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by

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STABILIZATION OF SOILS WITH FLY ASH ALONE

by

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Stabilization of Soils with Fly Ash Alone

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Fly ash reacts with lime to form a cementing material used to strengthen soils for the construction of bases and subbases for pavements. To sustain the cementitious reaction, lime must be added or supplied to the fly ash. Nevertheless, a survey of fly ashes revealed that some of them contain cementing materials—lime or other products—in a quantity sufficient for good strength. The stabilization of soils with fly ashes that do not need added lime should be a very competitive method when the transportation cost of the fly ash is within economical limits. This paper presents the results obtained with several fly ashes used without lime to stabilize several soils with different textures.

•SOIL STABILIZATION, a relatively new science, aims at the improvement of the engineering characteristics of soils, either by physical means or by treating the soils with different products. Some of the successful stabilizing agents are cement, lime, and lime plus fly ash. Fly ash, an artificial pozzolan, reacts with lime to produce strength through cementation (1).

The stabilization of soils with lime and fly ash is a well-known process used in the construction of pavements for roads, airfields and parking lots. The advantages of this method of soil stabilization stem from the fact that fly ash is a waste product of power plants and is available at a low price. However, from 2 to 9 percent lime is added, bringing this method to a cost comparable to that of other methods of soil stabilization.

Although the general understanding is that fly ash reacts only with lime, exploratory studies showed that some fly ashes produce strength without the addition of lime (2). Extensive studies made with two cementitious fly ashes in the stabilization of several soil materials are presented in this investigation.

MATERIALS

Fly Ashes

Preliminary studies were made using several fly ashes selected from a group of 21 fly ashes extensively studied by the author (3, 4, 5). Five fly ashes were found to produce an adequate cementation of a sandy soil, and two of these fly ashes gave such high strengths that they were further evaluated with a variety of soil materials. The analyses of the five fly ashes are given in Table 1.

Fly Ash A.—This sample was collected by mechanical precipitators (cyclone type). The coal was from Missouri and was pulverized and burned in suspension in Combustion Engineering boilers. The sample was from Montrose Station Power Plant of the Kansas City, Mo., Power and Light Company.

Fly Ash B.—This sample was collected by mechanical precipitators (multicone dust collectors). The coal was from Iowa, unwashed, pulverized and tangential fired. The sample was from the Des Moines Power Plant of the Iowa Power and Light Company.

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TABLE 1

ANALYSIS OF FLY ASHES

Fly Ash Designation	Analysis (%)							Passing No. 325 Sieve (%)	Spec. Grav. (g/cm^3)	Spec. Surf. (cm^2/g)
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	C			
A	39.2	30.2	11.9	11.6	0.8	1.9	2.8	57.4	2.33	1,730
B	40.1	36.6	13.1	5.8	0.3	2.4	0.2	31.8	2.82	1,460
C	35.3	43.4	7.8	5.3	0.9	1.4	3.8	64.8	2.69	2,048
D	40.5	20.8	12.4	10.6	0.3	2.0	7.8	57.6	2.44	2,109
E	51.2	20.2	10.0	6.3	1.6	1.7	1.0	80.7	2.34	2,539

TABLE 2

ANALYSES OF SOILS

Soil	Passing Sieve (%)[a]						Liquid Limit (%)	Plasticity Index
	¾ in.	No. 4	No. 10	No. 40	No. 100	No. 200		
Sonon limestone	100	32	15	6	4	3	-	NP
Rapid limestone	100	30	17	8	7	6	-	NP
Limestone screenings	100	98	68	48	29	19	-	NP
Bottom furnace ash	100	100	65	18	7	3	-	NP
Dune sand	100	100	100	ND	ND	4	-	NP
Colfax sand-loess mix	100	100	100	ND	ND	29	19	3
Friable loess	100	100	100	100	99	98	32	7
Gumbotil	100	100	100	97	93	81	76	50

[a]ND = Not determined.

TABLE 3

COMPRESSIVE STRENGTH RESULTS OF DUNE SAND-FLY ASH MIXTURES[a]

Fly Ash	Curing Period (days)	Compressive Strength (psi)			
		80:20[b]	73:27[b]	65:35[b]	100:0[b]
A	7	102	138	172	310
	28	193	273	378	746
	90	288	440	606	982
B	7	46	51	51	150
	28	136	217	288	665
	90	272	452	593	1,110
C	7	26	41	43	ND
	28	43	89	145	392
	90	74	175	298	702
D	7	60	69	74	ND
	28	110	152	192	276
	90	244	267	350	475
E	7	33	66	95	ND
	28	43	101	167	196
	90	51	138	201	238

[a]Cured at 71 F. [b]Sand to fly ash.

Fly Ash C.—This sample was collected by mechanical precipitators (cyclone type). The coal was from Missouri and Kansas mines. The coal was pulverized and burned in suspension in Combustion Engineering boilers. The sample was sent from the Hawthorne Station Power Plant of the Kansas City, Mo., Power and Light Company.

Fly Ash D.—This sample was sent by the Kansas City, Mo., Power and Light Company. No data are available on the source.

Fly Ash E.—This sample was collected by electrical precipitators. The coal was from southern Illinois and was crushed in a bowl crusher. The sample was from the Meramec Station Power Plant of the Union Electric Company of Saint Louis, Mo.

Soils

Eight different kinds of soil materials and aggregates were selected to represent a wide variety in physical and chemical characteristics; their analyses are given in Table 2.

PROCEDURES

The soils were air dried and the soil aggregations broken down by grinding. The dried soils were mixed with the dry fly ash in a laboratory mixer for 0.5 min. Test specimens of the two crushed limestone soils, 4 in. in diameter by 4.6 in. in height were molded according to ASTM Specification D 558-57 (6). Test specimens of the other six soils, 2 in. in diameter by 2 in. in height, were molded with the Iowa State Compaction Apparatus (1, 2, 3, 4, 7) to a maximum density close to that of the other samples. Specimens were molded at several moisture contents.

After molding, the specimens were wrapped in waxed paper, sealed with cellophane tape, and stored for curing in a moist room at 71 ± 3 F and greater than 90 percent RH. The specimens were cured for 7, 28 and 90 days, followed by immersion in water for 1 day. They were then tested under unconfined compression to determine their maximum water stable strength.

RESULTS

Part of the preliminary studies made using fly ashes and a dune sand soil are presented in Table 3. The results indicate that some fly ashes alone can cement soil particles. Two of the five fly ashes (A and B) gave such high strengths that they could be used with the dune sand in the construction of base and subbase courses for pavements.

These two fly ashes were further evaluated with more soils (Figs. 1 to 4). Strengths of 400 psi or more were obtained after 28 days curing with six of the soils. The only two soils that gave 28-day strengths lower than 400 psi were the friable loess and the gumbotil (Fig. 4). However, these soils are not satisfactory, stabilized even with fly ash plus added lime (1, 5).

In recent studies with soil-cement mixtures (8), it has been found that a 7-day laboratory unconfined compressive strength of 453 ± 22 psi is adequate for a base course. If it is assumed that the same strength requirements are valid for soil and

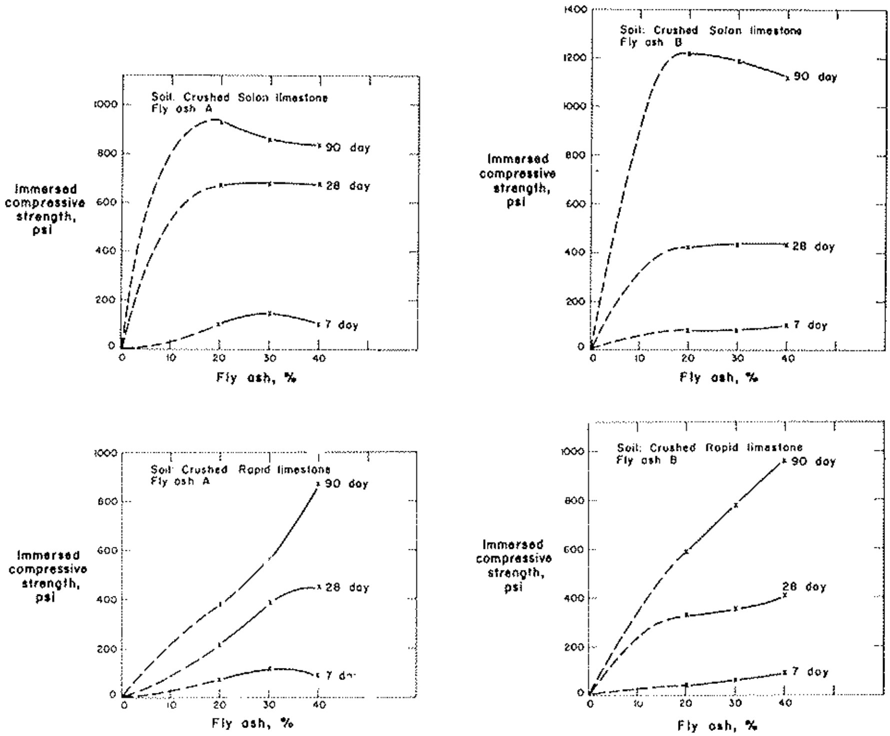

Figure 1. Immersed unconfined compressive strength of soil-fly ash mixtures moist cured for 7, 28 and 90 days.

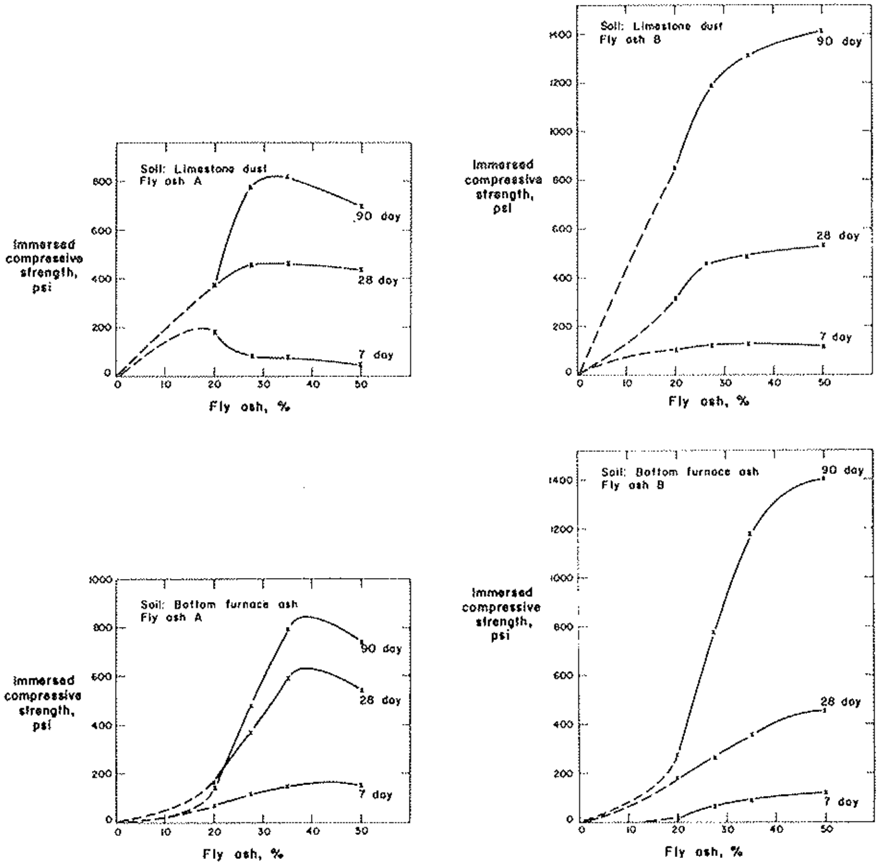

Figure 2. Immersed unconfined compressive strength of soil-fly ash mixtures moist cured for 7, 28 and 90 days.

fly ash mixtures cured for 28 days, fly ashes A and B can be used with six of the soils in the construction of base courses for pavements.

It should be emphasized that the strength of most of the soils treated continued to increase after 28 days, reaching strengths of 1,000 psi or more after 90 days of curing. The 7-day strengths are very low, usually about 100 psi, but this is true also for soils stabilized with lime plus fly ash (1, 5).

MECHANISM

Fly ash is a by-product of the power plants burning powdered coal. The suspended noncombustibles during the burning process are subjected to very high temperatures, such that individual mineral grains melt to form individual grains of fly ash. Possibly marly materials in the fly ash suffer changes in structure during the burning process similar to those in the formation of portland cement clinker, although this is highly speculative and has not been verified by X-ray analysis. Fly ash can thus be a kind

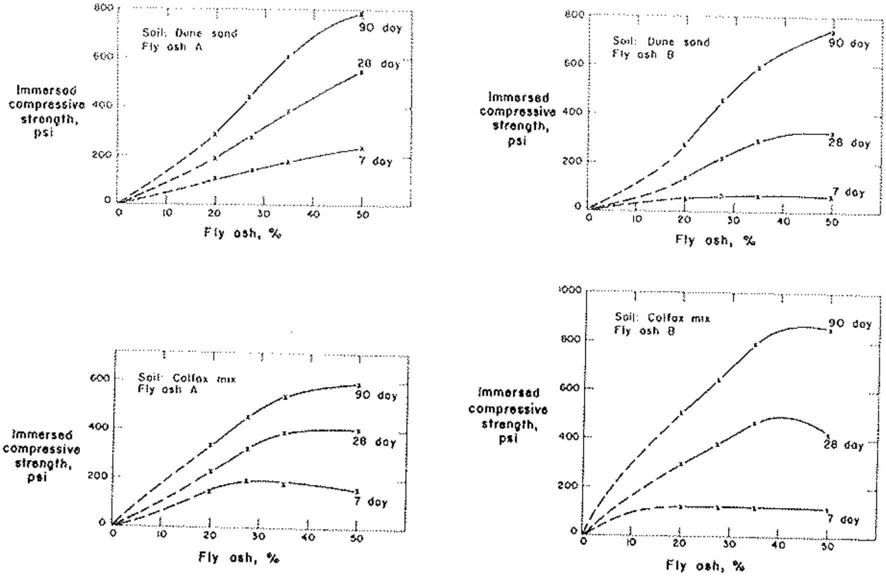

Figure 3. Immersed unconfined compressive strength of soil-fly ash mixtures moist cured for 7, 28 and 90 days.

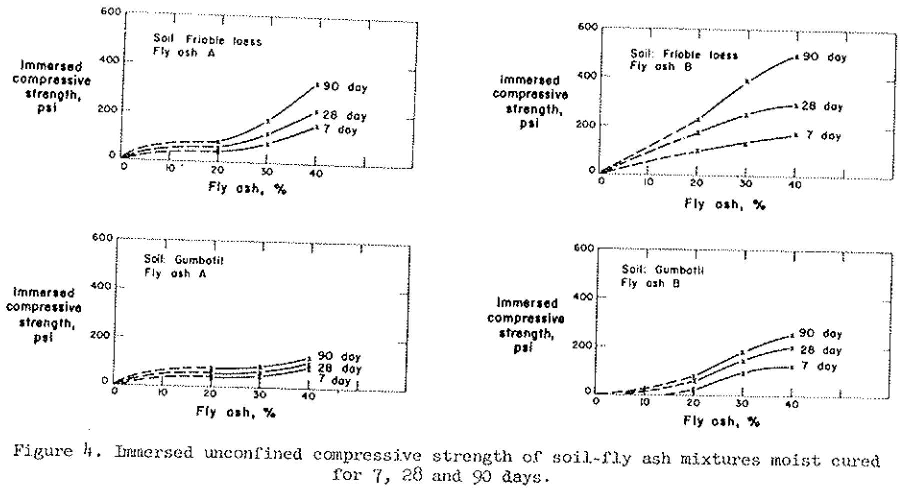

Figure 4. Immersed unconfined compressive strength of soil-fly ash mixtures moist cured for 7, 28 and 90 days.

of cement similar to ground clinker. Because the fly ash is minute, the particles may not require grinding to act with water as a cementing agent.

Free lime may already be present in the reactive fly ashes, so that none must be added for the lime-fly ash reaction to occur. Small amounts of free lime were found by chemical analysis (Table 1), and $Ca(OH)_2$ has been found in X-ray traces.

TABLE 4

COMPRESSIVE STRENGTH RESULTS OF SPECIMENS OF FLY ASH[a]

Fly Ash	Compressive Strength (psi)	
	1 Day	3 Days
A	876	923
B	687	827
C	445	570
D	205	242
E	167	220

[a]Curing period under steam at 248 F and 1 atm pressure.

SELECTION OF FLY ASHES

The choice of a fly ash to be used in concrete or in mixtures with lime is difficult because the strength and other requirements of fly ash are difficult to predict from physical or chemical characteristics (3). The ASTM has set standards for selecting a fly ash for such uses, but these standards need revision (3, 4).

A fly ash to be used alone in the stabilization of a soil should be carefully chosen. The best way to determine the suitability of a fly ash is to mold specimens under different moisture contents for several soil and fly ash combinations and cure them under standard conditions, up to 90 days. Selection can be made more simply by a quick test using steam to cure the specimens (4, 9). Specimens of fly ash for this quick test are prepared in the Iowa State Compaction Apparatus, giving five blows to each side of the specimen with the 5-lb hammer. The specimens are then wrapped in polyvinylidene chloride and sealed with cellophane tape. The specimens are preheated for about 2 hr in a 140 F oven and then autoclaved at 248 F and 1 atm pressure. The specimens are preheated to make the increase in temperature more gradual. After 24 hr of curing, the specimens are removed from the autoclave and placed in distilled water for 2 hr. They are then tested for unconfined compressive strength. Those fly ashes giving a strength of 600 psi or more may be considered good cementing materials for stabilizing soils for base and subbase courses of pavements (Table 4). The fly ashes with more than 600 psi under the quick test should be further evaluated with the actual soils to be used.

Another correlation found is that those fly ashes showing greatest strengths without added lime are more alkaline than others (2). The alkalies may make the fly ashes as reactive without lime as mixtures with lime (10, 11, 12). Until more information is obtained, the quick test should be used for the preliminary selection of a cementitious fly ash.

CONCLUSIONS

1. Some fly ashes possess cementitious qualities in themselves without addition of lime.
2. Some fly ashes can be used to stabilize soils. The soils that respond best are nonplastic coarse-grained soils, such as gravel, sand and slag. Strengths of 400 psi or more can be reached after 28-days curing with some combinations of soil and fly ash. These combinations are sufficient in strength to be used for the base courses of pavements.

ACKNOWLEDGMENT

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I. INTERNATIONAL SYMPOSIUM ON PUBLIC WORKS CONSTRUCTION IN GYPSIFEROUS TERRAINS

GYPSUM AS AN ADDITIVE IN STABILIZED SOILS

SUMMARY

The effects of addition of small quantities of calcium sulfate to soils stabilized with cement, lime and lime and fly ash were studied. The laboratory test specimens were prepared at standard Proctor compactive effort and tested for strength after moist curing. The results indicate that gypsum may benefit or impair the strength of stabilized specimens depending on the type of soil used. Also presented is an investigation to find the effects of gypsum in soils submitted to freezing and thawing.

COMUNICACION

Tema 1.° C. 1-5.

EL YESO COMO ADITIVO EN LOS SUELOS ESTABILIZADOS

Manuel Mateos y Donald T. Davidson.

(U. S. A.)

RESUMEN

Se presentan los efectos de la adición de pequeñas cantidades de sulfato cálcico en los suelos estabilizados con cemento, cal y cal y cenizas volantes. Las probetas de ensayo se moldearon a la máxima densidad Procton y se rompieron a compresión después de varios períodos de curado húmedo. Los resultados indican que el yeso puede beneficiar o disminuir la resistencia dependiendo del tipo de suelo usado. También se presenta una investigación sobre los efectos del yeso en suelos sometidos a la prueba de congelación y descongelación.

LE GYPSE CONSIDERE COMME UN ADDITIF DANS LES TERRAINS STABILISES

RESUME

Cette étude traite des effets de l'addition de petites quantités de sulfalte de calcium dans les terrains stabilisés à l'aide de ciment, de chaux et de chaux et cendres volantes («fly ashes»). Les échantillons devant être soumis aux tests du laboratoire ont été moulés à la densité Proctor maximum et cassés par compression après plusieurs périodes de cure d'humidification. Les résultats obtenus montrent que le gypse peut améliorer ou réduire la résistance suivant les caracteréristiques du sol. Cette étude concerne également des travaux de recherche sur les effets du gypse dans les sols soumis à des essais de congélation et de décongélation.

GYPSUM AS AN ADDITIVE IN STABILIZED SOILS

By MANUEL MATEOS AND DONALD T. DAVIDSON.

INTRODUCTION

The engineering characteristics of a soil can be improved with several treatments to make of it a better construction material. Several of these treatments are included in the chemical stabilization of soils. The chemical stabilizing agents most commonly used are Portland cement and lime.

Since part of the interaction between cement or lime with the moist soil in a compacted state is believed to form calcium silicates, similar to some of the reaction products of concrete, there has been some concern on the stabilization of sulfate bearing soils, suspecting they may attack soil-cement and soil-lime in the same manner as they attack concrete.

Several investigations have been made on the effect of calcium sulfates in soil-cement (1) (2) (3) (4) and soil-lime (4). Some soils containing calcium sulfate and stabilized with cement were found to disintegrate or deteriorate when immersed in water (2) (4) but calcium sulfate had a beneficial effect on strength in some (1) (3) (4).

Increasing the strength of soil-cement, soil-lime and soil-lime-fly ash mixtures by the addition of small amounts of chemical additives has been previously tried by the authors (5) (6) (7). Since some of the chemicals tried substantially increased the strength, it was supposed that gypsum might, under certain conditions or with some materials, benefit the strength of stabilized mixtures.

This paper presents an investigation of the effects of addition of small amounts of gypsum on the strength of compacted mixes of soil and cement, soil and lime, and soil, lime and fly ash. An evaluation of the effects of gypsum in soils subjected to freezing and thawing is also included.

MATERIALS

The materials used vary with each of the three different phases of this investigation. The description and properties of the soils are given in Tables I and II and the analysis of the fly ash in Table III. The limes used were commercial calcitic hydrated, $Ca(OH)_2$ + impurities, dolomitic monohydrate, $Ca(OH)_2$ + MgO + impurities, and reagent grade calcium hydroxide, $Ca(OH)_2$. The gypsum used was reagent grade. $CaSO_4 + 2H_2O$.

METHODS

Mixing of batches for preparing test specimen was done in a kitchen mixer. The dry ingredients were mixed 25 seconds; then the mix water was added, and mixing was continued for 3 more minutes. The mixing bowl was scraped with a trowel after every minute.

Molding was started immediately after a batch was mixed. The test specimens were molded near standard Proctor density using the Iowa State Compaction Apparatus (figure 1) (8). The specimens made with this apparatus are 2 inches in diameter by 2 inches high.

Specimens of each batch were moist cured at near 70° F. and 100 percent relative humidity for 7 days, for 28 days, or for 4 months. To preserve moisture better and to reduce entry of carbon dioxide from the air, all specimens were wrapped in waxed paper and sealed with celophane tape.

After each curing period, specimens were unwrapped and inmmersed in distilled water for one day. Then they were tected for unconfined compressive strength using a load travel rate of 0.1 inch per minute. Tests were run in triplicate, and the average strengths are reported.

TABLE I. DESCRIPTION OF SOILS.

Soil	Organic clay	Organic silt	Red clay	Glacial clay	Organic sand	Ottawa sand	Friable loess
Sampling location.	Calhoun Co.. Iowa.	Wayne Co., Iowa.	Durham Co., No. Carolina.	Ingham Co., Michigan.	Snohomish Co., Washington.	Ottawa Illinois.	Harrison Co., Iowa.
Geological identification.	Surficial sediment derived from Wisconsin-stage drift.	Leached fine textured Wisconsin-stage drift.	Triassic sediments.	Wisconsin-stage glacial till.	Cemented gravelly till.	—	Oxidized, friable, calcareous. Wisconsin-stage loess.
Great soil group.	Wiesenboden.	Planosol.	Red-Yellow Podzolic.	Gray-Brown Podzolic.	Brown Podzolic.	— —	Regosol.
Soil series.	Webster.	Edina.	White Store.	Miami.	Alderwood.	—	Hamburg.
Horizon.	A	A	B	B	—	—	C
Sampling depth, in.	0-12	0-12	18-21	12-36	0-120	—	49-50

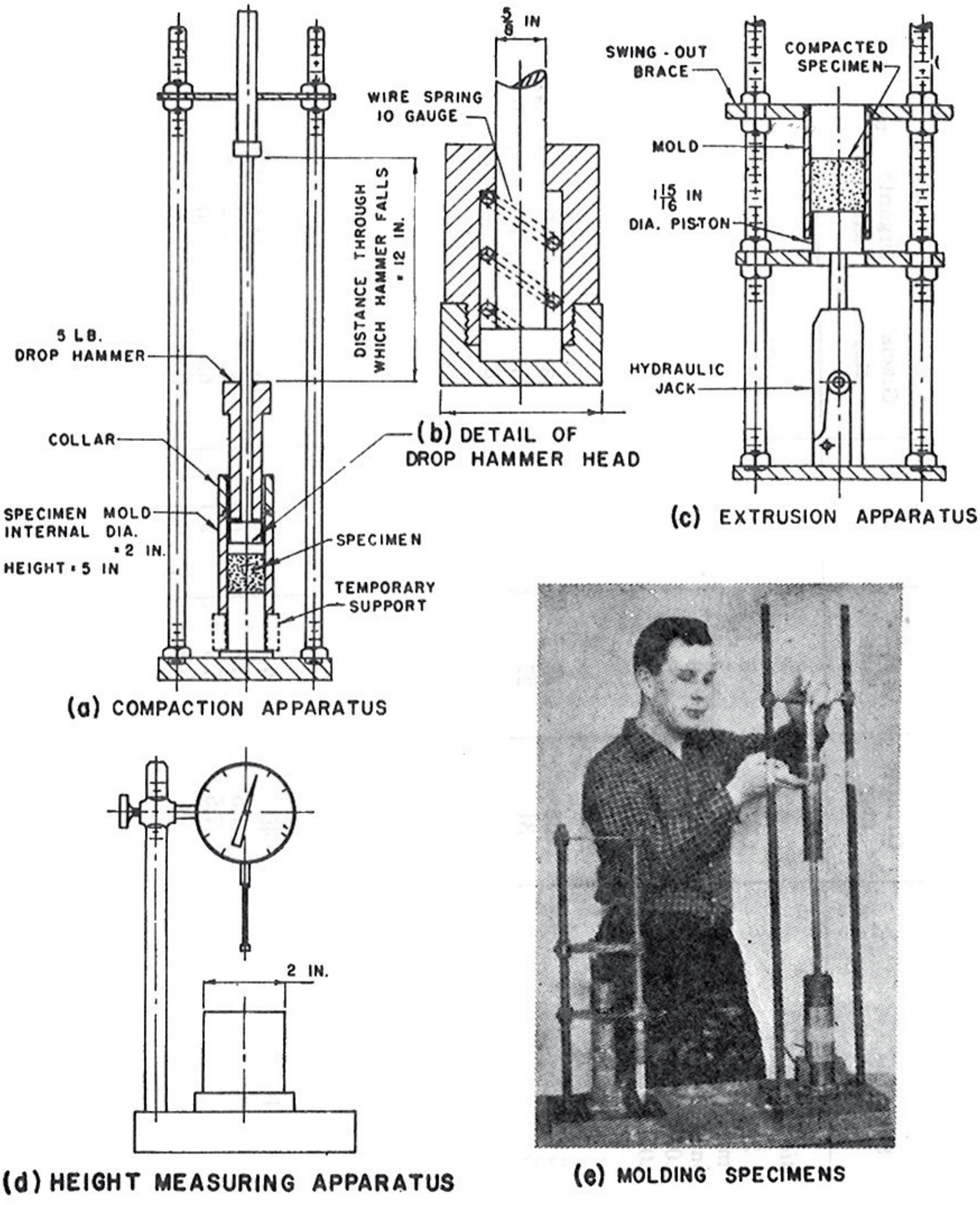

Figure 1.—Iowa State University's Compaction Apparatus.

TABLE II. PROPERTIES OF SOILS

Soil	Organic clay	Organic silt	Red clay	Glacial clay	Organic sand	Ottawa sand	Friable loess
Textural composition (a), %							
Gravel (above 2mm).	0	0	0	0	0	0	0
Sand (2-0.074mm).	13	5	13	14	75	100	1
Silt 0.074-0.005mm).	39	68	22	29	19	0	82
Clay (below 0.005mm).	47	26	65	57	6	0	17
Clay (below 0.002mm).	28	12	50	35	0	0	14
Plasticity (b).							
Liquid Limit, %	58	35	74	43	NP	NP	32
Plastic Limit. %	31	27	26	25	NP	NP	25
Plasticity index.	27	8	48	18	—	—	7
Classification.							
Textural (c).	Clay	Silty clay loam	Clay	Clay	Sandy loam	Sand	Silty loam
Engineering (AASHO) (d).	A-7-5 (18)	A-4 (8)	A-7-6 (20)	A-7-6 (12)	A-3	A-3	A-4 (8)
Chemical.							
C. E. C. (e), m. e./100g.	40	19	36	15	3.3	0	14
Carbonates (f), %	1.5	0.8	0.9	3.3	0.2	0	10.4
ph (g).	7.5	5.3	5 4	6.9	6.0	—	8.4
Organic matter (h), %	7.0	5.6	0.3	0,8	1.8	0	0.1
Predominant clay mineral (i).	Montm.	Montm.	Kaol.-Halloy.	Musc.-Ill.	Chl. Mont.	None	Montm

(a) ASTM Method D 422-6IT.—(b) ASTM Methods D 423-6IT and D 424-59.—(c) Triangular chart, U. S. Bureau of Public Roads.—(d) AASHO Method M 145 49T.—(e) Cation exchange capacity; ammonium acetate method (pH=7). (f) Versenate method for total 1N HCl soluble calcium.—(g) Glass electrode method using suspension of 15 g soil in 30 cc distilled water.—(h) Potassium dichromate method.—(i) X-ray diffraction analysis.

TABLE III. PROPERTIES OF FLY ASH.

Compound or property:	
Silicon dioxide, %	41.9
Magnesium oxide, %	1.0
Calcium oxide, %	2,7
Aluminum trioxide, %	22.5
Iron trioxide, Fe_2O_3, %	25.8
Available alkalies, %	0.3
Loss on ignition (a), %	3.3
Specific gravity.	2.61
Fineness, % passing # 325 sieve.	88.7
Spêcific surface (Blaine), cm^2/g.	2720.0

(a) Approximately equal to carbon content.

In the freeze-thaw studies (3rd phase), the Iowa State method was used. Five especimens of each mixture were cured for 28 days in a moist room at 70° ± 3° F., and then were immersed in distilled water for 24 hours. After 24 hours immersion three specimens of each mixture were tested for unconfined compressive strength; the fourth specimen, designated the control specimen, was left immersed for 10 more days; and the fifth specimen, designated the freeze-thaw specimen, was exposed alternately to temperatures of 20° ± 2° F. (16 hours) and 77° ± 4° F. (8 hours) for 10 cycles, each cycle lasting 24 hours. A vacuum flask specimen container was used to cause freezing from the top down and to supply unfrozen water, kept at 35° ± 2° F. by a light bulb, to the bottom of the specimen throughout the freeze-thaw test. After these additional treatments, the unconfined compressive strength of the freeze-thaw specimen (P) and the control specimen (P_c) were determined. These values were used to evaluate the durability of the stabilized soils. The Index of Resistance to the effect of freezing (R_f) was calculated from the formula:

$$R = \frac{100 P_f}{P_c} \%$$

GYPSUM AS AN ADDITIVE IN SOIL-CEMENT AND SOIL-LIME MIXTURES

Cement and lime are widely used soil stabilizing agents. They improve the engineering properties of many soils, making them sufficiently stable to be used in bases and subbases of pavements, or to improve pavement subgrades.

Some chemicals have been used in trace amounts in soil-cement and soil-lime mixtures to find if they could improve the mixtures (3) (5) (6). Some improved the strength of soil-cement or soil-lime mixtures; this beneficial effect may allow the amount of cement or lime necessary to obtain the same strength to be reduced, which may bring some economy to the stabilization process. If gypsum could be a beneficial additive, the low price and availabilty of this material would represent an economy to the stabilization of soils with cement and lime.

An investigation was carried out to find the effects of small amounts of gypsum on the strength of several soils stabilized with cement and lime. Five soils, selected to represent a variety in geological, physical and chemical characteristics, were used. The stabilizing agents were ordinary Portland cement, and calcitic hydrated and dolomitic monohydrate limes.

Presentation and discussion of results.

The effects of addition of gypsum to soil-cement or soil-lime gives erratic results (tables IV and V). Gypsum was found beneficial in some and detrimental in others.

Gypsum was beneficial to some soil-cement mixtures made with the soils, organic clay, glacial clay, and organic sand; and detrimental with red clay. In soil-lime mixtures, it was beneficial with organic silt, red clay, and glacial clay, detrimental with organic sand and organic silt, and sometimes beneficial and sometimes detrimental with organic clay.

Based on the data at hand no correlations could be found between the behavior of gypsum as an additive and any characteristics of the soils. Until more basic data are available the effects of addition of gypsum should be studied for every combination of materials to be evaluated, since no general trends have yet been observed.

TABLE IV. EFFECT OF ADDITION OF GYPSUM TO SOIL-CEMENT MIXTURES.

Soil	Cement %	$CaSO_4$ %	Unconfined compressive strength after immersion 7 day (psi)	28 day (psi)
Organic clay.	4	0	105	129
	4	0.5	115	127
	4	1.5	106	128
	8	0	212	276
	8	0.5	280(I) (a)	321(I)
	8	1.5	266(I)	298
	12	0	301	381
	12	0.5	343(I)	410
	12	1.5	321	399
Organit silt.	4	0	68	84
	4	0.5	64	55(D) (b)
	4	1.5	63	62(D)
	8	0	183	220
	8	0.5	172	175(D)
	8	1.5	206	259(I)
	12	0	301	351
	12	0.5	309	349
	12	1.5	290	333
Red clay.	4	0	90	90
	8	0	149	192
	8	0.5	162	200
	12	0	284	399
	12	0.5	287	400
	12	1.5	165(D)	190(D)
Glacial clay.	4	0	175	182
	4	0.5	175	258(I)
	8	0	425	531
	8	0.5	465	570
	12	0	709	860
	12	0.5	752	1048(I)
Organic sand.	4	0	133	172
	4	0.5	205(I)	264(I)
	8	0	504	745
	8	0.5	537	758
	12	0	593	1219
	12	0.5	1113(I)	1150

(a) I stands for an increase superior to 15 percent.
(b) D stands for a decrease inferior to 15 percent.

TABLE V. EFFECT OF ADDITION OF GYPSUM TO SOIL-LIME MIXTURES.

Soil	Lime Type	Lime %	Gypsum %	Unconfined compressive strength after immersion 7 day (psi)	Unconfined compressive strength after immersion 28 day (psi)
Organic clay	Calcitic	1	0	40	24
		1	0.5	22(D) (a)	0(D)
		1	1.5	46	0(D)
	Calcitic	3	0	90	113
		3	0.5	112	126
		3	1.5	103	130
	Calcitic	6	0	90	115
		6	0.5	96	136
		6	1.5	96	150(I) (b)
	Calcitic	9	0	83	116
	Dolomitic	1	0	0	23
		1	0.5	23(I)	27
		1	1.5	20(I)	27
	Dolomitic	5	0	122	220
		5	0.5	113	144(D)
		5	1.5	144	173(D)
	Dolomitic	9	0	139	258
		9	0.5	117	234
		9	1.5	109(D)	206(D)
Organic silt	Calcitic	1	0	0	24
		1	0.5	20(I)	41
		1	1.5	18(I)	40
	Calcitic	3	0	31	37
		3	0.5	33	48
		3	1.5	52(I)	73(I)
	Calcitic	6	0	32	42
		6	0.5	53(I)	57(I)
		6	1.5	73(I)	81(I)
	Calcitic	9	0	38	54
	Dolomitic	1	0	0	0
		1	0.5	0	32(I)
		1	1.5	0	40(I)
	Dolomitic	3	0	28	41
		3	0.5	47(I)	51(I)
		3	1.5	47(I)	54(I)
	Dolomitic	6	0	36	57
		6	0.5	54(I)	68(I)
		6	1.5	75(I)	91(I)
	Dolomitic	9	0	36	57

TABLE V. (Cont.).

Soil	Lime		Gypsum %	Unconfined compressive strength after immersion	
	Type	%		7 day (psi)	28 day (psi)
Red clay	Calcitic	3	0	40	60
	Calcitic	6	0	73	123
		6	0.5	113(I)	150
	Calcitic	9	0	90	156
	Dolomitic	3	0	0	0
	Dolomitic	6	0	83	103
	Dolomitic	9	0	103	188
		9	0.5	173 I)	190
		9	1.5	274(I)	197
Glacial clay	Calcitic	3	0	113	113
	Calcitic	6	0	116	119
		6	0.5	119	175(I)
	Calcitic	9	0	103	106
	Dolomitic	3	0	110	152
	Dolomitic	6	0	123	205
	Dolomitic	9	0	152	195
		9	0.5	175(I)	284(I)
Organic sand	Calcitic	6	0	103	149
		6	0.5	83(D)	123(D)
	Dolomitic	9	0	116	149
		9	0.5	87(D)	100(D)

(a) I stands for an increase superior to 15 percent.

(b) D stands for a decrease inferior to 15 percent.

GYPSUM AS AN ADDITIVE IN SAND-LIME-FLY ASH MIXTURE

Fly ash is an artificial pozzolan which has been used with lime to stabilize soils that do not react well with lime alone. These stabilized soils are used in base and subbase courses. The use of lime and fly ash in soil stabilization stems from the fact that fly ash, a by-product of power plants burning powdered coal, is available at a nominal cost. Fly ash is being produced in great quantities in several highly industrialized countries. Production is in the United States about 10 million tons per year, in Britain about 4 million and in France about 3 million. Only a small part of the fly ash produced is utilized as a pozzolan in concrete, in soil-cement and soil-lime-fly ash stabilizaton, and for many other minor uses.

Soils stabilized with lime and fly ash gain strength at a very slow rate; consequently pavements constructed with soil-lime-fly ash mixtures require a longer than ordinary field curing period. Some chemicals are known to accelerate the rate of strength gain of soil-lime-fly ash mixtures (7). Presented here are the results obtained in evaluating the accelerating effects of gypsum.

Natural monomineralic silica sand (ASTM Designation C109) from Ottawa, Illinois, was used as the soil component of mixtures to eliminate variables due to the complex mineral composition of natural soil. The lime was calcium hydroxide, reagent grade. The fly ash was of a medium to good quality (table III).

The mixtures were composed of 75 percent Ottawa sand and 25 percent lime-fly ash with the ratio of lime to fly ash either 1:9 or 1:4.

TABLE VI. EFFECT OF GYPSUM ON THE STRENGTH OF OTTAWA SAND-LIME-FLY ASH MIXTURES.

Mixtures proportions			Gypsum %	Unconfined compressive strength after immersion		
Ottawa sand %	Lime %	Fly ash %		7 day (psi)	28 day (psi)	4 month (psi)
75	2.5	22.5	0	9	34	589
75	2.5	22.5	0.5	44	222	543
75	2.5	22.5	1.0	32	443	692
75	5	20	0	7	66	652
75	5	20	0.5	17	166	684
75	5	20	1.0	16	342	879

Presentation and discussion of results.

The addition of gypsum accelerated the early strength of Ottawa sand-lime-fly ash mixtures (table VI). Seven and 28-day strengths increased several times when either 0.5 or 1.0 percent gypsum was added to the Ottawa sand-lime-fly ash mixtures tested. Gypsum did not significantly affect 4-month strengths.

The strength improvement obtained at early age may reduce the field curing period of lime-fly ash stabilized soil; this will allow an earlier opening of the pavement to traffic or lengthen the construction season in climates having severe winters, as the pavement will gain more rapidly the strength needed to withstand freezing temperatures.

It is necessary to point out that these results were obtained with only one type of soil, lime, and fly ash. The complex composition of soils, fly ashes, and even limes may not reproduce the results obtained here when any of the compositional materials are changed.

EFFECTS OF GYPSUM ON FREEZING AND THAWING

Recent information given in the technical literature states that gypsum treated soils do not expand when placed in a freezer (9). Another source of information indicates that 1.5 percent gypsum in a mixture of 90 parts of sand and 10 parts of lime is the optimum amount of gypsum for maximum strength and that gypsum improves the resistance of sand-lime mixes to repeated freezing (10).

Although some unpublished research previously done at the Soil Engineering Research Laboratory of the Iowa State University had shown gypsum to be a poor stabilizer against the detrimental effects of freezing and thawing, much inferior for this purpose than other commonly used products such as lime, lime-fly ash, cement, etc., the promising claims made in the technical literature led to the following investigation of the effects of gypsum in a soil subjected to freezing and thawing.

A friable loess, mostly silt-size, was used as the soil. Compacted specimens of this soil containing no chemical additive have very low resistance to alternate freezing and thawing cycles, exhibiting a large amount of heave after only one cycle. The lime used was dolomitic monohydrate.

Presentation of Results.

Soil specimens treated with up to 6 percent gypsum failed completely during the 24-hours immersion period (table VII). Consequently it was not possible to submit them to freezing and thawing.

Specimens treated with lime and gypsum in a 50:50 ratio showed better stability than those treated with gypsum alone. The mixture with 2 percent combined additives failed during immersion, but those with 4 and 6 percent combined additives withstood immersion and a number of freeze-thaw cycles.

Lime treated mixtures were better than those with gypsum alone or those with gypsum and lime. All the lime mixtures withstood immersion even with such a low lime content as 2 percent. Mixtures with 2 and 4 percent lime failed after 7 or 8 freeze-thaw cycles, respectively, which is good performance with such small amounts of lime. Six percent lime gave very good strengths, over 300 psi after any treatment, withstood all 10 freeze-thaw cycles, and showed an Index of Resistance of 87 percent.

Discussion.

An unconfined compressive strength of 300 psi after 10 cycles of freeze and thaw in the Iowa Freeze-Thaw test is considered indicative of satisfactory resistance to frost action. Addition of 6 percent dolomitic monohydrate lime to the silty soil gave a strength to the speci-

TABLE VII. RESULTS WITH THE IOWA FREEZE-THAW TEST.

Mix No.	Materials %			As molded dry density (psi)	Strenght (psi)			R_f %
	Soil	Lime	Gypsum		28-day cured, 1-day immersed	P_f	P_c	
1	98	0	2	104.3	0	ND (*)	0	—
2	96	0	4	104.8	0	ND	0	—
3	94	0	6	103.5	0	ND	0	—
4	98	2	0	101.0	169	Failed @ 7 cycles	187	—
5	96	4	0	101.0	350	Failed @ 8 cycles	356	—
6	94	6	0	99.9	348	343	396	87
7	98	1	1	101.5	Partially disintegrated	ND	ND	—
8	96	2	2	99.9	139	Failed @ 4 cycles	122	—
9	94	3	3	99.3	256	Failed @ 7 cycles	254	—

(*) Not determined because specimens failed during immersion.

mens cured for 28 days of well over 300 psi and also after either immersion in water (P_c) or freezing and thawing (P_f). Another criterion of satisfactory freeze-thaw resistance is an Index or Resistance of at least 80 percent. The mixture with 6 percent lime had an Index of Resistance (R_f) of 87 percent, very satisfactory for base courses of roads in Iowa. The use of gypsum or lime-gypsum as additives in the silty soil did not produce satisfactory freeze-thaw resistance for base courses of roads in Iowa.

It is felt that stabilized soils used in pavement base courses in climates of the severity of Iowa should pass the above requirements. Otherwise base course and pavement stability may be impaired. It is of course possible that gypsum-treated silty soils subjected to a less severe freeze-thaw or freezing test may stand up; however, it is likely that a much smaller lime treatment of equal or less cost would produce equal or better results.

Unless otherwise demonstrated, the use of gypsum does not appear to be promising for counteracting the destructive freezing and thawing effects in silty soils to be used in pavement base courses.

SUMMARY AND CONCLUSIONS

The effect on strength of adding small amounts, 0.5 or 1.0 percent, of gypsum to mixtures of soils and cement, soils and lime, and sand, lime and fly ash was investigated.

Based on the results obtained, gypsum may be beneficial or detrimental to the soil-cement and soil-lime mixtures, depending on the type of soil and kind of stabilizing agent used. No trends were found of a possible relationship between the characteristics of the soils used and the effects of gypsum additive. When strength is increased by the addition of gypsum, this may represent an economy, if the gypsum can replace part of the stabilizing agent and give the same or higher strength at lower cost.

Of paramount importance is the many-fold increase of early strength obtained by the addition of 0.5 or 1.0 percent gypsum to sand-lime-fly ash mixtures. This early strength increase may permit pavements built with lime-fly ash stabilized sandy soil to be opened to traffic sooner.

The effects of gypsum in minimizing the detrimental effects of freezing and thawing were re-evaluated in a silty soil and compared with the effects obtained with lime. Gypsum does not seem to help a soil resist the effects of freezing and thawing; lime was found very effective.

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Manuel Mateos

Clayey Soil-Lime Specimens Hardened by Steam

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Clayey Soil-Lime Specimens Hardened by Steam

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ABSTRACT: Four soils, three clayey and one sandy, were mixed with different amounts of high-calcium hydrated lime, dolomitic monohydrate lime, and portland cement. Compacted test specimens were made from the mixes. Some of the specimens were steam cured (248 F, 1 atm), and others were cured at ambient temperatures (70 F, over 90 per cent relative humidity). The specimens steam cured for 1 h had much greater strengths than specimens cured for 90 days at ordinary temperature. High-calcium hydrated lime gave higher strengths, in steam cured specimens, than portland cement or dolomitic monohydrate lime.

Specimens containing clayey soil treated with as low as 5 per cent high-calcium hydrated lime, molded at near standard compaction, and steam cured for 1 h showed compressive strengths of 600 psi after water immersion. Sand-lime specimens molded and cured in the same manner had a strength of only 100 psi. The strengths were found to increase with an increase in the amount of lime or cement added, with an increase in the curing time for high levels of additive treatment and an increase in the compactive effort.

This investigation suggests an economical way to manufacture bricks with clayey soils using lower curing temperatures, lower steam pressures, and less lime than customarily used in the manufacture of sand-lime bricks.

KEY WORDS: sand-lime bricks, soil-lime bricks, soil stabilization, steam hardening, evaluation

Lime is used extensively in soil stabilization to improve the engineering characteristics of clayey and silty soils used in the construction of foundations for highway and airport pavements. Compacted specimens of soil-lime increase in strength upon curing in a moist medium. The strength developed in soil-lime specimens cured at ambient temperature takes place at a very slow rate. However, the rate can be greatly increased by curing at higher temperatures [*1*].[2]

[1] Consulting engineer, Madrid, Spain. Personal member ASTM.

[2] The italic numbers in brackets refer to the list of references at the end of this paper.

The use of lime in soil stabilization is recommended only with clayey and silty soils. The cementitious reaction which takes place is believed to be pozzolanic between the lime particles and the clay particles of soils. Sand does not react with lime at ordinary temperatures [*2*].

During the last 80 years bricks made with sand and lime cured under steam have been in common use mainly in areas lacking in good clays for the manufacture of baked bricks [*3,4*]. The presence of clay in sand-lime bricks generally is considered deleterious, although small amounts of clay may be beneficial. Since clay particles in a compacted state behave with lime as a pozzolan material, a preliminary investigation was carried out to find if the compacted clayey soil-lime mixture would develop strength when cured under steam [*5,6*]. The results obtained indicated that the pozzolanic reaction between clay particles and lime also takes place at high temperatures.

Materials

Soils

Four natural soils—dune sand, friable loess, plastic loess, and heavily weathered glacial till—were selected for these studies (Table 1).

Additives

Two hydrates limes were used, one a calcitic hydrated, $Ca(OH)_2$ + impurities, and the other a dolomitic monohydrate, $Ca(OH)_2 + MgO$ + impurities; both limes were commercial grade "Kemical" and "Kemidol" supplied by the U. S. Gypsum Co. The portland cement used was commercial Type 1 from the Penn-Dixie Cement Corp., Des Moines, Iowa.

Procedures

Preparations

The soils were first air dried and ground with mortar and pestle to pass the No. 10 (2-mm opening) sieve. The amount of additive based on the oven dry weight of the soil was first mixed with the ground dry soil for ½ min, water was added, and then the materials were wet mixed for 2 min. The batches were mixed in a Hobart kitchen mixer, Model C-100.

Cylindrical 2 by 2-in. test specimens were prepared using the Iowa State Compaction Apparatus [*7*]. The standard energy of compaction was that given with a 5-lb hammer falling 12 in. and applying 5 blows to each side of the specimen. The modified energy of compaction was obtained by increasing the number of blows in each side from 5 to

TABLE 1—*Properties of soils.*

Soil Sample / Laboratory Designation	Dune Sand (S-6-2)	Friable Loess (20-2)	Plastic Loess (528-4)	Gumbotil (528-8)
Sampling location, Iowa	Benton County	Harrison County	Keokuk County	Keokuk County
Soil series	Carrington	Hamburg	Mahaska	...
Horizon	C	C	C	Fossil B
Sampling depth, ft	6 to 11	39.0 to 40.0	3.0 to 6.5	6.5 to 8.5
Textural composition, %:				
Gravel (above to 2 mm)	0	0.0	0.0	0
Sand (2 to 0.074 mm)	95.5	0.8	3.5	20.1
Silt (0.074 to 0.005 mm)	1.5	82.8	55.0	16.5
Clay (below 0.005 mm)	3.0	16.4	41.5	63.4
Clay (below 0.002 mm)	2.6	11.6	33.0	60.4
Atterbere limits:				
Liquid limit,' %	...	32	51	68
Plastic limit, %	...	27	21	23
Plasticity index	0	5	30	45
Chemical properties:				
pH[a]	6.6	8.4	6.0	7.1
Cation exchange capacity[b], me/100 g	1.0	15.6	23.5	39.9
Carbonates,[c] %	0.4	10.9	1.2	1.8
Organic matter,[d] %	0.1	0.5	0.3	0:2
Predominant clay minerals	montmorillonite	montmorillonite	montmorillonite	montmorillonite
Classification:				
Textural[e]	sand	silty loan	silty clay	clay

[a] Glass electrode method using suspension of 15 g soil in 30 cm^3 distilled water.
[b] Ammonium acetate (pH7) method on soil fraction below 2 mm.
[c] Versenate method for total calcium.
[d] Potassium bichromate method.
[e] From the soil texture chart used by the U. S. Bureau of Public Roads.

22. Several batches were prepared using different moisture contents; in this way a maximum strength is obtained at an optimum moisture content for the compactive effort.

Curing

After being molded, the specimens were wrapped in poly(vinylidine chloride) (Saran wrap) and sealed with cellophane tape. Specimens were cured by two procedures. Some were kept at 70 F and nearly 100 per cent relative humidity, and others were placed in an autoclave at 248 F and steamed at one atmosphere of pressure. The specimens cured in the autoclave were first heated for 2 h in a 140 F oven, so that the increase in the temperature of the specimens was more gradual.

Strength Testing

After each curing period, specimens were removed from the curing chambers and immersed for one day in distilled water. They were then tested for unconfined compressive strength using a load travel rate of 0.1 in./min. The maximum strength obtained for the different compaction moisture contents is reported.

Presentation and Discussion of Results

Test specimens of soil stabilized with lime and cement gain strength at a very high rate when exposed to high temperatures accompanied by a supply of moisture. Specimens after 1-h steam curing in the autoclave at 248 F gave strengths that were not attained by moist curing for 90 days at 70 F (Tables 2 to 5). The effect of high-temperature

TABLE 2—*Strengths obtained with dune sand treated with admixtures and cured in steam (248 F, 1 atm) and at ordinary temperature.*

Admixture	Amount, %	Immersed Compressive Strength, psi					
		Steam Curing, h			Ordinary Curing, days		
		1	3	8	7	28	90
Calcitic lime.................	8	100	240	440	7	23	30
	12	100	230	430	19	30	42
Dolomitic monohydrate lime...	8	70	120	330	20	28	55
	12	80	130	380	32	51	93
Portland cement.............	8	330	520	700	400	480	540
	12	700	870	1000	710	750	910

TABLE 3—*Strengths obtained with friable loess treated with admixtures and cured in steam (248 F, 1 atm) and at ordinary temperature (70 F).*

Admixture	Amount, %	Immersed Compressive Strength, psi: Steam Curing, h 1	3	8	Ordinary Curing, days 7	28	90
Calcitic hydrated lime.....	2	250	250	250	60	100	270
	5	640	930	950	50	100	400
	8	800	1120	1400	70	150	490
	12	760	1250	1600	60	140	420
Dolomitic monohydrate lime..................	2	0	140	140	100	230	230
	5	470	470	470	150	350	580
	8	600	910	900	170	400	600
	12	850	1100	1450	180	370	590
Portland cement..........	2	180	220	230	190	150	160
	5	500	500	500	270	420	630
	8	950	1100	850	350	510	540
	12	1040	1350	1400	480	630	1130

TABLE 4—*Strengths obtained with a plastic loess treated with admixtures and cured in steam (248 F, 1 atm) and at ordinary temperature (70 F).*

Admixture	Amount, %	Immersed Compressive Strength, psi: Steam Curing, h ½	1	3	8	24	Ordinary Curing, days 7	28	90
Calcitic hydrated lime....	2	70	80	95	95	95	60	65	60
	5	530	610	680	730	780	75	110	180
	8	520	790	1060	1280	1420	75	110	210
	12	520	970	1450	1680	1910	100	130	290
Dolomotic monohydrate lime..................	2	0	0	0	0	0	40	45	30
	5	280	290	310	290	330	105	210	280
	8	540	610	650	610	700	135	230	330
	12	570	890	990	1040	1260	150	270	340
Portland cement.........	2	150	190	200	210	240	110	130	100
	5	360	400	410	460	500	150	220	250
	8	610	790	820	860	1020	300	370	540
	12	740	1010	1220	1350	1800	450	650	780

curing was greater in soils treated with calcitic hydrated lime followed by dolomitic monohydrate lime and then cement.

Steam cured soil-lime and soil-cement mixtures which attained strengths of more than 500 psi after 1-h curing may be a cheap construction material that could be employed in multiple uses. Some of the possible uses are the manufacture of bricks and rammed earth wall construction and the building of foundations for pavements quickly. This material deserves a thorough investigation for the best appraisal of its possibilities. Following is a discussion of some of the factors that affect the strength of soil-lime mixtures cured under steam.

At low steam pressure, the sandy soils treated with lime did not produce appreciable strength after short curing periods. The strengths obtained after 1-h curing were only about 100 psi, although they were increased up to 300 or 400 psi after 8-h curing. For the sandy soil, the highest strengths under steam curing were obtained with cement.

TABLE 5—*Strengths obtained with a gumbotil soil treated with admixtures and cured in steam (248 F, 1 atm) and at ordinary temperature (70 F).*

Admixture	Amount, %	Immersed Compressive Strength, psi					
		Steam Curing, h			Ordinary Curing, days		
		1	3	8	7	28	90
Calcitic hydrated lime........	3	140	150	140	100	145	97
	6	380	540	500	120	160	320
	9	640	720	860	130	220	390
	12	850	980	1060	130	230	490
Dolomitic monohydrate lime...	3	0	40	40	0	0	0
	6	260	260	330	90	100	190
	9	520	540	580	190	270	430
	12	760	800	760	190	290	490
3% lime + cement[a]..........	3	580	570	410	310	380	460
	6	800	820	780	450	510	880
	9	960	960	960	530	600	880

[a] Calcitic hydrated lime was first added to facilitate mixing of this highly plastic soil with cement.

The clayey and silty soils treated with admixtures responded better than the sandy soil. After 1-h steaming, strengths of 500 psi or more were obtained depending on the amount and kind of additive used. These strengths increased with curing time mainly at the higher levels of additive treatment. With the clayey and silty soils, calcitic hydrated lime was the best additive followed by portland cement and dolomitic monohydrate lime in that order (Fig. 1).

The gain in strength depends on both the amount of additive and the period of curing. For low levels of additive, a terminal strength value was reached in a short time, after which further increase in strength was not possible even with further curing (Fig. 2). This is caused by depletion of the lime when used in small amounts. High amounts of lime make the soil-lime reaction last for longer periods of time.

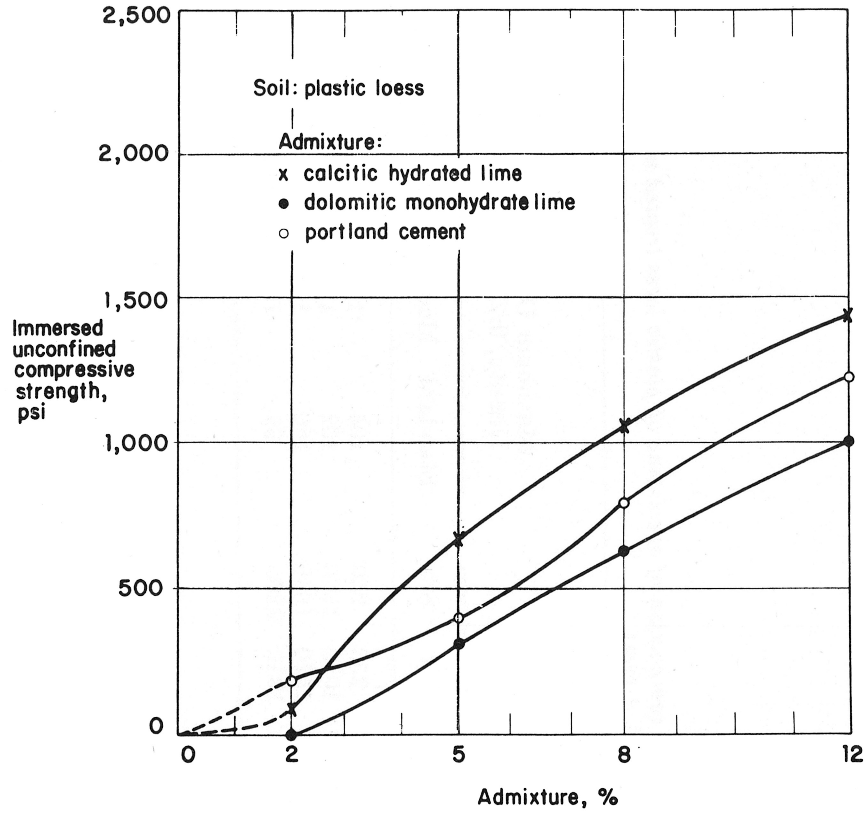

FIG. 1—*Comparative effects of limes and cement in the strength of specimens made with a clayey soil, after curing in steam (248 F, 1 atm) for 3 h.*

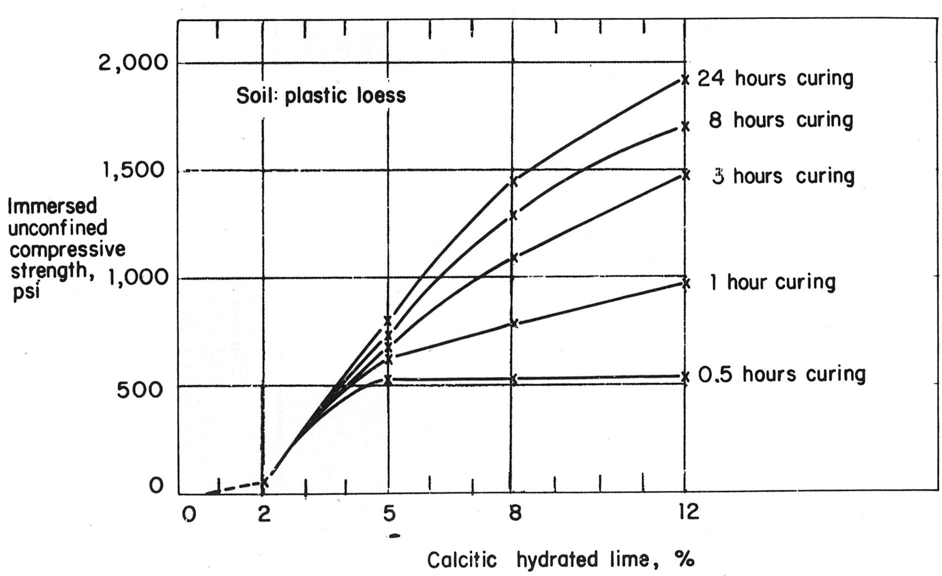

FIG. 2—*Effect of time of steam curing on the strength of clayey soil-lime specimens.*

TABLE 6—*Comparison of strengths obtained with standard and modified compaction of specimens of plastic loess treated with lime and cured in steam (248 F, 1 atm).*

	Amount, %	Immersed Compressive Strength, psi						Maximum Dry Density, lb/ft³		Optimum Moisture, %	
		Standard			Modified						
		1 h	3 h	8 h	1 h	3 h	8 h	Standard	Modified	Standard	Modified
Calcitic hydrated lime.......	2	95	95	95	250	250	250	104	113	18	15
	5	640	680	700	850	1050	1200	102	111	20	15
	8	720	1060	1280	1020	1570	1860	100	109	21	15
	12	1000	1450	1680	1070	1910	2265	99	107	21	17

The high strengths obtained even after 1-h steam curing posed the possibility of using still shorter curing periods. For instance, test specimens made with the plastic loess soil gave very good strengths even after only ½-h steam curing. It is possible that curing periods shorter than even ½ h could be sufficient to obtain strength in soil-lime mixtures.

The compactive effort also affects the strength of soil-lime mixtures (Table 6 and Fig. 3). In tests performed with plastic loess treated with calcitic hydrated lime, the strength increased about 35 per cent

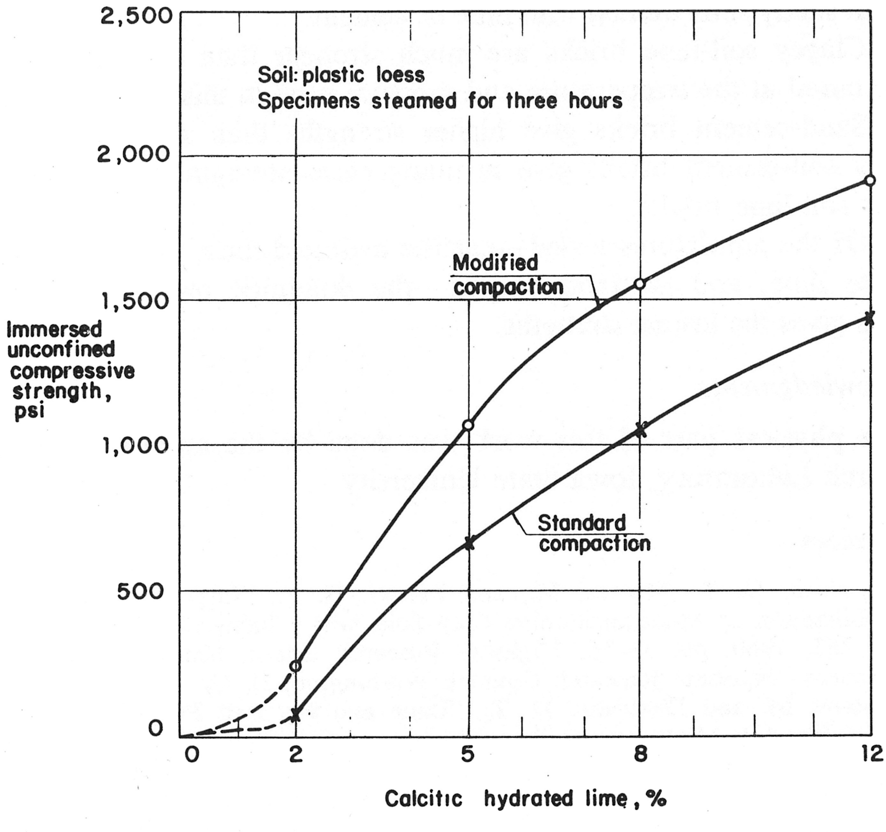

FIG. 3—*Effect of compactive effort on the strength of clayey soil-lime specimens cured under steam.*

for an increase in the compactive effort from standard to modified. This increase in strength was due to an increase in the dry density of about 10 per cent.

The present study indicates that it is possible to make bricks utilizing clayey, silty, and sandy soils treated with lime. With clayey and silty soils from 600 to 1500 psi could be obtained after submitting the bricks to steam (248 F 1 atm) for less than 8 hours. Curing periods longer than 8 h and high compactive effort could bring the strength above 1500 psi. Higher strengths could possibly be obtained by using higher steam pressures. The amount of lime needed ranges from about

5 to 10 per cent by weight, depending on the soil compacting and curing conditions and the ultimate strength desired. The moisture content should be that which gives a maximum dry density for the compactive effort applied.

Conclusions

On the basis of this investigation on curing soil-lime and soil-cement compacted specimens at 248 F and 1 atm of steam pressure, the following conclusions are pertinent:

1. Steam cured bricks can be manufactured with clayey soils as well as with sandy soils treated with lime or cement.
2. Clayey soil-lime bricks are much stronger than sand-lime bricks when cured at the temperature and pressure used in this investigation.
3. Sand-cement bricks give higher strengths than sand-lime bricks. Clayey soil-cement bricks give in many cases strengths comparable to clayey soil-lime bricks.
4. Of the admixtures tested—calcitic hydrated lime, dolomitic monohydrate lime, and portland cement—the dolomitic monohydrate lime always gives the lowest strengths.

Acknowledgments

The physical part of this work was done by the author at the Soil Research Laboratory, Iowa State University.

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SOIL LIME RESEARCH AT IOWA STATE UNIVERSITY

By Manuel Mateos,[1] A.M. ASCE

SYNOPSIS

Lime is one of several products that can be successfully used in the improvement of the engineering characteristics of soils. There are many factors affecting a soil-lime water system. The primary factors are differences in soil gradation, types of clay minerals and amount of organic matter, etc., present in the soil, and the kind and amount of lime and other chemicals which are added to the soil. Some secondary factors include moisture content, manner of applying the lime, amount of compaction, delay of compaction after wet mixing, curing time and curing temperature. A summary of the work done at Iowa State University during the period 1947-1963 on the influence of these factors in soil-lime stabilization using soils and limes from many parts of the United States is presented herein. The effects of lime on the plasticity, shrinkage, strength and swell characteristics of soils as well as the freeze-thaw and wet-dry resistance were studied. Basic and applied research and field trials were made in order to evaluate the different aspects of soil-lime stabilization.

Lime can be used with silty and clayey soils to modify some of their physico-chemical characteristics and improve the soil as an engineering material. Small amounts of lime are needed for this modification of the soil properties. Generally from 1% to 3%. Lime can also be used to cement silty and clayey soils and produce a water-stable material. This cementation is produced by the formation of crystalline silicates, some of them analogous to

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those formed in concrete. The lime needed for cementation ranges between 2% and 8%.

INTRODUCTION

Lime as a soil additive, brings several beneficial changes to soil containing silt and clay particles. Sine lime is a product that can be manufactured cheaply in most countries of the world, the development of soil-lime stabilization may bring economic benefits in the construction of pavements to highly developed as well as underdeveloped countries.

The use of lime in the construction of highways is not new. The Romans used lime, alone or with pozzolanic materials, in the construction of their roads. Research in soil stabilization has shown that lime can benefit soils by upgrading them as a construction material. As a result of laboratory and field experiments soil-lime is used in several parts of the United States as well as in other countries.

Work on lime stabilization research at Iowa State University, Ames, Iowa, began in 1947. The most important aspects have been evaluated using soils and limes from several parts of the United States. Research work, both in the laboratory and in the field, is still (as of 1964) in progress. A summary of the work done to date is presented herein.

MAIN FACTORS IN SOIL LIME STABILIZATION

Soil.—Some of the soil variables that may affect lime stabilization are gradation, amount and type of clay minerals, organic matter, moisture content and amount of sulfates or other minerals.

No definite trends have been found to establish a criterion as to the minimum amount of clay in a soil to be effectively stabilized with lime. With montmorillonite-rich soils it has been found that about 15% 2-micron clay is the minimum amount necessary for a proper development of strength by cementation (14).[2]

Clayey and some silty soils benefit from the addition of lime. Sandy soils should not be stabilized with lime although they also show some strength increases by the addition of lime. For instance after 7 days curing at 70° F and 1 day immersion a dune sand with only 4% clay showed compressive strengths of 240 psi with 15% calcitic quicklime, 320 psi with 15% dolomitic quicklime and 53 psi with 15% dolomitic monhydrate lime (3, 14). The same strengths can be obtained with a lesser amount of Portland cement.

The type of clay has been found to be a major factor in soil-lime stabilization (6, 8). Montmorillonitic and kaolinitic clay soils respond better to lime than illitic and chloritic clay soils. Soils rich in halloysite clay attain lower

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[2] Numerals in parentheses refer to corresponding items in the Bibliography.

strengths than any other type. Representative strengths of those obtained with different types of fine-grained soils are given in Table 1.

Although no studies have been made on the influence of gradation of soil in soil-lime mixtures, uniformly graded soils will probably give less strength than well graded ones (14).

An attempt has been made to correlate the agricultural soil series with lime requirements for stabilization of Iowa soils (16). Some relationships were found, but no definite conclusion can be made based on the studies made so far. Soils of the B and C horizons respond better to lime stabilization than soils of the A horizon.

TABLE 1.—REPRESENTATIVE IMMERSED UNCONFINED COMPRESSIVE STRENGTHS OF LIME STABILIZED SOILS[a] (14)

Type soil	Curing time days[b]	Type of Lime			
		Calcitic hydrated		Dolomitic monohydrate	
		Optimum lime content, in percentage	Strength, in pounds per square inch	Optimum lime content, in percentage	Strength in pounds per square inch
(1)	(2)	(3)	(4)	(5)	(6)
Montmorillonite and kaolinite-rich	7	2-8	60-120	8-12	100-200
	28	2-8	150-250	8-14	250-400
Illite- and chlorite-rich	7	3-5	50-100	4-6	100-150
	28	4-6	130-170	4-8	200-250
Halloysite-rich	7	4-8	50-100	4-8	50-100
	28	4-8	75-125	6-14	150-200

[a] 2 in. high by 2 in. diameter samples molded to near standard Proctor maximum density and immersed one day prior to testing.

[b] Cured at 70° F and 90% or higher relative humidity.

[c] Percentage dry weight of soil.

Soils with moisture contents higher than the optimum for compaction appear to dry out with the addition of lime. Quicklimes absorb part of the moisture for the hydration process and thus reduce the moisture content. Lime flocculates the clay particles of the soil and makes the soil fluffy. This increases the natural aeration of the soil and causes the loss of part of the moisture. It has been found that lime, after being mixed with clayey soils, increases the optimum moisture content for the same compactive effort. The optimum moisture content increases further with an increase in the delay of compaction (Fig. 13).

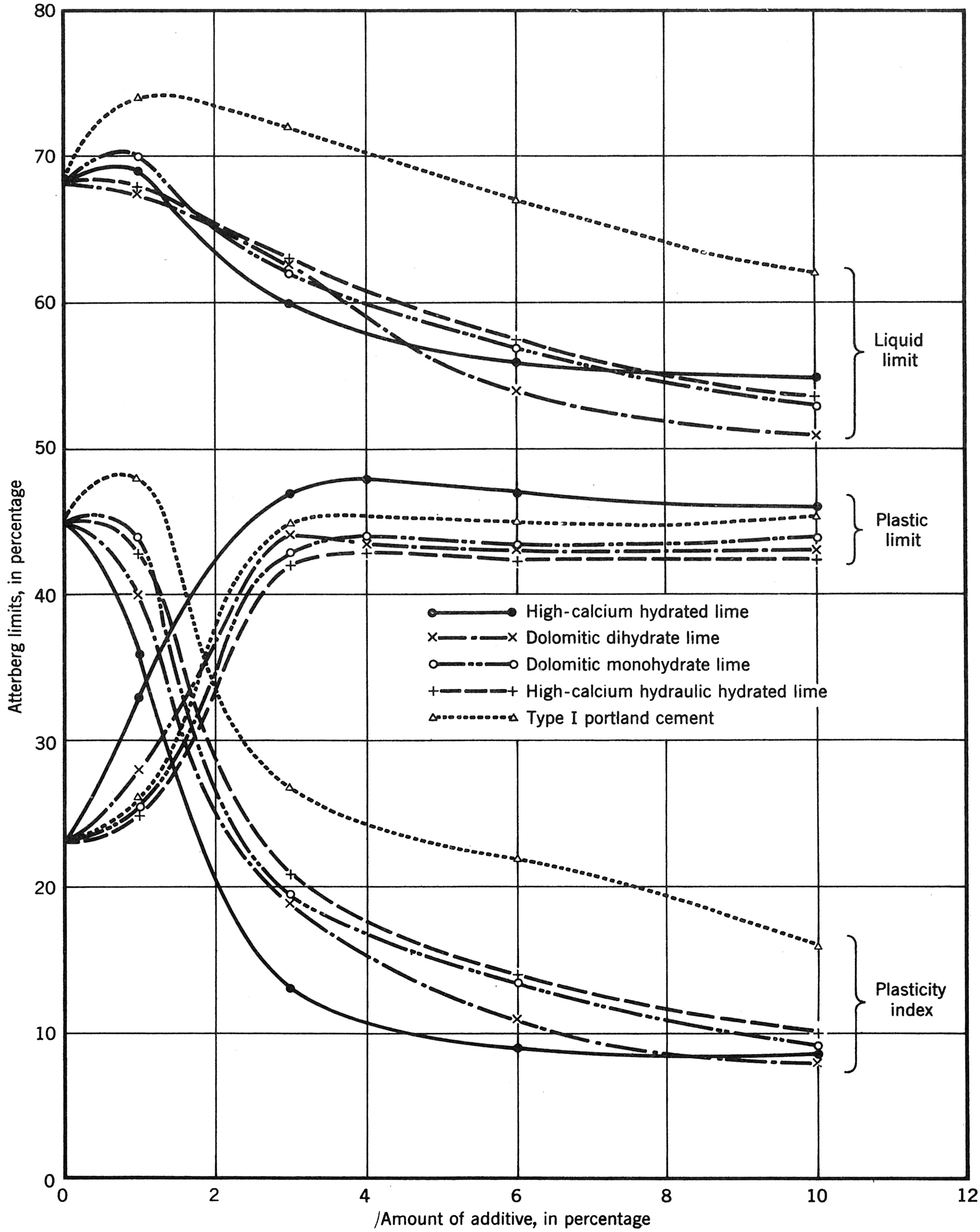

FIG. 1.—EFFECT OF VARIOUS ADDITIVES ON THE ATTERBERG LIMITS OF A GUMBOTIL SOIL (28)

Lime.—Lime can be divided chemically into two categories: quicklimes and hydrated limes. Quicklimes are of two types: calcitic (CaO) and dolomitic ($CaO + MgO$). Hydrated limes are of three types: calcitic $[Ca(OH)_2]$, dolomitic monohydrate $[Ca(OH)_2 + MgO]$ and dolomitic dihydrate $[Ca(OH)_2]$. The degree to which a lime is calcitic or dolomitic can be expressed by the calcium-magnesium ratio. Although generally the calcitic limes have less than 2% MgO and the dolomitic limes between 25% and 45% there is no definite borderline. Limes are also classified on the basis of its plasticity as Type N (normal) or Type S (special or slick). Most Type S limes are dolomitic dihydrates, although Type S can be a calcitic hydrated lime.

Another type is hydraulic lime, which can be considered as an intermediate product between lime proper and Portland cement.

The relative effects of the different types of lime vary according to the purpose of the lime treatment either for modification or for cementation of the soil.

TABLE 2.—RESULTS OF SHRINKAGE TEST ON GUMBOTIL TREATED WITH VARIOUS ADDITIVES (28)

Additive		Shrinkage Limit, in percentage	Shrinkage Ratio
Kind (1)	Amount, in percentage (2)	(3)	(4)
None	0	7.7	2.08
High-calcium hydrated lime	2	25.4	1.52
	8	37.1	1.26
Dolomitic monohydrate lime	2	13.5	1.86
	8	41.8	1.22
Dolomitic dihydrate lime	2	13.5	1.86
	8	38.5	1.20
High-calcium hydrualic hydrated lime	2	13.3	1.78
	8	35.7	1.28
Type I Portland cement	2	15.3	1.65
	8	37.4	1.22

Modification of Soil.—The quick changes in a soil caused by the addition of some stabilizing agents, as reflected in such physical properties as plasticity and shrinkage can be considered as a modification of the soil.

In a comparative study of hydrated limes, the calcitic lime lowered the plasticity index of a clayey soil the greatest extent (Fig. 1). The compound chiefly responsible for lowering the plasticity in hydrated limes is calcium hydroxide: Magnesium hydroxide causes practically no reduction and magnesium oxide lowers the plasticity index to an intermediate degree between calcium hydroxide and magnesium hydroxide (27). Quicklimes lower the plasticity more than the equivalent amount of the corresponding hydrated lime (2).

Quicklimes are also more effective in improving the shrinkage properties of a soil than the corresponding hydrated limes (2). Among the hydrated limes, the calcitic lime is slightly better at low amounts of addition (Table 2).

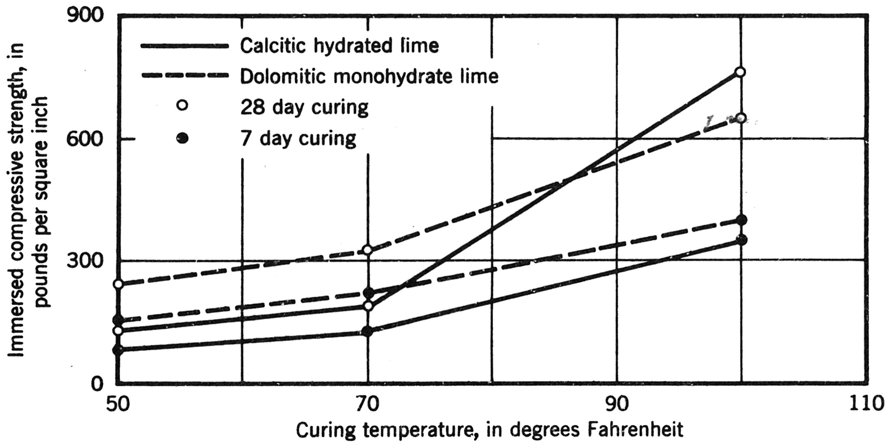

FIG. 2.—COMPARISON OF STRENGTHS OBTAINED WITH CALCITIC AND DOLOMITIC LIMES CURED AT DIFFERENT TEMPERATURES (5)

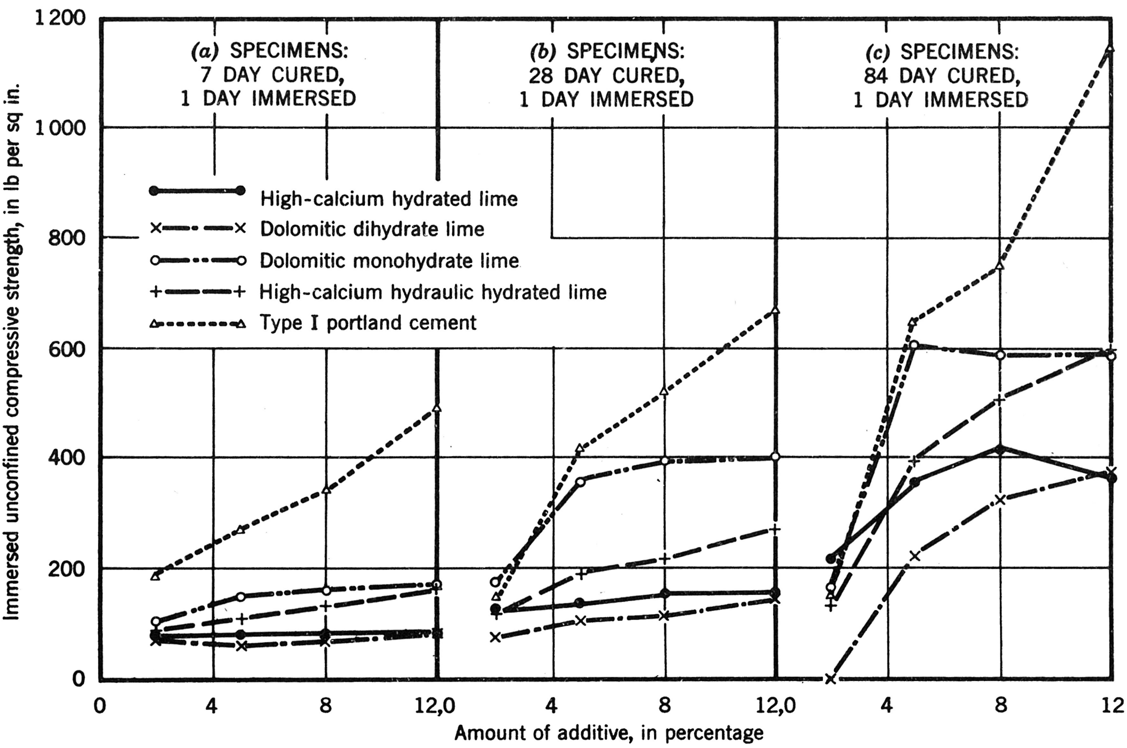

FIG. 3.—EFFECT OF VARIOUS ADDITIVES ON THE STRENGTH OF A FRIABLE LOESS SOIL (28)

Cementation of Soil.—The gain of strength of soil-lime mixtures, through the formation of cementitious compounds while being cured can be considered as a cementation of the soil.

Some dolomitic quicklimes have been found to surpass dolomitic monohydrate limes in strength improvements (3). Dolomitic dihydrate gave lower strength than dolomitic monohydrate and dolomitic quicklime (2). Calcitic quicklime may be better than calcitic hydrated lime in small amounts up to about 3% (2, 3, 4). However, general conclusions can not be drawn as to which one may be superior in greater amounts.

Dolomitic limes (quicklime and monohydrate) were found to give greater strengths than calcitic limes, based on curing temperatures close to 70° F except with kaolinitic clay soils in which calcitic hydrated and dolomitic monohydrate limes gave approximately the same strengths (2, 3, 4, 5, 8, 13, 17, 18, 28). Possibly at higher field curing temperature the calcitic limes may give a better strength performance than dolomitic limes (Fig. 2). The optimum calcium to magnesium molar-part ratio in dolomitic monohydrate lime is between 1:1 and 1.5:1 (3, 18). Most commercial monohydrate limes have a calcium to magnesium ratio within these limits.

TABLE 3.—EFFECTS OF SODIUM CARBONATE ON THE STRENGTH OF A SOIL STABILIZED WITH 4.5.% HIGH-CALCIUM QUICKLIME (33)

Soil (1)	Sodium carbonate, in percentage (2)	Application of lime (3)	Dry density, in pounds per cubic foot (4)	Unconfined compressive strength, psi: 7 day cured + 1 day immersion (5)	Unconfined compressive strength, psi: 28 day cured + 1 day immersion (6)
Silt (friable loess)	No	Powder	96.7	60	93
Silt (friable loess)	0.5	Powder	96.7	116	207
Silt (friable loess)	No	Slurry	95.3	89	115
Silt (friable loess)	0.5	Slurry	94.2	73	90

A great variation was found in the strengths obtained with dolomitic limes of different brands, but calcitic limes gave uniform strength regardless of brand (18). The differences in strength obtained with different dolomitic limes appear to be influenced by several factors; raw materials, type of kiln, firing conditions of the kiln, fineness of crystallite sizes, ratio of calcium to magnesium, degree of hydration and impurities (3, 18).

A comparative strength study using several types of lime and cement is presented in Fig. 3.

Effect of Additives.—The possibility of improving the strength of soil-lime mixtures by the incorporation of other chemicals has been evaluated. The chemicals used were sodium silicate, sodium hydroxide, sodium phosphate, potassium permanganate, sodium carbonate, calcium sulfate, sodium sulfate, magnesium oxide and calcium chloride (5, 9, 11, 13, 21, 24, 32). The more promising chemical additives appear to be sodium silicate, sodium hydroxide and sodium carbonate.

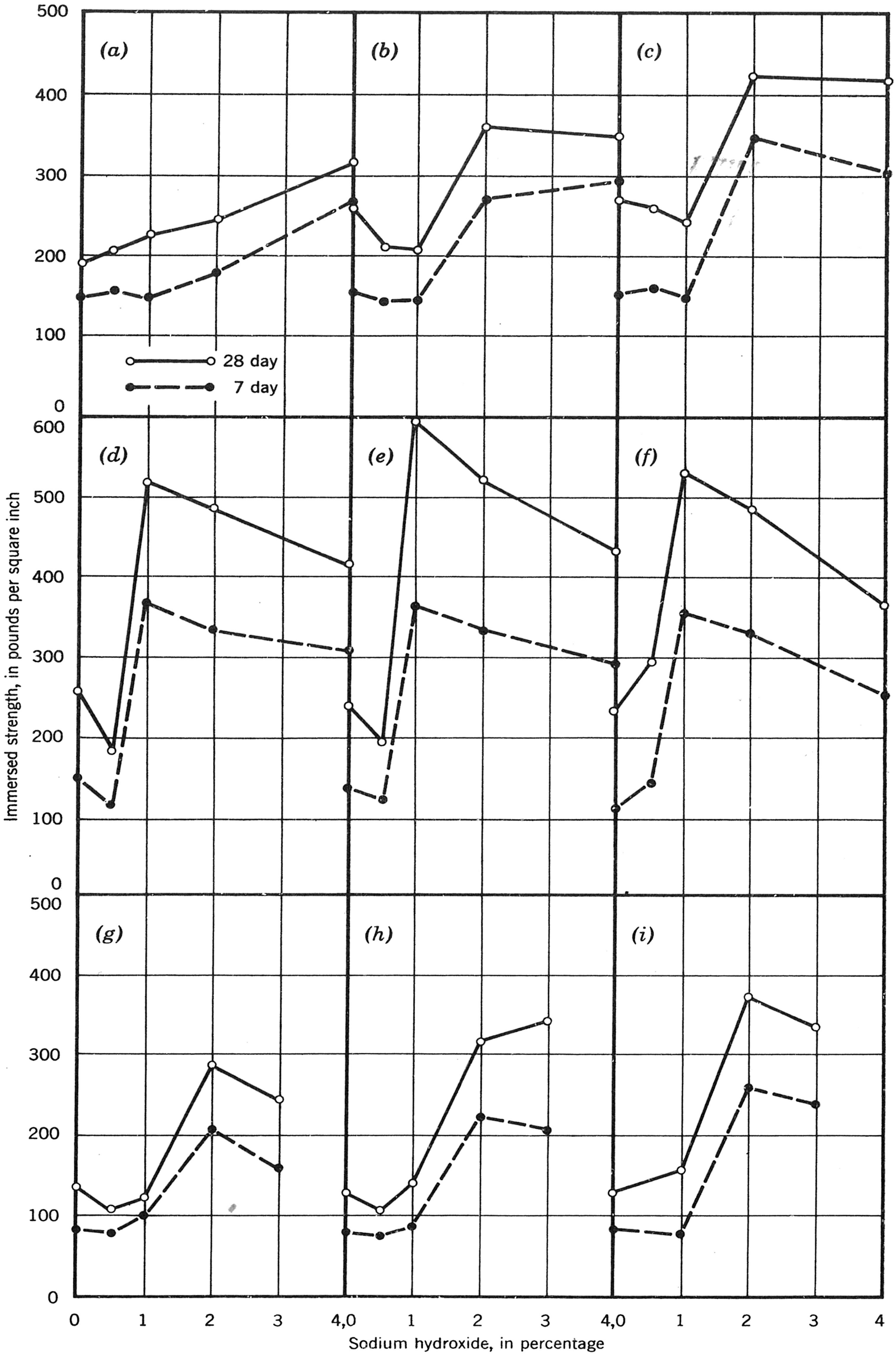

FIG. 4.—EFFECTS OF ADDITION OF SODIUM HYDROXIDE ON THE STRENGTH OF THREE MONTMORILLONITE CLAY SOILS STABILIZED WITH LIME AND MOIST CURED (5)

The effects of addition of different amounts of sodium hydroxide on the strength of montmorillonite clay soils stabilized with lime are presented in Fig. 4. In Fig. 4 (a),(b) and (c) are Kansan gumbotil, (d),(e) and (f) are Kansan till and (g),(h) and (i) are Plastic Loess; (a),(d) and (f) have 4% calcitic lime, (b),(e) and (h) have 6% and (c),(f) and (i) have 8%.

The addition of chemicals to soil-lime mixtures appears to be uneconomical at the present time. The effects of chemicals are unpredictable (Table 3). Consequently, before field usage, they should be extensively evaluated with various mixtures of soil and lime. It is also suspected that after curing periods longer than 28 days some highly alkaline chemicals might cause harmful effects on the stabilized soils (32).

Sulfates in small amounts may be beneficial or detrimental depending on the soil and lime used (21, 24).

SECONDARY FACTORS IN SOIL-LIME STABILIZATION

Moisture Content.—The addition of lime to a soil decreased the maximum density by several pounds per cubic foot, which is generally accompanied by an increase in the optimum moisture content. This is observed even for amounts of added lime as small as 1%. Dolomitic monohydrate lime decreases the maximum density less than calcitic hydrated lime, (2, 3, 4, 5, 8, 13, 17, 18, 28).

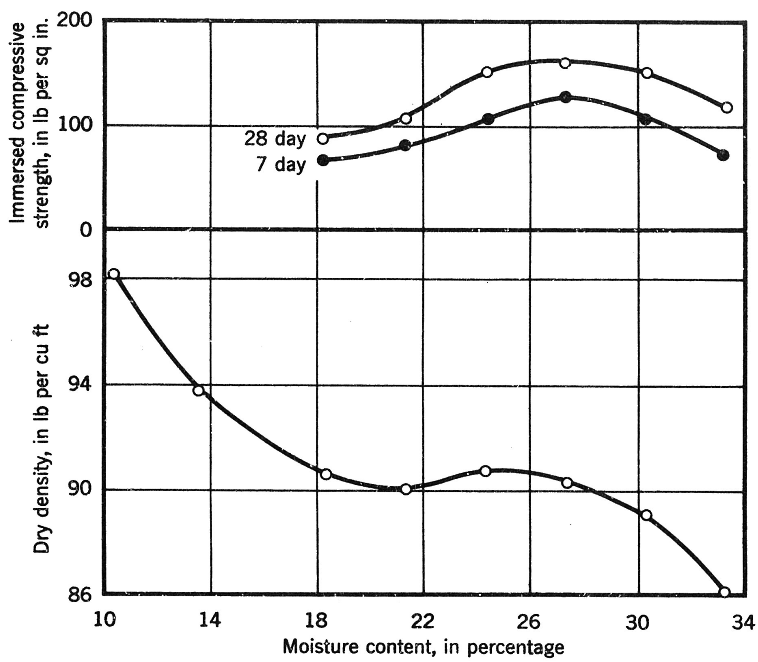

FIG. 5.—MOISTURE-DENSITY AND MOISTURE-STRENGTH RELATIONSHIPS OF A MIXTURE OF 91% MONTMORILLONITE CLAY SOIL AND 9% CALCITIC HYDRATED LIME, COMPACTED AT STANDARD PROCTOR COMPACTIVE EFFORT (17)

In soils with high montmorillonitic clay content the addition of lime may so distort the shape of the moisture-density compaction curve that a well defined maximum density is not shown (Figs. 5, 6, 7). This was found at both standard and modified compaction. The optimum moisture for compaction in these high clay soils should be the one that gives a maximum strength. The optimum moisture for compaction based on the moisture-density curve is difficult to determine, but the moisture-strength curves will indicate which is the optimum desired at the time of compaction. In general, the optimum moisture content for maximum density for most soils is near the optimum moisture content for strength (Fig. 8).

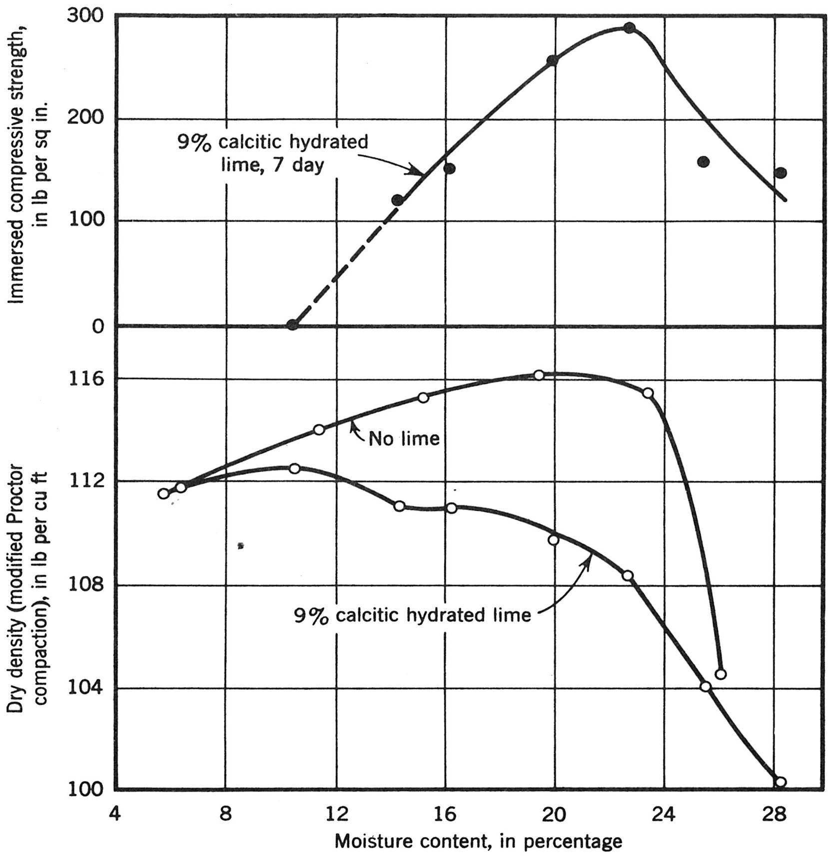

FIG. 6.—MOISTURE-DENSITY AND MOISTURE-STRENGTH RELATIONSHIPS OF A MONTMORILLONITE CLAY SOIL WITH AND WITHOUT LIME, COMPACTED AT MODIFIED PROCTOR COMPACTIVE EFFORT (17)

Application of Lime as Powder or in Slurry.—Quicklimes are very caustic and may cause severe skin burns. This hazard can be eliminated by applying quicklimes in slurry form. Quicklimes added in slurry form were found to give greater strengths than when added in powder form (Fig. 9 and Table 3). Hydrated limes gave approximately the same strength used either in powder or slurry form (4).

Effect of Compactive Effort.—The compactive effort has been found to influence the strength greatly. When the compactive effort was increased from standard ASTM-AASHO to modified, the compressive strength of the soil-lime mixtures increased by 50% to 250% for both 7 and 28 day curing periods (8). This increase in strength was obtained by an increase in maximum dry density of about 10%. The highest possible amount of field compaction should therefore be applied, since the extra cost of higher compaction is offset by the strength increases.

Curing Time.—The strength increase with curing time depends on the kind of soil, type, brand and amount of lime, molding moisture, curing tempera-

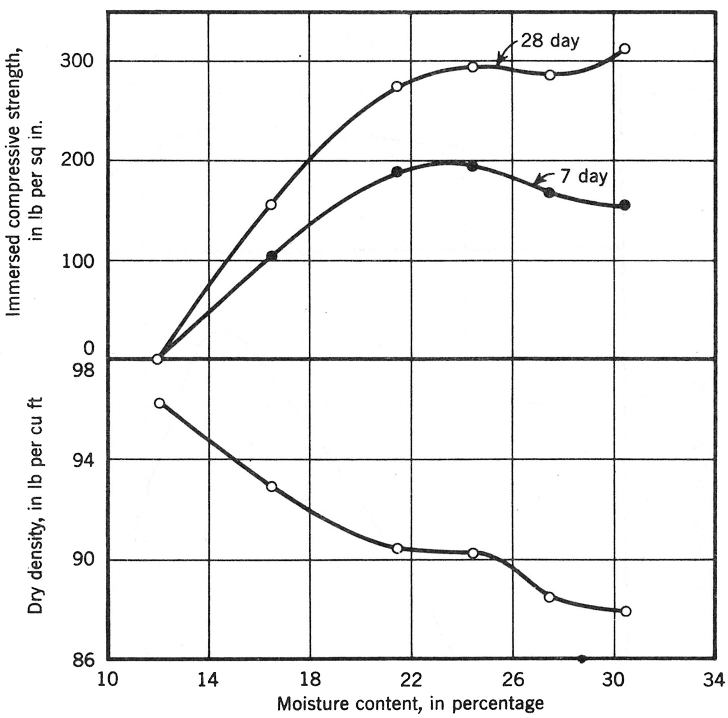

FIG. 7.—MOISTURE-DENSITY AND MOISTURE-STRENGTH RELATIONSHIPS OF A MIXTURE OF 85% MONTMORILLONITE CLAY SOIL AND 15% DOLOMITIC MONOHYDRATE LIME, COMPACTED AT STANDARD PROCTOR COMPACTIVE EFFORT (17)

ture, and compactive effort (4, 5, 6, 8, 13, 17, 18, 24). The strength after 28 days in relation to 7 day strength varied from a decrease of 2% to an increase of 155% (8). The same has been found true of the strengths at 90 days and 28 days (Fig. 10, 11, and 12).

With low amounts of lime all the possible strength seems to be obtained within a few days. If it is desirable to let the strength producing reaction continue for several months, greater amounts of lime should be used. From 3% to 10% lime, depending on the amount and type of clay in the soil, could be sufficient for the soil-lime mixtures to gain strength during several months or perhaps years.

Effect of Curing Temperature.—The temperature of curing influences greatly the strength of soil-lime mixtures (2, 5, 12, 30). For instance in specimens cured at 100° F the strengths are 100% or more higher than in those cured at 70° F (Fig. 2). Mixtures stabilized with dolomitic monohydrate lime and cured to about 100° F appear to give higher strengths than with calcitic hydrated lime, at least for curing periods up to three months. For very high curing temperatures, calcitic lime is better than dolomitic (Fig. 2, Tables 4,5).

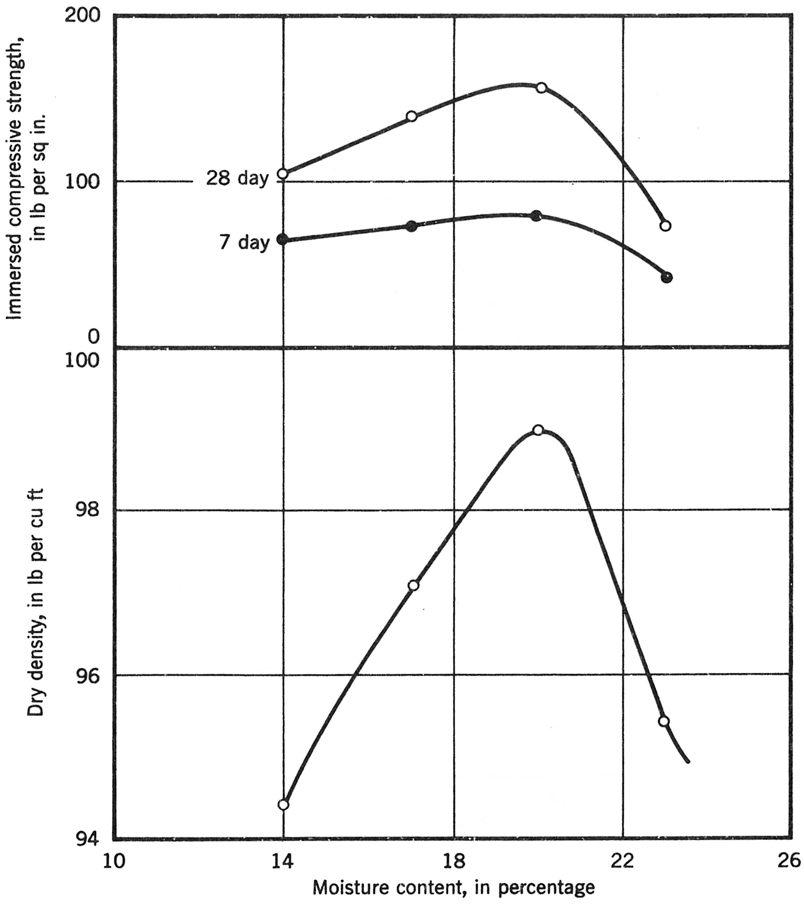

FIG. 8.—MOISTURE-DENSITY AND MOISTURE-STRENGTH RELATIONSHIPS OF A MIXTURE OF 91% SILTY SOIL AND 9% CALCITIC HYDRATED LIME, COMPACTED AT STANDARD PROCTOR COMPACTIVE EFFORT (17)

Because of the great influence of temperature in the strength obtained through cementation it is highly recommended that any soil-lime stabilization work should be done in the early part of the summer in temperate climates. The stabilized soil mixture would thus be exposed to relatively high curing temperatures for at least two months. The strengths obtained when the work is done early in the summer may be about twice as high as those obtained when the work is done in the last part of the summer or early in the fall. If

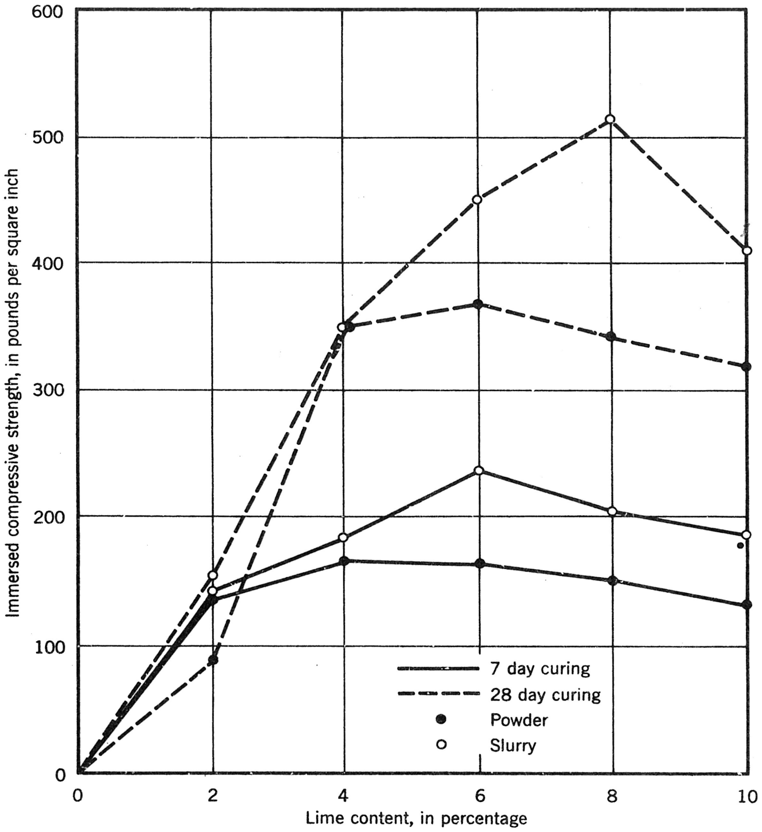

FIG. 9.—EFFORT OF APPLICATION IN SLURRY AND POWDER FORM OF A DOLOMITIC QUICKLIME ON THE STRENGTH OF A SILTY SOIL (4)

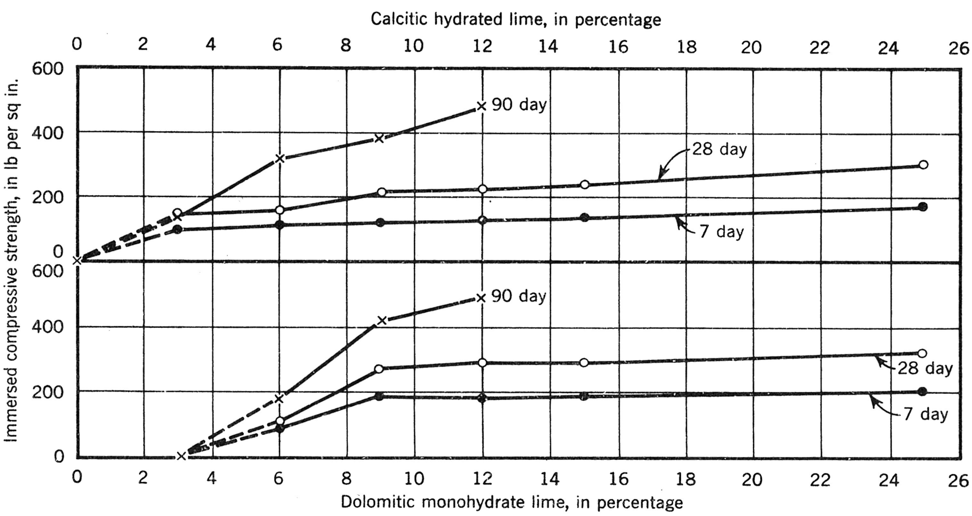

FIG. 10.—EFFECTS OF ADDITION OF DIFFERENT AMOUNTS AND KINDS OF LIME ON THE STRENGTH OF A MONTMORILLONITE CLAY SOIL (GUMBOTIL) (17)

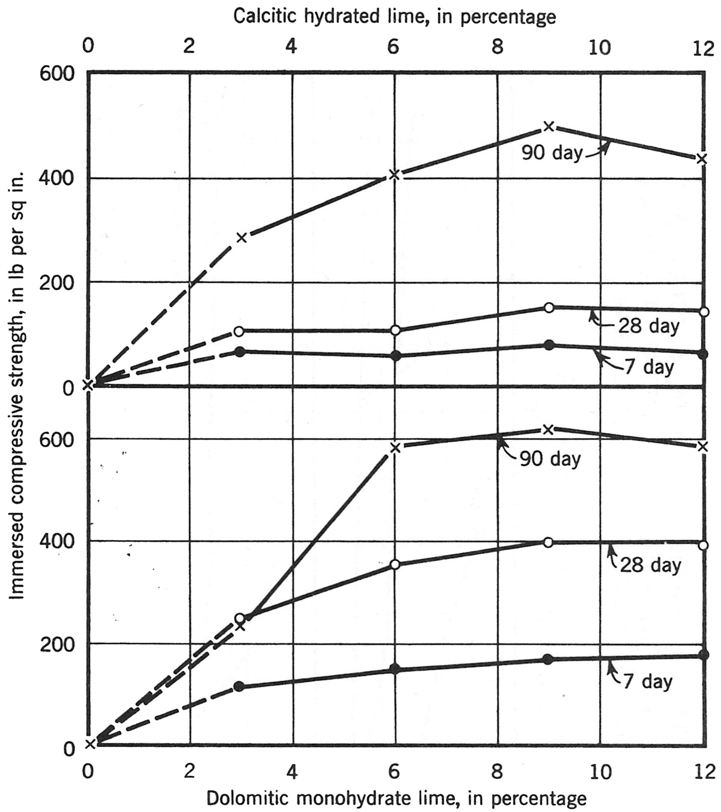

FIG. 11.—EFFECTS OF ADDITION OF DIFFERENT AMOUNTS AND KINDS OF LIME ON THE STRENGTH OF A SILTY SOIL (FRIABLE LOESS) (17)

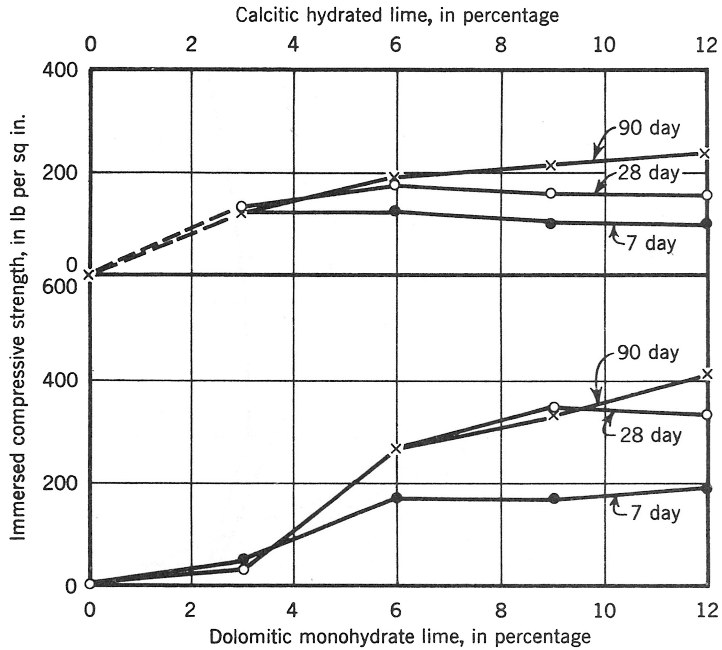

FIG. 12.—EFFECTS OF ADDITION OF DIFFERENT AMOUNTS AND KINDS OF LIME ON THE STRENGTH OF A MONTMORILLONITE CLAY SOIL (ALLUVIAL CLAY) (17)

TABLE 4.—EFFECT OF STEAM CURING ON SOIL-LIME MIXTURES (12)

Soil	Lime		Unconfined compressive strength, in pounds per square inch	
	Kind[a]	Amount, in percentage	1 day steam-curing at 248° F + 1 day immersion	90 days moist-curing at 70° F + 1 day immersion
(1)	(2)	(3)	(4)	(5)
Dune Sand	C	8	311	30
Friable loess	C	3	630	287
	D	3	254	234
	C	6	1792	403
	D	6	1396	584
	C	9	1441	499
	D	9	1344	621
Alluvial clay	C	9	921	218
	D	9	613	336
Gumbotil clay	C	9	1188	386

[a] C = calcitic hydrated; D = dolomitic monohydrate

TABLE 5.—STRENGTHS OBTAINED WITH A PLASTIC LOESS SOIL TREATED WITH ADMIXTURES AND CURED IN STEAM [248° F, 1 ATMOSPHERE AND AT ORDINARY CURING 70° F, 95% RELATIVE HUMIDITY (30)]

Admixture		Immersed compressive strength, in pounds per square inch			
		Steam curing			Ordinary curing
Kind (1)	Amount (2)	0.5 hr (3)	3 hr (4)	8 hr (5)	90 day (6)
Calcitic hydrated lime	2	73	95	95	60
	5	531	680	730	180
	8	524	1060	1280	210
	12	516	1453	1683	290
Portland cement	2	150	200	210	100
	5	360	410	460	250
	8	610	820	860	540
	12	740	1220	1350	780
Dolomitic mono-hydrate lime	2	0	0	0	30
	5	280	310	290	280
	8	540	650	610	330
	12	570	990	1040	340

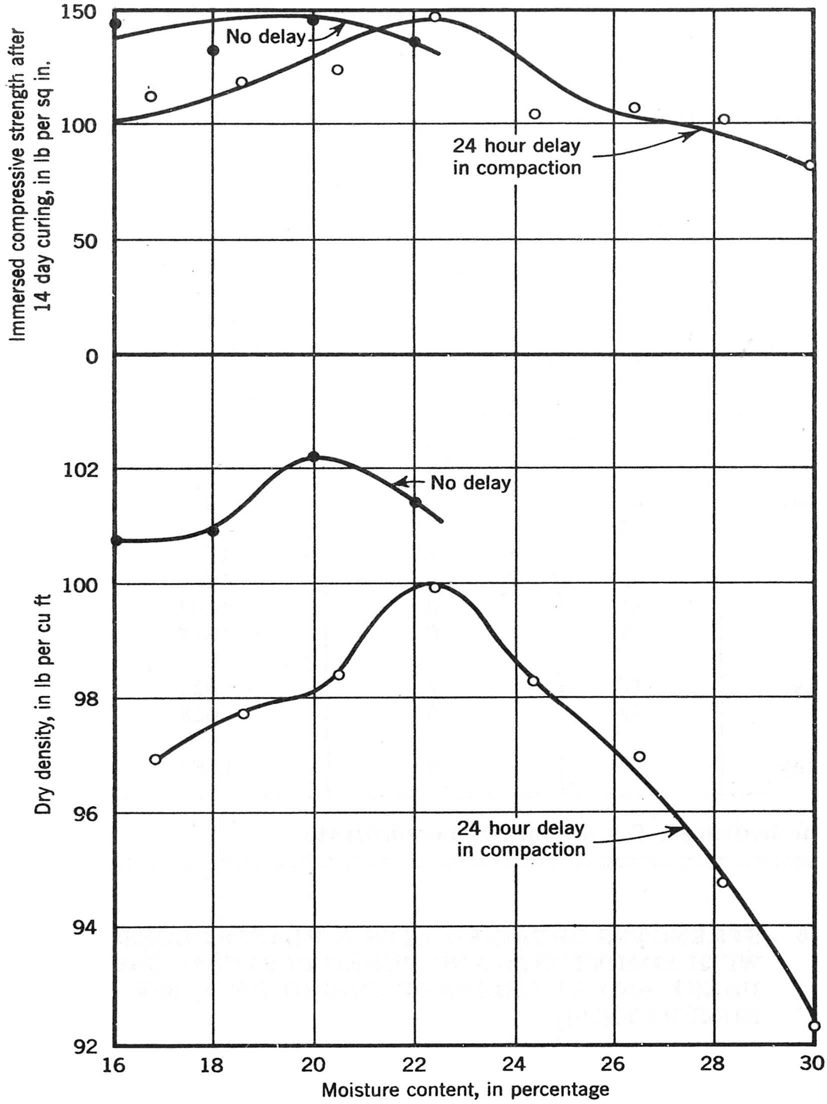

FIG. 13.—EFFECT OF DELAY OF COMPACTION ON THE STRENGTH AND DENSITY OF A SILTY CLAY (PLASTIC LOESS) SOIL TREATED WITH 9% DOLOMITIC MONOHYDRATE LIME (33)

stabilization work is scheduled for late in the summer, dolomitic monohydrate lime should be used rather than calcitic hydrated lime.

Of paramount importance are the very high strengths obtained by steam curing soil-lime stabilized specimens. For instance, after one day in the authoclave the strengths were much higher than those obtained after curing for 90 days at ordinary temperatures (Table 4). A further study on steam curing (30) revealed that strengths adequate for a base course could be obtained with only 5% calcitic lime after a steam curing period of only 1/2 hour (Table 5).

The results obtained in the steam curing experiments may be very important in the future development of the technique of soil stabilization. A revolution in the practice of soil stabilization may be brought about by the development of a portable machine able to heat and supply steam economically to a 4 in. to 6 in. layer of compacted stabilized soil. A temperature of about 250° F with applied steam maintained for 1/2 hour, or probably less, is sufficient to develop a strength of 500 psi. Since only 5% calcitic lime is needed, this construction method will be competitive with those in practice as of 1964.

Steam curing of compacted mixtures of soil and lime can be used also as a cheap method of manufacturing bricks (30).

Effect of Delay of Compaction.—Construction schedules sometimes make it impossible to compact a soil-lime mixture right after wet mixing. The effect of delay in compaction after wet mixing was studied and the results presented in Fig. 13. The maximum density after a delay of 24 hours in compaction was at a moisture content of 22.5%. With no delay in compaction maximum density was at a moisture content of 20.0%. The maximum density for the same compactive effort was 2% lower, but there were no changes in the maximum compressive strength.

EFFECTS OF LIME IN SOILS

Plasticity.—Lime quickly changes the physico-chemical properties of the clay fraction. A plastic soil mixed with lime changes its appearance to that of a friable soil.

Lime added to clayey soils increases the plastic limit (PL) to a certain point and then the PL levels off (Fig. 14). The number after the letter for the curves of Fig. 14 indicate the percentage of the specific clay mineral: Thus M-33 represents a soil with 33% montmorillonite. This increase in PL, which is pronounced in montmorillonitic clay soils, is accompanied by a decrease in the liquid limit (LL). Consequently the plasticity index (PL = LL -PL) is greatly reduced [Fig. 14 (c)]. In illitic clay soils, the increase in PL is also accompanied by an increase in LL. Therefore the PI is not greatly affected [Fig. 14 (b)].

Soils treated with lime change their soil classification due to changes in the plasticity characteristics (1, 27). For instance, a soil classified as A-7-6(20) changed to A-5(11) after 48 hours of treatment with 2% calcitic quicklime (Table 6). Very small quantites of lime are required to bring about these changes in plasticity. Generally the amount needed is from 1% to 3%, depending on the amount and type of clay present in the soil. The minimum amount of calcitic hydrated lime for montmorillonitic clay soils for a maximum decrease in plastic limit (L_{om}) is (6).

$$L_{om} = \frac{\text{percentage of 2 micron clay}}{35} + 1.25 \quad \ldots\ldots\ldots \quad (1)$$

These changes in plasticity are a function of time, although eventually there will be a leveling point.

The amount of lime L_{om} is that necessary for a complete "lime fixation" in the clay. Lime fixation is the process that brings the changes in the PL of a soil until it levels off. Only lime that is in excess of the fixation point contributes to cementation. Studies have been made to find the lime fixation point for different soils (16). In Iowa till C horizon soils, the lime fixation point occurs for an addition of dolomitic monohydrate lime between 2% and 3%, and

TABLE 6.—RESULTS OF PLASTICITY TESTS ON GUMBO

Mixture (1)	One-Hour Hydration: Liquid limit, in percentage (2)	Plastic limit, in percentage (3)	Plasticity index (4)
Natural Soil	69.0	27.3	41.7
Soil + 1% lime	64.0	47.0	17.0
Soil + 2% lime	61.5	49.5	12.5
Soil + 3% lime	57.0	46.0	11.0
Soil + 4% lime	54.5	44.5	10.0
Soil + 8% lime	51.0	43.5	7.5

appears to be interrelated to particle size and geologic age. Complete lime fixation in the C horizon of Iowa loessial soils occurs for amounts of dolomitic monohydrate lime between 2% and 4%; the amount required is proportional to the amount of clay size material in the soil and independent of carbonate content. The lime fixation is related to the cation exchange capacity of a soil (19, 27). Sedimentation tests show that for each soil there is an amount of lime above which further increase does not cause a corresponding increase of flocculation. This amount is nearly the same as the lime fixation capacity of the soil (19).

The different chemical compounds present in lime affect the plasticity in different ways (28). For instance among the chemicals that may be present in a hydrated lime, calcium hydroxide is mainly responsible for lowering the plasticity index; magnesium hydroxide causes an insignificant reduction; and magnesium oxide lowers the plasticity index to a degree intermediate between calcium hydroxide and magnesium hydroxide (Table 7). These compounds also affect the changes in plasticity obtained with commercial limes of the same type, particularly with dolomitic limes (31). Calcitic hydrated lime lowers the plasticity to a greater extent and dolomitic dihydrate to a lesser extent (Fig. 1). Quicklimes have been found to be more effective in reducing the plasticity than their corresponding hydrated limes (2).

Shrinkage.—The shrinkage characteristics of clayey soils can be greatly improved by the addition of lime (1, 2, 28). As seen in Table 2 for low amounts of lime, high-calcium hydrated lime increases the shrinkage limit in a much greater proportion than other hydrated limes or cement. For 8% additive all limes as well as cement cause a similar increase in the shrinkage limit. Quicklimes appear to be more effective than hydrated limes in the improvement of the shrinkage characteristics of soils (2).

The increase in shrinkage limit and the decrease in shrinkage ratio when lime is added indicate that a soil will shrink less upon drying.

Strength.—The effects of lime on the strength of a soil have been examined in previous sections. The immediate strength obtained in some soils upon addition of lime upgrades them for use as an engineering material to support loads. The soil is treated with lime to improve a subgrade, thus reducing the

SOIL AND VARIOUS MIXTURES OF SOIL-LIME (1)

48-Hour Hydration			
Liquid limit, in percentage (5)	Plastic limit, in percentage (6)	Plasticity index (7)	BPR-AASHO Classification (8)
			A-7-6(20)
60.5	46.0	13.5	A-7-5(13)
55.5	47.5	8.0	A-5(11)
51.0	46.0	5.0	A-5(10)
48.5	44.5	4.0	A-5(10)
45.5	43.5	2.0	A-5(9)

TABLE 7.—RESULTS OF PLASTICITY TESTS ON GUMBOTIL TREATED WITH CHEMICAL REAGENTS (28)

Chemical		Liquid limit, in percentage	Plastic limit, in percentage	Plasticity index	AASHO Classification
Kind (1)	Amount, in percentage (2)	(3)	(4)	(5)	(6)
None	0	68	23	45	A-7-6(20)
$Ca(OH)_2$	2	60	43	17	A-7-5(15)
	8	55	45	10	A-5(11)
MgO (heavy)	2	63	30	33	A-7-5(20)
	8	68	39	29	A-7-5(20)
MgO (light)	2	70	39	31	A-7-5(20)
	8	75	45	30	A-7-5(20)
$Mg(OH)_2$	2	70	28	42	A-7-6(20)
	8	70	31	39	A-7-5(20)

TABLE 8.—CALIFORNIA BEARING RATIO FOR STANDARD ASTM-AASHO COMPACTION OF GUMBO SOIL TREATED WITH LIME (1)

Mixture	California Bearing Ratio at 0.1 in. penetration		
	As molded	Soaked 4 days	
	CBR	CBR	Swell, in percentage
(1)	(2)	(3)	(4)
Natural soil	4	2	1,0
Soil + 2% lime	17	45	0.0

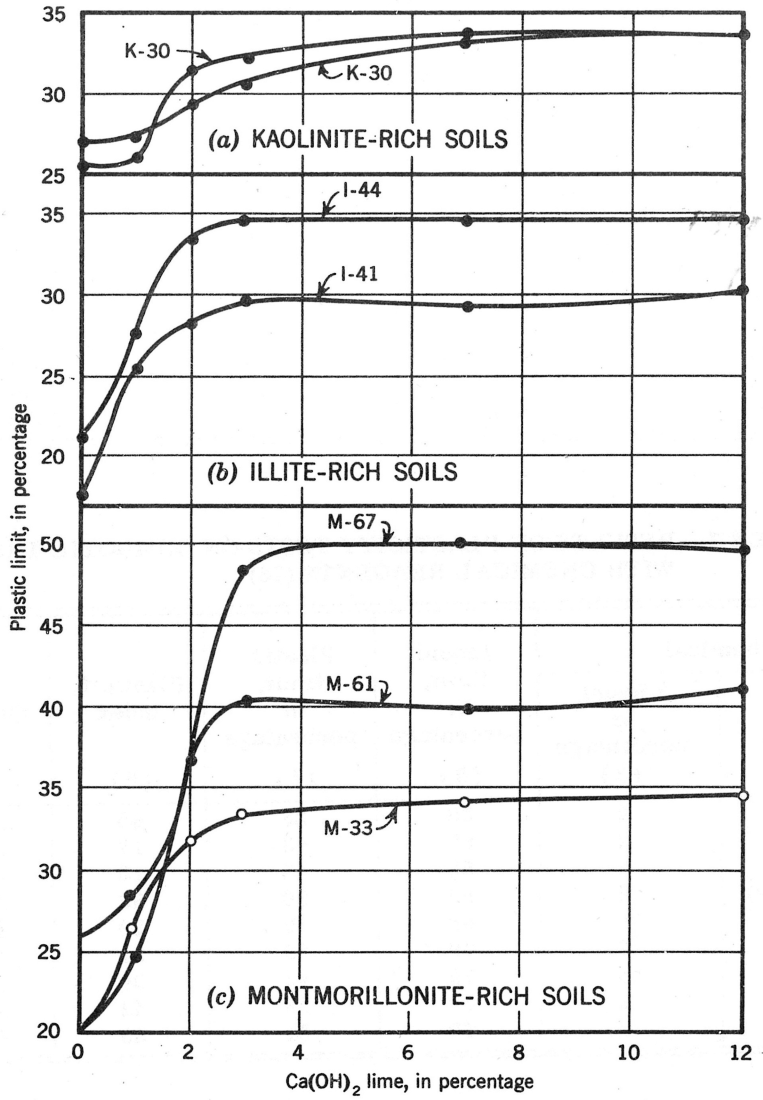

FIG. 14.—EFFECT OF ADDITION OF LIME ON THE PLASTIC LIMIT OF SOILS (6)

thickness of a pavement or to build subbases and in some instances bases for pavements.

The CBR of a fine grained soil increases immediately when lime is added, and then continues increasing with time if there is lime in excess of the "fixation" or "lime retention" point (Table 8 and Fig. 15), (1, 2, 33). The nature of the improvement can be considered stable. Specimens cured for 28 days and then broken and remolded show an improvement over uncured specimens (Fig. 15).

The common practice in soil stabilization is to saturate soil specimens with water before testing for strength. This is done to simulate the worst conditions to which a stabilized soil may be subjected in the field. Immersion

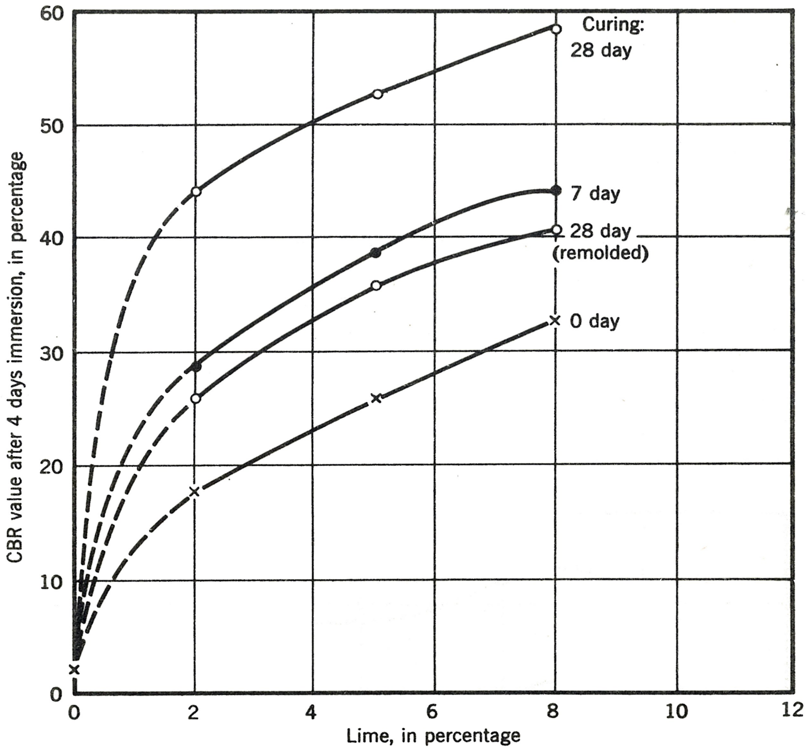

FIG. 15.—EFFECT OF ADDITION OF LIME IN THE CBR OF A SILTY CLAY SOIL (33)

destroys the apparent cohesion and dissolves any cementitious but soluable compounds formed in the stabilization processes. In studies made with calcitic hydrated lime after one day immersion the strength was found to be approximately half of the unimmersed strength (Fig. 16). In another study with dolomitic monhydrate lime the strength after immersion was approximately 75% of the unimmersed strength (16).

Swell.—An immediate benefit obtained by the addition of lime to swelling soils is to reduce or completely eliminate the increase in volume upon immersion in water (Table 8). The reduction of swelling, believed to be mainly due to substitution of other cations by calcium, is of great importance in building and pavement construction.

Freeze-Thaw Tests.—The first freeze-thaw tests of soil-lime mixtures were made according to the standard ASTM-AASHO tests used to evaluate soil-cement mixtures (2). These tests, which include a brushing test, were thougth to be too severe and did not give an accurate indication of the performance of stabilized soil mixtures subjected to alternate cycles of freezing and thawing in the field.

Several preliminary studies have resulted in the Iowa freeze-thaw test which reflects climatic conditions of the severe Iowa winters. These studies included one in which the specimens were fully exposed to the freezing and thawing cycles (3) and a Modified British Freeze-Thaw test, in which the specimens were held in a thermos bottle in which only the top part of the specimen was exposed (5). These tests indicate that mixtures made with dolomitic monohydrate lime or with dolomitic quicklime showed a better performance in the freezing and thawing tests.

Only a limited work has been done on soil-lime mixtures submitted to the Iowa freeze-thaw test (11, 17, 21). Some of these tests (11, 17), made with a friable loess, a soil highly susceptible to the detrimental action of freezing and thawing, indicate that lime is a good additive to minimize these effects. While specimens of raw soil heaved and failed after the first cycle, specimens made with 6% dolomitic monohydrate lime and cured for 28 days at 70° F did not show any expansion and gave a strength of 350 psi after 10 cycles. This strength is sometimes adequate for a base course (5).

Wet-Dry Tests.—Another criterion of durability of soil stabilized mixtures is the wetting and drying test. The wet-dry test results are difficult to evaluate. In one study the specimens gained strength during the first cycles

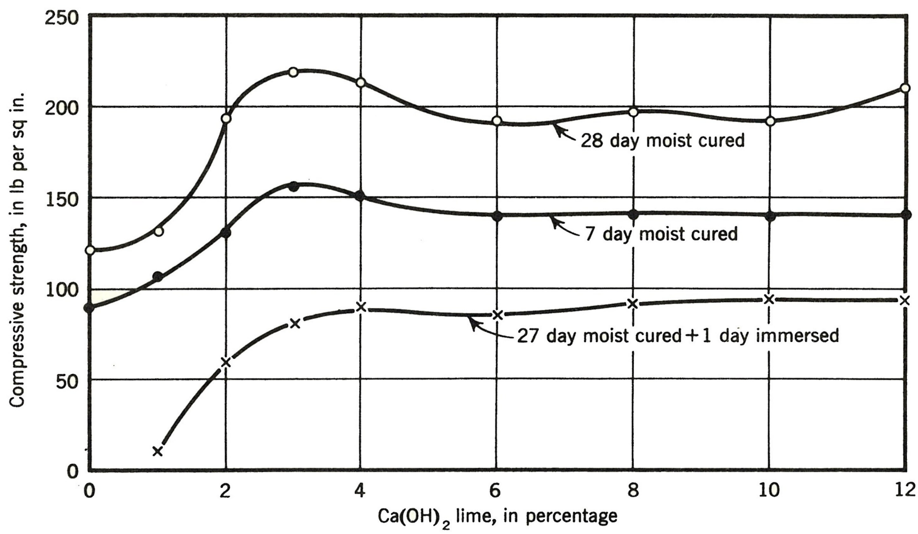

FIG. 16.—EFFECT OF WATER IMMERSION ON THE STRENGTH OF A SOIL (I-44) STABILIZED WITH LIME (7)

and then failed by swelling (2). In another study part of the specimens failed depending on the amount and type of lime and kind of soil, although the resistance to wet and dry increased with an increase in the curing period (3).

LIME IN OTHER METHODS OF SOIL STABILIZATION

Lime can be used in connection with other methods of soil stabilization (15, 19). Lime is mainly used as a mixing aid in the stabilization of clayey soils with cement, quaternary ammonium salts, etc. Lime is also one of the main components of stabilization of soils with lime and fly ash (12, 14, 17).

FIELD TRIALS IN TEST ROADS

As a complement to the laboratory investigation, lime stabilization has been used in some of the test roads constructed in cooperation with the Iowa Highway Commission. In the test road on Iowa Highway 117, lime stabilization was used in the constrction of a section of subbase. This section of natural soil stabilized with 6% dolomitic monohydrate lime has performed as well as the soil-aggregate subbase (20). In another test road built in 1959 near Fort Dodge, Iowa, lime was used as a base material; other materials used in the base course were lime-fly ash, and cement. The final results of comparative evaluation of the bases stabilized with these three materials will be made available.

BASIC RESEARCH ON LIME AND SOIL-LIME

Identification of Compounds Formed.—Work is being advanced in the identification and classification of crystalline compounds formed by the reaction between lime and soil particles (6, 7, 8, 22, 26). Early X-ray studies of soil-lime mixtures showed the formation of new peaks corresponding to similar compounds to those formed in lime-pozzolan mixtures. A calcium aluminate hydrate was first classified (8). Other reaction products found are the calcium silicate hydrate 10 Å tobermorite, 8.2 Å and 7.9 Å polymorphs of tetracalcium aluminate hydrates, and several compounds of unknown composition (26).

Physical Chemistry of Soil-Lime Mixtures.—Changes brought to the physico-chemical characteristics of soils by the addition of lime are being studied (25). The floc sedimentation rate of a clayey soil suspension reached a maximum for an amount of lime near the lime fixation point and then leveled off (19). The viscosity of slurries and the floc size also reach a maximum at the lime fixation point (or "lime retention point") (27). Lime used for fixation does not show on differential thermal analysis curves, suggesting utilization of the ions of lime rather than of lime as a compound.

Studies on Magnesium Oxide.—An investigation is in progress (as of 1964) into the physico chemical characteristics of magnesium oxide, one of the components of dolomitic limes. The crystallite size appears to be one of the important factors in the differences in strength observed with different dolomitic limes (16). The results reported to date indicate that the crystallite size of magnesium oxide depends on the temperature of calcination of magnesium carbonate (13).

CONCLUSIONS

The most important conclusions drawn from this investigation are as follows:

1. Clayey and some silty soils, or the clayey and silty fraction of granular soils, improve their engineering characteristics greatly upon addition of lime.

2. Montmorillonitic and kaolinitic clay soils respond better to lime stabilization than illitic and chloritic clay soils. Soils rich in halloysite clay attain lower strength than other types.

3. Soils of the B and C agricultural horizons respond better to lime stabilization than soils of the A horizon.

4. Clayey and silty soils are modified by the addition of lime as reflected in an improvement of plasticity, shrinkage and other properties, and are cemented with lime by the formation of calcium, silicates, some of them analogous to those formed in concrete.

5. When lime is added to soils, their ions are first combined or adsorbed in the clay structure, causing physico-chemical changes in the soil particles. These changes continue to occur up to an amount of lime at which further additions of it do not bring more appreciable changes. This breaking point is the "lime fixation" or "lime retention" point.

6. Amounts of lime up to the fixation point are utilized by the soil in ionic form to cause a modification of the soil characteristics. Lime in excess of the fixation point remains in molecular form in the soil and is believed to be utilized in the cementitious process.

7. The amount of lime generally needed for modification of a soil are from 1% to 3% and for cementation from 2% to 8%.

8. In general quicklimes are more effective than hydrated limes.

9. Calcitic limes are more effective in the modification of a soil and dolomitic limes more effective in the cementation.

10. Dolomitic dihydrate limes are not recommended for soil stabilization since they are less effective than other dolomitic or calcitic forms of lime.

11. Quicklimes added in slurry form give greater strengths than when added in powder form.

12. The effects of addition of chemicals to soil-lime mixtures are unpredictable.

13. The addition of lime decreases the maximum density of a soil, which is generally accompanied by an increase in the optimum moisture content, for the same compactive effort.

14. A delay in compaction after wet mixing lowers further the maximum density and increases further the optimum moisture content of compacted soil-lime as compared with no delay.

15. In soils with high content of montmorillonitic clay, the addition of lime distorts the shape of the moisture-density compaction curve and a well defined maximum density is not shown.

16. Increasing the compactive effort from standard ASTM-AASHO to modified, the compressive strength of soil-lime mixtures increases by 50% to 250%.

17. Temperature has a great effect on the strength of soil-lime mixtures. When strength through cementation is sought in soil-lime stabilization, the construction should be done in the early part of the summer. Dolomitic limes, except in the dihydrate form, give higher strengths than calcitic limes, at low curing temperature.

ACKNOWLEDGMENTS

Thanks are given to Richard L. Handy, Director of the Soil Engineering Research Laboratory, Harold B. Ellis, Asst. Professor of Civil Engineering, and

Jerry W. H. Wang, Research Assistant, of Iowa State University, for reading and commenting on the manuscript.

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DISCUSSION

SOIL STABILIZATION WITH CEMENT AND SODIUM ADDITIVES[a]

Discussion by Manuel Mateos

MANUEL MATEOS,[3] A. M. ASCE.—The writer began an investigation in 1956 that was, in part, a continuation of Moh's work at Iowa State University on lime-fly ash stabilization (13). First the effects of chemical additives on lime-fly ash mixtures were studied (14, 15, 16, 17, 18, 19, 20). Encouraged by the first results, the writer expanded his work to the effects of chemical additives on soil-cement, soil-lime, and soil-cement-fly mixtures (17, 20, 21, 22, 23). The work done by the writer has consequently paralleled, in some aspects, that done by Moh. The writer wishes to present that part of his work that was conducted on additives which might indicate some of the benefits and limitations of the additives tested.

The work on the evaluation of additives in stabilized soils began in Iowa State as early as 1950 and represented one of the various aspects of a general program on soil stabilization conducted under the late Donald T. Davidson.

In the early work, several organic and inorganic compounds were tried in soil-cement mixtures; vinsol resin and calcium chloride were found to be the most promising additives (24). The strength of the soil-cement specimens was found to increase on immersion in a solution of sodium hydroxide (25, 26). The effect of calcium chloride as an additive on soil-lime-fly ash was studied by Moh during his stay at Iowa State University, Ames, Iowa (27); calcium chloride was found to increase the strength of some soil-lime-fly ash mixtures.

The apparent benefits of the addition of trace chemical additives in soil-cement and soil-lime-fly ash led to an extensive investigation to find more chemicals that could improve the early strength of soil-lime-fly ash mixtures. Forty-seven chemicals were first evaluated, and several were found to be promising (14, 15). Based on this work, trace chemicals were further evaluated in soil-lime-fly ash and were also tried with soil-cement, soil-lime, and soil-cement-fly ash (16, 17, 18, 19, 20, 21, 22, 28, 29, 30, 31, 32, 33, 34). Field experiments were also conducted with soil-lime-fly ash mixtures that were treated with chemical additives (36), or with soils that were previously treated with additives (35).

The work conducted at Iowa State University's Soil Engineering Research Laboratory includes the study of chemical mechanisms and field trials. Its presentation would make this discussion unduly long. For those who wish to study further the use of additives for the stabilization of soils, a list of references is given herein.

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[a] December, 1962, by Za-Chieh Moh (Proc. Paper 3356).

[3] Research Engr., Engrg. Experimental Sta., Iowa State Univ., Ames, Iowa.

Permanency of Soil-Lime and Soil-Cement Mixtures Treated with Chemical Additives.—Most of the work conducted by Moh and others involved curing the specimens to 28 days only. The writer doubts the permanency of the

TABLE 6.—UNCONFINED COMPRESSIVE STRENGTH OBTAINED FOR A FRIABLE LOESS SOIL TREATED WITH CEMENT AND SODIUM

Additive		Immersed unconfined compressive strength, in psi		
Cement, % (1)	Sod. carb., % (2)	7 day (3)	28 day (4)	90 day (5)
5	0	239	381	572
5	0.5	344	447	431
8	0	396	627	879
8	0.5	481	708	893

TABLE 7.—EFFECTS OF CHEMICAL ADDITIVES ON THE STRENGTH OF A 76.5 TO 6 TO 17.5 MIXTURE OF ALLUVIAL CLAY-CALCITIC HYDRATED LIME-FLY ASH NO. 3, MOIST CURED AT 70°F FOR SEVERAL PERIODS

Additive		Immersed unconfined compressive strength, in psi		
Kind (1)	Amount (2)	7 days (3)	28 days (4)	90 days (5)
None	0	240	310	460
Sodium carbonate	1%	180	211	0
Sodium silicate	1%	252	339	0
Sodium hydroxide	1%	191	237	0

TABLE 8.—IMPROVEMENT IN STRENGTHS OBTAINED BY SUBSTITUTING TYPE III (HIGH EARLY STRENGTH) CEMENT FOR TYPE I CEMENT [AMOUNT OF CEMENT USED IS 8% (37)]

Soil (1)	Curing days (2)	Immersed strength, in psi		Improvement, in % (5)
		Type I (3)	Type III (4)	
Dune Sand	7	293	450	53
	28	415	550	32
	90	439	562	28
Silty sand	7	714	1150	61
	28	996	1457	46
	90	1400	1760	26

strength when clayey soils are stabilized. In one group, soil-cement-sodium carbonate specimens cured from 28 to 90 days, and sodium carbonate passed from a beneficial additive to be a rather detrimental additive (Table 6).

Experiments made with clayey soils stabilized with lime-fly ash and treated with additives might bring some light to the problem of permanency of soil-lime and soil-cement mixtures treated with chemical additives (16, 19). In those experiments, it was found that the effect of two clayey soils, alluvial clay and gumbotil, was nil and sometimes detrimental when curing was extended to 90 days; part of the results obtained are given in Table 7.

Alkaline additives appear to act as catalysts in the soil-lime and soil-cement reaction. Once the reaction is completed, the alkaline additives remain free. These additives so react with the clay particles that the strength already gained through cementation is disrupted and upset, weakening the stabilized soil. Obviously, more research is needed to ascertain whether the additives are beneficial or detrimental after long curing periods when used in the stabilization of clay soils.

Additives in Soil-Lime.—In some lime stabilized soils, the addition of critical quantities of some chemicals may improve their strength (21). The concentration of a chemical above or below the critical optimum may greatly lower the strengths.

Soils stabilized with calcitic limes respond better to chemical treatments than soils stabilized with dolomitic limes (17, 21). Because magnesium oxide in dolomitic monohydrate limes is believed to act as an accelerator of the soil-lime cementitious reaction, dolomitic monohydrate limes usually give the same strengths as calcitic hydrated lime plus additives (17, 21). The use of additives to soil-lime mixtures appears at present (1963) to be uneconomical.

Additives in Soil-Cement.—Many chemicals obviously improve the strength of soil-cement mixtures. But a word of caution is needed regarding the concentration of chemicals; most of them are beneficial at a critical optimum amount. Levels of concentration above or below the critical optimum may impair the strength (23, 33, 34).

More consideration should be given to obtaining the desired strength improvement with easy-to-handle materials. For instance, the same degree of improvement obtained with the addition of the critical optimum amount of chemical additives to soil cement mixtures (see Table 8) could probably be obtained by substituting Type III cement (high early strength) for Type I cement (unpublished research by the writer).

The author has possibly overestimated the economic advantages of the use of additives in soil-cement. There is a great danger to the workers when compounds like sodium hydroxide are used in pavement construction. The handling and spraying of some chemicals may make their use prohibitive under normal circumstances.

Apart from the extra expense of adding one more stabilizing agent, considering only the prices of cement and chemicals, there may be no economical advantages at all. The relative costs of stabilizing three soils with cement alone, and with cement plus the optimum amount of the best additive for each soil, are given in Fig. 7. In order to obtain the points for the curves of Fig. 7, the percentages of cement required at 7-day cure were determined. These percentages were multiplied by the cost of cement for each of the mixtures. The relative cost of chemical additives in cents per pound was then added to the relative cost of cement in order to obtain the total relative cost for each of the mixtures. Relative costs of soil-cement and soil-cement plus additive

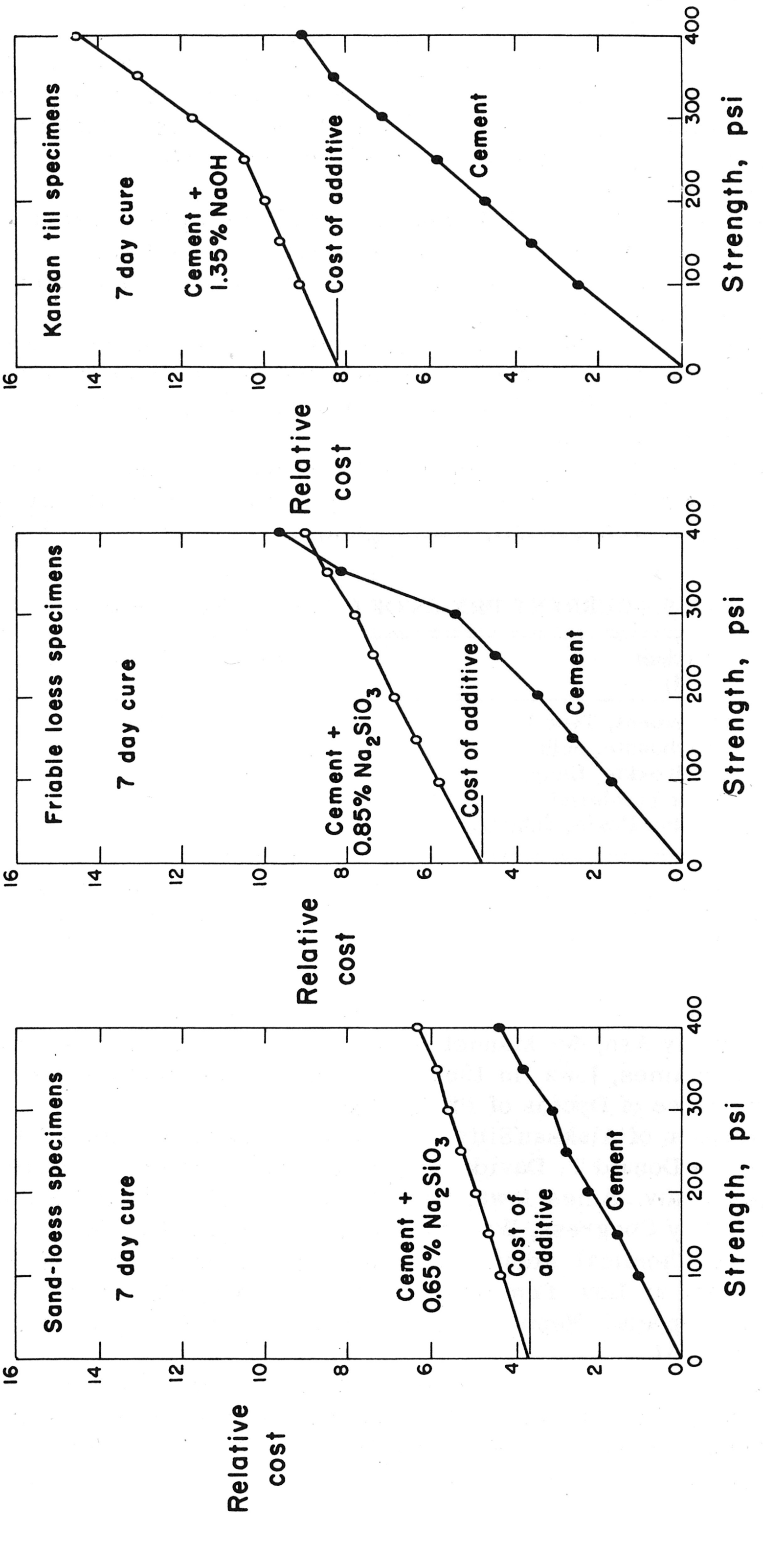
Kansan till specimens
7 day cure
Cement + 1.35% NaOH
Cost of additive
Cement
Relative cost
Strength, psi
Friable loess specimens
7 day cure
Cement + 0.85% Na_2SiO_3
Cost of additive
Cement
Relative cost
Strength, psi
Sand-loess specimens
7 day cure
Cement + 0.65% Na_2SiO_3
Cost of additive
Cement
Relative cost
Strength, psi
0
2
4
6
8
10
12
14
16
100
200
300
400

FIG. 7

were then plotted against strength for each soil. Prices used for the Portland cement and the three chemicals are given in Table 9.

The use of additives was economical only with the friable loess when a strength greater than 350 psi was desired. (Fig. 7). The desired strength in the other two soils may be obtained more economically through the use of additional cement. This does not agree with the findings of Moh that definite savings can be effected through the use of chemical additives.

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TABLE 9.—CURRENT PRICES OF CEMENT AND CHEMICALS (23)

Product (1)	Price[a], dollars per pound (2)
Portland cement, Type I	0.0106
Sodium carbonate, bulk	0.0155
Sodium hydroxide, flake, ground or powdered	0.0618
Sodium metasilicate, anhydrous	0:0570

[a] Prices based on car load lots without cost of freight to work site. When applicable, prices were adjusted to allow for one pound of pure anhydrous chemical.

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COMPACTION CHARACTERISTICS OF SOIL-LIME-FLY ASH MIXTURES

by

MANUEL MATEOS and DONALD T. DAVIDSON

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Compaction Characteristics of Soil-Lime-Fly Ash Mixtures

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Field compaction is one of the most important steps to success in the stabilization of soils. There are several factors that influence compaction, including water content, amount of compaction, temperature of mix materials, and effect of delay in compaction after mixing. A laboratory investigation was made to study these factors using four soils, three fly ashes, and one lime. Specimens were molded near standard and modified AASHO compactive effort and moist cured up to 90 days.

The results indicate that the best compacting moisture for maximum strength is to the dry side of the optimum moisture for maximum density in the sandy soil and on the wet side in the two clayey soils. The temperature of the materials does not have a marked influence on the strength. Of paramount importance is the minimizing of the delay between wet mixing and compaction of the soil-lime-fly ash mixtures when the soil contains clay particles that can react with lime, lowering the density and strength for the same compactive effort. The modified compactive effort gave strengths from 50 to 160 percent higher than the standard.

•FIELD COMPACTION is one of the most important steps in the stabilization of soils. Several factors affect compaction; among them water content, amount and type of compaction, temperature of mix materials, and effect of delay in compaction after mixing. These also affect other kinds of soil stabilization using cementitious compounds (1, 2, 3).

In laboratory investigation, some of the factors that affect the compaction of soil, lime, and fly ash mixtures were studied. The results of this investigation are presented in this paper.

MATERIALS

Dune sand, friable loess, alluvial clay, and gumbotil, all from Iowa, were used. An analysis of the soils and other materials used is given elsewhere (4, 5). The sand was Wisconsin-stage eolian sand, fine grained, oxidized, and leached. The friable loess was a Wisconsin-stage silt, friable, oxidized, and calcareous. The alluvial clay was a recent alluvial fill, plastic, slightly calcareous, with 72 percent 5-μ clay and 1.6 percent organic matter. The gumbotil was a Kansan-stage highly weathered till, plastic, noncalcareous, with 66 percent 5-μ clay. The predominant clay mineral in these soils is montmorillonite.

Three representative fly ashes were selected. Based on the pozzolanic reactivity with lime, fly ash No. 1 is of a medium to good quality, fly ash No. 2 is of a poor quality, and fly ash No. 3 of a very good quality (6).

A commercial grade calcitic (high-calcium) hydrated lime, $Ca(OH)_2$ was used.

Paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization

METHODS

The mix proportions used were 76.5 percent soil, 6 percent lime, and 17.5 percent fly ash, on a dry weight basis. Only the soil fraction passing a No. 10 (2-mm) sieve was used.

Molding was started immediately after a batch was mixed, except in the studies on delay of compaction. Test specimens 2 in. in diameter by 2 in. high were molded in the Iowa State compaction apparatus. Five blows on each side with a 5-lb hammer dropping 12 in. were given to approximate standard Proctor compaction (ASTM Designation D698-58T; AASHO Designation T99-57) (7). Ten blows on each side with a 10-lb hammer dropping 12 in. were given to approximate modified Proctor compaction (ASTM Designation D1557-58T and AASHO Designation T180-57) (8).

After being molded, specimens were moist cured at 70 ± 4 F at a relative humidity of over 90 percent. The specimens wrapped in waxed paper and sealed with cellophane tape were placed in the humid room.

After each curing period, specimens were removed from the curing chamber and immersed for one day in distilled water. They were then tested for unconfined compressive strength using a load travel rate of 0.1 in. per min. Tests were run in triplicate; the average strengths are reported.

INVESTIGATION

Moisture-Density and Moisture-Strength Relationships

The most common practice in soil stabilization is to compact specimens at a moisture content as near to the optimum for maximum dry density as possible. Previous tests made at the Engineering Experiment Station of Iowa State University with mixtures of soil, lime, and fly ash showed some differences between the optimum moisture for maximum dry density and that for maximum 7-day strength of a silty soil (7).

Inasmuch as little is known of the effects of molding moisture on the strength of lime-fly ash-stabilized soils, an investigation was conducted to find if there is any correlation between the moisture for maximum strength. Specimens were molded with different moisture contents and were cured for periods of 7, 28, and 90 days.

Two compactive efforts were used—one approximating the standard Proctor and the other approximating the modified Proctor. The soils used were the dune sand, friable loess, alluvial clay, and gumbotil; lime was commercial calcitic hydrated and the fly ashes were No. 3 with all the soils and Nos. 1 and 2 also with dune sand and gumbotil (Figs. 1 to 8).

Dune Sand. —The moisture for maximum dry density and the moisture for maximum 7- or 28-day strength in any of the six sets of mixtures show no correlation (Figs. 1 to 3). The moistures for maximum strength are far to the dry side of the optimum moisture for maximum density. Both moistures of the specimens cured 90 days are closer, but there is a difference of about 2.0 percent for the mixtures compacted at the standard Proctor and 1.0 percent or less for the modified Proctor; the moisture for maximum strength is on the dry side of the optimum moisture for maximum density. The strength curves for 7- and 28-day curing are rather flat, but for 90 days there is a very sharp peak for the maximum strength.

Gumbotil. —The moisture contents for maximum strength for gumbotil contrasted with that for sand are to the wet side of the moisture for maximum density (Figs. 4 to 6). Some of the density and strength curves are rather flat, making it difficult to define the maxima.

Friable Loess. —The moistures for maximum dry density and maximum strength for standard Proctor compaction of friable loess practically coincide (Fig. 7). That is not so for modified Proctor compaction, in which 7- and 28-day curing strength curves, although rather flat, show a maximum strength at moisture contents less than the optimum for maximum density, and a maximum is well defined at a moisture content greater than the optimum for maximum density for 90-day curing.

Alluvial Clay. —The moisture-density curves for alluvial clay do not show a peak for maximum dry density, and the density increases as the moisture content decreases

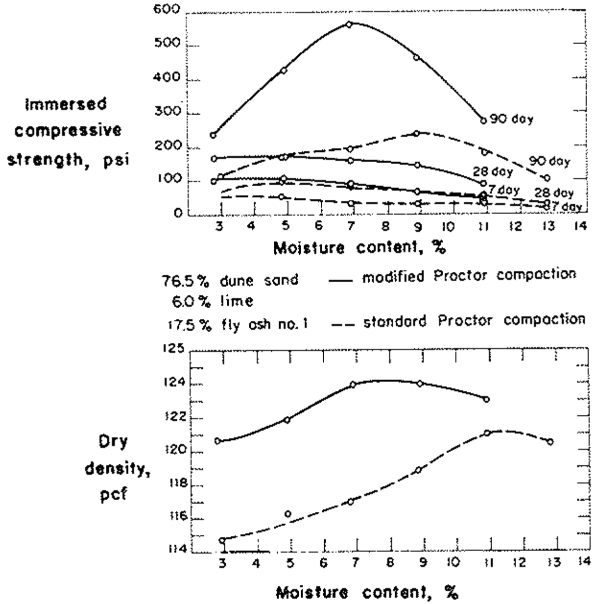

Figure 1. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 1 for standard and modified Proctor compactive efforts.

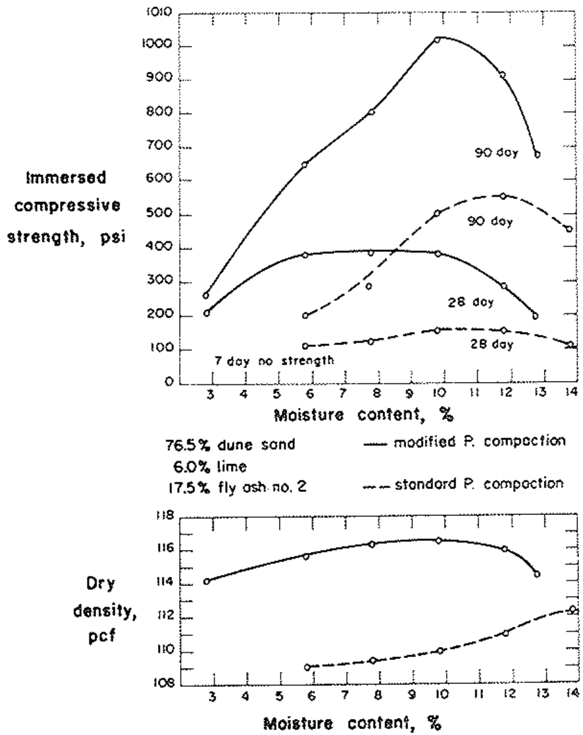

Figure 2. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 2 for standard and modified Proctor compactive efforts.

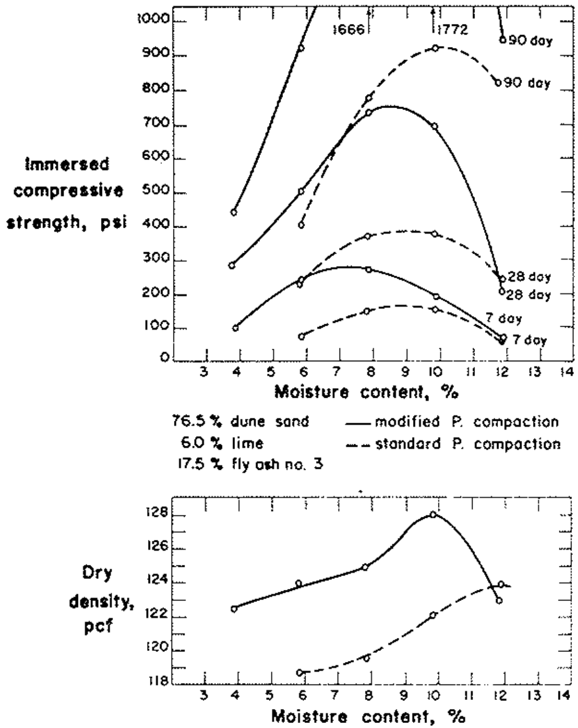

Figure 3. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

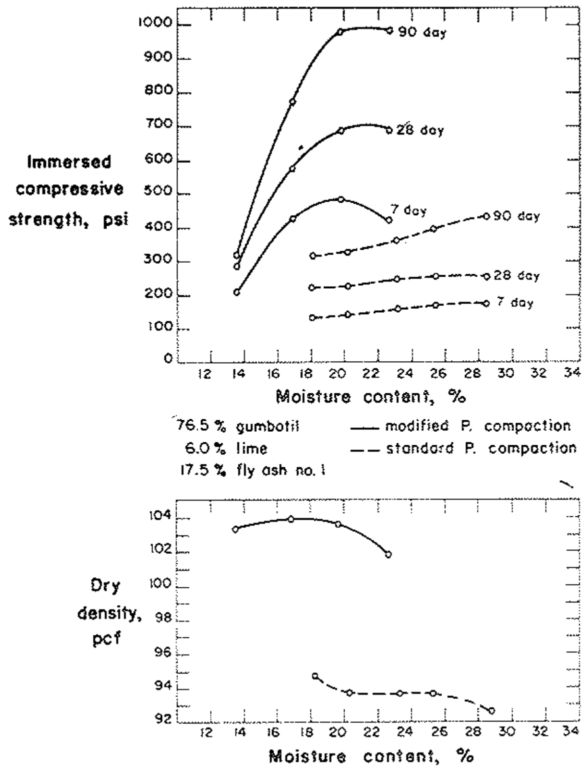

Figure 4. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 1 for standard and modified Proctor compactive efforts.

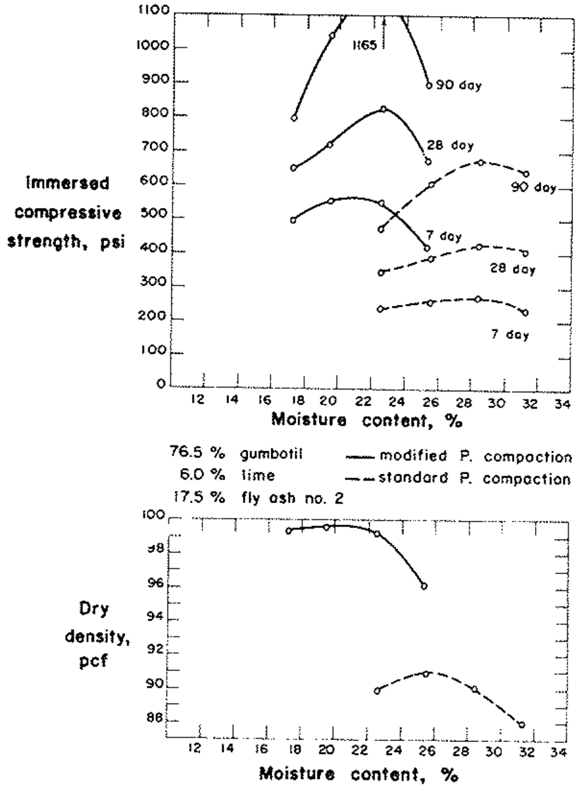

Figure 5. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 2 for standard and modified Proctor compactive efforts.

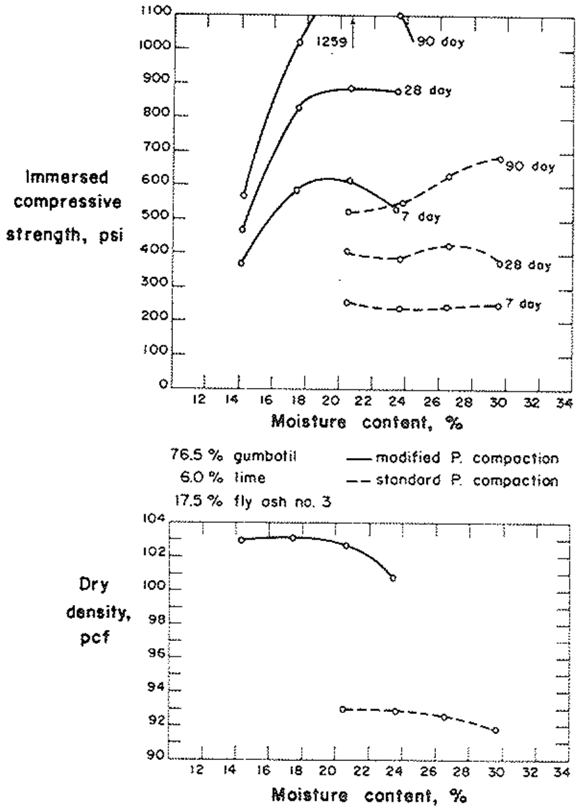

Figure 6. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of gumbotil cley, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

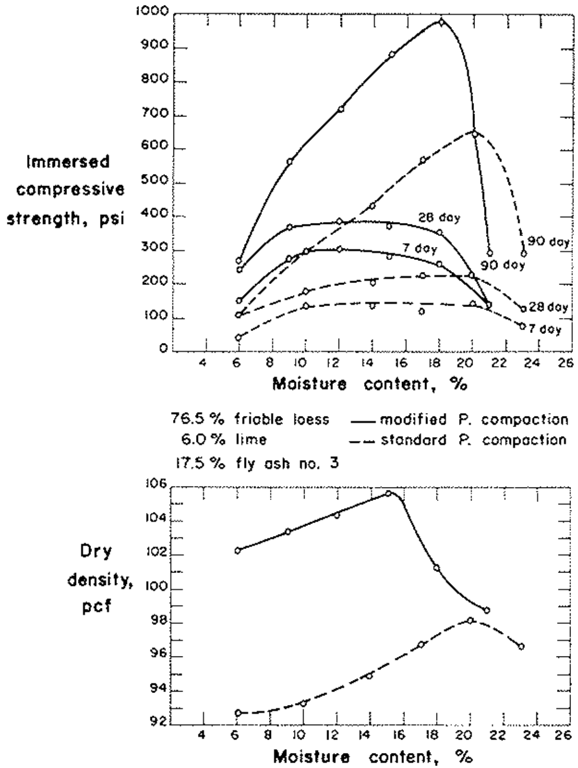

Figure 7. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of friable loess, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

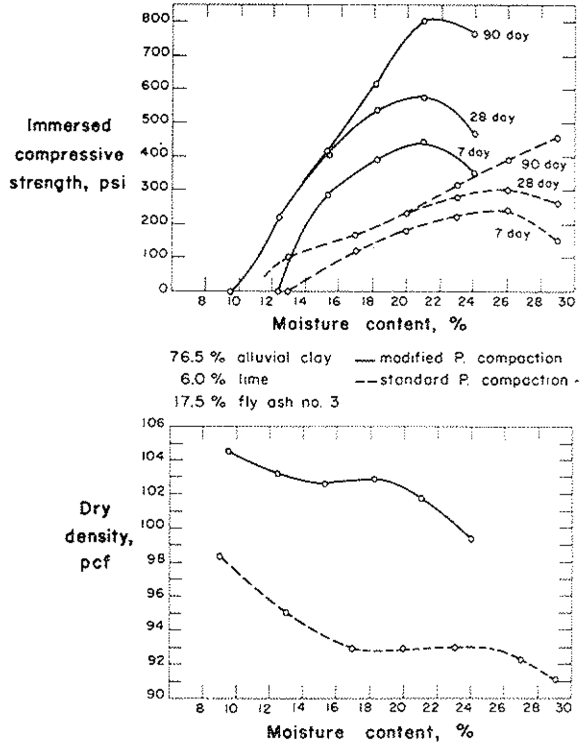

Figure 8. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

(Fig. 8). The strength curves show, however, a definite optimum moisture that changes conspicuously with curing time for standard compaction and slightly for modified.

Analysis.—The results obtained present new facts on the relations between maximum density and maximum strength in soil-lime-fly ash stabilization. The common practice has been to compact the stabilized soil as the optimum moisture for maximum density. It has been assumed that a maximum density should give a greater strength through a more dense packing of the soil and stabilizer particles, thus putting into contact more surface area for the development of the chemical reactions that lead to the formation of cementitious compounds. But in processes developing cementitious compounds by hydration, as that of the lime-fly ash reaction, the role of the water is of paramount importance.

Analyzing the results, the following have in general been observed:

1. The optimum moisture for maximum strength increased with the increase in curing time.

2. The optimum moisture for maximum strength was to the dry side of the optimum moisture for maximum dry density with the dune sand soil.

With both clayey soils (the gumbotil and the alluvial clay), it was on the wet side. With the friable loess both optimums coincide rather well.

The results indicate that a supply of water is needed for the hydration processes to continue. With dune sand, an amount of moisture two percentages below the optimum for maximum density will develop a maximum, or close to the maximum strength over a long curing period.

The moisture content is critical with friable loess. Reasonably good strengths were obtained at the optimum moisture content for maximum density, but an excess of water brought about a sharp decrease in strength; and amounts of water below the optimum reduced the strength. The optimum moisture for maximum density represents an amount of water sufficient for the chemical process of hydration which, therefore, should be the recommended moisture to stabilize the friable loess. The moisture should be on the dry side of the optimum.

The clayey soils showed great avidity for water. This is because complex reactions take place between the lime and soil particles apart from the lime-fly ash reaction. A rearrangement of the structure of the clay or colloidal particles may take place due to the excess of Ca ions in the stabilized soil. These Ca cations use up H and O ions and H_2O molecules. Based on long-term strengths, amounts of water much greater than the optimum for maximum density are advisable with clayey soils containing high percentages of montmorillonitic clay. It is observed that the shape of the moisture-density curves for both clayey soils is rather flat. In some instances the maximum density is not sharply shown, being undefined. The same happened when lime alone was used. This peculiarity has already been discussed (5).

Effect of Compactive Effort

The trend in compaction of earth embankments, subgrades, and stabilized soils is towards compactive efforts greater than the standard Proctor. The Corps of Engineers and other agencies specify the required density in airfield construction as a percentage of the modified maximum density. Although some work has been done in comparing the strengths obtained at different compactive efforts (8, 9) only one fly ash was used, and the specimens were cured only up to 28 days.

In this work three fly ashes were used with the sand and gumbotil, and one fly ash was used with the alluvial clay and loess. Curing periods were carried up to 90 days. The results for different moisture contents and the maximum strengths vs time are plotted (Figs. 1 to 12).

The modified compaction gave strengths considerably greater than the standard compaction in all eight comparative studies. In all curing periods, the increase ranges from a minimum of 50 percent to a maximum of 160 percent without any correlation.

The rate of strength increase for 7-, 28-, and 90-day curing is almost a straight-line relationship, except for those mixes made with the gumbotil. Greater rate of in-

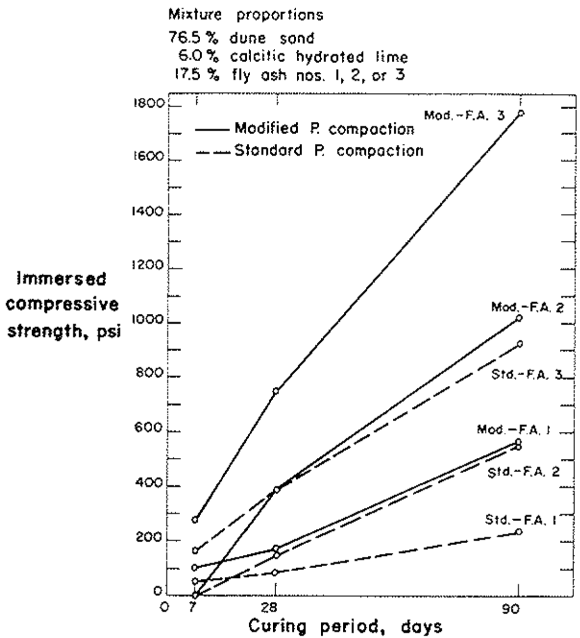

Figure 9. Effect of compactive effort on strength of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash.

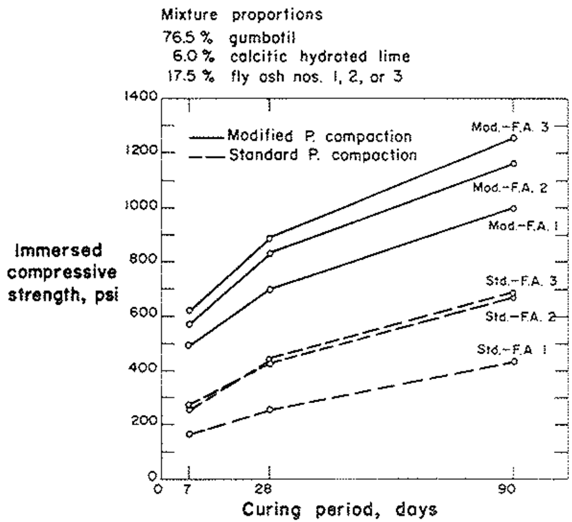

Figure 10. Effect of compactive effort on strength of 75.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash.

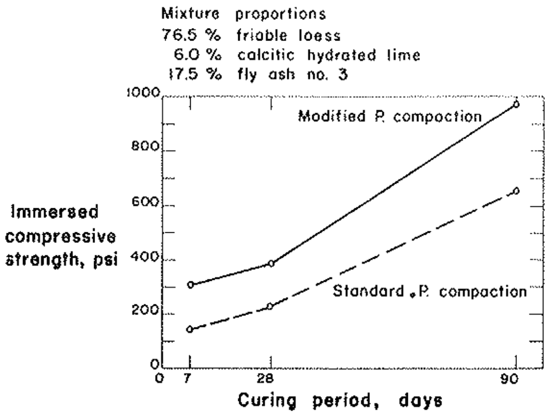

Figure 11. Effect of compactive effort on strength of 76.5:6:17.5 mixture of friable loess, calcitic hydrated lime, and fly ash No. 3.

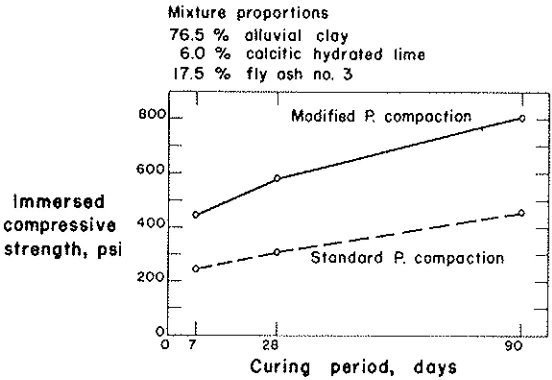

Figure 12. Effect of compactive effort on strength of 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3.

crease with time is found in the friable soils (dune sand and friable loess), in which there is not a break in the rate of increase up to the longest curing period used. After 90-day curing, all the mixtures show that the strength increase also takes place at longer curing periods.

The convenience of compacting the mixtures of soil, lime, and fly ash to the highest possible degree is obvious. By a closer contact of particles at the proper moisture, the surface reactions have more opportunity to develop. This results in the higher strength obtained with the modified compaction.

When lime and fly ash are used to stabilize soils, the steady increase in strength with time has to be accounted for (Figs. 9 to 12). Early strengths may be low, but the continuous gain in strength over long periods of time increases the quality of the pavement made with lime-fly ash stabilized courses. This is desirable when the volume of traffic is expected to increase with time.

Influence of Temperature of Materials at Time of Compaction

So far as known, the influence of temperature of the materials at the time of compaction on soil, lime, and fly ash mixtures has not been studied. The ambient mean temperature between two consecutive days may be as much as 40 F, and that between a cool day in the early working season and another day in the hot part of the summer may be more than 60 F. This work was undertaken to determine the influence of extremes in ambient temperature during the working season on the strength of soil, lime, and fly ash mixtures.

The soils used were dune sand and gumbotil. The very reactive fly ash No. 3 was used because it should accentuate the findings. A series of batches at different moisture contents was mixed and compacted with the soil, lime, fly ash, and water in a cooled state (about 54 F), and another series in a heated one (about 104 F). The soil-lime-fly ash mixtures, molded at several water contents, were stored in the moist room at 70 ± 3 F. The maximum immersed unconfined compressive strength and density values were obtained from the tests of these specimens (Table 1).

Although the data do not show a marked trend, mixing and compacting with hot materials may be detrimental in clayey soils stabilized with lime and fly ash. The density and strength were somewhat reduced.

The results show that the basic reaction between lime and fly ash with sand is not influenced by the temperature, in the range of 54 to 104 F of the materials at the time of mixing. The slight decrease in strength and density in the hot batches made with the clayey soil (gumbotil) is caused by the reaction between the lime and the highly active surface of clay particles before compaction.

Further tests were made in which the materials were mixed at the same temperatures with different water moisture contents and then stored at the same temperatures of mixing for 4 hr before compaction (Table 2). The compacted test specimens were cured in the moist room. Dune sand was the only soil used.

The results obtained further prove that the reaction between lime and fly ash in itself is not affected by the temperature of the materials, (between 54 and 104 F) at the time of mixing. Nevertheless, lime when used in clayey soils reacts in several ways with the clay particles, and some of these reactions may be activated by temperature. These reactions subtract or make inactive part of the lime for the pozzolanic reaction with fly ash and soil particles, causing a decrease in compacted density and in subsequent strength.

Effect of Delay of Compaction After Wet Mixing

When interruptions in road construction occur after lime and fly ash are mixed with

TABLE 1

INFLUENCE OF MIXING TEMPERATURE OF MATERIALS ON STRENGTH OF 76.5:6:17.5 MIXTURE OF SOIL, CALCITIC HYDRATED LIME, AND FLY ASH NO. 3, WITH COMPACTION AFTER MIXING

Soil	Temp. (°F)	Max. Immersed Unconf. Compress. Strength (psi)			Max. Dry Density (pcf)	Optimum M. C. for Max. Density (%)
		7-Day	28-Day	90-Day		
Dune sand	54	154	422	1,004	123.8	12
Dune sand	70	165	390	930	124.2	12
Dune sand	104	158	382	1,010	124.2	12
Gumbotil	54	302	455	620	94.1	25
Gumbotil	70	255	445	685	93.0	25
Gumbotil	104	238	350	492	92.5	25

TABLE 2

INFLUENCE OF MIXING TEMPERATURE OF MATERIALS ON STRENGTH OF 76.5:6:17.5 MIXTURE OF DUNE SAND, CALCITIC HYDRATED LIME, AND FLY ASH NO. 3 IN WHICH COMPACTION WAS DELAYED 4 HR AFTER MIXING

Temperature (°F)	Max. Immersed Unconf. Compress. Strength (psi)			Max. Dry Density (pcf)	Optimum M. C. for Max. Density (%)
	7-Day	28-Day	90-Day		
54	140	369	960	124.0	12
70	141	348	935	122.7	12
104	148	342	973	122.0	12

soil and water and compaction is delayed, the strength of the stabilized soil may be affected. A few tests were made to establish a criterion on the maximum permissible length of time to be allowed soil, lime, and fly ash mixtures between wet mixing and compaction.

Selected mixes using dune sand or gumbotil were made. The mixtures were prepared with different amounts of water to obtain maximum values for strength and density. After mixing the soil, lime, fly ash, and water, one set of mixtures was immediately compacted into specimens; another set was stored for 4 hr in the moist room at 70 F, and then specimens were compacted; another set was stored for 24 hr in the same moist room before compaction of specimens. The maximum values for strength and density are givein in Tables 3 and 4. It was found that the longer the compaction was delayed, the higher the moisture content required to obtain a maximum strength.

Dune Sand.--Strength and density of the mixture with dune sand decrease slightly as the time between wet mixing and compaction increases. The greatest decrease in strength is found in mixtures made with fly ash No. 3. For 7-day curing it dropped from 165 psi for no delay in molding to 118 psi for a 24-hr delay; for 28-day curing the drop is from 390 to 243 psi; for 90-day curing there is no difference between the

TABLE 3

RESULTS OBTAINED WITH 76.5:6:17.5 MIXTURES OF DUNE SAND, CALCITIC HYDRATED LIME, AND FLY ASH COMPACTED AFTER DIFFERENT LAPSES OF TIME FOLLOWING WET MIXING

Fly Ash No.	Setting Time[1]	Max. Dry Density (pcf)	Max. Immersed Unconf. Compress. Strength (psi)		
			7-Day	28-Day	90-Day
1	0	121.2	55	90	240
	4	120.3	45	81	219
	24	118.6	41	60	210
2	0	112.3	0	150	560
	4	112.5	0	159	532
	24	110.8	0	141	417
3	0	124.1	165	390	930
	4	122.6	141	348	935
	24	122.6	118	243	945

[1] No. of hours elapsed between mixing and molding.

TABLE 4

RESULTS OBTAINED WITH 76.5:6:17.5 MIXTURES OF GUMBOTIL, CALCITIC HYDRATED LIME, AND FLY ASH COMPACTED AFTER DIFFERENT LAPSES OF TIME FOLLOWING WET MIXING

Fly Ash No.	Setting Time[1]	Max. Dry Density (pcf)	Max. Immersed Unconf. Compress. Strength (psi)		
			7-Day	28-Day	90-Day
1	0	Undefined	170	260	440
	4	Undefined	151	260	431
	24	Undefined	136	279	327
3	0	Undefined	255	445	685
	4	Undefined	260	405	596
	24	Undefined	173	244	351

[1] No. of hours elapsed between mixing and molding.

strength of specimens molded after mixing and of those molded after a 24-hr delay. With fly ash No. 2 specimens after 90-day curing there is also a great difference between the strengths of mixtures with no delay in compaction and those with a 24-hr delay, the strength for these two cases being 560 and 417 psi, respectively. The decrease is not very significant with fly ash No. 1, although it is steady with time of delay.

In general, the decrease in strength is very slight in mixtures when compaction was performed 4 hr after wet mixing. The decrease is more accentuated for the mixtures stored 24 hr before compaction.

A delay in compaction after wet mixing also brings about a decrease in dry density of sand, lime, and fly ash mixtures. The decrease amounts to less than 2 percent after a 24-hr delay.

Gumbotil.—A great decrease in strength correlates with the time of delay in compaction after wet mixing of gumbotil, calcitic hydrated lime, and fly ash mixtures. With a 24-hr delay for fly ash No. 3 the strengths were reduced from 32 to 49 percent, depending on the curing period. The reduction in the fly ash No. 1 mixture is less important, showingup in 7- and 90-day strengths but not in those of 28 days.

The density diminished consistently as compaction time was delayed. Because the maximum dry density was undefined, the moisture-dry density relationships in mixtures with gumbotil are plotted for the range in moisture content in which the maximum strengths were obtained (Figs. 13 and 14). The compacted density is lowered to a great extent by a delay in compaction. The drop in dry density is about 2 pcf for a 4-hr delay and about 5 pcf for a 24-hr delay.

Analysis.—The results stress the importance of proceeding with compaction as soon as possible after wet mixing of soil, lime-fly ash mixtures. This is highly recommended with montmorillonitic clayey soils in which strengths may drop by about 40 percent and dry density but about 6 percent for the same compactive effort if compaction is delayed one day after wet mixing. With sandy soils the drop in strength and dry density is not very important, and compaction may proceed the following day after wet mixing without significantly impairing the strength or dry density.

The lowering of strength and density may be for one or more of the following reasons:

1. Formation of carbonates by chemical reaction between lime and the carbon dioxide of the atmosphere.
2. Pozzolanic reactions between lime and fly ash.
3. Reactions between lime and soil particles.

The first two are probable in sandy soils and all three in clayey soils.

A small reduction in strength and density in sandy soils indicates that the first two processes are not developed to a great extent. Because the carbonation of lime takes place at a rapid rate in a moist condition and because of the unlikeliness of quick pozzolanic reactions between lime and fly ash in a loose state, the first reaction is likely mainly responsible for the lowering of density and strength in sandy soils.

The reactions between lime and clay mineral particles are very important in montmorillonitic clay soils. The unbalanced electrical surface forces of the clay particles adsorb calcium cations of lime; calcium ions also produce a crowding action of clay particles; and lime reacts with the soil particles in a pozzolanic action. These reactions account for a great part of the reduction of strength and density when compaction does not soon follow wet mixing of clayey soil, lime, and fly ash mixtures.

CONCLUSIONS

1. Maximum strength of soil, lime, and fly ash mixtures is produced by a compaction moisture content that is not necessarily the optimum moisture content for maximum density. The compaction moisture for maximum strength of specimens with sandy soils is to the dry side of the optimum moisture for maximum density. In soils having a high clay content, at least of the montmorillonite type, the compaction moisture is to the wet side. With such other soils as friable loess maximum strength and maximum density may occur at the same compaction moisture.
2. If no water is added during curing, the required compaction moisture content to produce maximum strength changes with the curing period–the longer the curing period, the greater the compaction moisture content needed for maximum strength.
3. Increasing the compactive effort from standard Proctor to modified increases the strength of soil, lime, and fly ash mixtures. The strength increase obtained varies from 50 to 160 percent.
4. If the materials are at high temperature at the time of mixing, the density and strength of clayey soil, lime, and fly ash mixtures are lowered, suggesting pre-compaction reactions. Sandy soils are not affected.
5. Compaction should proceed as soon as possible after wet mixing of soil, lime, and fly ash mixtures; otherwise density and strength may be substantially lowered. With clayey soils, compaction should be completed not later than 4 hr after wet mixing, whereas with sandy soils, compaction can be delayed until the day after wet mixing without appreciable loss of strength.

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