

Improvement of Soil-Cement with Alkali Metal Compounds

T. W. LAMBE, Director;

A. S. MICHAELS, Associate Director; and

Z. C. MOH, Research Assistant;

Soil Stabilization Laboratory, Massachusetts Institute of Technology,
Cambridge, Mass.

A large number of soils of widely differing geographical origin, fineness and mineralogical composition have been tested to determine their response to stabilization by portland cement in the presence and absence of a selected group of alkali metal compounds at low concentration. The tests showed that, with virtually all soils studied, cement-stabilization (as measured by soaked compressive strength after varying periods of humid cure) can be substantially improved (2- to 10-fold) by the incorporation of relatively small quantities of sodium compounds which form insoluble compounds with calcium. The most beneficial additives are caustic soda, soda ash, sodium sulfite, sodium sulfate, sodium metasilicate, and sodium aluminate. Lithium and potassium compounds act similarly but less effectively. Optimum additive concentration is found to correspond very nearly to a sodium ion concentration in the molding water of 1.0 N; that is, between 0.5 and 2.5 percent by weight, depending on soil and additive.

Caustic soda is found to be the most beneficial additive in heavy clay soils, sodium metasilicate in clean sands, and sodium aluminate and sodium sulfate in silts. Sodium sulfate appears to be uniquely effective in organic sands. Use of these additives not only permits more economical stabilization of soils responsive to cement, but also allows successful stabilization of soils which normally cannot be stabilized with cement at economic levels.

An hypothesis to explain the action of these additives is proposed. Although the formulations developed must await extensive durability tests to establish their field serviceability, current results indicate that chemically modified soil-cement offers considerable promise as a low-cost soil stabilization method.

● DURING THE past few years, the M.I.T. Soil Stabilization Laboratory has been conducting research on improving the properties of soil-cement by the use of chemical additives. An earlier paper (Lambe and Moh, 1957) described the initial phases of the research. The primary objectives of the investigation are:

1. To increase the effectiveness of portland cement as a soil stabilizer, so as to reduce the quantity of cement required to treat responsive soils.

2. To find trace additives which will enhance the effectiveness of cement as a stabilizer of problem soils which cannot be stabilized with cement alone at economic levels.

3. To elucidate the mechanisms by which chemical additives alter the soil-cement reaction.

In the initial study, some 40 chemicals were first screened as additives to three silty soils; that is, New Hampshire silt, Massachusetts clayey silt, and Vicksburg loess. Significant improvements in the compressive strength of soil-cement were obtained from the addition of selected chemicals at low concentrations (0.5 to 1.0 percent on dry soil weight). The most effective additives were a group of sodium compounds; specifically, the hydroxide, carbonate, sulfite, and metasilicate.

The apparently unique effectiveness of alkali metal compounds provided a useful point of departure for the selection of additives of even greater effectiveness. This paper describes the most recent laboratory studies of the effect of a selected group of alkali metal compounds on cement stabilization of a number of soils. Compressive strengths were used as criteria for evaluation. Investigation of the effect of additives on the durability of soil-cement is under way with the cooperation of the Soil-Cement Bureau of Portland Cement Association.

MATERIALS AND PROCEDURE

Materials

Soils.—Eleven soils, varying from sands to heavy clays, some of them having a significant amount of organic matter, were employed in this investigation.

Three soils, a well-graded clayey silt from Massachusetts (MCS), a uniform loess from Vicksburg, Mississippi (VL), and a uniform silt from New Hampshire (NHS) were used in screening tests. New Hampshire silt was then adopted as the primary soil in this part of the study, in view of its less complex composition and its established marked response to cement treatment.

Three soils, designated as Illinois clay (1055), Wisconsin sand 1 (1056) and Wisconsin sand 2 (1057), provided by the Portland Cement Association, were included in the study. Illinois clay was from Champaign County, Ill., a B horizon material of Illinois Soil Series No. 1126. The two Wisconsin sands were A and B horizon materials of the Plainfield Series, Racine County, Wis. About 15 percent or more of cement is ordinarily required for adequate stabilization of these soils. The two heavy-textured soils studied were from the Gulf Coast of Texas, Texas clay 1 and 2 (MIT 1058 and 1059), and contain a relatively high concentration of organic matter (about 3 percent).

In addition, three soils rich in carbonate content were also studied. These soils, designated as Iraq clay 1 (IrCl), Iraq clay 2 (IrC2), and Iraq silty clay (IrSC) (MIT 1052, 1067, and 1068, respectively), were provided by the government of Iraq for study of the feasibility of using soil stabilizers in its road construction program.

The characteristics of all 11 soils are summarized in Table 1. Figure 1 shows the grain size distribution curves.

Cement.—Type I portland cement was used; Table 2 summarizes its prop-

TABLE 1
PROPERTIES OF SOILS INVESTIGATED

Properties	Soils									
	New Hamp.	Mass. Clayey	Vicksburg	Wis. Sand	Wis. Sand	Illinois	Texas Clay	Texas Clay	Iraq Clay	Iraq Clay
	Silt	Silt	Loess	1	2	Clay	1	2	1	2
	NHS	MCS	VL	WS1	WS2	IC	TC1	TC2	IrCl	IrCl
	NHS	M21	VL	1,056	1,057	1,055	1,058	1,059	1,052	1,067
Textural composition ^a , % by wt										
Sand 0.06 mm to 2 mm	3	47	6	82	85	12	5	3	0	17
Silt 0.002 mm to 0.06 mm	90	42	73	18	15	52	45	28	42	62
Clay < 0.002 mm	7	11	21	0	0	36	50	69	58	25
Physical properties										
Liquid limit, %	28	20	41	—	—	51	62	71	61	39
Plastic limit, %	20	14	26	—	—	23	28	42	28	20
Elasticity index, %	8	6	15	N.P.	N.P.	28	34	29	33	19
Specific gravity, 20 °C/20 °C	2.72	2.77	2.67	2.64	2.64	2.67	2.69	2.71	2.76	2.72
Max dry density ^b , pcf	99.5	122.3	104.5	102	103	100	98	94	97.6	106.3
Opt water content ^b , %	19.9	13.3	18.5	14.2	12.5	20.9	23.0	25.8	24.0	19.5
Classification										
Unified	ML	ML	ML-CL	SM	SM	CH	CH	CH	CH	CL
BR	Silty loam	Loam	Silty clay loam	Sand	Sand	Clay	Clay	Clay	Clay	Clay
HRB	A-4(8)	A-4(4)	A-7-6(10)	A-2-4	A-2-4	A-7-6(17)	A-7-6(20)	A-7-5(20)	A-7-6(20)	A-6(12)
Chemical properties ^c :										
Organic matter, % by wt	0.4	—	1.8	1.9	0.2	1.3	3.1	2.9	1.0	0.9
pH	5.4	—	4.6	6.7	6.2	6.4	7.4	7.3	7.5	7.5
Carbonates, % by wt	—	—	—	—	—	—	—	—	25	27
Total soluble salts, m eq NaCl/100 gm	—	—	0.2	0.1	0.1	0.2	0.6	1.6	15.3	1.7
Soluble sulfates, m eq NaCl/100 gm	—	—	—	—	—	—	—	—	3.9	0.4
Cation exchange capacity, m eq/100 gm	3	—	16	16	10	30	—	27	23	20
Glycol retention, mg/gm	6	22	33	32	24	70	69	93	62	45
Mineralogical composition										
Clay composition, % by wt	10	30	35	0	0	45	— ^d	65	60	45
Illite: montmorillonoid:										
Clay chlorite	1:0:0	1:0:0	1:1:0	—	—	1:2.5:1	—	3:2.5:1	1:1:1	1:1:1
Chlorite, nonclay, %	—	—	—	—	—	—	—	—	10	15
Calcite, %	—	—	—	—	—	—	—	—	25	30
Free iron oxide, %Fe ₂ O ₃	1.0	2.9	1.6	—	—	1.7	—	2.0	1.6	1.0
Gypsum, %	0	—	—	—	—	—	—	—	0.6	0.1

^aM.I.T. Classification System.

^bHarvard Miniature Compaction, 40 lb tamper, 3 layers, 25 blows per layer.

^cFor -0.074 mm fractions.

^dMineralogical composition of Soil Texas Clay 1 is similar to that of Texas Clay 2.

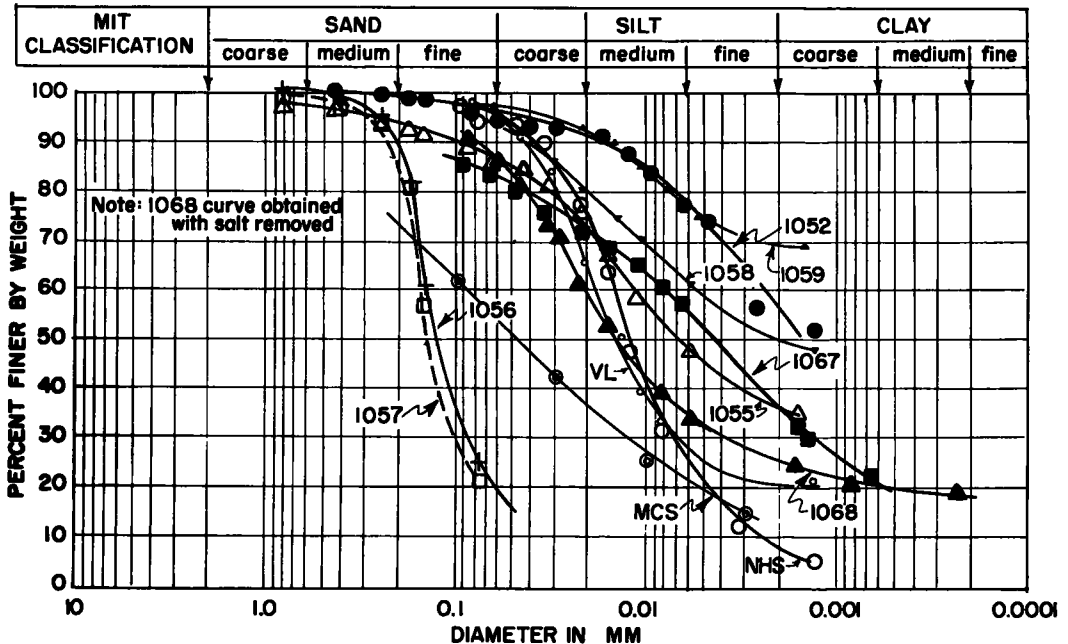


Figure 1. Grain size distribution.

erties. In order to obtain full benefit of the additives, a relatively low cement concentration (5 percent on dry soil weight) was used for most of the experiments.

TABLE 2
COMPOSITION^a OF CEMENT USED

Composition	% by Weight
Silica, SiO ₂	19.78
Aluminum oxide, Al ₂ O ₃	5.54
Ferric oxide, Fe ₂ O ₃	3.45
Calcium oxide, CaO	62.59
Magnesium oxide, MgO	3.90
Sulfuric anhydride, SO ₃	2.25
Sodium oxide Na ₂ O	0.25
Potassium Oxide, K ₂ O	0.71
Manganese oxide, Mn ₂ O ₃	0.07
Insoluble residue	1.30
Loss on ignition	0.08
Specific surface (Blaine)	3,270 sq cm/gm

^aAnalyzed by Analytical Laboratories, Portland Cement Association.

Additives.—Table 3 lists the alkali metal compounds investigated. Selection was based on the observation from earlier studies that alkali metal compounds beneficial to cement stabilization were those forming insoluble salts with calcium. Additive concentrations are expressed either as normally of the alkali ion in the molding water, or as the percent by dry soil weight.

TABLE 3
CHEMICAL ADDITIVES TESTED

Material	Formula	Source
Sodium hydroxide	NaOH	Reagent grade
Sodium carbonate	Na ₂ CO ₃	Reagent grade
Sodium metasilicate	Na ₂ SiO ₃ ·9H ₂ O	Reagent grade
Sodium sulfate	Na ₂ SO ₄	Reagent grade
Sodium aluminate	NaAlO ₂	Reagent grade
Sodium fluosilicate	Na ₂ SiF ₆	Reagent grade
Sodium fluoride	NaF	Reagent grade
Sodium fluoborate	NaBF ₄	Reagent grade
Sodium tetraborate	Na ₂ B ₄ O ₇ ·10H ₂ O	Reagent grade
Potassium hydroxide	KOH	Reagent grade
Lithium hydroxide	LiOH	Reagent grade

Procedure

Preparation of Soil, Cement and Additive Mixture.—All soils were pulverized (at the water content as received in the laboratory for soils IrCl, IrC₂, and IrSC, and air dried for all other soils) through a U. S.

standard No. 10 sieve. Each batch of soil was hand-mixed with enough water to bring the moisture content to about one-half of the desired water content, and then equilibrated for 24 hr before adding the stabilizers. (This equilibration step was omitted for the two Wisconsin sands.) Cement was then mixed into the equilibrated soil, the remaining portion of water added, and mixing completed in a finger-blade mechanical mixer. (Mixing time was 7 min for the three Iraq soils, and 5 min for all others.) Chemical additives were dissolved in the second portion of water except for sodium fluosilicate, sodium fluoride, sodium fluoborate and sodium tetraborate, which were added as water slurries.

The molding water contents were those giving maximum density for compaction of unmodified soil-cement for all but the Iraq soils; for the latter, optimum water contents for compaction of the soil alone were used. All optimum water contents, and densities, were determined using the Harvard miniature compaction procedures; that is, 40-lb tamper, 3 layers, 25 blows per layer.

Molding.—All samples were compacted from both ends in a Harvard miniature size mold (1.313 in. in diameter and 2.816 in. high) by static compression with a hydraulic jack immediately after mixing. In order to eliminate the effect of density variations on the strength, each soil-cement-additive mixture was compacted to a density roughly equal to the maximum density of the untreated soil-cement or soil.

Curing.—After the specimens were molded, they were cured for various periods of time under approximate 100 percent relative humidity at room temperature. In addition to this moist-curing, a 43 percent relative humidity (samples over saturated potassium carbonate solution) cure was provided for the three Iraq soil samples.

Testing.—All cured specimens were immersed in water for one day at room temperature prior to being failed in unconfined compression. Weights and volumes of the specimens were recorded both after cure and after immersion.

RESULTS AND DISCUSSION

Influence of Soil Composition on Response to Alkaline Additives

Because the original tests showed the response of a soil to cement plus additive treatment depended on the composition of the soil in question, the results are presented and discussed under soil type, and then the influence of soil type considered.

Silty Soil (Soil NHS).—Table 4 summarizes some of the results obtained with the three silty soils; specifically, NHS, MCS, and VL, used in the screening tests.

A study of the effect of type and concentration of additive on the strength (both magnitude and rate of increase with time), was made on NHS treated with nine sodium compounds, listed as Nos. 1 to 9 in Table 3. Table 5 and Figures 2 to 7 summarize the test results.

Effect of Additive Type on Strength. Only six of the nine additives tested appear to be beneficial in increasing the strength of cement-New Hampshire silt. Sodium sulfate and sodium aluminate proved to be the best, giving strengths higher than those with 10 percent cement (no additive) at all curing times, and at all three additive concentrations studied. Sodium

TABLE 4

SUMMARY RESULTS OF EFFECT OF SODIUM COMPOUNDS ON THE COMPRESSIVE STRENGTH OF THREE CEMENT-SILTY SOILS

Cement Content = 5 Percent by Dry Soil Wt

Additive	Additive Conc. % by Dry Soil Wt	Curing Days	Wet Compressive Strength, psi		
			NHS	MCS	VL
Control	—	7	110	300	180
		28	180	375	260
Sodium hydroxide	0.5	7	165	805	345
		28	240	1,370	390
	1.0	7	260	815	340
		28	360	1,185	465
Sodium carbonate	0.5	7	345	575	260
		28	500	800	290
	1.0	7	370	895	310
		28	375	1,125	335
Sodium sulfite	0.5	7	325	320	330
		28	410	500	300
	1.0	7	260	685	305
		28	445	1,030	345
Sodium metasilicate	1.0	7	359	—	345
		28	—	—	—
Sodium sulfate	0.5	7	260	—	275
		28	400	—	—
	1.0	7	—	590	—

metasilicate proved to be the third most effective additive, giving strengths comparable to those with 10 percent cement. The hydroxide and carbonate are less effective, but still provide significant strength improvement over the control. Sodium fluoborate is the last beneficial additive, increasing the strength only slightly; the other three sodium compounds (that is, fluosilicate, fluoride and tetraborate) proved to be detrimental.

Effect of Additive Concentration on Strength. The effect of concentration of each of the six beneficial additives on the strength of cement-stabilized New Hampshire silt is shown in Table 5 and Figure 2.

The first observation to be made from this figure is that there is an optimum concentration for each additive. The optimum for all chemicals appears to be in the neighborhood of one normal (at all curing ages), except for sodium aluminate, which shows peak strength at 0.5 normal concentration.

It is significant that the dependence of strength on additive concentration (in the 0.5 - 2.0 N ranges) becomes less marked with increasing cure-time, although the strength-improvements produced by the additives become more marked with time. This implies that the ultimate increase in cementation caused by the additives is not very sensitive to additive con-

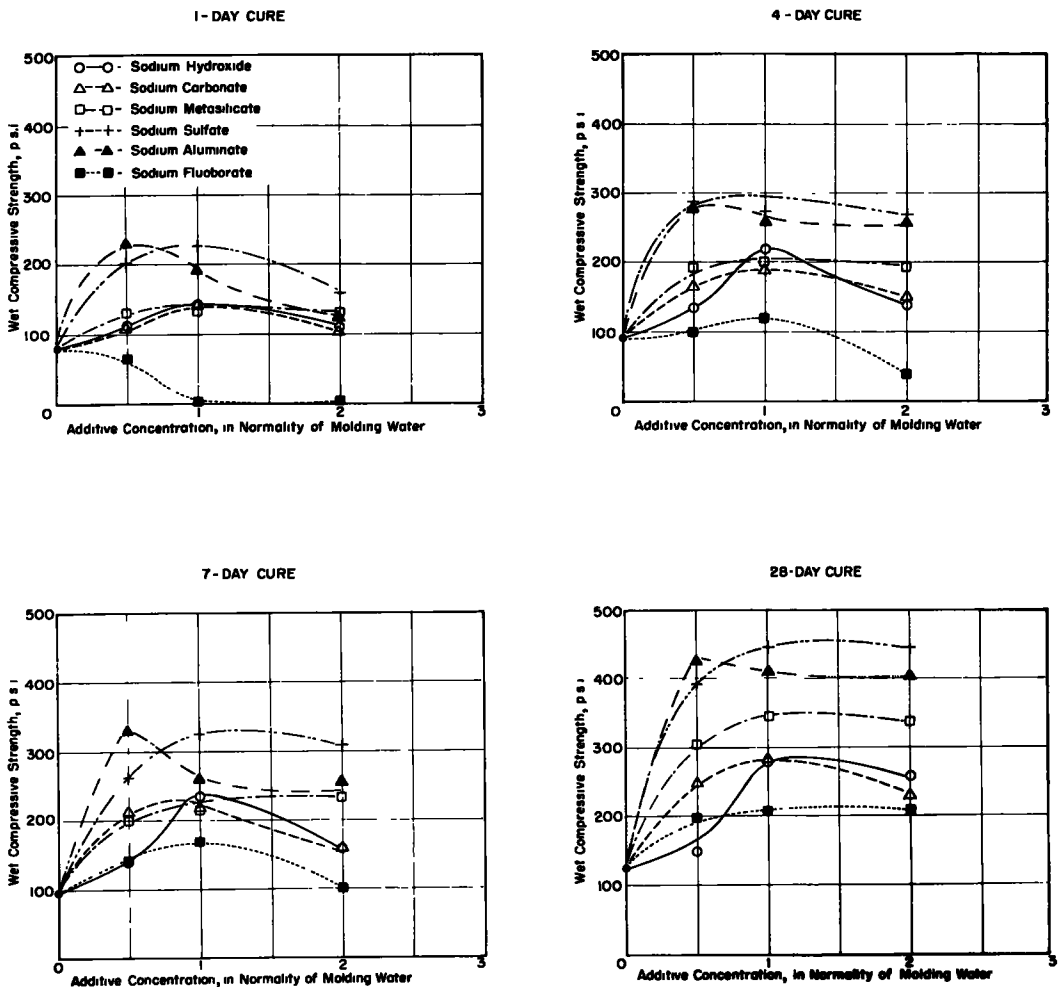


Figure 2. Effect of type and concentration of additives on the strength of New Hampshire silt stabilized with 5 percent cement.

centration above a certain minimum level, although the rate of strength build-up is quite concentration dependent.

Effect of Additive Type on Curing Rate. Figure 3 illustrates the effect of additives (at 1.0 normal in molding water) on the curing rate. The curvature of the lines between zero and one day cure is in doubt because no specific data within this time interval are available. However, Figure 7 shows the general trend in the first 24 hr of cure.

Most of the ultimate strength (the 28-day strength is considered as ultimate strength in this study) of untreated cement-NHS develops in a very short period of time (about 5 to 6 hr). Addition of sodium metasilicate or aluminate increased the early strength and accelerated the rate of curing. Sodium carbonate has a similar effect, but to a lesser degree. Considerable delay of strength development occurred with sodium sulfite and hydroxide, as indicated by the disintegration in water of specimens treated with these two additives after 5 hr of curing. The longest delay

TABLE 5
EFFECT OF SODIUM COMPOUNDS ON THE PROPERTIES OF CEMENT STABILIZED
NEW HAMPSHIRE SILT

Cement Content = 5.0 Percent on Dry Soil Wt

Additive	Concentration		At Molding		Curing ^c Days	After Curing		At Testing		Wet Com- pressive Strength, psi
	wt %	pcf	Moisture Content, %	Dry Den- sity, pcf		Moisture Content, %	Dry Den- sity, pcf	Moisture Content, %	Dry Den- sity, pcf	
Control	—	—	19.8	99.4	1	19.0	98.9	23.2	98.7	80±0
			19.8	98.5	4	19.1	97.8	24.0	97.8	90±0
			19.8	98.2	7	18.4	97.5	23.9	97.3	95±0
			19.8	98.5	28	15.7	97.9	23.7	97.9	125±5
Sodium hydroxide	0.5	0.45	21.5	98.2	1	20.2	96.9	23.3	96.8	110±0
			21.5	98.5	4	19.2	96.5	23.5	97.0	135±15
			21.5	99.3	7	20.0	97.3	23.2	97.8	140±5
			21.5	98.8	28	17.8	99.0	23.8	98.8	150±0
	1.0	0.88	20.9	98.1	1	19.3	98.5	24.1	97.1	145±5
			20.9	98.6	4	20.6	98.3	23.2	98.3	217±7
			20.9	98.8	7	20.5	98.3	23.3	98.1	235±0
			20.9	98.1	28	19.8	98.1	22.9	98.1	280±15
	2.0	1.77	21.0	100.0	1	19.5	100.0	22.4	99.5	110±0
			21.0	99.4	4	21.1	99.0	23.3	98.6	138±12
			21.0	99.0	7	23.1	98.1	24.1	98.3	157±18
			21.0	99.3	28	24.8	98.7	25.4	99.2	258±22
Sodium carbonate	0.5	0.56	20.0	98.6	1	18.9	98.3	23.4	98.0	108±2
			20.0	99.1	4	18.3	98.3	23.3	98.5	166±4
			20.0	99.2	7	18.1	98.5	23.2	98.5	215±0
			20.0	98.6	28	18.8	97.6	23.3	97.8	250±15
	1.0	1.15	20.6	98.7	1	19.8	98.5	23.3	98.3	140±0
			20.6	98.9	4	20.3	98.6	23.6	98.3	186±2
			20.6	98.7	7	20.5	97.8	23.4	98.0	220±20
			20.6	100.2	28	21.0	99.3	22.8	98.7	285±35
	2.0	2.26	20.2	99.5	1	19.7	98.3	23.0	98.4	105±10
			20.2	99.6	4	20.7	98.8	23.7	98.6	150±5
			20.2	98.8	7	21.3	97.9	24.3	98.0	158±13
			20.2	99.1	28	24.7	98.3	24.8	98.7	233±2
Sodium metasilicate	0.5	0.60	21.2	99.5	1	20.6	98.7	23.5	98.0	130±5
			21.2	98.8	4	20.3	98.0	23.4	98.1	153±7
			21.2	98.5	7	20.3	97.5	24.1	97.6	202±6
			21.2	99.0	28	18.5	97.4	24.2	97.2	305±35
	1.0	1.33	20.8	98.2	1	19.8	97.3	23.9	97.5	135±15
			20.8	98.5	4	19.5	98.1	24.4	97.5	198±12
			20.8	98.4	7	19.2	97.9	24.3	98.2	218±7
			20.8	100.5	28	18.5	101.0	23.2	99.8	344±45
	2.0	2.70	19.5	98.8	1	18.9	98.3	24.2	98.3	138±2
			19.5	98.0	4	19.9	97.8	24.5	97.8	195±0
			19.5	98.5	7	19.3	98.0	24.6	97.8	235±5
			19.5	99.1	28	21.9	98.1	24.0	99.0	337±23
Sodium sulfate	0.5	0.76	20.4	99.6	1	18.9	99.1	22.6	99.3	202±28
			20.4	99.8	4	19.6	98.8	23.1	98.8	285±15
			20.4	99.5	7	18.4	98.4	23.7	98.1	263±2
			20.4	98.8	28	18.9	97.5	23.3	98.0	395±25
	1.0	1.52	20.2	101.0	1	19.4	99.5	22.8	98.8	228±7
			20.2	100.0	4	19.0	99.2	23.0	99.2	275±15
			20.2	100.5	7	19.1	99.8	21.7	99.7	325±25
			20.2	100.8	28	19.0	99.2	22.2	99.9	435±35
	2.0	2.96	19.8	101.0	1	19.6	98.8	23.3	98.2	130±30
			19.8	101.0	4	20.1	99.6	23.1	99.6	270±10
			19.8	102.4	7	20.1	100.7	22.9	100.3	308±27
			19.8	102.0	28	23.3	99.6	23.6	99.0	435±15
Sodium aluminate	0.5	0.91	21.2	99.5	1	20.1	98.0	22.8	98.6	230±10
			21.2	98.7	4	19.8	97.8	23.7	97.3	282±8
			21.2	99.5	7	19.0	98.0	23.3	98.1	330±35
			21.2	98.9	28	18.0	98.0	23.4	98.1	425±5
	1.0	1.71	19.8	100.3	1	19.4	99.1	22.5	98.8	190±30
			19.8	100.3	4	19.3	99.2	22.4	98.8	260±20
			19.8	99.9	7	18.9	99.0	22.5	99.5	260±15
			19.8	100.6	28	18.8	98.7	22.0	99.3	410±20

TABLE 5 (Continued)
EFFECT OF SODIUM COMPOUNDS ON THE PROPERTIES OF CEMENT STABILIZED
NEW HAMPSHIRE SILT

Cement Content = 5.0 Percent on Dry Soil Wt

Additive	Concentration		At Molding		Curing ^c Days	After Curing		At Testing		Wet Com- pressive Strength, psi
	N ^a	% ^b	Moisture Content, %	Dry Den- sity, pcf		Moisture Content, %	Dry Den- sity, pcf	Moisture Content, %	Dry Den- sity, pcf	
Sodium fluosilicate	2.0	3.35	19.5	100.5	1	18.7	98.7	22.8	97.8	128±10
			19.5	101.5	4	18.9	100.3	21.7	100.3	258±22
			19.5	101.6	7	19.8	100.0	21.1	100.1	255±20
			19.5	102.0	28	23.0	99.8	23.0	101.0	405±5
	0.5	1.06	21.5	98.1	1	19.8	98.4	D ^d	D ^d	0
			21.5	97.5	4	20.2	98.3	D	D	0
			21.5	98.0	7	20.3	97.5	D	D	0
			21.5	97.3	28	21.2	97.5	D	D	0
	1.0	2.08	21.0	98.3	1	19.6	99.3	D	D	0
			21.0	98.2	4	19.1	98.5	D	D	0
			21.0	98.2	7	19.6	97.9	D	D	0
			21.0	98.0	28	20.2	98.2	D	D	0
Sodium fluoride	2.0	4.04	20.4	98.9	1	19.4	98.8	D	D	0
			20.4	99.0	4	18.8	97.5	24.0	97.5	40±0
			20.4	98.4	7	18.7	97.8	24.1	97.0	50±0
			20.4	98.8	28	14.5	97.2	25.0	97.7	45±5
	0.5	0.15	20.8	99.4	1	20.0	99.2	D ^d	D ^d	0
			20.8	99.0	4	20.2	98.3	D	D	0
			20.8	99.7	7	19.5	98.5	22.8	98.8	160±10
			20.8	99.5	28	16.6	98.5	23.5	97.8	300±0
	1.0	0.90	20.3	99.2	1	20.2	99.0	D	D	0
			20.3	99.4	4	19.7	98.9	D	D	0
			20.3	99.5	7	20.2	99.2	D	D	0
			20.3	99.6	28	18.4	99.3	D	D	0
Sodium fluoborate	2.0	1.93	21.8	99.1	1	21.3	98.9	D	D	0
			21.8	98.9	4	21.8	98.5	D	D	0
			21.8	99.1	7	21.7	98.8	D	D	0
			21.8	98.8	28	22.3	98.8	D	D	0
	0.5	1.18	20.5	99.2	1	20.0	99.3	23.0	99.1	64±4
			20.5	99.2	4	19.9	98.4	23.8	98.4	98±12
			20.5	99.2	7	19.8	98.0	23.6	97.7	140±0
			20.5	98.8	28	18.3	98.5	23.7	98.4	198±12
	1.0	2.40	20.8	99.5	1	20.0	98.7	D ^d	D ^d	0
			20.8	99.4	4	21.2	98.5	23.5	98.6	118±2
			20.8	100.0	7	20.8	99.0	23.0	99.0	168±2
			20.8	99.7	28	19.0	99.2	22.4	98.7	208±7
Sodium tetraborate	2.0	4.48	19.5	100.7	1	20.0	101.0	D	D	0
			19.5	100.9	4	20.3	100.5	20.7	100.5	40±0
			19.5	100.9	7	21.0	100.0	21.7	100.0	103±2
			19.5	100.4	28	19.8	99.7	22.8	99.7	210±30
	0.5	1.12	21.2	100.0	1	21.2	99.5	D ^d	D ^d	0
			21.2	99.0	4	20.4	97.6	D	D	0
			21.2	99.0	7	19.5	98.6	D	D	0
			21.2	99.3	28	17.4	98.4	D	D	0
	1.0	2.26	21.4	99.8	1	21.4	99.3	D	D	0
			21.4	98.8	4	19.5	97.8	D	D	0
			21.4	99.0	7	20.2	99.0	D	D	0
			21.4	98.8	28	19.1	98.2	D	D	0
	2.0	4.50	21.3	99.0	1	21.3	99.0	D	D	0
			21.3	98.6	4	21.3	98.3	D	D	0
			21.3	98.2	7	21.2	97.5	D	D	0
			21.3	98.2	28	22.0	94.5	D	D	0

^aNormality on molding water content.

^bPercent on dry soil weight.

^cCuring under 100 percent relative humidity and room temperature.

^dSpecimen disintegrated upon immersion.

Note: Wet compressive strengths for untreated soil with 10 percent cement were 128, 208, 283, and 360 psi for 1, 4, 7 and 28 days curing, respectively.

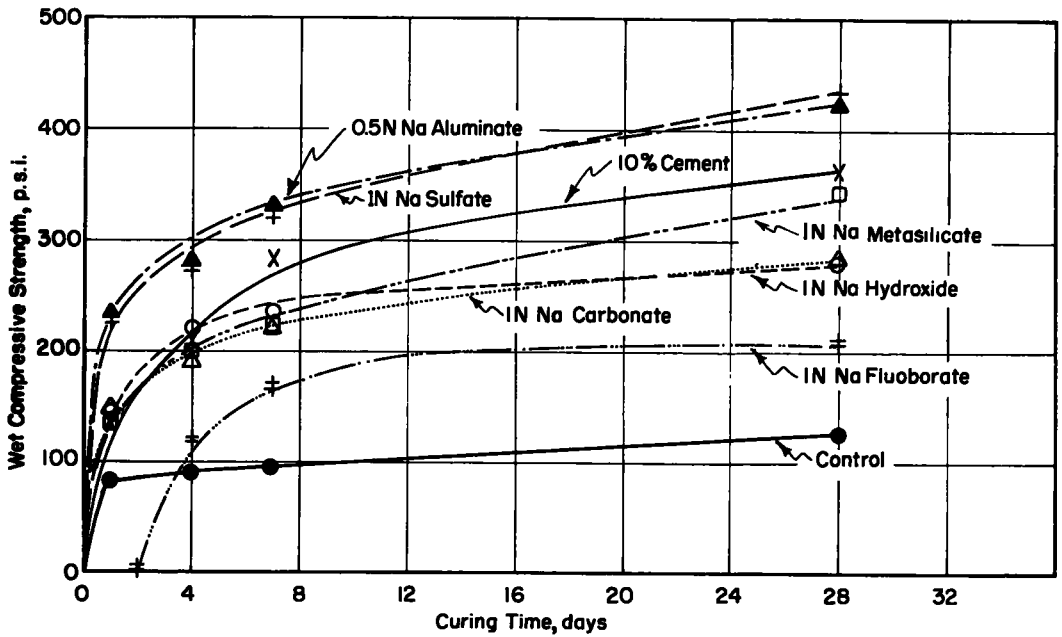


Figure 3. Effect of type of additive (at optimum concentration) on curing rate of New Hampshire silt stabilized with 5 percent cement.

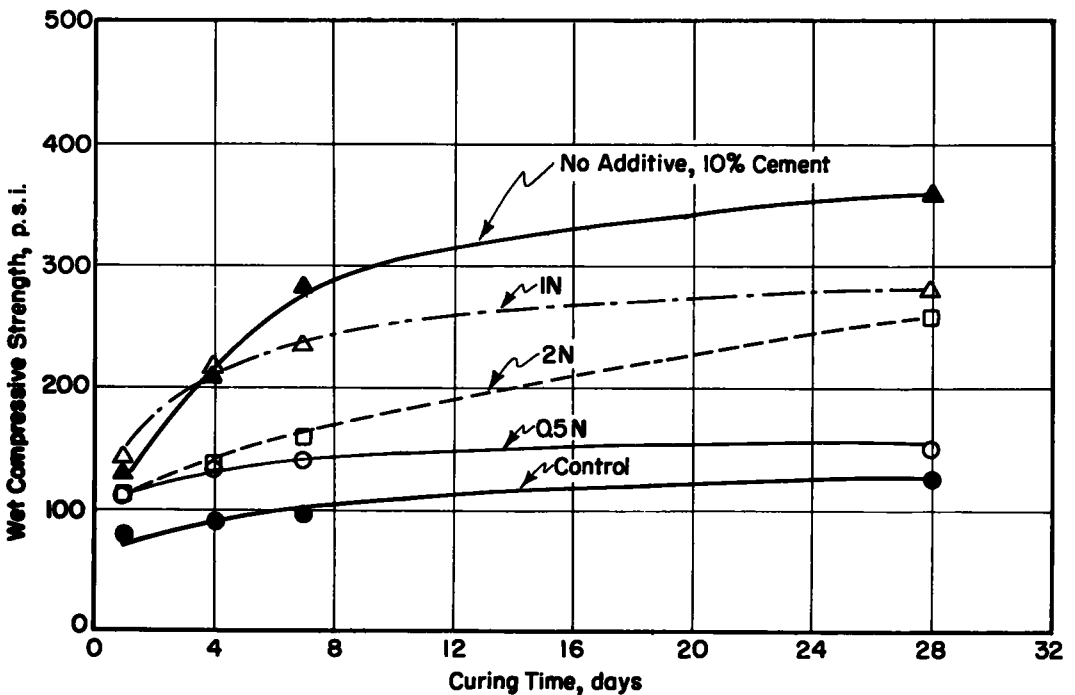


Figure 4. Effect of concentration of sodium hydroxide on strength development of New Hampshire silt stabilized with 5 percent cement.

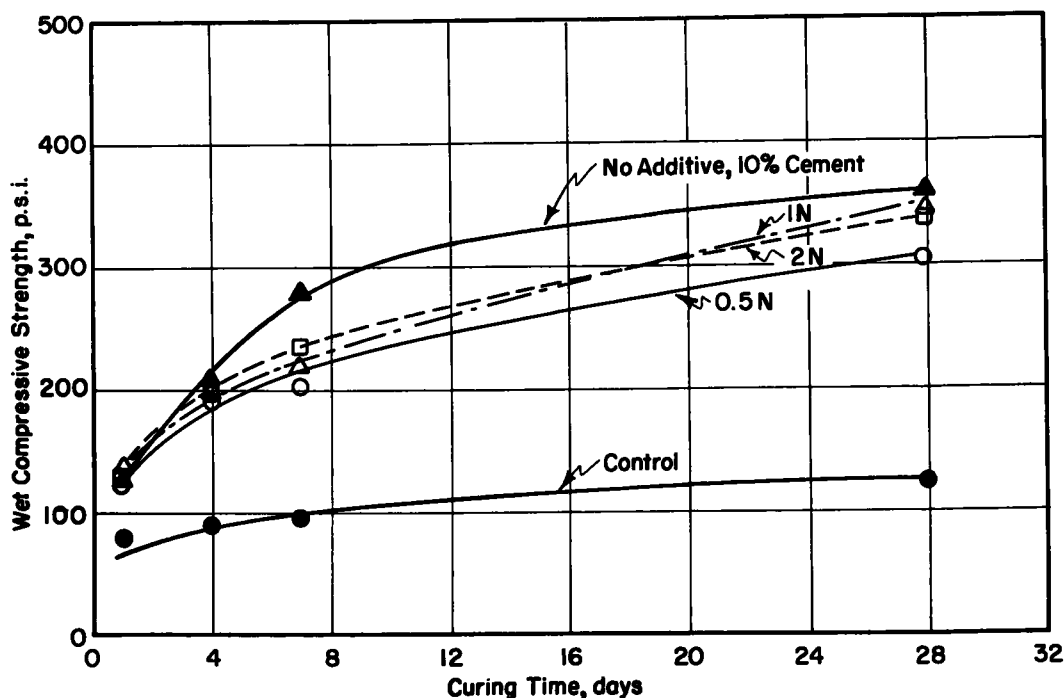


Figure 5. Effect of concentration of sodium metasilicate on strength development of New Hampshire silt stabilized with 5 percent cement.

in setting is with the most alkaline compound; that is, the hydroxide. Sodium sulfate not only increases the final strength, but greatly enhances cure rate. The results are particularly surprising. Because several investigators (Mehra and others 1955, Sherwood 1957) have claimed that sulfates are generally detrimental to soil-cement.

Effect of Additive Concentration on Curing Rate. Figures 4, 5 and 6 illustrate the relationships between strength, curing time and concentration of three beneficial additives. A curve for soil plus 10 percent cement (without additive) is also included for comparison.

In all cases (except with sodium metasilicate) a 2.0 normal additive concentration gives a lower strength than does a 1.0 normal concentration at early cure (say, one day) but the strengths at 28 days are about the same. Furthermore, the 0.5 normal concentration generally gives as high early strength as does 1.0 normal, but shows lower strength after longer cure, probably because the full benefit of the additive is not utilized.

Moreover, the curves in Figure 2 clearly indicate that the slopes of the curves in the 0 to 0.5 normal range become steeper with time. These observations indicate that high additive concentrations tend to delay strength development. The optimum concentration for sodium metasilicate is much less well-defined at all cure times studied.

These observations lead to two conclusions: (a) the strength development of soil-cement will be delayed by the presence of a high concentration of additive, but the full beneficial effect (different for each additive) will be achieved after a longer time of cure; and (b) the op-

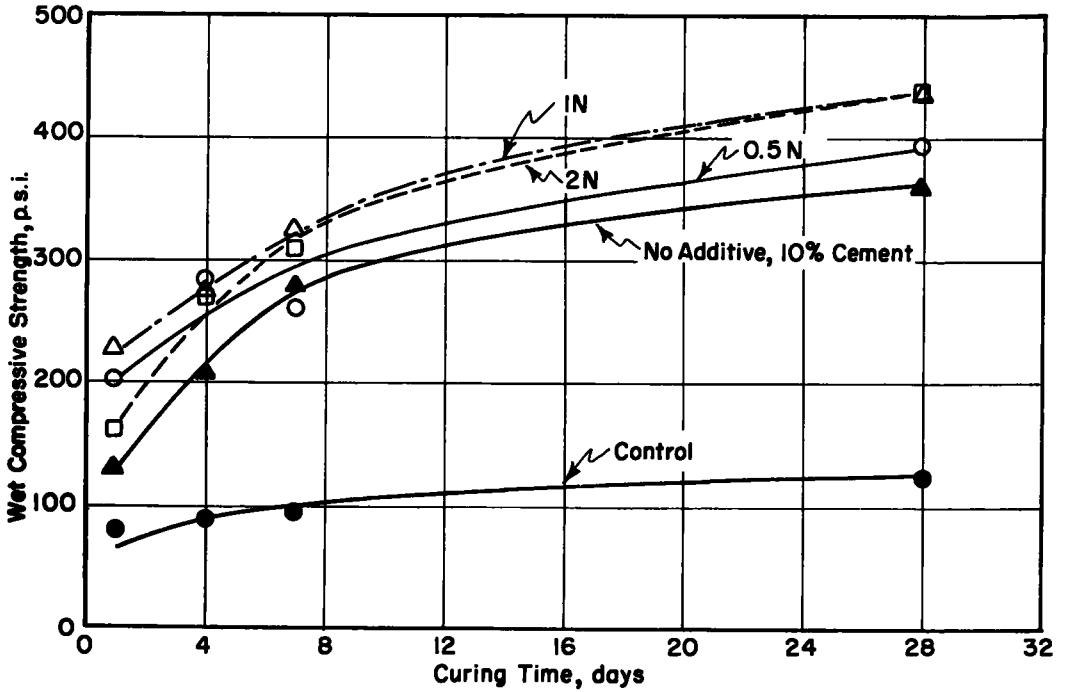
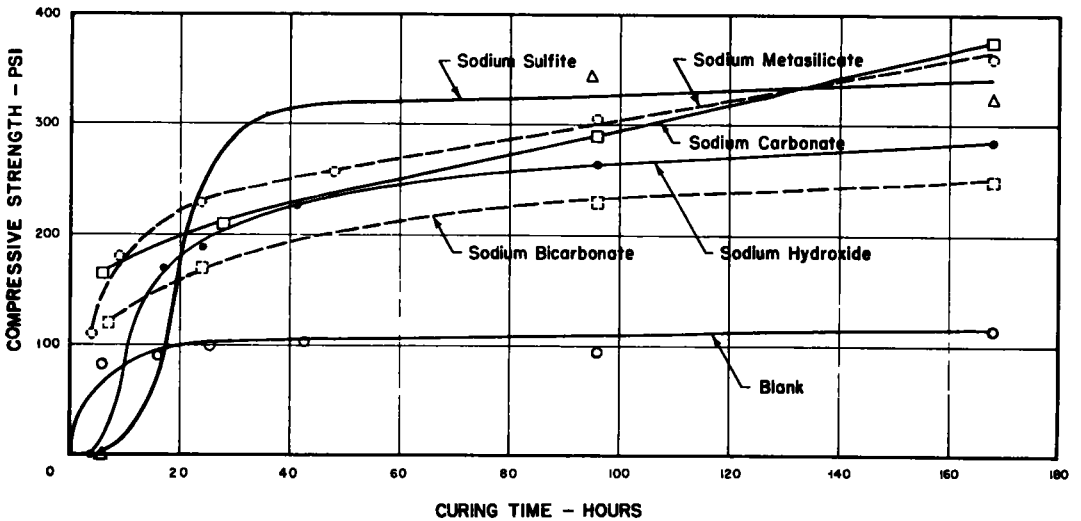


Figure 6. Effect of concentration of sodium sulfate on strength development of New Hampshire silt stabilized with 5 percent cement.



NOTE: 1 CEMENT CONTENT FOR ALL SYSTEM = 5% ON DRY SOIL WEIGHT
 2 ADDITIVE CONCENTRATION = 1% ON DRY SOIL WEIGHT
 3 ALL SPECIMENS TESTED AFTER 24-HOURS COMPLETE IMMERSION

Figure 7. Effect of sodium compounds on the strength development of cement stabilized New Hampshire silt.

imum additive concentration observed at early cure times (say, one day) represents the minimum concentration required to obtain the maximum effect of the additive.

Sandy Soil (Soil WS2).—Wisconsin sand 2 responds satisfactorily to cement and additives as shown in Figure 8. Sodium metasilicate accelerates

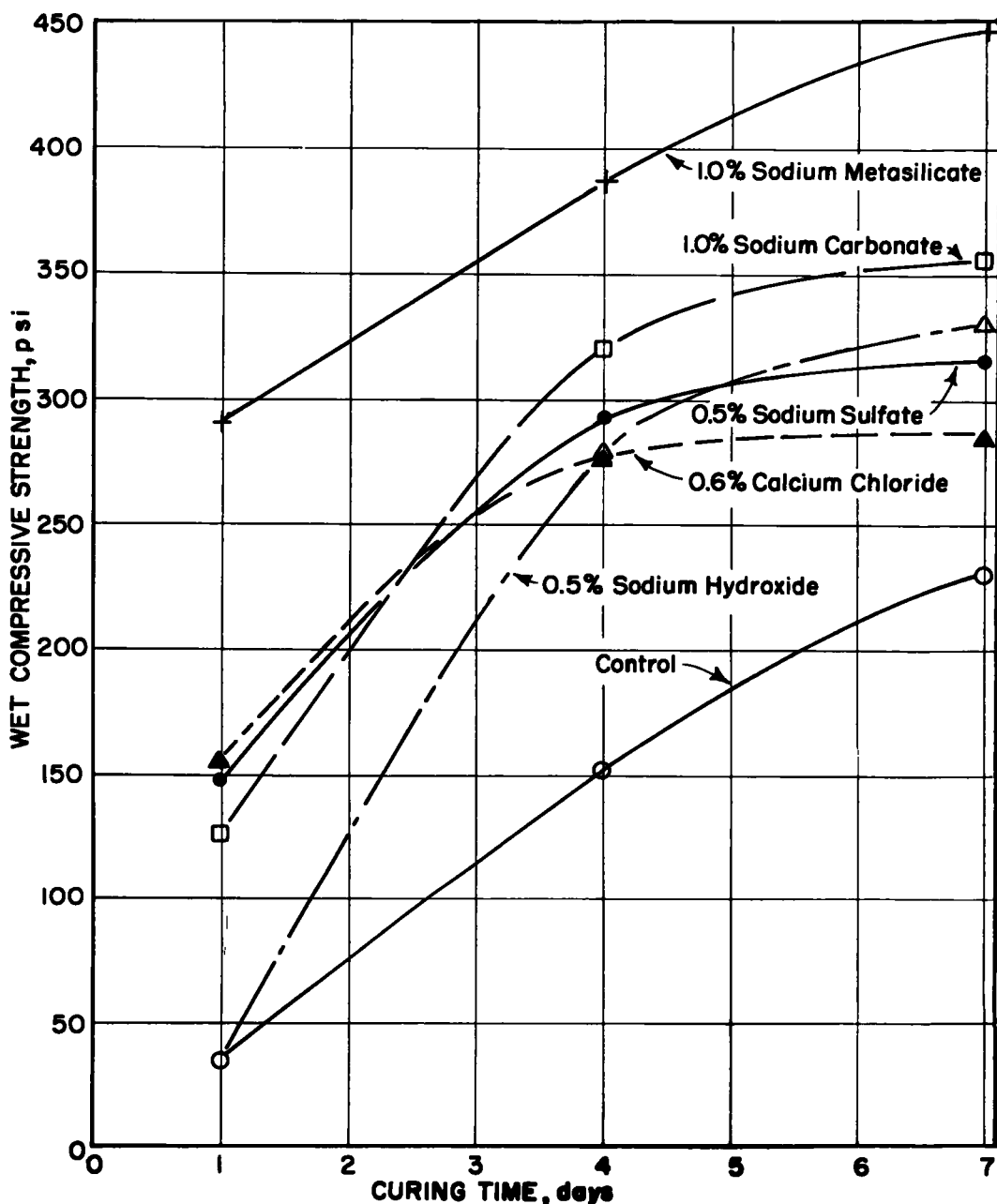


Figure 8. Effect of additives on rate of strength development of soil 1057 stabilized with 10 percent cement (Wisconsin sand 2).

cure and increases the 7-day strength more than any other additive tested. Strength-development with sodium hydroxide was slower than with other additives. Sodium metasilicate thus appears to be more effective than hydroxide in improving the 7-day strength with sandy soils, while the converse is true with silts.

Calcium chloride is often recommended as an additive to sand-cement. The PCA has reported that this WS2 required either 13 percent of cement by volume or 10 percent plus 0.6 percent of calcium chloride by weight for adequate stabilization. The curve shown in Figure 8 indicates that calcium chloride merely serves to accelerate cure, and that the actual degree of improvement was much less than with sodium metasilicate.

Clayey Soils (Soils IC, TC1 and TC2).—

Illinois Clay (IC). The results of tests on the Illinois clay treated with cement and additives are summarized in Figure 9. Only sodium hydroxide improved strength, and the degree of effectiveness was much less than that obtained with the three soils studied earlier (Lambe and Moh 1957, MIT 1955, 1956). However, the 7-day strength of samples with 5 percent cement and 1 percent sodium hydroxide was considerably higher than the strength of samples with 10 percent cement as reported by PCA. The two salts of weak acids (that is, sodium sulfite and carbonate) at 1 percent concentration had an adverse effect on strength development.

Texas Clays 1 and 2 (TC1 and TC2). The two Texas clays have about the same composition; both are highly montmorillonitic soils with TC2 slightly less plastic than TC1. Test results with sodium hydroxide, sulfite, sulfate, and carbonate indicate that only the hydroxide increased significantly the strength of these clay-cement mixtures. All the other salts had adverse effects, as was true with the Illinois clay.

It was observed that significant volumetric changes occurred during curing and subsequent immersion for samples of soil TC2-cement treated with sodium salts, more than that of the control samples. However, only slight volume changes occurred after immersion for samples treated with 1 percent sodium hydroxide as shown in Table 6. The observed physical changes of the samples after immersion were much more apparent than is indicated by the density variations reported in the table. Excessive expansion of the samples caused numerous cracks in the samples and thereby decreased strength. The amount of sample expansion (that is, density decrease) was dependent on the curing time: the shorter the curing time, the more the expansion.

It is believed that the observed expansion on immersion, and attendant deterioration, of samples containing sodium carbonate and sulfite results primarily from partial conversion of the montmorillonoid component of the soil into the highly swelling sodium form; this occurs as a consequence of the extremely high ratio of sodium to calcium ion in the pore fluid when these salts are present. This swelling tendency is, of course, opposed by the cementation of particles resulting from silicate gel formation. If cementation develops relatively rapidly, then both volume increase and strength loss on immersion even after short cure may be small; this is evidently the situation with caustic soda present as the data of Table 6 indicate.

If this analysis is correct, it would then be expected that, if the montmorillonoids could be retained in a low-swelling ionic form, the ben-

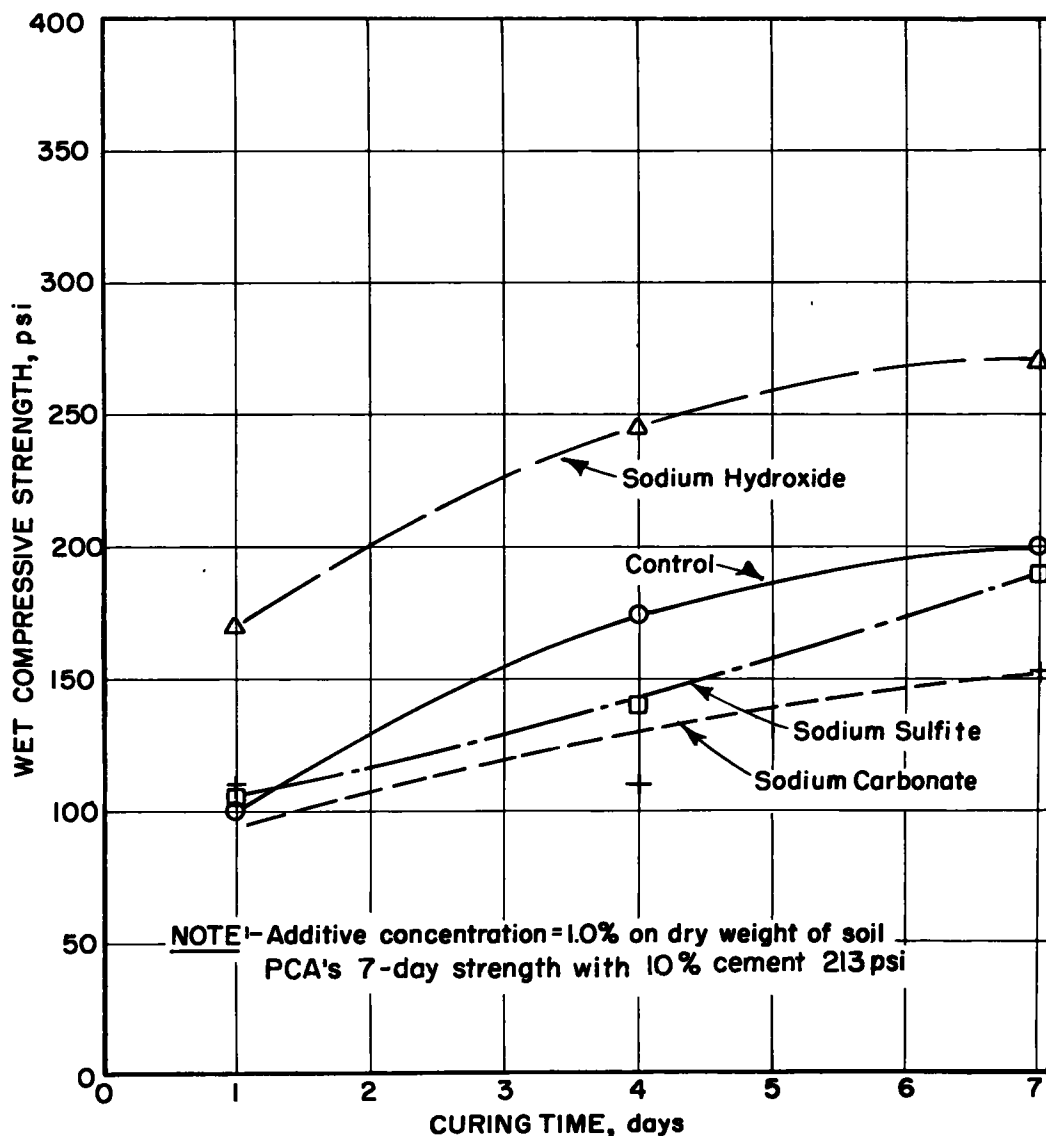


Figure 9. Effect of three sodium compounds on wet compressive strength and rate of curing of soil 1055 stabilized with 5 percent cement (Illinois clay).

eficial effects of caustic soda on this soil-cement composition could be enhanced. Barium chloride was selected as a secondary additive for this purpose. Although no significant difference in volume change was observed, samples containing 0.1 percent barium chloride did show higher strength after 7-day curing, as shown in Figure 10.

Calcareous Soils (Soils IrC1 and IrC2).—The two Iraq clays contained fairly large amounts of carbonates (about 25 percent by weight, mostly calcite). The pH values indicated, however, that they were only slightly alkaline, about the same as the two Texas clays.

TABLE 6

EFFECT OF ALKALI SODIUM COMPOUNDS ON DENSITY AND STRENGTH OF
CEMENT STABILIZED SOIL TC2 (1059)

Cement Content = 5.0 Percent on Dry Soil Wt

Additive	Additive Concentra- tion % on Dry Soil Wt	Molding Dry Density, pcf	Curing Days	Dry Density After Im- mersion, pcf	Wet Com- pressive Strength, psi
Control	—	94	1	92	55
		94	4	94	95
		95	7	95	150
Sodium carbonate	1.0	95	1	92	50
		94	4	94	85
		95	7	93	95
Sodium sulfite	1.0	94	1	91	45
		95	4	94	105
		95	7	93	105
Sodium hydroxide	1.0	96	1	95	160
		95	4	96 ^a	185
		94	7	94	185
Sodium hydroxide and barium chloride	1.0	97	1	96	115
		97	4	97	195
		97	7	98 ^a	230

^aSample shrank during curing.

In general all three sodium additives tested (that is, hydroxide, carbonate, and metasilicate) improved the strengths of both soils as shown in Figures 11 and 12. Sodium hydroxide once again was the most effective additive for increasing strength at both 5 and 10 percent cement levels. A treatment of 5 percent cement plus 1.0 percent sodium hydroxide was about equivalent to 10 percent cement alone. However, none of the additives (at the concentrations tested) improved a 10 percent cement mixture as much as an additional 5 percent cement.

Iraq clay 2 is a fairly well graded soil and less plastic than Iraq clay 1, but it still contains about 35 percent clay-size particles. The strength values of soil IrC2 were much higher than that of soil IrC1 at the same cement content, and the additives were also slightly more effective for the former.

It can then be concluded that the two Iraq soils with fairly high carbonate content responded to additive treatment in the same order of magnitude as other soils with predominantly clay minerals.

Influence of Soil Type and Additive Concentration on Strength Improvement.—Because some of the additives retard the cure of a soil-cement mixture, the ultimate effectiveness of the additives can be better shown by examining the ratio of 7-day strengths of the treated to the control sam-

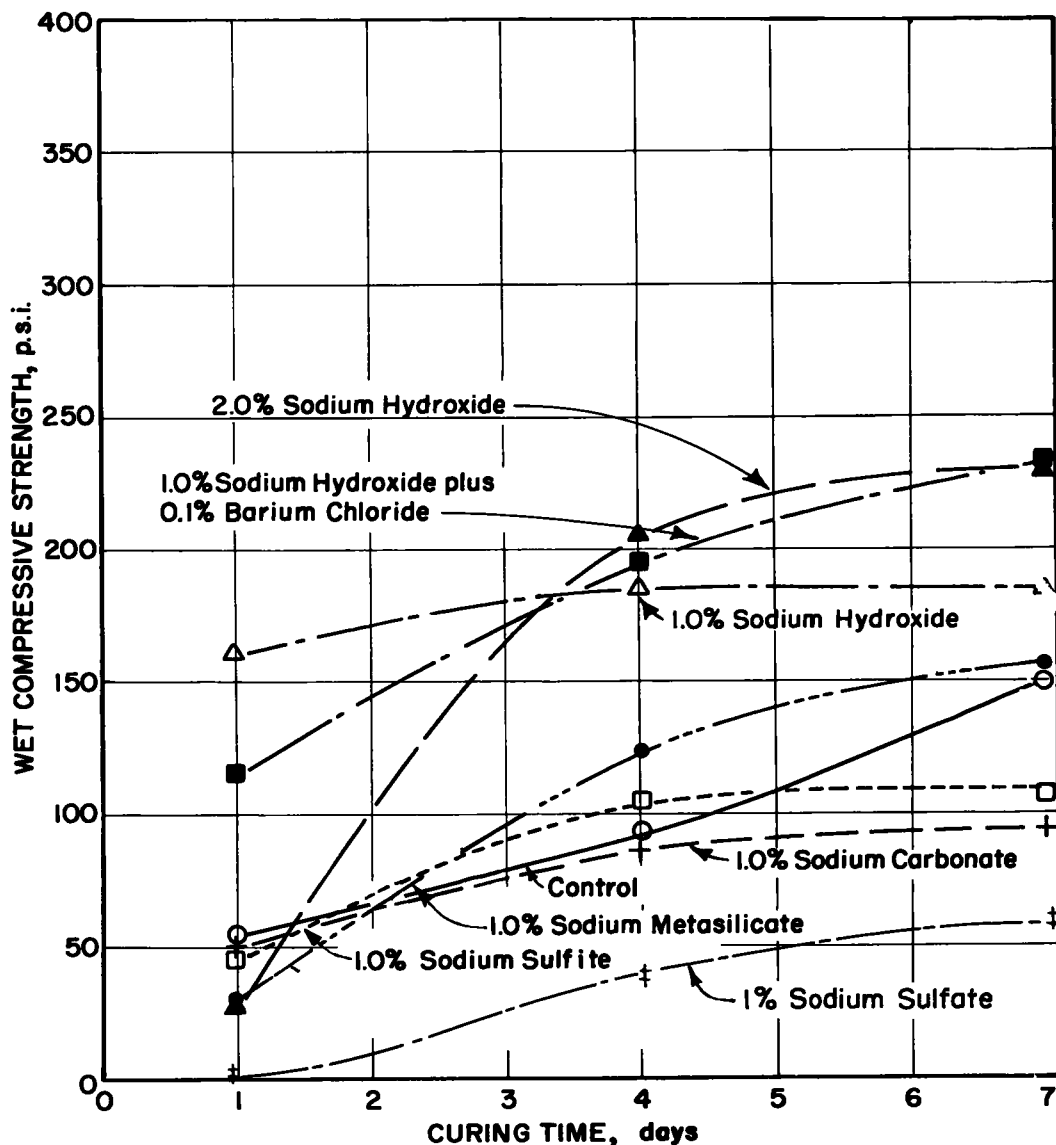


Figure 10. Effect of additives on rate of strength development of soil 1059 stabilized with 5 percent cement (Texas clay 2).

ples. Figure 13 shows the strength ratio vs initial sodium hydroxide concentration in the molding water (expressed as Normality) for various soils.

From this plot, it is observed that: (a) the optimum concentration of hydroxide (expressed as Normality) is about the same for all fine-grained soils, and (b) the degree of effectiveness of this additive decreases with increasing soil plasticity and/or organic matter content. Soil TC2 departed from these trends slightly, possibly due to its considerably greater total surface area.

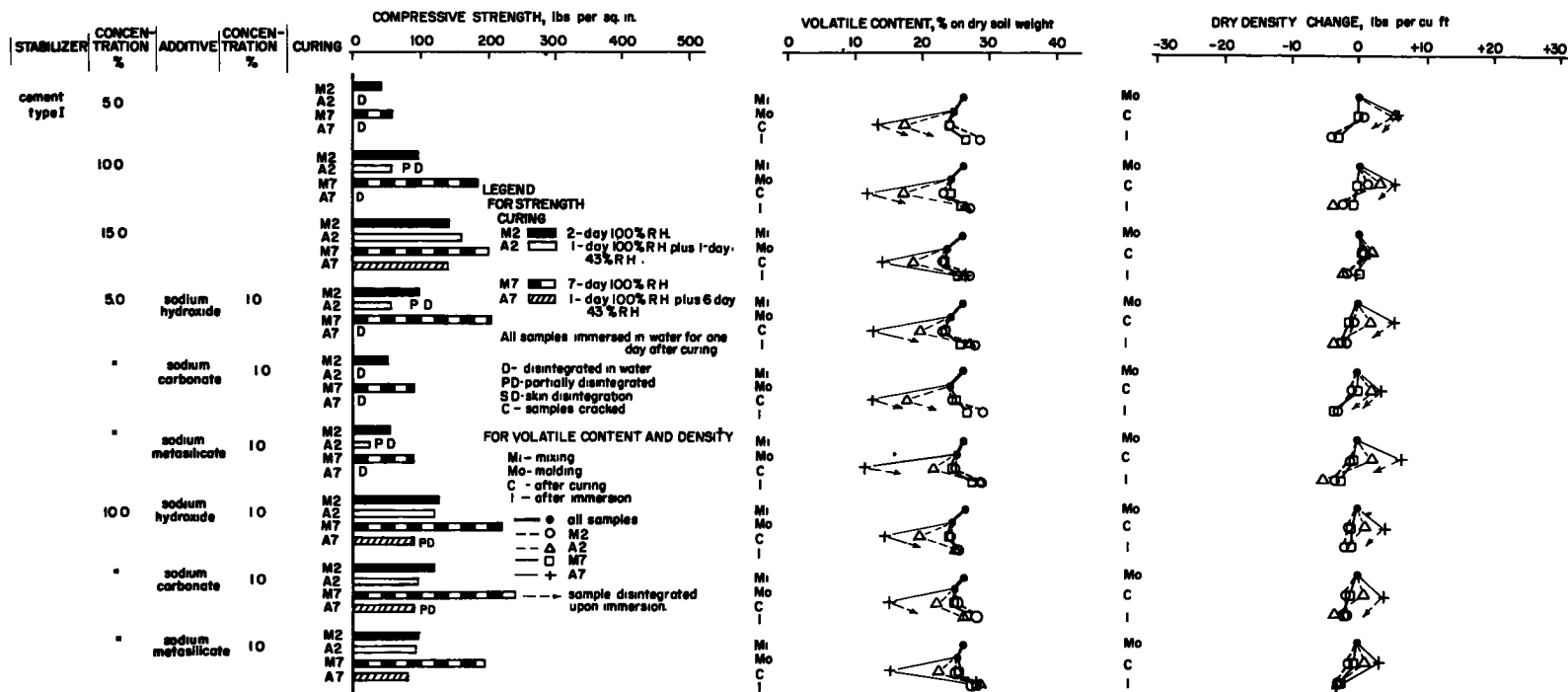


Figure 11. Stabilized soil Iraq clay 1: strength, volatile content, and density.

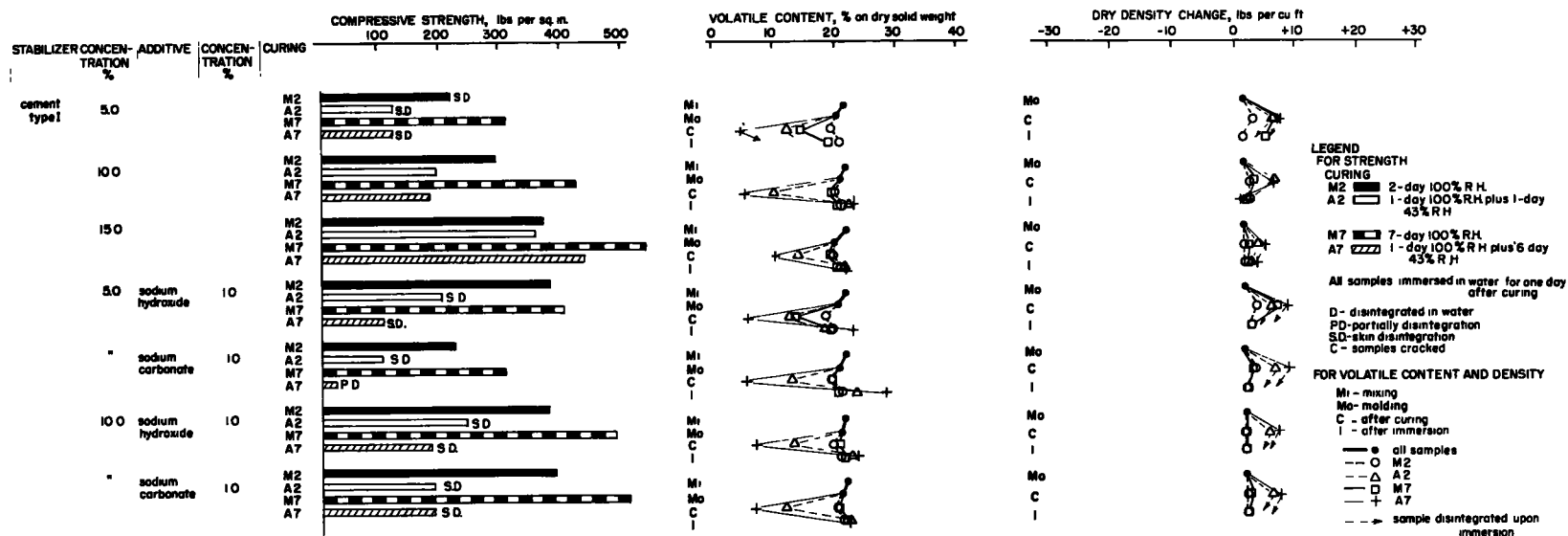


Figure 12. Stabilized soil Iraq clay 2: strength, volatile content, and density.

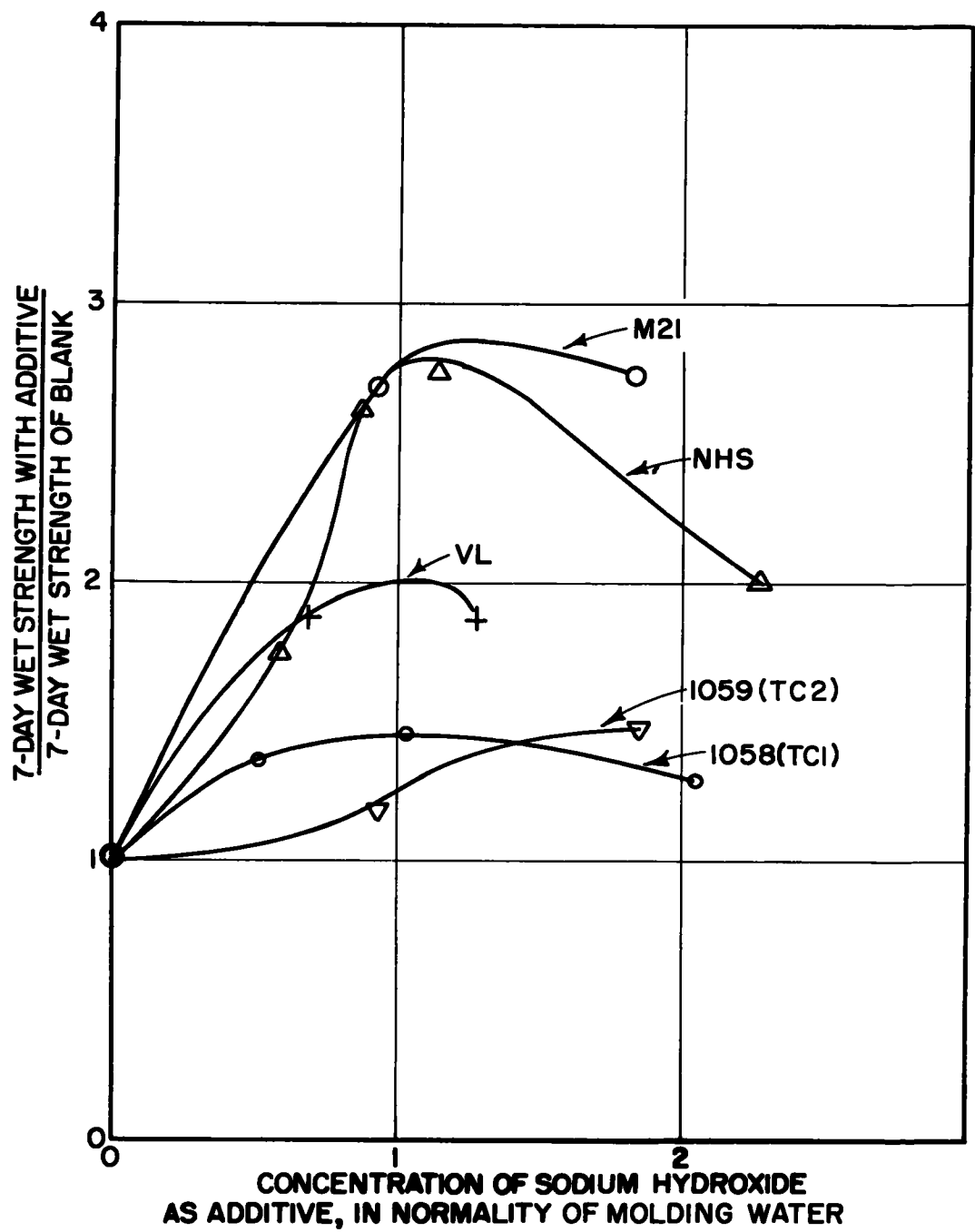


Figure 13. Degree of effectiveness of sodium hydroxide as additive to soil-cement vs concentration of additive in Normality (cement content = 5 percent on dry soil weight).

Effect of Sodium Additives on Problem Soils

Soils which cannot be stabilized with cement alone at an economical level (say about 15 percent), are termed herein "problem soils." This section describes the use of additives to enhance the effectiveness of cement as a primary stabilizer with such problem soils. Two soils were studied; one contained a fairly high amount of soluble salts, and the other, a sand, contained organic matter.

Soil High in Soluble Salt Content (IrSC).—In addition to its high carbonate content (about 50 percent by weight), the Iraq silty clay contained about 5 percent of water-soluble salt, mostly sodium chloride. Because sodium chloride reduces the vapor pressure of the water in the soil pores, it increases the equilibrium water content for any given humidity. Samples of IrSC with cement and additives showed considerable water absorption and swelling during the humid cure, as shown by the water content and density changes in Figure 14. Furthermore, all samples suffered a decrease in dry weight on immersion due to the removal of salts by leaching. Therefore the reduction in dry density after immersion was due partly to the leaching of salt and partly to swelling of the sample.

The use of up to 10 percent cement, as shown in Figure 14, was ineffective with this soil. Sodium hydroxide (at 1.0 percent) greatly increased the strength and reduced the swelling of IrSC plus 10 percent cement. The results were even more favorable than those with 15 percent cement. Sodium carbonate and metasilicate were, on the other hand, only slightly beneficial.

The poor response of this soil to cement stabilization was believed to be caused primarily by the salt present. In order to confirm this, a series of experiments was conducted by leaching the soil with distilled water to reduce the salt content of the soil, without altering other properties.

Table 7 and Figure 14 confirm the fact that the high salt content is the only factor responsible for the adverse results. On the leached soil much higher strengths were obtained with 10 percent cement both alone and with 1 percent sodium hydroxide. No absorption of water during moist-curing and no reduction of dry weight after immersion were observed. Only very slight swelling occurred during the immersion period. It is interesting to note that the absolute strength increase (in psi) due to the addition of 1 percent sodium hydroxide is about the same for this soil whether the salt is removed or not; that is, about 100 psi for 2-day moist cure and 170 psi for 7-day moist cure.

Soil Containing Organic Matter (WS1).—Wisconsin sand 1 was a very uniform sand of A horizon material of the same profile as Wisconsin sand 2, which was from the B horizon. The properties of these two sands were very similar except that WS1 had higher organic matter content. However, the responses of these two soils to cement and chemical treatments were entirely different.

Sodium hydroxide, carbonate, and metasilicate were totally ineffective in cement-WS1, but exceptionally good results were obtained with sodium sulfate. The only apparent reason which could account for this discrepancy was the higher organic matter content in soil WS1.

The fact that organic matter is harmful to soil-cement has long been

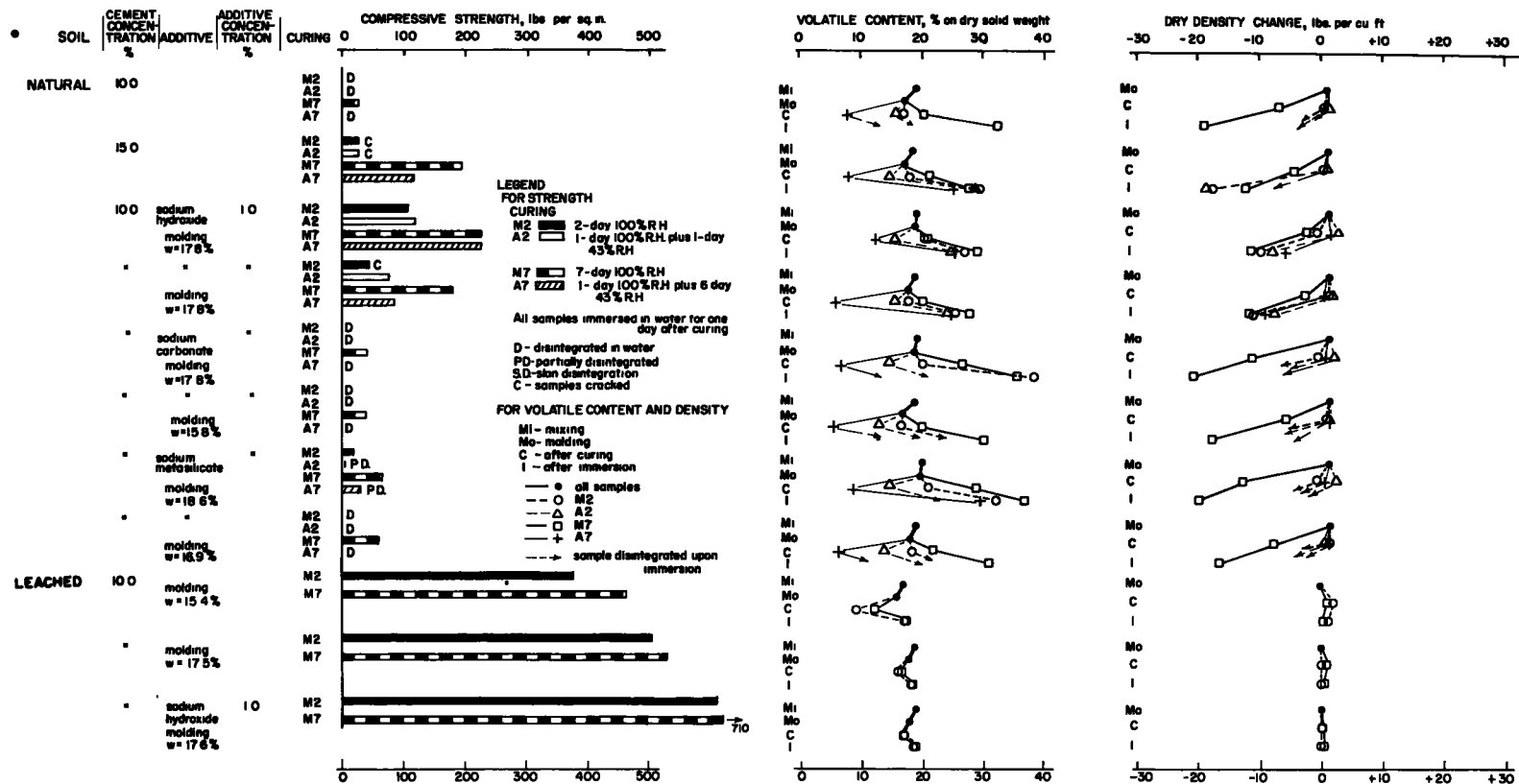


Figure 14. Stabilized soil Iraq silty clay: strength, volatile content, and density.

TABLE 7
EFFECT OF HIGH SALT CONTENT IN THE SOIL ON THE STRENGTH OF
CEMENT STABILIZED SOIL 1068 (IrSC)

Cement Content = 10 Percent on Dry Soil Wt

Curing ^a Days	Soil Type	Additive	
		None	1.0% Sodium Hydroxide
2	Natural	5	106
	Leached ^b	505	612
7	Natural	56	223
	Leached ^b	531	710

^aSamples cured under 100 percent relative humidity and subjected to 24 hr immersion prior to being tested.

^bSoil leached with distilled water, the total soluble salt content reduced to 0.4 m eq NaCl/100 gm.

recognized. Clare and Sherwood (1956) found that the retardation of the setting of organic soil-cement is due to the absorption of calcium ion by replacing hydrogen ions dissociated from the phenolic or carboxylic constituents of organic matter, thus reducing the calcium ion concentration below that required for silicate precipitation. This dissociation will occur only at high pH values. The addition of alkali to the mixture will raise the pH and therefore encourage more dissociation and hence more absorption of calcium ions. This means less calcium is available for proper setting of the cement. On the other hand, in the presence of sulfate, the pH is lowered initially, dissociation of acid bodies may not occur so that the organic matter remains inactive, or is less active; therefore the usual benefits of the sodium ion can then be achieved. The results obtained with 0.5N sodium sulfate are comparable to that of WS2, which is of virtually the same composition, but contains practically no organic matter. Moreover, it was observed that, during the experiments, the color of the immersion water became deep yellow for samples treated with caustic, of medium color for the control, but only slightly colored when sulfate-treated samples were present. These observations suggest that the solubility of the organic matter is suppressed by sodium sulfate and enhanced by caustic.

In order to verify that organic matter was responsible for the ineffectiveness of cement and additive stabilization of WS1, a series of tests was performed on WS1 by separating the organic matter from the soil. The soil was first suspended in distilled water and the sand separated from the organic matter by sedimentation. The solid portion of organic matter was preserved by the water soluble part was leached out.

Table 8 compares the results obtained with the sand before and after washing. It is interesting to note that a marked increase in strength (particularly 28-day) was obtained by the removal of organic matter, when stabilized either with cement alone, or with cement and sodium metasilicate. The delay of strength development of the sand-cement relative to the lower-horizon soil (WS2) and the ineffectiveness of sodium hydroxide may be attributed to the incomplete removal of organic matter. The strength of sulfate-treated soil was only slightly changed by the wash-

TABLE 8
EFFECT OF ORGANIC MATTER ON THE STRENGTH OF ADDITIVE TREATED
SOIL 1056 (WS1)—CEMENT

Cement Content = 10 Percent of Dry Soil Wt

Additive	Concentration, N ^a	Wet Compressive Strength, psi			
		Curing Days	Natural Soil	Water Washed ^b	Organic Re-added ^{c,d}
Control	—	7	19	65	22
		28	23	170	55
Sodium hydroxide	1.0	7	10	0	0
		28	7	0	0
Sodium sulfate	1.0	7	342	340	—
		28	425	380	—
Sodium metasilicate	1.0	7	0	200	148
		28	0	300	170

^aIn normality of molding water.

^bSoil suspended in distilled water. Solid organic matter preserved. The organic matter content reduced to 0.6 percent.

^cThe preserved organic matter re-added to the washed soil (water soluble organic matter leached off). The organic matter content was 1.5 percent.

^dThe 7-day and 28-day compressive strength of soil WS2 (1057) with 10 percent cement was reduced from 230 and 370 psi to 80 and 188 psi, respectively, by adding 1.0 percent of organic matter separated from soil SW1.

ing process. Moreover, by recombining the solid organic matter with the sand and cement, significant decreases in strength were obtained as given in Table 8. Furthermore, by adding 1 percent of the organic matter to the organic-free sand WS2, considerable strength reduction occurred. These results confirm that (a) poor response of soil WS1 to cement is attributable solely to its organic matter content, and (b) sodium sulfate virtually eliminates the undesirable effect of the organic matter on cement stabilization.

Effect of Curing Conditions on Strength Development

Effect of Curing Time.—The effects of curing time, up to 100 days, on the strength of soil-cement are shown in Figure 15. The continuous increase in strength of chemically treated soil-cement with time strongly suggests that the improvement of the soil-cement strength with additives is permanent.

Effect of Curing Method.—It has been known for a long time that humid conditions are necessary for proper strength development in concrete and soil-cement. However, it would be important in practice to know whether chemical additives will also improve properties of soil-cement under unfavorable curing conditions. Because air-drying always presents a major problem in arid or semi-arid regions, the three Iraq soils (IrC1, IrC2, and IrSC) were therefore selected for a study of response to cement-additive treatment under drying conditions.

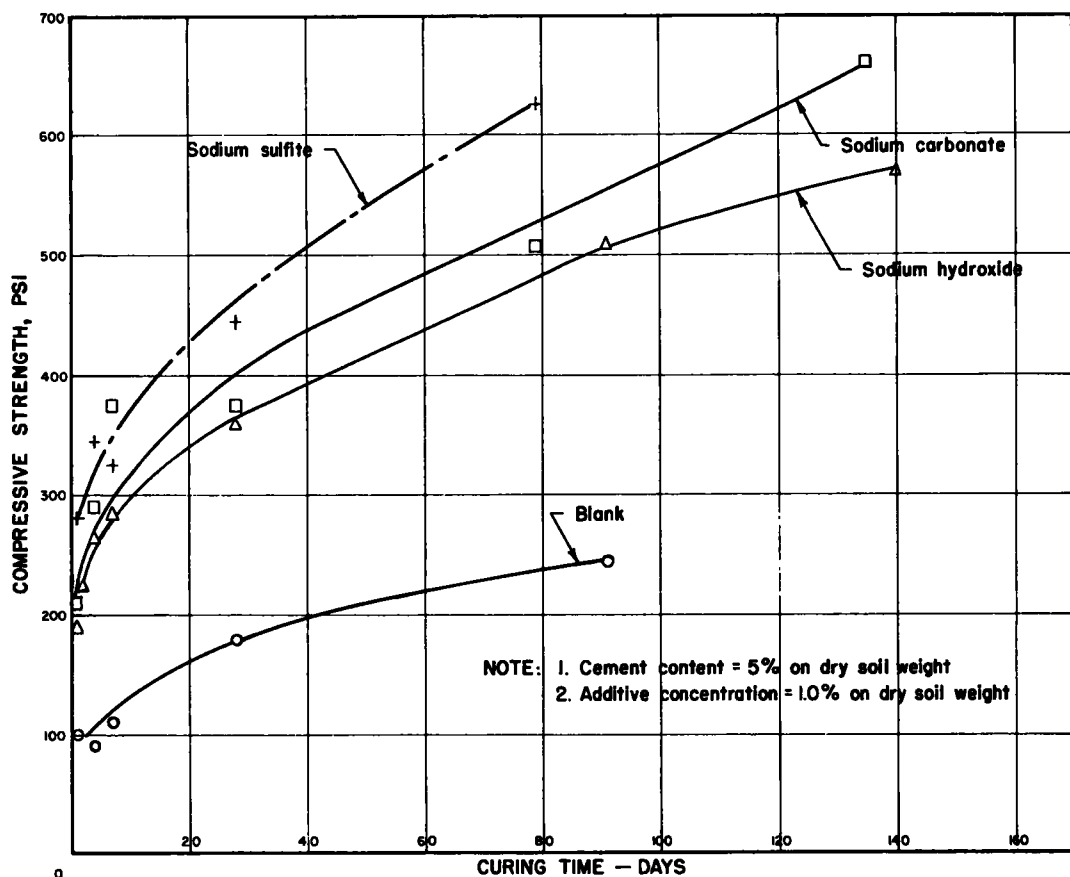


Figure 15. Effect of curing time on the compressive strength of cement stabilized New Hampshire silt with different additives.

One set of specimens was humid-cured for one day then removed to a 43 percent humidity chamber for the rest of the curing period. Strength, moisture content, and density variations are presented in Figures 11, 12 and 14 in comparison with humid-cured data.

Under both air-dry and humid-cure conditions, the strength of soil-cement increases with cement content, though not in direct proportion. The most significant advantage of using a higher cement content is shown in the behavior of the air-dried samples. For example, samples of IrCl disintegrated upon immersion when only 10 percent cement was used but retained a 2-day strength of 140 psi with 15 percent cement. To obtain adequate strength under poor curing, therefore, requires a very high stabilizer concentration.

In general, the effect of additives under air-dry cure was comparable to that observed with moist-cure; that is, sodium hydroxide was the most effective additive in increasing strength, reducing water pickup and volumetric changes during both curing and immersion.

One important observation is that, in all cases, with or without additives, specimens disintegrated in water if the density increase during

cure was more than 5 pcf, corresponding to about 5 percent shrinkage. It should be emphasized at this point that the beneficial additives generally reduce volumetric changes during both curing and immersion for highly plastic soils.

Effect of Cement Content on Strength Improvement with Additives

Table 9 compares the influence of additives on the strength of NHS stabilized with 5 and 10 percent cement. The absolute increase in the 7-day strength (in psi) produced by the additives may be considered as a quantitative measure of additive effectiveness. Analyzed in these terms, with a silty soil such as NHS, the additives are less effective at 10 percent cement concentration than at 5.

TABLE 9
COMPARISON OF MAGNITUDE OF STRENGTH INCREASE DUE TO ADDITION OF
ADDITIVES TO NEW HAMPSHIRE SILT STABILIZED WITH 5 AND 10
PERCENT CEMENT

Additive	Additive Concen- tration ^a	Increase in Compressive Strength over Untreated Soil-Cement, psi			
		1-Day Cured		7-Day Cured	
		Soil with 5% cement	Soil with 10% cement	Soil with 5% cement	Soil with 10% cement
Sodium hydroxide	1.0N	65	64	140	79
Sodium sulfate	1.0N	148	209	230	87
Sodium hydroxide ^b	1.0%	188	132	178	150
Sodium carbonate ^b	1.0%	109	180	268	180
Sodium metasilicate	1.0%	126	265	252	200

^aAdditive concentration expressed either in normality of molding water or in percent on dry weight of soil.

^bSpecimens were compacted under constant pressure instead of constant density; densities of additive treated specimens in general were few pounds higher than those of untreated.

ECONOMICS OF ADDITIVE TREATMENT

The test results presented in this paper indicate that a very large increase in the strength of soil-cement can be obtained with low-level chemical treatment. A consideration of the economics of replacing cement alone with a mixture of cement plus additive for soil stabilization was, therefore, made.

Table 10 compares the cost of cement alone with that of cement plus additive. As a basis of comparison, the treatment level of each combination required to give a strength of 300 psi (after 7 days of cure) was

determined from the test data for each soil type tested. The total cost in dollars for stabilizer per cubic yard of treated soil was then computed.

TABLE 10
COST^a COMPARISON OF STABILIZED SOILS WITH CEMENT ALONE AND WITH
CEMENT PLUS ADDITIVE FOR A REQUIRED 7-DAY STRENGTH OF 300 PSI

Soil	Cement Content % by Dry Soil Wt	Additive	Additive Concen- tration % by Dry Soil Wt	Stabilizer and Addi- tive Cost ^b per Cu Yd Stabilized Soil	Percent Saving in Material Cost by Using of Additive over Cement Alone
New Hamp- shire silt	11.0 7.5 6.5 5.0	— NaOH Na ₂ CO ₃ Na ₂ SO ₄	— 0.9 1.0 0.8	\$3.21 3.18 2.60 1.86	— 1 19 42
Wisconsin sand 2 (WS2)	13.0 7.0 10.5 ^c 9.0 9.5	— Na ₂ SiO ₃ CaCl ₂ NaOH Na ₂ SO ₄	— 1.0 0.6 0.5 0.5	3.89 3.73 3.47 3.34 3.13	— 4 10 14 19
Iraq clay 1 (IrCl)	18.5 12.0	— Na ₂ CO ₃	— 1.0	5.00 4.07	— 19
Iraq silty clay (IrSC)	18.5 13.0	— NaOH	— 1.0	5.43 5.19	— 4
Wisconsin sand 1 (WS1)	20.0 16.0 ^c 12.5 9.0	— CaCl ₂ Na ₂ SO ₄ Na ₂ SO ₄	— 0.6 0.5 1.1	5.62 4.94 3.96 3.27	— 12 30 42

^aCosts of chemical additives are obtained from O:l, Paint and Drug Reporter Weekly, Oct. 27, 1958. Cement price based on bulk truck load price in Massachusetts, November 1958.

^bThe cost estimates of cement and additive are for 1 cu yd of compacted stabilized soil with compacted dry density of 100 pcf for NHS, IrCl, 105 pcf for WS1, WS2 and 110 pcf for IrSC.

^cCompositions recommended by PCA based on durability tests.

Table 10 clearly shows that considerable financial saving can be realized by the use of additives. In addition to the lower material cost resulting from the use of small quantities of additives, there will also be savings on material handling and processing.

A further advantage of the use of additives is that considerable construction and cure time can be saved because a number of the chemicals accelerate the rate of strength development of soil-cement.

Moreover, it should be noted that the cement-additive concentrations required to produce a 300 psi strength are estimated on the basis of strength data obtained with constant density compaction. It has been in-

indicated previously (Lambe and Moh, 1957) that the addition of a small amount of sodium additive, in general, slightly increases the compacted density of soil-cement. A slight increase in density will often cause a significant improvement in strength. Hence, the estimated savings realized in practice can even be greater than those indicated in Table 10.

THE MECHANISM OF ADDITIVE ACTION IN SOIL-CEMENT

Analysis of the experimental results of this investigation, augmented by a few confirmatory tests outlined below, reveals a pattern of behavior of alkali metal compounds in soil-cement from which an hypothesis of the mechanism of additive-action can be developed. Nine salient facts which bear on such an hypothesis are:

1. Incorporation of the hydroxides and a large number of salts of alkaline metals (sodium, potassium and lithium) in concentrations of 1.0 to 4.0 percent by weight greatly increases the compressive strength of cement-stabilized soils (Fig. 18).

2. All the sodium compounds found to be beneficial to soil-cement are those forming rather insoluble salts with calcium; specifically, sodium hydroxide, carbonate, sulfite, sulfate, metasilicate and aluminate.

3. The effectiveness of sodium compounds on soil-cement varies with soil type, decreasing with increasing soil plasticity and/or organic matter content.

4. Individual soils vary widely in their response to sodium compounds:

- (a) Sodium hydroxide is effective with all soils with low to moderate organic matter content.

- (b) Sodium metasilicate is most effective on clean sandy soils.

- (c) Sodium sulfate is uniquely effective in sandy soils containing organic matter.

- (d) Sodium salts of weak acids are not effective in heavy clays.

- (e) In silty soils the effectiveness of sodium compounds decreases in the order of sulfate > aluminate > metasilicate > carbonate > hydroxide > sulfite.

5. The optimum concentration for sodium compounds in soil-cement appears in most cases to correspond to an alkali concentration of 1.0 normal in the molding water. Higher additive concentrations tend to retard the rate of strength development of soil-cement, but do not alter ultimate strength.

6. The degree of response to additives of various soils increases with the amount of reactive silica present in the soil, as shown in Figure 16.

7. Caustic extraction of a soil to remove part of its "reactive" silica has little effect on its response to cement stabilization but greatly reduces the improvement in strength resulting from the additives. This is given in Table 11.

8. Treatment of soil with additive prior to the addition of cement produces less strength improvement than simultaneous incorporation of additive and cement. This is shown in Figure 17.

9. Improvement in ultimate (fully cured) strength of cement-stabilized silty soils by alkali metal additives becomes less marked at higher cement concentrations; however, improvement in early strength by additive incorporation increases with cement content.

To explain these observations in consistent physicochemical terms, it

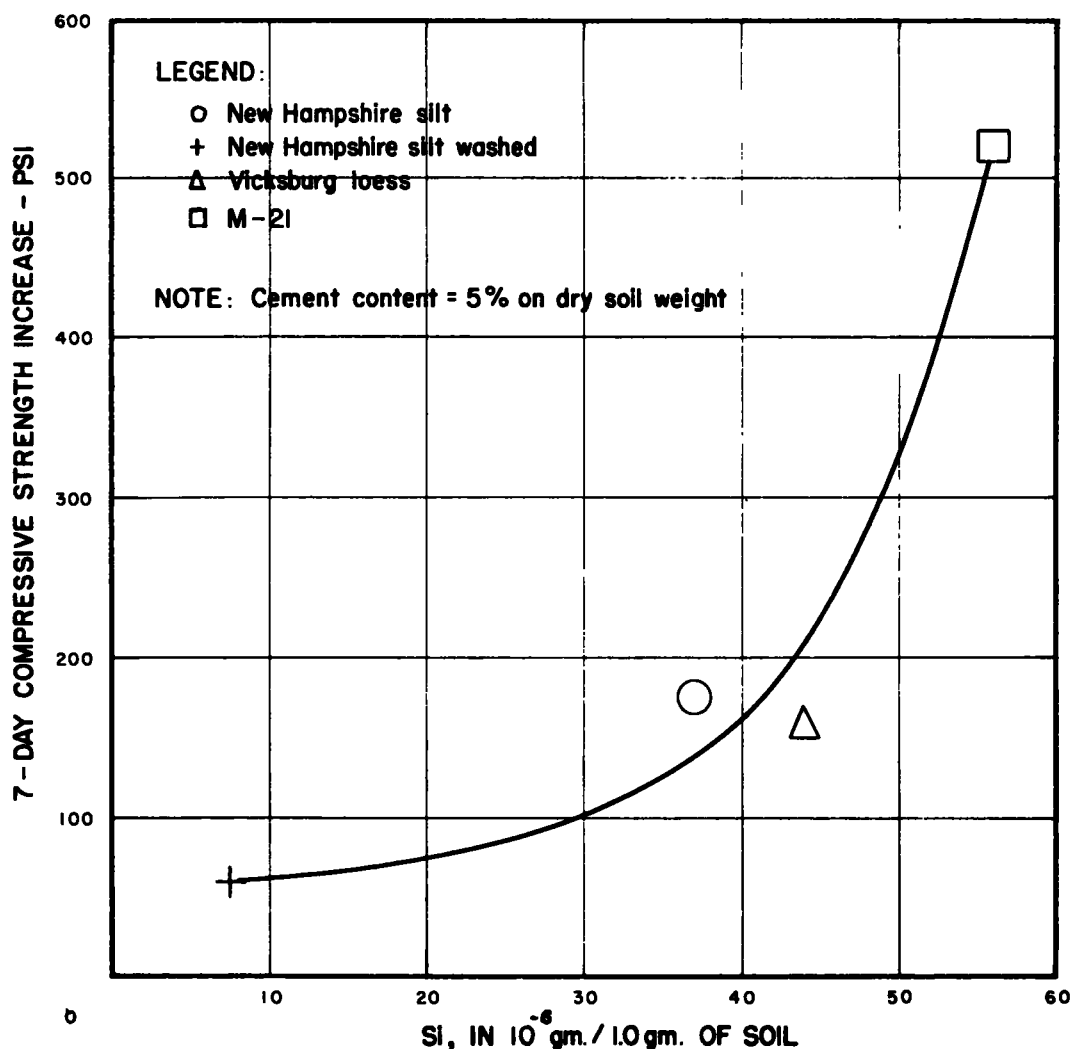


Figure 16. Effect of extractable silica content on the increase in compressive strength of soil-cement treated with 1 percent sodium hydroxide.

is at the outset necessary (1) to define the primary chemical processes which are believed to occur during the hydration of portland cement, (2) to cite some important chemical properties of the alumino-silicate components of soils, and (3) to point out certain interactions of cement with soils which follow from (1) and (2).

According to Bogue (1955), the major hydration products of neat portland cement are (a) hydrated basic calcium silicate, (b) calcium aluminate, and (c) hydrated lime. The first two products constitute the major cementitious components, while the lime is deposited as a separate crystalline solid phase. Basic calcium silicate (Ca:Si ratio of 1.5:1) and aluminate are evidently stable only at a pH equal to or greater than that corresponding to saturated lime water. Reduction in pH (for example, by neutraliza-

TABLE 11
COMPARISON OF COMPRESSIVE STRENGTH OF CEMENT STABILIZED NATURAL AND
TREATED NEW HAMPSHIRE SILT WITH ADDITIVES
Cement Content = 5 percent of Dry Soil Wt

Additive	7-Day Compressive Strength ^a , psi	
	Natural Soil	Treated Soil ^b
No	110	110
1.0% Sodium hydroxide	285	170
1.0% Sodium metasilicate	360	250

^aObtained by unconfined compression test after 7 days moist curing and 24 hr complete immersion.

^bSoil treated with 4N sodium hydroxide solution and washed with distilled water until pH value of the soil was about 7.

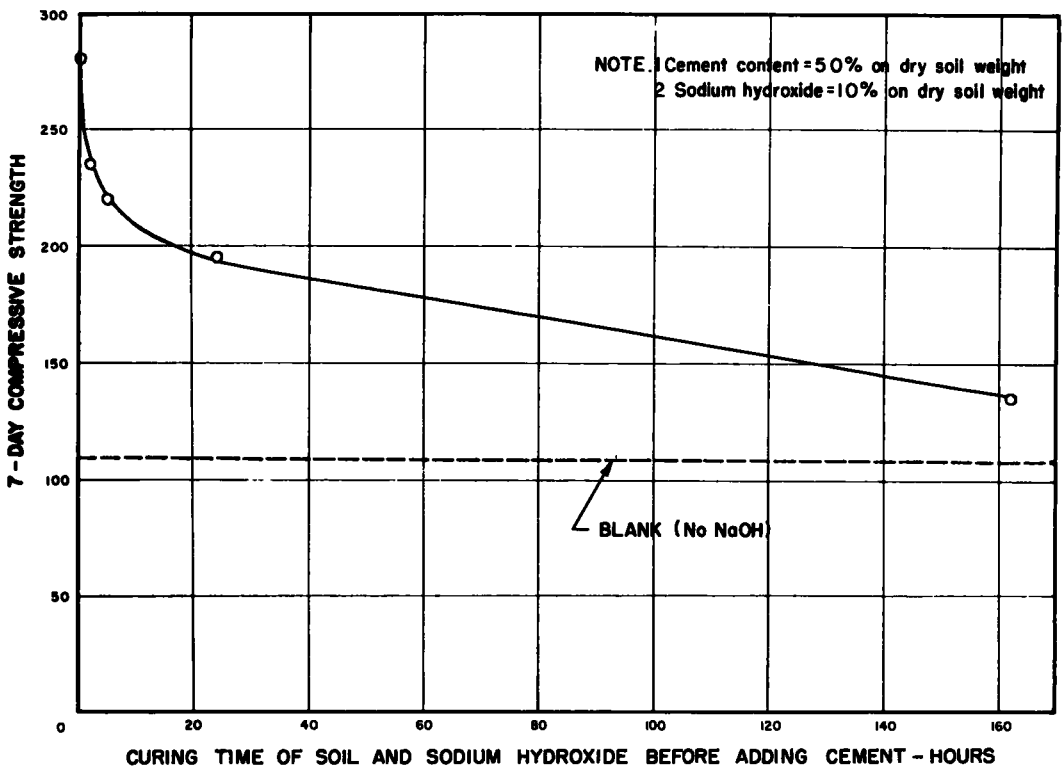


Figure 17. Effect of curing time of sodium hydroxide with New Hampshire silt prior to the addition of cement on 7-day compressive strength.

tion of excess lime) will favor hydrolysis of these salts, with formation of alumina, and of silicate gels with lower Ca:Si ratios. Such pH reduction can eventually occur in neat cement by reaction of lime with atmos-

pheric CO_2 , and in concretes or mortars by reaction of lime with acidic components of the aggregate (mainly, silica).

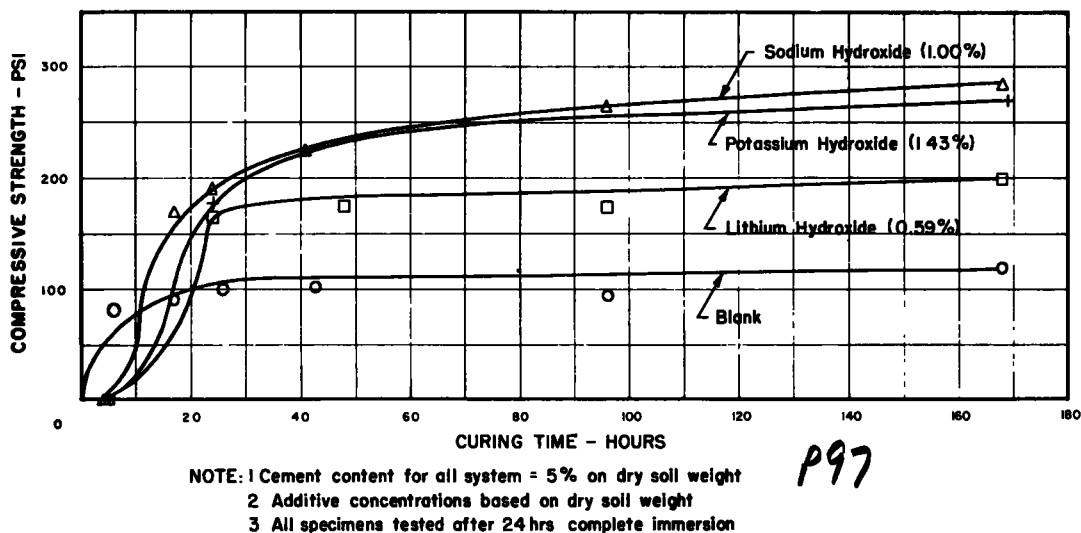


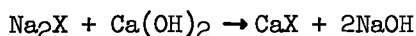
Figure 18. Effect of alkali metal hydroxides on the strength development of cement-stabilized New Hampshire silt.

Most fine-grained soils contain large quantities of crystalline silica, feldspar, or colloidal clay minerals, in a high degree of subdivision. These compounds are inherently acidic in nature, and a small but important fraction of the silica and aluminosilicates present in soils is in a highly reactive, hydrous state on the particle surfaces. When exposed to strong alkalis, soils of this type function as powerful buffers, the surface silica and alumina reacting rapidly with the alkali to form silicate and aluminate salts, and thereby reducing pH. The finer the particle size of the soil, the greater the proportion of reactive silica and alumina available, and thus the more rapid and more extensive its buffering or alkali-consuming capacity.

When cement is admixed with soil and water, hydration of the cement leads initially to the formation of lime, calcium silicate, and calcium aluminate. However, reaction of the lime with reactive silica and alumina from the soil leads to formation of additional calcium silicate and aluminate, reduction of pH, and subsequent hydrolysis of the more basic calcium silicate and aluminate. The ultimate reaction products of soil and cement are surmised to be hydrous alumina, and a calcium silicate gel of rather low Ca:Si ratio. It is to be noted that, in soil-cement, virtually all the reactive calcium present initially in the cement is eventually available for production of cementitious silicate gel; hence, the quantity of cementitious material available for bonding in soil-cement is inherently greater than that in neat cement. Because, however, any lime which reacts with soil silica (or alumina) is immediately immobilized as insoluble silicate, and because cement particles are rather sparsely distributed between soil particles in typical soil-cement, the formation of

cementitious silicate gel can be expected to be confined to a rather thin zone around each cement particle. Only when the cement concentration is high enough to permit these zones of gel formation to overlap will the soil become adequately stabilized.

It has been pointed out that all the alkali metal compounds which are beneficial to soil-cement form insoluble compounds with calcium. This fact, coupled with the observation that the alkali metal silicates and aluminates are highly water-soluble, provides an important clue to the chemistry of additive action. When a compound such as caustic soda, soda ash, sodium sulfite, etc., is added to cement and soil, the calcium ion concentration in solution is greatly depressed either by the common ion effect (with NaOH), or by the causticization reaction:



At the same time, the hydroxyl ion concentration, or pH, is significantly elevated. Suppression of the calcium concentration retards precipitation of insoluble calcium silicate gel, while elevation of pH accelerates attack of soil silica and/or alumina and formation of soluble alkali silicate and/or aluminate. Because the alkali silicate is free to diffuse through the pore fluid, there is opportunity for rather uniform distribution of silicate throughout the soil mass. Eventually, however, neutralization of the free alkali by reaction with the soil reduces the pH and permits the calcium ion to go into solution. Reaction of calcium with the uniformly distributed alkali silicate or aluminate in the pore fluid results in formation of mixed calcium-sodium silicate and gelation. Formation of an increased volume of well-distributed, hydrous silicate gel can thus account for the generally beneficial influence of alkali metal compounds on soil-cement.

In terms of this mechanism, it becomes rather simple to explain why different sodium compounds differ so widely in their effects on various soils. In coarse-grained soils, such as sands, the amount of reactive silica present is small, and thus the amount of cementitious silicate gel which can be contributed by the soil is limited. If gel-forming material can be provided from an external source, however, the reactive silica deficiency of the soil can be compensated for; hence, sodium silicate or aluminate are more effective in sands than other sodium compounds. With heavy clays, on the other hand, there is present a large amount of reactive silica—so much, in fact, that neutralization of alkali by such a soil occurs with great rapidity. When the generation of free caustic soda must result from reaction with lime from the cement as shown above (for example, with soda ash or sodium sulfate), the rate of generation of caustic is likely to be no faster than its consumption by reaction with the soil, so that the pH never becomes greatly elevated. Because of this, the calcium solubility is but little depressed, and calcium silicate formation occurs promptly; hence, uniform distribution of cementitious gel will not occur. If caustic soda is used as the additive, however, the pH is immediately raised to a high level and the calcium concentration correspondingly reduced; rapid formation of sodium silicate and delayed gelation by calcium will thus contribute to more extensive and uniform cementation.

The observation that pretreatment of soil with caustic soda is less beneficial to cement stabilization than its simultaneous incorporation with the cement is also consistent with the preceding picture. Contact of soil with caustic in the absence of cement results in rapid formation of

sodium silicate and rapid reduction of pH. As neutralization of the alkali by the acidic silica continues, the sodium silicate initially formed is reprecipitated; consequently, the alkali metal ceases to be available for silicate solubilization when cement is added.

With soils of intermediate fineness (for example, silts) it is likely that the supply of reactive silica is adequate, and that the rate of reaction of the soil with alkali is sufficiently slow that the reaction with lime can proceed virtually to completion before the free caustic is consumed. Under these circumstances, it is of relatively little importance which sodium compound is employed, at least in terms of ultimate strength development. Results with New Hampshire silt appear to bear out this prediction.

The observation that, in all soils studied, all sodium compounds (except the aluminate) show maximum strength-improvement at a concentration of roughly 1.0 normal in the pore water, merits more than casual attention. It can be inferred from this that there is an optimum concentration of sodium ion (irrespective of the anions which are present in the pore water, although in most instances the most prevalent anion is probably hydroxyl) at which adequate production of soluble silicates will occur in the presence of cement hydration products. Any amount of sodium in excess of this will not contribute further to generation of potential cementing material, but will merely reduce the calcium solubility further, and retard development of cementitious calcium silicate gel. The further observation that excessive treatment with sodium compounds (up to 2.0 N) does not affect ultimate strength, but significantly retards cure is also consistent with this argument. The anomalous behavior of sodium aluminate is not clear, although it is possible that the alumina formed from this compound plays a direct part in gel-formation. It has also been observed that the degree of retardation of cure by sodium compounds (particularly when present in excess) increases as the solubility of the corresponding calcium salt decreases. This is consistent with the present hypothesis, because the more insoluble the calcium salt is formed, the more the initial calcium ion concentration in the pore fluid is depressed and the longer time is required for the conversion of the alkali silicate to calcium silicate gel. The detrimental effect of sodium fluoride and sodium tetraborate on soil-cement appears to be a consequence of extreme suppression of calcium ion concentration: calcium fluoride is one of the most insoluble of all calcium salts, and tetraborate ion forms with calcium a soluble but extremely stable chelate with a very low ionization constant. Another source of difficulty with fluorine-bearing additives arises from the ability of fluorine to replace oxygen in the silica tetrahedral unit; such replacement prevents formation of polysilicate ions, and thus discourages silicate gel formation. This may account for the detrimental effect of sodium fluosilicate. Because, however, the affinity of boron for fluoride ion is greater than that of silicon, the fluoborate ion may retain its identity in the presence of silicates; this may explain the beneficial action of sodium fluoborate relative to other fluorine-bearing additives.

The unique action of sodium sulfate in promoting strength development of cement-stabilized, organic-containing sand demands special comment. It is generally believed that the detrimental effect of organic matter on soil-cement results from the complexing of calcium from the cement by organic carboxylic acids or phenolic compounds, with consequent delay in, or

prevention of, the formation of a continuous, coherent silicate gel. These deleterious organic compounds are relatively insoluble in water at normal pH's, but are solubilized by lime, caustic soda, and other alkalis. Clearly, their ability to interfere with cementitious gel formation will depend on the degree to which they are rendered water-soluble and distributed through the soil pore water. Observations of the behavior of stabilized soil samples on water immersion indicate that, whereas caustic soda increases the solubility of organic matter, sodium sulfate reduces it relative to cement alone. This suppression of the solubility of organic matter by sodium sulfate in the presence of cement may thus be the major reason for the beneficial action of this salt. One possible explanation for suppression of the solubility of organic matter by sodium sulfate may be as follows: immediately upon incorporation of this neutral salt with soil and cement, the calcium ion concentration in the pore water is depressed without significant elevation of the pH, and the sodium and sulfate ion concentration is high. This condition favors reaction of sodium with the organic acid bodies relative to calcium, but the high total electrolyte concentration in the pore water prevents swelling and dissolution of the organic matter by "salting-out" action. As the causticization reaction with cement ensues, and the sulfate ion concentration is reduced with consequent rise in pH, conditions for dissolution of the organic matter become more favorable; however, formation of sodium and calcium silicate is now taking place simultaneously, and there is opportunity for formation of cementitious gel before significant amounts of calcium can be complexed by the organic components. The uniqueness of sodium sulfate in this situation arises from the fact that it is a neutral salt and a good hydrotrope, yet is capable of causticizing with lime.

It is pertinent to inquire whether the foregoing hypothesis of additive action in soil-cement permits any prediction of the long-term stability of modified soil-cement relative to that of cement-stabilized soil without additives. In unmodified soil-cement, it is reasonable to expect that ultimate end products of hydration will be hydrous calcium silicate and alumina; because of the acidic character of aluminosilicate soils, the calcium silicate gel produced will undoubtedly be of rather low Ca:Si ratio—certainly far lower than that found in neat cement. Incorporation of alkali metal compounds can be expected to (a) increase the quantity of silica participating in gel-formation, (b) produce a silicate gel containing both sodium and calcium, and (c) reduce the amount of calcium available for silicate formation if the calcium salt of the corresponding anion is less soluble than the silicate. The ultimate cementitious phase formed with the additives will thus be more voluminous, but also somewhat more water-soluble (due to its alkali metal content) than that formed with cement alone. Increased water solubility of the gel would be expected to result in poorer resistance to leaching; fortunately, however, hydration studies of mixed sodium-calcium silicates have indicated that a significant increase in water solubility does not develop until the sodium-calcium ratio in the gel reaches a very high value. Under the circumstances encountered in modified soil-cement, therefore, it would appear that the final cementing phase should be virtually as durable as that found with cement alone.

In summary, the hypothesis herein proposed attributes the beneficial action of additives to enhanced participation of soil-derived silica in the cement-hydration process. Alkali metal compounds exert their major influence on cementation in soils at the earliest stages of the cure proc-

ess by promoting silica solubilization and retarding calcium silicate precipitation, but have relatively little effect upon the composition of the final cementing components. Although much of the evidence supporting this picture is admittedly circumstantial, the proposed mechanism at least provides a basis for a more detailed chemical analysis of cement stabilization, which is now in progress. An entirely satisfactory explanation of additive action in soil-cement must await these results.

CONCLUSIONS

The laboratory test results presented in this paper show that a very large increase in the strength of soil-cement mixtures can be obtained by the addition of low-level treatments of certain chemicals. Preliminary analyses suggest that both a considerable financial saving and a successful stabilization of soils which normally cannot be stabilized economically can result from the use of additives with soil-cement.

Detailed conclusions are as follows:

1. The rate of strength development of soil-cement-alkaline sodium compounds depends on the nature of the additives—metasilicate, aluminate and sulfate gave the fastest cure.
2. Sodium hydroxide was effective in improving the strength of all cement-soils (the soils tested varied from non-plastic sands to heavy clays with low to moderate organic matter content).
3. Sodium metasilicate was the most effective on the clean sandy soils.
4. Sodium sulfate was uniquely effective on sandy soils with organic matter.
5. Sodium salts of weak acids (that is, carbonate and sulfite) were not effective in heavy clays in the concentration ranges studied.
6. The effectiveness of sodium compounds decreased with increasing plasticity and/or organic matter of the soil.
7. Soil containing free sodium chloride was much less responsive to cement-stabilization than was the same soil after salt removal.
8. The effectiveness of sodium hydroxide was in the same order of magnitude for soil containing free sodium chloride as for the same soil after salt removal.
9. The presence of a small amount of organic matter in sandy soils interfered with cement stabilization.
10. The treatment level of sodium additives for maximum strength of the fine-grained soils was that corresponding to a sodium concentration in the molding water of roughly one normal (23 gm Na per liter).
11. The rate of strength development of soil-cement was very sensitive to additive concentration, increasing greatly in the range of 0 - 1.0 normal and generally decreasing in the range of 1.0 to 2.0 normal (except aluminate).
12. The final strength (28-day) of additive treated soil-cement was virtually independent of additive concentration when the latter was above a certain minimum (0.5 to 1.0 normal).
13. The strength increase of soil-cement due to addition of alkaline sodium compounds appeared to be permanent.
14. With silty soils, the strength improvement produced by sodium additives became smaller at higher cement contents.
15. The magnitude of strength increase obtained by addition of alkaline sodium compounds appeared to increase with the amount of reactive silica (or silicates) present in a soil.

16. Pretreatment of silty soils with caustic soda diminished the beneficial effects obtained by the incorporation of this additive simultaneously with the cement.

17. Hydroxides or weak-acid salts of any alkali metal or cation which yields soluble silicates (or aluminates) are beneficial to soil-cement.

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Suggestions from R. T. Martin of the M.I.T. Soil Engineering Division have aided the research. Some of the results reported were obtained by I. Arango, graduate student in Soil Engineering, M.I.T., in connection with his M.S. Thesis.

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DISCUSSION

L. T. NORLING and R. G. PACKARD, Soil-Cement Bureau, Portland Cement Association—This paper presents valuable data on the use of chemical admixtures with soil-cement. The improvement in compressive strength of two types of "problem" soils (heavy clays and poorly-reacting sands) is particularly significant.

As mentioned, the Portland Cement Association's Soil-Cement Laboratory has studied the effect of the additives on durability as measured by the standard freeze-thaw and wet-dry tests for soil-cement. Four soils were studied, using with each soil one or two of the chemical admixtures that produced significant improvement in compressive strength. This discussion gives the results of these durability tests.

Further tests to evaluate the permanency of the improvement due to the addition of chemical admixtures are under way. These include compressive strength and outdoor weathering tests.

MATERIALS

Soils

Durability tests were run, using the following soils:

1. "Poorly-reacting" Wisconsin sand No. 1 (No. 1056).
2. Illinois clay (No. 1055).
3. New Hampshire silt (No. NHS).
4. Massachusetts clayey silt (No. M21).

The characteristics of these soils are summarized in the authors' Table 1.

Cement

Type I portland cement, consisting of a blend of four brands purchased on the open market in the Chicago area, was used.

Chemical Admixtures

One or two chemical admixtures (reagent grade) producing significant improvement in compressive strength, based on the authors' data and similar tests in the PCA laboratory, were used with each soil:

1. Sodium sulfate with the Wisconsin sand No. 1.
2. Sodium hydroxide with the Illinois clay.
3. Sodium sulfate and sodium metasilicate with the Massachusetts clayey silt.
4. Sodium hydroxide with the New Hampshire silt.

TEST METHODS

Moisture-density relationships for the soil-cement and soil-cement-chemical additive mixtures were determined using ASTM D558-57 or AASHTO T134-57. Results of these tests showed that neither the type nor concen-

tration (up to 2 percent) of additive nor cement contents ranging from 5 to 14 percent had any significant effect on moisture-density relationships. Average values of maximum density and optimum moisture at chemical additive content of 1.0 percent are given in Table 12. (In this discussion, chemical contents are based on percent by weight of dry soil.)

TABLE 12
MOISTURE-DENSITY DATA FOR SOIL-CEMENT-CHEMICAL ADDITIVE^a MIXTURES

Soil	Cement Content, % by wt	Maximum Density, pcf	Optimum Moisture, % by wt
Wisconsin sand (1056)	14	101.3	17.7
Illinois clay (1055)	14	107.0	14.8
New Hampshire silt (NHS)	10	100.8	19.1
Massachusetts clayey silt (M21)	10	123.0	10.8

^aChemical additive content is 1 percent by weight of dry soil.

Test specimens were then molded at maximum density and optimum moisture content and tested using the freeze-thaw test (ASTM D560 or AASHTO T136) and the wet-dry test (ASTM D559 or AASHTO T135).

The cement requirements of the soil-cement and soil-cement-chemical additive mixtures were determined, using the usual soil-cement loss criteria. (Soil-cement losses during 12 cycles of either the freeze-thaw or wet-dry test shall conform to the following limits: (a) soil groups A-1, A-2-4, A-2-5 and A-3, not over 14 percent; (b) soil groups A-2-6, A-2-7, A-4 and A-5, not over 10 percent; and (c) soil groups A-6 and A-7, not over 7 percent.)

After completion of the freeze-thaw and wet-dry tests, and after 2-day saturation in water, the specimens were broken in compression. Weight losses and compressive strengths determined by these tests are given in Table 13. Results of wet-dry tests are omitted because only a minimum number of specimens were molded and they showed the same trend as the freeze-thaw test results. The data are also plotted separately for each soil in Figures 1-4.

DISCUSSION OF RESULTS

Wisconsin Poorly-Reacting Sand No. 1 (No. 1056)

Soil-cement losses incurred during the freeze-thaw test and compressive strengths of the specimens after test, are given in Figure 1.

Specimens containing 14, 16 and 18 percent cement by weight with no additive failed completely, having a loss of 100 percent. When 1 percent sodium sulfate was added, 9 percent cement was required to hold the weight loss down to a maximum allowable 14 percent. (When 2 percent sodium sulfate was added, the cement requirement was 10 percent.) Thus 1 percent sodium sulfate reduced the cement requirement of this poorly-reacting sand from a quantity over 20 percent down to 9 percent. Results of the compressive strength tests on these specimens likewise indicated improvement due to the addition of sodium sulfate.

TABLE 13
RESULTS OF FREEZE-THAW TESTS

Soil	Cement Content, % by wt	Soil-Cement Loss—%				Strength After Test—psi			
		No Additive	0.6% CaCl ₂	1.0% Na ₂ SO ₄	2.0% Na ₂ SO ₄	No Additive	0.6% CaCl ₂	1.0% Na ₂ SO ₄	2.0% Na ₂ SO ₄
Wisconsin sand (1056)	8	-	-	16	28	-	-	278	112
	10	-	100	11	11	-	0	342	382
	12	-	35	9	6	-	298	503	485
	14	100	5	-	-	0	397	-	-
	16	100	-	-	-	0	-	-	-
	18	100	-	-	-	0	-	-	-
		No Additive	0.5% NaOH	1.0% NaOH		No Additive	0.5% NaOH	1.0% NaOH	
Illinois clay (1055)	6	-	27	-	-	211	-	-	
	8	-	10	23	-	352	196	-	
	10	6	5	14	564	550	278	-	
	12	4	-	10	652	-	387	-	
	14	4	-	-	705	-	-	-	
		No Additive	1.0% NaOH		No Additive	1.0% NaOH			
New Hampshire silt (NHS)	9	-	17		-	692			
	12	-	9		-	684			
	15	15	7		613	990			
	18	1	-		1097	-			
		No Additive	1.0% Na ₂ SO ₄	1.0% Na ₂ SiO ₃ ·9H ₂ O	No Additive	1.0% Na ₂ SO ₄	1.0% Na ₂ SiO ₃ ·9H ₂ O		
Massachusetts clayey silt (M-21)	6	32	7	7	-	1193	1177		
	9	4	4	5	1161	2625	1591		
	12	3	-	-	1750	-	-		
	15	1	-	-	2450	-	-		

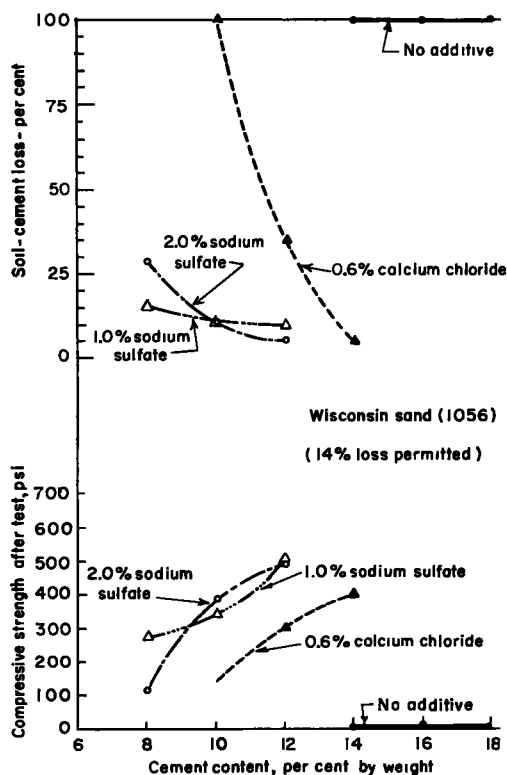


Figure 19. Effect of sodium compound admixtures on resistance of soil-cement to freezing-and-thawing—Wisconsin sand.

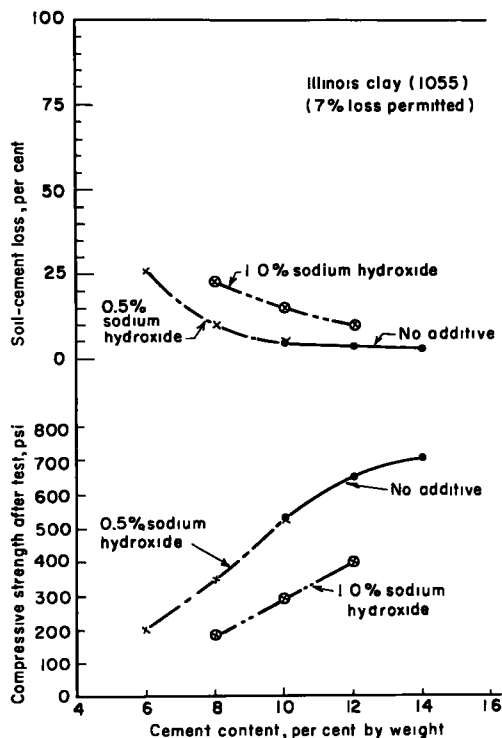


Figure 20. Effect of sodium compound admixtures on resistance of soil-cement to freezing-and-thawing—Illinois clay.

Calcium chloride is commonly used to reduce the cement requirement of poorly-reacting sands. As a basis of comparison, results of tests using calcium chloride are also plotted in Figure 19. With the addition of 0.6 percent calcium chloride, 13.5 percent cement is required. Thus, sodium sulfate was more effective than calcium chloride in improving the reaction of this poorly-reacting sand.

Illinois Clay (No. 1055)

Data for the Illinois clay are plotted in Figure 20. With no additive, using a maximum allowable soil-cement loss of 7 percent, this soil requires somewhat less than 10 percent cement. When 0.5 percent sodium hydroxide is added, 9.5 percent cement is required. With the addition of 1.0 percent sodium hydroxide, slightly more than 12 percent is required. Thus, the addition of 0.5 percent sodium hydroxide did not significantly improve the durability of this clay while 1.0 percent sodium hydroxide was detrimental. Compressive strengths of the specimens after test also show the same trend. For example, after test, the strength of the specimen containing 10 percent cement with no additive is 564 psi. The strength at this same cement content with 0.5 percent sodium hydroxide added is similar (550 psi) while the strength of the specimen containing 1.0 percent sodium hydroxide is only 278 psi.

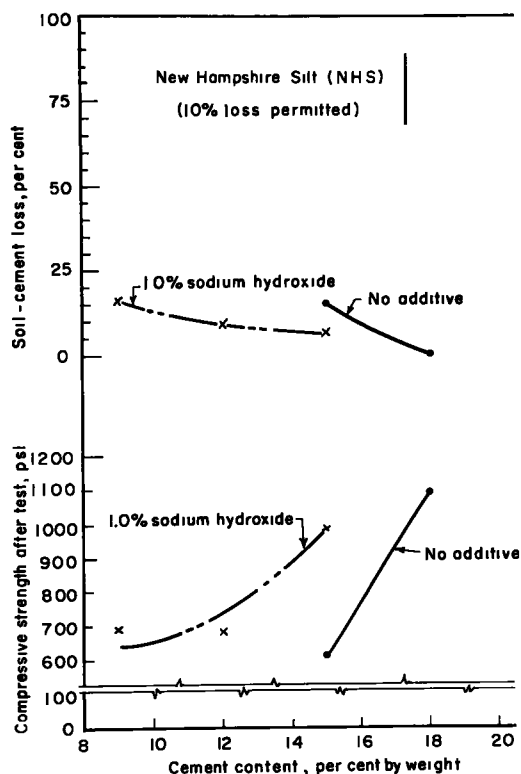


Figure 21. Effect of sodium compound admixtures on resistance of soil-cement to freezing-and-thawing—New Hampshire silt.

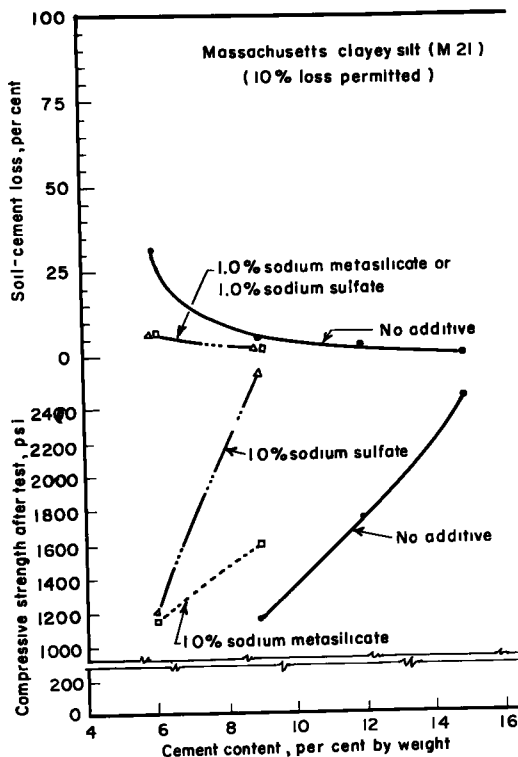


Figure 22. Effect of sodium compound admixtures on resistance of soil-cement to freezing-and-thawing—Massachusetts clayey silt.

New Hampshire Silt (No. NHS)

Data for the New Hampshire silt are plotted in Figure 21. Using a maximum allowable soil-cement weight loss of 10 percent, this soil requires 16 percent cement with no additive. The addition of 1.0 percent sodium hydroxide reduces this cement requirement to 12 percent representing a savings of 4 percent cement.

The compressive strengths after test also show that considerable benefit is obtained by adding 1.0 percent sodium hydroxide. For example, the strength at 15 percent cement with no additive is 613 psi, while the strength at this cement content with 1.0 percent sodium hydroxide is 980 psi.

Seven-day compressive strengths indicate that sodium sulfate or sodium metasilicate may be as effective with this soil as sodium hydroxide. Durability tests to determine whether or not this is true are under way.

Massachusetts Clayey Silt (M21)

Data for the Massachusetts clayey silt are plotted in Figure 22.

With no additive, using a maximum allowable soil-cement loss of 10 percent, this soil requires 8.5 percent cement. Somewhat less than 6.0

percent cement is required when 1.0 percent sodium sulfate or sodium metasilicate are added. The compressive strengths of the specimens after test also show beneficial effects from the addition of the chemical additives.

SUMMARY

The authors present data which show that the addition of certain chemical admixtures to soil-cement may increase the compressive strengths. The Portland Cement Association's Soil-Cement Laboratory has run tests to determine the effect of the chemical admixtures on durability. The results indicate that the effects of the admixtures on durability, as measured by the standard freeze-thaw and wet-dry tests, were similar to the effects on compressive strength.

1. The addition of 1 percent sodium sulfate reduced the cement requirement of the Wisconsin poorly-reacting sand from over 20 percent to 9 percent. The addition of 2 percent sodium sulfate reduced the cement requirement to 10 percent. Sodium sulfate was more effective than calcium chloride in improving this poorly-reacting sand.

2. The addition of 0.5 percent sodium hydroxide to the Illinois clay did not significantly reduce the cement requirement. The addition of 1.0 percent sodium hydroxide was detrimental, because it increased the cement requirement of the clayey soil from 10 percent to 12 percent.

3. The addition of 1.0 percent sodium hydroxide to the New Hampshire silt reduced its cement requirement from 16 percent to 12 percent.

4. The addition of 1.0 percent sodium sulfate or sodium metasilicate reduced the cement requirement of the Massachusetts clayey silt from 8.5 percent to less than 6 percent.

Further tests to evaluate the permanency of the improvement due to the chemical admixtures are under way. These include compressive strength and outdoor weathering tests.

T. W. LAMBE, A. C. MICHAELS, AND Z. C. MOH, Closure—The authors' evaluation of the beneficial effects of trace additives to portland cement as a soil stabilizer was based entirely on strength tests. One may well question whether strength tests alone constitute a fair measure of the potential effectiveness of trace additives. The discussion by Norling and Packard presents weathering data which correlate very well with the strength data presented by the authors. The discussers have thus contributed significantly to the value of the paper by showing that strength tests do indeed give a good measure of the beneficial effects of the trace additives and that the conclusions drawn by the authors are thus valid for resistance to weathering as well as for strength. From both strength and weathering data, the additives appear most promising. The authors are indebted to the discussers for their contribution.