HIGHWAY RESEARCH BOARD

Bulletin 262

Preconditioning and Stabilizing Soils By Lime Admixtures

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Preconditioning and Stabilizing Soils By Lime Admixtures

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Contents

Lime Stabilization Using Preconditioned Soils

W.H. TAYLOR, JR., Bituminous Construction Engineer; and
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Baton Rouge

The scope of this investigation was to study the development of a new method of base construction using lime stabilization with a different concept than the conventionally accepted ones.

In this construction method, a first application of lime is used to condition the soil constituents; a second, to stabilize the conditioned material. This new method was adopted after a study of different soil-lime projects and their laboratory tests, the main objective being subsequent failures and their reasons. All tests, and field experience, led to the conclusion that to obtain the desired properties of stabilization with these types of soils they must be treated with lime before being stabilized and must be compacted within 48 to 72 hr after the second application of lime.

A further time study of the soil-lime reaction was made, based on information yielded by the soil characteristics tests. These tests revealed that lime has an initial reaction, taking place during the first 48 to 72 hr after mixing, and a secondary reaction, which starts after this period and continues indefinitely.

Also, an investigation of moisture-density relations of soils pointed out the effectiveness of conditioning before stabilization. Conditioned material produced higher densities at lower moisture contents after stabilization.

● THE SCARCITY of select material in Louisiana has imposed on the highway builder the necessity of finding an admix which would make possible the economical use of the local soil deposits for base construction. The use of soil-lime stabilization for this purpose was explored, and a number of roads were built with lime stabilized bases. The construction of these roads, however, produced various technical problems, which aroused questions in the minds of Louisiana engineers as to the value of lime stabilization. Therefore, the latter practice was abandoned for a period of three years pending further studies.

In 1957, a study was undertaken by Louisiana Department of Highways to evaluate the lime stabilized bases. The performance of these bases was investigated in relation to their construction methods, maintenance, traffic conditions and materials test results.

Date yielded by this study showed that the primary reasons for the failure of a lime stabilized base were poor mixing and delay in compaction after the completion of the mixing.

Based on the knowledge gained from this investigation, a base was designed in one of the problem areas of Louisiana; and a new construction method was developed.

The new procedure called for two applications of lime; the first, to condition the soil, and the second to serve as the actual stabilizing agent.

This paper summarizes results of the condition surveys of old bases and presents the new method of construction, its application, the end-product and test results.

Prior to this time, all soil-lime construction had been built under specifications which called for the soil to be scarified, pulverized and lime applied to it in one operation (1). Mixing was continued until such time as the pulverized soil, exclusive of gravel or stone, when tested by laboratory sieves, met the following gradation requirements:

Sieve	Percent Passing (by dry weight)
½-in.	100
No. 4	60

After this requirement was met, compaction operation was started. Projects constructed under these provisions can now be divided into two groups (Table 1).

Group One—projects in this group were constructed where the soil-lime base was compacted within 48 hr after mixing.

Group Two—projects in this group were constructed where the soil-lime base was compacted within 48 hr or more after mixing.

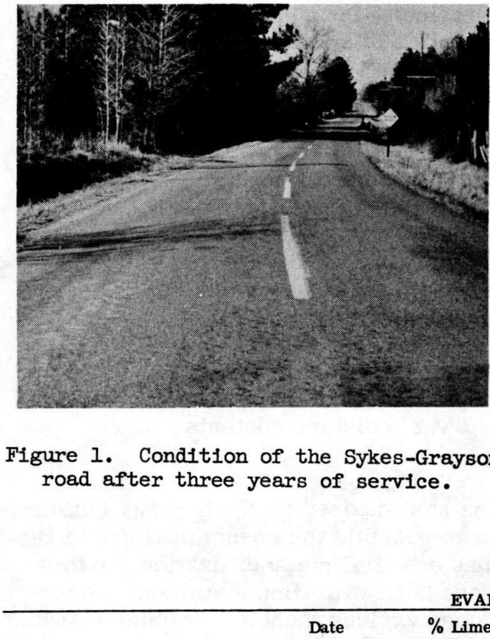

Figure 1. Condition of the Sykes-Grayson road after three years of service.

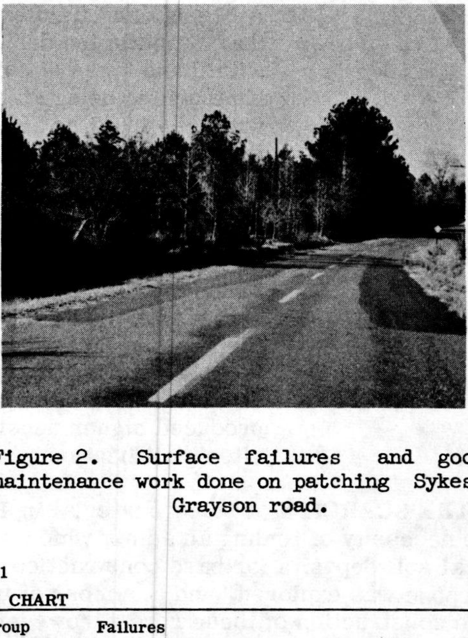

Figure 2. Surface failures and good maintenance work done on patching Sykes-Grayson road.

TABLE 1

EVALUATION CHART

Name	Date Constructed	% Lime by Weight	Group 1	Group 2	Failures Surface	Failures Base	Remarks
McCall-White Castle	1957	3		X	X	X	Compacted 5 days after mixing, roadway generally in fair condition. Localized base failures.
Labadieville-Paincourtville	1957	3		X	X	X	
Sikes-Grayson	1956	3	X		X		Roadway in very good condition. (Figs. 1 & 2)
Milhaven-Swartz	1955	3	X		X	X	No shoulders, base failures. Failure areas do not have any lime as a result of poor mixing. (Fig. 3)
Oak Grove-Lake Providence	1957	3		X	X	X	Some of the base failures are attributed to poor subgrade condition. (Fig. 4)
Newellton Road	1957	3		X	X	X	No Shoulders, generally the road is in a good condition. (Fig. 5)

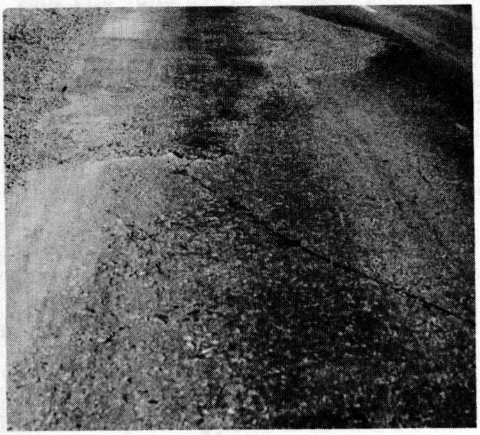

Figure 3. Base failure areas of Milhaven-Swartz road.

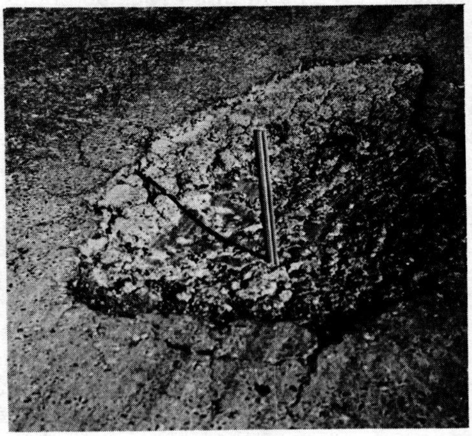

Figure 4. Base failure on Oak Grove-Lake Providence road.

Figure 5. Condition of the Newellton road after two years of service.

Figure 6. Condition of Highway 14 at Holmwood during the winter of 1958.

GROUP 1

Base material of the roads included in this group was pulverized, mixed and compacted immediately after the mixing. As of this date, these bases have been in service from 2 - 4 yr, yet they exhibit few surface failures and fewer base failures. Surface failures consist of shoving and subsequent cracking of the surface. Surface failures of well maintained roads have not affected the base.

Base failures have occurred where the full design depth was not stabilized, generally due to poor mixing.

GROUP 2

During the construction of these roads, lime was mixed with the base material, left open, but not compacted within 48 hr. In some cases it was compacted late because of the construction trend followed by the contractor, in others because of climatic limitations.

Surface failures in this group do not exceed in number those in group one, and they have the same characteristics. On the other hand, they have more base failures than those of group one. These failures are pronounced at the unsupported edges of those roads which have narrow shoulders. Base material is well packed, extremely crumbly, and friable; can be broken down to individual grains without any effort; and generally speaking, there was no cementation. Where the soil-lime stabilized material was confined and had full support on four sides, the bases have held up under traffic as well as those in the first group. It has exhibited the general characteristics of sand; if confined it makes a strong base, otherwise, it does not have any strength.

In conclusion, all of these projects point out the fact that if and when a soil-lime stabilized base is compacted within 48 hr after mixing, cementation takes place, and the whole base becomes a homogeneous slab, whereas, delayed compaction densifies the carbonated, friable material with no cementation (Fig. 7). Bases in the first group had the full advantage of both chemical and mechanical stabilization, while the latter group had only been stabilized mechanically, thus producing a relatively weaker base.

Sorting all of the information obtained from this investigation led to the necessity of working out a new method of construction, which would eliminate prolonged mixing and the curtailment of time before compaction.

PROJECT DOUBLE APPLICATION

About the time this study was completed, a familiar problem arose at Lake Charles, Louisiana. Approximately 18 mi southeast of Lake Charles, on State Route 14, two sections were let for construction with soil-cement stabilized bases. This construction required 210,000 cu yd of borrow material. Routine soil tests of the available borrow pits indicated that select material, which would be stabilized with portland cement, was insufficient, therefore, a change in the plans was deemed necessary.

Material from these pits was tested for suitability to stabilization with hydrated lime. Atterberg limit tests and Texas triaxial tests were run. There were four different types of soil; ranging from a sandy loam A-4 with a P.I. of 12 to a light silty A-6 with a P.I. of 27. The predominant material, a light silty clay, was tested triaxially. It produced a very high triaxial Class 1 material, with four percent lime by weight added and compacted with an effort of 13.26 ft lb per cu in.

The results of these routine tests favored lime stabilization. Therefore, a soil-lime stabilized base was designed to take the place of the previous one. The design called for a base thickness of 8 in. stabilized with 18 percent hydrated lime by volume. In the construction provisions of this road (2), measures were taken to prevent carbonation to take place before cementation. Thus, it was specified that the base be compacted within 24 hr after the final mixing, and lime applied in two separate operations. The first application was to condition the soil; prepare it for an easy, fast and most of all, uniform mixing. Otherwise, it would have been practically impossible to get a uniform mixture from the combination of clayey soils and lime within 24 hr prior to compaction, while the second application would provide enough lime for stabilization.

To decide the rate of the first and second applications of lime, another set of Atterberg limit and Texas triaxial tests were run.

Samples representing the predominant types of soils were secured and mixed with different percentages of lime, and

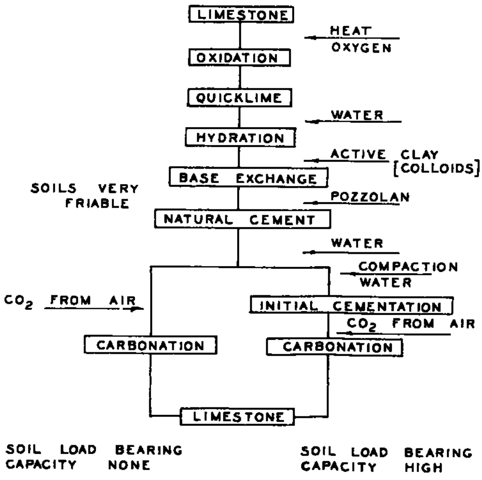

Figure 7. Flow diagram for lime stabilization.

water was added to bring the moisture content of the mix to the plastic limit of the raw soil. These specimens were put into covered pans and stored in the moist room for 72 hr. At the end of this period they were taken out of the moist room, dried at room temperature for 6 hr and broken down by hand, the only tool used being a 4-in. soft spatula.

The specimens tested represented a light silty clay A-6 with a P.I. of 27, and a sandy loam A-2 with a P.I. of 12.

In the discussion of the test results, two points were taken into consideration.

First, the amount of lime to be added during the first application should bring the plasticity index of this material down to a limit where pulverization and perfect mixing would be possible 24 hr after the second application. This limit was accepted as 10, based entirely on field experience. Second, this amount should condition the soil, but must not agglomerate all of the particles, leaving insufficient active clay for the cementation reaction to take place after the second application.

Test results indicated that the light silty clay would produce a P.I. of 8 by the addition of 9 percent lime by volume, and the sandy loam A-2 would produce the same if mixed with 6 percent lime by volume.

To confirm the base design, four sets of "double application" triaxial specimens were prepared (Table 2) using the foregoing percentages as guides, with four different types of soil, representing the entire project. All of these specimens produced a very high triaxial class 1 (Appendix).

From these test results, it was decided that both the first and the second application of lime would be 9 percent by volume.

CONSTRUCTION

The construction of this project was under the supervision of Lawrence Doucet, Project Engineer for the Louisiana Department of Highways, and the contract, dated June 17, 1957, was awarded to W.R. Aldrich and Company of Baton Rouge, La. Work was begun in July 1957, with the earthwork being started in April 1958. In January 1959, a special agreement was made between the Department and W.R. Aldrich and Company. This special agreement was made to substitute a soil-lime base course in place of a soil-cement base course as per original contract.

Treatment of the base was started in June 1959. It was decided to apply the first portion of lime throughout the entire length of the roadway and then apply the second portion of lime.

FIRST APPLICATION OF LIME

Prior to the application of lime, the roadway was graded and shaped to conform with the lines, grades and cross-section as set forth in the plans (Fig. 8). The roadway was then scarified to a depth of 4 in. and the first application of lime was applied. Bulk lime was spread uniformly on the scarified roadway for the full width of 22 ft. Preliminary mixing was done with a 30-in. disc which broke down the large clay lumps (Fig. 9) and mixed the soil-lime simultaneously. A Seaman Pulvimixer completed the mixing with water being added as necessary to obtain specified moisture contents. After a uniform mixture was obtained (Fig. 10) the base was re-shaped and sealed with a 5-ton rubber-tire roller to facilitate the operation of local traffic.

TABLE 2

TRIAXIAL TEST RESULTS

Triaxial Sample No.	Raw Soil Classification	Group	P.I.	% Lime—by Volume First Application	% Lime—by Volume Second Application	Triaxial Classification
TRX-1	Loam	A-4	15	9	9	1+
TRX-2	Sandy loam	A-2	12	6	12	1+
TRX-3	Clay loam	A-4	17	9	9	1+
TRX-4	Lt. silty clay	A-6	27	9	9	1+

Figure 8. Shrinkage cracks developed on the base before treatment with lime.

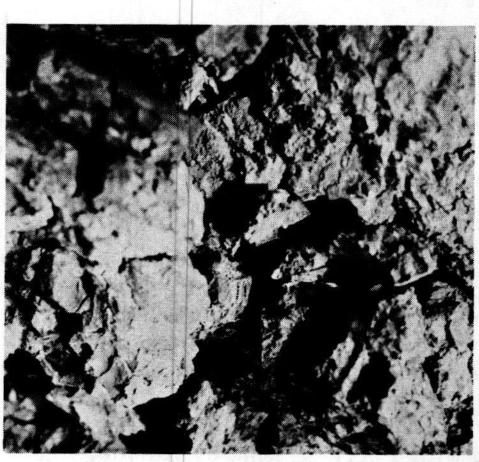

Figure 9. Condition of the soil after two passes of the disk.

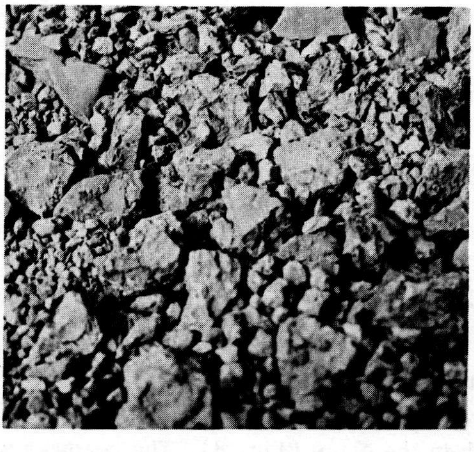

Figure 10. Uniformly mixed and pulverized material after the first application of the lime.

Figure 11. Mixed and pulverized soil-lime before compaction after the second application.

SECOND APPLICATION OF LIME

The second application of lime, the actual stabilization of the base, started 30 days after the beginning of the initial "conditioning" operation. Prior to this operation, the base material had become highly friable, which made additional discing unnecessary.

After the base was re-shaped and its edges marked by the grader, lime was spread over its entire width, scarified to a depth of 4 in., and mixed to the specified depth of 8 in. with a Seaman Pulvimixer. Regardless of the type of soil, a very uniform mixture was obtained and pulverization was such that 80 percent of the material passed the No. 4 screen; which was above the requirement of the specifications (Fig. 11). Following the dry pulverization, water was added and mixed uniformly with soil-lime mixture by the use of a Seaman Pulvimixer with a watering attachment, bringing the moisture content to the required optimum.

After the moisture content and depth of the base were checked, compaction operations were started, with a 35-in. diameter 10-ton sheepsfoot roller and a 5-ton rubber-tire roller.

The density control tests, however, indicated that even after the sheepsfoot roller had walked out completely, 100 percent of the laboratory density (Modified Proctor Density—50 blows) could not be obtained. Therefore, the original sheepsfoot roller was replaced with a 35-ton, 76-in. sheepsfoot roller, which increased the average density obtained to 102 percent of the laboratory density, with the lowest being 100 percent.

As the rolling was completed, the surface was swept and kept wet until sealed with emulsified asphalt (EA-4), applied at the rate of 0.30 gal. per sq yd. The application of emulsified asphalt was made in six shots, being applied over a period of five days. During this five-day curing period, through traffic was detoured. Only local traffic was permitted on the road, which was insignificant as far as repetition and weight were concerned. After the curing period, the three-application surface treatment was applied and the road (Fig. 12) was opened to traffic.

Figure 12. The finished road after it was covered with three-course bituminous treatment.

A crew from the District Laboratory in Lake Charles was assigned to this project for sampling and testing the material and to assist the project engineer. This project was only 18 mi from the District Laboratory at Lake Charles, therefore, samples were taken to the laboratory and tested immediately. Tests run during the construction consisted of Atterberg limits and moisture density tests.

ATTERBERG LIMIT TESTS

As a section of the base was prepared for the first application of lime, sampling of the material started. The sampling schedule was as follows: One sample, approximately 2 lb was obtained from every 500 ft of the base and at every soil change. The first sample was taken prior to the application of lime. Additional samples were taken at frequent intervals, ranging from two hours to 40 days from completion of mixing. Extreme care was exercised in obtaining a representative sample and also in taking them from the exact same spot of the road every time. These were transported to the laboratory in sealed cans and tests were started as soon as the material arrived at the laboratory.

Soil Preparation

The preparation of this material deviated from the standard AASHO method as follows: (1) A moisture specimen was taken from every can before the preparation started. (2) The material was transferred into an aluminum bowl and was broken down by a soft steel spatula until all of the material passed a No. 40 screen. Then the standard Atterberg limit tests were run. It was rather a tedious operation, but was found to be the only practical way which allowed immediate testing without spoiling the mix by overheating or grinding. In an effort to check the adequacy of this modified method, paralleled tests were run, using the same soil in a raw condition and the results were found satisfactory.

Figures 13 through 16 show the relationship of Atterberg limits—time from mixing to testing. It will be noted that a radical change took place in soil characteristics during the first three hours. Regardless of the soil type, all plasticity indices show a reduction. It will further be noted that, from three hours to the second application of lime, very little additional reduction is indicated in P.I. with the exception of the light silty clay. Because this material contained a higher percentage of clay a longer reaction time is noted.

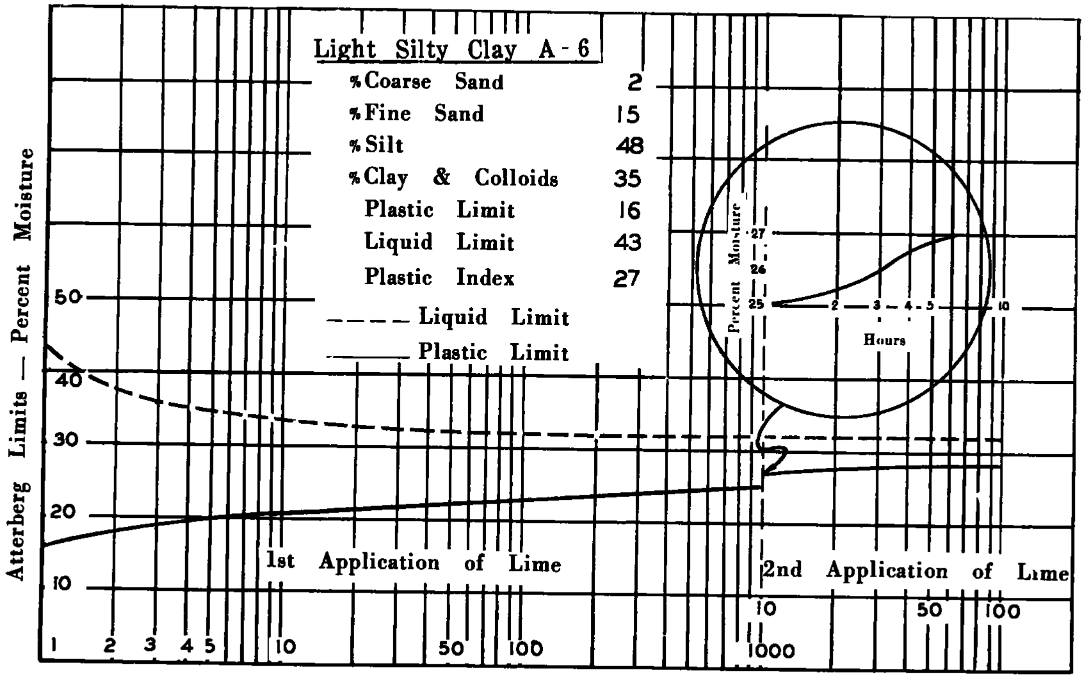

Figure 13. Time elapse between mixing and testing—hours.

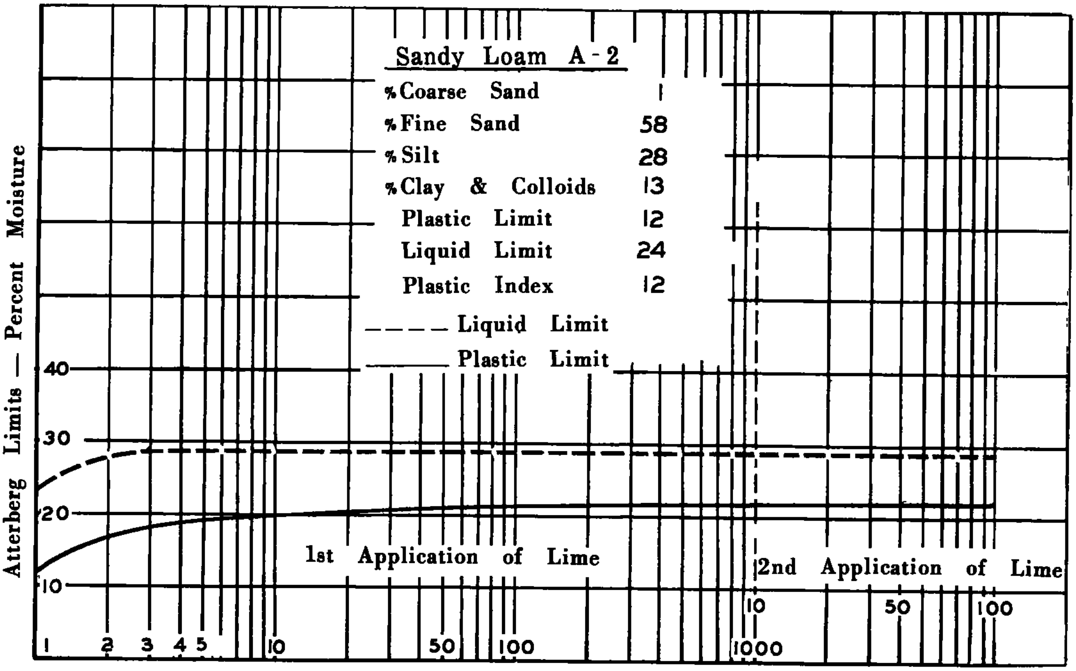

Figure 14. Time elapse between mixing and testing—hours.

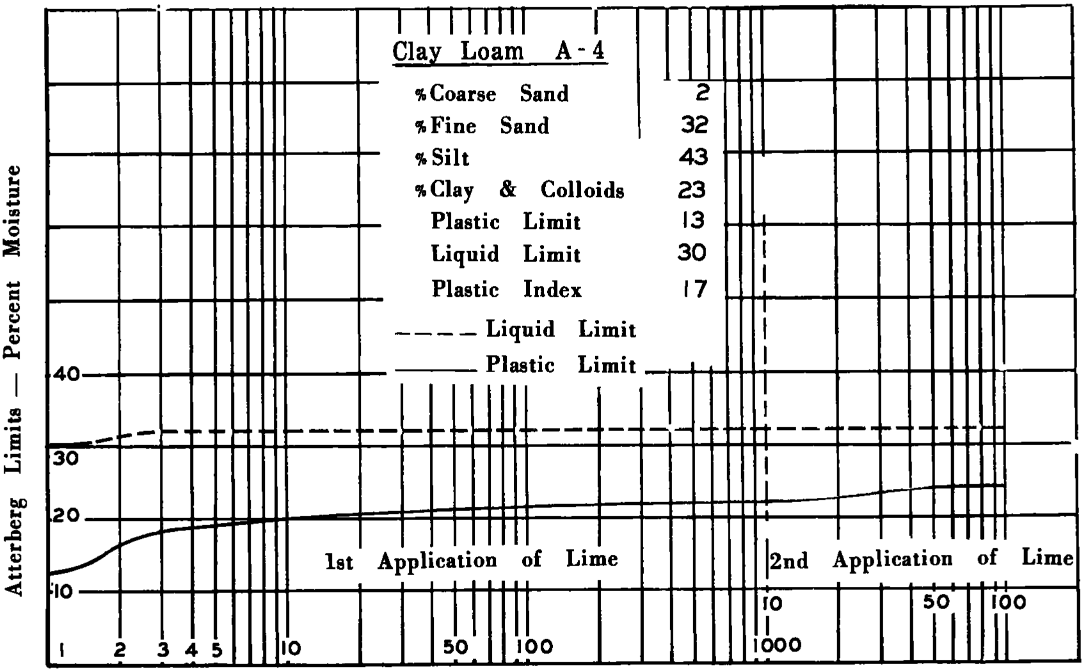

Figure 15. Time elapse between mixing and testing—hours.

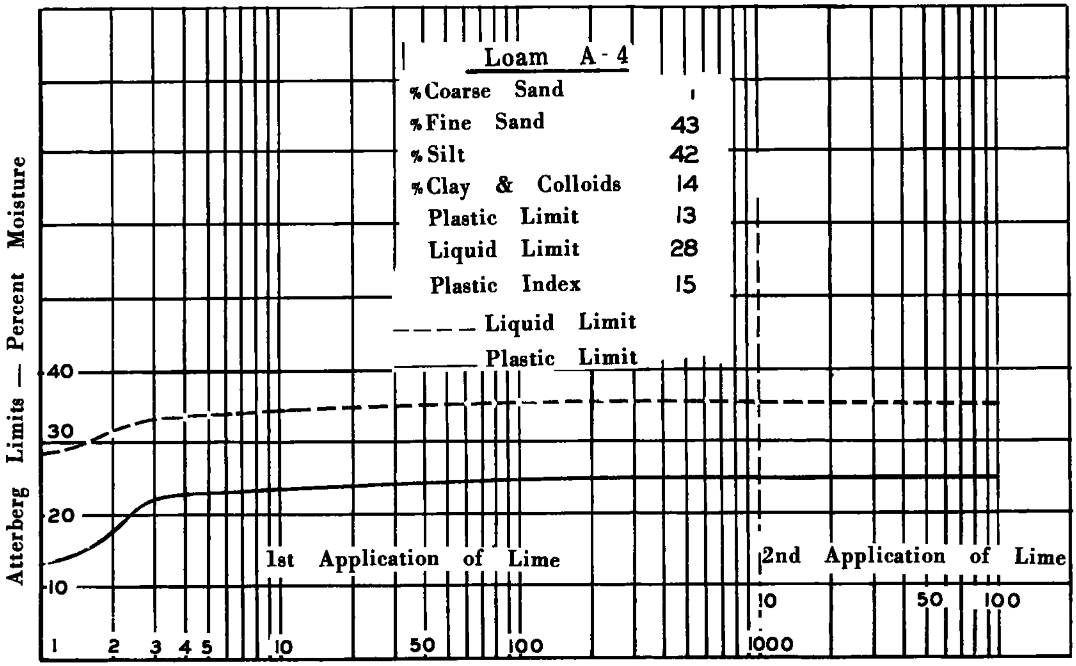

Figure 16. Time elapse between mixing and testing—hours.

The second application shows little change in liquid limit, with a moderate increase in plastic limit.

Results of the moisture-density tests are summarized in Figure 17. The optimum moisture content of each type of soil versus the maximum density obtained was plotted. Soils for the first three sets of moisture-density curves were prepared in the laboratory. The soils treated with the double application of lime (18 percent by volume) produced higher densities at lower moisture contents than those treated with a single application of lime. However, after construction was started, it was found that the curves prepared in the laboratory did not meet field conditions. Therefore, a fourth set of compaction curves were prepared where the soils were mixed with the actual construction equipment, cured in place and sampled four days prior to the second application of lime. The second application of lime was added in the laboratory. The results of these curves produced a lower density at a considerably higher moisture content than those of previous tests. Also, the results checked close to field conditions.

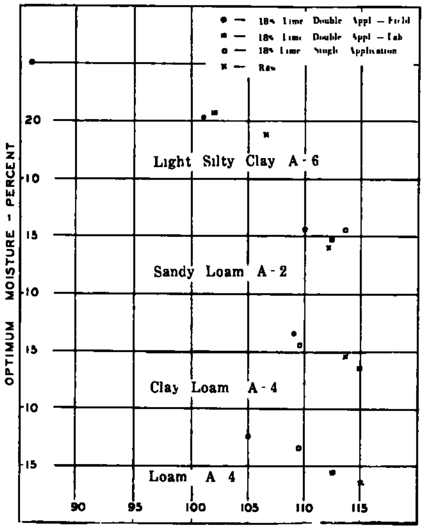

Figure 17. Maximum density (pcf).

CONCLUSIONS

1. Failures of soil-lime stabilized bases are caused by lack of cementation, which in turn is the result of one or all of the following deficiencies:

   a. Poor mixing due to high clay content.
   b. Insufficient depth and width.
   c. Delayed compaction of soil-lime mixtures.

2. On the basis of observations made during and after the construction, "the double application method" proved itself capable of solving some of the more important problems in stabilization.

   a. The first application of lime rendered the soil highly workable, changing its characteristics from worse to better.
   b. Facilitated the operation of the mixing equipment, materializing a most uniform and accurate mixing with sufficient depth and width coverage.
   c. Permitted immediate compaction following the mixing.
   d. Brought out the fact that very heavy compaction equipment is necessary for this type of construction.
   e. Eliminated surface cracks which were a problem in single application projects.

3. Information yielded by the test results indicated that:

   a. There is a harsh initial reaction taking place immediately after the addition of the first portion of lime.
   b. This reaction is fairly fast, rendering the soil friable within 3 to 25 hr after mixing.
   c. These facts, combined with the results of the study of previous construction, reinforced the theory that soil-lime mixtures should be compacted within 24 hr after mixing in order to obtain cementation.
   d. Equipment used for mixing, curing conditions, continuous changes of moisture and temperature in the field which cannot be duplicated exactly in a labora-

tory, created combined factors not present in the running of moisture-density curves for soil-lime stabilization in the laboratory; thus rendering the moisture-density curves run under the present conventional methods obsolete. A moisture-density curve prepared, using material mixed and cured in the field, is the only remedy found so far for this problem.

The construction method and test results reported herein should, by no means, be considered as a solution to all soil-lime stabilization problems, or as a complete picture of their general behavior. Further research in this field will produce better systems and methods which will warrant a more successful end-product.

ACKNOWLEDGMENT

The authors wish to express their appreciation to Sidney B. Norris, Assistant District Engineer and Lawrence Doucet, Project Engineer for their help and cooperation; the assistance of District 07 Testing Laboratory Personnel, especially that of Abraham Fontenot, Jr., Laboratory Technician, is also gratefully acknowledged.

REFERENCES

1. "Soil Lime Base Course Specifications—CS-3 6/56." Louisiana Department of Highways.
2. Soil Lime Base Course—Special Provisions—Special Agreement State Project No. 196-02-04.

Appendix

TRIAXIAL TEST RESULTS

STATE OF LOUISIANA
DEPARTMENT OF HIGHWAYS

TESTING & RESEARCH SECTION

Date 9/18/59

Project No. 196-01-04 Lab. No. 11529

Material Loam A-4

Remarks TRX-1

Opt.Moisture 17.4 Opt. Density 105.0 Comp.Effort 13.26 Ft.Lb./cu. in.

TRI-AXIAL COMPRESSION TEST CLASS 1^{+}

20 YEAR ROAD REQUIRES ________ INCHES OF BETTER MATERIAL FOR ________ POUND WHEEL LOAD

10 YEAR ROAD REQUIRES ________ INCHES OF BETTER MATERIAL FOR ________ POUND WHEEL LOAD

MOLDING DATA			CURING DATA			TESTING DATA			
Cylinder No.	Moisture % Dry Wt.	Dry Den. Lbs.Per Cu.Ft.	Cap. Moist. Time Days	Moisture After Drying % Dry Wt.	Moisture After Cap. Absorption % Dry Wt.	Applied Lateral Pressure P.S.I.	Ulti. Comp. Strength	Strain at Ulti. %	Swell Volume %
20	16.3	107.7	10	14.0	16.9	0	101.00	0.911	0.13
21	16.3	107.4	10	14.0	16.9	5	144.52	1.609	0.11
3	16.3	107.4	10	13.9	16.8	10	169.94	1.856	0.09
30	16.1	108.0	10	14.1	16.3	15	172.50	1.901	0.10
7	16.2	107.3	10	13.8	16.2	20	177.79	2.105	0.11

Figure 18.

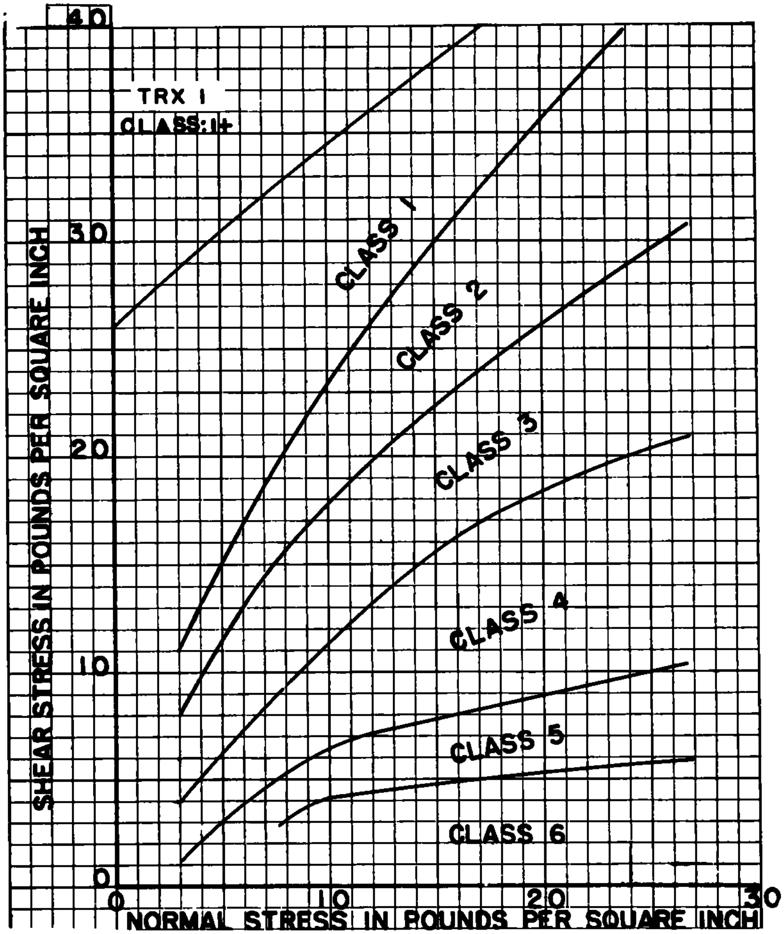

Figure 19.

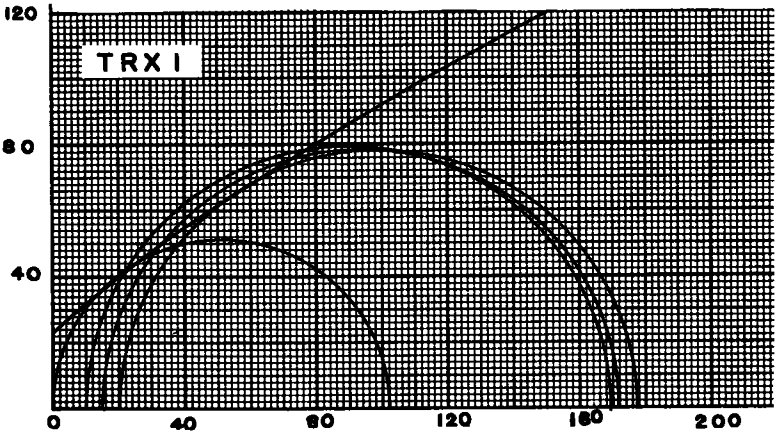

Figure 20.

STATE OF LOUISIANA
DEPARTMENT OF HIGHWAYS

TESTING & RESEARCH SECTION

Date 9/17/59

Project No. 196-01-04 Lab. No. 11530

Material Sandy Loam A-2

Remarks TRX-2

Opt.Moisture 15.6 Opt. Density 109.8 Comp.Effort 13.26 Ft.Lb./cu. in.

TRI-AXIAL COMPRESSION TEST CLASS 1^{+}

20 YEAR ROAD REQUIRES ______ INCHES OF BETTER MATERIAL FOR ______ POUND WHEEL LOAD

10 YEAR ROAD REQUIRES ______ INCHES OF BETTER MATERIAL FOR ______ POUND WHEEL LOAD

MOLDING DATA			CURING DATA			TESTING DATA			
Cylinder No.	Moisture % Dry Wt.	Dry Den. Lbs.Per Cu.Ft.	Cap. Moist. Time Days	Moisture After Drying % Dry Wt.	Moisture After Cap. Absorption % Dry Wt.	Applied Lateral Pressure P.S.I.	Ulti. Comp. Strength	Strain at Ulti. %	Swell Volume %
2	14.09	110.7	10	10.26	16.18	0	109.94	0.582	0.03
39	14.05	111.0	10	10.34	16.17	3	140.28	.622	0.03
27	14.10	110.7	10	10.38	16.77	5	183.33	1.120	0.04
24	13.98	111.1	10	10.97	16.35	10	198.21	1.240	0.00
6	14.16	110.9	10	11.10	16.60	15	212.00	1.62	0.00
18	14.20	111.0	10	11.03	16.10	20	235.30	1.68	0.02

Figure 21.

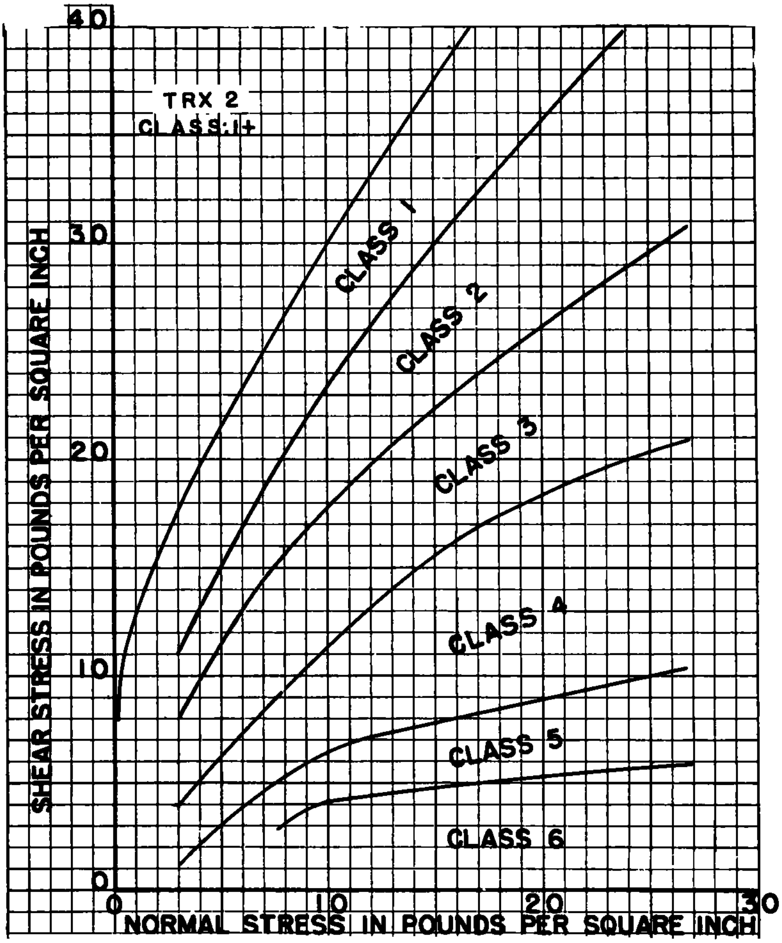

Figure 22.

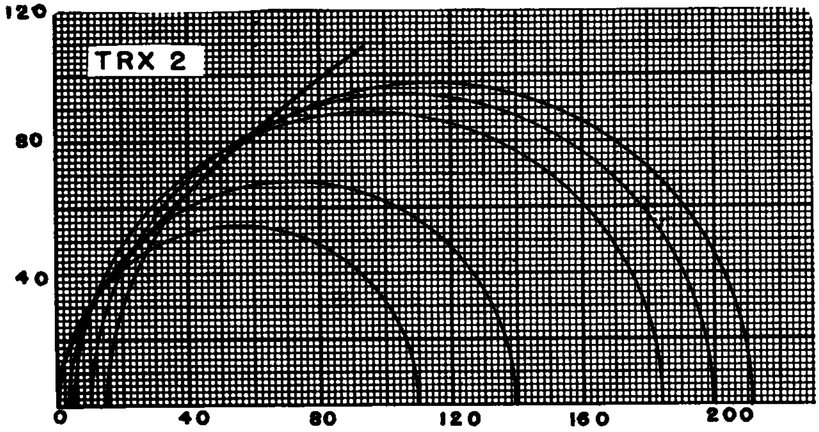

Figure 23.

STATE OF LOUISIANA
DEPARTMENT OF HIGHWAYS

TESTING & RESEARCH SECTION

Date 9/17/59

Project No. 196-01-04 Lab. No. 11531

Material Clay Loam A-4

Remarks TRX-3

Opt.Moisture 16.8 Opt. Density 109.0 Comp.Effort 13.26 Ft.Lb./cu. in.

TRI-AXIAL COMPRESSION TEST CLASS 1^+

20 YEAR ROAD REQUIRES ______ INCHES OF BETTER MATERIAL FOR ______ POUND WHEEL LOAD

10 YEAR ROAD REQUIRES ______ INCHES OF BETTER MATERIAL FOR ______ POUND WHEEL LOAD

MOLDING DATA			CURING DATA			TESTING DATA			
Cylinder No.	Moisture % Dry Wt.	Dry Den. Lbs.Per Cu.Ft.	Cap. Moist. Time Days	Moisture After Drying % Dry Wt.	Moisture After Cap. Absorption % Dry Wt.	Applied Lateral Pressure P.S.I.	Ulti. Comp. Strength	Strain at Ulti. %	Swell Volume %
41	16.22	106.3	10	14.2	17.7	0	126.2	0.992	0.02
60	16.59	107.0	10	13.9	17.1	3	170.7	1.384	0.04
37	15.98	107.2	10	14.4	17.4	5	175.8	1.121	0.01
38	16.24	107.4	10	14.6	17.2	10	190.91	1.116	0.01
19	16.63	107.5	10	14.1	17.0	15	202.6	1.741	0.05
31	16.01	107.3	10	14.8	17.5	20	220.0	2.020	0.03

Figure 24.

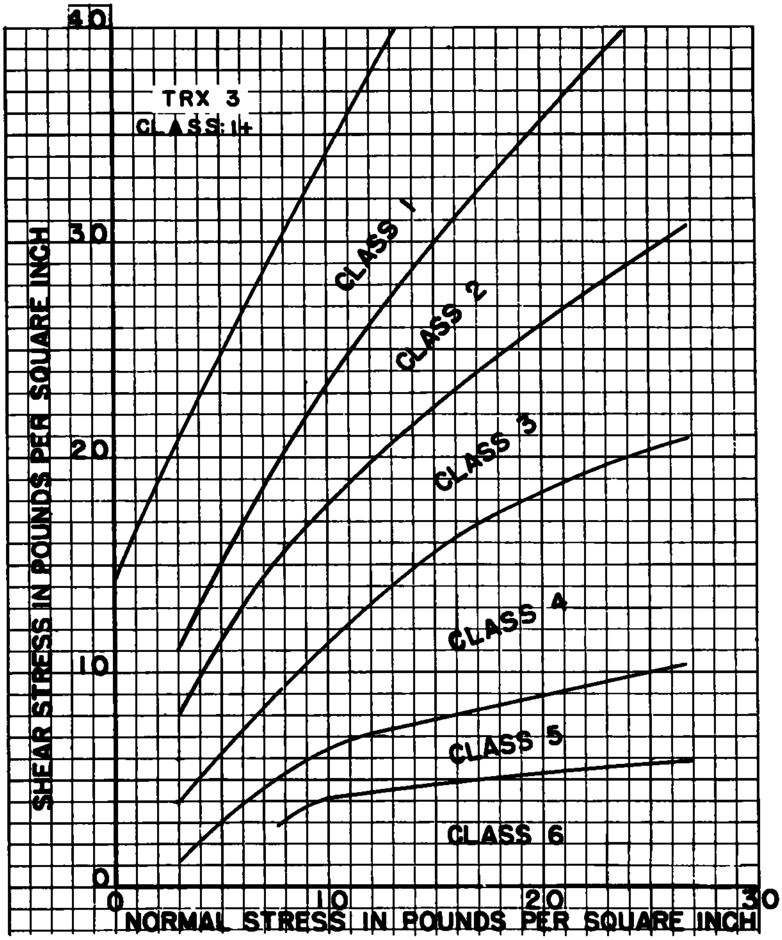

Figure 25.

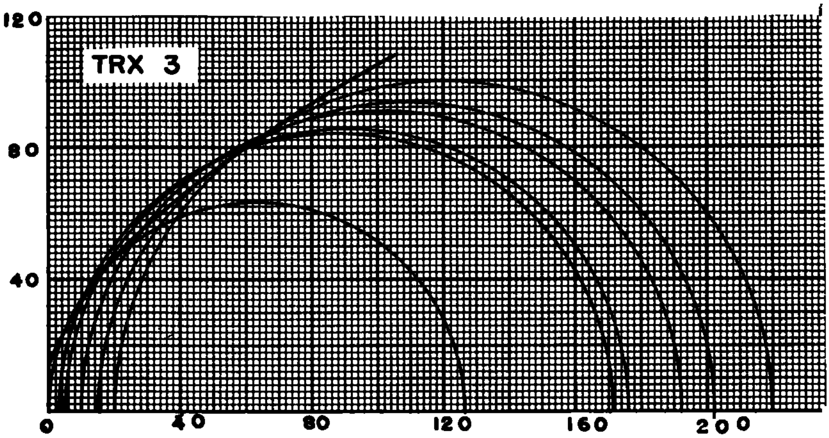

Figure 26.

STATE OF LOUISIANA
DEPARTMENT OF HIGHWAYS

TESTING & RESEARCH SECTION

Date 9/17/59

Project No. 196-01-04 Lab. No. 11532

Material Light Silty Clay A-6

Remarks TRX-4

Opt.Moisture 20.0 Opt. Density 101.6 Comp.Effort 13.26 Ft.Lb./cu. in.

TRI-AXIAL COMPRESSION TEST CLASS 1^+

20 YEAR ROAD REQUIRES ______ INCHES OF BETTER MATERIAL FOR ______ POUND WHEEL LOAD

10 YEAR ROAD REQUIRES ______ INCHES OF BETTER MATERIAL FOR ______ POUND WHEEL LOAD

MOLDING DATA			CURING DATA			TESTING DATA			
Cylinder No.	Moisture % Dry Wt.	Dry Den. Lbs.Per Cu.Ft.	Cap. Moist. Time Days	Moisture After Drying % Dry Wt.	Moisture After Cap. Absorption % Dry Wt.	Applied Lateral Pressure P.S.I.	Ulti. Comp. Strength	Strain at Ulti. %	Swell Volume %
28	16.5	105.8	10	16.1	16.7	0	115.92	1.332	0.06
33	16.9	105.5	10	16.4	17.1	3	168.79	0.997	0.09
49	16.1	106.0	10	16.6	17.3	5	146.47	1.247	0.03
26	16.7	106.1	10	16.7	17.4	10	169.59	1.475	0.07
10	17.1	105.1	10	16.2	17.0	15	182.31	1.512	0.07
45	16.8	105.8	10	16.2	17.4	20	199.03	1.965	0.09

Figure 27.

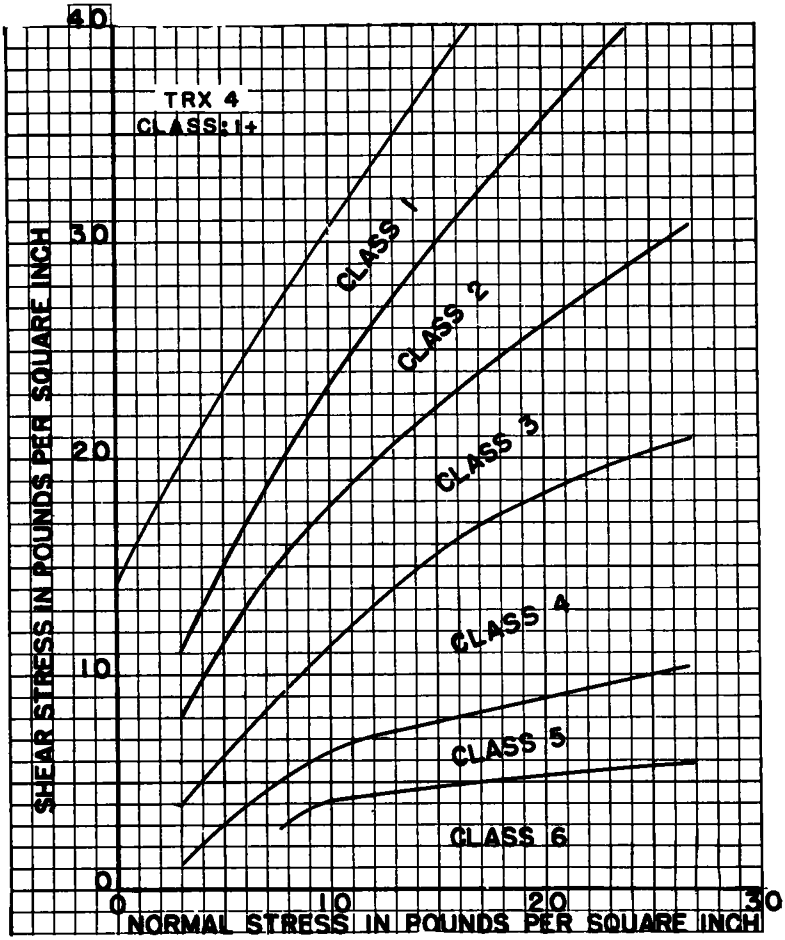

Figure 28.

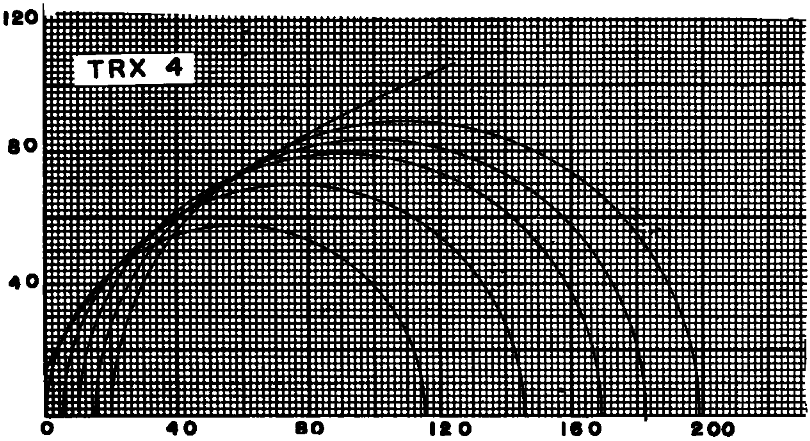

Figure 29.

Lime Fixation in Clayey Soils

G. HARRISON HILT, 1st Lt, U.S. Army Corps of Engineers; and
D.T. DAVIDSON, Professor of Civil Engineering, Iowa Engineering Experiment Station, Iowa State University, Ames

Previous work in stabilization of clayey soils with lime has shown that small amounts of lime considerably improve workability but contribute little to strength, whereas larger amounts of lime also improve the strength and bearing capacities of these soils. This suggests the possibility that lime added to soil must first satisfy an affinity of the soil for lime, an affinity referred to as "lime fixation." In some clayey soils the addition of flyash with the lime caused an even more significant gain in strength.

The research described in this paper was undertaken to determine whether lime fixation does occur, and if so, to determine the mechanisms involved and the amount of lime utilized.

Samples of six natural clayey soils were mixed with varying amounts of lime (0 to 12 percent), cured two days at 100 percent humidity and 70 F temperature, and subjected to Atterberg limits tests. Similar mixes were compacted at optimum moisture content to standard Proctor density and tested in unconfined compression after 7 and 28 days moist curing.

Curves of lime content vs. Atterberg limits and lime content vs. unconfined compressive strength indicate that when the plastic limit increases, with small amounts of lime, the strength remains relatively constant, whereas with larger amounts of lime the plastic limit remains constant and strength increases. Thus, the plastic limit is indicative of the amount of lime fixation in clayey soils.

Further correlations show that the amount of fixation is proportional to the type and amount of 2-micron clay present and is independent of the adsorbed cation present.

As a result of the unconfined compressive strengths, kaolinitic and montmorillonitic clayey soils were found to be well stabilized with lime alone, whereas illitic-chloritic clayey soils require additions of flyash to obtain significant gains in strength.

●THE USE OF lime and lime-flyash additives to improve the engineering properties of clayey soils is growing. Desirable results obtained from lime treatments include better workability, increased immersed and dry strengths, increased resistance to freeze-thaw cycles, and better volume change characteristics.

Previous research has indicated that the addition of a very small percentage of lime improved the workability of heavy clay soils many-fold but added little to strength. Additional lime improved the strength and bearing capacities of these soils, and the addition of flyash caused an even more significant strength gain in some clayey soils.

That lime added to soil must first satisfy an affinity of the soil for lime was suggested by previous research. It this is true then it would be suspected that lime would not be available for the pozzolanic reactions with the soil constituents or flyash needed to produce strength gains until the affinity of soil for lime is satisfied. Because this lime is "fixed" in the soil and is not available for other reactions, the process by which the lime becomes fixed may be termed lime fixation. The percentage amount of calcium hydroxide by oven dry weight of the soil which can be fixed by a given soil may be identified as the lime fixation capacity of the soil.

If there is lime fixation in a clayey soil, the strength of compacted and cured specimens of the soil should not increase with small additions of lime. To confirm this, unconfined compressive strength tests were used, because unconfined compression is a reliable indication of cohesive and cementing strength. This strength test can be performed relatively rapidly on a large number of specimens.

Inasmuch as the liquid and plastic limits of a soil are affected by cohesiveness, one or both of these tests were investigated to determine if they also can be used as parameters of lime fixation capacity.

REVIEW OF LITERATURE

Much has been written of the desirable effects of adding lime to a soil rich in clay. The National Lime Association (14) reports that the addition of lime to over-wet clayey soils appears to dry them out and materially improve their workability. Fuller and Dabney (8) report that in highly plastic soils in Texas the ease of pulverizing clay balls after addition of lime and water exceeded expectations and that during final mixing and placing with motor patrols the material was friable and had many characteristics of a non-plastic mix. Reductions in the plasticity index with additions of less than three percent lime were noted in both of the foregoing references.

Increases in strength with the addition of lime have been observed by a great many researchers. The Iowa State University Engineering Experiment Station Soil Research Laboratory since 1953 has been carrying out research projects on the treatment of soils with lime and lime-flyash. Publications on the research show favorable results of increasing strength of soils with the addition of lime and lime-flyash (12).

Some of the basic mechanism involved have been explained by Davidson and Handy (7). First, calcium ions cause a reduction in plasticity of cohesive soils so they become more friable and more easily worked. The mechanism is either a cation exchange or a crowding of additional cations onto the clay. Both processes change the electrical charge density around the clay particles. Clay particles then become electrically attracted to one another, causing flocculation or aggregation. The clay particles, now acting as aggregates, behave as a silt which has a low plasticity or cohesion. A second chemical reaction is carbonation of lime by carbon dioxide of the air, producing calcium carbonate, a weak cement which is deleterious to over-all strength gains. A third class of reactions, termed pozzolanic reactions, results in a slower, long-term cementation of compacted mixtures of lime and soil. Pozzolanic reactions apparently involve interactions between hydrated lime and minerals in the soil.

Lime contents of 1 percent and less in a clayey soil are reported to produce a metastable state; but when lime contents greater than that are used, the flocculation of the clay particles is of a more permanent and progressive nature (5). Calcium silicate and aluminate formed by chemical breakdown of the clay lattice material contribute to flocculation by bonding adjacent soil parcticles. Ionic flocculation and silicate bonding commence at the same time, the former being an immediate effect while the latter takes a considerable time to complete. Nearly all of the clays used in their investigation were already saturated with adsorbed calcium; changes in properties as a result of additions of calcium hydroxide could not involve a cation exchange relationship.

An addition of 8 percent calcium hydroxide to clayey soils resulted in the complete conversion of $Ca(OH)_2$ to other forms after one month (10, 13). Reactions other than ion exchange probably accounted for the conversion. However, in other research calcium hydroxide was found to be still present after 12 months curing of specimens (5).

Changes in the engineering properties of clayey soils with addition of lime depend appreciably on the cation originally adsorbed on the clay surfaces, and on the type of clay (11). The nature of the exchangeable cation does not make much difference in kaolinitic soils, but it makes a tremendous difference in montmorillonitic soils.

Expanding clays containing montmorillonite react readily with lime immediately losing plasticity, and after compaction slowly gain pozzolanic strength. Clays containing mainly illite, chlorite, vermiculite, or kaolinite are less effective users of lime (7).

Laboratory tests on two soils of high clay content indicate that no appreciable pozzolanic reactions can take place between lime and flyash until lime is present in excess of the requirements of the soil (6).

SPECIMEN PREPARATION AND TESTING

Materials

Soils.—Seven soils were used in the investigation. The choice of these soils was based on the type and amount of the principal clay minerals present. Three soils containing montmorillonite, two containing illite-chlorite mixtures, and two of the kaolinite group (one containing kaolinite, and the other halloysite) were selected. Each of the soils is identified by a letter designating the principal clay minerals present, and a number indicating the percentage content of the soil less than two microns in diameter. For example, the designation, M-75, indicates a soil containing montmorillonite as the principal clay mineral, with 75 percent of this soil less than 2 μ in effective diameter. The locations from which the soil samples were taken and other pertinent information appear in Table 1. Table 2 gives the physical and chemical properties of the seven soils.

Lime.—Reagent grade calcitic hydrated lime, $Ca(OH)_2$, was used to minimize compositional variables. Individual 1 lb bottles of lime were kept sealed until immediately before use to prevent carbonation of the lime.

Flyash.—Flyash is "the finely divided residue that results from the combustion of ground or powdered coal and is transported from the boiler by flue grass" (4). The flyash used was collected at the St. Clair Power Plant of the Detroit Edison Company, Detroit, Mich. (2). This flyash had a loss-on-ignition 3.6 percent, and 88.7 percent of the ash was finer than the No. 325 sieve.

MIXTURE AND SPECIMEN PREPARATION

Soil Preparation

The soil to be used was selected from the appropriate bin and was pulverized repeatedly until all soil aggregations were reduced to particle size or were fine enough to sieve through either the No. 10 or the No. 40 mesh sieve, depending on whether the soil was to be used for strength tests or for liquid and plastic limits tests. The soil passing the appropriate mesh sieve was then put through a sample splitter, placed in covered cardboard containers, and stored until needed.

Mixing

A predetermined amount of air dry soil was weighed on a balance sensitive to 0.1 gram and then placed in a mixing bowl. Additives, if used, were weighed and mixed in at low speed with a mechanical mixer. After mixing the soil and additives together dry for 30 sec, distilled water was added in appropriate amounts, and mixing was continued for another 4 min.

Unconfined Compression Test Specimen Preparation

Strength test specimens were 2 in. in diameter by 2 in. high and were molded in an apparatus developed at the Iowa State University Engineering Experiment Station Soil Research Laboratory. The apparatus (Fig. 1) is a hand-operated drop hammer with which a predetermined amount of soil mixture in a 2-in. diameter mold is compacted to a density near standard Proctor density.

Approximately 200 grams of the mixture of soil, additives, and water is placed in the mold by means of a scoop and funnel. This mixture is then given five blows from the hammer, the mold is inverted, and another five blows are applied. The resulting soil cylinder is extruded from the mold with an hydraulic jack. The compacted specimen is weighed to the nearest 0.1 gram, and the height is measured to the nearest 0.001 in. Any specimen not measuring 2.000 in. ± 0.050 in. is rejected. The soil specimen is then wrapped in waxed paper and sealed with cellulose tape to prevent carbonation of the lime by the carbon dioxide in the air. The wrapped specimens are placed in shelves in a curing room where the relative humidity is maintained at 95 ± 5 percent and the temperature at 70 ± 5 F.

TABLE 1

SOIL SITE CHARACTERISTICS

Sample	Location	Classification	Soil Series and Morizon	Sampling depth (in.)
M-67	Keokuk Co., Iowa	Kansan-age gumbotil	Mahaska,[a] fossil B horizon	91-101
M-51	Harris Co., Tex.	Coastal plane deposit, largely deltaic	Lake Charles, probably B horizon	39-144
M-33	Keokuk Co., Iowa	Plastic Wisconsin-age loess	Mahaska, C horizon	36-77
IC-44	Monroe Co., Mich.	Probably Wisconsin-age glacial till	Unknown, probably C horizon	Unknown
IC-41	Livingston Co., Ill.	Wisconsin-age glacial till	Clarence, C horizon	46-56
K-30	Durham Co., N.C.	Residual soil over medium grained biotite granite	Durham, B Horizon	24 in. below A horizon
K-29.5	Orange Co., Va.	Residual soil over diorite	Davidson, B horizon	Unknown

[a] Under soil M-33.

TABLE 2

PROPERTIES OF SOILS

Sample	M-67	M-51	M-35	IC-44	IC-41	K-30	K-29.5
I.E.E.S. designation	528-8	AR-3	528-4	AR-4	AR-8	AR-6	AR-5
Textural composition							
Gravel[a] > 2mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sand (2-0.074mm)	16.0	3.0	0.2	7.0	10.0	45.2	21.0
Silt (74-5μ)	15.5	36.0	60.8	36.0	38.0	18.3	37.0
Clay (5μ)	70.5	61.0	39.0	57.0	52.0	36.5	42.0
Clay (2μ)	67.0	51.0	33.0	44.0	41.0	30.0	29.5
Passing No. 10 sieve	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Passing No. 40 sieve	96.0	99.0	100.0	98.0	96.0	67.0	90.0
Physical properties							
Liquid limit, %	76.6	64.6	52.1	44.0	35.5	51.0	43.5
Plastic limit, %	25.6	17.6	20.0	21.1	17.5	25.5	27.0
Plasticity index	50.0	47.0	32.1	22.9	18.0	25.5	16.5
Chemical properties							
pH	7.1	8.2	5.6	8.4	-	5.7	5.9
C.E.C. (soil passing No. 10 sieve), m.c./100g	–	27.5	23.5	14.5	-	8.4	11.0
C.E.C. (soil passing No. 40 sieve), m.c./ 100g	41.0	33.1	26.8	13.4	-	13.5	12.4
Carbonates, %	0.8	16.6	0.0	7.2	-	0.1	0.7
Organic matter %	0.2	0.1	0.2	0.6	-	0.1	2.6
Predominant clay Mineral[b]	M	M	M	I & C	I & C	K	H & V
Classification							
Textural[c]	Clay	Clay	Silty Clay	Clay	Clay	Clay	Clay
Unified	CH	CH	CH	CL	CL	CH-CL	CL-ML
BPR (AASHO)	A-7-6(20)	A-7-6(20)	A-7-6(18)	A-6-6(14)	A-6 (11)	A-7-6(11)	A-7-6(12)

[a] Textural gradation tests were performed only on the soil fraction passing the No. 10 sieve. All soils used contained less than 5 percent gravel.

[b] Symbols are M-montmorillonite, I-illite, C-chlorite, K-kaolonite, H-halloysite, and V-vermiculite. Determinations were made by X-ray diffraction.

[c] U.S. Dept. of Ag. textural classification was used.

Testing

Liquid and Plastic Limits.—ASTM Methods D423-54T and D424-54T (1) were followed except that after the soil, lime, and distilled water were mixed together, the mix was scraped into a porcelain pan, covered, and stored in a near 100 percent humidity room for two days. This allowed the water to infiltrate the clay particles thoroughly and produce uniform wetting of the sample. Preliminary tests after different storage periods up to four days showed no perceptible daily change in the liquid and plastic limits after two days' storage.

After seasoning for two days the contents of the covered pan were removed from the humidity room, and enough of the mixture was placed in an evaporating dish for four liquid limit tests. This procedure was followed on the soil passing the No. 40 mesh sieve with additives of 0, 1, 2, 3, 7, and 12 percent lime by oven dry weight of soil (hereafter abbreviated dry weight of soil). Liquid limits were determined only for mixtures prepared with the montmorillonitic and the illitic-chloritic soils. Because of the wide variety of variables which enter into a liquid limit test, consistency and reproducibility of results were difficult to obtain. Because the plastic limit was found to produce reliable and consistent results correlating well with the data to be presented, liquid limit tests were discontinued.

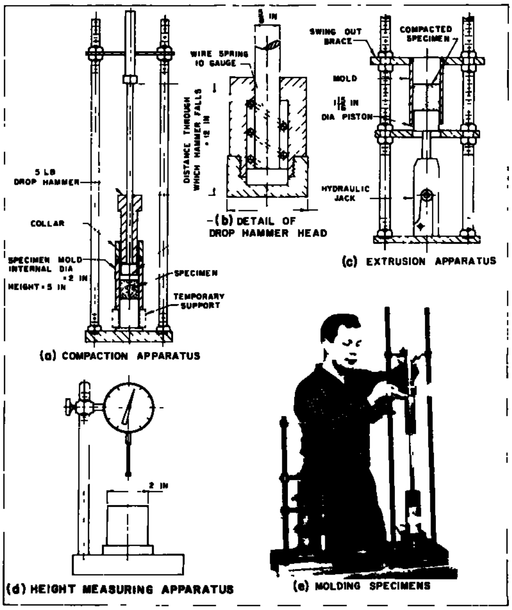

Figure 1. Molding apparatus.

A sample weighing about eight grams was taken from the mixture prepared for the liquid limit test. Four plastic limits were rolled for each soil-lime mixture studied (0, 1, 2, 3, 7, and 12 percent additions of lime by dry weight of soil). The plastic limit of the mix at each percentage additive was determined as the average of the moisture contents of the four threads rolled.

Strength Testing.—The testing apparatus was a model AP-170 Stability Testing Machine. Loads are indicated on a 10,000-lb capacity proving ring, which has a dial indicator reading to 0.0001-in. deflection. Strain is applied to the test specimens at a constant rate of 0.1 in. per minute.

Because the objective of the investigation was to study the process of lime fixation in clayey soils, it was important to obtain positive values of strength for all mixtures of soils and additives. Therefore, strength testing was done on specimens which had been moist cured but not subjected to immersion, inasmuch as immersion causes specimens of low lime content to slake.

To obtain the optimum moisture content for maximum strength for molding the 2- by 2-in. specimens, moisture-strength tests were conducted in series with four sets of three specimens each, molded for each soil mix at varying moisture contents. After seven days moist curing (95 + 5% R.H. 70 ± 5 F) these specimens were tested for unconfined compressive strength, and the strengths of the specimens at failure were recorded. Graphs of molding moisture content versus seven day strength were prepared for each mixture studied, and optimum moisture contents for maximum strengths were interpolated. This procedure was carried out for additives of 0, 6, and 12 percent lime for each soil and also for the same percentages of lime plus 20 percent flyash. The optimum moisture contents thus obtained were then plotted against lime contents for each soil. The resulting curves were used for interpolating moisture contents for mold-each soil. The resulting curves were used for interpolating moisture contents for molding specimens of the various mixtures used in the final work.

Final Testing.—The soils with the highest percentage of each type of clay mineral (M-67, IC-44, and K-30) were selected for final testing. Additives to the soils fell into two groups: the first was lime and the second, lime and flyash. Lime alone was added to each of the soils in amounts of 0, 1, 2, 3, 4, 6, 8, and 12 percent by dry weight of soil. In the second group the same percentages of lime by dry weight of soil were used, but 20 percent flyash by dry weight of soil also was added to provide an excess of pozzolanic material.

Batches for molding nine specimens out of each were prepared to obtain uniformity of mixing. All batches of each group for a soil were molded on the same day to assure uniform curing conditions. Of the nine specimens molded, three were tested at the end of seven days curing in the humidity room, three at 28 days, and the final three after 27 days moist curing and one day immersion in distilled water.

RESULTS

Effect of Lime on the Plastic Limit

The plastic limits of all soils and mixtures tested showed that this limit was materially increased with small additions of lime (Fig. 2). The largest increases in the plastic limit (P. L.) due to lime treatment were obtained in the soils containing montmorillonite as the principal clay mineral; the greater the amount of clay-size material in these soils, the greater was the increase in the P. L. Increases in the P. L. of the illitic-chloritic clayey soils also were considerable, but not as great as in the montmorillonitic soils of comparable clay-size content. The smallest increases of the P. L. were observed in the kaolinitic rich soils.

Of particular interest is the "point" on each curve at which the rate of change of the slope approaches zero and at which the slope itself approaches zero. Because the curve approximates that of a right hyperbola, the change in slope never reaches zero but approaches this value in soils M-67, M-51, and M-33 at lime contents of 3.2 percent, 2.7 percent and 2.2 percent, respectively. A plot of these lime percentages against respective 2 micron clay contents (Table 2) of the soils revealed the following linear relationship:

$$\begin{array}{l}\text{Optimum lime additive}\\ \text{for maximum increase}\\ \text{in plastic limit}\end{array} = \frac{\%\text{ of } 2\ \mu\text{ clay}}{35} + 1.25 \qquad (1)$$

Inasmuch as only two illitic-chloritic soils and two kaolinitic soils were tested, it is not known whether or not the optimum lime additive for these two soils is directly proportional to 2 micron clay content.

To determine the factors responsible for the observed change in P. L. with the addition of lime, the definition of the plastic limit must be stated in terms of the events occuring in the laboratory test. The definition of P. L. (1) as the boundary between the plastic and semi-solid states must be modified to a definition that reflects laboratory procedure. Thus a more descriptive definition of the P. L. as determined by the laboratory soil test is the lowest moisture content at which the bonds between soil particles or aggregates can be constantly renewed.

The nature of these bonds has been described as being due to cation exchange and to a crowding of additional cations onto the surfaces of the clay (7). However, one of the soils tested, M-51, already had an excess of carbonates present (16.6 percent). Certainly, then, this soil is already saturated with calcium, yet the P. L. of the soil was increased from 18 to 40 with the addition of less than 3 percent lime. Thus the crowding of additional calcium onto the clay must be the more important of the two mechanisms.

One other mechanism not previously mentioned enters into the bonding of clay particles and affects the plastic limit. The surface tension of water in minute pores such as those in clayey soils exerts a bonding force between clay size particles. Because

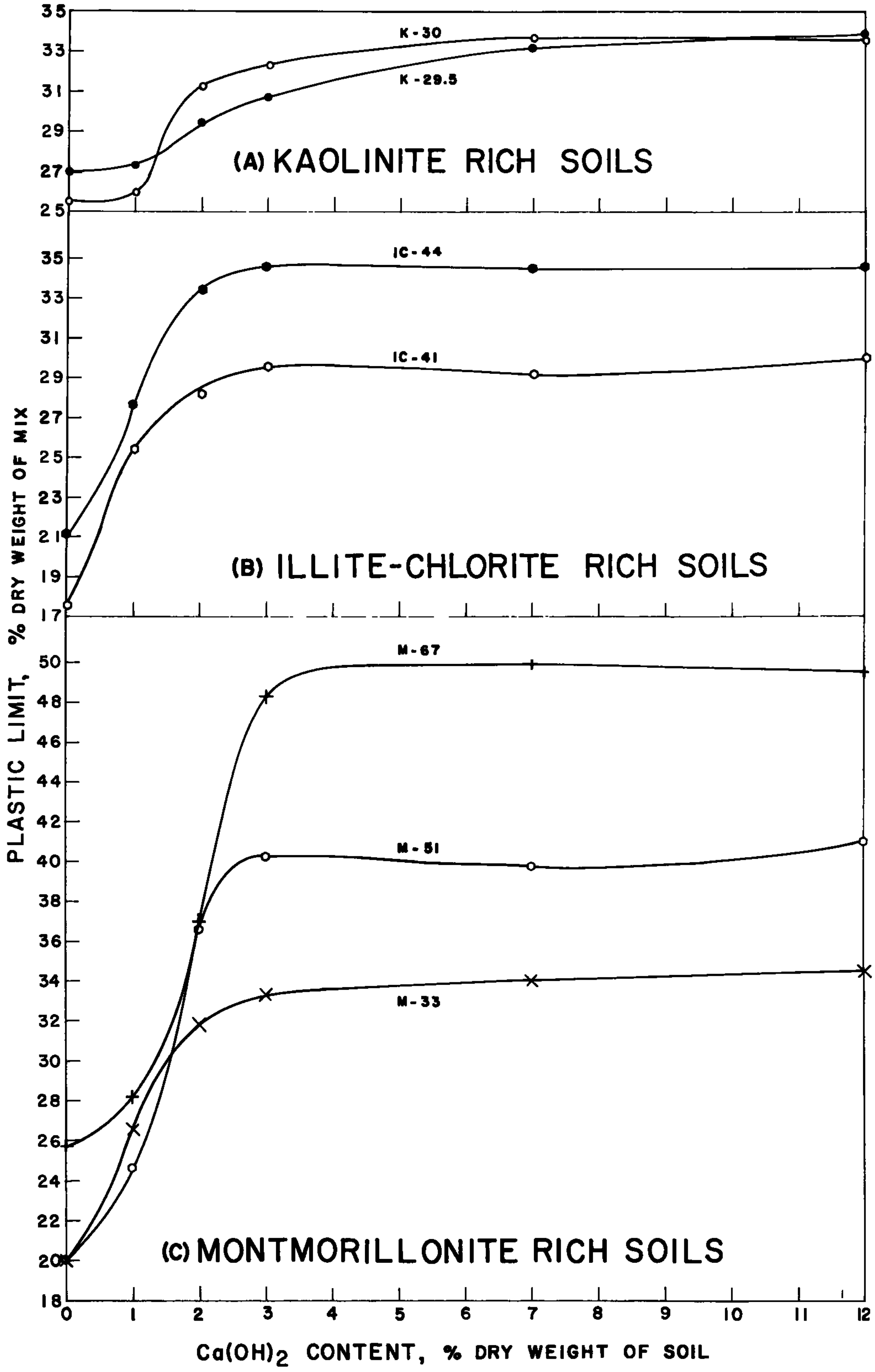

Figure 2. Plastic limits of seven clayey soils at varying lime contents.

capillary pressure is inversely proportional to the radius of curvature of the meniscus and directly proportional to surface tension, changes in either of these will be reflected in the amount of water necessary to renew the bonds continually between soil particles while a plastic limit is being rolled.

When the plastic limits of the soils tested are increased by lime additives, actually more water must be added to the soil-lime mixture to make the bonds between the soil particles capable of being renewed as rapidly as they are broken (Fig. 2). The addition of lime causes the clay particles to become electrically attracted, causing flocculation or aggregation. The clay then behaves more like a silt with each floc of clay particles acting like a silt grain. Though bonding between the particles within a floc has been increased, bonding between flocs is relatively weak. When a plastic limit is rolled, the bonds between individual clay particles within the floc remain relatively unaffected, but the bonds between the flocs are being constantly broken and reformed until the moisture content is reduced to the point where the bonds can no longer be reformed as fast as they are being broken, and the thread crumbles.

At some percentage of lime additive all of the calcium that can crowd onto the clay particles is present and further increases in lime result only in supplying to the soil an excess of calcium which is not effective in flocculation or other mechanisms which contribute to the increase in the plastic limit.

If the calcium which increases the plastic limit is so fixed in the soil that it cannot react with the natural pozzolans of the soil, then the percentage of lime present at the point where the plastic limit reaches its maximum will reliably indicate the percentage of lime fixation in the soil.

Effect of Lime and Lime-Flyash on Strength

Unconfined Compressive Strengths.—The three soils with the greatest amount of each clay mineral, M-67, IC-44, and K-30, were selected for determining the effect of lime and lime-flyash treatments on the unconfined compressive strengths of clayey soils (Figs. 3, 4, and 5).

The addition of lime increased the unconfined compressive strength of montmorillonitic soil M-67 the largest amount. The strength of kaolinitic soil K-30 also was greatly improved by lime treatment but the strength of illitic-chloritic soil IC-44 was only slightly increased.

The addition of 20 percent flyash to the soil plus lime had little effect on soils M-67 and K-30, but produced marked gains in unconfined compressive strength in soil IC-44. A comparison of the maximum unconfined compressive strengths of soil IC-44 plus lime after 28 days moist curing with and without flyash additive shows that the addition of 20 percent flyash has increased the strength of this soil by 28 percent.

From this data it appears that both montmorillonite and kaolinite are natural pozzolans; and they, or elements within their crystal lattices, react with lime to produce cementing materials. Because soil M-67 contains much more minus two micron material than soil K-30, it can be expected that lime mixed with soil M-67 will produce more cementing materials than will lime and soil K-30 even if both clays are equally reactive.

However, because the addition of lime to soil IC-44 produces only relatively small increases in unconfined compressive strengths, one can conclude that either illite or chlorite or both are not effective natural pozzolans. Thus it is necessary to add a pozzolanic material such as flyash to obtain significant increases in strength in stabilization with lime.

The initial and generally flat portion of the unconfined compressive strength curves is of particular interest. In this region small additions of lime do not produce corresponding increases in strength. This shows graphically that a certain amount of lime must be added to a clayey soil before cementing products which will increase the strength of the soil can be formed. Because lime fixation was defined as the process by which lime is held by the soil and is not available for pozzolanic reactions, this initial flat portion of the curves proves that lime fixation does occur in clayey soils.

The region of lime fixation may be defined as that portion of the unconfined compressive strength versus lime content curves in which strength does not perceptibly increase as the percentage of lime additive increases. Similarly, the lime fixation capa-

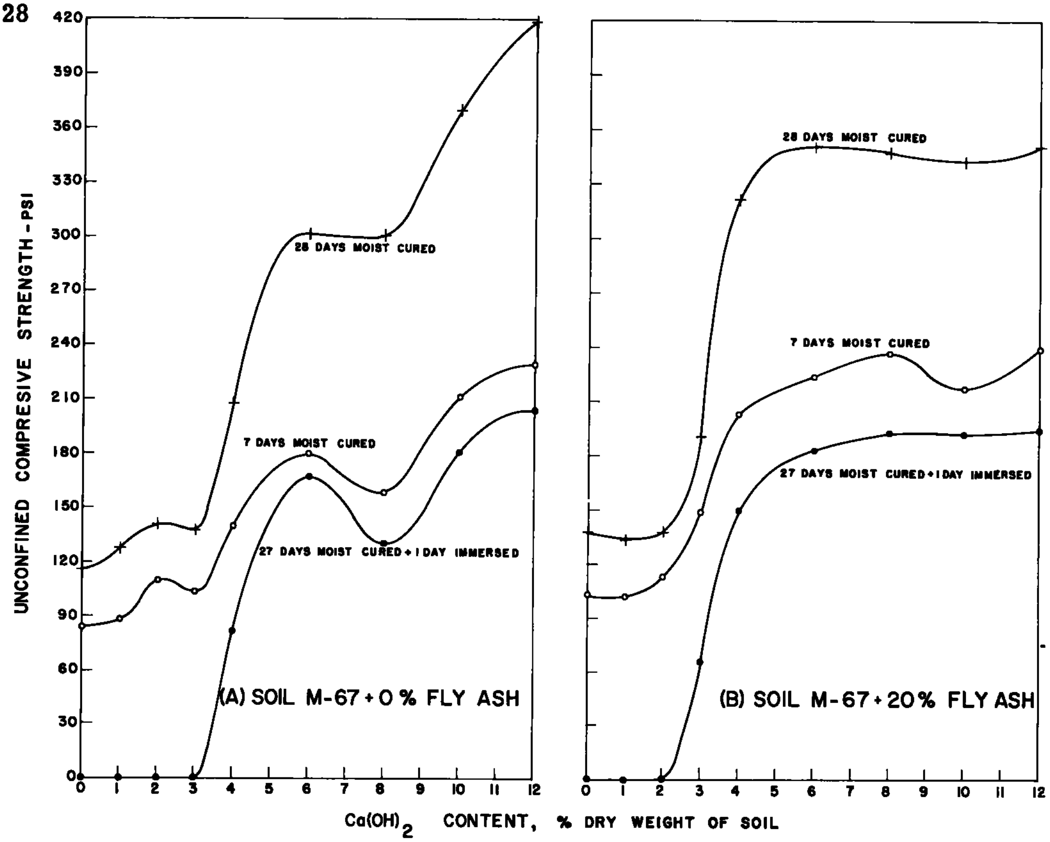

Figure 3. Unconfined compressive strengths of soil M-67 at varying lime and lime-flyash contents.

city of a soil is the percentage of lime additive at which strength just begins to increase.

Comparison of Plastic Limits and Strengths

Object of Comparison.—By comparing the optimum lime additive for maximum increase in the plastic limit (Fig. 2 and Eq. 1) with the maximum percentage of lime fixation which can occur in a particular soil (Figs. 3, 4, and 5) it can be shown that these two percentages are the same, and thus this optimum on the plastic limit curves is also a quantitative parameter of the lime fixation capacity of a particular soil.

Method of Comparison.—If the unconfined compressive strengths of the soils tested remain constant as the plastic limits increase with increasing percentages of lime additive, and if the plastic limit then remains constant with further additions of lime as the unconfined compressive strengths increase, then the optimum lime additive for maximum increase in the plastic limit will be a quantitative parameter of lime fixation (Fig. 6).

Because previous research (15) has shown that lime does not react with the coarse portion of the soil and that P. L. tests utilized the portion of the soil passing the No. 40 sieve whereas unconfined compressive strength testing was performed on cylinders molded from the soil passing the No. 10 sieve, a correction must be made. This correction is based on relating the percentage of lime additive to the amount of clay present in the soil passing the No. 10 sieve. Thus the equivalent percentage of lime in the plastic limit test is

$$L_E = L_o \times \frac{Q_{40}}{Q_{10}} \tag{2}$$

in which

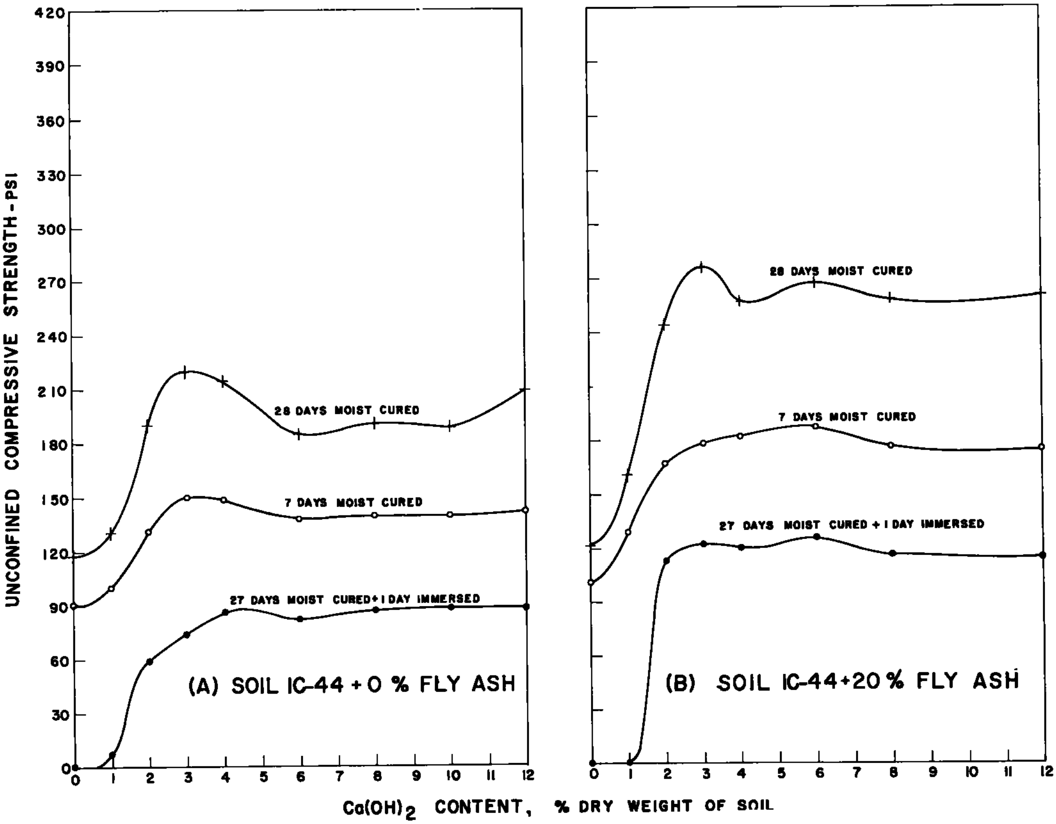

Figure 4. Unconfined compressive strengths of soil I-44 at varying lime and lime-flyash ratios.

L_E = equivalent lime content (%)
L_O = original lime added (%)
Q_{40} = amount of soil passing the No. 40 sieve (%)
Q_{10} = amount of soil passing the No. 10 sieve (%)

Results and Discussion.—The curves (Fig. 6) show that the compressive strengths of soil M-67 and K-30 remain constant as the plastic limits increase, and the plastic limits remain constant as the strengths increase.

However, in soil IC-44, which contains illite and chlorite as the principal clay minerals, the strength is increasing while the plastic limit is still increasing. A possible explanation for this is that if one of the two clay mineral constituents of the soil has a lower lime fixation capacity than the other, then, at a percent additive of lime at which one is still engaged in the process of lime fixation, the other may have completed this process and begun to engage in the production of cementing materials through pozzolanic reactions.

Conclusions from Comparison.—Based on the graphical results of this comparison, the optimum lime additive for maximum increase in the plastic limit is a reliable quantitative indicator of the lime fixation capacity of the montmorillonitic and kaolinitic soils tested. However, it does not reliably indicate the lime fixation capacity of clayey soils containing a mixture of illite and chlorite, though it may be a valid indicator in soils containing one or the other of these minerals.

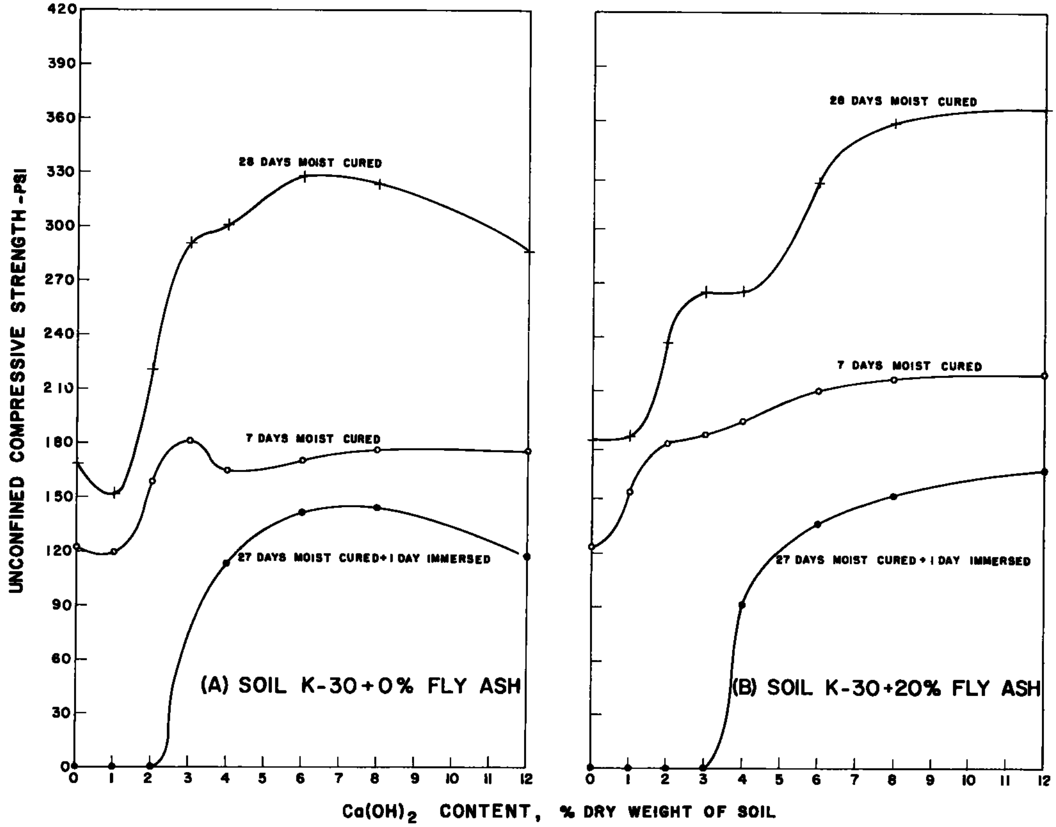

Figure 5. Unconfined compressive strengths of soil K-30 at varying lime and lime-flyash ratios.

CONCLUSIONS

1. Large increases in the plastic limits of clayey soils can be obtained by adding small quantities of lime, $Ca(OH)_2$. The largest increases are in soils containing montmorillonite; illitic-chloritic clayey soils are affected somewhat less, and the plastic limits of kaolinitic clayey soils are the least changed.

2. A descriptive definition of the plastic limit as determined by the standard laboratory method is the lowest moisture content at which the bonds between soil particles or aggregations can be constantly renewed.

3. Both montmorillonite and kaolinite are effective pozzolanic reagents. They or elements within their crystal structure will react with lime to produce a cementing material equal to or greater in strength producing qualities than the cementing agents produced in the reaction of lime with flyash. It is not necessary to add flyash to soil containing large amounts of montmorillonite or kaolinite when treating with lime. Such additions may even be detrimental.

4. The percentage amount by oven dry weight of the soil of calcium hydroxide which can be fixed by a given soil is the lime fixation capacity of that soil. This lime contributes to the improvement of soil workability but not to increases in strength. Amounts of lime added above the lime fixation capacity cause the formation of cementing materials within clayey soils.

5. Lime fixation in clayey soils does take place. The lime fixation capacity of a montmorillonitic or kaolinitic clayey soil is the same as the optimum lime additive for maximum increase in the plastic limit of the soil.

ACKNOWLEDGMENT

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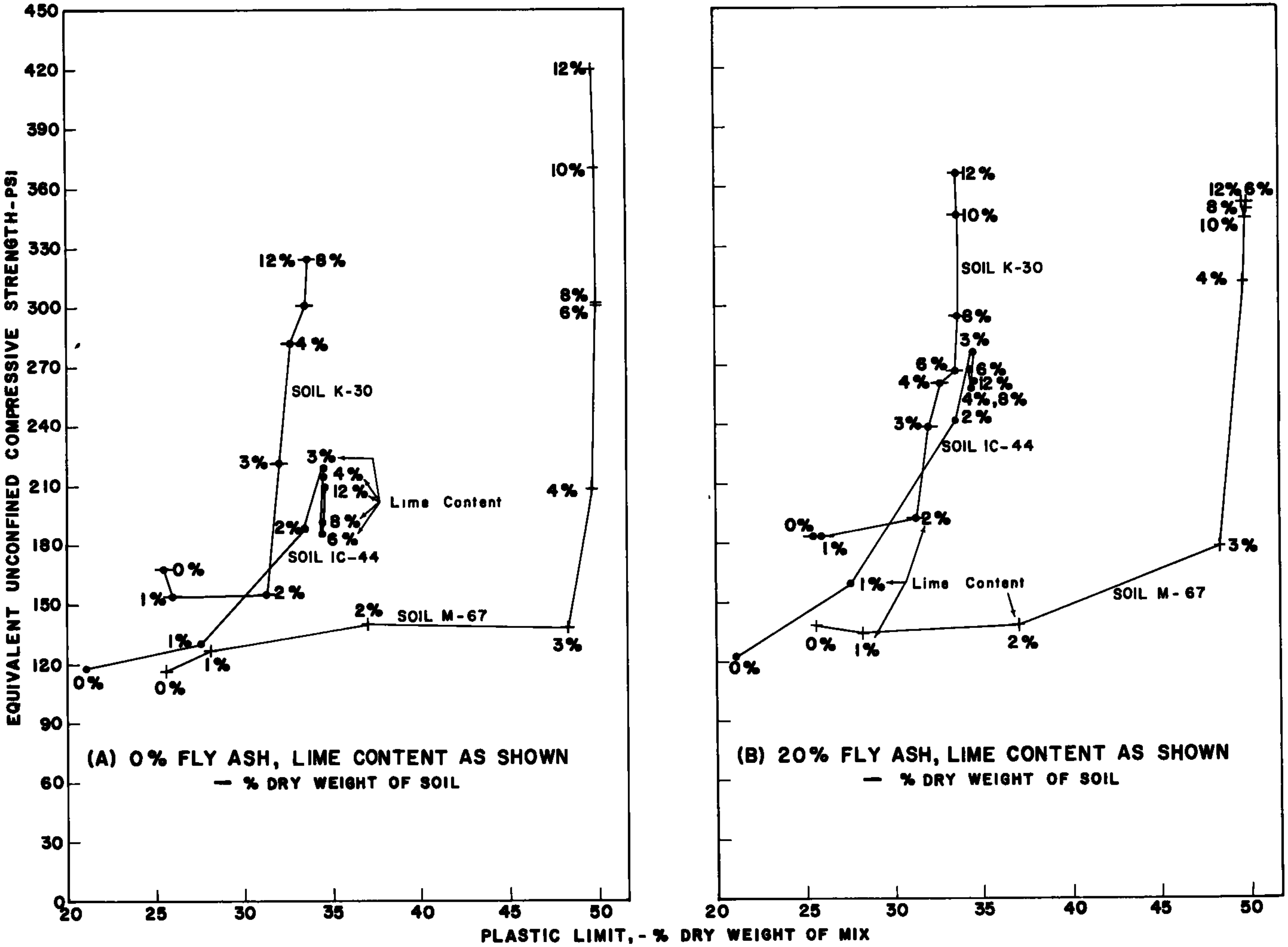

Figure 6. Comparison of plastic limits and unconfined compressive strengths for three lime-treated clayey soils.

283-S of the Engineering Experiment Station of Iowa State University. This project ("The Loess and Glacial Till Materials of Iowa; an Investigation of Their Physical and Chemical Properties and Techniques for Processing Them to Increase Their All-Weather Stability for Road Construction") is under contract with the Iowa Highway Research Board as Project HR-1 and is supported by funds supplied by the Iowa State Highway Commission. Certain equipment used in the research is on loan from the Office of Naval Research under Contract Nonr-2625(00).

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Improvement of Lime Stabilization Of Montmorillonitic Clay Soils With Chemical Additives

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Over the past decade, research has shown that lime produces beneficial results with clayey materials, although the unconfined compressive strengths of clayey soil-lime mixtures are relatively low. The investigation reported in this paper shows that lime in combination with small quantities of an inexpensive inorganic chemical may be the answer to an economical stabilization of clayey soils for highway usage.

Three Iowa soils ranging in clay content from 35 to 74 percent were studied in combination with varying amounts of both hydrated calcitic and hydrated dolomitic limes and three inorganic chemicals—sodium phosphate, sodium carbonate, and sodium hydroxide.

Additions of 1 to 3 percent of sodium hydroxide doubled the strength of soil-lime mixtures. Additions of sodium phosphate to soil-lime mixtures actually decreased the strength, and additions of sodium carbonate gave inconsistent results. It appears that sodium hydroxide can be successfully used in soil-lime.

A study of the effects of curing temperature and the freeze-and-thaw resistance of the soil-lime and soil-lime-chemical mixtures is also reported.

● RESEARCH AND FIELD experience have shown that lime treatments of clayey soils produce beneficial property changes, but that the strength gain of compacted mixtures may be too slow to meet base course requirements, particularly in the northern United States where desirably high curing temperatures cannot be counted on in late season construction, and where alternate cycles of freeze and thaw may cause failures of insufficiently hardened lime stabilized clayey soils. The results of recent work with chemical additives to improve the strength of soil-cement and soil-lime-flyash (1, 2, 3, 4, 5, 6) suggested that perhaps chemical additives could be used to improve the cement producing (pozzolanic) reactions in clayey soil-lime mixtures, giving rise to greater early strengths up to 28 days

Heat is another possible way to accelerate the hardening of lime treated soils (7). Although it may not be economical at present to cure a soil-lime base course with artificial heat, future cheap sources of heat may make this feasible. The effect of curing temperature on the rate of strength gain of compacted soil-lime mixtures is of practical interest in the natural temperature range attained under field conditions.

This paper presents the results of a laboratory investigation of the foregoing methods of improving the strength and durability of compacted clayey soil-lime mixtures.

Stability requirements for road bases in Iowa are used as the basis for evaluating the need for and the adequacy of the improvements.

MATERIALS

Properties of Soils

Three montmorillonitic clay soils were selected for the investigation. A description of each is given in Table 1, and physical and chemical properties are given in Table 2. The soils will be referred to as Kansan till, plastic loess and Kansan gumbotil.

They are typical of subgrade soils found in southern Iowa and parts of adjacent states, where, due to a lack of local deposits of granular road materials, stabilization methods for clayey soils are badly needed.

Kansan till and plastic loess contain approximately the same amount of montmorillonitic clay; but the non-clay size fraction of the two soils is considerably different. In Kansan till this fraction is about one-half silt sizes and one-half sand sizes; in plastic loess it is all silt sizes. Another difference is in carbonate content; Kansan till is calcareous, and plastic loess in noncalcareous or leached. The clay particles in a clacareous soil should be in a flocculated state with their appetite for calcium ions mostly satisfied, and nearly all added lime is available for pozzolanic reactions. In a leached soil, initial additions of lime furnish the calcium ions needed to flocculate the clay particles. Thus less lime should be required to stabilize Kansan till than plastic loess.

Kansan gumbotil is a unique soil type. Supposedly a fossil B-horizon developed from Kansan till, this highly weathered noncalcareous soil contains about 70 percent montmorillonitic clay, almost twice as much as the other two soils (Table 2). The non-clay fraction of Kansan gumbotil is about equal parts sand and silt-size material.

Properties of Limes

The properties of the two types of lime, dolomitic and calcitic, used are given in Table 3. Both were commercial grade hydrated limes produced by plants of the U.S. Gypsum Company, Chicago, Ill.

Properties of Chemicals

Three chemical additives were used, chosen as among the more promising for the improvement of pozzolanic reactions (6). The sodium carbonate (Na_2CO_3) was produced by the J. T. Baker Chemical Company, catalog no. 3602; the sodium phosphate ($Na_3PO_4 \cdot 12H_2O$) by the Mallinckrodt Chemical Works, catalog no. 7940; and the sodium hydroxide ($NaOH$) by the Mallinckrodt Chemical Works, catalog no. 7708. All three chemicals were analytical reagent grade.

TABLE 1

BRIEF DESCRIPTION OF SOILS

Soil	Kansan Till (409-12C)[a]	Plastic Loess (528-4)	Kansan Gumbotil (528-8)
Location	Ringgold Co., Iowa	Keokuk Co., Iowa	Keokuk Co., Iowa
Geological description	Kansan-age glacial till, plastic, calcareous, oxidized	Wisconsin-age loess, plastic, noncalcareous	Kansan-age gumbotil highly weathered, plastic, noncalcareous
Soil series	Shelby (Burchard)	Mahaska	Mahaska[b]
Horizon	C	C	Fossil B
Sampling depth	4½ - 10½ ft	3 - 6½ ft	7½ - 8½ ft

[a] Numbers in parentheses are those assigned by the Soil Research Laboratory of the Iowa Engineering Experiment Station.

[b] Underlies C horizon loess of Mahaska series.

TABLE 2

PROPERTIES OF SOILS

Soil	Kansan Till	Plastic Loess	Kansan Gumbotil
Textural composition[a] %			
Gravel (> 2mm)	0.0	0.0	0.0
Sand (2.0 - 0.074 mm)	31.5	0.2	16.0
Silt (0.074 - 0.005 mm)	30.0	60.8	13.5
Clay (< 0.005 mm)	38.5	39.0	70.5
Clay (< 0.002 mm)	31.0	33.0	67.0
Atterberg limits [b]			
Liquid limit, %	42.4	52.1	75.6
Plastic limit, %	20.5	20.0	25.6
Plasticity index, %	21.9	32.1	50.0
Classification			
Textural[c]	Clay	Silty Clay	Clay
Engineering (AASHO)[d]	A-7-6 (12)	A-7-6 (18)	A-7-6 (20)
Chemical			
Cat. Exch. Cap.,[e] m.e./100g	29.5	23.5	41.0
pH[h]	8.25	5.6	7.1
Carbonates,[g] %	4.9	0.0	0.8
Organic matter,[h] %	0.17	0.2	0.2
Predominant clay mineral[i]	Montmorillonite	Montmorillonite	Montmorillonite

[a] ASTM Method D 422-55T (8).

[b] ASTM Method D 423-54T and D 424-54T (8).

[c] Triangular chart developed by U.S. Bureau of Public Roads (9).

[d] AASHO Method M 145-49 (10).

[e] Ammonium acetate (pH = 7) method on soil fraction < 0.42 mm (No. 40 sieve).

[f] Glass electrode method using suspension of 15 g soil in 30 cc distilled water.

[g] Versenate method for total calcium.

[h] Potassium bichromate method.

[i] X-ray diffraction analysis.

METHODS

Preparation of Mixtures

Air dried soil passing the No. 10 sieve was dry mixed with the lime additive for 30 sec by a Hobart Model C-100 mixer. (The weight of lime or chemical additive used was expressed as a percentage of the oven-dry weight of the soil. The percentages of lime, sodium carbonate or sodium hydroxide refer to the as-received chemical; the percentages of sodium phosphate refer to anhydrous chemical.) Sufficient water was then added to bring the moisture to the desired optimum content and mixing was continued for 2 min. The mixture was next hand mixed a few times to loosen any of the soil stuck to the sides of the mixing bowl. It was then machine mixed for another 2 min. Chemical additives, when used, were dissolved in the mix water prior to adding to the soil-lime mixture. The crystal water of sodium phosphate was accounted for in calculating the amount of mix water required.

Molding Moisture Contents

The moisture-density, and moisture-7 day cured plus 1 day immersed strength relationships of the three soils treated with a 2 percent and 12 percent of each lime plus 0, 0.5 and 2 percent of sodium carbonate, and with 4, 6 and 8 percent of each lime plus

0, 0.5 and 2 percent of sodium hydroxide, were determined as described by Davidson and Bruns (11). The moisture-density and moisture-immersed strength curves showed that for each mixture the optimum molding moisture contents for maximum dry density and for maximum immersed strength were nearly the same. Hence it was decided to mold all test specimens at optimum moisture for maximum density.

Molding of Specimens

Each mixture was molded into cylindrical shaped specimens, 2 ± 0.05 in. high and 2 in. in diameter, having a density near 100 percent standard Proctor. The drop-hammer compaction apparatus and the molding method used have been described (11).

Curing of Specimens

Specimens made for evaluating the effect of chemical additives on the strength of soil-lime mixtures were cured for 7 and 28 days in a moist curing room maintained at a relative humidity of 90 percent or higher. The temperature in the moist curing room was within a few degrees of 70 F, except for the mixes with sodium hydroxide, which were cured at a temperature between 75 and 80 F (due to malfunctioning of the temperature control system). After being molded and prior to storing in the curing room, each specimen was sealed in wax paper to reduce the loss of moisture and to prevent carbon dioxide of the air from reacting with the lime in the specimens during curing.

The specimens for the variable temperature curing studies, after being molded, were sealed in wax paper. (Those treated with sodium hydroxide were further wrapped with Saran wrap and aluminum foil.) They were then placed in metal containers having tight fitting lids. A small can of water inside each container maintained the relative humidity near 100 percent. Little loss in weight by the specimens was observed, indicating little or no loss of moisture during curing. The specimens for curing temperature versus immersed strength tests were cured for 3, 7, 14, and 28 days at temperatures of 50, 70, 100 and 140 F. Additional sets of specimens were cured 7 days at each temperature in preparation for freeze-thaw testing.

TABLE 3

PROPERTIES OF LIMES

	Hydrated Limes Dolomitic (Monohydrate, Type N)	Hydrated Limes Calcitic (Hi-calcium)
Chemical analyis, percent by weight:		
Silicon dioxide	0.4	0.28
Iron and aluminum oxide	0.3	0.6
Magnesium oxide	31.8	0.59
Sulfur trioxide	1.1	0.25
Carbon dioxide	1.0	ND[a]
Total calcium oxide	48.8	73.82
Available calcium oxide	47.1	70.3
Loss on ignition	17.0	24.1
Combined H_2O	18.0	ND[a]
Processing Location	Genoa, Ohio	New Braunfels, Texas
Trade Name	Kemidol Hydrated	Kemikal Hydrated

[a] Not determined.

Immersed Strength Testing

The cured specimens were immersed in distilled water for 24 hr and then tested for unconfined compressive strength. The rate of loading specimens in the testing machine was 0.1 in. per minute. The maximum load causing failure was taken as the immersed strength of the specimen. Strength values reported in psi are the average of three test specimens; the difference between the individual values and the average value rarely exceeded 10 percent of the average value.

Durability Testing

A modified British standard freeze-thaw test (B.S. 1924:1957) (11), was used to evaluate the durability of selected mixtures. Two identical 2- by 2-in. specimens from each mixture were cured 7 days at each of the previously mentioned temperatures, then immersed in distilled water at room temperature for 24 hr. One specimen, designated the control specimen, was left immersed for 14 more days; and the other specimen, designated the freeze-thaw specimen, was exposed alternately to temperatures of 23 ± 2 F (16 hr) and 77 ± 4 F (8 hr) for 14 cycles, each cycle lasting 24 hr. (A vacuum flask specimen container was used to cause freezing to occur from the top down and to supply unfrozen water to the bottom of the specimen throughout the test.) After these treatments, the unconfined compressive strength of the freeze-thaw specimen (p_f) and of the control specimen (p_c) were determined. These values were used to evaluate the durability of the stabilized soils. The index of the resistance to the effect of freezing (R_f) was calculated from the formula:

$$R_f = \frac{100\, p_f}{p_c} \qquad (\%)$$

TEST RESULTS AND INTERPRETATIONS

Effect of Lime on Immersed Strength

Dolomitic Hydrated Lime.—Specimens of Kansan till, plastic loess, and Kansan gumbotil treated with 2 percent to 12 or 14 percent dolomitic lime, in 2 percent increments, were tested for immersed strength (unconfined compressive strength after 24 hr immersion) after 7 and 28 days moist curing at approximately 70 F and 90 + % R.H. The test results are plotted in Figure 1. The general trend of the data is similar for each soil at each curing period, showing low immersed strengths at low lime contents, near maximum strengths at intermediate lime contents, and little or no further increase of strength at higher lime contents. Recommended base course mix designs for roads might be: Kansan till plus 4 percent lime, plastic loess plus 6 percent lime, Kansan gumbotil plus 8 percent lime, but there might be an advantage in using more lime with the latter soil. These mixtures gave 7 and 28 day cured immersed strengths of 163 and 276 psi (Kansan till), 77 and 228 psi (plastic loess), 141 and 203 psi (Kansan gumbotil). The use of higher lime contents with Kansan till and Kansan gumbotil gave 28 day strengths of about 300 psi.

Calcitic Hydrated Lime.—The results of comparable tests using calcitic lime instead of dolomitic lime are plotted in Figure 2. Immersed strengths reached a fairly well-defined maximum value at fairly low lime contents and showed no increase at the higher lime contents used. Mix designs probably would be: Kansan till plus 4 percent lime, plastic loess plus 4 percent lime, Kansan gumbotil plus 6 percent lime. Corresponding 7 and 28 day cured immersed strengths were: 133 and 209 psi (Kansan till), 54 and 153 psi (plastic loess), 69 and 151 psi (Kansan gumbotil).

Summary—Dolomitic Lime vs Calcitic Lime.—The immersed strengths obtainable with treatments of dolomitic monohydrate (Type N) lime indicate that the three clay soils could probably be satisfactorily stabilized for base courses of roads in Iowa, providing construction was completed early enough to take advantage of high summer temperatures. Mixtures of the soils with calcitic lime probably would not be satisfactory for base courses, but should be satisfactory for subbases or subgrade treatments.

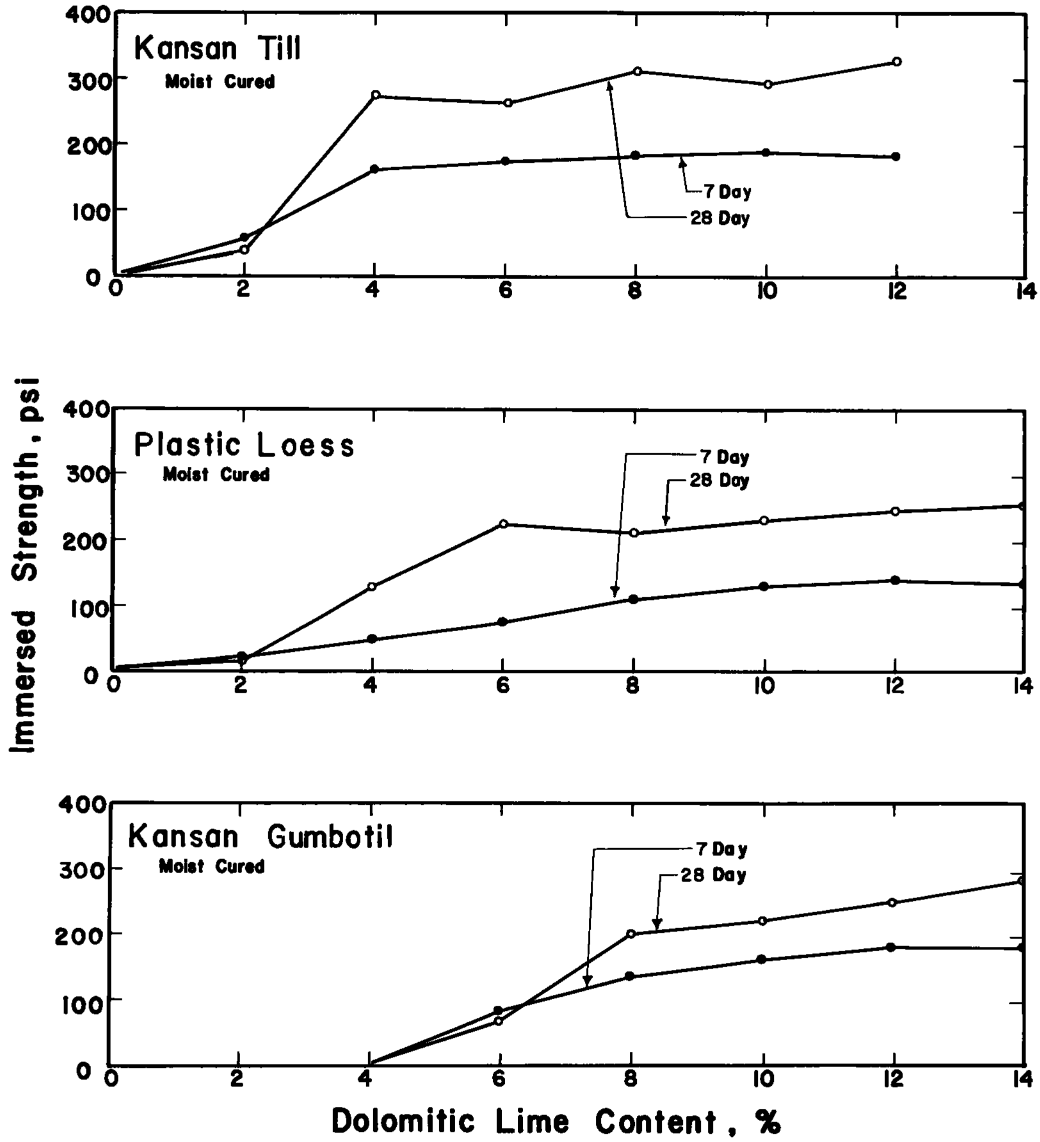


Figure 1. Immersed strength-dolomitic lime content relationships for Kansan till, plastic loess and Kansan gumbotil.

Effect of Lime Plus Chemical Additives on Immersed Strength

Dolomitic Hydrated Lime Plus Sodium Carbonate or Sodium Phosphate.—Specimens of Kansan till treated with 4, 6 and 8 percent of dolomitic lime plus 0, 0.25, 0.5, 1, 2 and 4 percent of each chemical were cured 7 and 28 days at approximately 70 F and 90 + R.H., immersed in distilled water for 24 hr, then tested for unconfined compressive strength. Test results indicated that the use of sodium carbonate or sodium phosphate in Kansan till-dolomitic lime mixtures caused a marked decrease in immersed strength. Therefore these chemicals were not evaluated with the other two soils.

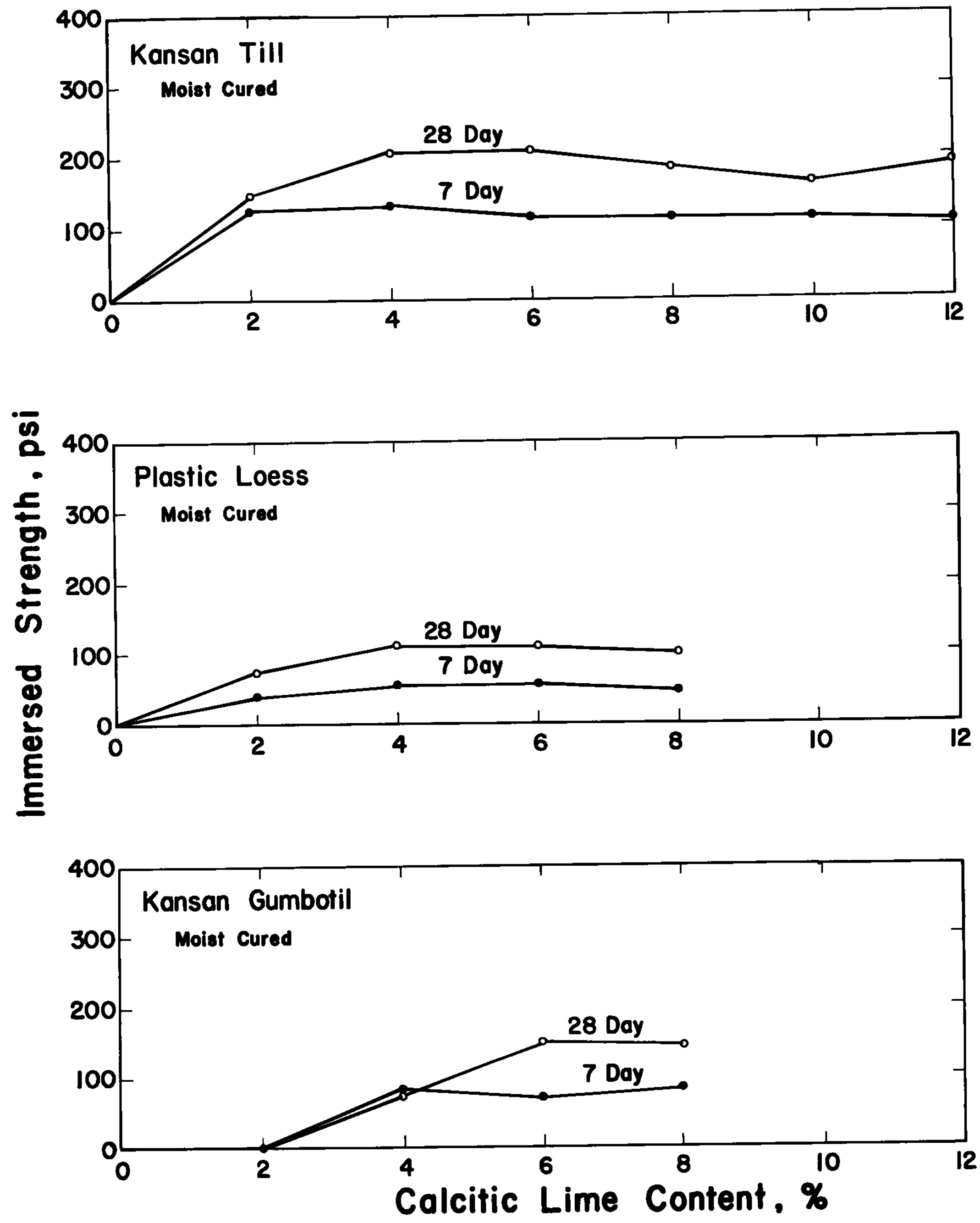


Figure 2. Immersed strength-calcitic lime content relationships for Kansan till, plastic loess and Kansan gumbotil.

Calcitic Hydrated Lime Plus Sodium Carbonate or Sodium Phosphate.—Specimens of Kansan till with combiantion treatments of calcitic lime and each chemical, proportioned the same as the combination dolomitic lime-chemical treatments, gave the immersed strength results shown in Figure 3. Definite optimum combination treatments are indicated, the best being 6 percent lime plus 2 percent sodium carbonate, and 6 percent lime plus 2 percent sodium phosphate. The former treatment gave 7 and 28 day cured immersed strengths of 251 and 292 psi; the latter treatment gave 183 and 278 psi, compared to 117 and 210 psi with 6 percent lime and 0 percent chemical. Since sodium phosphate is more expensive than sodium carbonate and did not produce as high strengths, it was not evaluated further.

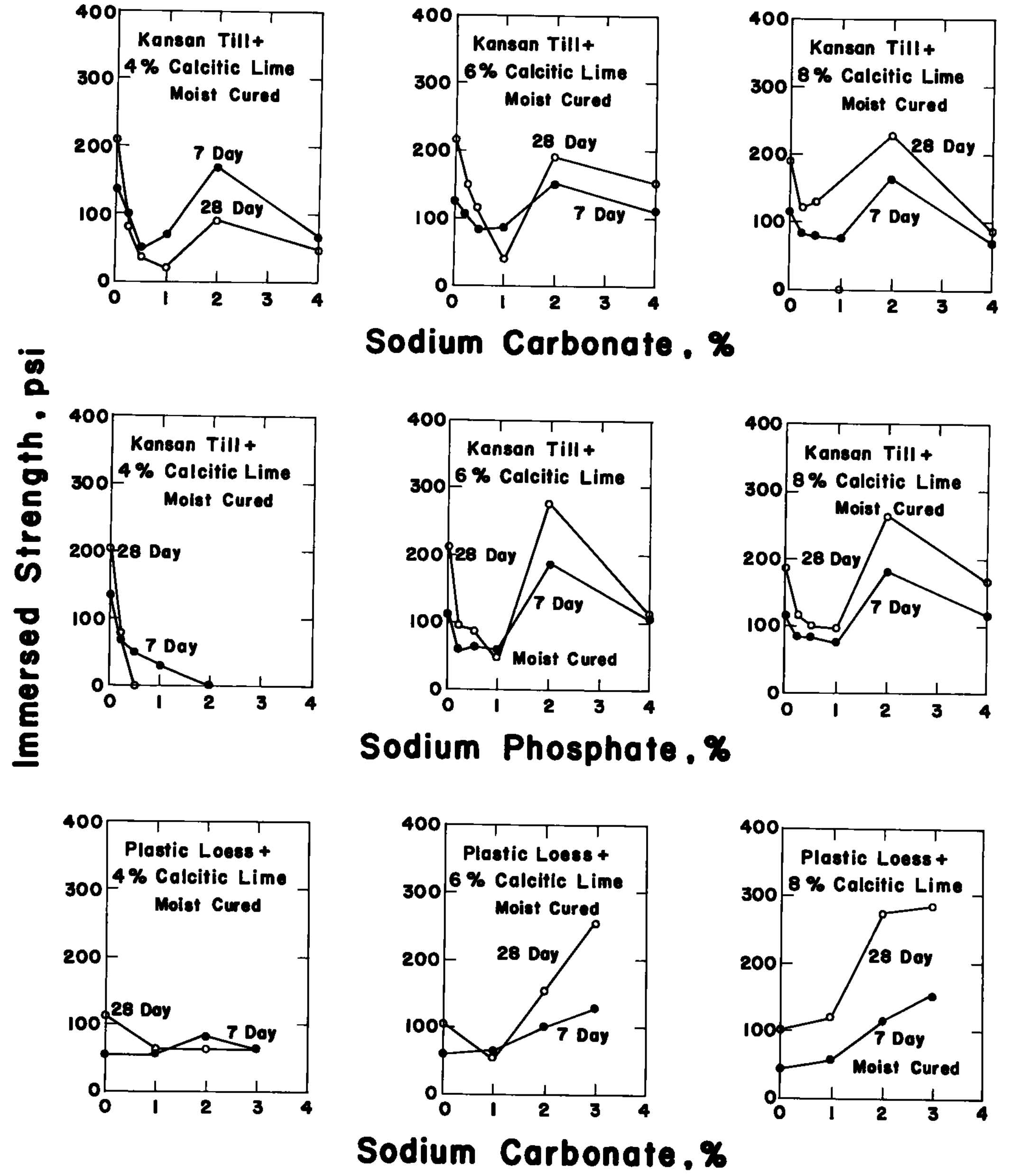


Figure 3. Immersed strength-sodium carbonate or sodium phosphate content relationships for calcitic lime-treated Kansan till and plastic loess.

The effects of additions of 1, 2 and 3 percent sodium carbonate on the immersed strength of plastic loess-lime mixtures are shown in Figure 3. Smaller amounts of sodium carbonate were not tried because of the adverse effects observed with Kansan till-lime mixtures (Figure 3). A good combination treatment of plastic loess was 6 percent lime plus 3 percent sodium carbonate; the 7 and 28 day cured immersed strengths were 130 and 256 psi. Another, slightly better but more costly, was 8 percent lime plus 3 percent sodium carbonate; the 7 and 28 day strengths were 143 and 291 psi. For comparison, the 7 and 28 day strengths of plastic loess-6 percent lime were 56 and 109 psi, and of plastic loess-8 percent lime were 45 and 99 psi.

The combination treatments used with plastic loess also were tried with Kansan gumbotil. Test results are not shown, because all amounts of sodium carbonate decreased the immersed strength of Kansan gumbotil-lime mixtures, both after 7 and 28 day curing.

Summary—Sodium Carbonate and Sodium Phosphate.—The foregoing test results indicated that the search for a chemical additive to improve clayey soil-lime mixtures was not ended. Additives of sodium carbonate and sodium phosphate decreased the immersed strengths of the soil-dolomitic lime mixtures. Optimum combination treatments of lime and chemical gave marked improvements to the immersed strengths of Kansan till and plastic loess, but use of a combination treatment other than the optimum generally had an adverse effect on strength. Sodium carbonate was judged more promising than sodium phosphate, but even sodium carbonate decreased the immersed strength of Kansan gumbotil-calcitic lime mixtures. Thus it was decided to continue the search for a more versatile and beneficial additive. Exploratory tests indicated that sodium hydroxide was a likely prospect.

Each Lime Plus Sodium Hydroxide.—The sodium hydroxide treatments of each soil-lime mixture were 0, 0.5, 1, 2 and 3 or 4 percent. The following mixtures were so treated: each soil plus 4, 6, and 8 percent dolomitic lime, and each soil plus 4, 6 and 8 percent calcitic lime. Specimens were moist cured 7 and 28 days at temperatures in the range 75 to 80 F, which were 5 to 10 F higher than the curing temperature of the specimens in the previously discussed tests. The resulting improvements of immersed strength are seen by comparing the strength values for soil-lime mixtures (0 percent sodium hydroxide) in Figures 4, 5, and 6, with those for identical mixtures in Figure 3.

Kansan Till.—Test results with Kansan till are shown in Figure 4. Sodium hydroxide, in amounts of 1 to 4 percent, improved the 7 and 28 day cured immersed strengths of both dolomitic lime and calcitic lime treated-soil mixtures; 0.5 percent sodium hydroxide was detrimental to the strengths of all mixtures. There was generally an optimum amount of chemical for each Kansan till-lime mixture, and strength improvements at and near the optimum treatment were exceptional. For example, the 7 day strength of the Kansan till-6 percent calcitic lime mixture was 135 psi; 1 percent sodium hydroxide boosted it to 363 psi. The 28 day strength was improved even more: 240 psi without chemical, 582 psi with 1 percent chemical. Sodium hydroxide treatments made possible 7 day strengths near or above 350 psi with all Kansan till-lime mixtures regardless of the type of lime; the same treatments produced 28 day strengths of 500 psi or more. A comparison of the following mix designs, which might be considered satisfactory for a road base course, illustrates the possibilities for economical stabilization of Kansan till: 6 percent dolomitic lime (marginal), 6 percent dolomitic lime + 2 percent NaOH (safe), 4 percent calcitic lime + 1 percent NaOH (safe).

Plastic Loess.—Test results with plastic loess (Fig. 5) indicate that although the optimum amounts of sodium hydroxide were generally beneficial to immersed strength of dolomitic lime-treated mixtures, best strength improvements were obtained with the calcitic lime-treated mixtures, which needed the most improvement. It is evident that the extent of improvement of plastic loess-lime mixtures was not as exceptional as with Kansan till-lime mixtures, but economical mix designs which may meet base course requirements are made possible by use of sodium hydroxide. For example, plastic loess plus 6 or 8 percent calcitic lime and 2 percent NaOH look promising. Plastic loess plus 8 percent or 10 percent dolomitic lime and 2 percent NaOH would probably

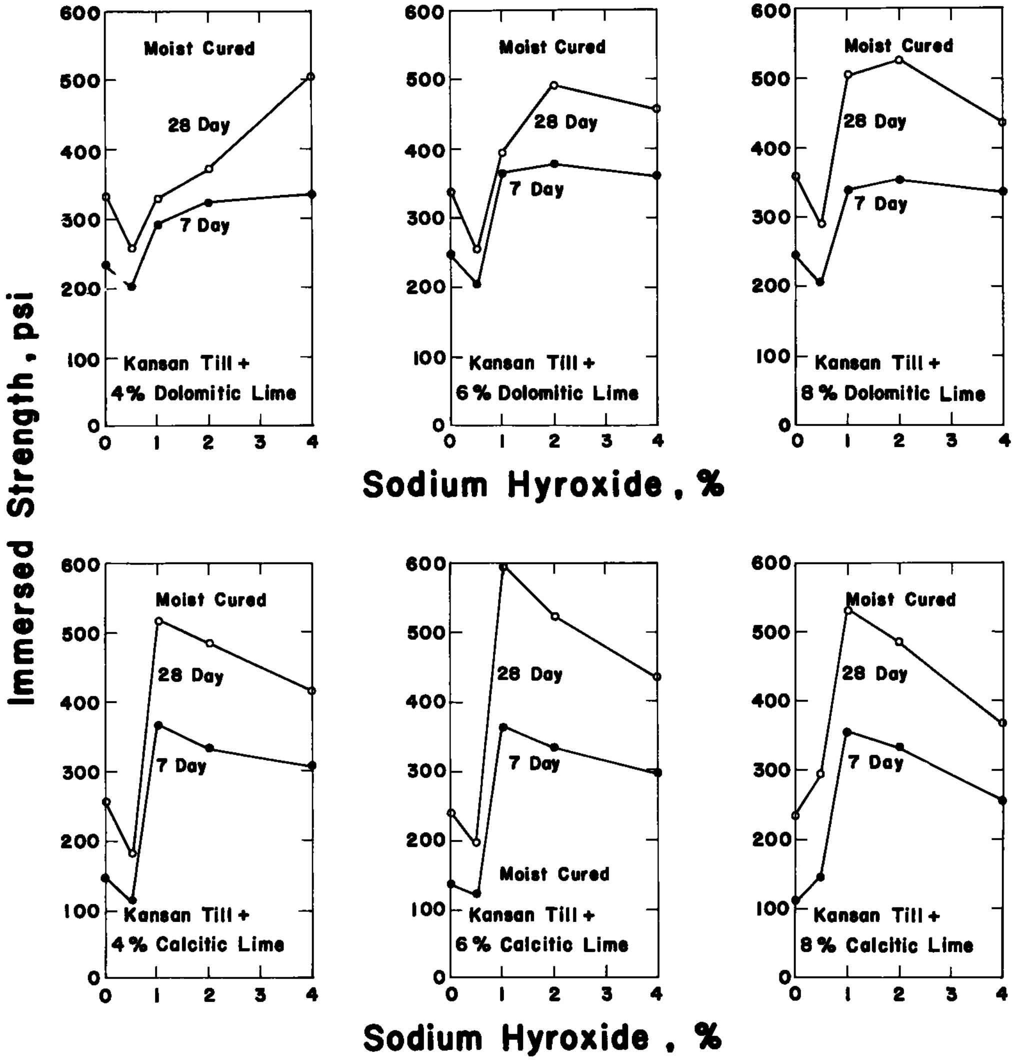


Figure 4. Immersed strength-sodium hydroxide content relationships for dolomitic lime-treated and calcitic lime-treated Kansan till.

give equivalent performance, although no data are shown for 10 percent dolomitic lime.

Kansan Gumbotil. —The optimum amount of sodium hydroxide for each Kansan gumbotil-lime mixture (Fig. 6) greatly improved 7 day cured immersed strength, and, in the case of the calcitic lime mixtures, also 28 day strength. The 28 day strengths of the dolomitic lime mixtures did not show such marked improvements. For example, 2 percent sodium hydroxide increased the 7 and 28 day strengths of the 8 percent calcitic lime-treated mix-

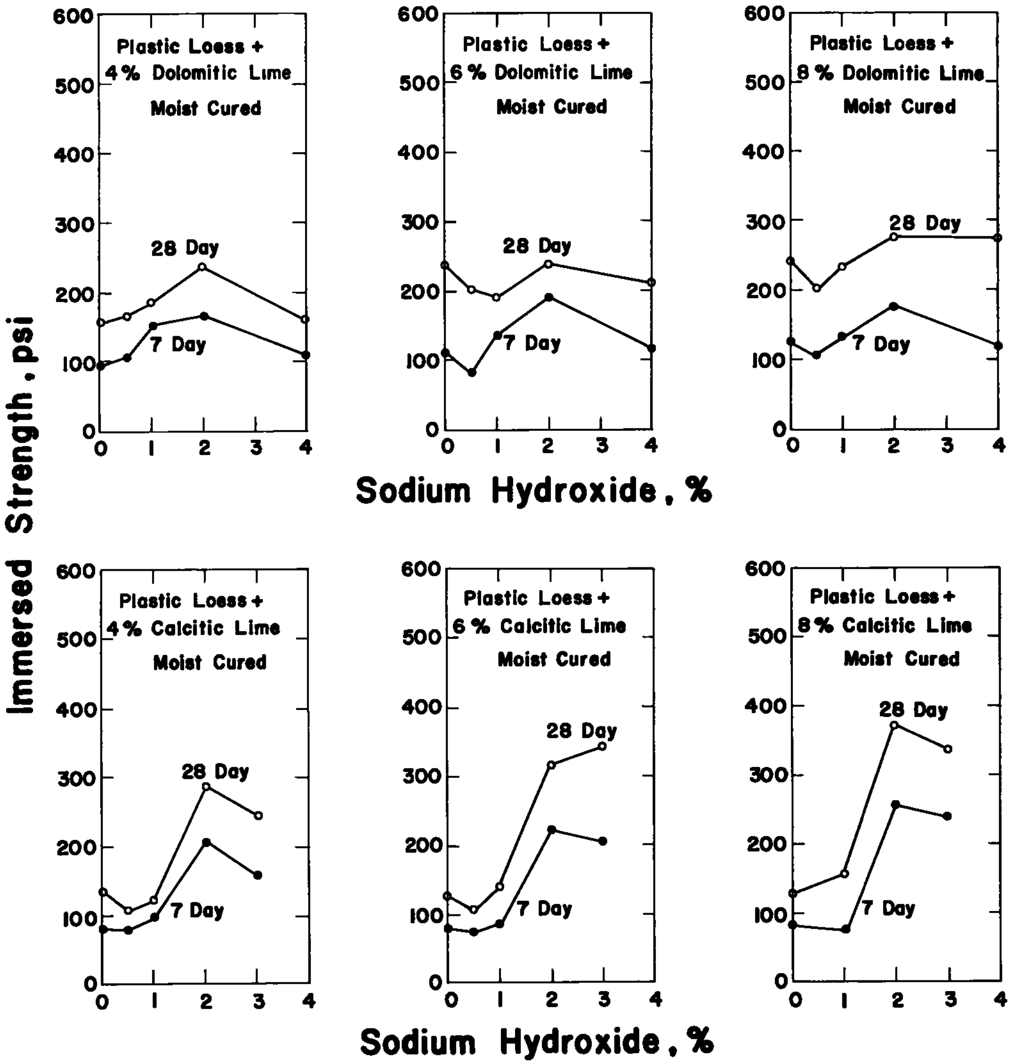


Figure 5. Immersed strength-sodium hydroxide content relationships for dolomitic lime-treated and calcitic lime-treated plastic loess.

ture from 155 and 271 psi to 348 and 421 psi, respectively, and the same amount of chemical increased the 7 and 28 day strengths of the 8 percent dolomitic lime-treated mixture from 211 and 382 psi to 324 and 390 psi, respectively. Satisfactory mix designs for road base courses might be with: 8 percent dolomitic lime, 6 or 8 percent dolomitic lime plus 2 percent NaOH, 6 or 8 percent calcitic lime plus 2 percent NaOH.

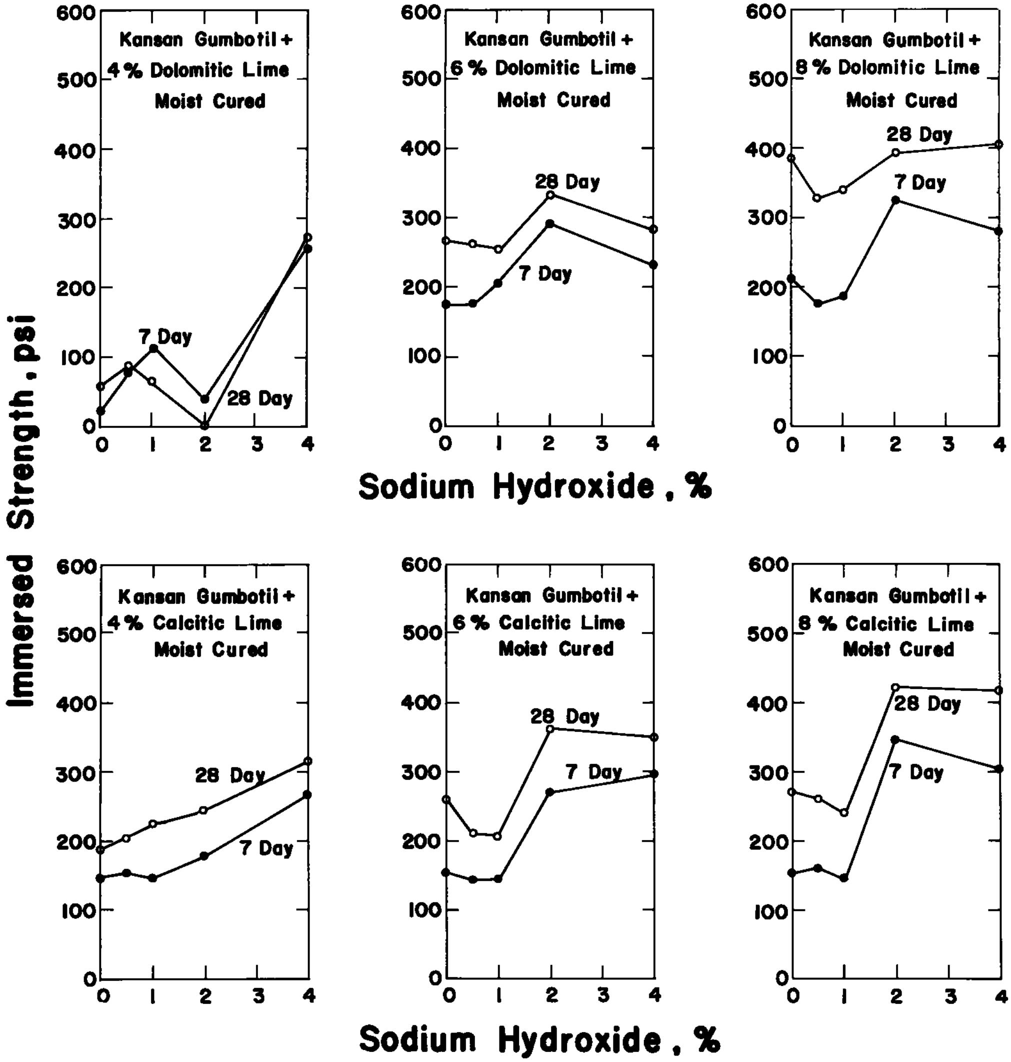


Figure 6. Immersed strength-sodium hydroxide content relationships for dolomitic lime-treated and calcitic lime-treated Kansan gumbotil.

Summary—Sodium Hydroxide.—Sodium hydroxide may be the much need chemical activator for pozzolanic reactions in clayey soil-lime mixtures. The clayey soils used in the tests contained montmorillonite as the dominant clay mineral (Table 2), and hence represent about as difficult materials to stabilize as will be found anywhere. Work now in progress will show whether combination treatments of lime and sodium hydroxide are equally beneficial to soils dominated by other clay materials.

The test data indicate that most montmorillonitic clay soils can probably be stabilized satisfactorily with lime and sodium hydroxide to meet minimum road base course strength requirements. Apparently the amounts of lime and chemical needed vary only slightly with the amount of clay in the soil, because the clay (0.005 mm) contents of the soils used in the tests covered a wide range (38.5 to 70.5 percent), and best immersed strengths generally were obtained with 6 or 8 percent lime and 1 or 2 percent NaOH. Lime contents higher than 8 percent were not tried, but they may give added strength to soils such as plastic loess and Kansan gumbotil. The exceptional response of the Kansan till to lime-NaOH treatments may be related to its gradation: approximately equal parts by weight of sand, silt and clay sizes. Plastic loess, with approximately the same amount of clay as Kansan till, but no sand, was improved to a considerably lesser extent by the same treatments.

A most encouraging finding was that sodium hydroxide made the calcitic hydrated lime equally or more reactive than the dolomitic monohydrate (Type N) lime with the clayey soils. It is hoped that further study will confirm that sodium hydroxide is an equalizer for hydrated limes in soil stabilization, thus eliminating the need for specifying dolomitic monohydrate (Type N) lime for base course stabilization in Iowa.

Effect of Curing Temperature on Immersed Strength

The following four treatments of Kansan till were selected for the immersed strength-curing temperature relationship study: 6 percent dolomitic lime, 6 percent calcitic lime, 6 percent calcitic lime plus 2.25 percent sodium carbonate, 6 percent calcitic lime plus 1 percent sodium hydroxide. Specimens of these mixtures were cured at 50, 70, 100 and 140 F for 3, 7, 14 and 28 days. Cured specimens were immersed for 24 hr, then tested for unconfined compressive strength. The test results are shown two ways in Figure 7, immersed strength versus curing time for each temperature, and immersed strength versus curing temperature for each time.

Kansan Till Plus 6 Percent Dolomitic Lime.—At each curing temperature, immersed strength increased with curing time up to 14 days; thereafter except at 50 F, the rate of increase was less. At 140 F, 28 day strength was less than 14 day strength. The greatest rate of strength gain up to 28 days was at 100 F; the immersed strength increased from 300 psi at 2 days to over 600 psi at 28 days. The least change of strength was at 140 F; at this temperature the soil-lime reaction may have been nearly completed at 2 days.

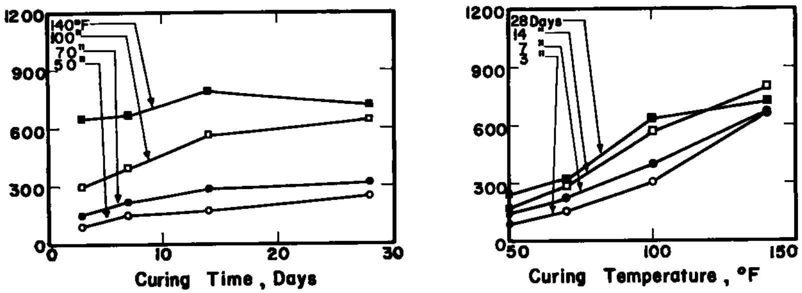
It appears that for emergency mix design purposes, accelerated curing for 3 or 7 days at 140 F could be used to obtain a fairly accurate estimate of immersed strength after 28 days curing at 100 F. Similarly, 3 days curing at 100 F was comparable with 28 days curing at 70 F.

The plots of immersed strength versus curing temperature further illustrate the beneficial effect of high temperature curing on strength after each curing period. At 7 days, where the relationship was nearly linear, the increase in immersed strength per degree Fahrenheit increase in curing temperature was roughly 6 psi. The effect of curing temperature on 14 and 28 day strengths, if anything, was even greater.

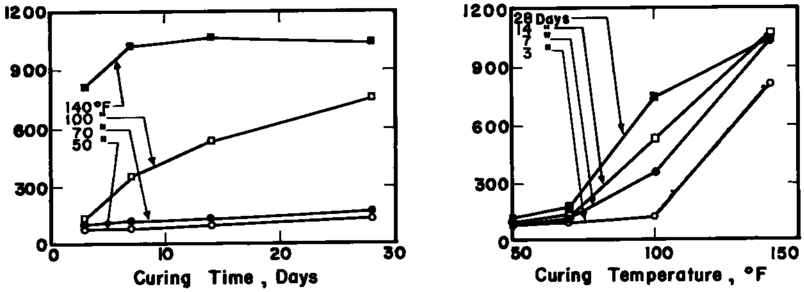
There would be little question of the adequacy of this mixture for a road base in regions having atmospheric temperatures of 100 F during the construction season; three days of such curing would probably suffice.

Kansan Till Plus 6 Percent Calcitic Lime.—The results of tests with this mixture may explain why calcitic lime is considered satisfactory for soil-lime stabilization in southern climates, and why it may not be equally satisfactory for base course stabilization in the north. At curing temperature of 50 and 70 F, immersed strengths up to 28 days are too low for base courses, if the curing period is to be followed by freeze-thaw cycles. At 100 F the hardening mechanism was tremendously accelerated, and immersed strength increased from about 140 psi at 3 days to about 750 psi at 28 days, adequate for base courses in any climate. At 140 F the hardening was about completed at 7 days, and the immersed strength was over 1,000 psi.

Indications are that for speedy mix design the immersed strength after 3 days curing at 140 F could be used to predict immersed strength after 28 days curing at 100 F.



Kansan Till + 6 % Dolomitic Lime



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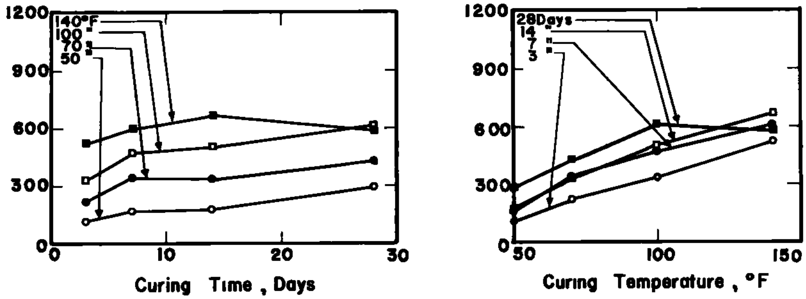
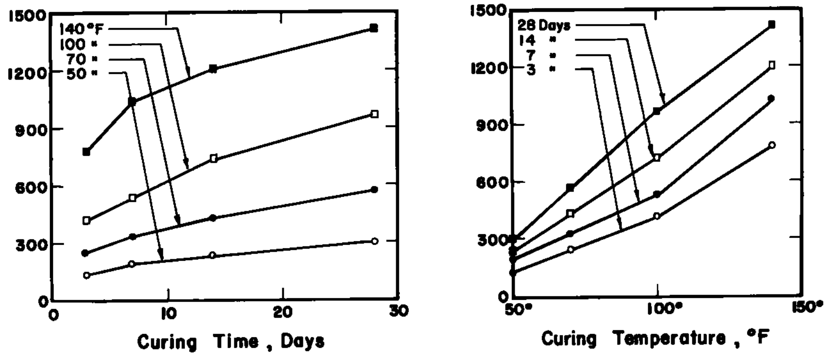


Kansan Till + 6 % Calcitic Lime + 2.25 % Sodium Carbonate



Kansan Till + 6 % Calcitic Lime + 1 % Sodium Hydroxide

Figure 7. Immersed strength-curing temperature and curing time relationships for Kansan till treated with 6 percent dolomitic lime, 6 percent calcitic lime, plus 2.25 percent sodium carbonate, or 6 percent calcitic lime plus 1 percent sodium hydroxide.

Also, 3 day strength at 100 F seems indicative of 28 day strength at 70 F.

The immersed strength versus curing temperature curves also illustrate the great benefit to strength gain of curing temperatues above 70 F. Fourteen days strength showed a linear relationship in the temperature range between 70 and 140 F; each degree Fahrenheit increase in temperature increased (14 day immersed) strength about 13 psi.

Kansan Till Plus 6 Percent Calcitic Lime and 2.25 Percent Sodium Carbonate.- A comparison of the plotted test data for this mixture of Kansan till plus 6 percent calcitic lime (0 percent sodium carbonate) indicates that use of the chemical additive would be worthwhile only when early strength up to 3 days is of paramount importance, or when curing would be at temperatures around 50 F to 70 F. At 100 F curing there was little or no benefit to immersed strength, except at 3 days, from use of the chemical, and at 140 F the chemical additive was definitely detrimental to strength at all ages. It appears that either high temperatures or sodium carbonate can accelerate the pozzolanic reactions. Of the two, high temperature is more effective.

Kansan Till Plus 6 Percent Calcitic Lime and 1 Percent Sodium Hydroxide.—This mixture showed exceptionally good immersed strength gains with increase of curing at 50 F from 137 psi at 3 days to 297 psi at 28 days; at 70 F, this increase was from 250 psi to 567 psi; at 100 F, this increase was from 418 psi to 960 psi; at 140 F, this increase was from 780 psi to 1,426 psi. It is of interest to note that 7 day strength at 140 F is approximately equal to 28 day strength at 100 F; and that 7 day strength at 100 F is approximately equal to 28 day strength at 70 F.

The immersed strength versus curing temperature relationship was nearly linear for each curing period. For 7 and 28 day curing, each degree Fahrenheit increase of temperature increased immersed strength about 10 and 13 psi, respectively.

Comparison of the strength data for Kansan till plus 6 percent calcitic lime with and without sodium hydroxide treatment, indicates that inasmuch as both heat and sodium hydroxide benefit the hardening mechanism, the sodium hydroxide treatment would be advantageous for base course construction in any climate, but particularly so in warm climates, where appreciable reductions in lime content might be made possible.

Summary—Curing Temperature.—High temperature curing greatly accelerated the hardening mechanism of Kansan till stabilized with 6 percent of either dolomitic monohydrate (Type N) lime or calcitic hydrated lime. At 100 F, both mixtures gave immersed strengths which exceeded 300 and 600 psi after 7 day and 28 day curing, respectively.

The 2.25 percent additive of sodium carbonate to the Kansan till-calcitic lime mixture accelerated hardening at curing temperatures of 50 and 70 F; but at 100 F curing the chemical was beneficial only to 3 and 7 day strengths; and at 140 F curing the chemical greatly nullified the beneficial effect of heat on strength at all periods up to 28 days. The adverse effects of sodium carbonate on strength may have been due to heat-induced swelling, and consequent weakening by disruptive internal pressures.

The addition of 1 percent sodium hyroxide to the Kansan till-6 percent calcitic lime mixture acted as an excellent accelerator for the hardening mechanism, both at normal and high curing temperatures. Thus its beneficial effects were in addition to those due to heat, a desirable trait in a chemical accelerator.

Durability of Lime, or Lime and Chemical-Treated Kansan Till

The four mixtures used to study immersed strength-curing temperature relationships were further evaluated by the modified British freeze-thaw test (11). The control and freeze-thaw specimens of each mixture were moist cured 7 days at 50, 70, 100, or 140 F prior to evaluation. Cured control specimens were immersed in distilled water for 15 days, then tested for unconfined compressive strength (p_c). Cured freeze-thaw specimens were immersed for 1 day, subjected to 14 freeze-thaw cycles (14 days), then tested for unconfined compressive strength (p_f). Test results and the calculated indices of the resistance to the effect of freezing (R_f) are given in Table 4.

TABLE 4

RESULTS OF FREEZE-THAW TESTS BY MODIFIED BRITISH METHOD, B.S. 1924: 1957

Additive (s)	As-molded Density (pcf)	Curing Temperature (7 days), deg F	p_f (psi)	p_c (psi)	R_f[1] (%)
6% Dolomitic monohydrate (Type N) lime	107.5	50	177	277	65
	107.5	70	235	254	90
	107.5	100	367	392	95
	107.5	140	617	653	95
6% Calcitic hydrated lime	106.2	50	109	138	80
	106.2	70	103	122	85
	106.2	100	277	289	95
	106.2	140	798	974	80
6% Calcitic hydrated lime plus 2.25 % sodium carbonate	107.0	50	225	351	65
	107.0	70	322	418	75
	107.0	100	421	472	90
	107.0	140	650	597	110
6% Calcitic hydrated lime plus 1% sodium hydroxide	110.2	50	212	357	60
	110.2	70	341	420	80
	110.2	100	449	599	75
	110.2	140	981	828	120

[1] $R_f = \dfrac{100p_f}{p_c}$ reported to nearest 5 percent.

Criteria of Durability.—The criteria which may be used to evaluate the results of the modified British freeze-thaw test are: (1) the R_f value should equal or exceed a specified value, (2) the individual p_f and p_c values should equal or exceed a specified value. The following minimum values appear to be conservative for the design of stabilized mixtures for road base courses in climates such as that in Iowa: R_f = 80 percent, p_c = 250 psi, p_f = 250 psi. A discussion of these criteria may be found in reference (11). When both p_c and p_f values greatly exceed 250 psi, a lower minimum R_f may be permissible, for example, 75 percent as used in England.

Interpretation of Test Results.—High temperature curing improved the freeze-thaw resistance of specimens of the Kansan till-6 percent dolomitic lime mixture, and those cured at 100 and 140 F showed satisfactory durability. The specimens cured at 70 F were indicative of marginal quality for road bases, and those cured at 50 F failed to meet the recommended minimum durability values. Thus a road base of this mixture should have some hot weather curing before undergoing wintering in Iowa, and completion of construction in August, at the latest, would be recommended.

If the mixture of Kansan till and 6 percent calcitic lime is judged on the basis of test results after 50 or 70 F curing, it does not meet base course requirements. However specimens cured at 100 or 140 F proved more than adequate, indicating that this mixture might make a satisfactory road base in warm climate.

For northern climates where temperatures of 70 F or higher prevail during the construction season, the test results in Table 4 indicate that the Kansan till-6 percent calcitic lime mixture could be brought up to base course quality by the addition of either 2.25 percent sodium carbonate or 1 percent sodium hydroxide. Of the two chemical accelerators, sodium hydroxide would permit the greatest flexibility in construction planning and the longest construction season.

Summary—Durability.—The durability test data for Kansan till indicate that, whereas dolomitic monohydrate (Type N) lime stabilization may give adequate durability for road bases in Iowa, calcitic hydrated lime stabilization may not, unless a chemical accelerator is used. Sodium hydroxide appears especially promising for this purpose.

CONCLUSIONS

1. Addition of a small amount of sodium hydroxide to mixtures of montmorillonitic clay soil and lime acts as an effective accelerator for the hardening mechanism of the compacted mixture. The optimum sodium hydroxide treatment is about 1 to 2 percent, based on the dry weight of the soil component.
2. Sodium carbonate and sodium phospate are not as promising as sodium hydroxide for improving lime stabilization of montmorillonitic clay soils, particularly when the lime is dolomitic monohydrate (Type N).
3. The magnitude of strength improvement up to 28 days, due to the use of sodium hydroxide, varies with the composition of the lime and the clay soil; calcitic (high-calcium) hydrated lime may give somewhat better results than dolomitic monohydrate (Type N) lime, but the presence of sand-size quartz in the soil is definitely beneficial.
4. Heat also accelerates the hardening of compacted mixtures of montmorillonitic clay soil and lime, and temperatures around 100 F or higher during the early curing period are extremely beneficial to strength and durability, the beneficial effects apparently supplementing those obtainable from the use of sodium hydroxide as an additive.
5. Dolomitic monohydrate (Type N) lime should be used for lime stabilization of montmorillonitic clay soils for road base courses in Iowa or regions of similar or more severe climate, unless an additive of sodium hydroxide is specified; in which case, either the dolomitic lime or a calcitic hydrated lime may be used. In Iowa, without sodium hydroxide additive, calcitic lime appears satisfactory only for subbase or subgrade stabilization.

ACKNOWLEDGMENT

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Reaction of Hydrated Lime With Pure Clay Minerals in Soil Stabilization

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The use of hydrated lime has been growing in the field of soil stabilization. Although it has been used from coast to coast in the United States and by some nations abroad, the reaction of hydrated lime with the soil is still a mystery, particularly with respect to its relative effectiveness and rates of reaction with various soils.

A research project to determine the reaction of hydrated lime and soil is under way at the University of Illinois. Because of the complexity of soils and because lime is of greater benefit to a heavy clay soil, the first part of the investigation has been devoted to a study of the effects of hydrated lime on pure clay minerals.

By the aid of X-ray diffraction and D.T.A. analysis, it has been possible to watch and identify the reactions which take place. The first reaction, which is brought about immediately when lime is added, is replacement of absorbed ions by calcium ions; the second, formation of a series of new minerals; the third, carbonation of the hydrated lime. These reactions, illustrated by typical X-ray examples, offer definite proof as to why different rates of reaction occur with different soils.

● THE DISCOVERY that the workability of a clay soil would be greatly improved by the addition of lime, $Ca(OH)_2$, dates back into the remote past. Highway and airport engineers found that lime as a stabilizing agent greatly improved subgrade soils containing high percentages of expansive clays, by reducing the plasticity indices and increasing the bearing value. Although lime has been used throughout this country and by several nations abroad for stabilization, the reactions of hydrated lime with soil are still for the most part a mystery. The literature contains many reports describing the benefits of lime additons and gives various explanations for the results obtained. Some of the reactions mentioned most often are (1, 2): (a) aggradation caused by flocculation of dispersed clays, (b) exchange of calcium ions for other adsorbed ions such as hydrogen, sodium or potassium, (c) pozzolanic reactions, which were thought to be the formation of calcium silicates by the reaction of the lime with free silica in the soil, (d) the gradual reaction of the lime and CO_2 from the atmosphere and the soil to form calcium carbonate and thereby cementing the soil particles together. Any or all of these phenomena may occur under the right conditions and with the right soil.

Many engineers have questioned the permanency of lime stabilization. Thus, if it were only a matter of flocculation or ion exchange, fluctuations of ground water levels or percolating ground waters might replace the calcium ion and reduce the beneficial effect of the added lime. It is for this reason as well as others that data are needed concerning the true nature of the reactions of lime and soil under stabilization conditions.

At the University of Illinois a research project has been set up by National Lime Association to study the reactions of hydrated lime with soils. The purpose of this study is to investigate the nature of reactions which take place when soil, lime and water are combined and to determine whether or not lime will react significantly with all types of soils It is planned particularly to study the reactions to see exactly how they influence properties.

The results of previous work, not reported here, (work done by Eades at the University of Virginia) showed that it would be almost impossible to study reactions of small percentages of lime and soils, because of the complexity of soils from the standpoint of mineral composition, particle size gradation, degree of crystallinity of the clay fraction and differences in adsorbed ions. In many cases it is extremely difficult to identify all of the mineral components of an unfractionated soil sample by X-ray diffraction or other means of analysis. It is even more difficult to identify the reaction of lime and soil components.

Grim (3) in 1940 showed that the clay minerals are the components of soil which largely control their physical properties. Therefore, in order to study the reaction of lime with soils more closely, it was believed the reactions with pure clay minerals, of the types which occur in soils, should be studied first. Then if all clay minerals did not react with lime, a clay mineral analysis could serve as a quick test to determine if lime would react with a soil. Further, the analytical data for clay mineral-lime reactions are more easily interpreted so that a start could be made for the interpretation of the more complex data for soil-lime reactions. The investigation reported herein was confined to the effects of treating eight pure clay minerals with lime. The clay minerals included the major types found in soils.

The approach used for this investigation consisted of making X-ray and differential thermal analysis of the untreated clays so that all of thier individual peculiarities could be noted before they were treated. The second step was to treat the clays with varying amounts of lime which was followed by curing periods ranging from 72 hr to 60 days at 140 F. The effects of the given treatment were evaluated by X-ray, differential thermal, and compressive strength analyses.

DESCRIPTION OF THE MATERIALS USED

Eight samples of four different groups of clay minerals were selected because they represent the various clay mineral groups and variations within the groups that are found commonly in soils. The groups are kaolinite, montmorillonite, illite, and a mixed layered mineral of chlorite and montmorillonite. The eight samples are as follows:

1. Kaolin (a) from Dry Branch, Georgia, a coarse-grained well-crystallized kaolinite with low cation excahnge capacity. Five milliequivalents per 100 grams (5 me/100 gr).
2. Kaolin (b) from near Anna, Illinois, a fine-grained poorly-crystalline kaolinite containing a small percentage of quartz. The cation exchange capacity is about 18 me /100 gm (4). The clay is plastic.
3. Halloysite ($2H_2O$) from Eureka, Utah, a mineral having the basic kaolinite-type lattice but being highly disordered and containing layered water in the structure. The cation exchange capacity is 12 me/100 gm (4).
4. Bentonite (a) from Upton, Wyoming, a plastic high swelling Na^+ montmorillonite having a cation exchange capacity of 89 me/100 gm (5). The material is about 92 to 95 percent montmorillonite with the remaining 5 to 8 percent made up of minute fragments of other minerals, the most abundant being feldspar.
5. Bentonite (b) from Aberdeen, Mississippi, a Ca^{++} montmorillonite with a cation exchange capacity of 64.7 me/100 gm (6). It is much coarser than the Wyoming montmorillonite and has relatively low swelling properties.
6. Bentonite (c) from White Springs, Mississippi, also a Ca^{++} montmorillonite, having a higher iron content than the Aberdeen montmorillonite and a lower pH than either the Aberdeen or the Wyoming montmorillonites. It is also a low swelling variety of montmorillonite.
7. Illite, from Fithian, Illinois, having a cation exchange capacity of 28 me/100 gm with calcium and magnesium being the chief exchangeable cation (3).
8. "Grundite," from Morris (Goose Lake), Illinois, a poorly crystallized mixed-layered chlorite, illite and montmorillonite, having a lower potassium content than does

the illite from Fithian and a higher plasticity. The cation exchange capacity is 35 me/100 gr.

Hydrated lime, calcium hydroxide, is a soft burned quick lime with 98.4 to 99.0 percent passing the 325 mesh screen. It is 95.4 to 96.6 percent $Ca(OH)_2$.

ANALYTICAL PROCEDURE

Preparation of Materials

The montmorillonite samples were received in a powder form with 100 percent passing a 100 mesh sieve. The kaolinites, illite, and Grundite were received in lump form and were crushed to pass the 100 sieve. Moisture contents were determined and the material was stored in containers with tight fitting lids as a means of trying to control the moisture content. Fresh lime samples were received every 60 days. Chemical analyses were furnished with each shipment by the lime plant's laboratory to insure that the same quality lime was used throughout the project. The lime was stored in airtight containers. (Periodic checks were made on the lime to make sure it was not carbonating.)

Treatment of Clay

Samples of the minus 100 mesh clay and dry hydrated lime were blended together in a dry state to obtain a uniform mix. Distilled water was then added to the dry mixture to bring it to its optimum moisture content as determined by the standard AASHO method of test. The material was then compacted in Proctor molds to the standard AASHO density. The specimens extruded from the molds were sealed in containers to prevent the moisture from evaporating and were cured at 140 F for 72 hr. The 4- by 4.5-in. cylinders were tested by unconfined compression. The deformed test pieces were crushed and representative samples removed for X-ray, and D.T.A. analyses. The samples were dried in a vacuum so that the calcium would not carbonate with the carbon dioxide of the atmosphere.

For each of the clays studied, hydrated lime contents of 2, 4, 6, and 8 percent were employed. For the montmorillonite the tests were extended to include 10 and 12 percent hydrated lime. The additions of hydrated lime were made on the basis of the oven dried clay.

At the beginning of the project it was decided to investigate the effects of lime on the structure of the clay minerals by mixing the clays with a large percentage of lime and curing them for a prolonged period to emphasize the reaction products for identification pruposes. This was accomplished by mixing small samples of the minerals with 20 percent lime and enough water to make the mixture fluid. Duplicate samples were sealed in containers and cured for 3, 6, 15, 30 and 60 days. These samples were studied with the aid of X-ray and D.T.A.

EXPERIMENTAL METHODS

Unconfined Compression Test

This test was used to measure the effects of the hydrated lime on the bearing strength of the clay. The vertical load was applied at a rate of 0.05 in. per minute.

X-ray Diffraction Analysis

The vacuum dried clays were ground in an agate mortar to pass a 200 mesh sieve and packed into an aluminum holder. Care was taken to minimize preferred orientation. Oriented aggregates prepared according to Bradley, Grim, and Clark (7) were also investigated. The X-ray diffraction patterns were obtained with a North American Philips Scintillation-Counter (type 52245) with a Pulse Height Analyzer.

Differential Thermal Analysis

Two nichrome-wire furnaces with a maximum range of 1000 C were used for the differential thermal analysis. The rate of temperature increase of the samples averaged about 6.5 up to 60 C per minute, then the temperature increased at a constant rate of 10 C per minute. A reflecting galvometer with a Brown Penograph Recorder was used to record the thermal reactions.

DISCUSSION OF TEST RESULTS

Compressive Strength of Treated Clays

In Figure 1, plots of Georgia kaolin, Fithian illite, Grundite, White Springs montmorillonite, Aberdeen montmorillonite and Wyoming montmorillonite are shown. The average compressive strength in pounds per square inch is plotted versus the percent of lime added. Anna kaolin and Eureka halloysite were added to the original study and were not available in quantities large enough for making a compressive strength study.

As shown in Figure 1, Georgia kaolin, which has a low cation exchange capacity and low plasticity, has the highest increase in strength with increments of lime up to 8 percent. Only one other clay equaled its strength with this amount, and that was the Aberdeen montmorillonite. The increase in strength of the kaolin at 8 percent was only slightly above the 6 percent level. This seems to indicate that an optimum amount of lime which will react with the kaolin for the 72-hr curing period is around 6 percent.

The Aberdeen montmorillonite and White Springs montmorillonite which have similar properties such as plasticity and cation exchange capacity gave about the same strength in the untreated state. But the two materials acted quite differently with the addition of lime. The Aberdeen clay increased in strength with each increment of lime and as it was still rising at 8 percent, additional specimens were tested with 10 and 12 percent. These specimens likewise gave an increase in compressive strength. Therefore, it is assumed the optimum lime content was not reached for the curing conditions used in this experiment. The White Springs montmorillonite on the other hand gave a lower compressive strenght with the addition of 2 percent lime, and 6 percent lime was required to raise the strength above that of the untreated cylinders. The material showed an improvement up to 8 percent but it did not equal the Aberdeen clay for the same amount of lime and had a reduction in strength with greater concentrations.

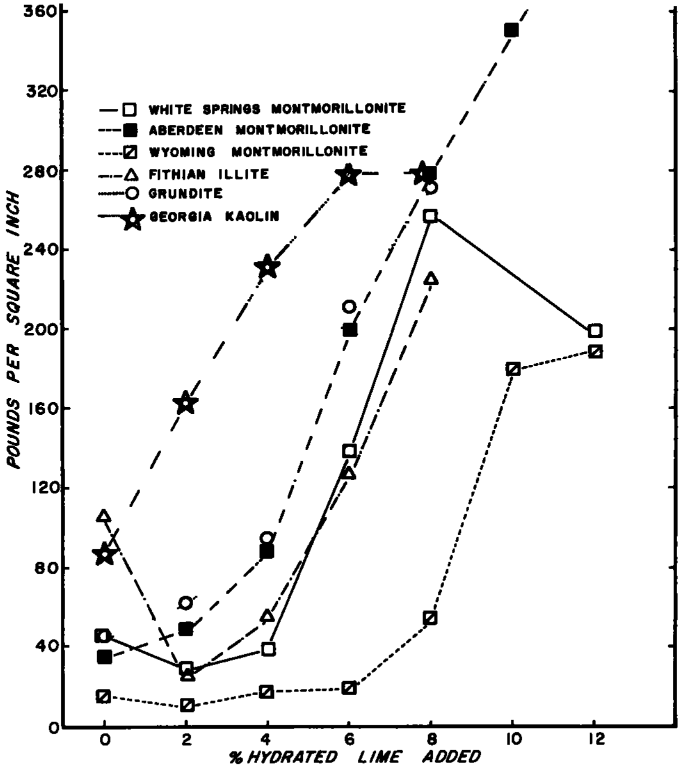


Figure 1. Compressive strengths of hydrated lime treated samples.

The Wyoming montmorillonite which is known for its high percentage of swell, cation exchange capacity and plasticity had a low compressive strength in the untreated condition and dropped off slightly when 2 percent lime was added. The specimens with 4 and 6 percent showed a slight increase but 8 percent was required to raise the compressive strength above the psi of the untreated specimens of White Springs and Aberdeen montmorillonites. There was only a slight increase in strength from 10 to 12 percent, therefore, it would appear the optimum would be near 12 percent.

The Fithian illite had the highest compressive strength in the untreated condition, but when 2 percent lime was added it reacted in the same manner as White Springs montmorillonite, and gave a much lower psi. But with the increased percentages of lime the compressive strength increased and it almost equaled the strength of the White Springs clay at 8 percent.

Grundite, the mixed layered material, reacted to give results which were close to those of the Aberdeen montmorillonite. Untreated Grundite gave a higher strength than the Aberdeen clay and gave a little higher strength for each increment of lime up to the 8 percent, at which point the strength was slightly less than the psi of the Aberdeen clay.

The Fithian and Grundite clays were not tested above 8 percent but it appears the optimum amount of lime for each of the clays would be above 8 percent.

Figure 1 shows that the strength of the kaolin samples increased significantly with the addition of the first increment of lime, whereas for all the other clay minerals there is little increase in strength until 4 percent or more lime is added. It appears that kaolinite and lime react easily, and only small amounts of lime are required to start the reactions. On the other hand for illites and montmorillonites, lime over and above a minimum amount must be added before there is a reaction accompanied by the development of strength.

In the case of montmorillonites which have high cation exchange capacities a certain amount of lime is required to drive the Ca^{++} ion into and onto the clay. After the clay has apparently been changed to a Ca^{++} variety and only after this does it develop strength. The Wyoming montmorillonite which is a Na^{+} clay requires more lime to become wholly Ca^{++} saturated than the Mississippi samples which naturally carry a little Ca^{++}. Thus the longer lag in the development of strength from Wyoming as compared to Mississippi montmorillonite is explained.

The Grundite samples carry K^{+} ions and again only after becoming Ca^{++} saturated does the strength increase. The initial reduction in strength of the Fithian sample can be explained by the presence of sulfate ions in the clay which are due to the oxidation of pyrite. The sulfate ions react first with the lime and it is not until the $SO_4^{=}$ ions are satisfied that the clays become Ca^{++} saturated and the strength increases.

The reasons for the strength increase with Ca^{++} saturation will be considered after the X-ray data are presented.

X-RAY DIFFRACTION STUDIES

Goldberg and Klein (2) on treating a Wyoming bentonite with amounts of calcium hydroxide up to 8 percent, reported no changes in the X-ray spectrum except that the calcium hydroxide reflections disappeared. Therefore, it was decided to use a much larger percentage of lime and to heat-cure the samples at 140 F for 60 days. If reactions were recorded for these conditions they would serve as a guide, and specimens cured for shorter periods of time and with smaller percentages of lime could be compared with these reactions.

Goldberg and Klein (2) reported that when clays treated with calcium hydroxide were exposed to the atmosphere, calcium carbonate was formed. In the experiments reported herein, when small samples were allowed to dry in an oven under atmospheric conditions, the lime carbonated. The X-ray diffraction patterns of these samples in addition to the clay reflections gave strong reflections for the carbonate and only a few additional lines. However, when steps were taken to dry the material in the absence of CO_2, new interplanar spacings appeared showing that there had been considerable reaction between the clay and the lime. Because many of the new reflections were close to those of the carbonate and the carbonate lines were strong, they tended to overshadow the new minerals.

Figure 2 shows the X-ray spectrometer tracings for the hydrated lime used, Georgia kaolin untreated, Georgia kaolin containing 6 percent lime cured for 3 days at 140 F, and Georgia kaolin containing 20 percent lime cured for 30 days at 140 F. Not shown in Figure 2 but the same reflections which occurred from the 60 day cured specimens with 20 percent lime can be obtained with specimens cured for 3 days with only 6 percent lime.

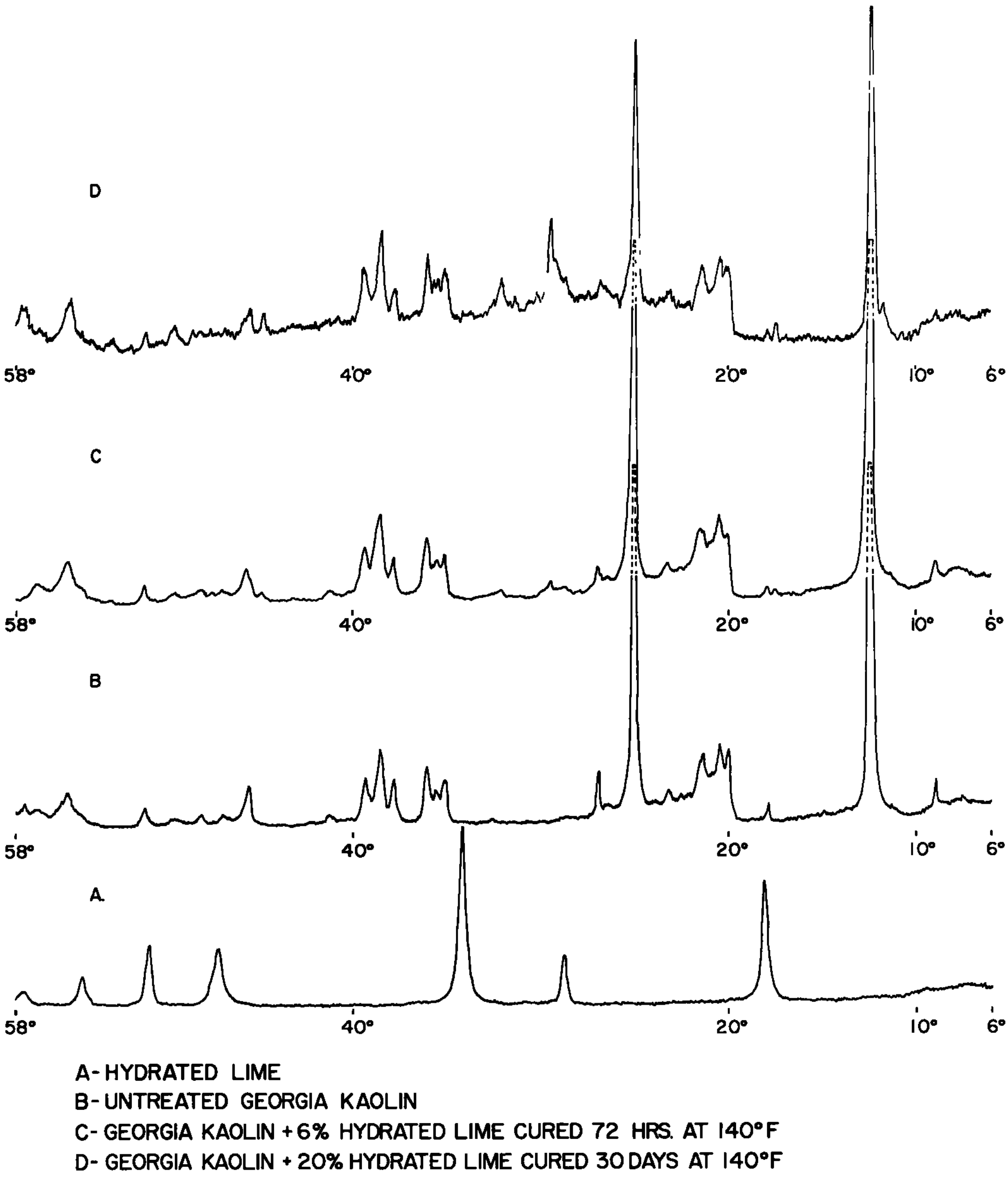


Figure 2. X-ray diagrams of lime-treated Georgia kaolin.

The Georgia kaolin which is well crystallized gives a diffraction pattern of kaolinite with sharp basal and prism reflections in the untreated state. As the kaolin is treated with small percentages of lime the prism reflections lose their sharpness and intensity. The basal reflections are not changed in sharpness. This seems to infer that this mineral, usually considered quite stable, was attacked at the edges and within the two-layer silicate sheets, thereby causing a weakening of the prism reflections. That is, the initial reaction is not merely one of spreading apart the silicate layers, but an attack on the basic structure. As the lime content and curing period were increased there also appeared to be a reduction of the basal reflection, and an increase in the percentage of new minerals as indicated by nonkaolinite diffraction lines. It is significant that new crystalline phases appear about immediately with the treatment of kaolinite with lime.

Figure 3 shows the changes which accompanied the treatment of Anna kaolin with 20 percent lime for 3, 15, and 60 days. The Anna kaolin is not as well crystallized as the Georgia kaolin which is shown by the ragged prism reflections. The low-angle diffraction in the samples treated with moderate amounts of lime suggests that for such kaolinite there is considerable spreading apart of the silicate sheets as well as an attack on the basic silicate structure in the initial reaction. As curing continues, the low-angle diffraction disappears and the material having caused it becomes reorganized into new phases.

Halloysite (Fig. 4) has the basic kaolinite structure but contains layered water in the structure. This mineral gave the same reflections after it was treated with 20 percent lime as the two kaolinites. The experiments were not continued with the smaller percentages of lime.

The Fithian illite which gave low compressive strength until more than 4 percent lime had been added did not react as quickly as the kaolinite. That is, diffraction patterns for the 20 percent lime series for 3 and 6 day curing periods still contained reflections for hydrated lime. The same new minerals, which occurred with the kaolinites, were present in the diffraction diagram for the 20 percent lime and 3 day curing period but they were in small percentages. The reflections for the illite were reduced in intensity and basal reflections were changed from a peak to a broad band suggesting a general gradual destruction of the illite lattice.

Figure 5, which shows the reactions of lime with Grundite, the mixed layered material, shows that after only 6 days the calcium tends to separate the mixture into more distinct reflections for illite and montmorillonite. However, as curing was continued, as shown by the diffraction pattern for the 30 day curing period, the clay mineral structures were gradually lost. The treated Grundite did not give as many reflections for new minerals as the illite. Reflections for lime were present for the 3 and 6 day curing periods but were not present on the patterns for the 15 day period. It appears that lime reacts much slower with the illites and mixed layered materials than it does with kaolinite.

Figure 6, showing the reaction of Aberdeen montmorillonite and lime, well represents the reaction of lime with all three montmorillonites tested inasmuch as diffraction data were the same for all of them. The diffraction patterns indicated a substantial breakdown of the structure after lime is in contact with the montmorillonite for prolonged periods. Diffraction data not shown in Figure 6 indicate that small percentages of lime do not affect the structure, and as a matter of fact, the basal reflections seemed to be intensified. This probably is to be correlated with adsorption of Ca^{++} between the silicate sheets replacing other cations. Only a few reflections were encountered that had not been present in the untreated state showing a scant formation of new crystalline reaction products.

It is impossible to be certain of the identity of the new crystalline reaction products, but the data give every indication that the new minerals are hydrous calcium silicates. The new reaction products for kaolinite give essentially the same X-ray diagram characteristics as those given by Bernal (8) for the low temperature calcium silicate hydrate and dicalcium silicate hydrates which are formed during the hydration of cement. The X-ray diagrams differ somewhat from specimen to specimen for the kaolinites. The strongest values correspond to spacings 5.09, 3.04, 2.8 and 1.8 Å. Additional spacings occurred

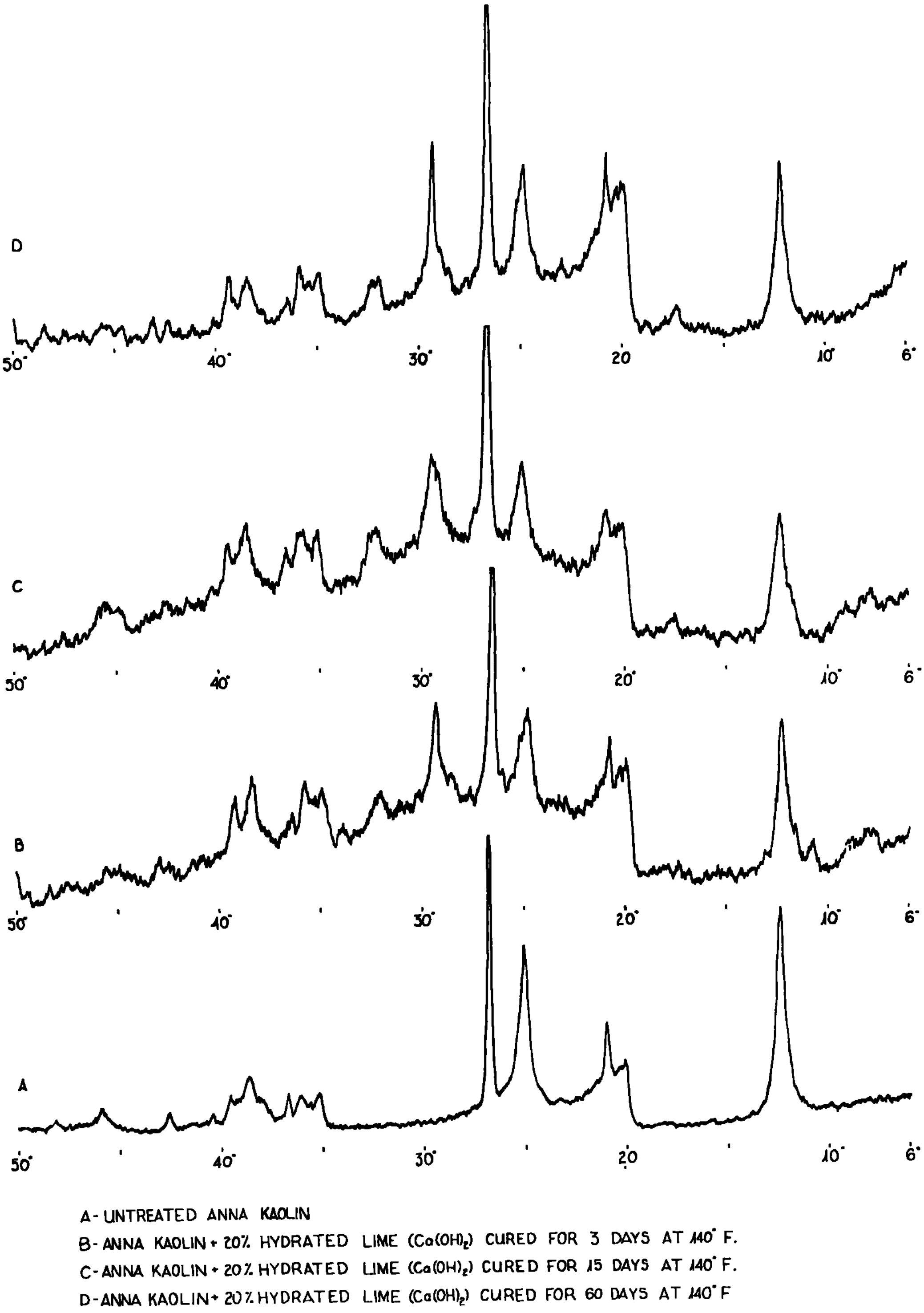
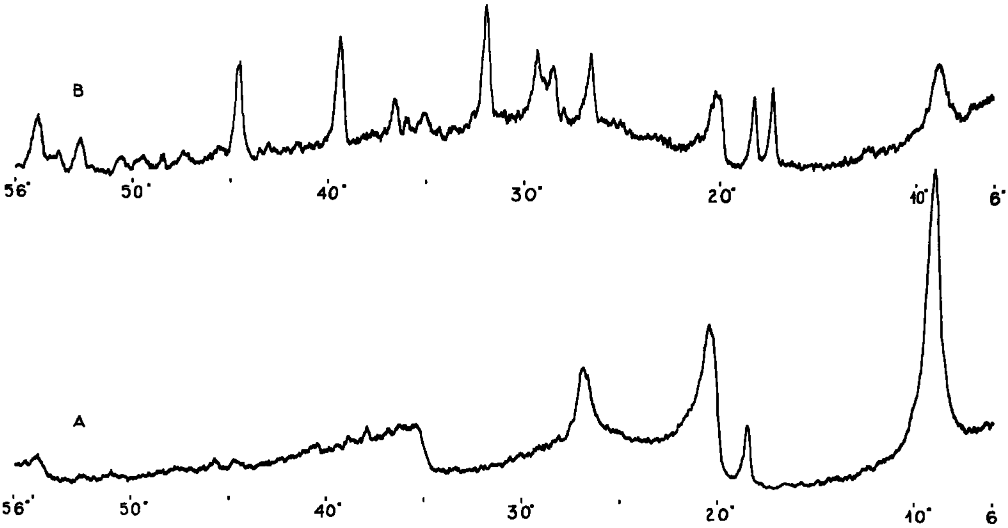


Figure 3. X-ray diagrams of lime-treated Anna kaolin.



A-UNTREATED HALLOYSITE
B-HALLOYSITE + 20% HYDRATED LIME($Ca(OH)_2$) CURED 60 DAYS AT 140° F

Figure 4. X-ray diagrams of lime-treated Halloysite.

with some samples. Because there are a number of intermediate products in the calcium silicate hydrate system it is believed that several different compounds may exist at one time until equilibrium between the silica which is removed from the structure of the clays and the excess lime is reached. Studies made of the reaction products of cement (9) have shown where there is an excess of $Ca(OH)_2$ the silicates are interlayered with the $Ca(OH)_2$. Work done at the Swedish Cement and Concrete Research Institute (9) has shown when the calcium silicate hydrates, in the presence of an excess of $Ca(OH)_2$, are examined by the use of an electron microscope they must be prepared in the absence of carbon dioxide to prevent the formation of calcite, which covers the silicate minerals. This probably explains why the silicate reflections do not appear with treated samples when the sample is allowed to dry in the presence of carbon dioxide.

For the illites, the diffraction data indicate only scant formation of new crystalline phases. They suggest, however, that the phases are the same as for the kaolinite.

The X-ray data for the montmorillonites demonstrate there is a destruction of the mineral structure with little formation of new minerals. However, the compresssion strength values for the treated clays seem to indicate there is a reaction after enough lime is added and the reaction results in added strength. There is a possiblity that although the X-ray diagrams do not contain reflections for new minerals that calcium silicate hydrate gels are formed which are not crystalline. These gels could just as easily interlock the particles together and give the added strength without having a crystalline structure. It is hoped that further research will clear up this aspect of the problem.

Differential Thermal Analysis

Treated and untreated samples of the clays were studied by differential thermal analysis up to 1000 C. It was felt that this method would aid in revealing the presence of new calcium compounds and would serve as a guide for their reduction.

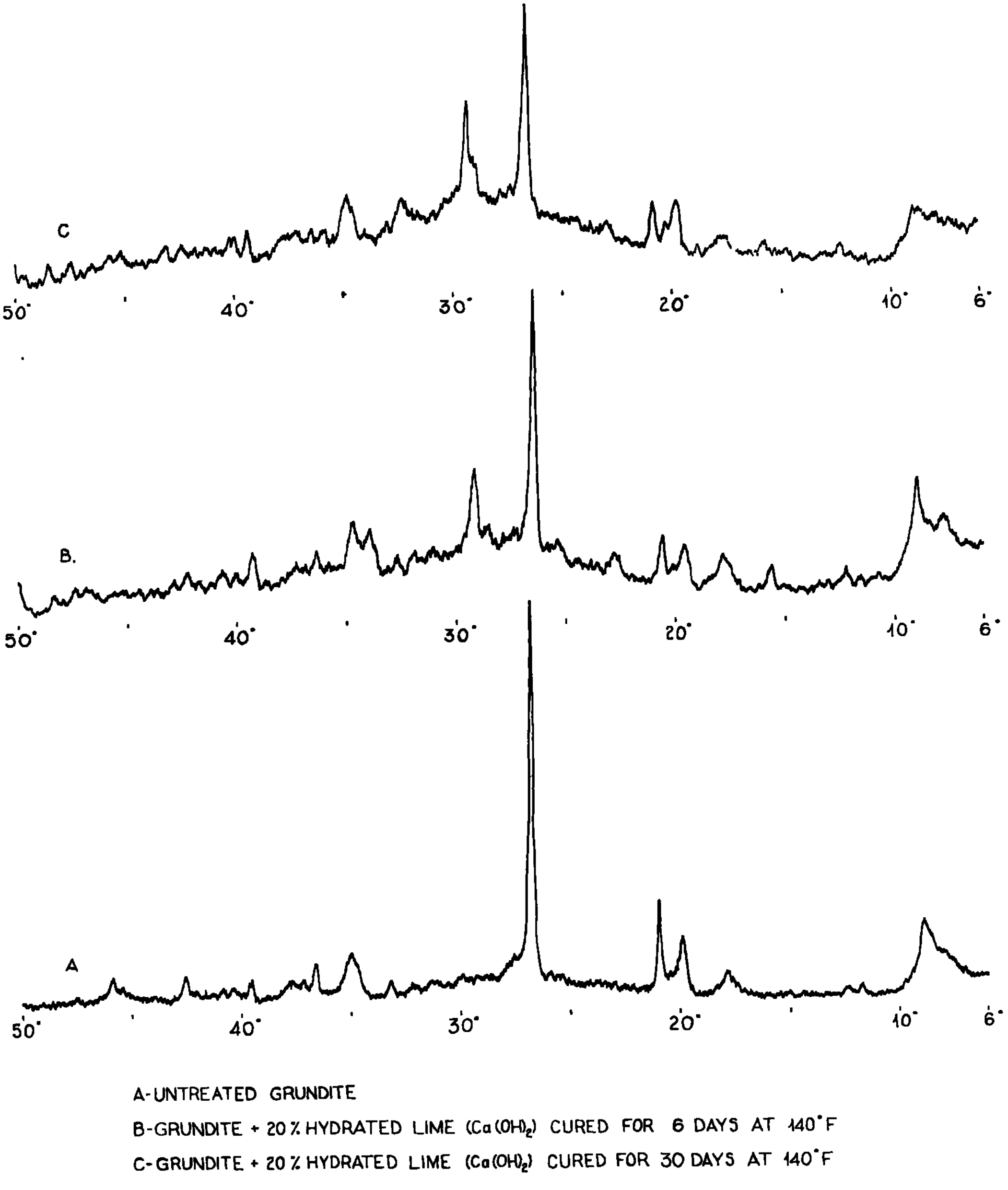


Figure 5. X-ray diagrams of lime-treated Grundite.

Figure 7 shows D. T. A. curves of the Georgia kaolin untreated (A), kaolin with 20 percent lime uncured (B), and with 20 percent lime cured for 3 days (C). Curve B clearly demonstrates the presence of lime by the endothermic peak at 500 C. A comparison of curve C with curve B shows that the endothermic peak disappears after treatment, and a new endothermic peak occurs between 300 and 400 C. The new peak indicates a new phase which could possibly be correlated with the hydrated calcium silicate suggested by the diffraction data.

Figure 8, a series of D. T. A. curves for Wyoming montmorillonite, shows the effects

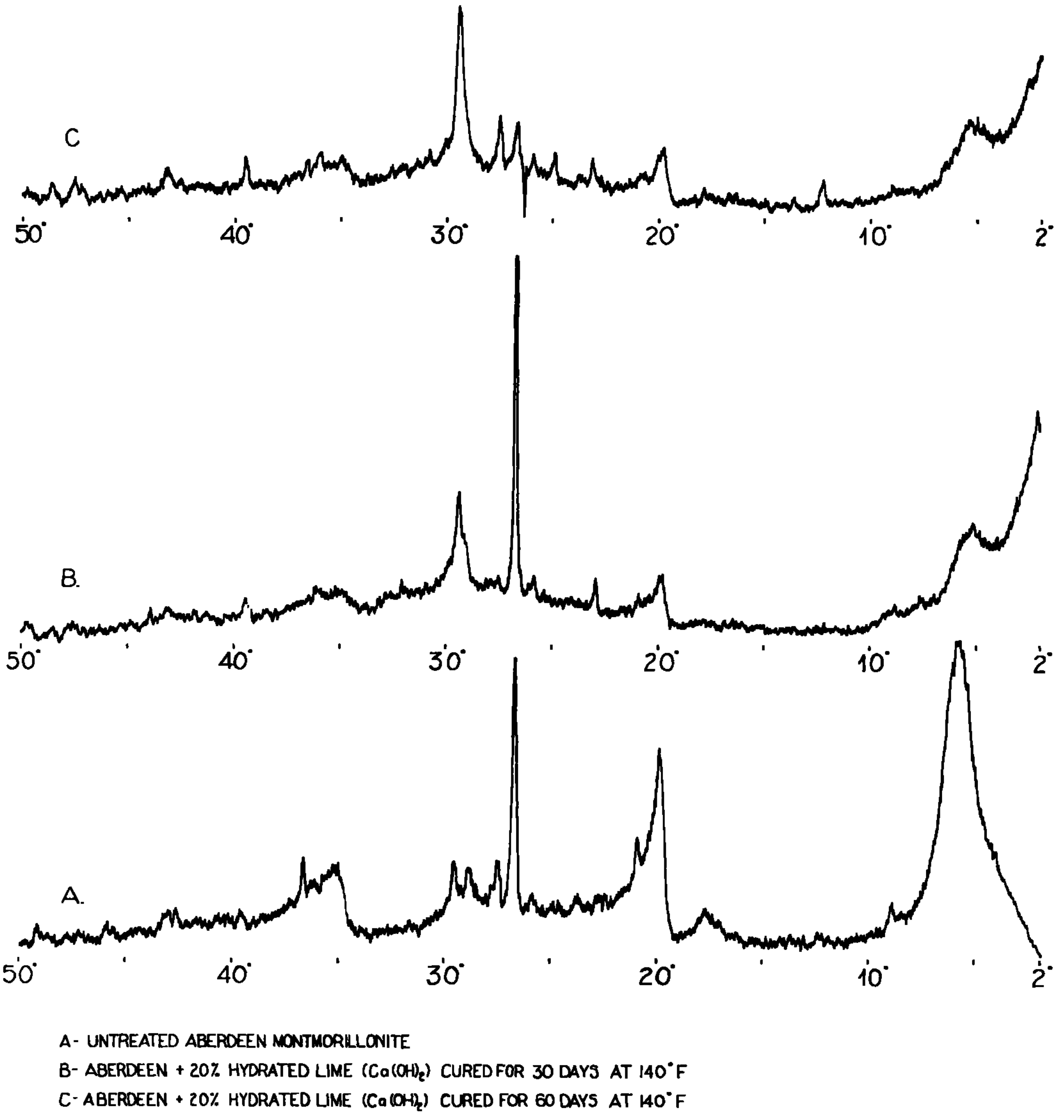


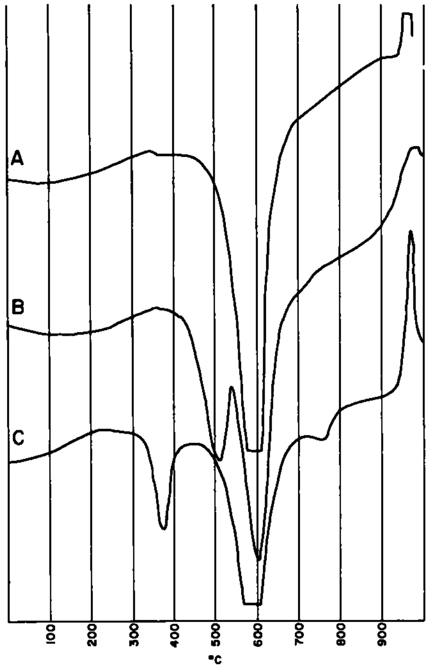
Figure 6. X-ray diagrams of lime-treated Aberdeen.

of lime on the montmorillonite structure. As in the case of the kaolinite, the presence of lime is not exhibited by the thermograph after the samples are allowed to cure. The curves demonstrate the exchange of the Ca^{++} ion for the Na^{+} ion. The single endothermic peak between 100 and 200 C in curve A is characteristic of the adsorbed water held by the Na^{+} clay. Curve C of the montmorillonite treated with 5 percent lime and cured for 3 days has a double peak between 100 and 200 C, which is characteristic of a Ca^{++} clay. Although curves for the montmorillonite treated with less than 5 percent lime are not shown by Figure 8, the double peak did not appear until the clay had been treated with 5 percent showing that an excess of lime is required before substantial ion exchange will take place in this particular clay. Curve D for the montmorillonite with 20 percent lime shows the structure of the mineral has been almost completely destroyed by the very small endothermic peaks. Details of the curve cannot be explained at this time; however, it is significant that there are no distinct low temperature thermal reactions suggesting a crystalline calcium silicate hydrate.

CONCLUSIONS

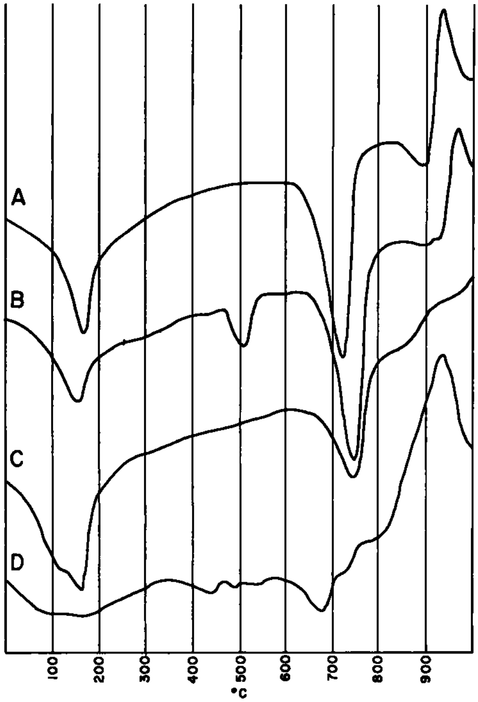
On the basis of results which have been presented in this paper it is shown that kaolinites, illites, montmorillonites and mixed layered clay minerals react with lime to give greater bearing strengths. The quantity of lime needed to effectively treat a clay mineral is dependent on the type of mineral present.

In the case of kaolinite clays, the increase in strength begins with the addition of the first increment of lime. In the case of illite, montmorillonite and some mixed layered structures, lime in excess of 4-6 percent must be added before any strength developed.



A-GEORGIA KAOLIN UNTREATED
B-GEORGIA KAOLIN + 20% HYDRATED LIME UNTREATED
C-GEORGIA KAOLIN + 20% HYDRATED LIME CURED 72HRS. AT 140°F

Figure 7. D.T.A. curves of lime-treated Georgia kaolin.



A-WYOMING MONT UNTREATED
B-WYOMING MONT. + 4% HYDRATED LIME UNTREATED
C-WYOMING MONT. + 5% HYDRATED LIME CURED 72HRS. AT 140°F
D-WYOMING MONT. + 20% HYDRATED LIME CURED 72HRS. AT 140°F

·Figure 8. D.T.A. curves of lime-treated Wyoming montmorillonite.

The reaction of lime and kaolinite leads to the formation of new crystalline phases which are tentatively identified as calcium silicate hydrates. This reaction seems to take place by the lime eating into the kaolinite particles around the edges with a new phase forming around a core of kaolinite. In contrast the reaction of lime with three layer clay minerals (illite, montmorillonite) begins by a replacement of existing cations between the silicate sheets with Ca^{++}. Following the saturation of the interlayer positions with Ca^{++} the whole clay mineral structure deteriorates without the formation of substantial new crystalline phases. For illite and montmorillionite there is little strength developed until after the clay is saturated and the clay mineral begins to be destroyed. For the kaolinite the strength begins to increase as some of the calcium attacks the edges of the kaolinite particles.

Although the X-ray and D.T.A. diagrams do not give reflections for calcium hydroxide it is concluded than an excess of calcium is present because of the rate at which calcium carbonate is formed when treated samples are explosed to the atmosphere. That is, during the reaction some free lime is available for the formation of carbonate.

Because the development of strength is accompanied by distinct structural changes in the clay minerals, it seems certain that the changes are relatively permanent. The reaction products causing the increase in strength would be expected to be no more susceptible to leaching than other forms of calcium silicates.

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Recent Soil-Lime Research at the Massachusetts Institute of Technology

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This paper summarizes the results of research on soil-lime stabilization conducted at M.I.T. during the past three years. Data are presented on:

1. The effect of varying percentages of lime (or quicklime) on the compaction and strength characteristics of four soils ranging from a clayey sand to an organic clay. Strength was determined by unconfined compression (or penetration resistance) tests on as-molded, as-cured, and/or on cured and soaked samples.
2. The effect of mixing varying percentages of quicklime with four very wet soils, ranging from a silt to a fat clay in order to increase the strength of these soils at a rapid rate.
3. The effect of secondary additives (various sodium compounds) at different concentrations on the soaked unconfined compressive strength after from 4 to 28 days curing of seven soil-lime mixtures. The soil-lime mixtures consisted of: pure minerals, ranging from quartz to kaolinite, plus 10 percent calcium hydroxide; and natural soils, ranging from an uniform silt to an organic clay, plus 5 percent calcium lime.

The test results show that:

1. Lime reduces the compacted density of the soils but greatly increases the soaked strength after curing periods of from 7 to 28 days.
2. From 1 to 5 percent quicklime can increase the strength of wet soils 3- to 10-fold within 2 hours.
3. Sodium compounds (such as sodium hydroxide, sodium silicate and sodium sulfate) can increase the soaked strength of soil-lime mixtures, often by several fold. The effectiveness of the sodium compounds varies with soil type, additive concentration, and length of curing. Sodium metasilicate was usually found to be the most effective additive. It increased the 7 day soaked compressive strength of six of the seven soils by 100 to 200 psi.

●THE M.I.T. SOIL STABILIZATION LABORATORY has conducted research for the past ten years on improving the properties of soils by the use of chemical additives. While most of the work has been directed toward the use of portland cement, asphalt, phosphoric acid and various other chemicals (especially polymers) as additives, recent work has investigated the use of lime.

Soil-lime stabilization is attractive because lime:

1. Is relatively inexpensive and often available in underdeveloped countries.
2. Is usually effective in reducing the plasticity of clay, thus making the clays

more "workable," even at low lime concentrations (less than 5 percent).

3. Reacts with soils to form cementitious components which increase the strength of soil.

4. Requires a less stringent construction schedule than many additives (for example, portland cement).

The research on soil-lime stabilization reported herein was conducted for the most part by students as thesis work. Inasmuch as theses were directed at different objectives and employed various test procedures, this paper presents much of the data in the form of theses abstracts.

THE FEASIBILITY OF LIME STABILIZED ROADS IN HONDURAS[1]

Scope

The Republic of Honduras has a network of some 1,000 mi of roads, of which 600 mi are impassable during the rainy seasons and only 25 mi are paved. The purpose of this undergraduate thesis was to investigate the use of soil-lime stabilization as a means of constructing low-cost durable base courses in this country which has an abundant supply of quicklime. A traffic count and soil survey were made on three of the main roads leading to the City of San Pedro Sula in northern Honduras. Seven soils were sent to M. I. T. for classification test; two of the seven soils which represented a low and a high plastic soil type were selected for compaction-strength tests at varying percentages of calcium quicklime. The test results and an economic study of construction costs in Honduras showed a 6-in. soil-lime base course to be less than one-half as expensive as a crushed stone base course.

Test Procedure

The two soils selected for stabilization testing were a clayey sand and a lean clay from Honduras. Table 1 gives the results of the classification tests.

Air-dried samples of soil were hand-mixed with a calcium quicklime at percentages (based on dry soil weight) of 0, 3, 6 and 9 percent for the clayey sand (scalped on No. 4 sieve) and 0, 5 and 10 percent for the lean clay. The desired amount of molding water was added by hand-mixing. Samples were compacted dynamically in 2.5 in. diameter by 3.0-in. cylindrical molds in five layers at a compactive effort of 32,400 ft lb/cu ft (halfway between Standard and Modified AASHO). The samples treated with lime were cured in the mold at 100 percent relative humidity for 21 and 7 days, respectively, for the sand and clay. After curing (or after compaction for the untreated samples), the molds were immersed in water with a 60 lb/sq ft surcharge for 3 and 2 days, respectively, for the clayey sand and lean clay. Strengths were measured by a "minature" CBR device both after compaction and soaking for untreated samples and after soaking for treated samples. The minature CBR tests is a scaled-down version of the standard CBR test where a piston with a diameter of 0.798 in. (area equals 0.500 sq in.) is forced into the top of the sample. The standard CBR penetration readings of 0.1 and 0.2 in. were changed to 0.04 and 0.08 in., and the pressures at 0.04- and 0.08 in. penetration divided by the standard 1,000 and 1,500 psi values in order to obtain miniature CBR values. (The miniature CBR values are comparable to the standard CBR values if one can assume that a stabilized sample has semi-infinite dimensions and a constant modulus of elasticity so that the ratio of pressure to deflection under a rigid plate varies inversely with the diameter of the loaded area.)

Test Results

The results of the tests are shown in Figures 1 and 2 for the clayey sand and lean clay, respectively, in the form of molded water content versus molded dry density, molded miniature CBR for untreated soil, and soaked minature CBR for treated and untreated soil.

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[1] B. S. Thesis in Civil Engineering by J. Rosenthal, 1958.

1. A large decrease in strength due to soaking for untreated soil, particularly dry of optimum water content.
2. A reduction (usually) in maximum dry density with increasing percentages of lime.
3. A considerable increase in soaked strength for soil-lime mixtures, the magnitude of which is usually increased with increased percent lime. Thus two soils with soaked CBR values of approximately 15 to 10 percent could be sufficiently stabilized with 3 to 5 percent quicklime to yield soaked values of over 80 percent, a value commonly employed for base course design.

THE USE OF LIME TO PREVENT EROSION OF SOIL[2]

Scope

The erosion of earth slopes and highways shoulders due to rainfall is a major problem. This graduate thesis investigated the use of lime stabilization as a method for reducing the erosion of soils.

Two soils of widely different properties were selected for testing. The effects of varying percentages of lime on the Atterberg limits, the compaction curves, the as-molded, as-cured and soaked strength were investigated. Cured and soaked samples were also subjected to an erosion test.

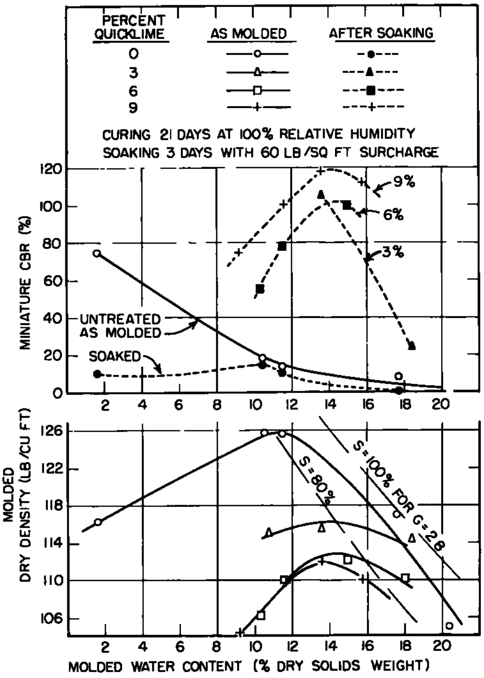

Figure 1. Effect of quicklime on compaction and strength characteristics of a clayey sand.

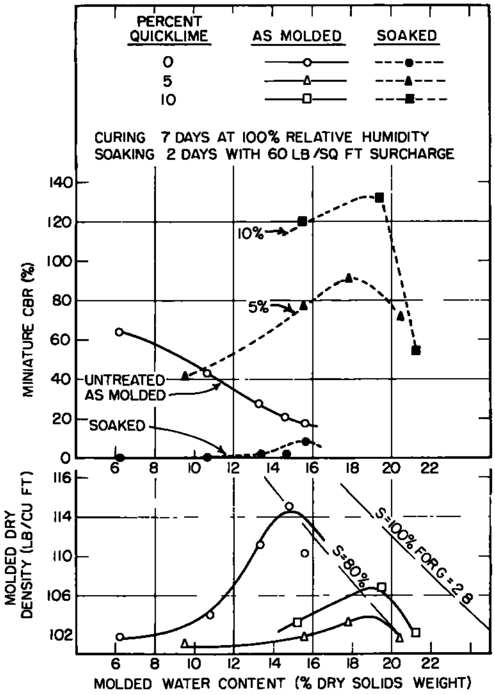

Figure 2. Effect of quicklime on compaction and strength characteristics of a lean clay.

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[2] M.S. Thesis in Civil Engineering by A.T. Khan, 1958.

Test Procedures

The two soils selected for testing were Massachusetts clayey silt (M-21) and Port Hueneme clay. The results of classification, chemical and mineralogical tests are given in Tables 1 and 2.

Air-dried samples of soil (soil scalped on No. 40 sieve for Atterberg limit determination and on No. 10 sieve for other tests) were hand-mixed with from 0 to 10 percent hydrated calcium lime and then hand-mixed with the desired amount of water.

Atterberg limits (liquid and plastic) were run on moist samples after storage periods, in airtight containers, of 0, 7 and 28 days for the clayey silt and 0 days for the clay.

The compaction curves were run on samples immediately after mixing. Samples were compacted in the Harvard miniature mold (1.312-in. diameter by 2.816 in. high) in 3 layers, each layer receiving 25 blows with a 40-lb tamper.

Unconfined compressive strength measurements were made on samples compacted at optimum water content for maximum density. The strength was determined on samples: immediately after compaction, after curing for 7 days at room temperature and 100 percent relative humidity, and after 7 days curing and 24-hr complete water immersion. Duplicate samples were made for each determination.

An erosion test was performed on as-molded and on cured and soaked samples of the Massachusetts clayey silt and on cured and soaked samples of the Port Hueneme clay. The erosion test consisted of spraying the sides of the cylindrical samples with 24 fine jets of water under a constant head of water of approximately 7 ft for a period of 30 min. The loss of soil, based on a percentage of the initial dry soil weight, during the erosion test was determined and is reported.

Test Results

The effects of lime on the Atterberg limits of the two soils after different storage periods are shown in Figure 3. In general, lime usually increases both the liquid and plastic limits and decreases the Plasticity Index (P.I.) of soils, but the trends vary with soil type and storage time (2).

Figure 4 shows the effects of lime on the compaction characteristics of the two soils. The data show a fairly consistent decrease in maximum dry density, and an increase in optimum water content with increasing percentages of lime.

The effects of lime concentration on the as-molded, on the cured, and on the soaked strengths of the two soils are shown in Figure 5. The data show that the percent of lime has a relatively minor effect on the as-molded strength, but a pronounced effect on the cured and on the soaked strengths. Whereas most soil-lime mixtures will show

TABLE 1

SUMMARY OF CLASSIFICATION TESTS ON SOILS

	Atterberg Limits (%)[1]			Grain Size (% Passing)				
Description and Location of Soil	Liquid	Plastic	Plasticity Index	4.7 mm	1.67 mm	0.42 mm	.074 mm	.002 mm
Clayey sand from San Pedro Sula, Honduras	27	19	8	85	70	20	-	-
Lean clay from San Pedro Sula, Honduras	34	16	18	-	-	-	-	-
Massachusetts clayey silt (M-21)	~23	~15	~8	-	-	~85	45-55	~10
Organic clay form Port Hueneme	59	39	20	-	-	-	~100	~50
Fat clay from Vicksburg, Miss. (Vicksburg buckshot clay)	~60	~25	~35	-	-	-	100	35
Lean clay (loess) from Vicksburg, Mississippi	41	26	15	-	-	-	~90	~5
Uniform silt from New Hampshire	28	21	7	-	-	-	95	~8
Peerless kaolin No. 2 from Bath, South Carolina[2]	~52	~29	~23	-	-	-	100	-
Ground quartz (Potter's Flint)[3]		Nonplastic					100	0
90% Ground quartz and 10% sodium montmorillonite (vol clay 325)[4]	-	-	-	-	-	-	100	9

[1] On material passing No. 40 sieve (0.42 mm).
[2] Supplied by R.T. Vanderbilt Co., New York, N.Y.
[3] Supplied by Newton Potters, Newton, Mass.
[4] Supplied by American Colloid Co., Chicago, Ill.

TABLE 2

SUMMARY OF CHEMICAL PROPERTIES AND MINERALOGICAL COMPOSITION OF SOILS[1]

	Name of Soil				
	Massachusetts Clayey-Silt (M-21)	Port Hueneme Clay	Vicksburg Loess	Vicksburg Buckshot Clay	New Hampshire Silt
Chemical properties					
1. Cation exchange capacity (meq/100gm)	10.3	36	16	30	3
2. pH	-	-	4.6	4.6	5.4
3. Soluble salts (%)	-	-	0.2	0.3	-
4. Organic matter (%)	0.2	7	1.8 ± 0.1	1.1 ± 0.1	0.4 ± 0.1
5. Ethylene glycol retention (mg/gm)	21	13	32	65	6
Mineralogical composition Determined by DTA and X-ray (% by weight)					
Quartz	35	-	30 ± 3	20 ± 3	40 ± 3
Feldspar	20	-	20 ± 10	20 ± 10	40 ± 20
Mica	-	-	-	-	10 ± 5
Kaolinite	-	5	-	-	-
Illite	30	80	15 ± 3	25 ± 3	10 ± 5
Montmorillonite	-	5	20 ± 3	25 ± 3	-
Fe_2O_3	2.9	-	1.6 ± 0.1	1.9 ± 0.1	1.0 ± 0.1

[1] On material passing No. 200 sieve.

a strength increase with curing at 100 percent relative humidity, the data on the Port Hueneme clay show the opposite trend. This may be explained by the fact that the samples of this plastic, organic soil picked up 10.9, 9.2, 8.9, 5.9 and 3.5 percent moisture during curing for the 2, 4, 6, 8 and 10 percent lime concentrations, respectively. By contrast, the clayey silt samples lost from 1 to 4 percent moisture during curing.

Although these data show an approximate optimum lime concentration for the maximum soaked strength, as is often the case for soil-lime mixtures, it must be remembered that only the conditions at optimum water content, which may not yield the maximum strength, were investigated.

The maximum soaked strength of from 30 to 80 psi for these two lime-stabilized soils (by comparison, 5 and 10 percent portland cement yield 7-day immersed strengths of 300 and 550 psi, respectively, for the Massachusetts clayey silt) would be considered inadequate for base course construction, where a compressive strength of 100 to 200 psi is normally desired. The relatively low strength of the Massachusetts clayey silt-lime mixture can be explained by the low amount of reactive silica and/or alumina in the soil which reacts with lime to form cementitious calcium silicates and aluminates. Data in the section on "Effect of Secondary Additives on Soil-Lime" support this hypothesis, because the addition of soluble silicates to the silt can more than double the strength. The low strength of the Port Hueneme clay-lime mixture can be attributed to organic matter which "complexes" lime (Clare and Sherwood, 3) and the swelling

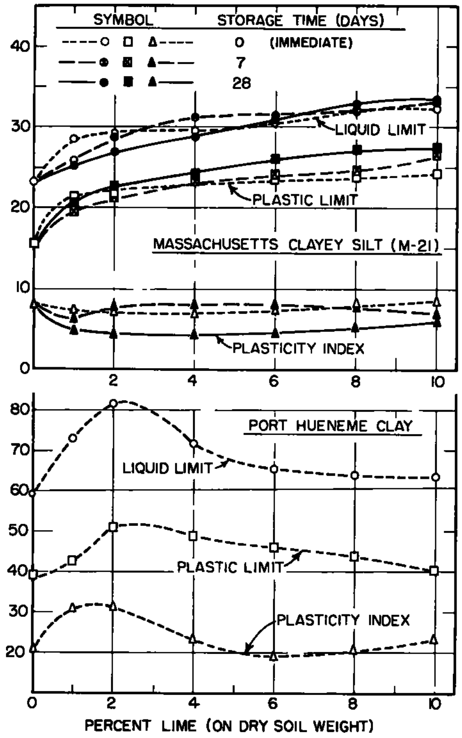

Figure 3. Effect of lime on Atterberg limits of two soils.

during curing and soaking which would tend to rupture cementitious bonds.

The results of the eriosion tests are given in Table 3. The data, although limited, suggest that a soaked strength of more than about 30 to 40 psi will yield a soil-lime mixture that is resistant to water erosion for this test procedure. The effects of alternate cycles of drying and spraying need investigation.

QUICKLIME STABILIZATION OF WET SOILS

Scope

The Corps of Engineers, U.S. Army, one of the sponsors of the M.I.T. Soil Stabilization Laboratory, has set up four stabilization categories based on military requirements. Category 1 stabilization requires that the strength of weak, that is, wet, soils be increased sufficiently in a period of 2 hr to support light wheel-driven traffic. The use of quicklime as a Category 1 stabilizer is reported.

Test Procedure

Trafficability studies by the Corps of Engineers (4) indicate a minimum cone index strength of natural soils (excluding peat, swamp soils, etc.) to be roughly 25 psi. A cone index of 100 to 125 psi is required to support light wheel-driven traffic. The cone index refers to the pressure required to force a 30-deg cone well into the soil, the pressure taken as the force divided by the base area of the cone.

The test procedure for evaluating quicklime as a Category 1 stabilizer for four soils was as follows:

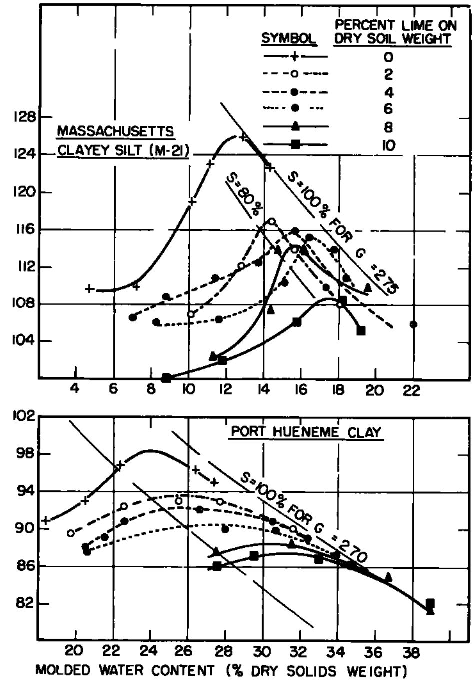

Figure 4. Effect of lime on compaction characteristics of two soils.

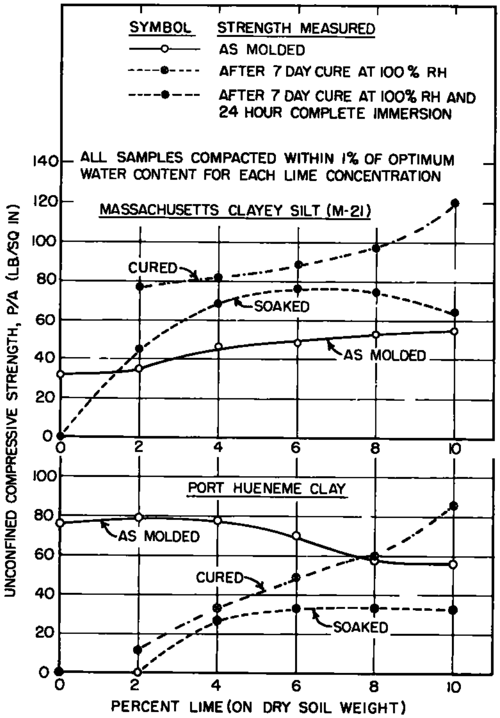

Figure 5. Effect of lime on compressive strength of two soils.

1. Minus No. 10 sieve air-dried soil hand-mixed with varying amounts of water and compacted by two-end static compaction with pressure of 330 psi in a Harvard miniature mold (except for New Hampshire silt, which was only hand tamped into the mold).
2. Cone index measured by penetrating a 30-deg cone, with base area of either 0.10 or 0.20 (for weak samples) sq in., about 1 in. into the sample (still in mold). The reported cone index is the average of readings taken on the top and bottom of the samples. A plot of cone index versus molded water content is thus obtained.
3. Sufficient water added to air-dried soil to yield a cone index of approximately 25 psi. From 1 to 5 percent (based on dry soil weight) calcium quicklime (in one test series, mixtures of pure calcium and magnesium oxide were added) was mixed by hand with wet soil. The soil-lime mixture was then compacted statically (except for New Hampshire silt, which was hand-tamped) in a mold and stored in the mold at 100 percent relative humidity for various times, but usually for less than 2 hr.
4. Cone index measured after curing. In some cases, the holes in the ends of the samples were compacted with soil and the samples extruded from the mold and subjected to unconfined compression after the cone index measurements.

Test Results

The four soils used for testing were: Massachusetts clayey silt (M-21), Vicksburg loess, New Hampshire silt, and Vicksburg buckshot clay. The results of the classification and the chemical and mineralogical tests on these soils are given in Tables 1 and 2. Figure 6 shows plots of cone index versus molded water content for the four soils.

Typical plots of cone index versus cure time (to log scale) at 100 percent relative humidity for quicklime treated soils are shown in Figure 7. The cone indexes of these soils were only 10 to 70 psi before treatment. A cure time of 0.1 hr represents the time required to mix, compact, and test a sample. The data show a large (often 10-fold) strength increase in only 2 hr. A summary of the compaction and strength data for all the soils at varying quicklime concentrations for cure times of 0.1 and 2 hr is given in Table 4. The Initial Conditions reported in Table 4 have been adjusted to account for moisture losses due to mixing and compaction. A comparison of columns F and G in Table 4 shows that the immediate (taken at 0.1 hr) strength of lime-treated soils is greater than can be accounted for solely on the basis of the water content decrease.

TABLE 3

EFFECT OF LIME ON THE EROSION RESISTANCE OF TWO SOILS

Soil	Percent Lime On Dry Soil Weight	As-Molded	Erosion Loss (%)[1]	
			As Cured[2]	After Curing and Soaking[3]
Massachusetts clayey silt (M-21)	0	100	100	100
	2	100	1	<1
	4	100	-	<1
	6	100	-	<1
	8	24	-	<1
	10	46	-	<1
Port Hueneme clay	0	54	-	100
	2	-	-	100
	4	-	-	11
	6	-	1	4
	8	-	-	1
	10	-	-	< 1

[1] After 30 min of spraying, except for as-cured samples, where 6 hr of spraying.

[2] Cured for 7 days at 100 percent relative humidity.

[3] 24-hr complete water immersion.

TABLE 4

COMPACTION AND STRENGTH DATA ON FOUR SOILS IN CATEGORY 1 TREATED WITH QUICKLIME (M.I.T. 1957)

		A	B	C	D	E	F	G	H
					After Additon of Quicklime				
	% Quicklime on	Initial Conditions[1]					C.I. (psi)	C.I.(psi) After Curing	
Soil	Dry Soil Weight	Wi (%)	γd(pcf)	C.I (psi)	Wm (%)	γd(pcf)	at Wm[2]	0.1 hr	2 hr
Massachusetts clayey silt	1	16.2	116.0	45	15.7	117.4	60	145	210
	2	15.6	117.5	70	14.7	118.5	140	160	460
	3	16.0	116.5	50	14.5	119.0	160	260	860
New Hampshire silt	3	27.8	93.5	10	26.0	95.0	30	40	230
Vicksburg buckshot clay	3	38	82	25	36	84	40	80	170
	5	35.5	84	45	32	89	85	110	340
Vicksburg loess	1	25.1	98.0	50	24.6	99.0	55	-	~160
	3	24.8	98.5	55	23.0	101.0	90	185	520
	5	24.7	98.5	55	22.0	103.0	120	-	~970

[1] Initial conditions have been adjusted to account for water content losses due to mixing and compaction. The difference between the initial (Wi) and molded (Wm) water contents is calculated from the theoretical water content decrease due to the hydration of quicklime and the solids content increase.

[2] Refers to the strength of untreated soil if it were at the molded water content of the treated soil.

Notation:

Wi = Initial water content
Wm = Molded water content
γd = Dry density
C.I. = Cone index
pcf = lb/cu ft
psi = lb/sq in.

Figure 8 shows that the cone index strength of quicklime-treated Massachusetts clayey silt and Vicksburg buckshot clay continues to increase with cure times of up to 100 hr. Unconfined compressive strength data are also plotted. (The smaller rate of increase of the unconfined compressive strength of the quicklime-treated samples of Massachusetts clayey silt may in part be due to "remolding" caused by the cone index measurements. One might also expect a non-linear relationship between penetration resistance and unconfined shear for strong, brittle samples.) Thus from 2 to 3 percent quicklime increased the compressive strength of a silt and a clay from only 2 to 5 psi to 75 and 40 psi, respectively, in 100 hr.

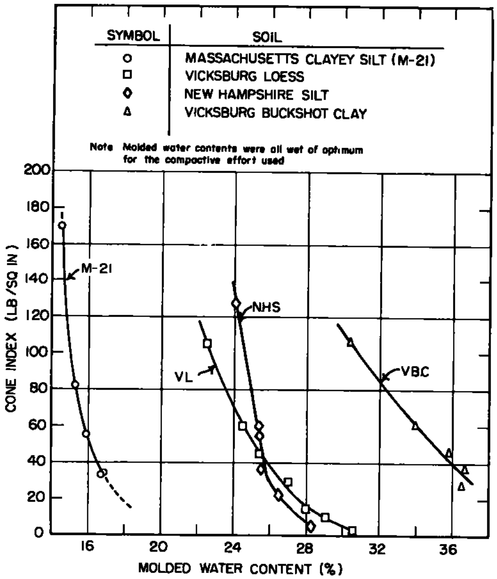

Figure 6. Molded water content vs cone index for soils used in category 1 stabilization.

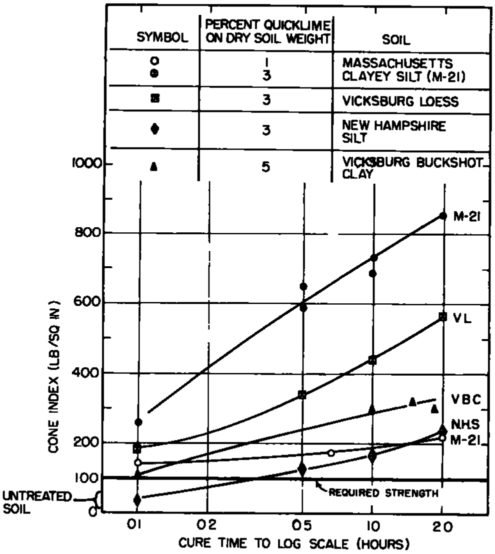

Figure 7. Effects of quicklime on the strength vs time characteristics of four soils—category 1 stabilization.

The effect of the calcium to magnesium oxide ratio on the strength of Massachusetts clayey silt in Category 1 is shown in Figure 9. The additives were pure (that is reagent grade) calcium and magnesium oxide, not calcium and dolomitic quicklimes. It is seen that calcium oxide is a more effective Category 1 stabilizer for this silt than is magnesium oxide, possibly due in part to the greater hydratability of calcium oxide. The strength of this silt after 1.5 hr curing with 2 percent calcium oxide is about twice that with 2 percent calcium quicklime (compare Figs. 8 and 9).

EFFECT OF SECONDARY ADDITIVES ON SOIL-LIME

Scope

The preceding work and published information—for example, National Lime Association, (9); Clare and Cruchley, (2); and Dumbleton, (5)—show that lime:

1. Usually is not effective with relatively nonplastic soils whereas portland cement is often effective.
2. At fairly low percentages, will make plastic clays more workable and may greatly increase the soaked strength. However, the soaked strength is still often less than 200 psi.
3. At fairly high percentages, can yield soaked strengths with plastic clays of over 200 to 400 psi, but a cure period of many months is often required.

An investigation was initiated at M.I.T. to examine the use of additives to make lime more effective with relatively nonplastic soils and to improve the rate of curing of plastic clay-lime mixtures.

Research on cement stabilization has shown that a group of alkali sodium compounds can materially improve the properties of cement-stabilized soils of varying texture and

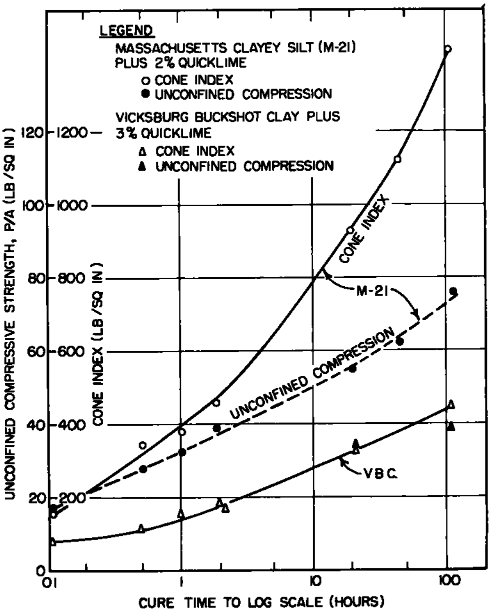

Figure 8. Effect of longer cure time on strength of two soils treated with quicklime.

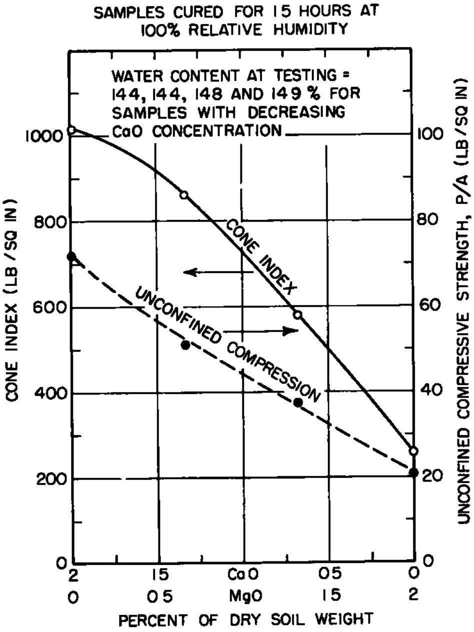

Figure 9. Effect of calcium to magnesium oxide ratio on strength of Massachusetts clayey silt—category 1 stabilization.

composition. An hypothesis to explain the improvement of soil-cement with alkali additives, proposed by Lambe, Michaels and Moh (7) suggests that the calcium hydroxide available in cement reacts with soil silicates (and aluminates), which have been solubilized by the alkali, to form additional cementitious calcium silicates (and aluminates). Hence, sodium compounds which improve soil-cement should also improve soil-lime.

Data are presented on the effects of a selected group of alkali sodium compounds at various concentrations on the lime stabilization of three soils composed of pure minerals and four natural soils ranging from a uniform silt to an organic clay. The evaluation is based on unconfined compressive strength measurements on soaked samples after humid cure periods of up to 28 days.

The data on the effects with the pure minerals were obtained by Chastanet (1), that with the natural soils by Somasekhara (11) and M.I.T. (8). Chastanet and Somasekhara were M.I.T. graduate students in Civil Engineering.

Materials and Procedures

Soils. —Soils composed of pure minerals were selected to facilitate a better understanding of the reactions occurring in a soil-lime-additive mixture. The three soils investigated were ground quartz, a mixture of 90 percent ground quartz and 10 percent bentonite (sodium montmorillonite), and kaolinite.

The four natural soils were: New Hampshire silt, Massachusetts clayey silt (M-21), Vicksburg buckshot clay, and Port Hueneme clay. These soils represent, respectively, two relatively nonplastic soils, one fat clay, and one clay with a high (7 percent) content of organic matter. Classification, chemical and mineralogical data on the seven soils are given in Tables 1 and 2.

Lime. —Ten percent (based on dry soil weight) reagent grade calcium hydroxide was added to the pure mineral soils. A commercial hydrated calcium lime, at 5 and/or 10 percent concentration, was added to the natural soils. Table 5 summarizes the properties of the commercial lime.

Additives. —The five alkali sodium compounds investigated with the pure mineral soils were reagent grade:

Sodium hydroxide - $NaOH$
Sodium sulfate - Na_2SO_4
Sodium metasilicate - $Na_2SiO_3 \cdot 9H_2O$
Sodium carbonate - Na_2CO_3
Sodium aluminate - $NaAlO_2$

Sodium hydroxide, sulfate and metasilicate were selected as additives for the natural soils. Additive concentrations, expressed as normality of the sodium ion in the molding water, ranged from 0.25 to 2.0 normal. The additive concentrations are reported in normality because research (Lambe, et al., (7) on soil-cement plus sodium additives often showed an optimum additive concentration of about 1 normal (for cement contents of 5 percent). (As an approximation for the data presented, a one normal concentration of sodium corresponds to a 1 to 2 percent sodium compound concentration based on the dry soil weight.)

Procedure: Moisture-Density-Strength Relationships for Untreated Soil-Lime Mixtures. —The natural soils were air dried, pulverized, and scalped on a No. 10 sieve. The pure mineral soils required no preparation. Lime (or calcium hydroxide) was hand-mixed with dry soil, various amounts of molding water added, followed by hand-mixing for 1 min. Mixing was then completed in a finger-blade mechancial mixer for 5 min.

The soil-lime mixtures were then compacted in the Harvard miniature mold in 3 layers with 25 blows per layer with a 40-lb tamper. This effort is comparable to Standard AASHO compaction. Thus a complete compaction curve was obtained for the soil-lime mixtures.

The molded samples of Massachusetts clayey silt, Vicksburg buckshot clay, and Port Hueneme clay with 5 percent lime were cured at 100 percent relative humidity for seven days followed by 24 hr of water immersion, both at room temperature.

TABLE 5

COMPOSITION OF COMMERCIAL HYDRATED LIME[1]

Chemical Analysis	Percent by Weight
CaO	72.1
MgO	1.2
Silica plus insoluble acid	1.0
Fe plus Al $_2O_3$	0.7
SO_3	1.1
Ignition loss	23.8
Composition	**Percent by Weight**
Hydrated lime	93.5
Unhydrated MgO	1.2
Impurities	5.3
Total unhydrated oxides	1.2

1. U.S. Gypsum Co., Mortar Seal Hydrate Data furnished by manufacturer.

Weights and volumes of the specimens were recorded both after curing and after immersion. The strength of the soaked samples was measured by the unconfined compression test. Thus a complete curve of molded water content versus soaked strength with 5 percent lime after 7 days curing was obtained for three of the natural soils. (Only the Port Hueneme clay showed a water content for maximum strength to differ appreciably, 3 percent higher, from the optimum water content.) For the other four soils, it was assumed that the optimum water content for density also yielded the maximum soaked strength.

Procedure: Strength Relationships for Treated Soil-Lime Mixtures.—The test procedure for evaluating additives was the same as the foregoing except that:

1. The sodium compounds were added to the molding water.
2. All molding water contents were equal (within about 1 percent water content) to optimum water content for the untreated soil-lime (except for Port Hueneme clay, where the water content equaled optimum plus 3.0 percent).
3. Samples were compacted by two-end static compaction in the Harvard miniature mold to a dry density equal (within 1 or 2 pcf) to that obtained for the same water content for untreated soil-lime. Thus the effect of density variations on strength was minimized.
4. Curing periods ranged from 4 to 28 days.
5. Duplicate samples were made, the average strength is reported.
6. For comparison, untreated (that is, no additive) samples of soil-lime were statically compacted, as previously, and the soaked strength measured after 4 to 28 days curing for 5 and/or 10 percent lime (or $Ca(OH)_2$).

Test Results

Untreated Soil-Lime Mixtures.—Plots of molded water content versus dry density and soaked compressive strength after 7 days curing for 5 percent lime-treated Massachusetts clayey silt (a different batch of this soil was used for the work described in the previous sections), Vicksburg buckshot clay, and Port Hueneme clay are presented in Figure 10. The data show a substantial strength decrease for water contents wet or dry of that yielding the maximum strength for the soils and a maximum strength considerably wet of optimum for the Port Hueneme clay.

Table 6 summarizes the compaction and strength (at 7 and 28 days) data for all seven lime-stabilized soils. All lime plus additive samples were compacted at conditions shown in columns D and E.

Effects of Additives on Pure Mineral Soil-Lime Mixtures.—Five sodium compounds at concentrations of 0.5, 1.0 and 2.0 normal were investigated. Samples were cured for 4, 7, and 28 days. The calcium hydroxide concentration was 10 percent.

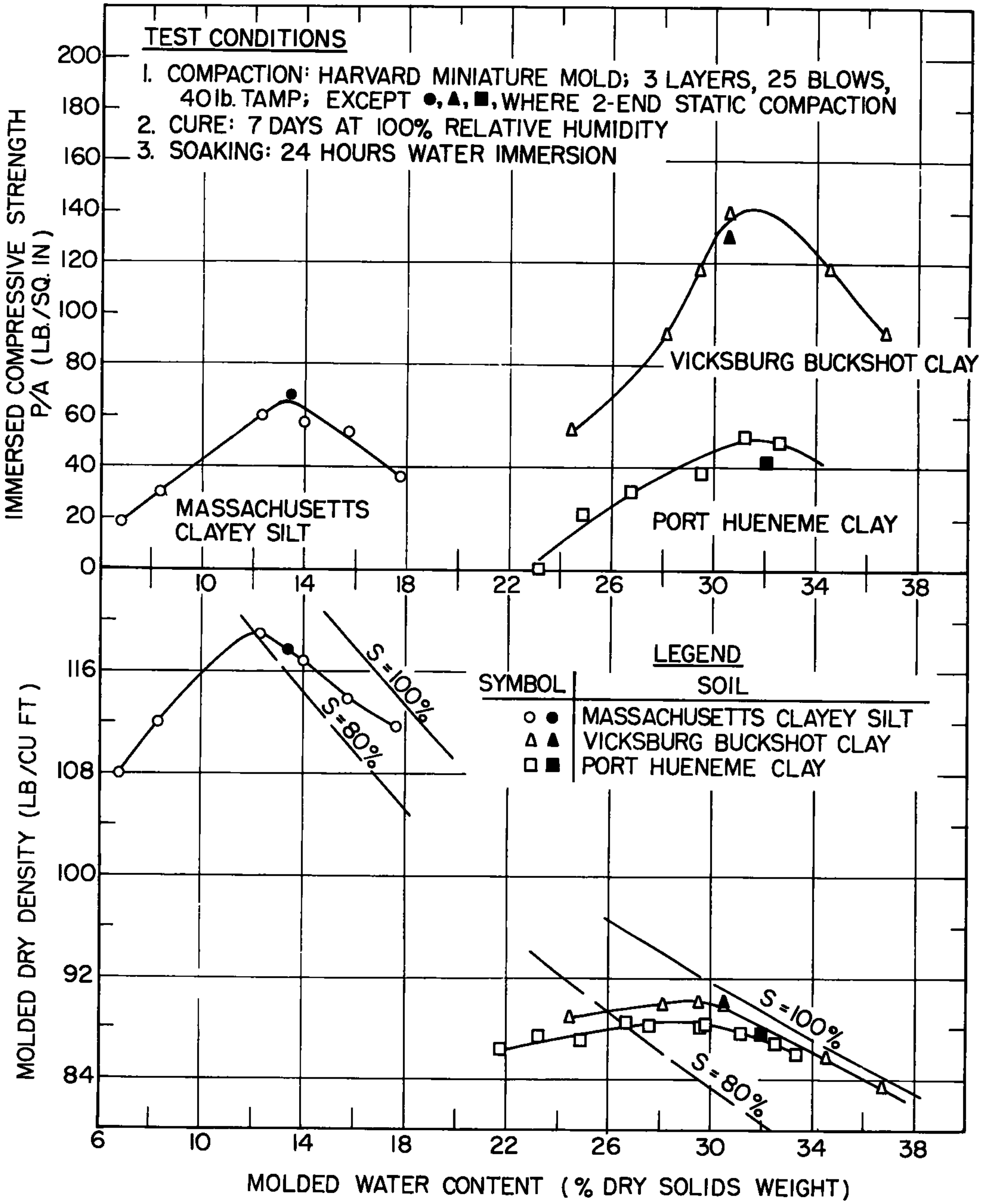

Figure 10. Effect of molded water content and density on the soaked strength of Massachusetts clayey silt, Vicksburg buckshot clay and Port Hueneme clay stabilized with 5 percent hydrated lime.

TABLE 6

MOISTURE-DENSITY-STRENGTH DATA FOR SOIL-LIME MIXTURES (NO ADDITIVES)

A	B	C	D	E	F	
Soil	Hydrated Lime or $Ca(OH)_2$ (% of Dry Soil Weight)	Optimum[1] Water Content (% of Dry Solids Weight)	Maximum[1] Dry Density (pcf)	Nominal Water Content Used for Testing (%)	Soaked Compressive Strength, P/A (psi)[2] After 24-Hr Immersion and Curing at 100% Relative Humidity for	
					7 Days	28 Days
Quartz	10 $Ca(OH)_2$	20	96	20 (optimum)	88 ± 2	290 ± 6
90% Quartz 10% Bentonite	10 $Ca(OH)_2$	19	103	19 (optimum)	158 ± 8	360 ± 20
Kaolinite	10 $Ca(OH)_2$	27	93	27 (optimum)	0	100
Massachusettes clayey silt	5 Lime	12.5	119	13.0 (optimum + 0.5%)	68 ± 3	90 ± 4
	10 Lime	-	-	13.0	90 ± 5	185 ± 5
Vicksburg buckshot clay	5 Lime	30	90	30.5 (optimum + 0.5%)	130 ± 2	200 ± 20
	10 Lime	-	-	30.5	105 ± 10	130 ± 2
Port Hueneme clay	5 Lime	28.5	88.5	31.5 (optimum + 3.0%)	42 ± 3	40 ± 2
	10 Lime	-	-	31.5	45 ± 10	120 ± 15
New Hampshire silt	5 Lime	19	100	19 (optimum)	30 ± 12	40 ± 10
	10 Lime	21	99	21 (optimum)	36 ± 7	56 ± 5

[1] Harvard miniature mold 3 layers, 25 blows per layer with 40-lb tamper

[2] Samples molded to same densities and water contents as shown in columns D and E by two-end static compaction, average strength of two or more samples reported

(a) Quartz. Figure 11 shows plots of immersed strength versus additive concentration for cure periods of 4, 7, and 28 days. Figure 12 shows the effect of type of additive (at 1.0 normal concentration) on the curing rate.

The data show sodium metasilicate to be most effective, particularly at 4 and 7 days where the strength is more than doubled for the highest concentration. The strength increase is proportional to the concentration, except at 28 days, where the efficiency

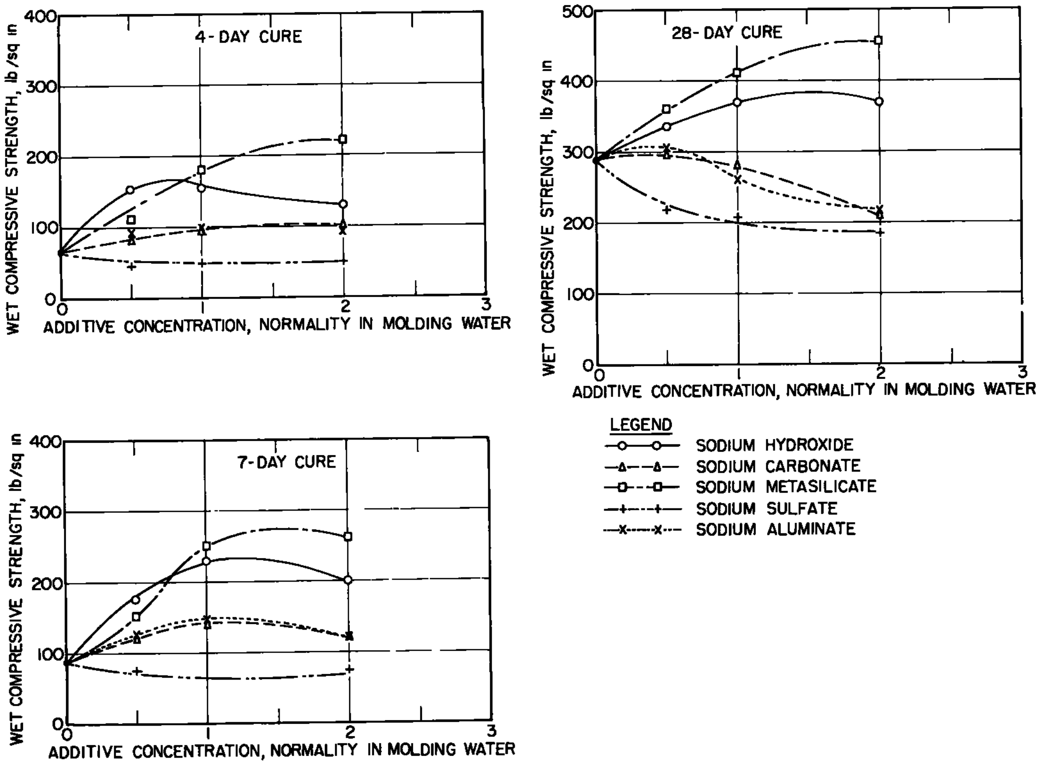

Figure 11. Effect of additive type and concentration on the strength of quartz stabilized with 10 percent calcium hydroxide.

decreased above 1 normal. Sodium hydroxide, the only other effective additive for all cure periods, shows an optimum concentration which tends to increase with time. Sodium sulfate proved detrimental, whereas, the sodium carbonate and aluminate increased the early strength somewhat, but had little or an adverse effect on the 28-day strength.

Untreated quartz-lime attained an unexpected high strength of almost 300 psi after 28 days cure.

(b) Quartz-Bentonite. The addition of bentonite to quartz increases the dry density (Table 6) and undoubtedly provides additional surface silica and alumina to react with lime, both effects tending to increase the strength. However, bentonite would also tend to cause more swelling and strength loss upon soaking. The strength data (Fig. 13 and Table 6) show the strength of untreated quartz-bentonite-lime to be uniformly higher (45 to 70 psi) than quartz-lime over all cure periods.

The effects of sodium metasilicate and hydroxide on the quartz-bentonite-lime (Fig. 13) are similar to that on quartz-lime. Likewise, sodium sulfate and aluminate had negligible or detrimental effects. However, sodium carbonate proved beneficial at low concentrations (about 0. 5 normal) after 4 days curing.

(c) Kaolinite. The effects of additives on the strength of kaolinite-lime are plotted in Figure 14. The data show that untreated kaolinite-lime failed to develop any strength within 7 days, but that several of the additives at high concentrations proved effective (except for the sulfate—for which the 7-day strength of zero at a 2 normal concentration may be questionable). However, all six sodium compounds produced a substantial 28-day strength increase, sodium hydroxide being the least effective (strength doubled). The optimum concentration at 28 days for the additives was about one normal, except for the metasilicate which produced a strength increase proportional to the additive concentration.

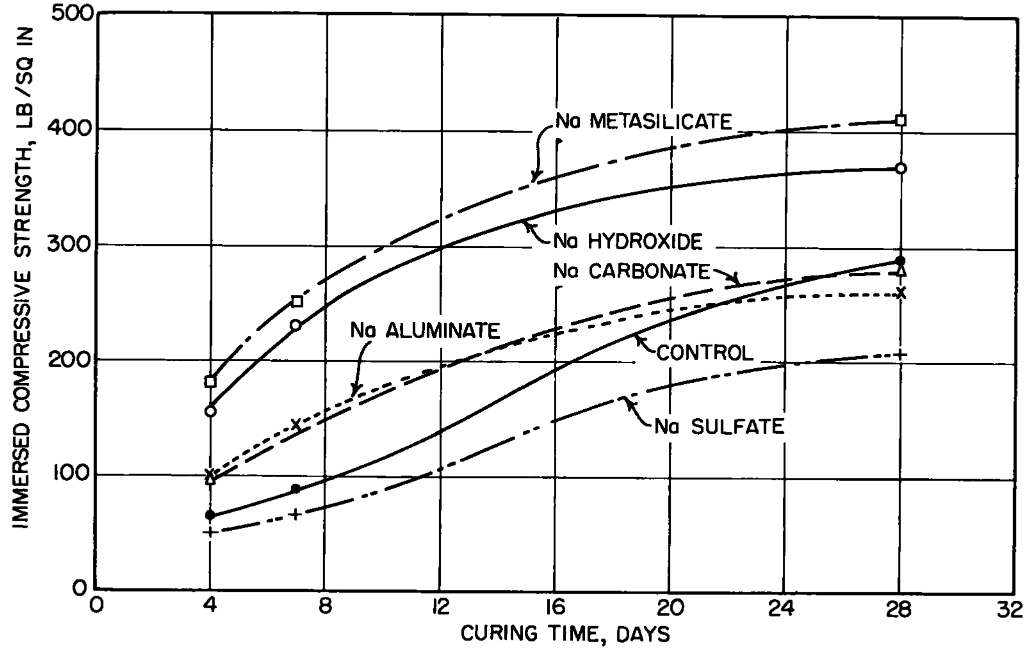

Figure 12. Effect of type of additive (at one normal concentration) on strength development of quartz stabilized with 10 percent calcium hydroxide.

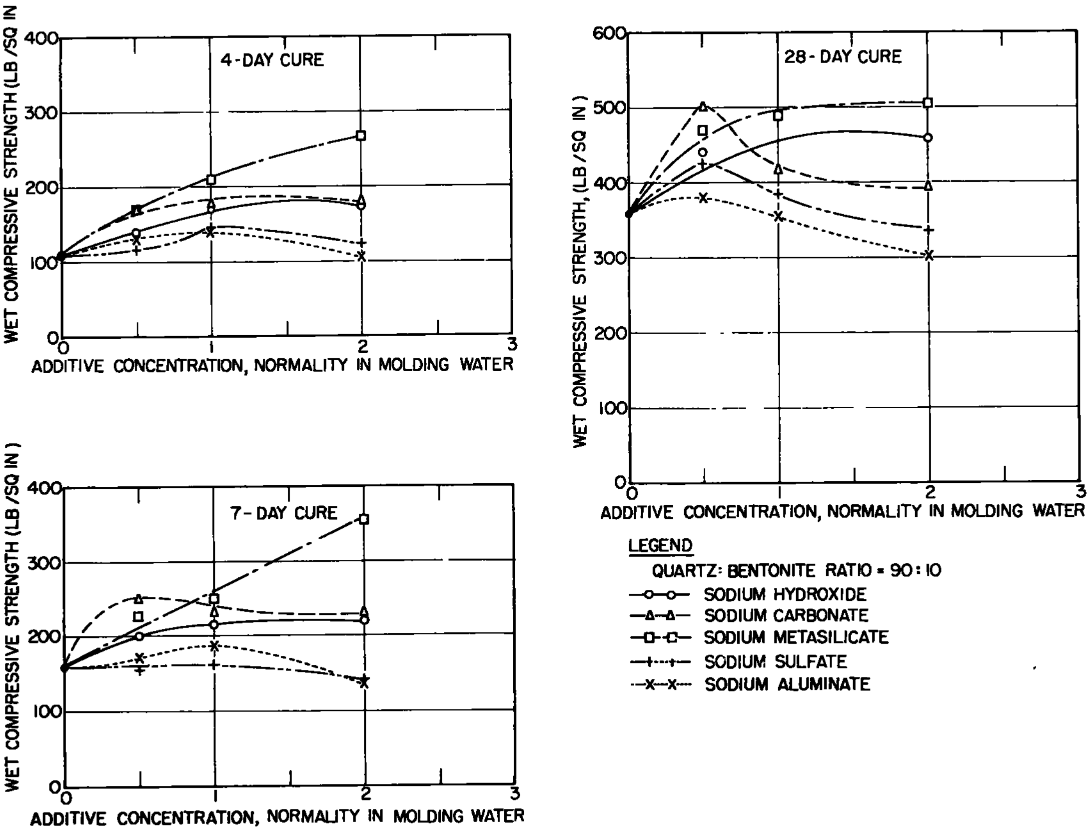

Figure 13. Effect of additive type and concentration on the strength of quartz-bentonite stabilized with 10 percent calcium hydroxide.

Effects of Additives on Natural Soil-Lime Mixtures.—Based on the results obtained with the pure mineral soils, the effects of 0.25, 0.5 and 1.0 normal sodium hydroxide, metasilicate, and sulfate were investigated. A commercial lime (Table 5) at a 5 percent level, was added to three of the soils. Five and 10 percent lime was added to the New Hampshire silt. The strengths were usually measured after 7 and 28 days humid curing.

(a) New Hampshire Silt. As given in Table 6, 5 and 10 percent lime yield 28-day soaked strengths of about 50 psi which only slightly exceed the 7-day strengths. This soil is low in reactive silica (Lambe, et al.,(7). Figure 15 shows the effects of three additives, at a one normal concentration, on the rate of cure of this silt stabilized with 10 percent lime. Sodium metasilicate, hydroxide, and sulfate all produced substantial (by 2- to 4-fold) strength increases over most of the cure period. Figure 16 shows that an increase in concentration of sodium hydroxide from 0.5 to 1.0 normal increases the cure rate of New Hampshire silt with 5 percent lime.

(b) Massachusetts Clayey Silt (M-21). The data in Table 6 and Figure 10 (and Fig. 5) show that this silt, like New Hampshire silt, is relatively unresponsive to lime stabilization, although the 28-day strength with 10 percent lime does attain a "respectable" value.

The effects of additive type and concentration are shown in Figure 17 for 7- and 28-day strengths. Both sodium metasilicate and sulfate, at concentrations of one normal, were effective, producing 28-day strengths of 610 and 360 psi, respectively, compared to only 90 psi for untreated soil-lime. Sodium hydroxide proved relatively ineffectual.

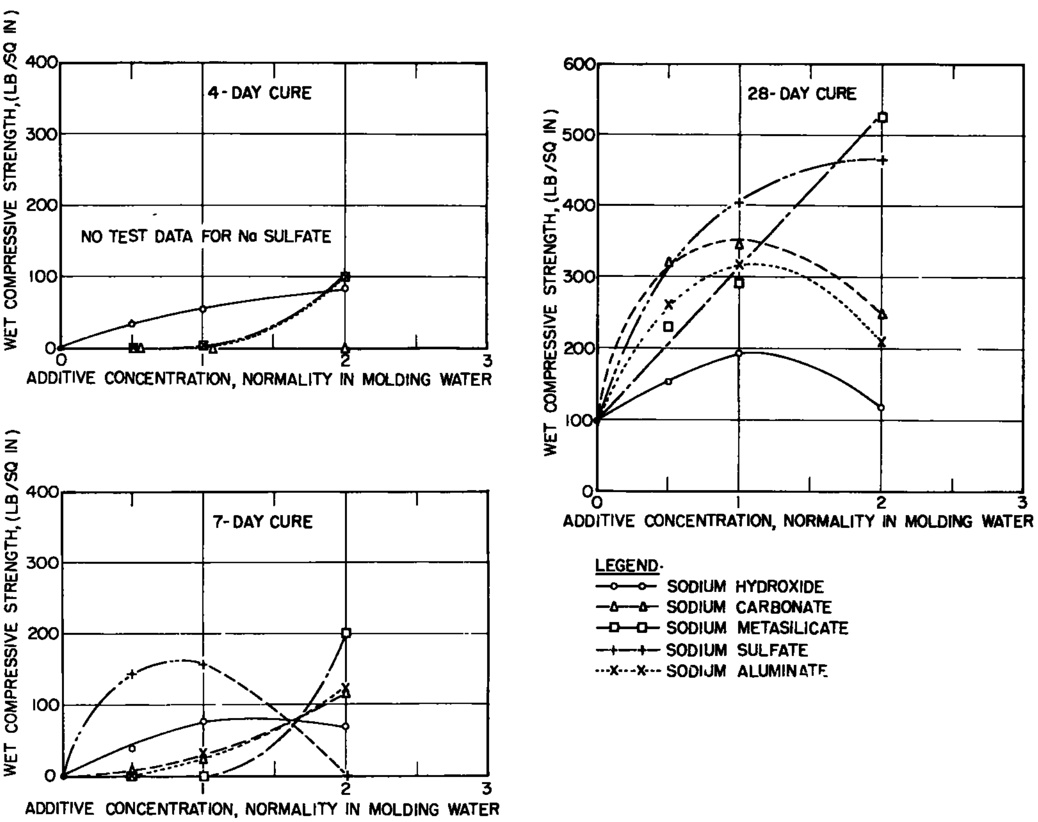

Figure 14. Effect of additive type and concentration on the strength of kaolinite stabilized with 10 percent calcium hydroxide.

(c) Vicksburg Buckshot Clay. Figure 18 shows the effects of additives on this plastic clay which is twice as responsive to 5 percent lime as the preceding clayey silt. Whereas sodium metasilicate is moderately effective at 7 days, 0.5 normal sodium hydroxide is more effective at 28 days. Sodium sulfate was deterimental at concentrations exceeding 0.5 normal.

(d) Port Hueneme Clay. Data in Table 6 and Figure 5 show that the 7-day strengths of Port Hueneme clay plus 5 and 10 percent lime are low, and that 8 to 10 percent lime is required before long cure periods are beneficial. This clay, in addition to the high clay content, contains 7 percent organic matter.

The effects of additives on the strength of this soil with 5 percent lime are presented in Table 7. None of the additives tested were effective; in fact, all additive treated samples suffered a decrease in strength with additional cure time. Furthermore, it was observed that all the clay-lime systems adsorbed large amounts of water and swelled during the curing periods and during subsequent immersion.

Summary of Effects of Additives.—Table 8 presents a summary of the strength increases at 7 and 28 days achieved by the best sodium additive for each soil-lime mixture. The table shows that, except for the Port Hueneme clay, sodium additives are effective in increasing both the 7- and 28-day strengths. For the six soils benefited, the average strength increase at 7 days was 160 psi, that at 28 days was 250 psi. The larger strength increases, both absolute and percentagewise, usually occurred with those soils having the lower untreated strengths. Except for the organic clay, all treated soils achieved a 28-day strength exceeding 200 psi and most exceeded 300 psi.

TABLE 7

EFFECT OF THREE SODIUM COMPOUNDS ON THE PROPERTIES OF PORT HUENEME CLAY WITH FIVE PERCENT HYDRATED LIME

	Additive Concentration		At Molding			After Curing		After Immersion		
Additive	Normality[1]	Percent[2]	Water Content (%)	Dry Density (pcf)	Curing Time (Days)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Compressive Strength (psi)
Control	-	-	32 0	87 7	7	35 0	82 5	36 2	80 7	42 ± 3
	-	-	32 0	87.8	28	37 2	82 6	37 2	79 9	40 ± 2
Sodium hydroxide	0 25	0 34	32 0	87 5	7	35 7	81 5	37 0	81 5	45 ± 1
			32 0	87 6	28	37 2	81 5	42 0	81 5	40 ± 0
	0 50	0 66	31 4	87 8	7	34 8	83 4	33 8	82 8	64 ± 3
			31 4	87 8	28	41 8	81 7	40 6	80 8	32 ± 0
	1 00	1 31	31 2	88 0	7	34 6	82 7	38 4	81 2	40 ± 0[3]
			31 2	87 8	28	41 2	79 9	40 6	79 8	42 ± 1
Sodium metasilicate	0 25	0 48	30 0	88 3	7	31 0	87 5	29 5	86 6	66 ± 2
			30 0	88 5	28	38 1	82 4	37 3	81 3	25 ± 2
	0 50	1 00	31 2	87 8	7	32 7	86 1	33 2	85 2	57 ± 3
			31 2	87 7	28	40 6	81 6	39 1	81 6	18 ± 0
	1 00	2 01	31 4	87 6	7	33 1	85 9	34 4	83 3	45 ± 5
			31 4	87 6	28	39 6	82 4	37 9	82 4	30 ± 0
Sodium sulfate	0 25	0 56	30 2	88 8	7	31 0	87 8	36 6	87 8	68 ± 5
			30 2	88 6	28	37 0	84 3	36 4	83 4	30 ± 0
	0 50	1 12	30 0	88 9	7	36 6	86 3	31 8	85 4	48 ± 4
			30 0	89 0	28	36 8	83 6	36 6	82 8	29 ± 1
	1 00	2 24	30 0	88 7	7	32 9	86 0	33 1	86 0	47 ± 2
			30 0	88 6	28	40 8	83 3	37 9	82 4	22 ± 0

[1] Normality of sodium on molded water content
[2] Percent of dry soil weight
[3] Specimens cracked during immersion
[4] The lower water content of some samples after immersion than after curing may be explained by different amounts of free water on the surface of the samples at the time of weighing

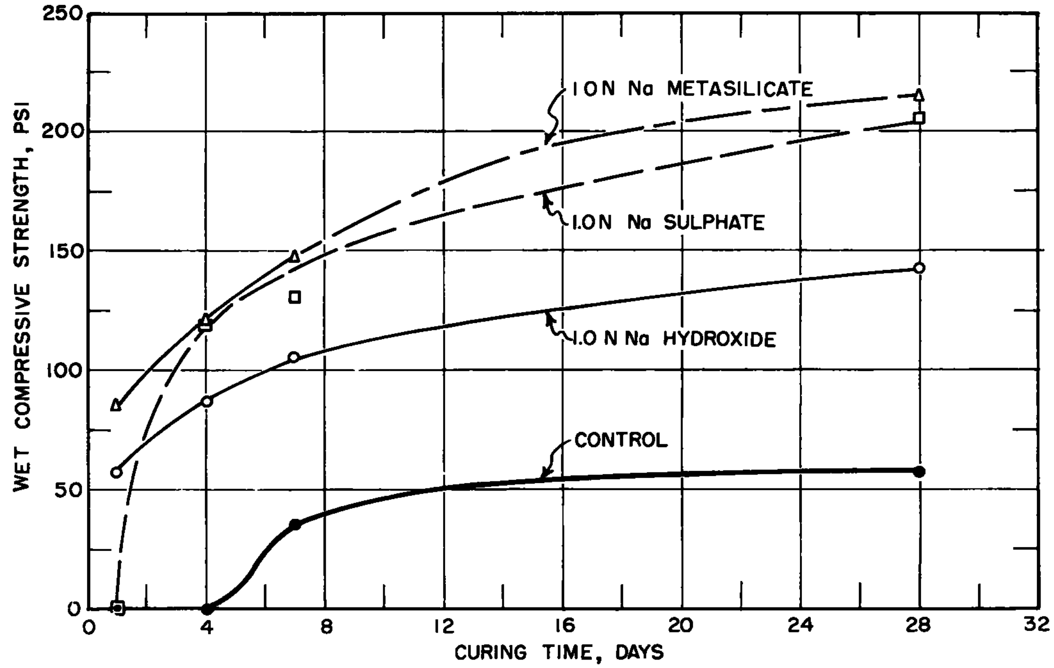

Figure 15. Effect of three sodium compounds on the strength development of New Hampshire silt stabilized with 10 percent hydrated lime.

A summary of the effects (excluding those on Port Hueneme clay) of the various sodium compounds show that:

1. Metasilicate was usually the most effective additive. It increased the 7-day strength of all soils by 100 to 200 psi and increased the 28-day strength of all but the Vicksburg buckshot clay by 150 to 520 psi. Metasilicate was most effective, percentage-wise, with the two natural silts and the kaolinite. The effectiveness usually increased with increasing additive concentration.

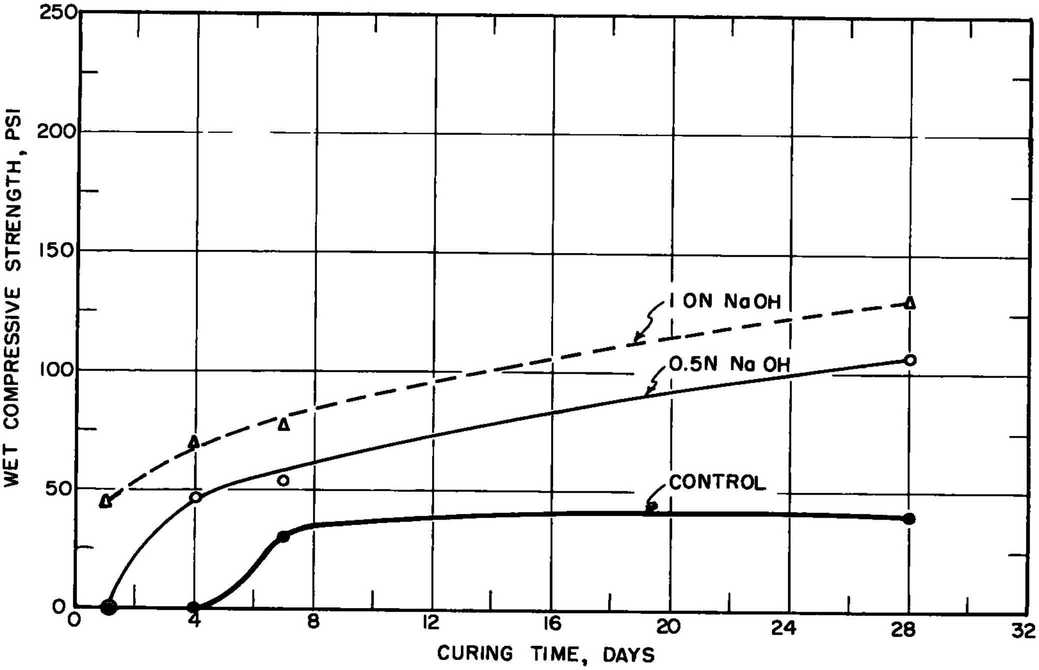

Figure. 16. Effect of sodium hydroxide on the strength development of New Hampshire silt stabilized with 5 percent hydrated lime.

TABLE 8

SUMMARY OF EFFECT OF BEST SODIUM ADDITIVES ON STRENGTH[1] OF SOIL-LIME MIXTURES

Soil	Percent Lime or $Ca(OH)_2$	After 7 Days Cure[2] and 1 Day Immersion: Strength Increase with Best Additive (psi)	Strength Ratio Treated to Untreated Sample	Concentration[3] and Type of Best Sodium Additive	After 28 Days Cure[2] and 1 Day Immersion: Strength Increase with Best Additive (psi)	Strength Ratio Treated to Untreated Sample	Concentration[3] and Type of Best Sodium Additive
Quartz	10 $Ca(OH)_2$	170	$\frac{260}{90} = 2.9$	2N (2.85) Metasilicate	165	$\frac{455}{290} = 1.6$	2N (2.85) Metasilicate
90% Quartz 10% Bentonite	10 $Ca(OH)_2$	195	$\frac{355}{160} = 2.2$	2N (2.70) Metasilicate	145	$\frac{505}{360} = 1.4$	2N (2.70) Metasilicate (or 5N Carbonate)
Kaolinite	10 $Ca(OH)_2$	200	$\frac{200}{0} = \infty$	2N (3.85) Metasilicate	425	$\frac{525}{100} = 5.3$	2N (3.85) Metasilicate
Massachusetts clayey silt	5 Lime	170	$\frac{240}{70} = 3.4$	1N (0.95) Sulfate	520	$\frac{610}{90} = 6.8$	1N (0.80) Metasilicate
Vicksburg buckshot clay	5 Lime	105	$\frac{235}{130} = 1.8$	5N (0.99) Metasilicate	90	$\frac{290}{200} = 1.5$	5N (0.65) Hydroxide
Port Hueneme clay	5 Lime	Strength increases slightly, but benefit lost with longer cure			Strength unchanged or decreases with all additives		
New Hampshire silt	10 Lime	110	$\frac{145}{35} = 4.1$	1N (1.38) Metasilicate	160	$\frac{215}{55} = 3.9$	1N (1.38) Metasilicate (1N Sulfate)

[1] Unconfined compressive strength of samples compacted to same water content and density as untreated soil-lime by two-end static compaction
[2] At 100 percent relative humidity
[3] Normality of sodium in molding water (and percent of additive on dry soil weight)

2. Sulfate was very effective with the two natural silts and the kaolinte, where the strength increase at 7 days was 100 to 170 psi, that at 28 days was 150 to 350 psi. However, sulfate proves ineffectual or detrimental with the other soils.

3. Hydroxide was reasonably effective with all soils with an average strength increase of 70 and 90 psi at 7 and 28 days, respectively. Relative to the other additives, hydroxide was most effective with the quartz, the quartz-bentonite mixture, and Vicksburg buckshot clay.

4. Aluminate and carbonate were both very effective with kaolinite, and carbonate very effective with the quartz-bentonite mixture. Neither additive improved quartz-lime.

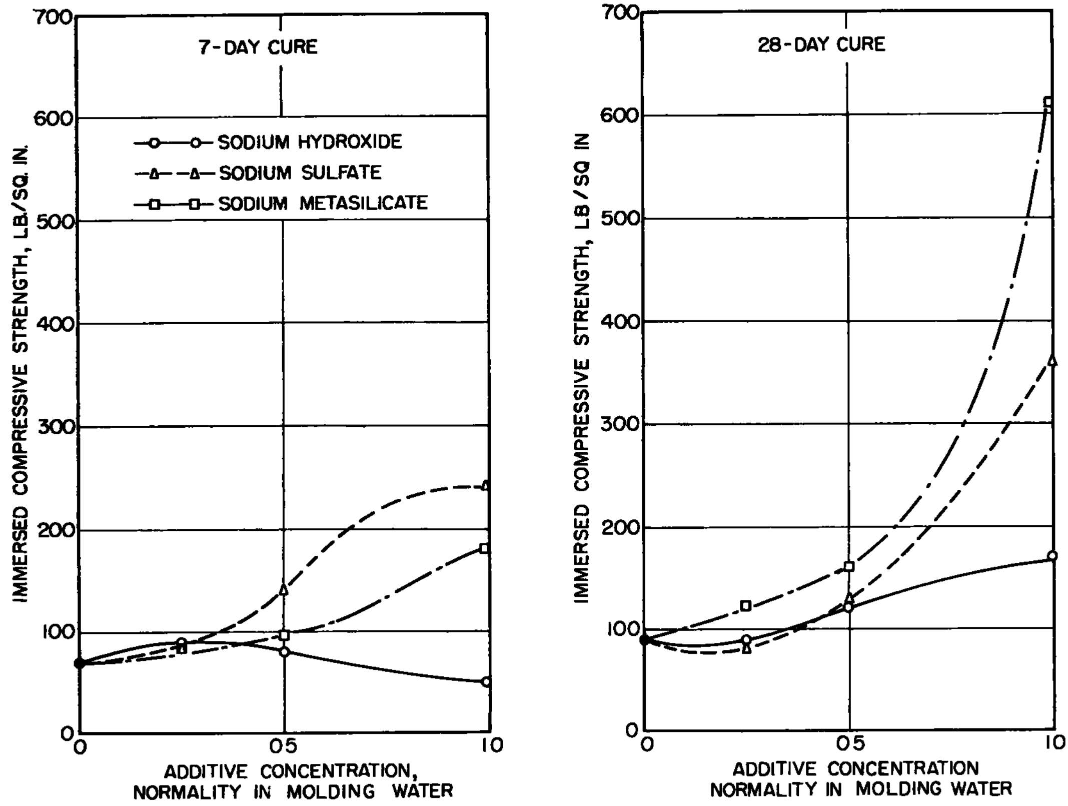

Figure 17. Effect of three sodium compounds on the strength of Massachusetts clayey silt stabilized with 5 percent hydrated lime.

Discussion of Mechanism of Additive Action

Reaction of Soil and Lime. —The addition of lime to soil causes an immediate increase in the pH of the molding water due to the partial disassociation of the calcium hydroxide. The calcium ions in turn combine with the reactive hydrous silica and/or alumina present on the surfaces of soil particles to form calcium silicates and/or aluminates (henceforth, mention of surface silica will also refer to surface alumina) which harden with time to effect stabilization of the soil. The relatively high pH in the pore water facilitates the formation of this cementitious gel by increasing the reactivity of the surface silica. However, data (for example, Clare and Cruchley, (2) show that the cementation process is slow with soils presumedly containing large amounts of reactive silica (such as clays) where several years might be required before equilibrium is reached. (Unpublished data by Moh suggest that most of the lime reacts within a period of several days, but that the character of the cementitious calcium silicates changes with time.) On the other hand, soils with low amounts of reactive silica (such as might occur in sands and silts) do not provide sufficient silica to react with the lime. Hence, the ultimate strength occurs rapidly but is low. New Hampshire silt shows this (Figs. 15 and 16).

Effects of Sodium Additives. —The presence of sodium additives can improve soil-lime by producing greater amounts of reactive silica and by controlling the rate of reaction of calcium with silica to obtain a more uniform distribution of calcium silicate throughout the soil.

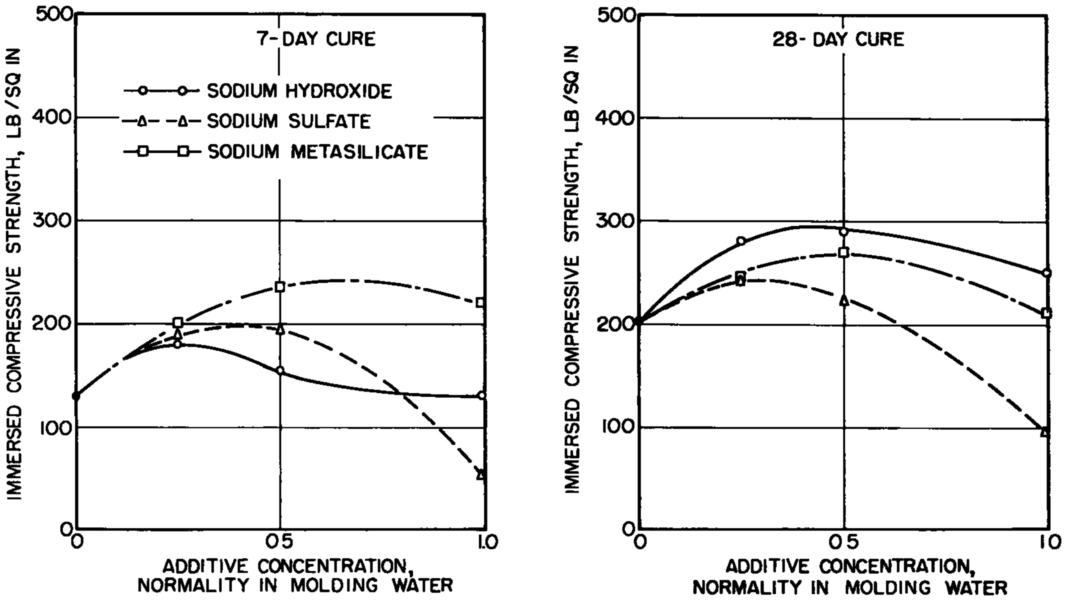

Figure 18. Effect of three sodium compounds on the strength of Vicksburg buckshot clay stabilized with 5 percent hydrated lime.

An increase in amount of silica can be obtained by addition of water soluble sodium metasilicate which will diffuse throughout the soil. The data show metasilicate to be effective. One might expect sodium aluminate to behave similarly (but to form cementitious calcium aluminates), however, the data do not always support this.

The addition of sodium hydroxide, or Na_2X where X is sulfate, carbonate, or aluminate, greatly reduces the calcium ion concentration in solution by the common ion effect or by the causticization reaction:

$$Na_2X + Ca(OH)_2 \rightarrow CaX + 2NaOH.$$

At the same time, the pH is significantly elevated. Suppression of the calcium concentration retards precipitation of calcium silicate. The pH elevation accelerates attack of soil silica and formation of soluble sodium silicate which is free to diffuse through the pore fluid. Eventually, however, neutralization of the free alkali by reaction with the soil reduces the pH which permits the calcium ions to go into solution and react with the uniformly distributed alkali silicate or aluminate (Lambe, Michaels, Moh, (7).

When a sodium salt, rather than sodium hydroxide, is added, the elevation of the pH may be smaller, particularly with a clayey soil that could "buffer" the sodium hydroxide as rapidly as it is formed by reaction of the sodium salt with lime. The amount of calcium ion depression may increase or decrease depending on the solubility of the calcium salt formed from the reaction with the sodium salt. The addition of sodium carbonate may also lead to the formation of cementitious calcium carbonate.

The above hypotheses generally explain the effects of additives. However, considerably more data are required for a detailed explanation inasmuch as many variables (for example, rate of formation and distribution of silica, sodium to calcium ratio in the cementitious silicates and aluminates) affect the rate of strength increase with time and the ultimate strength.

The Port Hueneme clay bears special mentioning. In an organic soil-lime system, both the soil silica and the organic matter are competing for calcium ions. In soils with large amounts of organic matter, the organic compounds can progressively extract calcium ions from any weakly bonded calcium silicates which results in a reduction in strength. Moreover, the addition of most alkali additives not only solubilizes the soil silicates, but also intensifies the organic activity. Although sodium sulfate is effective with organic sand-cement mixtures, it did not improve organic clay-cements (Lambe, Michaels, Moh, (7)), nor did it improve Port Hueneme clay-lime.

In summary, the above sodium compounds either provide additional silica (that is sodium metasilicate) or make the soil silica more reactive and at the same time control the rate of reaction between lime and silica to facilitate a more uniform distribution of the cementitious calcium silicates.

CONCLUSIONS

The laboratory test results presented in this paper (excluding the effects of sodium additives) show the following trends, which confirm published data (for example, National Lime Association, (9); Dumbleton, (5); Woods and Yoder, (12)):

1. Lime reduces the maximum compacted dry density of soils and increases the optimum water content.
2. Lime increases the soaked strength of soils after humid cure periods, but the effectiveness of lime treatment varies considerably with soil type. The less plastic soils, such as silts (and organic soils) are often less responsive to lime than soils of increased plasticity, such as clays. However, plastic clay-lime mixtures may require many months, or even years, to develop their ultimate strength.
3. The maximum soaked strength of lime stabilized soils usually occurs at optimum water content for compaction, except for plastic, or organic, clays where the maximum strength may occur wet of optimum.
4. Soils often have an optimum lime concentration, above which an increase in percent lime is relatively ineffective in increasing the soaked strength, at least for the shorter cure periods.
5. Quicklime, at 1 to 5 percent concentration, increased the strength of four very wet soils (ranging from an uniform silt to a plastic clay) by 3- to 10-fold within a period of 2 hr.

The data on the effect of sodium compounds on the soaked compressive strength of seven soil-lime mixtures show that:

1. None of the sodium additives improved the strength of the organic clay-lime, but for the other six soils, the best additives yielded an average increase in the soaked strength after 7 days curing of 160 psi. Except for the organic clay, all sodium treated soil-lime mixtures achieved a 28-day strength exceeding 200 psi and most exceeded 300 psi. These 28-day strengths represent a 1.4- to 6.8-fold strength increase over the strengths of the untreated soil-lime mixtures.
2. Sodium metasilicate was usually the most effective additive studied. The average strength increase for the treated soils at 7 and 28 days was 146 and 248 psi, respectively, excluding the organic clay. The effectiveness of metasilicate almost always increased with increased additive concentration.
3. Sodium hydroxide was the only other additive studied to prove reasonably effective with all soils, for which the average strength increase at 7 and 28 days was 70 and 90 psi, respectively (excluding the organic clay).
4. Sodium sulfate was effective with three soils (average strength increase of 140 and 250 psi at 7 and 28 days for two natural silts and the kaolinite), but was ineffectual or detrimental with the other soils.
5. The use of sodium additives with soil-lime is promising, however, the effectiveness varies widely with soil and additive type.

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