Recent Soil-Lime Research at the Massachusetts Institute of Technology

C.C. LADD, Z.C. MOH, and T.W. LAMBE, Respectively,
Instructor, Soil Engineering Division, Civil Engineering Department, M.I.T.; Formerly Research Assistant, M.I.T. Soil Stabilization Laboratory, now with Woodward, Clyde, Sherard and Associates, Omaha, Neb.; and Professor and Head of Soil Engineering Division, M.I.T.

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.

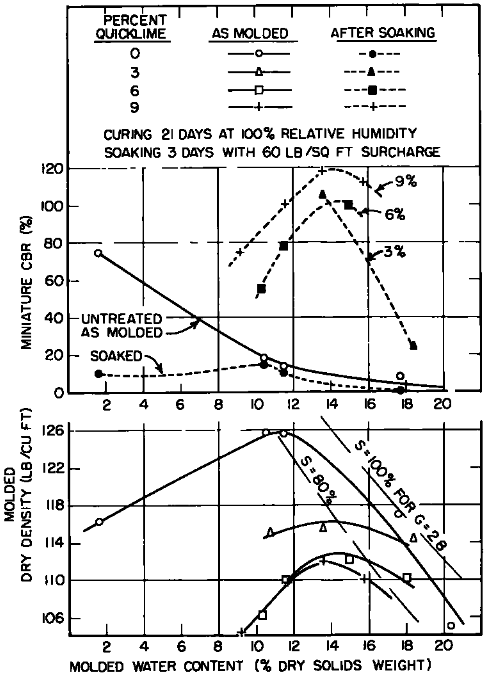

Figure 1. Effect of quicklime on compaction and strength characteristics of a clayey sand.

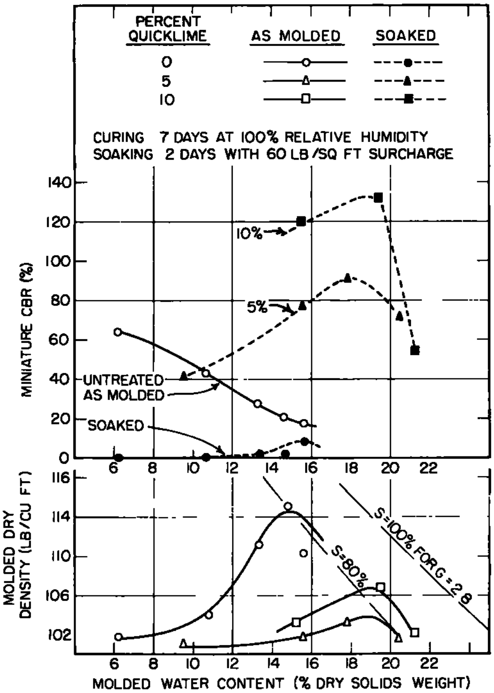

Figure 2. Effect of quicklime on compaction and strength characteristics of a lean clay.

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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

Description and Location of Soil	Atterberg Limits (%)[1] Liquid	Plastic	Plasticity Index	Grain Size (% Passing) 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

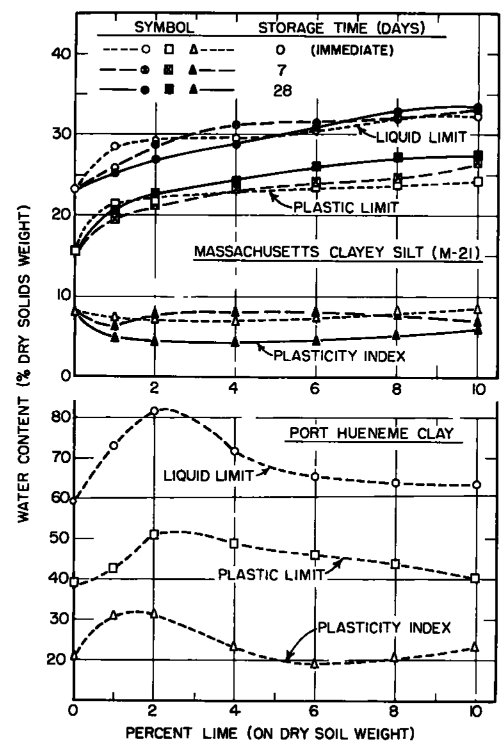

Figure 3. Effect of lime on Atterberg limits of two soils.

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:

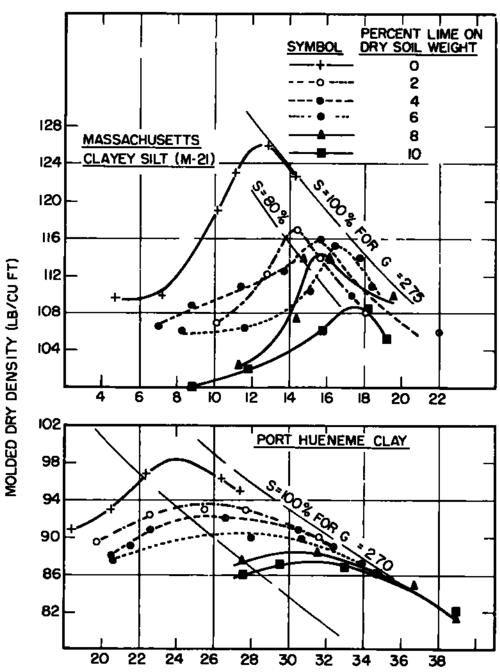

Figure 4. Effect of lime on compaction characteristics of two soils.

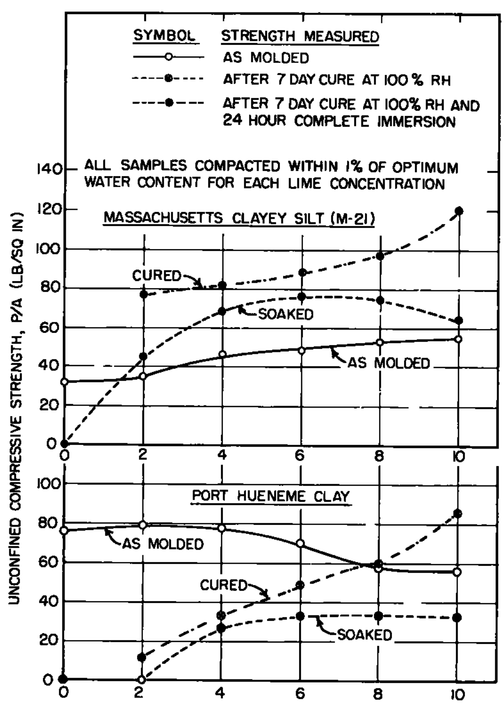

Figure 5. Effect of lime on compressive strength of two soils.

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	Erosion Loss (%)[1] As-Molded	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	1	16.2	116.0	45	15.7	117.4	60	145	210
silt	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	3	38	82	25	36	84	40	80	170
clay	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.

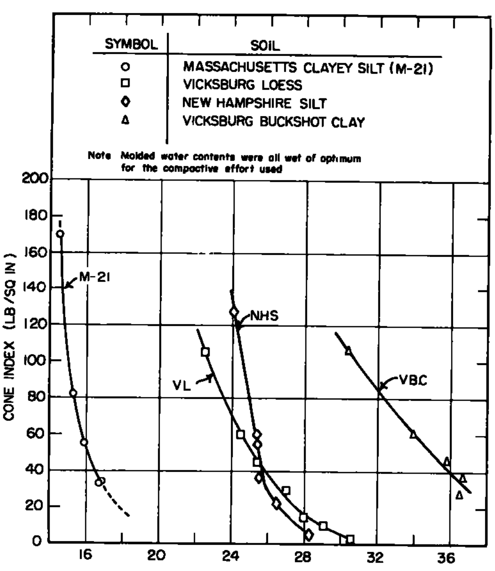

Figure 6. Molded water content vs cone index for soils used in category 1 stabilization.

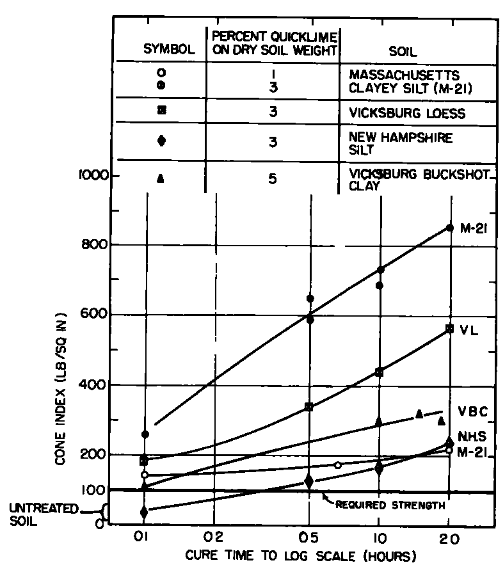

Figure 7. Effects of quicklime on the strength vs time characteristics of four soils—category 1 stabilization.

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

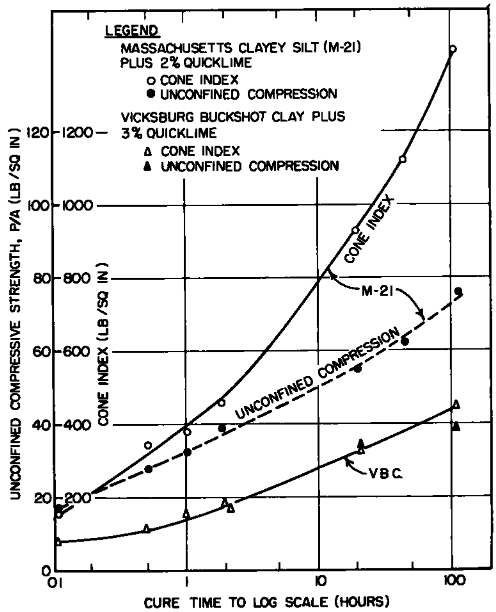

Figure 8. Effect of longer cure time on strength of two soils treated with quicklime.

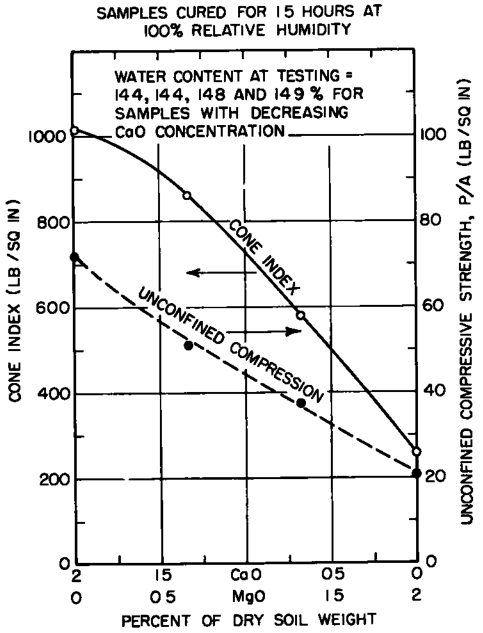

Figure 9. Effect of calcium to magnesium oxide ratio on strength of Massachusetts clayey silt—category 1 stabilization.

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.

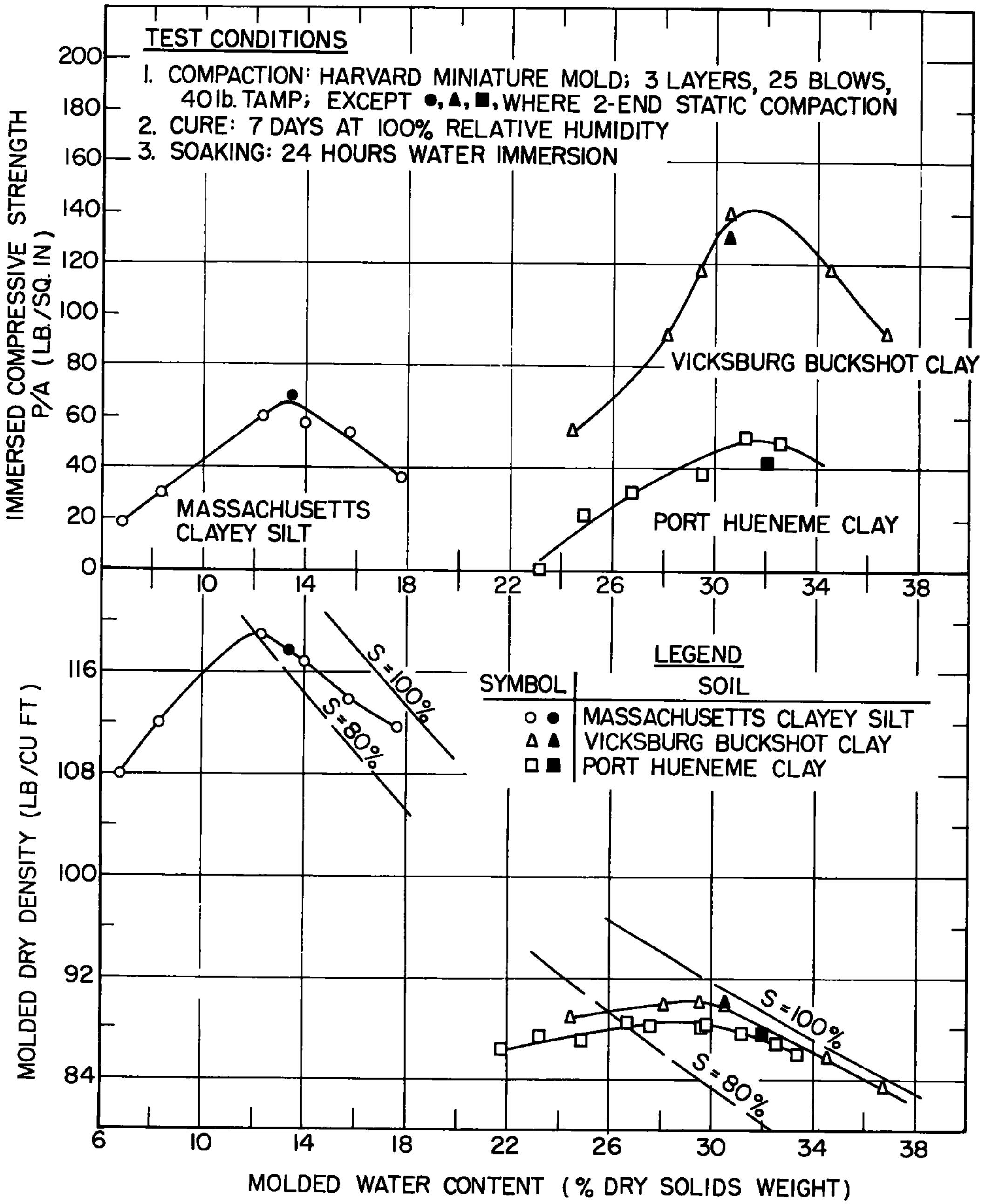

Figure 10. Effect of molded water content and density on the soaked strength of Massachusetts clayey silt, Vicksburg buckshot clay and Port Hueneme clay stabilized with 5 percent hydrated lime.

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

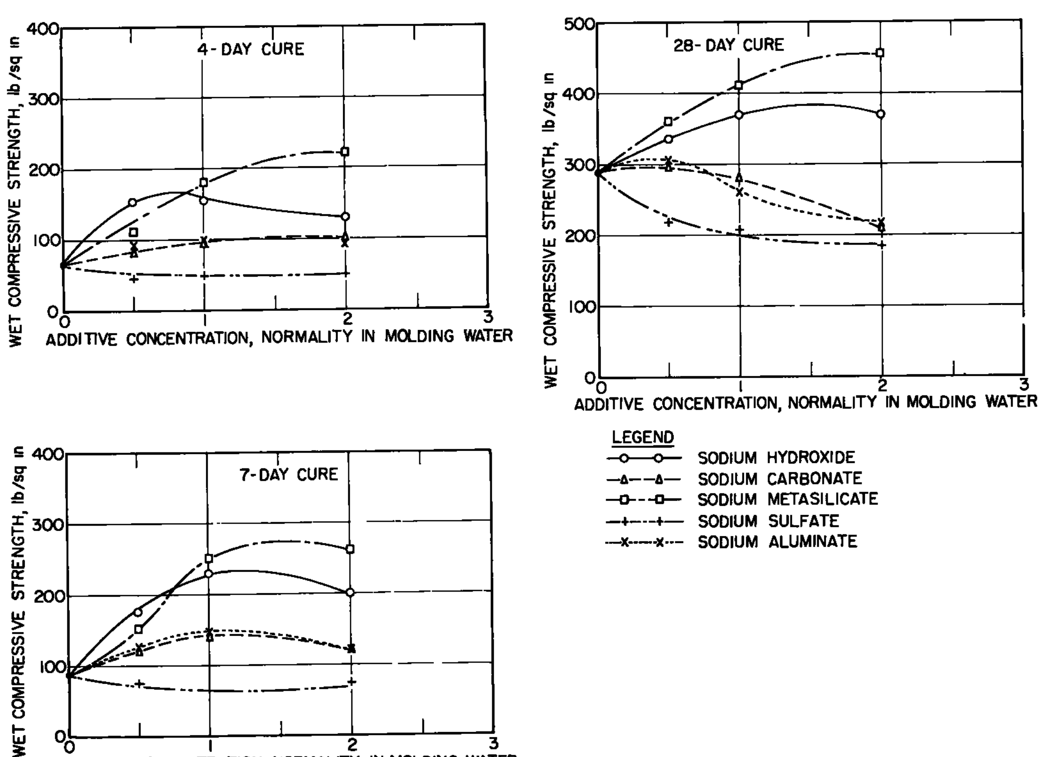

Figure 11. Effect of additive type and concentration on the strength of quartz stabilized with 10 percent calcium hydroxide.

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.

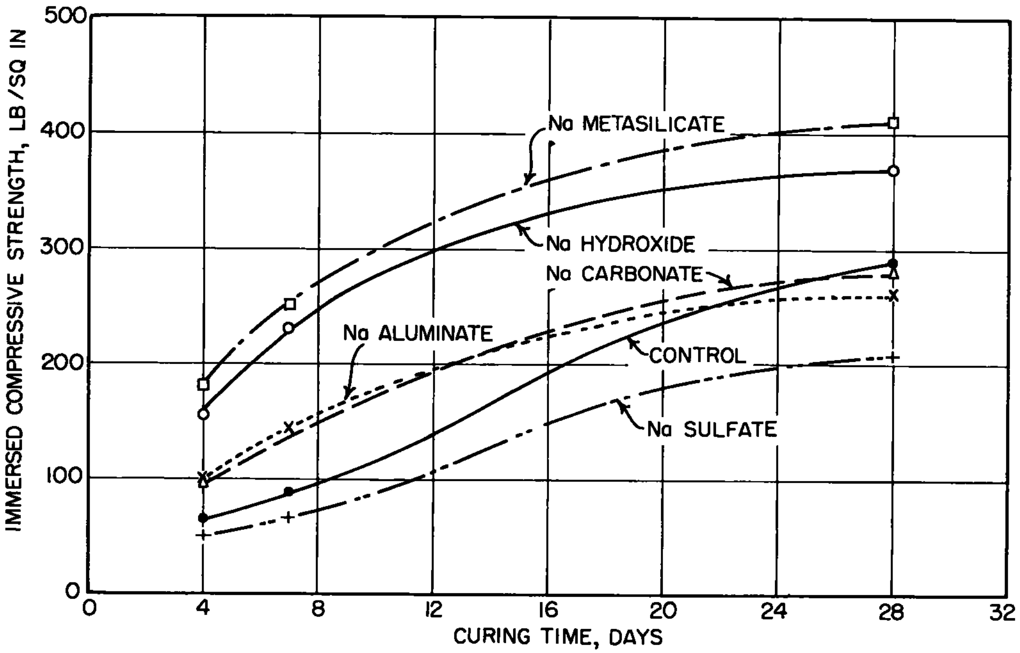

Figure 12. Effect of type of additive (at one normal concentration) on strength development of quartz stabilized with 10 percent calcium hydroxide.

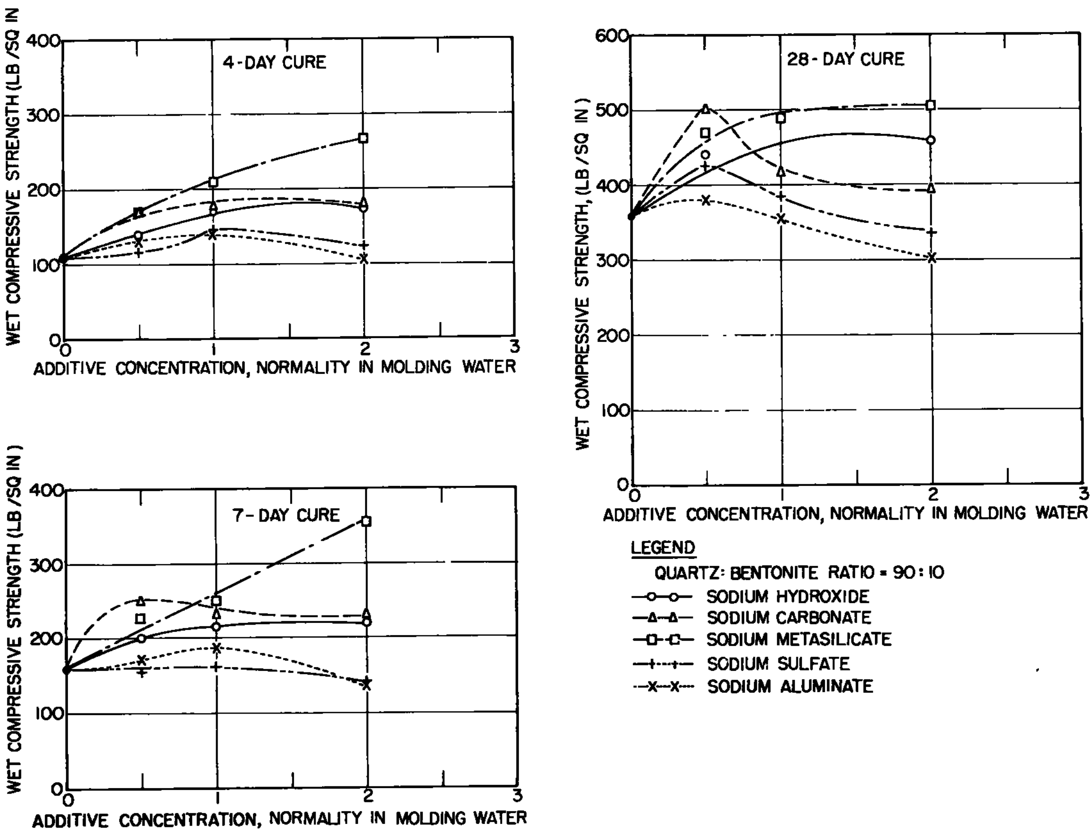

Figure 13. Effect of additive type and concentration on the strength of quartz-bentonite stabilized with 10 percent calcium hydroxide.

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.

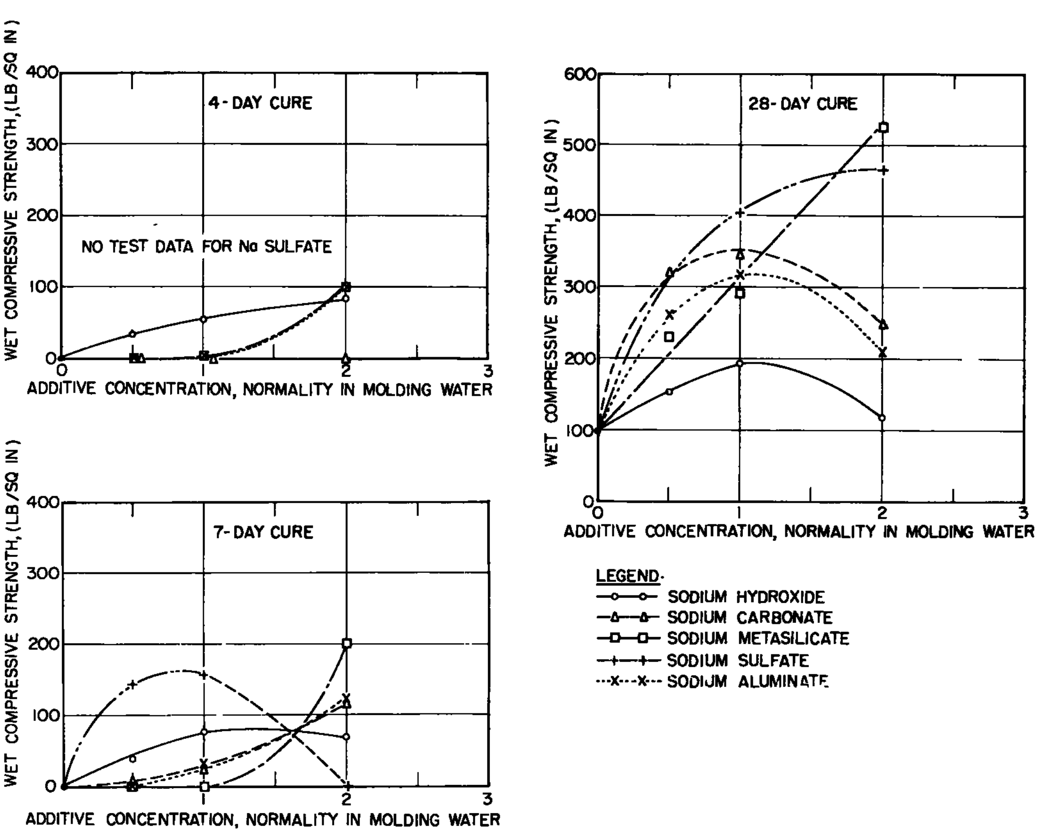

Figure 14. Effect of additive type and concentration on the strength of kaolinite stabilized with 10 percent calcium hydroxide.

(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	Additive Concentration: Normality[1]	Additive Concentration: Percent[2]	At Molding: Water Content (%)	At Molding: Dry Density (pcf)	Curing Time (Days)	After Curing: Water Content (%)	After Curing: Dry Density (pcf)	After Immersion: Water Content (%)	After Immersion: 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

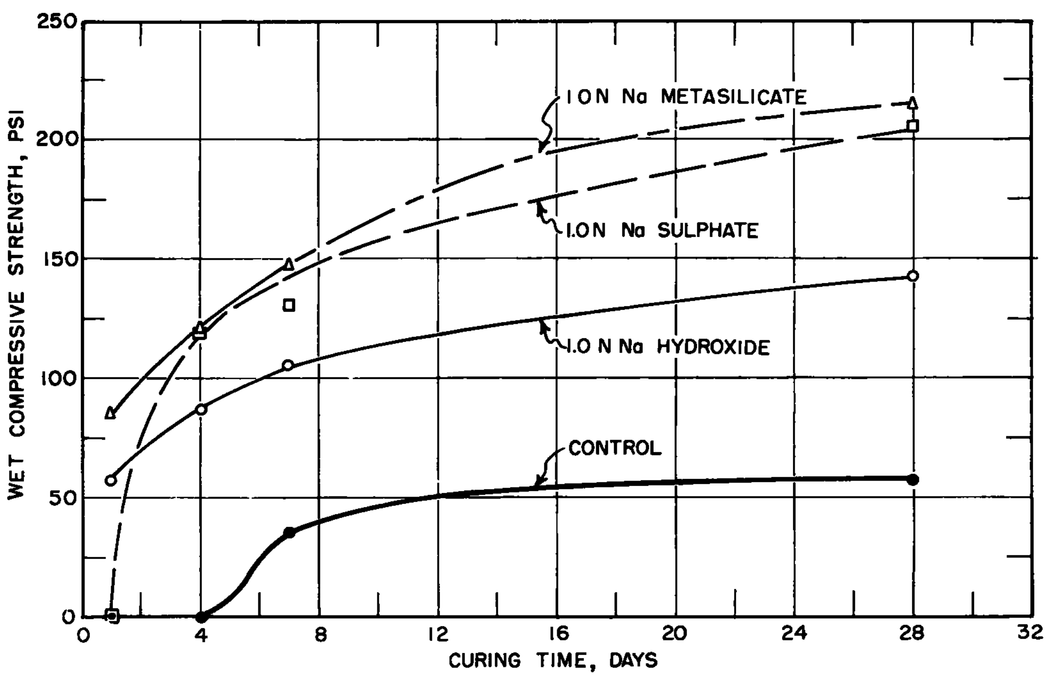

Figure 15. Effect of three sodium compounds on the strength development of New Hampshire silt stabilized with 10 percent hydrated lime.

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.

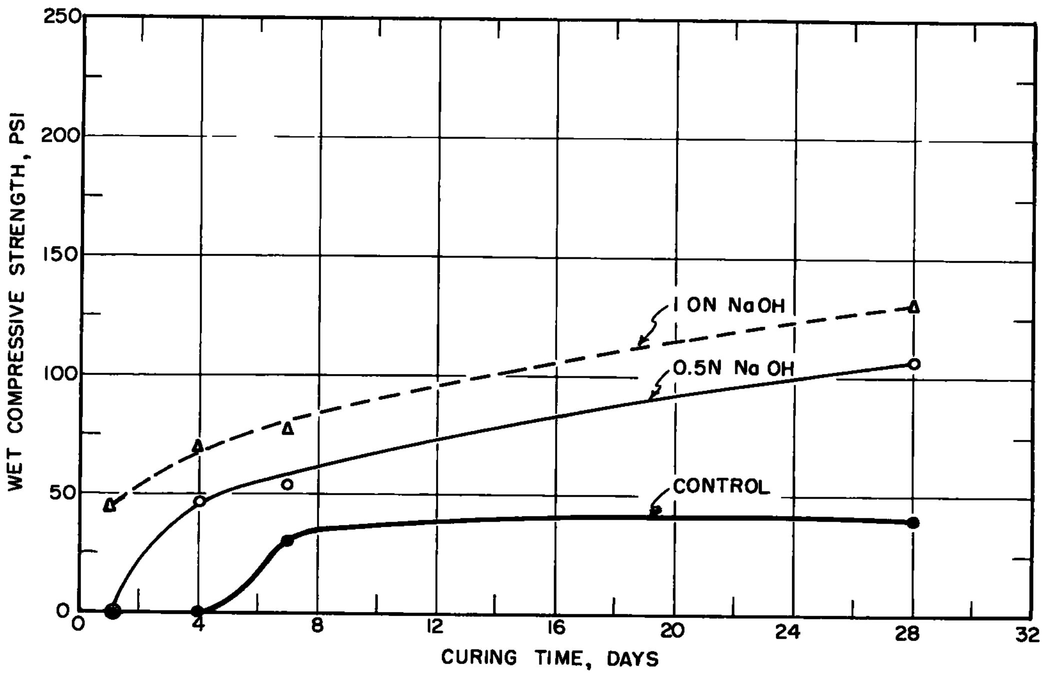

Figure. 16. Effect of sodium hydroxide on the strength development of New Hampshire silt stabilized with 5 percent hydrated lime.

TABLE 8

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

		After 7 Days Cure[2] and 1 Day Immersion			After 28 Days Cure[2] and 1 Day Immersion		
Soil	Percent Lime or $Ca(OH)_2$	Strength Increase with Best Additive (psi)	Strength Ratio Treated to Untreated Sample	Concentration[3] and Type of Best Sodium Additive	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	$\frac{200}{0}$ = ∞	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.

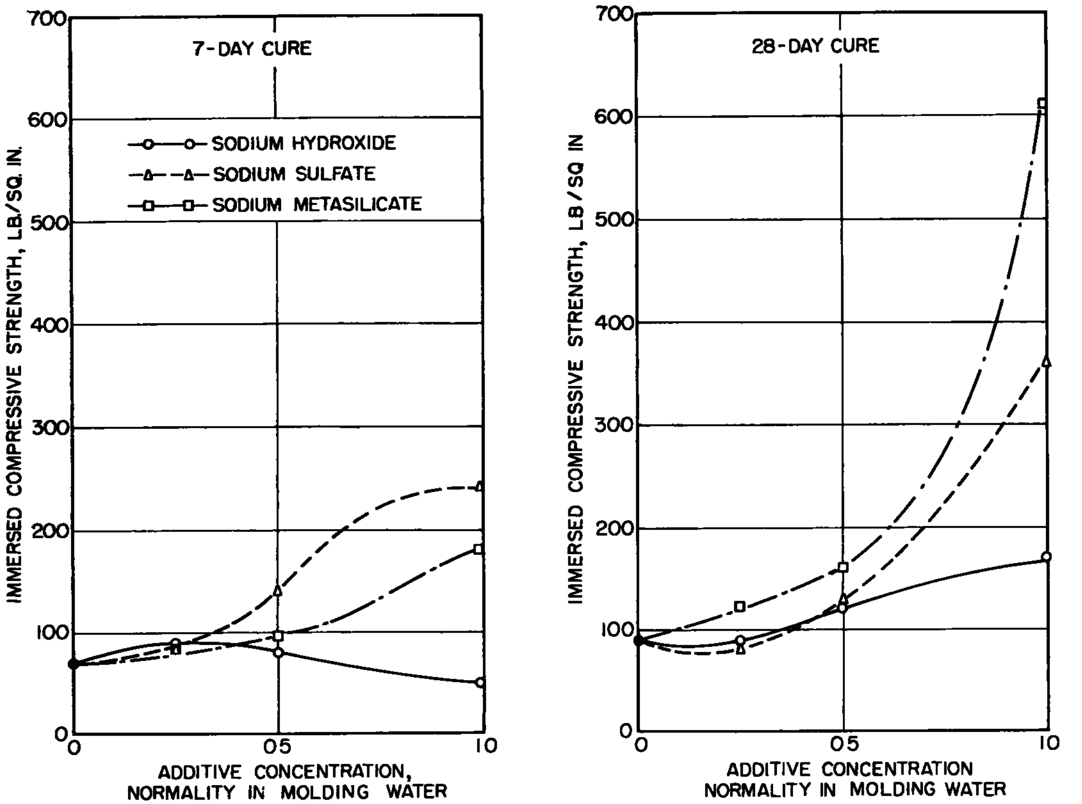

Figure 17. Effect of three sodium compounds on the strength of Massachusetts clayey silt stabilized with 5 percent hydrated lime.

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.

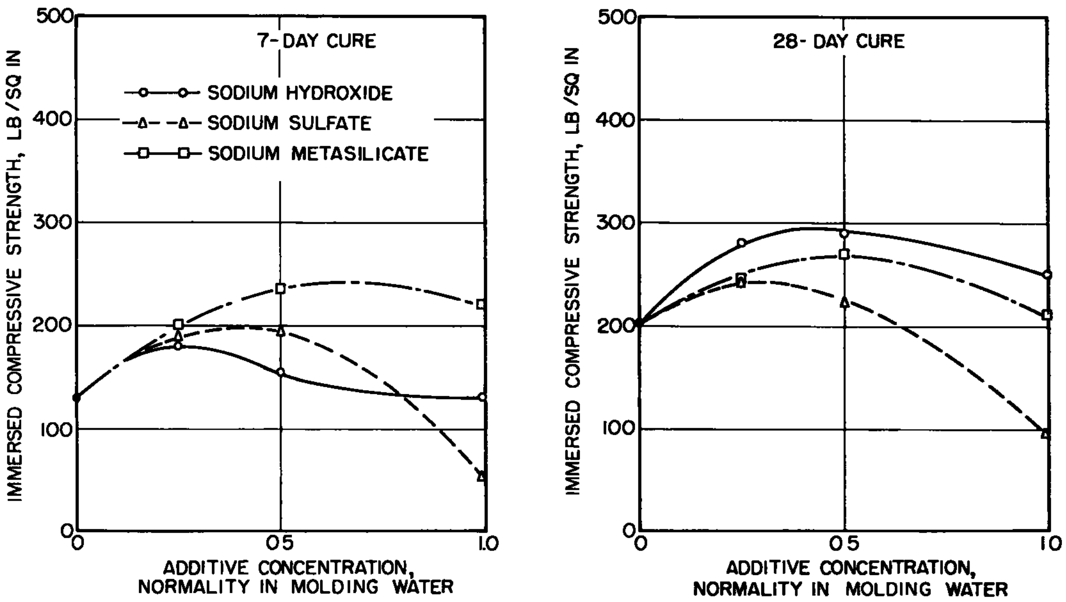

Figure 18. Effect of three sodium compounds on the strength of Vicksburg buckshot clay stabilized with 5 percent hydrated lime.

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:

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

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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