Relation of Strength to Composition and Density of Lime-Treated Clayey Soils

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This paper examines the effects of dolomitic monohydrate (Type N) and calcitic hydrated limes, Standard and Modified AASHO density compaction, and the predominant type of clay mineral in the soil, on the immersed strengths of soil-lime mixtures.

Dolomitic lime was found to give higher strengths in montmorillonite and illite clay soils, but only to give higher strengths to some kaolinite clay soils. This trend held at both compactive energies. Modified density compaction was found to give significantly higher strengths than Standard density compaction.

● IT IS KNOWN that small additions of lime to clayey soils may improve their consistency limits, workability and ease of pulverization, and volume change characteristics; and that use of additional amounts of lime may contribute to strength increases (3). However, much more information is needed on the relations of these property improvements to such variables as lime and soil composition, and compacted density. The purpose of this paper is to present some experimental findings concerning the relation of cured strength of lime-treated soil mixtures to predominant soil clay mineral, type and amount of lime, and compacted density.

PROPERTIES OF MATERIALS

Soils

Nine soils from various parts of the United States (Table 1) were used in the investigation. The major groups of soil clay minerals were represented in the clay fractions of these soils; three (AR-2, -3, -7) were dominated by montmorillonite, three (AR-4, -8, -9) by illite, and three (AR-5, -6, -10) by kaolinite group clay minerals. These and other property variations of the soils are given in Table 2. The montmorillonite clay soils contained some illite. One of the illite clay soils, AR-4, contained an appreciable amount of chlorite. The clay fraction of soil AR-5 was rich in halloysite, a kaolinite subgroup mineral. Soils AR-6 and AR-10 contained substantial amounts of mica.

Limes

Six commercial limes were used, three calcitic hydrated limes (A, B, C) and three dolomitic monohydrate "Type N" limes (D, E, F). Limes were used within six months of their receipt from manufacturers. When not in use, lime containers were sealed tightly to prevent carbonization of the lime. An analysis of each lime is given in Table 3.

Water

Distilled water (pH = 6 to 7) was used in all tests.

OPERATIONAL PROCEDURES

Soil Preparation

An identical procedure was used preparing each soil for all tests. As the soil was

TABLE 1

SOIL SITE CHARACTERISTICS

Soil[a] Designation	Sampling Location	Geological Description	Soil Series and Horizon	Sampling Depth (in.)
AR-2	Ringgold County, Iowa	Kansan-age glacial till, calcareous	Shelby (Burchard), C horizon	54-126
AR-3	Harris County, Texas	Coastal Plain deposit, largely deltaic, calcareous	Lake Charles, probably C horizon	39-144
AR-7	Keokuk County, Iowa	Plastic loess, Wiscosin age, noncalcareous	Mahaska, C horizon	36-77
AR-4	Monroe County, Mich.	Probably Wisconsin-age glacial till, calcareous	Unknown, C horizon	Unknown
AR-8	Livingston County, Ill.	Wisconsin-age glacial till, calcareous	Clarence, C horizon	46-56
AR-9[b]	Goose Lake region, Ill.	Commercial product, noncalcareous	Unknown, probably C horizon	Unknown
AR-5	Orange, Va.	Residual soil over diorite, noncalcareous	Davidson, B horizon	Unknown
AR-6	Durham County, N. C.	Residual soil over medium grained biotite granite, noncalcareous	Durham, B horizon	24 below A horizon
AR-10[c]	N. C.	Unknown, noncalcareous	Unknown, probably C horizon	Unknown

[a]Iowa Engineering Experiment Station Soil Research Laboratory Sample Designation.
[b]Commercial product Grundite, supplied by Illinois Clay Products Co., Joliet, Ill.
[c]Supplied by Harris Clay Co., Spruce Pine, N. C.

received it was spread out to air dry on brown wrapping paper placed on a concrete table. After a few days the soil was hand crushed, if necessary, and sieved through a No. 10 sieve. Material retained on the sieve was then placed in a steel bowl (mortar) for crushing. The crusher was a drill press on which was mounted a rubber pestle. A free sliding metal disk, the size of the top of the bowl, was mounted on the pestle stem to prevent loss of soil fines during crushing. The soil was crushed and sieved until the soil aggregations were completely broken down. Particles that would not pass the No. 10 sieve were discarded. Soil passing the No. 10 sieve was mixed to obtain uniformity and placed in 30-gal galvanized cans until used.

TABLE 2

PROPERTIES OF SOILS

Soil Designation	AR-2	AR-3	AR-7	AR-4	AR-8	AR-9	AR-5	AR-6	AR-10
Textural composition[a], %									
Gravel[b] (> 2 mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sand (2-0.074 mm)	20.9	3.0	0.3	7.0	10.0	6.4	11.0	45.3	38.4
Silt (0.074-0.005 mm)	40.6	36.0	60.8	36.0	38.0	18.6	37.0	18.3	34.4
Clay (< 0.005 mm)	38.5	61.0	39.0	57.0	52.0	75.0	42.0	36.5	7.0
Clay (< 0.002 mm)	33.0	51.0	-	44.0	41.0	59.3	29.5	30.0	4.0
Passing No. 10 sieve	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Passing No. 40 sieve	100.0	99.0	100.0	98.0	96.0	99.9	90.0	67.0	64.8
Atterberg limits[c], %									
Liquid limit	41.2	64.6	52.1	44.0	35.5	54.8	43.5	51.0	43.0
Plastic limit	16.7	17.6	20.0	21.1	17.5	27.1	27.0	25.5	N.P.
Plasticity index	34.5	47.0	32.1	22.9	18.0	27.7	16.5	25.5	N.P.
Chemical									
pH[d]	8.5	8.8	5.6	8.4	8.3	5.5	5.9	5.7	5.5
C.E.C.[e], me/100 g	17.5	27.3	23.5	14.5	10.8	19.1	11.0	8.4	4.6
Carbonates[f], %	7.4	16.6	1.5	7.2	22.5	1.92	0.65	0.1	0.07
Organic matter[g], %	0.06	0.13	0.2	0.64	0.7	1.54	2.62	0.1	0.02
Predominant clay mineral[h]	M	M	M	I and C	I	I[i]	H	K	K
Classification									
Textural[j]	Clay	Clay	Silty clay	Clay	Clay	Clay	Clay	Clay	Sandy loam
AASHO[k]	A-7-6(14)	A-7-6(20)	A-7-6(18)	A-7-6(14)	A-6 (11)	A-7-6(18)	A-7-6(12)	A-7-6(11)	A-5 (1)

[a]ASTM Method D 423-54T (2).
[b]Textural gradation tests were performed only on the soil fraction passing the No. 10 sieve. All soils used contained less than 5 percent gravel.
[c]ASTM Methods D 423-54T and D 424-54T (2).
[d]Glass electrode method using suspension of 15 g soil in 30 cc distilled water.
[e]Ammonium acetate (pH = 7) method on soil fraction > 2 mm (No. 10 sieve).
[f]Versenate method for total calcium.
[g]Potassium bichromate method.
[h]X-ray diffraction analysis method. Symbols mean: M, montmorillonite; I, illite; I and C, illite and chlorite; H, halloysite (kaolinite group mineral); K, kaolinite.
[i]By analysis of chemical constituents furnished by manufacturer, assuming all alkalies as potassium and determining the number of potassium ions per unit cell.
[j]From the triangular chart developed by the U.S. Bureau of Public Roads, but 0.074 mm was used as the lower limit of the sand fraction (6).
[k]AASHO Designation: M 145-49 (1).

TABLE 3

PROPERTIES AND PRODUCTION INFORMATION OF HYDRATED LIMES

	Calcitic Hydrated Lime			Monohydrate Type N Dolomitic Lime		
	A[a]	B[a]	C[a]	D[a]	E[a]	F[a]
Chemical constituent, % by wt[b]						
Calcium oxide, CaO	73.0	73.46	73.9[c]	49.1	47.52	48.3
Calcium hydroxide, $Ca(OH)_2$	96.5[d]	97.04	97.68	64.8[d]	61.81	63.7[d]
Magnesium oxide, MgO	0.3	0.93	0.64	32.0	33.50	33.2
Silica, SiO_2	0.6	0.34	0.69	0.4	0.6	0.6
Iron-alumina, R_2O_3	0.3	0.24	0.59	0.3	0.62	1.1
Total loss on ignition	24.5-27.0	24.92	24.22	17.0	17.84	16.8
Ca:Mg ratio	-	-	-	1.815:1[e]	1.682:1[e]	1.732:1[e]

[a]Designation of lime manufacturer.
[b]Data supplied by company concerned.
[c]Calculated by molecular weight ratios from amount of $Ca(OH)_2$ present.
[d]Calculated by molecular weight ratios from amount of CaO present.
[e]Calculated as ratio of calcium to magnesium by weight from amount of materials present as their oxides.

Mixing

A predetermined amount of air dry soil was weighed out on a balance sensitive to 0.1 grams and was placed in a mixing bowl. Lime additive (expressed as a percentage of the oven-dry weight of the soil), if used, was weighed and hand mixed with the soil. Additional dry mixing was accomplished for 1 min with a Hobart, Model C-100 ¼-hp mixer, at low speed. Distilled water was added, and the mixture was mixed for 2 min.

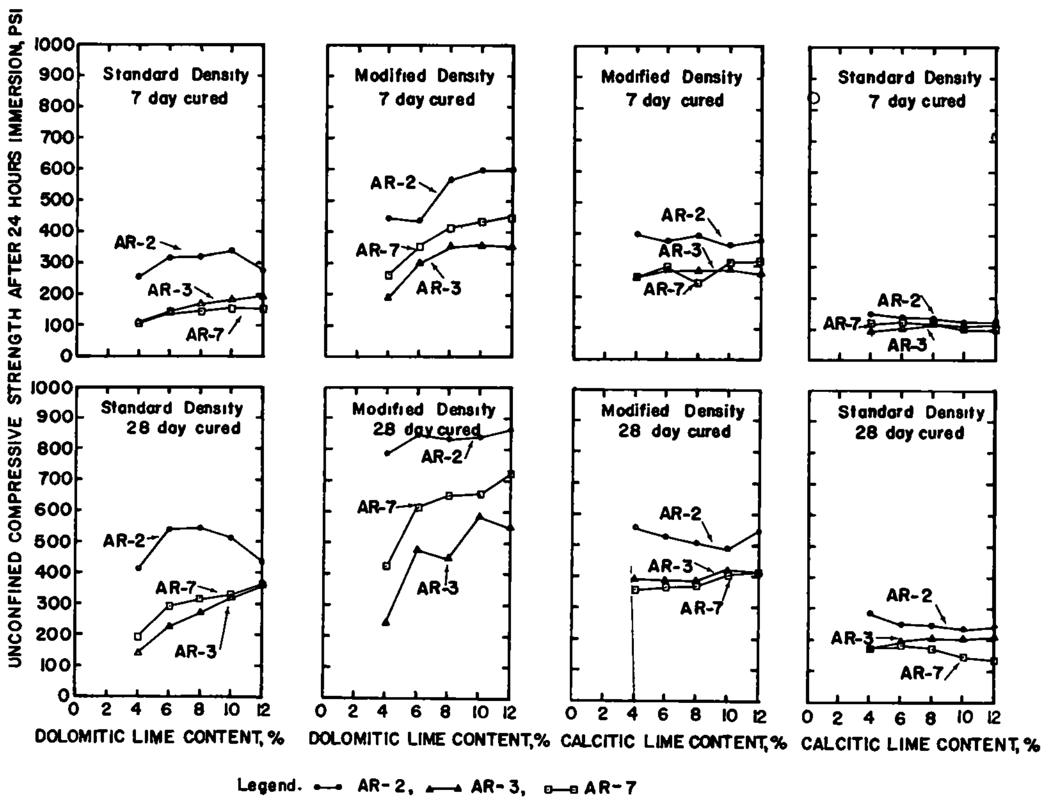

Figure 1. Immersed strength versus lime content relationships after 7- and 28-day curing for montmorillonite clay soils AR-2, AR-3 and AR-7, showing relative effects of Standard and Modified AASHO density compaction, and of dolomitic monohydrate Type N lime D and calcitic hydrated limes.

The mixture was then thoroughly stirred by hand to insure no materials were left unmixed on the sides and bottom of the bowl. The mixture was mixed again for 30 sec to complete the process.

Molding

Test specimens were prepared by use of the Iowa State University molding apparatus as described by Davidson and Bruns (8) and Viskochil, Handy and Davidson (7). The 5-lb hammer, called the standard hammer, is used to compact a predetermined amount of soil mixture in a 2-in. diameter mold to a density near Standard AASHO density (AASHO Designation:T99-57) (1). The 10-lb hammer, called the modified hammer, is used to compact a predetermined amount of soil in a 2-in. diameter mold to a density near Modified AASHO density (AASHO Designation:T180-57) (1).

After mixing and covering with a damp cloth to prevent evaporation, a predetermined amount of the mixture was placed in the compaction mold. The proper hammer was used to attain the desired density. The resultant soil cylinder was extruded from the mold with a hydraulic jack. The compacted specimen was weighed to the nearest 0.1 gram and the height measured to the nearest 0.001 in. The height of the specimen was required to be 2.000 in. ± 0.050 in. All specimens not within these limits were rejected.

Curing

Immediately after being weighed and measured, the specimen was wrapped in waxed

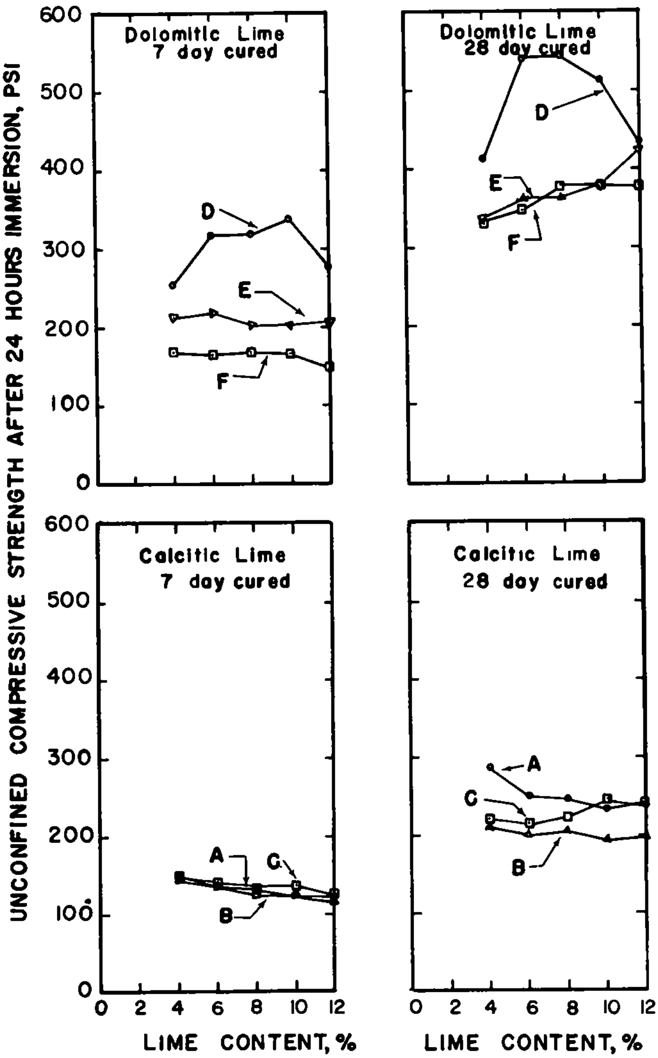

Figure 2. Immersed strength versus lime content relationships after 7- and 28-day curing for montmorillonite clay soil AR-2 and Standard AASHO density compaction, showing relative effects of three dolomitic monohydrate Type N limes and three calcitic hydrated limes.

paper and sealed to with cellulose tape to prevent loss of moisture and carbonization of lime from carbon dioxide in the air. The wrapped specimens were placed on shelves in a curing room where the relative humidity was at least 90 percent and the temperature was 75 F ± 6 deg.

Testing

The apparatus used for testing the strength of the specimens was a Model AP-170

Stability Testing Machine driven by a ⅛-hp electric motor with belt reduction. It was manufactured by Soil Test Inc., Chicago, Illinois. Loads are indicated on a sensitive, 10,000-lb capacity proving ring which is supplied with a dial indicator reading to 0.001-in. deflection. Strain was applied to the test specimen at a constant rate of 0.1 in. per min. Strain on the proving ring is related to load by means of a calibration chart.

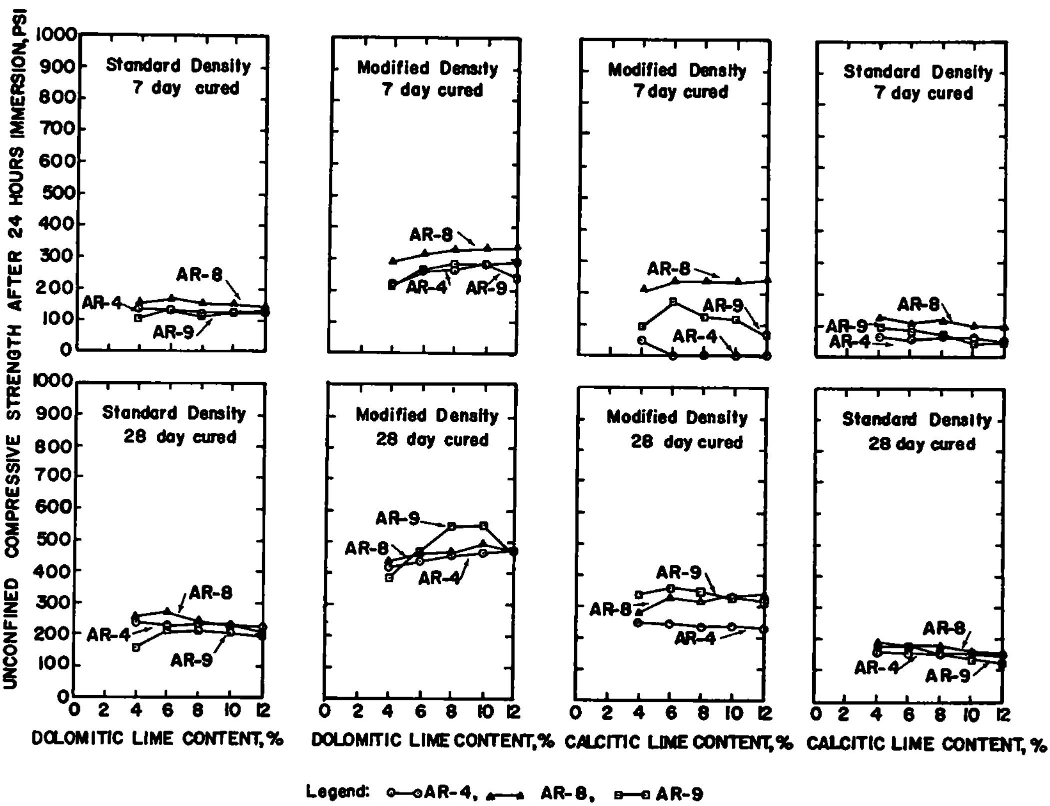

Figure 3. Immersed strength versus lime content relationships after 7-and 28-day curing for illite clay soils AR-4, AR-8 and AR-9, showing relative effects of Standard and Modified AASHO density compaction, and of dolomitic monohydrate Type N lime D and calcitic hydrated limes.

At the time of testing, specimens were removed from the curing room, unwrapped, immersed in distilled water for 24 hr ± 1 hr, and then tested to failure to determine their unconfined compressive strengths. Three identical specimens of each mixture were always tested, and strengths reported are generally the average of three specimens. If the strength of one specimen of a set fell out of the range of 10 percent of the average strength ± 3 psi, the other two samples supplied the average.

EXPERIMENTAL WORK PROCEDURES

Preliminary Study

A series of moisture-density and moisture-strength relationship tests were conducted on mixtures of each soil and 4, 8 and 12 percent of each lime, to evaluate and compare the optimum moisture contents for maximum dry density and maximum strength. These relationships were established for each compactive energy and each mixture by molding five sets of specimens at different determined moisture contents; each set contained three specimens. After being weighed and measured each specimen was moist cured for 7 days, immersed in water for 24 hr, and then tested for strength.

Graphs of dry density versus molding moisture content and of strength versus molding moisture content were plotted. A smooth curve was drawn connecting plotted points and the optimum moisture contents were extracted from the graphs. Optimum moisture contents of 6 and 10 percent lime mixtures were determined by straight-line interpolations.

Although the optimum moisture contents for maximum dry density and maximum

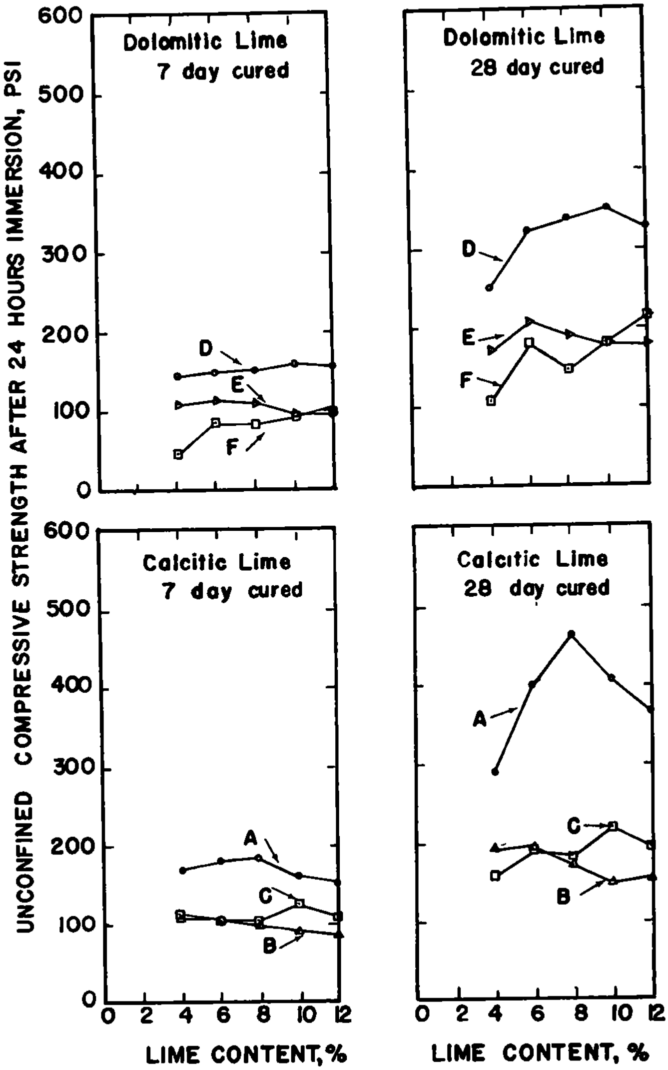

Figure 4. Immersed strength versus lime content relationships after 7- and 28-day curing for illite clay soil AR-8 and Standard AASHO density compaction, showing relative effects of three dolomitic monohydrate Type N limes and three calcitic hydrated limes.

strength were not always identical for each mixture studied, in the majority of cases they were nearly the same, and it seemed permissible and best to use optimum moisture content for maximum dry density as the molding moisture content for the mixtures evaluated in the study of strength versus lime content. This decision applied to the preparation of specimens at both Standard and Modified densities.

With few exceptions, the soils molded with Standard AASHO density compaction had their optimum moisture content for maximum dry density increased 1.7 to 6.8 percent by the lime treatments and their maximum dry density lowered 2.5 to 17.4 pcf. With the same lime treatments, but with Modified AASHO density compaction, the optimum moisture content for maximum dry density increased 0.5 to 3.4 percent and maximum dry density decreased 3.7 to 11.9 pcf.

The kind of lime used had a significant effect on the optimum moisture contents for maximum dry density and maximum strength. For treatments of a soil with equal amounts of different limes, the deviations among optimum moisture contents often exceeded 2 percent. Generally, however, the influence of kind of lime on the optimum moisture contents was least for mixtures at Modified density. Except with one soil, AR-6 at Modified density, dolomitic limes produced higher maximum dry densities than calcitic limes.

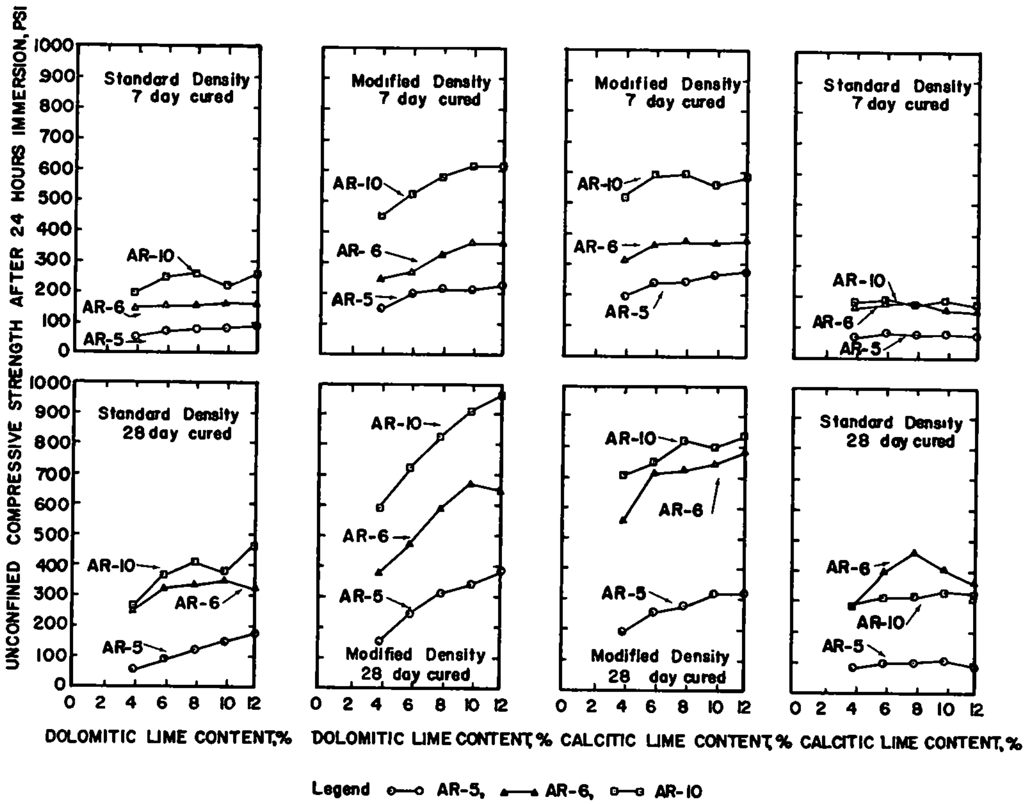

Figure 5. Immersed strength versus lime content relationships after 7- and 28-day curing for kaolinite clay soils AR-5, AR-6 and AR-10, showing relative effects of Standard and Modified AASHO density compaction, and of dolomitic monohydrate Type N lime D and calcitic hydrated limes.

Strength Versus Lime Content

Specimens of the nine soils were molded at 4, 6, 8, 10, and 12 percent lime, by dry weight of soil used, with calcitic lime A and Type N dolomitic limes. The mixtures were molded at densities near Standard and Modified AASHO densities.

Six specimens at each density were molded from each mixture. The moisture content used was the optimum moisture content for maximum dry density for the particular soil, lime content, type lime, and compactive effort used, as determined by the preliminary study. Moisture content samples were taken at the conclusion of mixing of each batch and again after the last specimen of the batch was molded. The average moisture content for the two samples taken was required to be within plus or minus 1 percent of the optimum moisture content specified. Specimens 1, 3, and 5 of each set were cured 7 days and specimens 2, 4 and 6 were cured 28 days.

After curing and immersion the samples were tested. Using average strength values for each three-specimen set, curves were constructed depicting strength versus lime content for each soil at the additional parameters of type of lime and compactive effort.

As a check to insure strengths obtained were indicative of type of lime used and not of one special lime, four other limes were used, two calcitic and two Type N dolomitic, with selected soils: montmorillonite clay soil, AR-2; illite clay soil, AR-8; and kaolinite clay soil, AR-6, were used. Mixtures were molded to near Standard AASHO density. Relative values obtained in this study could then be compared to those obtained in the main study. Using average strength values for each three-specimen set, curves were constructed depicting strength versus lime content for each lime at the additional parameter of soil type.

RESULTS

Montmorillonite Clay Soils

At both Standard and Modified AASHO density, 7- and 28-day cured unconfined compressive strengths of the three montmorillonite clay soils (AR-2, AR-3, AR-7) at lime contents at or greater than 6 percent were significantly higher for dolomitic lime D than for calcitic lime A; 150 to 250 psi higher at Standard density, and 150 to 300 psi higher at Modified density (Fig. 1). Mixtures of soil AR-2 and each of different limes, two dolomitic and two calcitic, also showed that dolomitic lime gives highest strengths (Fig. 2).

Soil-lime mixtures compacted at Modified density attained much higher strengths than when compacted at Standard density; for example, 200 to 350 psi higher for dolomitic lime mixtures and 200 to 250 psi higher for calcitic lime mixtures (Fig. 1).

There is probably an optimum lime content for maximum strength which varies for each soil (4, 5). If optimum lime content is taken to imply a strength maximum or a greatly decreased rate of strength gain with increasing lime content, Figure 1 indicates the optimum dolomitic lime content for maximum strength is at or more than 6 percent, whereas the optimum calcitic lime content is at or probably less than 4 percent.

Illite Clay Soils

At Standard density lime-treated illite clay soils (AR-R—illite-chlorite clay fraction, AR-8, AR-9) did not develop high strengths, at best only between 100 and 300 psi after 28 days of curing (Fig. 1). However, at lime contents above 6 percent, dolomitic lime gave higher strengths than calcitic lime. At Modified density, the illite clay soils did show significant strength improvements with dolomitic lime in relation to calcitic lime, with strength differences ranging from 150 to 200 psi. A comparison (Fig. 4) of strengths developed by mixtures of soil AR-8 and each of four limes, compacted at Standard density, also shows that dolomitic lime gives higher strengths than calcitic lime, particularly after 28 days of curing.

Strengths at Modified density were 150 to 250 psi higher than at Standard density for all mixtures except soil AR-4 and calcitic lime (Fig. 3). Mixtures of soil AR-4 and calcitic lime at Modified density tended to slake during immersion.

All strength versus lime content curves (Fig. 3), except for soil AR-9 and dolomitic lime, show slight or negative slopes above 6 percent lime, signifying that the optimum lime content of illite clay soils may be at or below 6 percent. Soil AR-9 with dolomitic lime had an optimum lime content of 8 percent, the higher lime requirement for maximum strength could be expected because, of the three illite clay soils used, soil AR-9 contained by far the highest percentage of clay-size material (Table 2).

Kaolinite Clay Soils

At both Standard and Modified density, the maximum strengths obtained with kaolinite clay soils AR-5 (clay mineral was predominately halloysite, kaolinite subgroup mineral) and AR-10 were at most only 130 psi higher with dolomitic lime than with calcitic lime (Fig. 5), and at lime contents of 6 to 8 percent, both limes A and D gave about equal strengths. With soil AR-6, calcitic lime A produced somewhat higher strengths than dolomitic lime D, especially in mixtures cured 28 days (Fig. 5). However, the other calcitic and dolomitic limes (Fig. 6) gave about the same strengths in mixtures with soil AR-6.

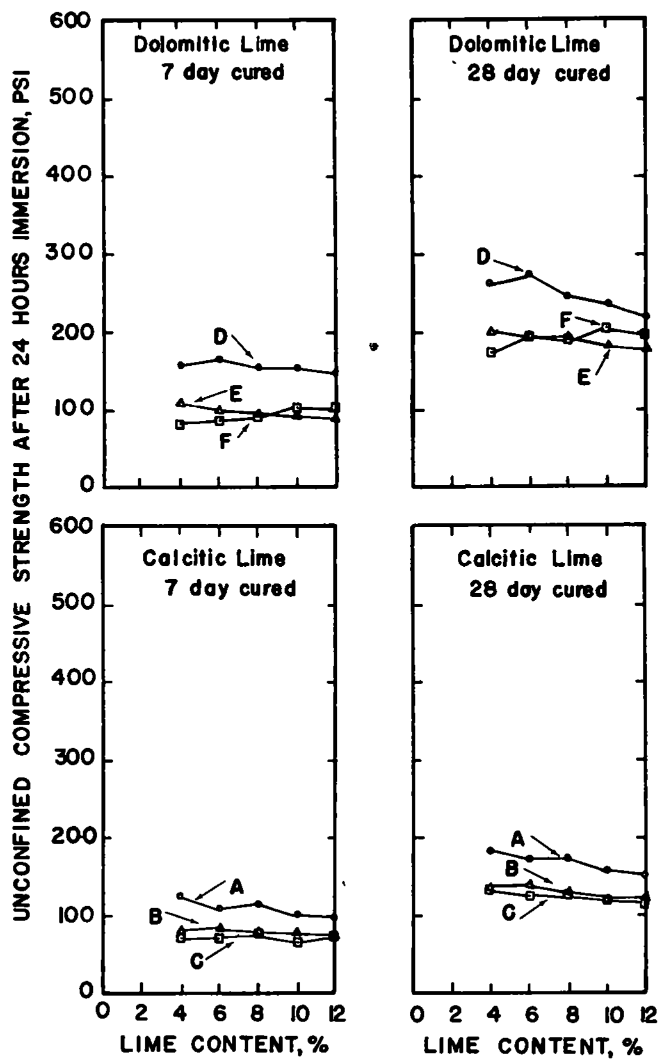

Figure 6. Immersed strength versus lime content relationships after 7- and 28-day curing for kaolinite clay soil AR-6 and Standard AASHO density compaction, showing relative effects of three dolomitic monohydrate Type N limes and three calcitic hydrated limes.

Strengths of all mixtures were significantly improved, 100 to 300 psi, by the use of Modified density compaction instead of Standard.

In general the optimum lime content for the soils was greater with dolomitic lime than with calcitic lime.

CONCLUSIONS

1. In mixtures with the montmorillonite and illite clay soils dolomitic monohydrate Type N lime produces higher immersed strengths than calcitic hydrated lime; more specifically: (a) the montmorillonite clay soils show strengths 130 to 250 psi higher at near Standard AASHO density and 150 to 300 psi higher at near Modified AASHO density, and (b) the illite clay soils show strengths 40 to 90 psi higher at near Standard AASHO density and 150 to 200 psi higher at near Modified AASHO density.

2. Neither dolomitic monohydrate Type N lime nor calcitic hydrated lime consistently produce the highest strengths in kaolinite clay soil-lime mixtures. Dolomitic lime produces the highest strengths in two of the three soils tested, and calcitic lime produces the highest strengths in the third.

3. With all soil-lime mixtures studied, Modified AASHO density compaction gives immersed strengths 100 to 350 psi higher than Standard AASHO density compaction; except for soil AR-2, strengths greater than 500 psi could be obtained only by use of Modified AASHO density compaction.

4. Optimum lime contents for maximum immersed strength are generally higher when using dolomitic monohydrate Type N lime than when using calcitic hydrated lime.

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REFERENCES

1. AASHO, "Standard Specifications for Highway Materials and Methods of Sampling and Testing. Part III. Additional Specification, Tests and Revisions to Parts I and II." 7th ed., Washington, D.C. (1958).
2. ASTM, "1958 Book of ASTM Standards Including Tentatives. Part 4. Cement, Concrete, Mortars, Road Materials, Water Proofing, Soils." Philadelphia, Pa. (1958).
3. Hilt, G.H., "Lime Fixation in Clayey Soils." Unpub. M.S. Thesis, Library, Iowa State University of Science and Technology (1959).
4. Lu, L.W., "Stabilization of Loess and Till in Iowa with Dolomitic and Calcitic Lime." Unpub. M.S. Thesis, Library, Iowa State Univeristy of Science and Technology (1956).
5. Lu, L.W., Davidson, D.T., Handy, R.L., Laguros, J.G., "The Calcium-Magnesium Ratio in Soil-Lime Stabilization." HRB Proc., 36:794-805 (1957).
6. Spangler, M.G., "Soil Engineering." International Textbook Co., 2nd ed. (1960).
7. Viskochil, R.K., Handy, R.L., and Davidson, D.T., "Effect of Density on Strength of Lime-Fly Ash Stabilized Soil." HRB Bull. 183:5-15 (1957).
8. Davidson, D.T., and Bruns, B.W., "Comparison of Type I and Type III Portland Cement for Soil Stabilization." HRB Bull. 267:28-45 (1960).