.

Since soil No. 1 was the weaker of the potential subbase soils (Table 6), it was selected for lime treatment. The supply of the sample was limited, however, and only one specimen could be prepared. Since the CBR values of the untreated soil had already been determined, this method of evaluation was also used for the lime-treated test. Other investigators working with similar soils found that about 3 percent lime gave significant improvement, so this lime content was selected.

The soil was prepared by breaking or cutting it into lumps of 1 in. or less in size. Although no sieve analysis was performed on the material, about 20 percent would probably have passed a No. 4 sieve. Three percent calcitic hydrated lime was added to the prepared soil, and moisture was added to bring the mixture to approximately optimum moisture content. The mixture was lightly turned over with a large spoon in a mixing bowl for a few seconds. Mechanical mixing was ruled out to avoid degradation of the soil lumps. The loose mixture was allowed to stand for 48 hr at 95 percent R.H., simulating a 48-hr field cure if lime pretreatment were used. The mixture was then compacted in a CBR mold using the standard equipment, methods, and sequences for the CBR test. Following the 4-day soaking period, the CBR test was run. The results given in Table 7 show a most gratifying degree of improvement. The test data, together with other available information, formed the basis from which the Project Special Provisions were drawn.

Project Special Provisions

The soil-lime subbase specifications were drawn along the usual lines for the sections covering the description of the work, the materials of construction, and the construction equipment. The section on construction methods reflects the work of Davidson, Demirel, and Handy, as well as the tests results given in Table 7. It is quoted, in part, from the Project Specifications as follows:

Mixed In-Place. Soil-lime subbase shall be constructed from subgrade soil to the width and thickness shown on the plans. The surface of the subgrade, prior to subbase construction, shall comply with . . . of this section.

Either bagged or bulk lime may be used except that bagged quicklime shall not be permitted. If bulk lime is used, approved spreading equipment shall be provided. If bagged lime is used, the manufacturer's bag weights shall be accepted. Bags shall be placed in a uniform and regular pattern providing the specified quantity of treatment. Spread lime that has been displaced prior to mixing shall be restored. Lime shall not be spread when the layer to be processed or the subgrade is frozen or when the air temperature is less than 40°F.

The surface of the subgrade shall be scarified to a depth necessary to provide the quantity of material, which when combined with the specified quantity of lime, will produce a compacted subbase of the thickness designated on the plans.

The scarified soil shall be processed with approved graders, discs, harrows, or rotary mixers. Either of the following construction sequences may be directed by the engineer, depending on the moisture content of the subgrade soil at the time of construction.

Sequence 1. For the condition of moderate to high moisture content of the subgrade soil, the scarified soil shall be processed into chunks 3 inches or less in diameter. Upon the surface of the soil, one-half of the specified amount of lime shall be spread. The lime shall be cut in with mixing equipment. The surface of the layer shall then be lightly rolled with a pneumatic roller to effect a surface seal and to prevent the entrance of surface water. The layer shall be left undisturbed for a period of not less than 24 hours and not to exceed 72 hours.

After the passage of the required curing period, the remaining one-half of the lime shall be spread. Mixing shall continue until the lumps of soil mixture are reduced in size to $1\frac{1}{2}$ inches diameter, or less. If required, water shall be added during mixing to obtain and maintain optimum moisture content, plus or minus 2 percent. Following the mixing, compaction and finishing . . . shall proceed. Final compaction shall be completed with 48 hours of final mixing.

Sequence 2. For the condition of low to moderate moisture content in the subgrade, the scarified soil shall be processed into lumps $1\frac{1}{2}$ inches or less in diameter. The total amount of lime as specified shall be spread on the prepared material. Mixing of the soil and lime shall proceed until a uniform mixture is obtained. If required, water shall be added during mixing to obtain and maintain optimum moisture content, plus or minus 2 percent. Following the mixing, compaction and finishing . . . shall proceed. Final compaction shall be completed within 48 hours of final mixing. . . .

Construction of Project Subbase

Subbase processing started on Oct. 12, 1964, and was substantially completed by Oct. 20, 1964. The contractor had no difficulty in meeting the requirements of the specifications. Since the weather was dry and mild throughout the period, Sequence 2 was used. Within the specification limits and the capabilities of the equipment on the job, the contractor requested approval of, and was permitted to try, different orders of mixing and adding lime and water as well as different lime spreading techniques. Although the contractor selected the optimum order for his particular equipment spread, there appears to be little difference between the various construction segments, insofar as the quality of the completed subbase is concerned. Some construction processes are shown in Figures 7 to 15.

Field Testing.—The project was inspected continuously during construction. On segments where the full depth was processed at one time, a minimum of three passes of the rotary mixer was required to effect complete mixing and the reduction of lumps to $1\frac{1}{2}$ -in. or less diameter. Although it was not a specification requirement, testing for the amount passing the No. 4 sieve gave a result of 36 percent for one test and a slightly higher value for an additional test. For the whole project, the fraction passing the No. 4 sieve was probably in the range of 30 to 40 percent.

The Soil Research Laboratory, Iowa Engineering Experiment Station, Iowa State University, conducted plate bearing tests at selected locations on the prepared subgrade and on the completed subbase. The field data was reduced to load/deflection information in appropriate units and is presented in that form in Table 8. It will be noted that the lime treatment has materially increased the bearing capacity of the soil. A given load causes much less deflection of the plate on treated soil than on untreated soil.



Figure 7. Unloading and spotting bagged lime.



Figure 8. Opening bags of lime.



Figure 9. Spreading bagged lime with motor grader.



Figure 10. Spreading lime with drill spreader.



Figure 11. Spreading bulk lime with a long sweep discharge elbow attached to bulk transport; only a slight amount of dusting and air-borne lime.



Figure 12. Completed spread from one load of bulk lime directly down runway edge (note uniformity of spread).



Figure 13. Mixing soil-lime with rotary mixer.

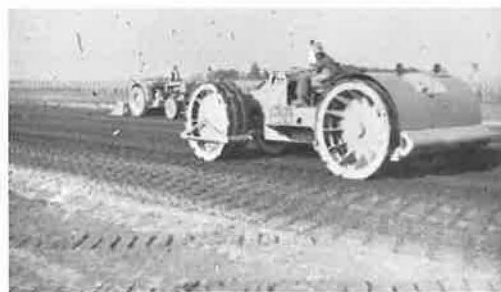


Figure 14. Compacting soil-lime with segmented roll static compactor.



Figure 15. Airstrip with subbase, MC-0 cure, and asphaltic concrete base.

The values of deflection of 0.05 and 0.10 in. were selected for reporting in Table 8, although plate bearing tests were made taking deflection readings up to 0.60 in. in one case, with the maximum readings generally in the range of 0.20 to 0.40 in. Corresponding unit loads ranged generally from 65 to 80 psi at maximum deflection.

Anticipated Performance.—To relate the plate bearing test to performance under design load, data for various aircraft were accumulated. Since no design contact pres-

TABLE 8
RESULTS OF PLATE BEARING TESTS, MOUNT PLEASANT,
IOWA, AIRPORT RUNWAY^a

Location	Applied Load (psi)			
	At 0.05-In. Deflection		At 0.10-In. Deflection	
	Subgrade	Subbase ^b	Subgrade	Subbase ^b
Sta. 6+00, centerline	17.7	—	30.5	—
Sta. 10+00, centerline	17.5	26.0	27.4	43.4
Sta. 15+00, centerline	21.8	29.2	38.2	53.7
Sta. 20+00, right 5 ft	19.5	34.0	38.8	60.4
Sta. 25+00, left 10 ft	26.0	27.4	45.9	52.7
Sta. 30+00, centerline	—	26.0	—	45.0
Average	20.5	28.5	36.2	51.0

^aUsing 12-in. diameter plate.

^bOf 6-in. soil-lime.

TABLE 9
LOAD AND PRESSURE DATA FOR AIRCRAFT

Aircraft	Fully Loaded Gross Wheel Load (lb)	Tire Contact Area (sq in.)	Contact Pressure (psi)	Pressure at 6-In. Depth (psi)	Pressure at 12-In. Depth (psi)
Aero Commander	3,000	153	19.6	5.7	2.6
Beech Twin Bonanza	3,000	153	19.6	5.7	2.6
Beech 18	4,650	171	27.2	8.2	3.9
Cessna 407 (jet)	3,725	171	21.8	6.6	3.1
Cessna 310	1,930	117	16.5	4.2	1.9
Fornaire Ercoupe	600	90	6.7	1.5	0.6
Mooney	1,300	108	12.0	3.0	1.3
Piper Apache	1,600	126	12.7	3.3	1.5
Navion	1,160	108	11.0	2.7	1.2
Luscombe Silvalire	600	90	6.7	1.5	0.6
DC-3	11,800	238	49.6	17.7	8.8
Convair 340	21,306	304	70.1	27.0	14.2
DC-6	46,300	468	99.0	44.5	25.2

sure criteria are used, the design wheel load of 10,000 lb is approached and exceeded by the aircraft wheel load data. Although not every craft of this size range is represented, the information includes typical light private, commercial, charter, and training planes of types most likely to use the runway. Also, the listing includes multiengine transports in commercial usage in this area (Table 9) for comparative purposes.

Data of Tables 8 and 9 show that under the field conditions at the time of the plate bearing tests, the pavement structure could successfully carry a fully loaded DC-3 and Convair 340 without exceeding the limiting deflection of 0.05 in. A fully loaded DC-6 would cause deflections greater than 0.05 in. but less than 0.10 in. The writer has observed overloaded flexible pavements deflecting as much as $\frac{3}{8}$ to $\frac{1}{2}$ in. without detectable damage. These large deflections and excessive loads were not repetitive in nature, however, but could be compared to emergency use of the airport by heavy craft.

Table 9 data were developed for a circular tire contact area and a 45° cone angle of stress distribution downward from the surface. An elliptical or oval-shaped contact area, more nearly like an aircraft tire print, would give a greater area of stress spread at the subbase and subgrade depths in the structure. Further, the 45° spread angle enjoys considerable support when applied to layers of granular material. But little is known regarding distribution of stress through layers of bituminous base or lime-stabilized soil. One study currently in progress shows that stresses transmitted through a 6-in. layer of bituminous concrete are about half the level of stresses transmitted through a 6-in. layer of compacted crushed stone. The stresses were distributed over a correspondingly larger area under the bituminous concrete.

Considering the shape of the contact and stress distribution areas, a safety factor between 3 and 4 seems to be operating. However, the plate bearing tests were made during mid-October in 1964 at a time when the soil moisture was low and the subgrade was stable. After the spring thaw, the subgrade may be soft. Based on the earlier CBR tests (Table 6) the subgrade soil will have a subgrade reaction (k) value of about 100 pci when saturated. At a k value of 100 pci, a unit load of 5 psi on the subgrade would produce a deflection of 0.05 in. The subgrade stress load produced by the DC-3 of 8.8 psi thus exceeds the limiting load (5 psi) by about 75 percent. This causes a reduction in the safety factor from the range of 3 to 4 to a range of 1.7 to 2.3. Since the DC-3 wheel load is about 10 percent greater than the design wheel load, a modest safety factor exists under poor subgrade conditions for the design wheel load of 10,000 lb.

Conclusions

Based on the data contained here, site inspection during construction, and all other available data and observations, the following conclusions are drawn:

1. The research data developed and reported here for coarse lump soil pulverization in soil-lime mixtures was verified in a full-scale airport construction project.
2. Pulverization requirements of the project specifications were readily attainable in the field with typical construction equipment and standard methods of processing.
3. The Federal Aviation Agency procedure for thickness design of flexible airport pavements embodies a modest but realistic factor of safety.
4. Plastic soils, which are generally subject to improvement by lime treatment but are difficult to pulverize to a high degree, can be successfully treated with lime if current pulverization requirements are relaxed.
5. Laboratory design testing can be limited to a determination of the susceptibility of a soil to improvement by lime treatment. If a soil reacts favorably, the presence of lumps up to 1½ in. in diameter, and probably greater, will cause but little difference in this determination.
6. Project operational sequence, within the limits of the specifications presented herein, produces no detectable difference in the completed layer. Capabilities of a given equipment spread on a given project can thus be optimized.
7. A new approach to lime treatment of heavy soils is opened. As the use of this technique increases, further economies will be realized.

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L. K. DAVIDSON, T. DEMIREL, and R. L. HANDY, Closure.—The only comment we would make is to repeat a remark overheard in the audience at the time of Professor Nady's presentation: "It takes guts." Additional reflection on the matter forces us to agree. Engineering, particularly when it employs unconventional methods, does "take guts," and we in teaching and research tend to overlook the "guts" involved in getting the technical paper parade into practice. When it is done, it is most gratifying.