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Physical and mineralogical factors in stabilization of Iowa soils with lime and fly ash

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PHYSICAL AND MINERALOGICAL FACTORS IN STABILIZATION OF IOWA SOILS WITH LIME AND FLY ASH

by

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Dean of Graduate College

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INTRODUCTION

Natural outcrops of sound bedrock are not common in Iowa. Quarries are sometimes difficult to open because the rock is generally covered by a thick overburden. This initial cost to uncover the bedrock and the high expenses of exploitation accounts for the scarcity of open quarries in Iowa and for a high initial price of the rock products. When the quarries are distant from the construction site and the amount of aggregate required does not warrant the opening of a new one, the hauling expense may make the aggregate very expensive. This may inhibit its use, and engineers must seek for other more economic solutions or materials.

Soil, cheap and abundant, has been used for thousands of years as a construction material. In its natural state it generally has very poor engineering qualities, but they are improved by ramming. The introduction in the early thirties of the concepts of lubrication effects of water and of an optimum moisture that produces a maximum density for a compactive effort, gave the soil engineer new tools in the improvement of a soil for its use as an engineering material (59)*. This concept of the moisture-density

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* Numbers in parenthesis refer to the Bibliography.

relationship was applied to soils treated with admixtures, and from this a separate science of soil stabilization has developed.

Several soil admixtures are used today to obtain a construction material with better engineering properties than those of the original soil. The most extensively used are cement and lime. Others, like lime with fly ash, appear to be satisfactory stabilizers but they have not been much used because their characteristics and behavior when added to soils are not well known. Many other admixtures are being evaluated in the laboratory before subjecting them to field testing.

The importance of the construction program of the vast network of interstate highways has given the investigations for new and better methods of soil stabilization additional emphasis. These investigations may bring some economy to the expenditures for the program. The item in a recent report on highway research for which the highest amount of money was recommended was the improvement of knowledge of aggregates and soils; a total of ten million dollars annually was suggested (38).

During the last ten years the Engineering Experiment Station of Iowa State University, in cooperation with the Iowa State Highway Commission and the Iowa Highway Research Board has been conducting an extensive evaluation of different methods of soil stabilization for road courses. Special attention has been given to the use of cheap available chemical and by-products or wastes. One of them is fly ash, which together with lime can be used in soil stabilization.

Fly ash is an artificial pozzolan produced as a waste material in the power plants that burn powdered coal. The American Society for Testing Materials has defined fly ash and pozzolan as follows (4):

> For the purpose of these specifications fly ash is defined as the finely divided residue that results from the combustion of ground or powdered coal and is transported from the boiler by flue gases.
>
> For the purpose of these specifications the term pozzolan is defined as a silicious or alumino-silicious material which in itself possesses little or no cementitious value but which in finely divided form and in the presence of moisture will chemically react with alkali and alkaline earth hydroxides at ordinary temperatures to form or to assist in forming compounds possessing cementitious properties.

Industries have the problem of disposing of over ten million tons of fly ash every year; the cost to haul and dump fly ash is approximately one dollar a ton. Since laboratory and field tests of soil stabilized with lime and fly ash have given promising results, highway engineers and power industry management are interested in further improving and promoting the use of fly ash in soil stabilization.

The work done until now to evaluate lime plus fly ash as an admixture to soils has been very restrictive. General conclusions as to the use of these materials have been drawn based on results obtained with a limited variety of the component materials---soil, lime and fly ash, or based on limited testing. The insufficient "know-how" of a method or process may lead to an erroneous evaluation of its qualities or properties. An attempt has been made in this investigation to introduce a reasonable number of variables in the main components: soil, lime and fly ash. Other factors had to be studied also: the investigation for this report was conducted to obtain information on the following aspects of soil-lime-fly ash stabilization:

1. Lime and fly ash proportions and amount
2. Moisture-density-strength relationships
3. Effect of compactive effort
4. Effect of curing temperature
5. Influence of temperatures of component materials at time of compaction
6. Effect of delay of compaction after wet mixing
7. Effect of chemical additions on the lime-fly ash reaction and their effects with soils
8. Study of the modification of fly ashes
9. Comparison with other methods of soil stabilization
10. Final evaluation including freezing and thawing tests.

REVIEW OF LITERATURE

As an artificial pozzolan, fly ash can be used in any of the numerous applications in which pozzolans are used, providing its quality competes with other available pozzolans (7,20,21,51,56). Mixtures of pozzolan, lime and water form a cement that was extensively used by the Romans. Philologically the name pozzolan comes from the city of Pozzuoli near Vesuvious and the bay of Naples, Italy, where the Romans quarried a volcanic ash. Roman structures built 2,000 years ago and still standing today attest the quality and durability of pozzolanic cements.

Development of Soil-Lime-Fly Ash Stabilization

With the expansion of the electric power industry in the United States during the early 1930's, power companies burning pulverized coal, and collecting fly ash from the smoke to prevent air pollution, found the disposal problem to be an expensive and sometimes a difficult one. Great quantities of fly ash had to be hauled away and dumped, then buried or otherwise prevented from blowing around (62,70). Much research has been done to find new uses for fly ash, but much more of the ash is still produced than can be used. The principal uses have been as a filler in grouting materials, as an ingredient in the manufacture of building blocks and in Prepakt concrete, as a pozzolan in Portland cement concrete, and as an admixture with lime in soil stabilzation. (9,11,47,51,66)

In 1934 a patent was granted on the use of fly ash with an alkaline earth base as a structural material (58). The cementitious properties of fly ash mixed with lime and water were studied in 1940; after that several compositions of soil, lime, and fly ash for use in base and subbase courses of pavements were studied, and the trade name Poz-O-Pac was given to them (13,24). A patent on the use of lime and fly ash with fine aggregate was obtained in 1951, and another in 1954 on the use of lime and fly ash for stabilizing finely divided materials such as soils (34,35). Another patent was issued in 1957 (36).

The first field trials of soil, lime and fly ash mixtures were made in the construction of a number of by-passes, interchanges and shoulders of the New Jersey Turnpike. It has been reported that they are giving satisfactory performance (52,53,54).

Since 1954 the Iowa Engineering Experiment Station has been studying the effect of both the amount of lime and fly ash and the ratio of lime to fly ash on the strength and durability of soil, lime and ash mixtures. This work has indicated that about 25 percent lime and fly ash in ratios varying between one lime to nine fly ash and one lime to two fly ash can be used satisfactorily for stabilizing various textured soils (14,22,28,55,64). It appears that the higher ratios are required for clayey soils (19,39). Dolomitic monohydrate lime produces higher strength than high-calcium hydrated lime in soil and lime mixtures with Iowa soils (44,48). The same was found to be true for soil, lime and fly ash mixtures at elevated temperatures greatly improves the early strength (14,28,63). The highest compressive strength occurs at or just below the optimum moisture content for the standard Proctor compactive effort (28). High carbon fly ashes do not react with lime as well as the low carbon fly ashes; fineness is also a measure of the reactivity (19,63,67). The strength increases with the increase of fly ash content (14,49). The addition of fly ash may not be necessary to lime stabilized soils containing large amounts of montmorillonite or kaolinite clays (39) or silt (64). The strength increases proportionately with the amount of compactive effort (40,68). Increasing the time of mixing in a mechanical mixer, at constant speed, gives increased unconfined compressive strength (28). Test specimens were still gaining strength after a curing period of one year (28). The relative humidity during curing should be maintained as near 100 percent as possible (28).

The addition of calcium chloride to soil-lime-fly ash mixtures has been known to increase its early strength (28,53,54). In field trials of soil-lime-fly ash paving near Detroit, Michigan, the best field performance was obtained with a stony sand which had been treated with about 0.5 percent of calcium chloride six weeks prior to lime-fly ash stabilization (17). The higher early strength obtained in this road, and thus greater resistance to freezing, was attributed to an acceleration of the lime-fly ash reaction by the calcium chloride.

The strength improvements when calcium chloride was added in small amounts to soil, lime and fly ash mixtures suggested that other chemicals may produce similar strength increases. An investigation was made with 47 chemicals and it was found that many of them improved considerably the early and/or long term strength of lime-fly ash mixtures. Among the more promising are sodium carbonate, sodium and potassium hydroxides, lithium carbonate, potassium and sodium permanganates, potassium carbonate, sodium chloride, aluminum chloride, potassium and sodium bicarbonates, sodium sulfite and a sodium tetraphosphate (18,50).

An evaluation of the most promising chemical additive, sodium carbonate, was then made (22,33,49,55). As a result a patent was obtained on the use of sodium carbonate to accelerate the setting of lime-fly ash-soil mixtures (32).

The serviceability of soil, lime, and fly ash mixtures with and without chemicals is being studied in field trials by the Iowa Engineering Experiment Station in co-operation with the Iowa State Highway Commission and the Iowa Highway Research Board. A test road was built near Colfax in 1958, and another was built near Fort Dodge in 1960. Both test roads have sections of base and/or subbase courses of soil treated with lime and fly ash. A report is being prepared on the Colfax test road (41).

Mechanism of Lime-Fly Ash Reaction

When lime and fly ash are mixed with the soil, part of the lime combines with the soil particles, part with carbon dioxide present in the soil air and soil water, and part with fly ash in a pozzolanic reaction.

Lime reacts with the clay minerals in the soil in two manners, one of which is ionic in nature. This is a complex reaction in which the excess of calcium cations supplied by the lime cause, by their crowding action on clay particles, a flocculation of the soil, and also an exchange of calcium for other cations in the clay structure. By this reaction soil plasticity is decreased, workability is greatly increased, and volume changes due to moisture are reduced. The other reaction, that takes place when the soil is in a compacted state, is pozzolanic in nature similar to the lime-fly ash reaction. Fine silt-size quarts minerals, in addition to clay minerals, are very likely involved in that reaction. Cementitious reaction products are formed which increase the bearing capacity of the soil.

Carbon dioxide combines with lime to form calcium carbonate or calcium magnesium carbonate, depending on the lime used. In practice this takes place at a very slow rate in soil-lime-fly ash mixtures. It has been found that the presence of carbon dioxide in the air does not affect the compressive strength of the soil-lime-fly ash specimens (14).

The main cementitious material created by the pozzolanic reaction is a hydrous calcium silicate, but since most pozzolans contain amounts of materials other than silica, other compounds involving iron, alumina and the alkalies are likely formed also (10,20,21). Calcium silicates and aluminates have been identified in the reaction between lime and fly ash (8,46). A compound has been isolated in the reaction between a lime and a fly ash which is tentatively formulated as $[(Ca_{89}\ Na_{11})\ O][(Si_{75}\ Al_{25})\ O_2]\ .9\ H_2O$*. Base exchange takes place between the pozzolan and lime, but this action is unlikely to be cementitious (45).

Pozzolans containing silica in amorphous forms react faster with lime than those containing silica in crystalline forms, and the rate of reaction varies inversely with crystal size (20). Strength increases with compacted density of soil-

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* Handy, R.L., Engineering Experiment Station, Ames, Iowa. Data on x-ray analysis of lime and fly ash mixtures.

lime-fly ash mixtures (40,68). This may be due to an increase in the number of contact points among the soil particles providing greater bond by the cementitious microcrystals or gels.

The reactivity of pozzolans is correlated with the alkaline nature of lime-pozzolan mixtures. The activation of silica by the hydroxyl ions plays an important part in the formation of calcium silicates. The maximum adsorption of calcium ions by quartz occurs at a pH of 11 (42). A study of the adsorption of calcium by a clay showed that the amount of calcium adsorbed increases with increase of pH up to about pH 11 (12). Therefore there seems to be an optimum pH for the formation of calcium silicates in the lime-pozzolan reaction.

MATERIALS AND METHODS

Materials Used

Soils

Four natural soils, a dune sand, a friable loess, an alluvial clay and a heavily weathered glacial till, were selected as being representative of important Iowa soil types. A field description of each sample is given in Table 1, and physical and chemical properties are given in Table 2.

Ottawa sand was used in the preliminary evaluation of the effects of chemical additives on the lime and fly ash reaction. It is a natural silica sand assumed to be unreactive with lime and water at the curing temperatures used. Its gradation met the requirements for graded standard sand (ASTM Designation: C 109-58) (4):

Sieve size	Percent passing
No. 16 (1190-micron)	100
No. 30 (590-micron)	98 ± 2
No. 50 (297-micron)	28 ± 5
No. 100 (149-micron)	2 ± 2

Table 1. Description of natural soils

Soil	Dune sand (S-6-2)[a]	Friable loess (20-2)	Alluvial clay (627-1)	Kansan gumbotil (528-8)
Location	Benton County, Iowa	Harrison County, Iowa	Harrison County, Iowa	Keokuk County, Iowa
Geological description	Wisconsin-age eolian sand, fine-grained, oxidized, leached	Wisconsin-age loess, friable, oxidized, calcareous	Recent fill, alluvial plastic, slightly calcareous	Kansan-age gumbotil, highly weathered, plastic, non-calcareous
Soil series	Carrington	Hamburg	None	Mahaska[b]
Horizon	C	C	Undefined	Fossil B
Sampling depth, ft.	6-11	49-50	0-4	7.5-8.5

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

[b] Underlies C horizon loess of Mahaska series.

Table 2. Properties of natural soils

Soil	Dune sand	Friable loess	Alluvial clay	Kansan gumbotil
Textural composition[a], %:				
Gravel (> 2mm)	0.0	0.0	0.0	0.0
Sand (2-0.074 mm)	95.5	0.7	2.4	19.4
Silt (0.074-0.005 mm)	1.5	82.3	25.6	14.6
Clay (< 0.005 mm)	3.0	17.0	72.0	66.0
Colloids (< 0.002 mm)	2.6	14.0	61.0	63.0
Atterberg limits[b]:				
Liquid limit, %		32	72	76
Plastic limit, %		25	26	26
Plasticity index	Non-Plastic	7	46	50
Classification:				
Textural[c]	Sand	Silty loam	Clay	Clay
Engineering (AASHO)[d]	A-3(0)	A-4(8)	A-7-6(20)	A-7-6(20)
Chemical:				
Cat. exch. cap.[e], m.e./100g	1.0	14.5	44.4	39.2
pH[f]	6.6	8.4	7.7	7.4
Carbonates[g], %	0.4	10.4	3.6	2.0
Organic matter[h], %	0.1	0.1	1.6	0.1
Predominant clay mineral[i]:	Montmorillonite (trace)	Montmorillonite	Montmorillonite	Montmorillonite

[a] ASTM Method D422-54T (3).
[b] ASTM Method D423-54T and D424-54T (3).
[c] Triangular chart developed by U.S. Bureau of Public Roads (65, p.47).
[d] AASHO Method M145-49 (2).
[e] Ammonium acetate (pH = 7) method on soil fraction 0.42 mm (No. 40 sieve).
[f] Glass electrode method using suspension of 15 g soil in 30 cc distilled water.
[g] Versenate method for total calcium.
[h] Potassium bichromate method.
[i] X-ray diffraction analysis.

Fly Ashes

Eight fly ashes were selected to represent variations in the properties of this by-product material.

Fly ash No. 1 was collected by multiple cyclone and electrical precipitators. The coal was from districts 3 and 8 in Ohio and from northern West Virginia, and was processed through pulverizing mills so that 70 percent passed a #200 mesh. The sample was sent from the St. Clair (Michigan) Power Plant of the Detroit Edison Company.

Fly ash No. 2 was collected by mechanical equipment. The coal was from northern Illinois, and was burned in a B & W boiler. This sample was sent from the Sixth Street Power Station in Cedar Rapids, Iowa, by the Iowa Electric Light and Power Company.

Fly ash No. 3 was collected by electrical precipitators from a dry bottom type of boiler using unwashed coal from western Kentucky. The sample was sent from the Paddy's Run Power Station at Louisville, Kentucky, by the Louisville Gas and Electric Company.

Fly ash No. 4 was collected by mechanical precipitators. The coal from northern Illinois was burned in a Springfield boiler. This sample was sent from the Sixth Street Station in Cedar Rapids, Iowa, by the Iowa Electric Light and Power Company.

Fly ash No. 5 was collected by mechanical (centrifugal) precipitators. The coal from Illinois was pulverized in a ball mill prior to burning. The sample was sent from Riverside Station Power Plant at Davenport, Iowa, by the Iowa-Illinois Gas and Electric Company.

Fly ash No. 6 was collected by mechanical precipitators (multicone dust collector). The coal from Iowa (Monroe, Polk, Marion and Mahaska counties) was unwashed steam coal which was pulverized and tangencial fired. The sample was sent from the Des Moines Power Plant by the Iowa Power and Light Company.

Fly ash No. 7 was collected by mechanical equipment (VGR multiclone). The coal from southern Illinois was washed, dried, and pulverized with Riley mills. The sample was sent from the Waterloo Power Plant by the Iowa Public Service Company.

Fly ash No. 8 was collected by mechanical precipitators (cyclone type). The coal from several Missouri and Kansas mines was pulverized and burned in suspension in Combustion Engineering boilers. The sample was sent from the Hawthorn Station Power Plant of the Kansas City Power and Light Company, Missouri.

Table 3. Analysis of fly ashes

Fly ash No.	1	2	3	4
Source	St. Clair Michigan	C. Rapids Iowa	Louisville Kentucky	C. Rapids Iowa
Loss on ignition, %[a]	3.9	7.2	2.6	18.6
Specific surface, Blaine (sq.cm/3)	2820	2663	3226	4550
Specific gravity	2.58	2.39	2.60	2.37
Fineness (% passing No. 325 sieve)	91.8	49.8	86.1	54.9
Silicon dioxide (SiO_2), %	43.5	36.7	42.5	36.2
Magnesium oxide (MgO), %	0.2	1.0	0.8	0.9
Calcium oxide (CaO), %	2.9	3.5	5.7	8.3
Aluminum oxide (Al_2O_3), %	23.2	21.3	23.4	15.8
Iron oxide (Fe_2O_3), %	24.8	24.3	20.0	16.7
Sulphur trioxide (SO_3), %	0.8	2.0	2.3	1.5

[a]Approximately equal to carbon content.

Table 3. (Continued)

Fly ash No.	5	6	7	8
Source	Davenport Iowa	Des Moines Iowa	Waterloo Iowa	Kansas Missouri
Loss on ignition, %a	0.7	0.2	13.9	3.8
Specific surface, Blaine (sq.cm/3)	576	1460	4240	2048
Specific gravity	3.43	2.82	2.34	2.68
Fineness (% passing No. 325 sieve)	22.6	31.8	54.9	64.8
Silicon dioxide (SiO_2), %	11.3	40.1	38.5	35.3
Magnesium oxide (MgO), %	0.3	0.3	0.2	0.9
Calcium oxide (CaO), %	12.3	5.8	3.2	5.3
Aluminum oxide (Al_2O_3), %	0.9	13.1	18.1	7.7
Iron oxide (Fe_2O_3), %	68.4	36.7	16.2	43.3
Sulphur trioxide (SO_3), %	3.2	2.4	1.1	1.4

Limes

Most of this investigation was made using two commercial grade limes furnished by the U.S. Gypsum Company. One is a hydrated calcitic lime, brand name Kemikal, and the other is a type N monohydrate dolomitic lime, brand name Kemidol. In the preliminary evaluation of chemical additives to Ottawa sand-lime-fly ash mixtures a calcium hydroxide (calcitic hydrated) lime, reagent grade, from Fisher Scientific Company was used. Two dolomitic monohydrate limes, from Western Lime and Cement Company and from Rockwell Lime Company, were also used in a comparative study of some commercial dolomitic monohydrate limes. The properties of all the limes used are given in Table 4.

Table 4. Analysis of limes

Kind of lime	Calcitic hydrated	Dolomitic monohydrate	Calcitic hydrated	Dolomitic monohydrate	Dolomitic monohydrate
Type	Commercial	Commercial type N	Reagent grade	Commercial type N	Commercial type N
Source	New Braunfels, Texas	Genoa, Ohio			
Company	U.S. Gypsum	U.S. Gypsum	Fisher	Western	Rockwell
Brand name	Kemikal	Kemidol			
Silicon dioxide, %	0.3	0.4		0.6	0.4
Iron and aluminum oxide, %	0.6	0.2		1.1	0.6
Calcium oxide, %	73.8	49.6		48.3	45.4
Magnesium oxide, %	0.6	31.8		33.2	36.3
Sulfur trioxide, %	0.3	1.1			
Loss on ignition, %	24.1	17.0		16.8	21.0
Passing No. 325 sieve, %	95.5	91.0		99.2	91.0

Cement

The portland cement used was commercial type I from the Penn-Dixie Cement Corporation of Des Moines, Iowa.

Table 5. Analysis of portland cement.

Source	Des Moines
Company	Penn-Dixie
Silicon dioxide, %	21.6
Aluminum oxide, %	5.1
Iron oxide, %	3.0
Calcium oxide, %	64.1
Magnesium oxide, %	2.9
Sulfur trioxide, %	2.3
Loss on ignition, %	0.6

Chemicals

The following chemicals evaluated as additives to lime-fly ash mixtures were reagent grade, except magnesium oxide which was USP grade:

Chemical	Formula
Sodium carbonate	Na_2CO_3
Sodium hydroxide	$NaOH$
Sodium metasilicate	$Na_2SiO_3 \cdot 9H_2O$
Sodium chloride	$NaCl$
Aluminum chloride	$AlCl_3 \cdot 6H_2O$
Calcium chloride	$CaCl_2$
Lithium carbonate	Li_2CO_3
Magnesium oxide	MgO
Manganese chloride	$MnCl_2 \cdot 4H_2O$
Phosphoric acid	85% H_3PO_4
Potassium permanganate	$KMnO_4$
Sodium phosphate	$Na_3PO_4 \cdot 12H_2O$

Water

Distilled water was used throughout all the experimentation to eliminate the variable that might result from impurities added with ordinary tap water. It was obtained from a Barnstead Automatic Water Still, model SLH-2.

Procedures

Mixture proportions

The proportions of soil plus lime or lime-fly ash or cement were made based on the dry weight of the soil-lime, soil-lime-fly ash or soil-cement mixtures. The chemical additive, when used, was computed on a dry basis excluding the water of crystalization, and is expressed as a percentage of the dry weight of the total Ottawa sand or soil, lime, and fly ash mixture. Chemicals were added either in powder form or as a component of the mix water.

Mixing and molding

Mixing of batches for preparing test specimens was done in a Hobart kitchen mixer, model C-100, at low speed in the following sequence of operation: The dry ingredients were machine mixed for 30 seconds, the mix water was added and machine mixed for one minute, the mixture was hand mixed for about 30 seconds to clean the sides and bottom of the mixing bowl, and the mixture was machine mixed for one minute.

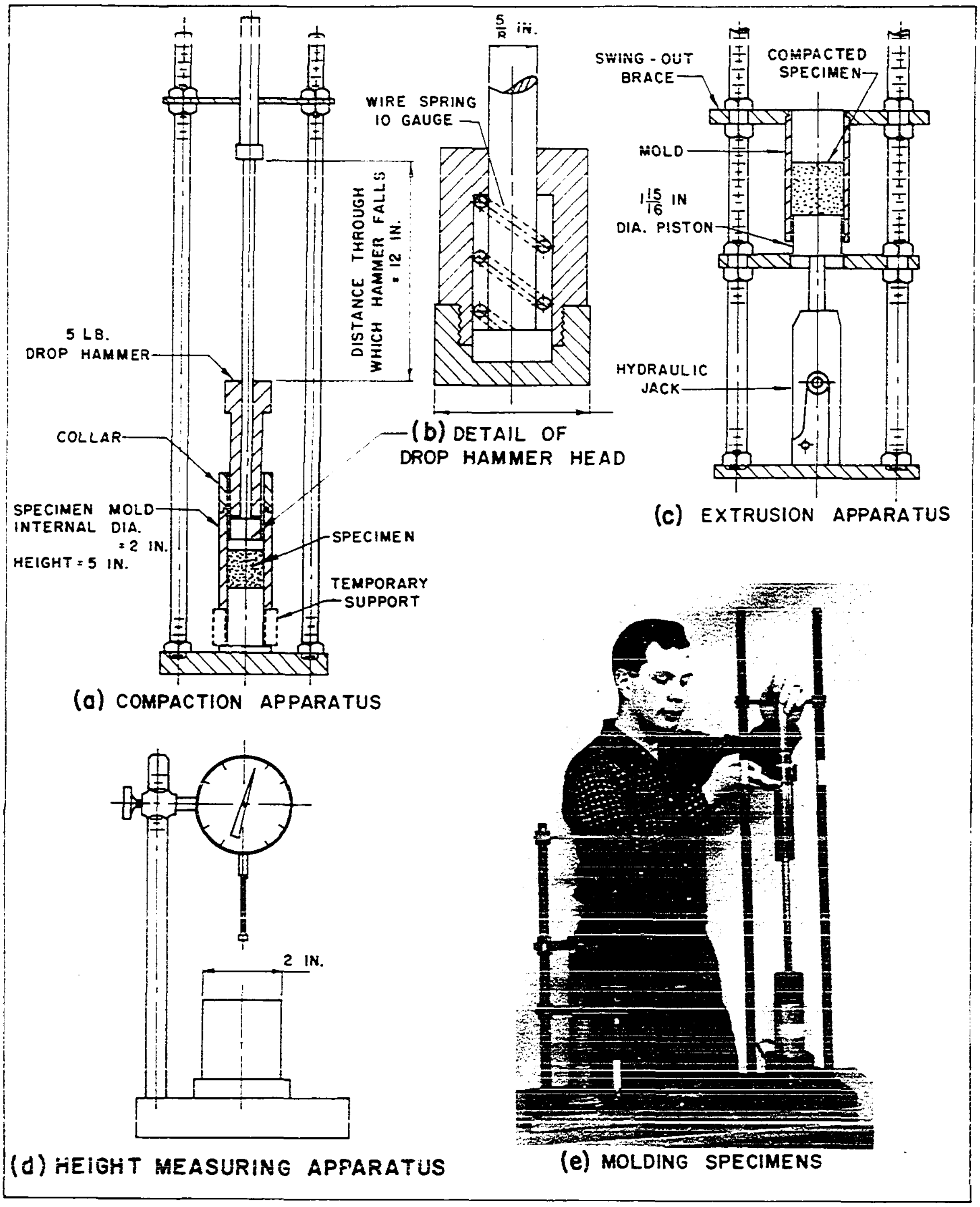
Molding of test specimens was started immediately after a batch was mixed, except where otherwise indicated. A double plunger drop-hammer apparatus was used to mold 2 inch diameter by 2 $\pm$ 0.05 inch high specimens, Figure 1. With this apparatus the equivalent of standard Proctor compactive energy was obtained when giving 5 blows on each side of the specimen using a 5 pound hammer dropping 12 inches with the molding apparatus fastened to a wooden table. The equivalent of modified Proctor compactive energy was obtained with a 10 blows on each side with a 10 pound hammer dropping 12 inches with the molding apparatus fastened to a concrete pedestal (3,28,68). The standard Proctor compaction was used in these studies except where otherwise specified. After molding, the specimen was extruded, weighed to the nearest 0.1 gram and measured to the nearest 0.001 inch. During molding, a wet cloth was kept over the bowl to prevent drying of the mixture.

Curing

Specimens of each batch were moist cured at 70 ± 4°F, except where otherwise indicated, at a relative humidity of over 90 percent for the desired periods of time. To preserve moisture better and to reduce absorption of carbon dioxide from the air, the specimens were wrapped in wax paper and were sealed with cellophane tape before being placed in the humid room.

Specimens cured at higher temperatures were wrapped in Saran wrap and kept in watertight containers with free water inside to assure a high relative humidity during the curing period. Steam cured specimens were wrapped in Saran wrap and put in an autoclave at 15 atmospheres of pressure and

Figure 1(a). Apparatus for molding 2 inch diameter by 2 inch high test specimens to near standard Proctor compaction.



(a) COMPACTION APPARATUS

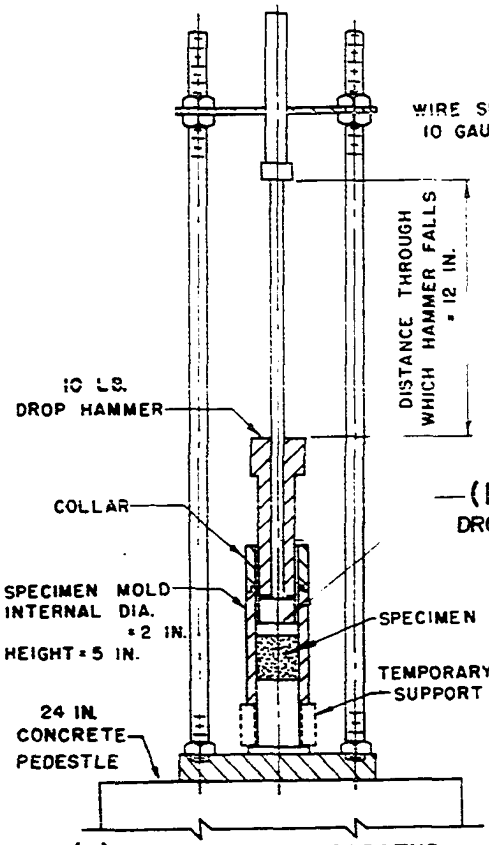
(b) DETAIL OF DROP HAMMER HEAD

(c) EXTRUSION APPARATUS

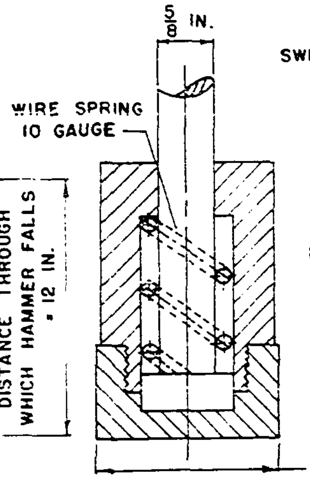
(d) HEIGHT MEASURING APPARATUS

(e) MOLDING SPECIMENS

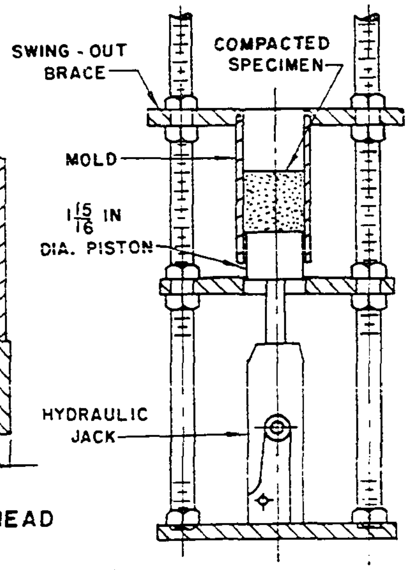
Figure 1(b). Apparatus for molding 2 inch diameter by 2 inch high test specimens to near modified Proctor compaction.



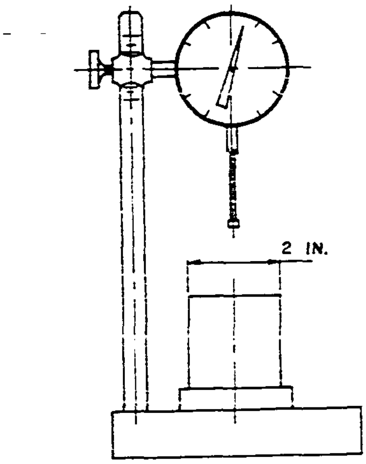
(a) COMPACTION APPARATUS



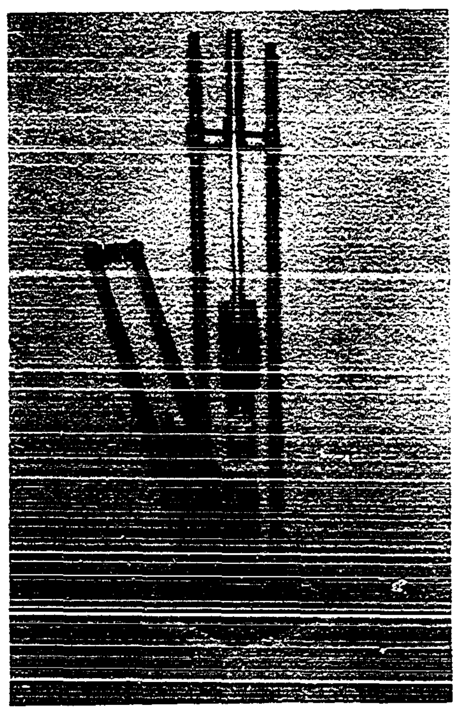
(b) DETAIL OF DROP HAMMER HEAD



(c) EXTRUSION APPARATUS



(d) HEIGHT MEASURING APPARATUS



(e) MOLDING SPECIMENS

248°F (120°C); the temperature was increased slowly up to the 248°F in order to prevent cracking of the specimens. Specimens cured at low temperatures were kept in a refrigerator after being wrapped in Saran wrap. The lost of moisture in no specimen was greater than 5 percent of the total moisture content.

Strength testing

After each curing period, specimens were unwrapped and immersed in distilled water for one day. Then they were tested 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 in psi. This is in accordance with ASTM specification designation C-109-58 which requires a minimum of three specimens for each set of curing conditions (4). A series of three observations is generally sufficient to detect any readings which deviate excessively. Specimens that differed by more than 10 percent from the average value of test specimens made from the same mix and tested at the same age were not considered in determining compressive strength. If two specimens were rejected, new specimens were prepared.

Durability tests

The Iowa freeze-thaw test (26) was used to evaluate the durability of selected mixtures. Four 2 inch by 2 inch specimens from each mixture were cured 28 days in the moisture room. Two specimens, designated the control specimens, were then left immersed for 10 days; and the other two specimens, designated the freeze and thaw specimens, were exposed alternately to temperatures of 20 ± 2°F (16 hours) and 77 ± 4°F (8 hours) for ten cycles, each cycle lasting 24 hours. A vacum flask specimen container (16) was used to cause freezing to occur 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 test. After these treatments, the unconfined compressive strength of the freeze-thaw specimens (p_f) and of the control specimens (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:

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

INVESTIGATION

Moisture-Density and Moisture-Strength Relationships

The most commonly accepted practice in soil stabilization is to perform the compaction 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 soil, lime, and fly ash mixtures revealed some differences between the optimum moisture for maximum dry density and that for maximum 7 day strength of a silty soil (28).

The information on the effects of molding moisture on the strength of lime-fly ash stabilized soils is then scarce and sometimes contradictory. This led to an investigation to find if there is any correlation between the moisture for maximum dry density and the moisture for maximum strength. The strength tests had to be made including short and long term curing periods; consequently specimens molded at different moisture contents were kept curing for 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,

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* A.S.T.M. Designation D698-57T (3).

** A.S.T.M. Procedure (3).

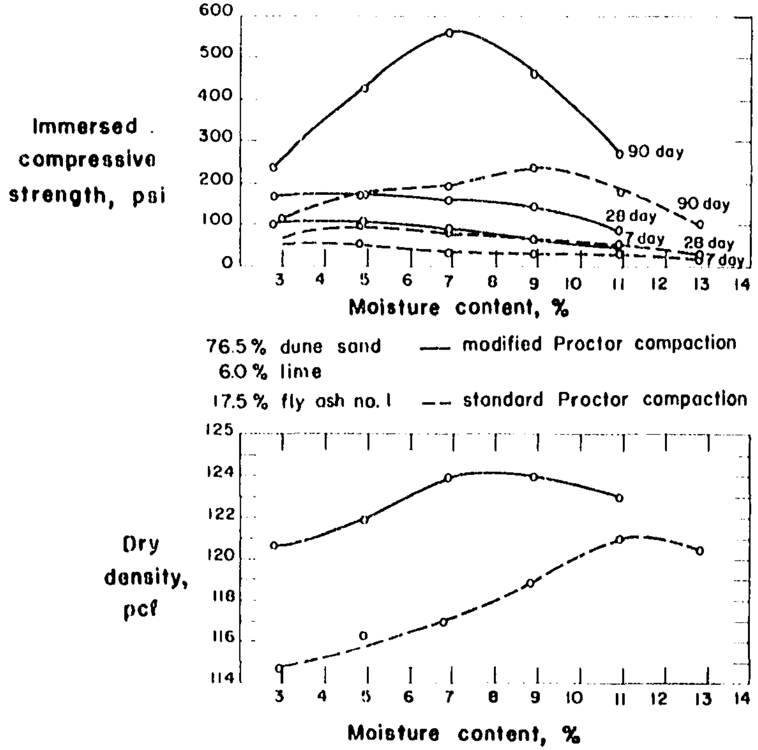
alluvial clay and gumbotil; lime was commercial calcitic hydrated; and the fly ashes were No. 3 with all the soils and Nos. 1 and 2 with dune sand and gumbotil. The proportions were 76.5 percent soil, 6 percent lime and 17.5 percent fly ash. The results are plotted in Figures 2 through 9.

Dune sand

The moisture for maximum dry density and the moisture for maximum 7 or 28 day strengths in any of the six sets of mixtures show no correlation (Table 6). 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 still 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 still on the dry side of the optimum moisture for maximum density. The strength curves for 7 and 28 days curing are rather flat, but for 90 days there is a very sharp peak for the maximum strength.

Figure 2. Moisture-density and moisture-strength relationships of a 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 3. Moisture-density and moisture-strength relationships of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 2 for standard and modified Proctor compactive efforts.


Immersed compressive strength, psi
90 day
90 day
28 day
7 day
28 day
7 day
Moisture content, %
76.5 % dune sand
6.0 % lime
17.5 % fly ash no. 1
modified Proctor compaction
standard Proctor compaction
Dry density, pcf
Moisture content, %

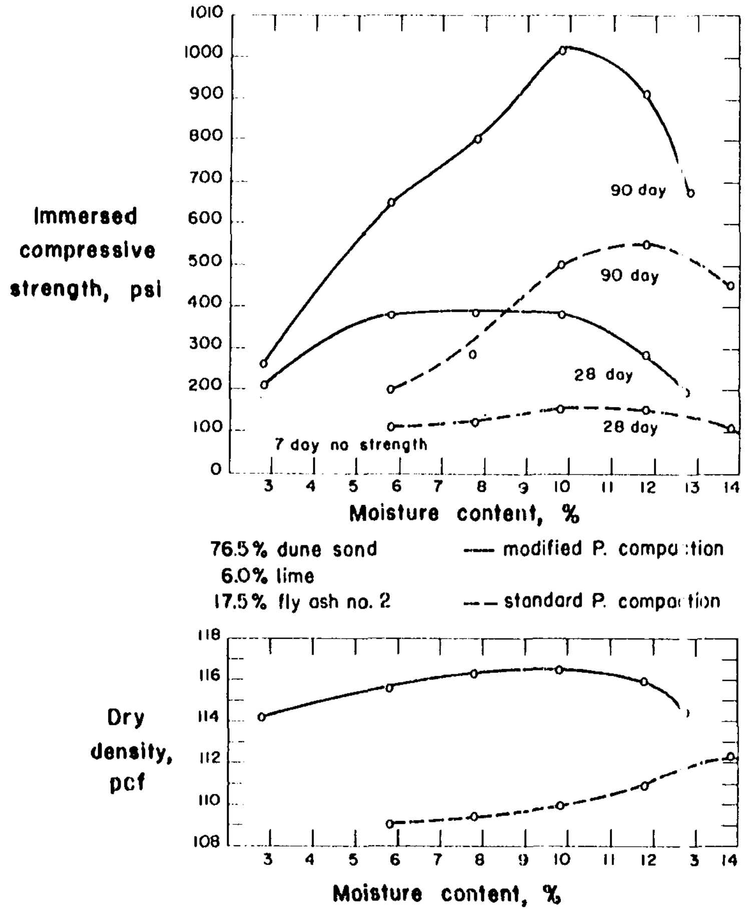
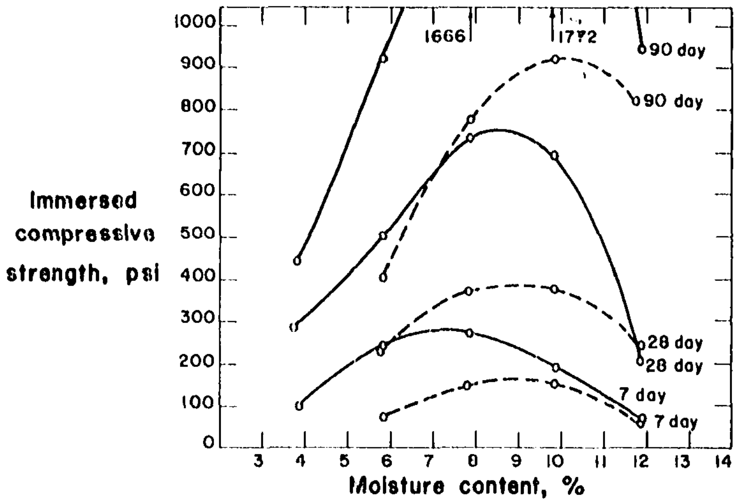
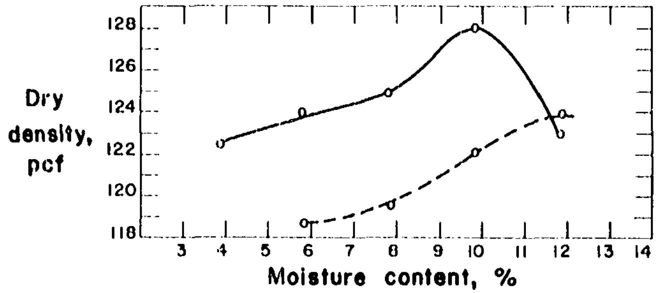

Immersed compressive strength, psi
90 day
90 day
28 day
28 day
7 day no strength
Moisture content, %
76.5% dune sand
6.0% lime
17.5% fly ash no. 2
modified P. compaction
standard P. compaction
Dry density, pcf
Moisture content, %

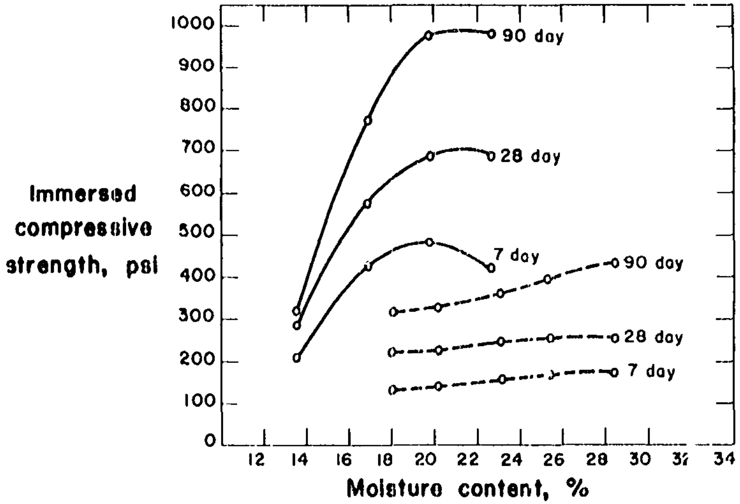
Figure 4. Moisture-density and moisture-strength relationships of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, fly ash No. 3 for standard and modified Proctor compactive efforts.

Figure 5. Moisture-density and moisture-strength relationships of a 76.5:6:17.5 mixture of gumbotil, calcitic hydrated lime, and fly ash No. 1 for standard and modified Proctor compactive efforts.



76.5 % dune sand — modified P. compaction
6.0 % lime - - standard P. compaction
17.5 % fly ash no. 3





76.5 % gumbotil — modified P. compaction
6.0 % lime - - standard P. compaction
17.5 % fly ash no. 1

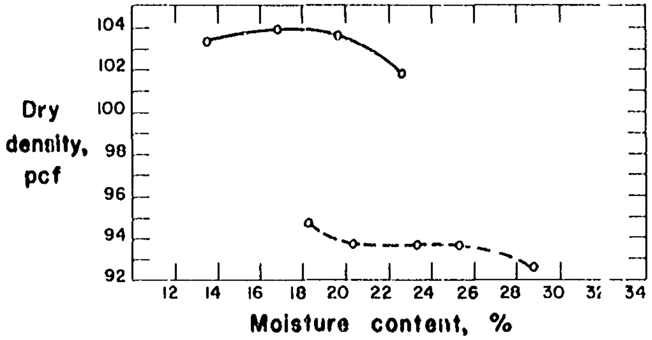
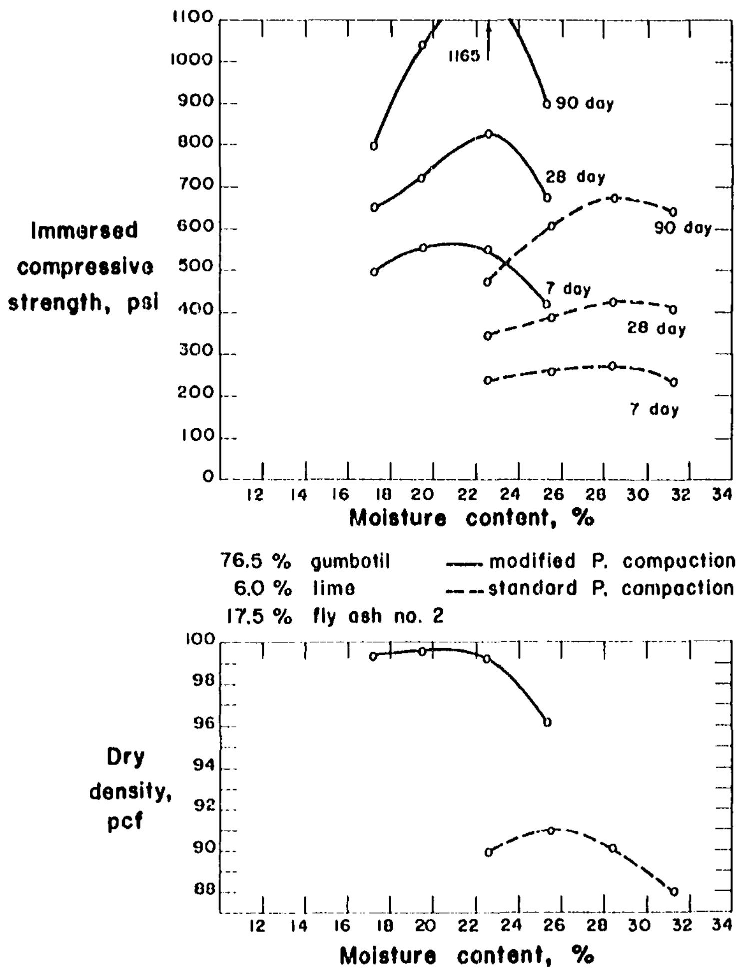


Figure 6. Moisture-density and moisture-strength relationships of a 76.5:6:17.5 mixture of gumbotil, calcitic hydrated lime, and fly ash No. 2 for standard and modified Proctor compactive efforts.

Figure 7. Moisture-density and moisture-strength relationships of a 76.5:5:17.5 mixture of gumbotil, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.


Immersed compressive strength, psi
1165
90 day
28 day
7 day
90 day
28 day
7 day
Moisture content, %
76.5 % gumbotil
6.0 % lime
17.5 % fly ash no. 2
—— modified P. compaction
- - - standard P. compaction
Dry density, pcf
Moisture content, %

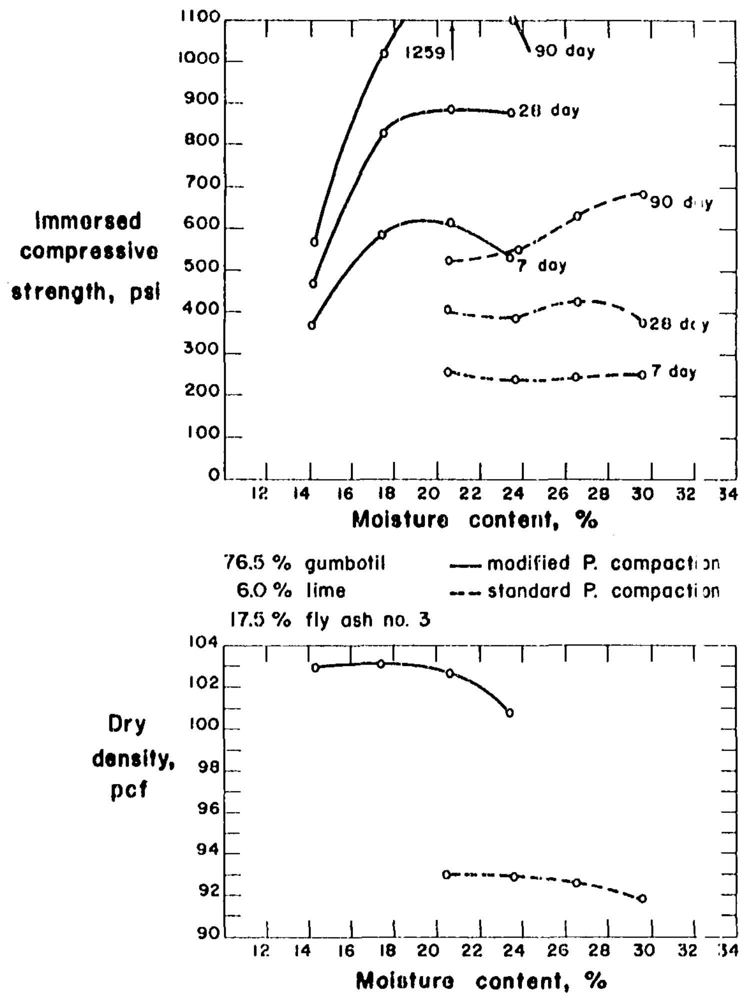
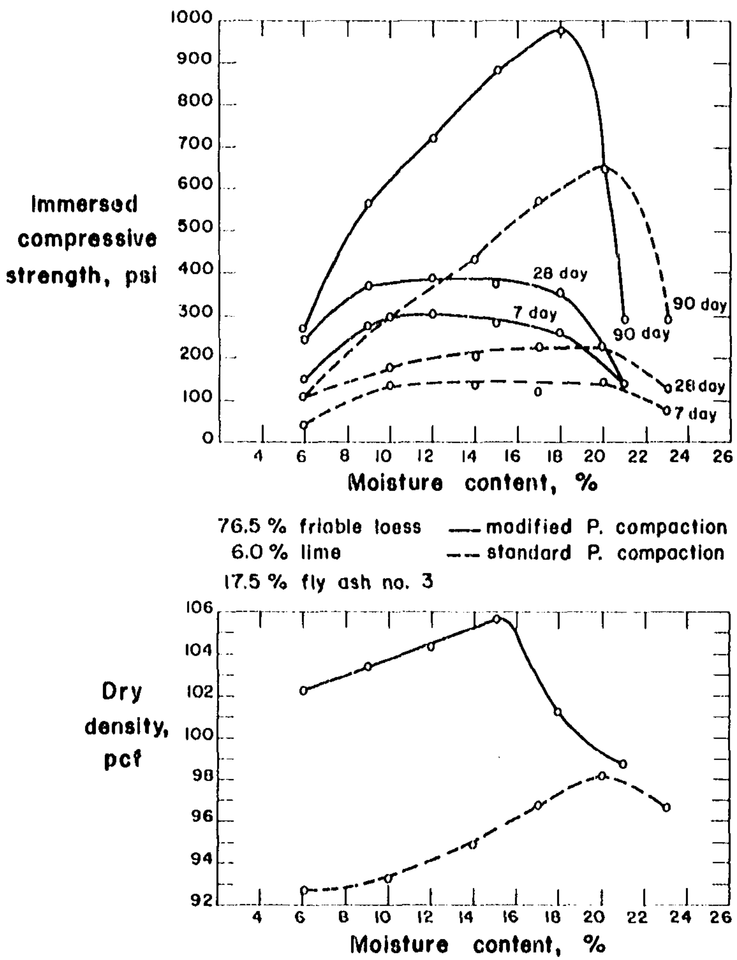

Immersed compressive strength, psi
1259
90 day
28 day
7 day
90 day
28 day
7 day
Moisture content, %
76.5 % gumbotil
6.0 % lime
17.5 % fly ash no. 3
—— modified P. compaction
- - - standard P. compaction
Dry density, pcf
Moisture content, %

Figure 8. Moisture-density and moisture-strength relationships of a 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 9. Moisture-density and moisture-strength relationships of a 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.


Immersed compressive strength, psi
28 day
7 day
90 day
90 day
28 day
7 day
Moisture content, %
76.5 % friable loess
6.0 % lime
17.5 % fly ash no. 3
— modified P. compaction
--- standard P. compaction
Dry density, pcf
Moisture content, %

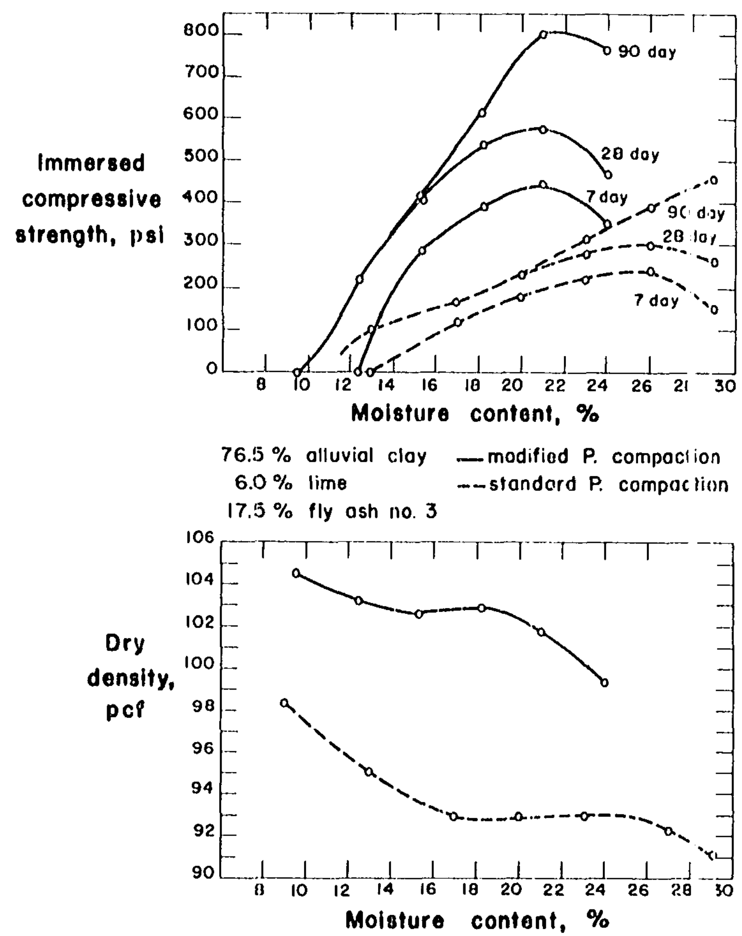

Immersed compressive strength, psi
90 day
28 day
7 day
Moisture content, %
76.5 % alluvial clay
6.0 % lime
17.5 % fly ash no. 3
— modified P. compaction
--- standard P. compaction
Dry density, pcf
Moisture content, %

Table 6. Moisture contents for maximum dry density and maximum strengths of dune sand, calcitic hydrated lime and fly ash mixtures for standard and modified Proctor compactive efforts

	Moisture contents			
	For max.	For maximum strength, %		
	density, %	7 day	28 day	90 day
Fly ash No. 1				
Standard	11.5	4.0	5.5	9.0
Modified	8.0	4.0	4.0	7.0
Fly ash No. 2				
Standard	13.8	No strength	11.0	11.0
Modified	10.0	No strength	8.5	10.0
Fly ash No. 3				
Standard	12.0	9.0	9.0	10.0
Modified	10.0	7.5	8.5	9.5

Gumbotil

The data on optimum moistures are given in Table 7. Contrary to what occurs with the sand the moisture contents for maximum strength for this soil are to the wet side of the moisture for maximum density. Some of the density and strength curves are rather flat, making it difficult to define the maxima.

Table 7. Moisture contents for maximum dry density and maximum strengths of gumbotil, calcitic hydrated lime, and fly ash mixtures for standard and modified Proctor compactive efforts

	Moisture contents			
	For max. density, %	For maximum strength, % 7 day	28 day	90 day
Fly ash No. 1				
Standard	undefined	undefined	undefined	undefined
Modified	17.5	19.5	21.0	28.5-
Fly ash No. 2				
Standard	24.0-	undefined	undefined	29.5-
Modified	19.0-	19.5	21.0	21.0
Fly ash No. 3				
Standard	25.0	28.5	28.5	28.5
Modified	21.0	21.0	22.5	22.5

Friable loess

The data on optimum moistures are presented in Table 8. The moistures for maximum dry density and maximum strength for standard Proctor compaction practically coincide. 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.

Table 8. Moisture contents for maximum dry density and maximum strengths of friable loess, calcitic hydrated lime, and fly ash mixtures for standard and modified Proctor compactive efforts

	Moisture contents			
	For max. density, %	For maximum strength, % 7 day	28 day	90 day
Fly ash No. 3				
Standard	20.0	20.0	20.0	20.4
Modified	15.3	12.0	12.0	18.0

Alluvial clay

The shape of the moisture-density curves for this soil is very peculiar (Figure 9). The curves do not show a peak for maximum dry density and the density increases as the moisture content decreases. The strength curves show, however, a definite optimum moisture that changes conspicuously with curing time for standard compaction and slightly for modified.

Discussion

The results obtained here are significant in that they present new facts on the relations between maximum density and maximum strength in soil stabilization. The common practice has been to compact the stabilized soil at 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 in 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 the lime-fly ash reaction is considered, the role of the water is of paramount importance.

Analyzing the results it is observed that, in general:

a) The optimum moisture for maximum strength increased with the increase in curing time;

b) 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, gumbotil and alluvial clay, it was on the wet side. With the friable loess the two optimums are rather coincident.

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

With friable loess the moisture content is critical. 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 hydration, therefore that should be the recommedded moisture to stabilize the friable loess, favoring moisture contents in the dry side of the optimum rather than in the wet side.

As indicated, the clayey soils showed great avidity for water. This is because complex reactions take place between the lime and soil particles apart of 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/or H_2O molecules. Based on long term strengths, it seems advisable to use amounts of water much greater than the optimum for maximum density with clayey soils containing high percentages of montmorillonitic clay. It is also observed that the shape of the moisture-density curves for both clayey soils are rather flat. In some instances the maximum density is not sharply shown, being undefined. This peculiarity will be discussed later in the section "Lime Stabilization".

Lime and Fly Ash Proportions and Content

One of the first questions to answer in soil-lime-fly ash stabilization is the amount of lime and fly ash to incorporate into the soil. The optimum amount and proportions of the lime and fly ash admixture are governed by the desired strength in the stabilized soils and by economy.

An unconfined compressive strength after 28 days curing of at least 300 psi after 24 hour immersion may be indicative of adequate stability for a base course mixture to withstand the imposed loads and the detrimental effects of freezing and thawing (6,37).

Lime-fly ash stabilization has to compete economically with other admixtures that might impart to the soil the same strengths at a cheaper cost. The price of lime ranges between 15 and 25 dollars a ton, including transportation to the job site. Fly ash sells for about one dollar a ton at the power plants. Even after transportation expenses the price of fly ash is several times cheaper than that of lime. Economic reasons favor consequently the use of greater amounts of fly ash than lime.

A great amount of work has been done to find the best proportions and amount of lime and fly ash, but this work has never been so comprehensive as to include enough kinds of fly ashes. In this work, eight fly ashes were evaluated with the dune sand and three fly ashes with the other three soils. The fly ashes are produced in Iowa or within a radius which make them economical for use in Iowa.

The reason for using eight fly ashes with the sand is that sandy and granular soils respond better to lime-fly ash stabilization than silty or clayey soils. These eight fly ashes represent a wide range in characteristics, sources, and pozzolanic activity, and the results obtained with them may indicate the best proportions and amount to be used.

The number of fly ashes to use with the loess and clayey soils was narrowed to three. These three represent such a variety in properties and composition that the effectiveness of fly ash addition to silty and clayey soils stabilized with lime and their optimum lime and fly ash proportions and amount may be determined.

Two types of commercial limes from U. S. Gypsum Company, a calcitic hydrated (Kemikal) and a dolomitic monohydrate (Kemidol), were used with all the fly ashes and soils. Two more dolomitic monohydrate limes, from Rickwell Lime Company, and from Western Lime and Cement Company, were used with fly ash No. 3 and dune sand to check on the effectiveness of available commercial dolomitic monohydrate limes.

The amounts of lime used were 3, 6 and 9 percent with all soils; with gumbotil 12 percent lime was also tried. For each of the above amounts of lime four mixes were prepared, one without fly ash and three with 10, 17.5 or 25 percent fly ash. All the percentages were based on the dry weight of the total soil, lime, and fly ash mixture. The above combinations of lime and fly ash gave sufficient data to plot strength contours, which was done for the 28 day strength results. After 7 days curing the strength developed was rather low. Contour graphs made for 7 day strength did not show very much and are not presented here.

In preliminary work, not included here, moisture-density and moisture-strength relationships were determined to select the molding moisture content for every combination of soil, lime, and fly ash. At least four sets of tests were run for every combination of soil and fly ash. Maximum strengths for calcitic hydrated lime and the same amount of dolomitic monohydrate lime were obtained for practically the same optimum amount of water. The molding moisture content needed for maximum 28 day strengths was chosen.

Specimens were molded and kept curing for 7 and 28 days. This was deemed sufficient to draw conclusions as to the best amount and proportions of lime and fly ash. The specimens were also immersed in distilled water for 24 hours before testing for unconfined compressive strength. The results are given in Figures 10 through 27. Molding dry densities are given in Appendix 1.

Dune sand

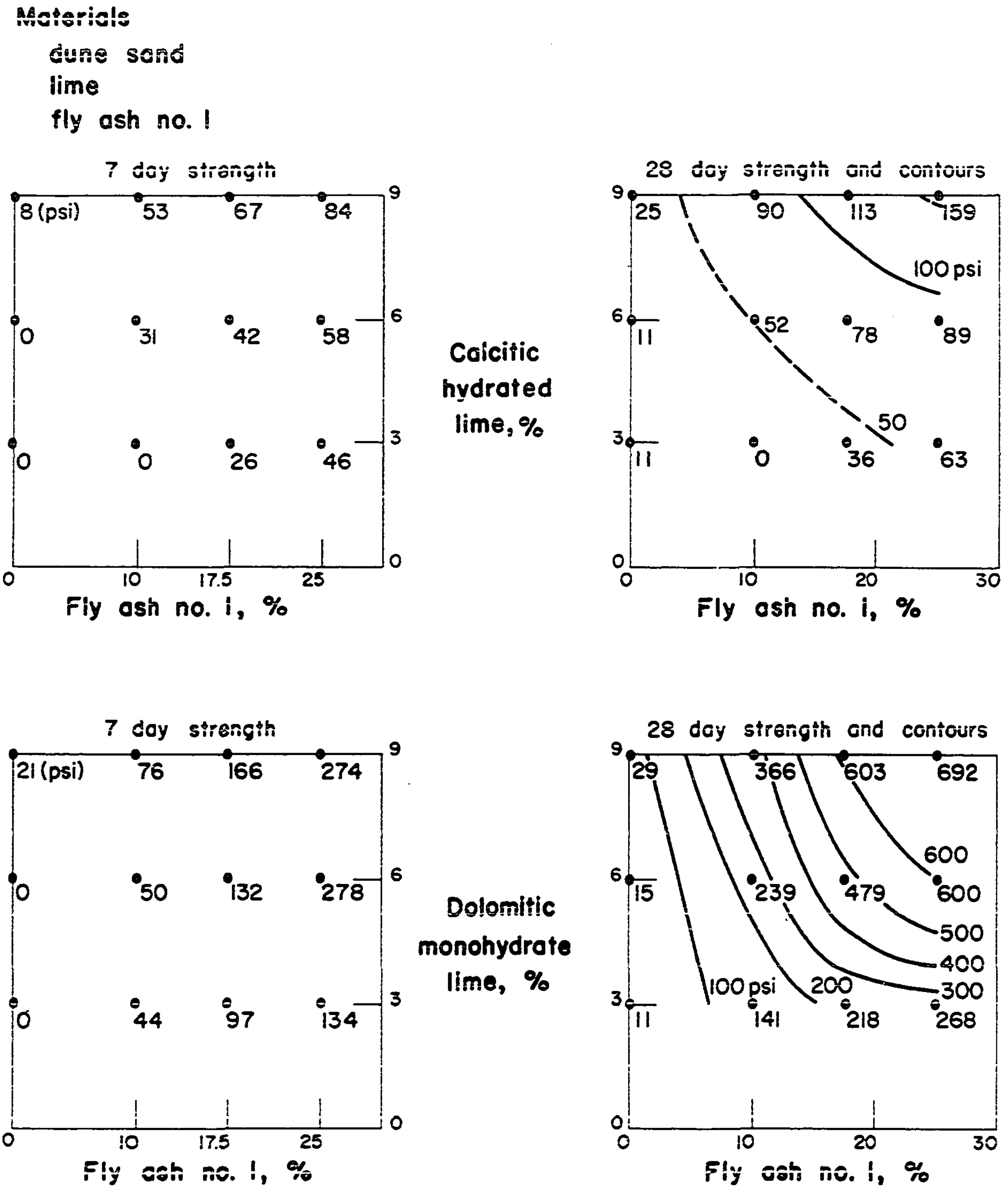
Strength contours. The plotted strength contours (Figures 10 to 18) indicate there is no optimum amount and ratio of lime and fly ash that might be used with any kind of lime and fly ash to stabilize dune sand. There is a great similarity among the contours obtained with the same fly ash but with different limes. In general the proportions and amount of lime and fly ash needed to stabilize dune sand vary according to the kind of fly ash used.

The inclination of the strength contours, approaching a vertical position, except with fly ash No. 10, indicates that with dune sand lower amounts of lime than fly ash should be favored. The recommended amounts are between 3 and 6 percent lime and between 15 and 25, or perhaps 30, percent fly ash. The best amount within these limits differs with the kind of fly ash.

Density. The density varied with the kind and amounts of lime an fly ash. There is no consistency on which lime, calcitic hydrated or dolomitic monohydrate, may give higher densities; it depends, apparently, on the kind of fly ash and the admixture proportions.

Lime. It has been observed by other investigators that in lime-fly ash stabilization, dolomitic monohydrate lime produces greater strength than calcitic hydrated lime

Figure 10. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 1 for 7 and 28 day curing periods, and strength contour lines for 28 day results.



Materials
dune sand
lime
fly ash no. I
7 day strength
8 (psi)
53
67
84
0
31
42
58
0
0
26
46
0
10
17.5
25
9
6
3
0
Fly ash no. I, %
28 day strength and contours
25
90
113
159
100 psi
11
52
78
89
50
11
0
36
63
0
10
20
30
Fly ash no. I, %
Calcitic hydrated lime, %
7 day strength
21 (psi)
76
166
274
0
50
132
278
0
44
97
134
0
10
17.5
25
Fly ash no. I, %
28 day strength and contours
29
366
603
692
600
15
239
479
600
500
400
100 psi
200
300
11
141
218
268
0
10
20
30
Fly ash no. I, %
Dolomitic monohydrate lime, %

Figure 11. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 2 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
dune sand
lime
fly ash no. 2

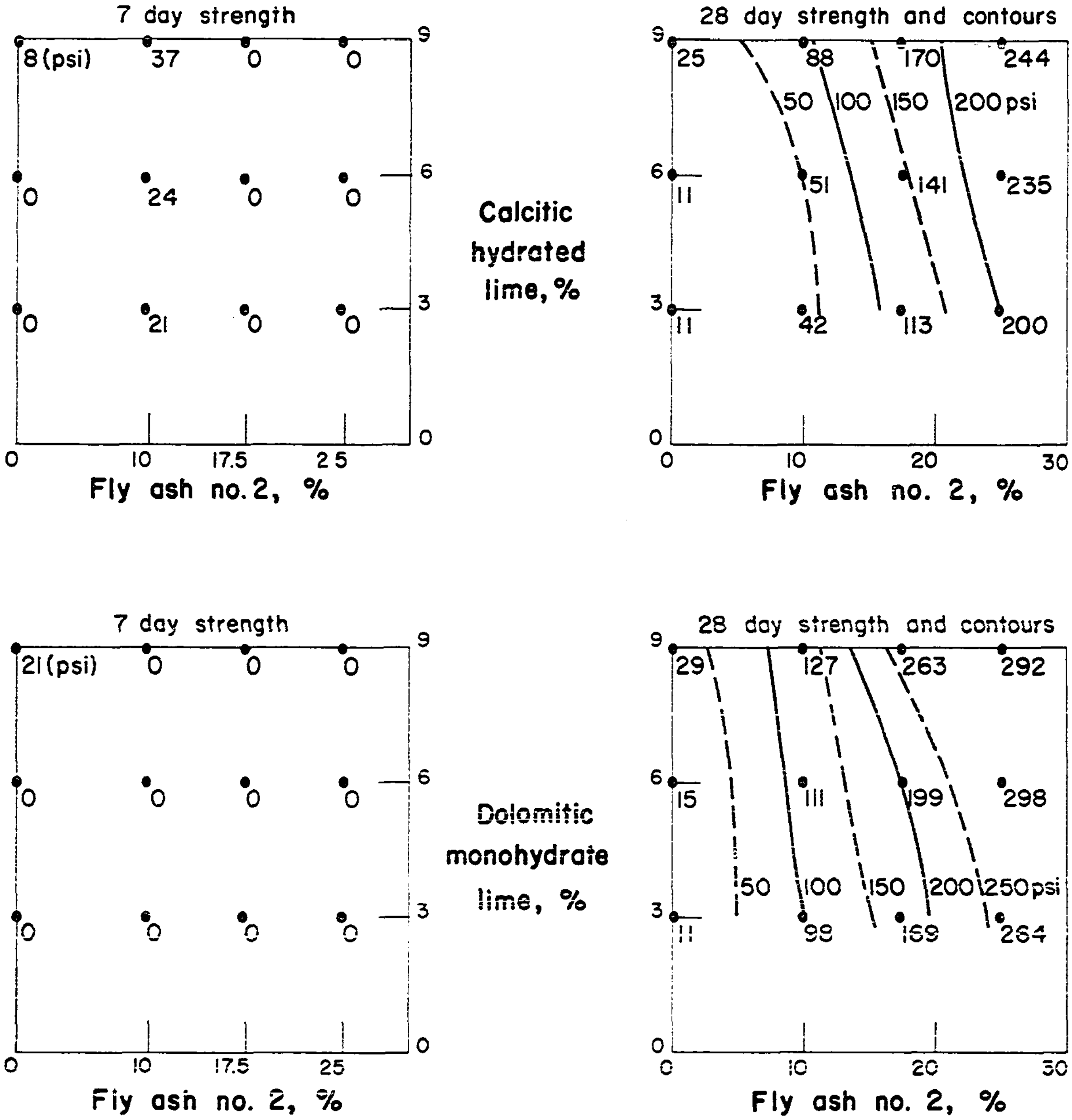


Figure 12. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 4 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
- dune sand
- lime
- fly ash no.4

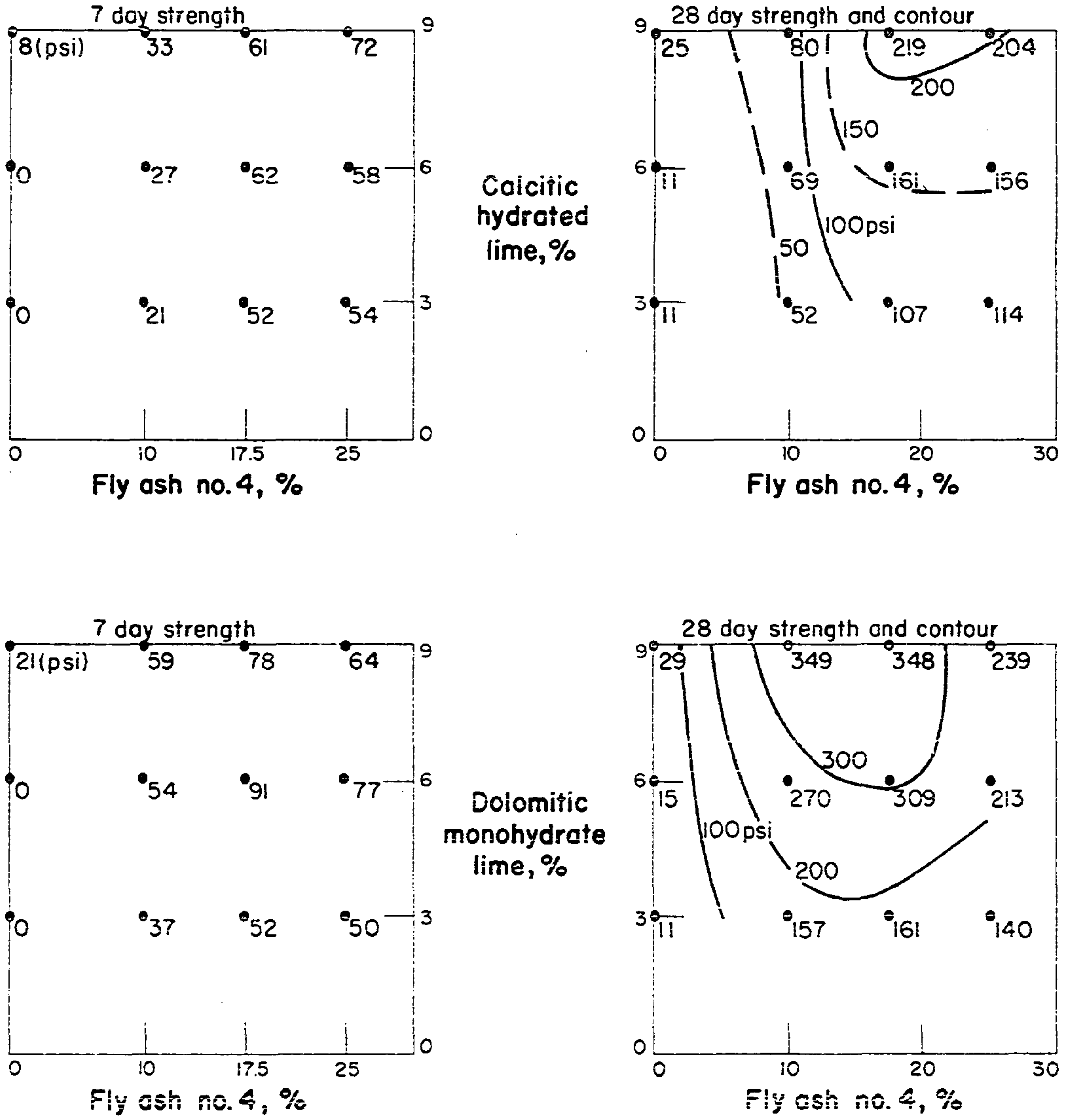


Figure 13. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 5 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
dune sand
lime
fly ash no. 5

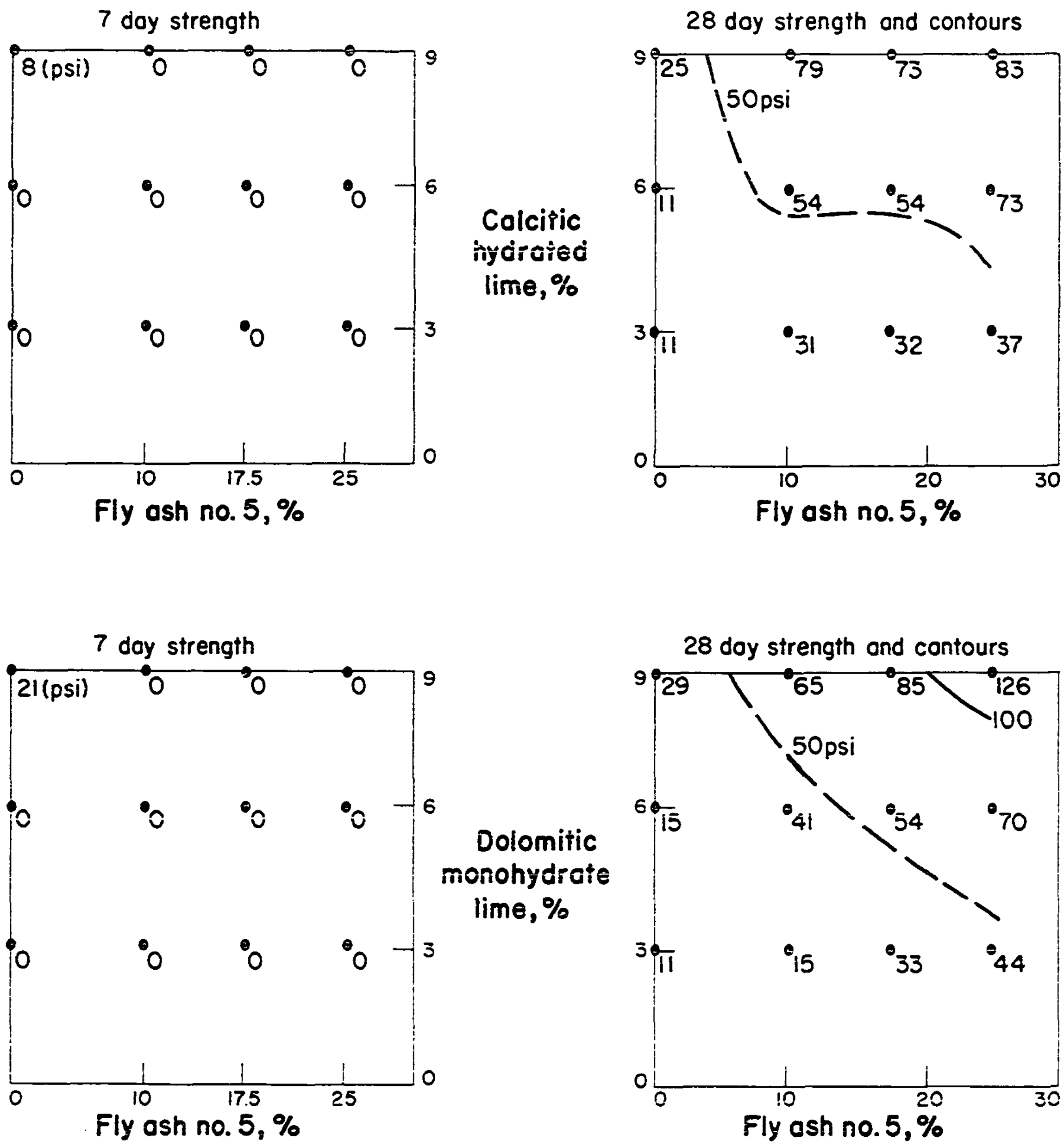


Figure 14. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 6 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
dune sand
lime
fly ash no.6

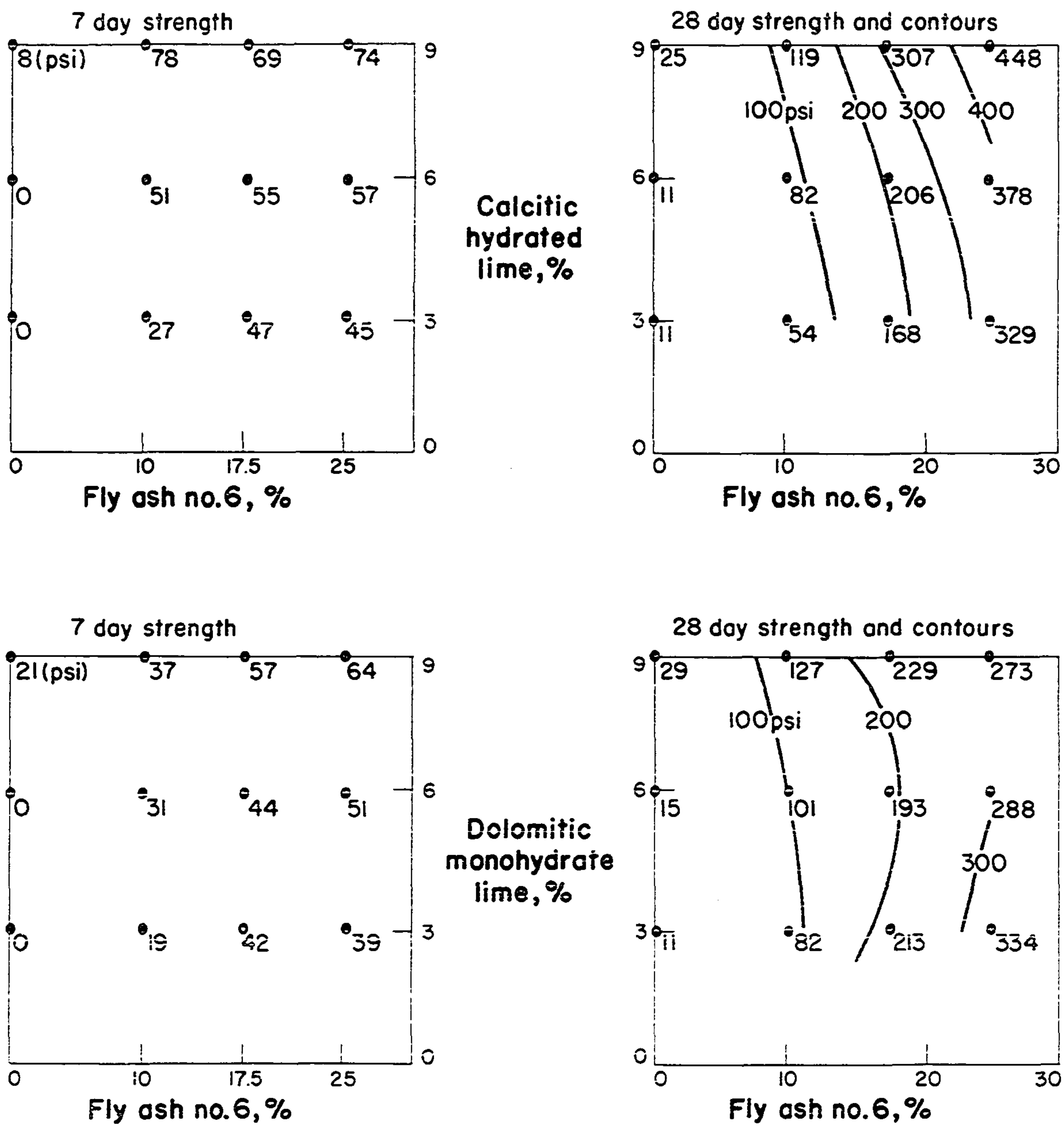
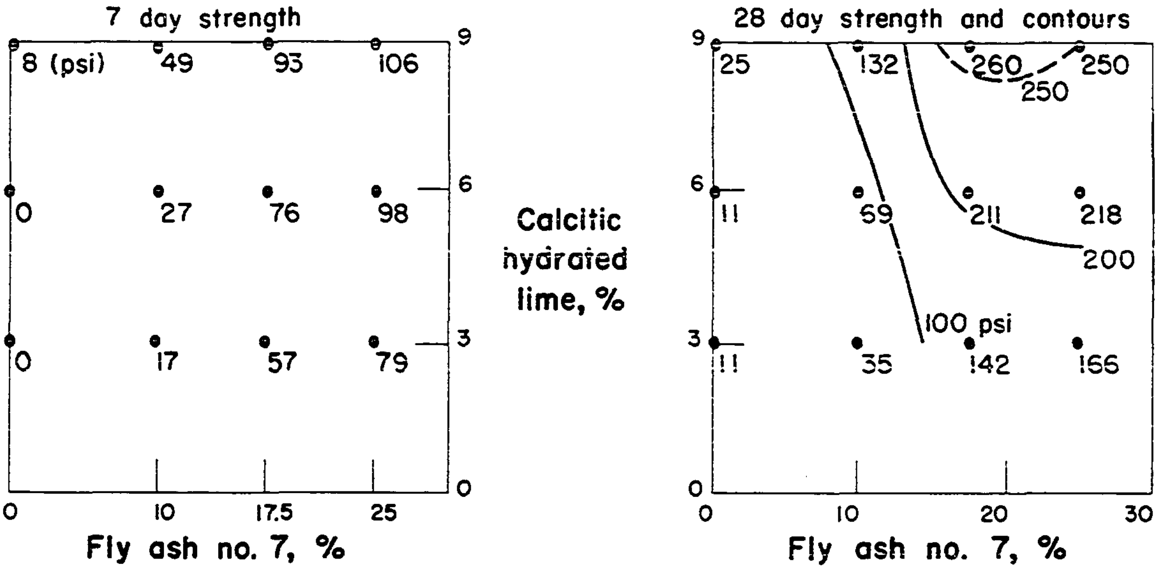


Figure 15. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 7 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
dune sand
lime
fly ash no. 7



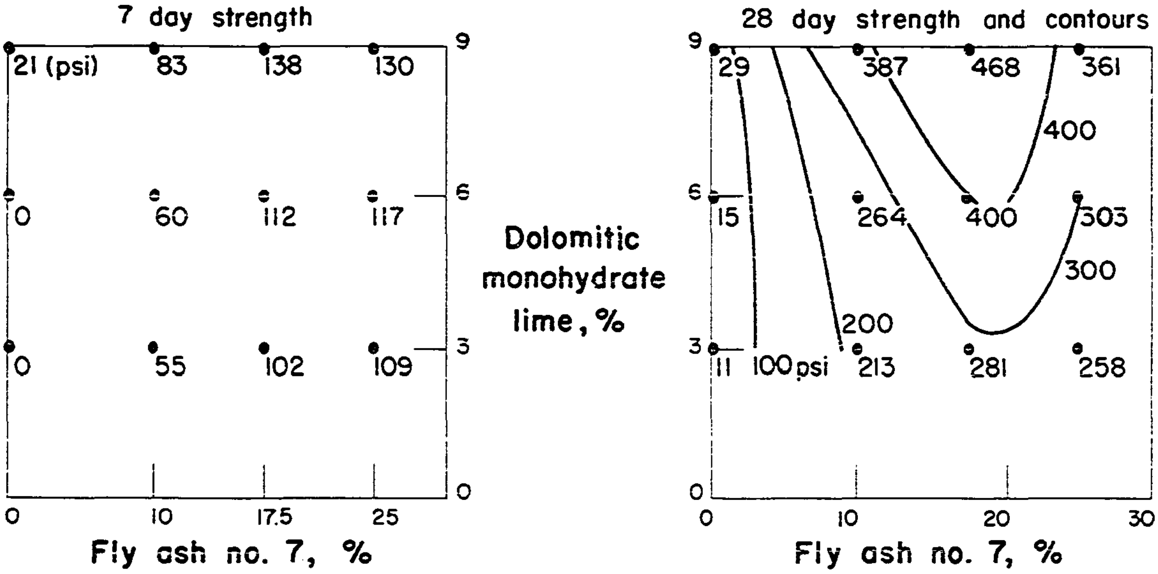


Figure 16. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 8 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
dune sand
lime
fly ash no. 8

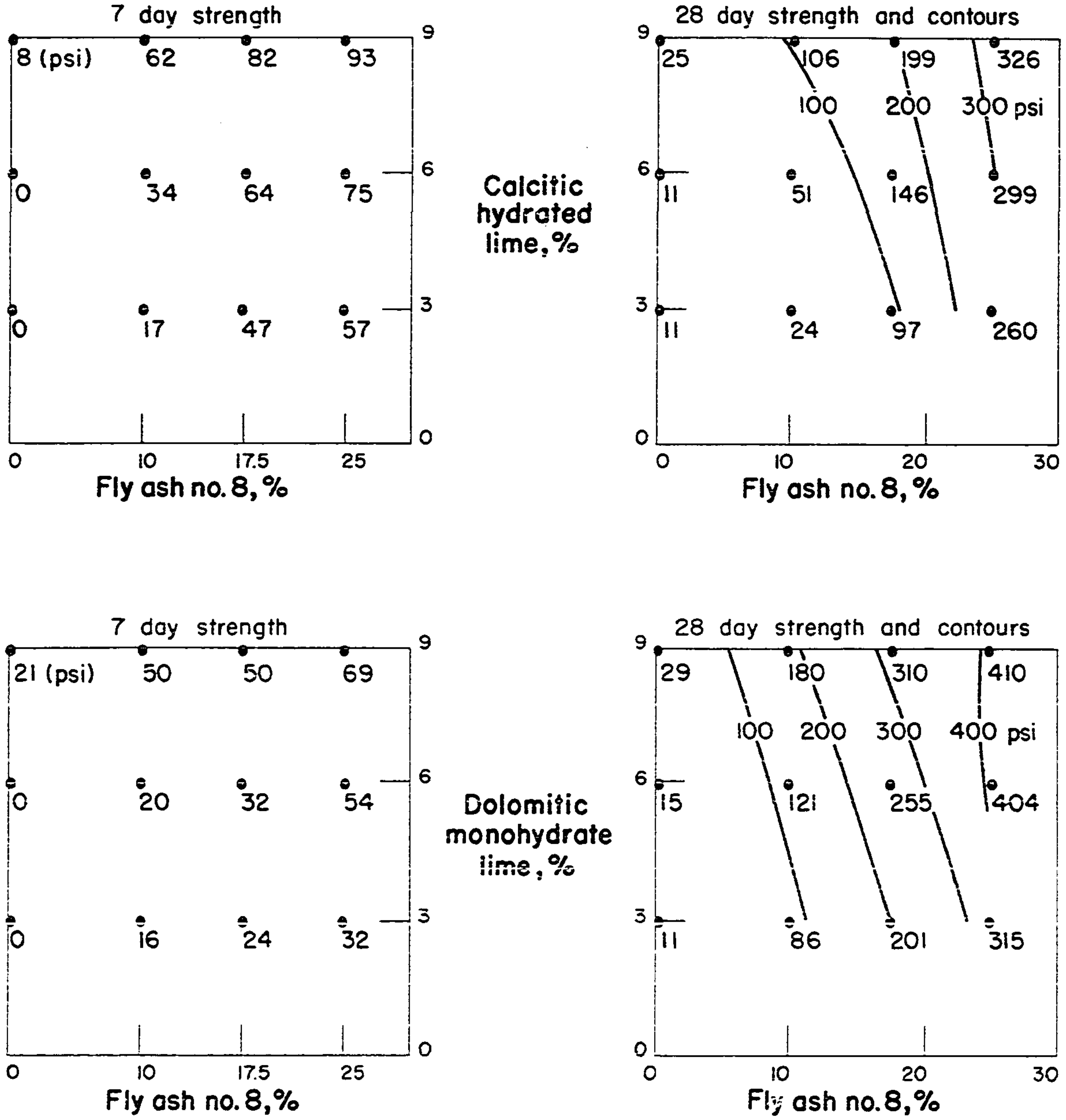
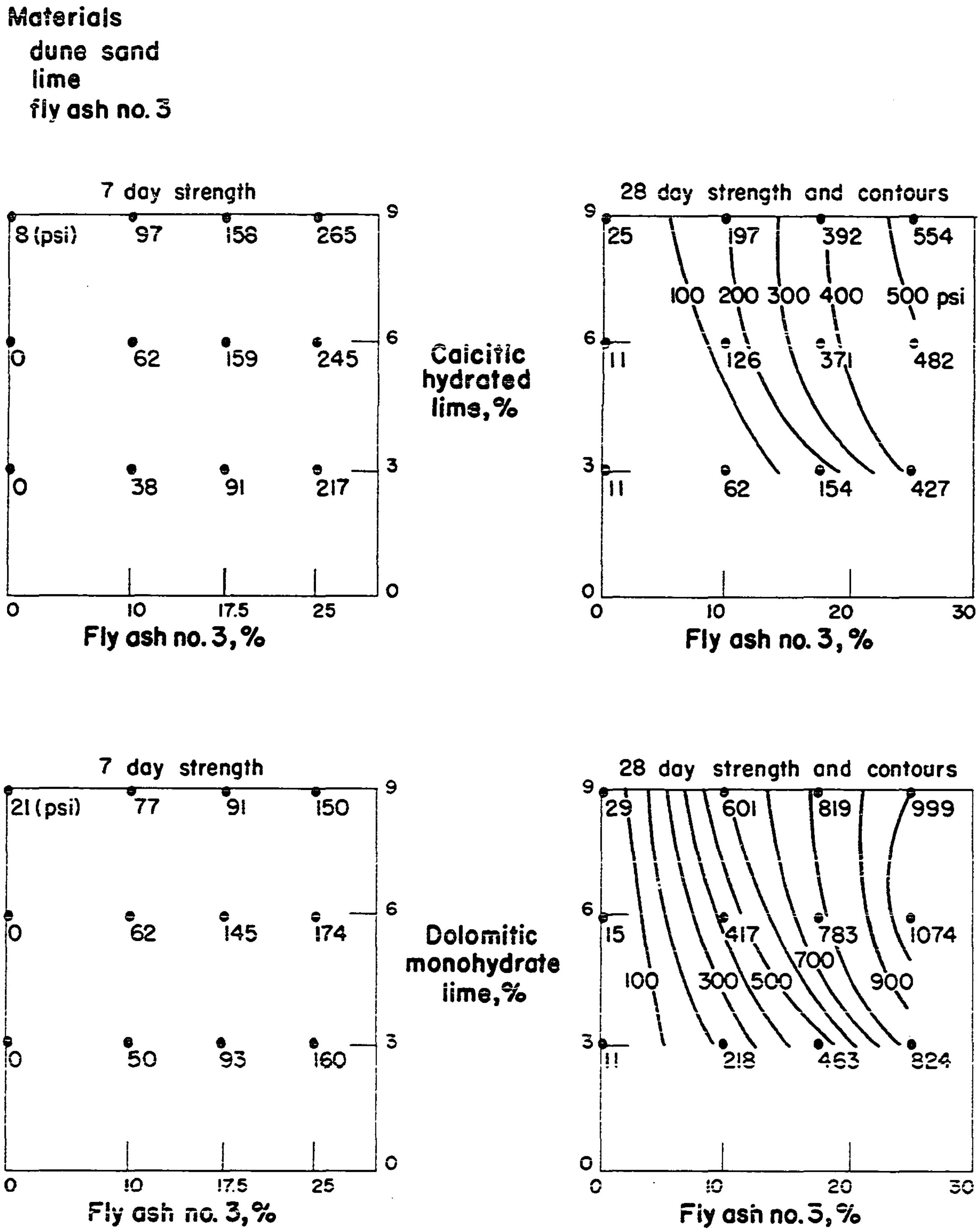


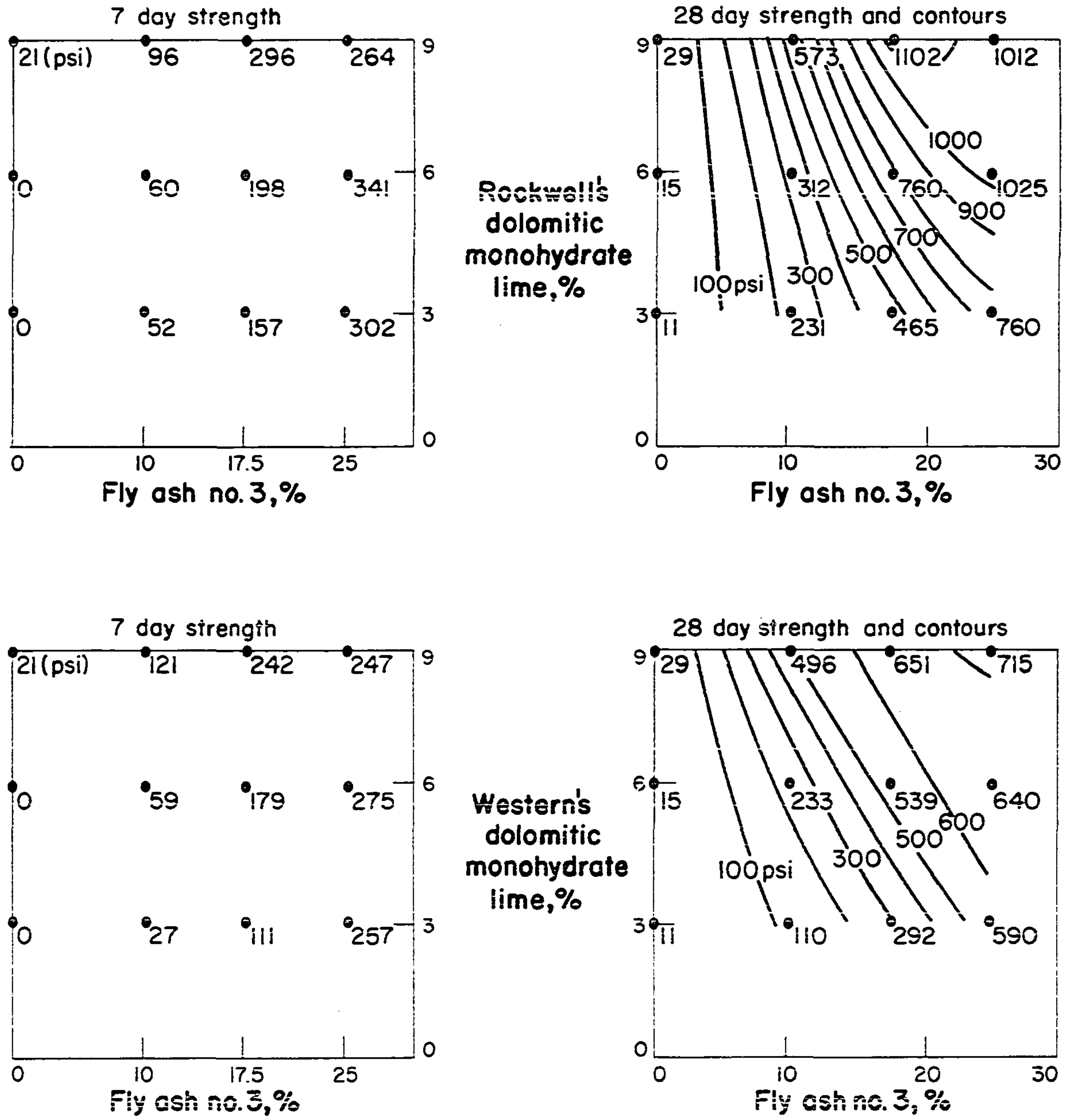
Figure 17. Immersed unconfined compressive strength values obtained for several combinations of dune sand, lime, and fly ash No. 3 for 7 and 28 day curing periods, and strength contour lines for 28 day results.



Materials
dune sand
lime
fly ash no. 3
7 day strength
8 (psi) 97 156 265
0 62 159 245
0 38 91 217
Fly ash no. 3, %
28 day strength and contours
25 197 392 554
100 200 300 400 500 psi
11 126 371 482
11 62 154 427
Fly ash no. 3, %
Calcitic hydrated lime, %
7 day strength
21 (psi) 77 91 150
0 62 145 174
0 50 93 160
Fly ash no. 3, %
28 day strength and contours
29 601 819 999
15 417 783 1074
100 300 500 700 900
11 218 463 824
Fly ash no. 3, %
Dolomitic monohydrate lime, %

Figure 18. Immersed unconfined compressive strength values obtained for several combinations of dune sand, dolomitic monohydrate limes, and fly ash No. 3 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
dune sand
dolomitic monohyrate lime
fly ash no.3



(15,19,28,49,55,63). The analysis of the effectiveness of the limes which follows is based on the variety of lime and fly ash combinations used in this investigation.

In mixtures of dune sand, lime, and fly ash No. 1, No. 2, No. 4, or No. 7, dolomitic monohydrate lime was more effective than calcitic hydrated lime for both 7 and 28 day curing periods. With fly ash No. 5 test results were erratic, and conclusions can not be made as to which lime was more effective. With fly ash No. 6, calcitic hydrated lime was more effective than dolomitic monohydrate lime. With fly ash No. 8, 7 day strengths of mixtures with calcitic hydrated lime were greater than with dolomitic lime, but dolomitic monohydrate lime gave better 28 day strengths. Thus no general conclusion can be made as to which kind of lime, calcitic hydrated or dolomitic monohydrate, is best in lime-fly ash stabilization of dune sand; the kind of lime to use depends strictly on the properties of the fly ash. Nevertheless it can be concluded on the basis of 28 day strengths only, that dolomitic monohydrate limes generally give better strengths than calcitic hydrated lime. The only exception to this was in mixtures containing fly ash No. 6.

Tests with fly ash No. 3 deserve special discussion (Figures 17 and 18). Three dolomitic monohydrate limes were used with this fly ash: one produced by U. S. Gypsum Company, one by Rockwell Lime Company and one by Western Lime and Cement Company. Comparing the effectiveness of of calcitic hydrated lime with the dolomitic monohydrate limes, it was observed that for 7 day strength the U. S. Gypsum calcitic lime was better than the dolomitic lime from the same company but slightly less effective than the dolomitic limes from Rockwell and Western. All three dolomitic limes gave 28 day strengths much higher than the calcitic lime. Of the three dolomitic monohydrate limes tested the one from Rockwell was most effective. No explanation was found for the differences in strength produced by the dolomitic limes. An investigation is presently being conducted in the Engineering Experiment Station of Iowa State University to compare the effectiveness of various commercial dolomitic and calcitic limes (69). It appears that the effectiveness of dolomitic limes depends upon the temperature and period of burning, the amount of impurities, the gradation, and probably other factors.

Fly ash. The strength of mixtures made with fly ash No. 3 attained very high strengths. Mixtures made with dolomitic monohydrate limes, either from U. S. Gypsum or Rockwell, showed a strength of 1000 psi after 28 days of curing. This strength approaches that of a lean concrete. Mixtures made with the other dolomitic monohydrate lime from Western and fly ash No. 3 showed a strength after 28 days curing of about 600 psi, which is also very good. Strengths of about 500 psi for the same curing period were obtained with calcitic hydrated lime. Seven day strengths of 200 or 300 psi, depending on the type of lime used, were obtained with this fly ash.

Fly ash No. 1 also gave good strengths. Six hundred psi was obtained after 28 days curing in mixes with dolomitic monohydrate lime. The 7 day strength for the same mixes was close to 300 psi, but the results obtained with this fly ash and calcitic hydrated lime after 28 days curing were very poor, barely reaching 100 psi.

Other fly ashes that gave strengths over 300 psi after 28 days curing were: fly ash No. 6 in mixes with calcitic hydrated lime, and fly ash No. 7 with dolomitic monohydrate lime. Many fly ashes did not reach the desired figure of 300 psi after 28 days curing in mixes with either of the limes used.

The above results point out that the strengths obtained depend very greatly on the fly ash used. This indicates the great disparity of pozzolanic properties of fly ashes. Some of them with lime may give strengths comparable to those obtained with cement while others develop barely any strength.

Fly ash No. 3 was used with three different dolomitic monohydrate limes; the densities varied also for mixtures with these three dolomitic limes, but the strengths were not in relationship to the density but to the admixture content and amount. Fly ashes of low specific gravity (Nos. 2, 4 and 7) imparted very low dry densities to the sand, lime and fly ash mixtures.

Friable loess

Strength contours. The strengths obtained in the friable loess mixtures with lime only, were decreased by the addition of fly ash No. 1. Additions of fly ash No. 2 did not increase the strength of the friable loess and lime mixtures to a great extent. Additions of fly ash No. 3 increased the strength some but not greatly. The strength contours with friable loess are therefore sparse and difficult to draw (Figures 19 to 21).

The only type of fly ash that may be recommended to use with lime to stabilize friable loess is a high quality fly ash like No. 3. The verticality of the contours with fly ash No. 3 favors the use of small amounts of lime and large amounts of fly ash. The recommended amounts are 3 percent dolomitic monohydrate lime, 25 percent fly ash No. 3, and 72 percent friable loess. If the price of the fly ash is prohibitive this soil can be stabilized with lime alone.

Density. Calcitic hydrated lime gave lower density than equal amounts of dolomitic monohydrate lime. Fly ash No. 2, of low specific gravity, lowered the density in proportion to the amount of fly ash in the mixture. No correlation was found between density and strength.

Lime. Dolomitic monohydrate lime with or without fly ash always gave better strengths than calcitic hydrated lime. Nine percent dolomitic monohydrate lime added to friable loess showed an immersed strength of 400 psi, which is considered adequate for a road base or a subbase course.

Fly ash. Fly ashes Nos. 1 and 2 either did not greatly improve the strength of friable loess and lime mixtures or were detrimental to the point where they actually lowered the strength in some cases. This may be due to the fact that friable loess may have greater pozzolanic activity with lime than fly ashes Nos. 1 or 2. Fly ash No. 3 gave strength improvements to friable loess and lime mixtures, particularly for mixtures with low lime contents. This is the only fly ash tested that may be recommended to use with lime, preferably dolomitic monohydrate, in the stabilization of friable loess.

Gumbotil

Strength contours. Strength contours tend to be horizontal for low lime contents and become vertical for

Figure 19. Immersed unconfined compressive strength values obtained for several combinations of friable loess, lime, and fly ash No. 1 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

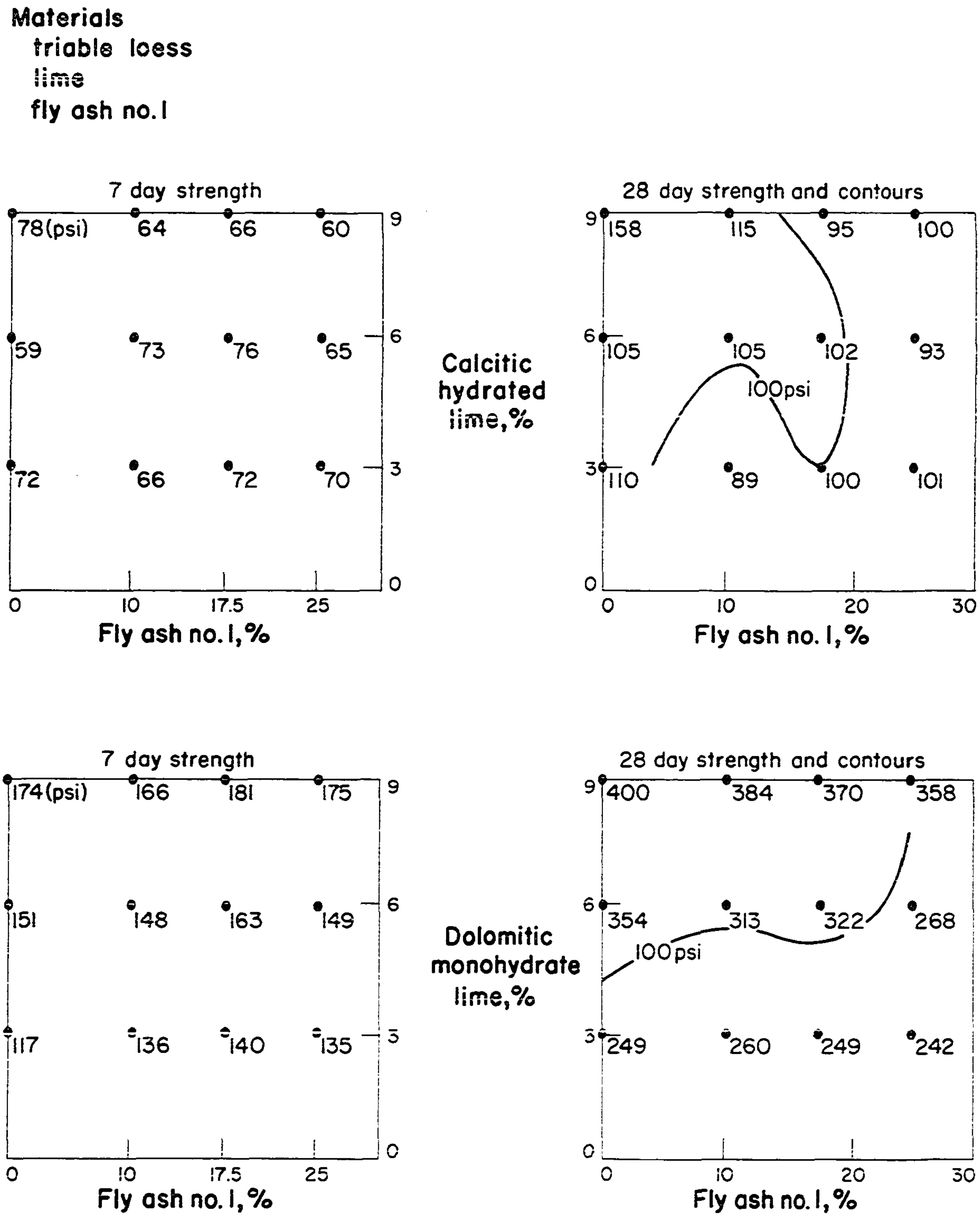

Materials
triable loess
lime
fly ash no. 1
7 day strength
78(psi)
64
66
60
59
73
76
65
72
66
72
70
28 day strength and contours
158
115
95
100
105
105
102
93
100psi
110
89
100
101
Calcitic hydrated lime, %
Fly ash no. 1, %
7 day strength
174(psi)
166
181
175
151
148
163
149
117
136
140
135
28 day strength and contours
400
384
370
358
354
313
322
268
100psi
249
260
249
242
Dolomitic monohydrate lime, %
Fly ash no. 1, %

Figure 20. Immersed unconfined compressive strength values obtained for several combinations of friable loess, lime, and fly ash No. 2 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
friable loess
lime
fly ash no. 2

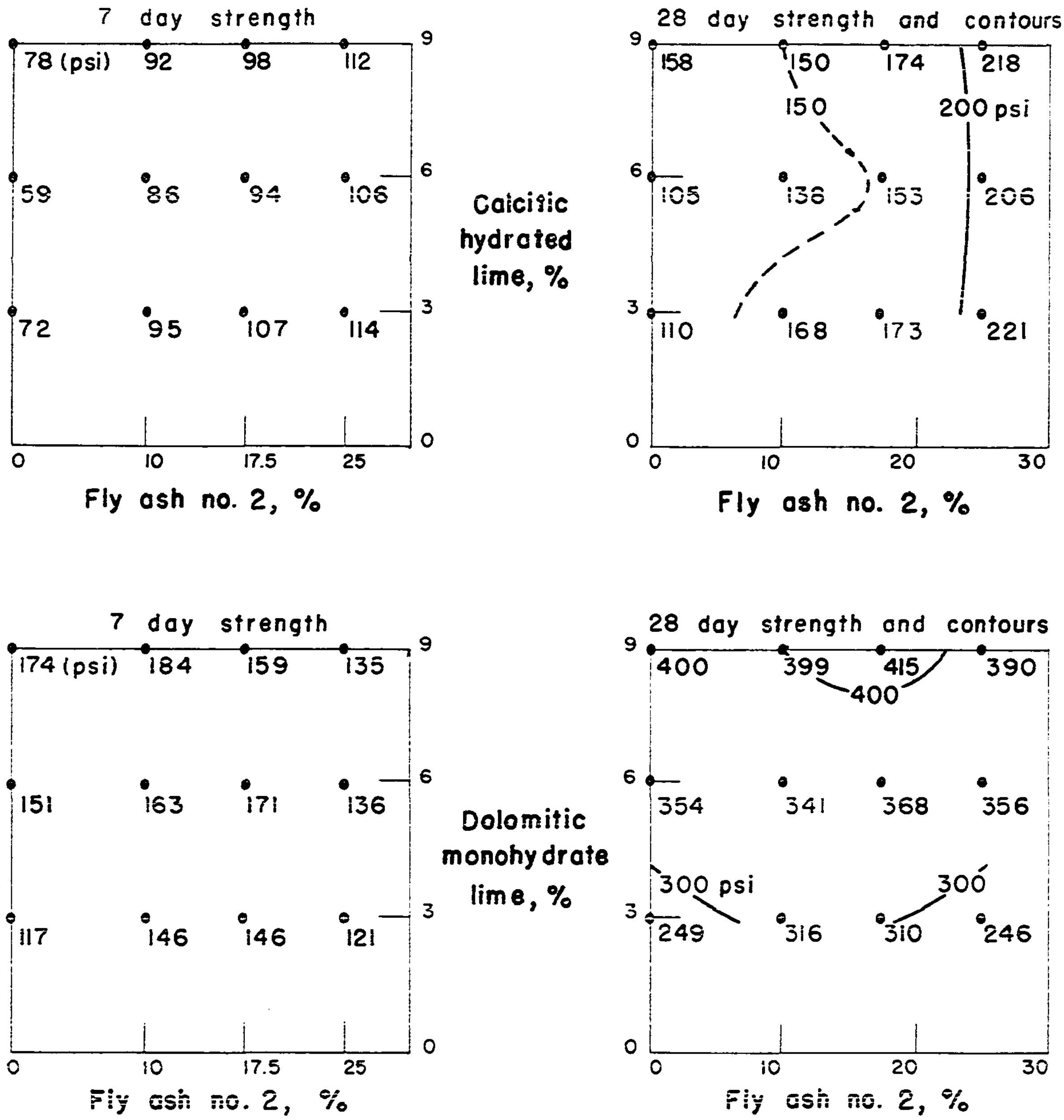
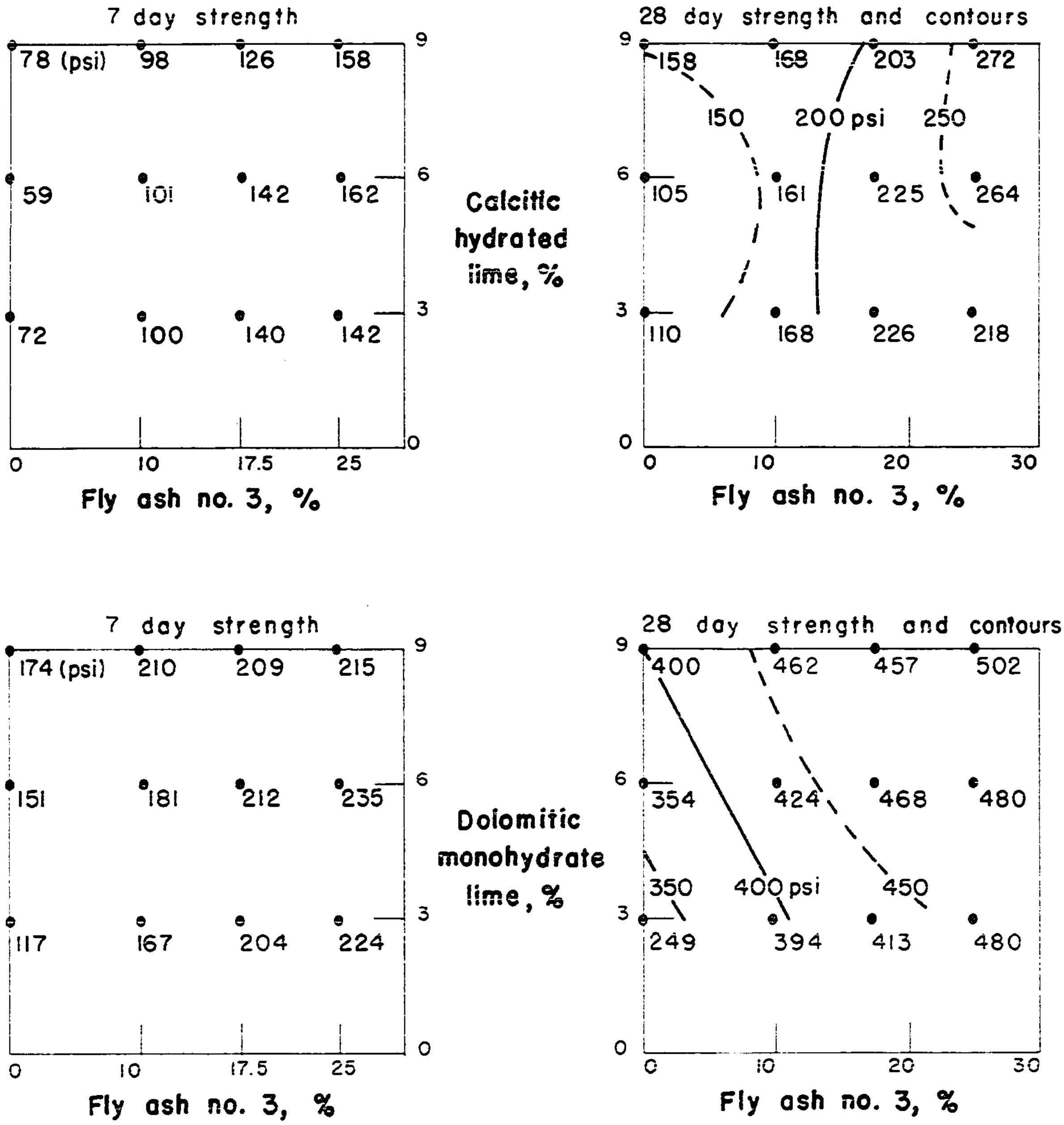


Figure 21. Immersed unconfined compressive strength values obtained for several combinations of friable loess, lime, and fly ash No. 3 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
- **friable loess**
- **lime**
- **fly ash no. 3**



high amounts (Figures 22 to 24). This indicates that lime up to a certain amount increases strength, and then fly ash becomes important in the development of strength. There is no definite ratio of lime to fly ash that gives the highest strengths. Recommendations on the amounts of lime and fly ash to be used should be based on the need of a minimum amount of lime, which is about 5 percent. Low amounts of lime required high amounts of fly ash and high amounts of lime required low amounts of fly ash. Several combinations of lime and fly ash may be chosen depending on the desired strength. The amount of lime required will be between 5 and 9 percent, and that of fly ash between 10 and 25 percent.

Density. Density values did not correlate with strength, neither did they correlate with the kind of lime used. The fly ash of low specific gravity, No. 2, gave lower densities than the other two fly ashes used.

Lime. The calcitic hydrated lime in low amounts gave greater strengths than low amounts of dolomitic monohydrate lime. Dolomitic monohydrate lime was better than calcitic in high amounts. This was observed for mixtures with and without fly ash. High amounts of lime may stabilize gumbotil soil satisfactorily. For instance, 12 percent dolomitic monohydrate lime gave a 7 day strength of 190 psi and a 28 day strength of 298 psi.

Figure 22. Immersed unconfined compressive strength values obtained for several combinations of gumbotil, lime, and fly ash No. 1 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
gumbotil
lime
fly ash no. 1

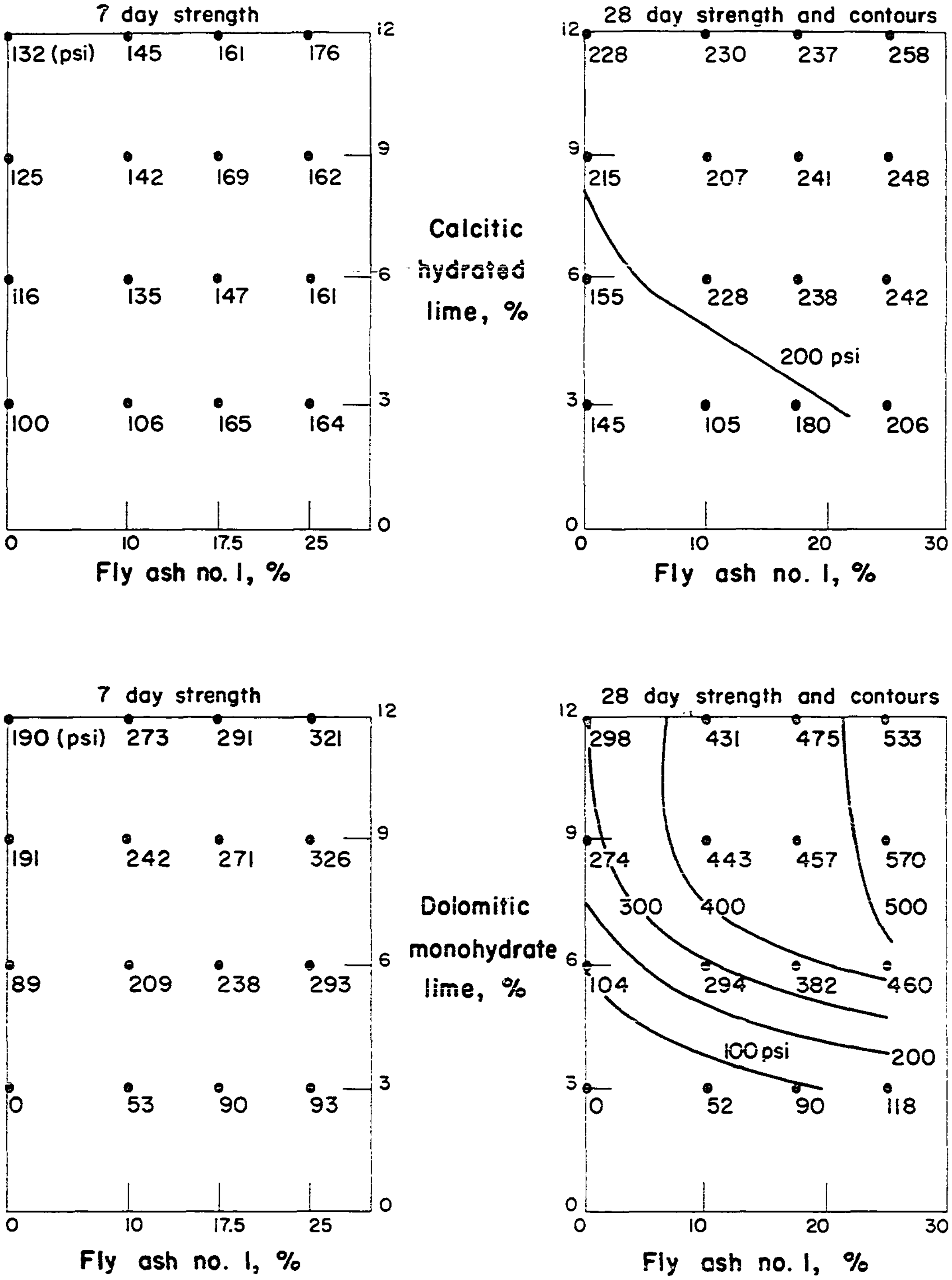


Figure 23. Immersed unconfined compressive strength values obtained for several combinations of gumbotil, lime, and fly ash No. 2 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
gumboil
lime
fly ash no. 2

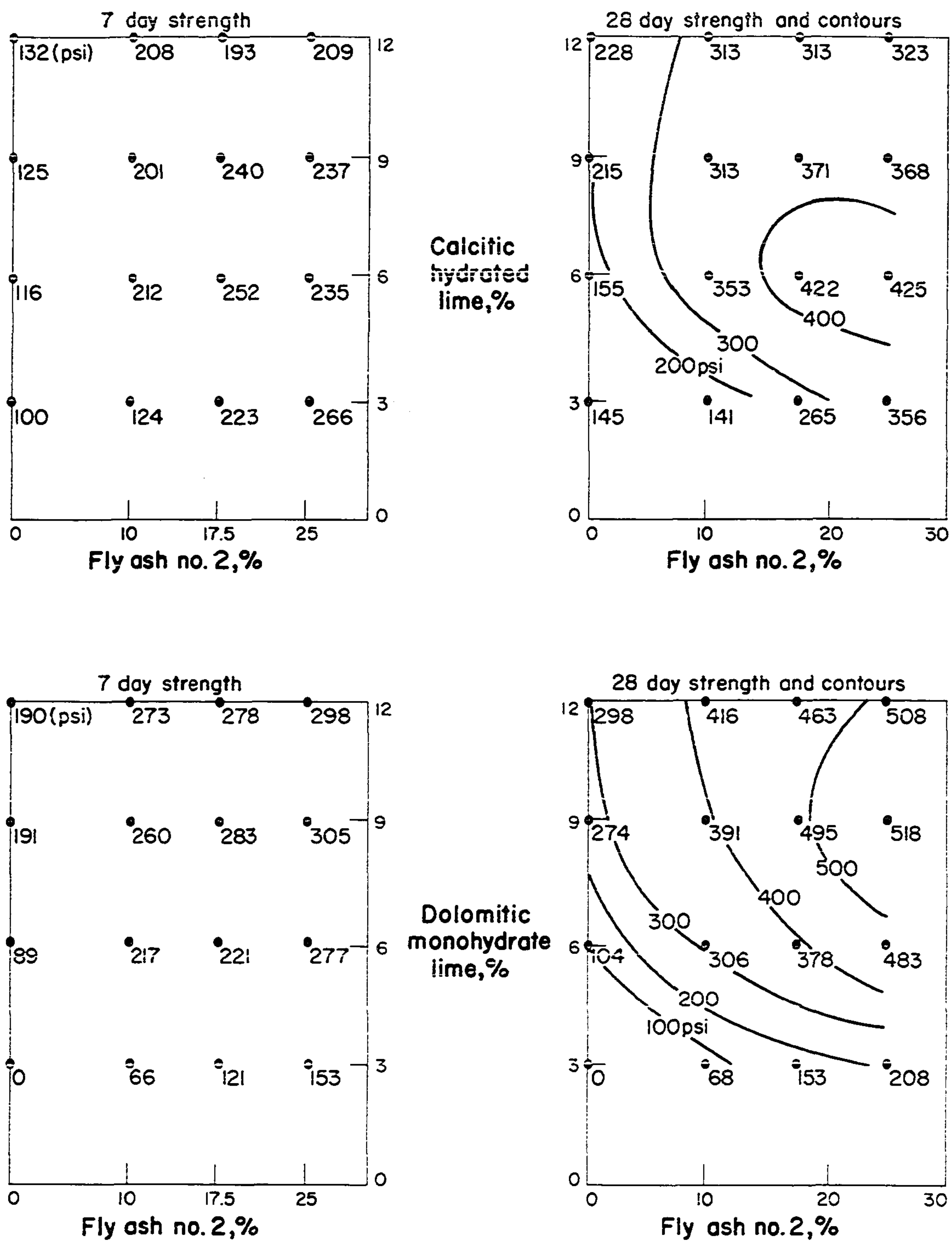
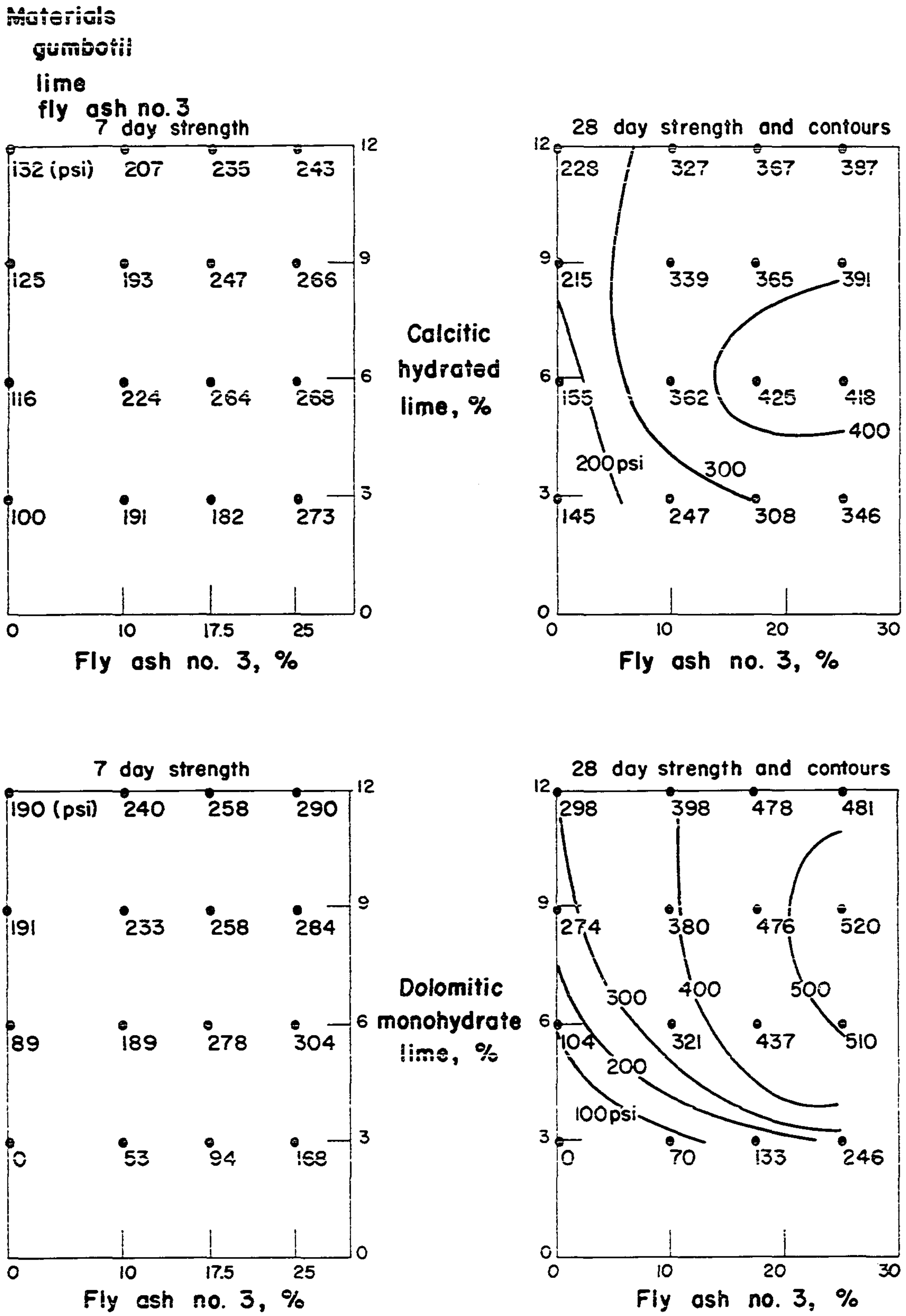


Figure 24. Immersed unconfined compressive strength values obtained for several combinations of gumbotil, lime, and fly ash No. 3 for 7 and 28 day curing periods, and strength contour lines for 28 day results.


Materials
gumbotil
lime
fly ash no. 3
7 day strength
132 (psi) 207 235 243
125 193 247 266
116 224 264 268
100 191 182 273
28 day strength and contours
228 327 367 387
215 339 365 391
155 362 425 418
145 247 308 346
200 psi
300
400
Calcitic
hydrated
lime, %
Fly ash no. 3, %
7 day strength
190 (psi) 240 258 290
191 233 258 284
89 189 278 304
0 53 94 168
28 day strength and contours
298 398 478 481
274 380 476 520
104 321 437 510
0 70 133 246
100 psi
200
300
400
500
Dolomitic
monohydrate
lime, %
Fly ash no. 3, %

Fly ash. All three fly ashes tested were effective in improving the strength that may be obtained with gumbotil and lime alone. Strengths of from 400 to over 500 psi were obtained. Consequently the use of fly ash with lime may be recommended to stabilize gumbotil to meet the standards of a base course.

Alluvial clay

Strength contours. There is no definite optimum ratio of lime to fly ash in the tests made with alluvial clay soil (Figures 25 through 27). The dolomitic monohydrate lime content of mixtures was very critical for the development of strength. For high amounts of dolomitic lime the fly ash content was more critical. With calcitic hydrated lime, the fly ash content was almost the only component contributing to strength as seen by the verticality of the contours for mixtures with calcitic lime.

The recommended amounts and kinds of lime and fly ash to stabilize alluvial clay are from 5 to 7 percent dolomitic monohydrate lime with from 10 to 25 percent of any fly ash used, or else 3 percent calcitic hydrated lime with 25 percent fly ash No. 3. Fly ashes Nos. 1 and 2 are not recommended with calcitic hydrated lime because the same strengths may be obtained with dolomitic monohydrate lime only, in amounts from 6 to 9 percent.

Figure 25. Immersed unconfined compressive strength values obtained for several combinations of alluvial clay, lime, and fly ash No. 1 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
alluvial clay
lime
fly ash no. 1

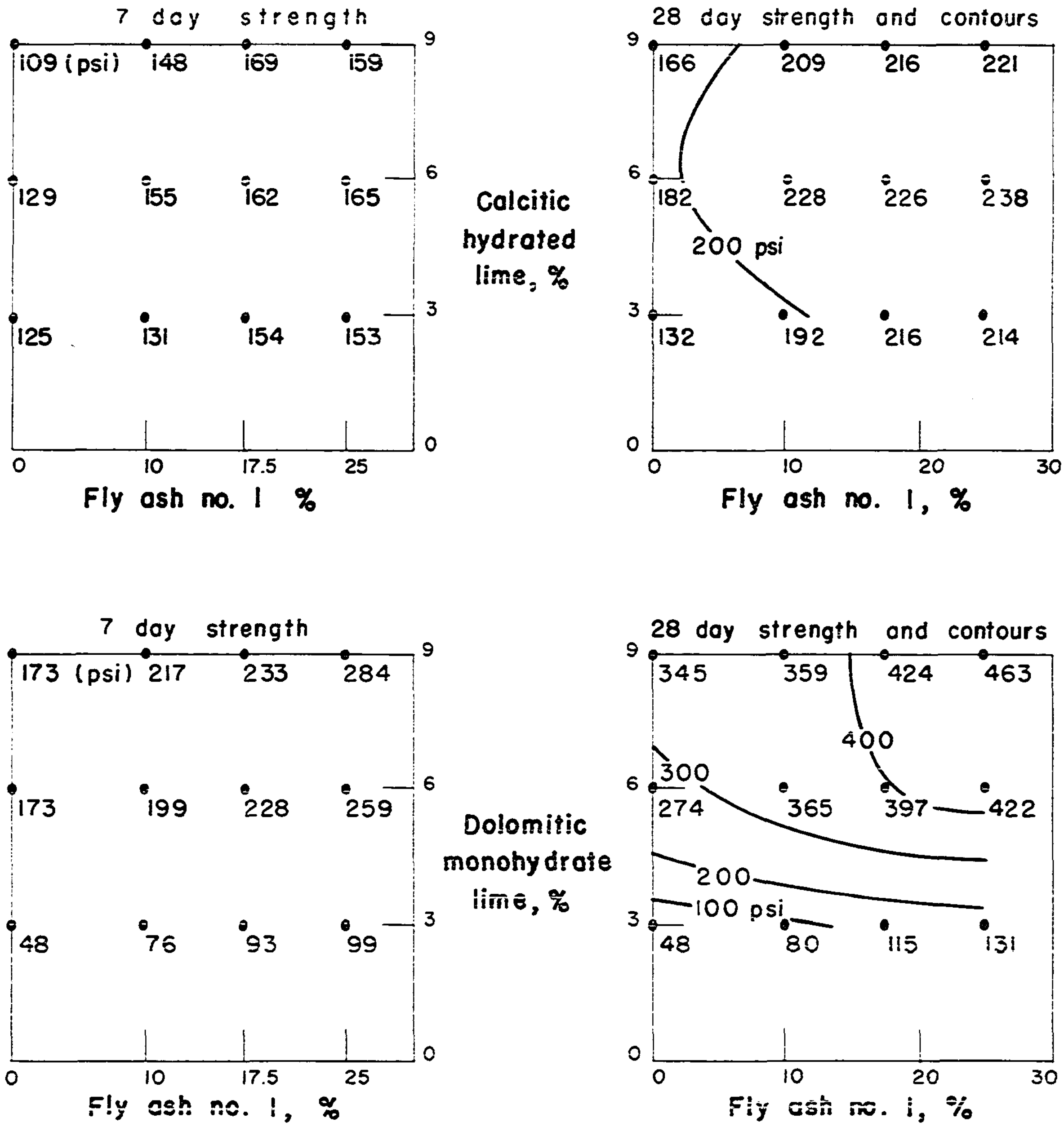


Figure 26. Immersed unconfined compressive strength values obtained for several combinations of alluvial clay, lime, and fly ash No. 2 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials
alluvial clay
lime
fly ash no. 2

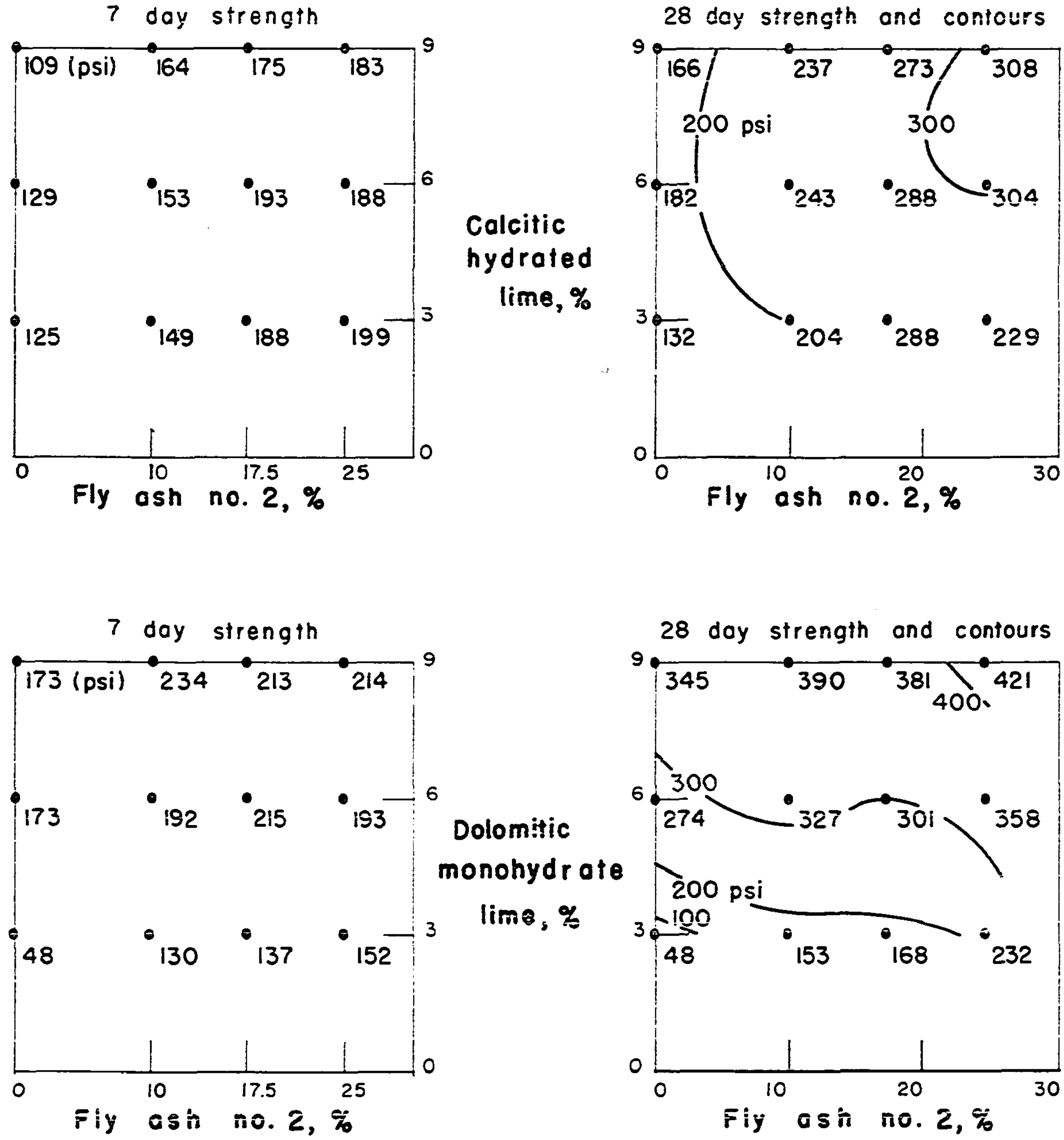
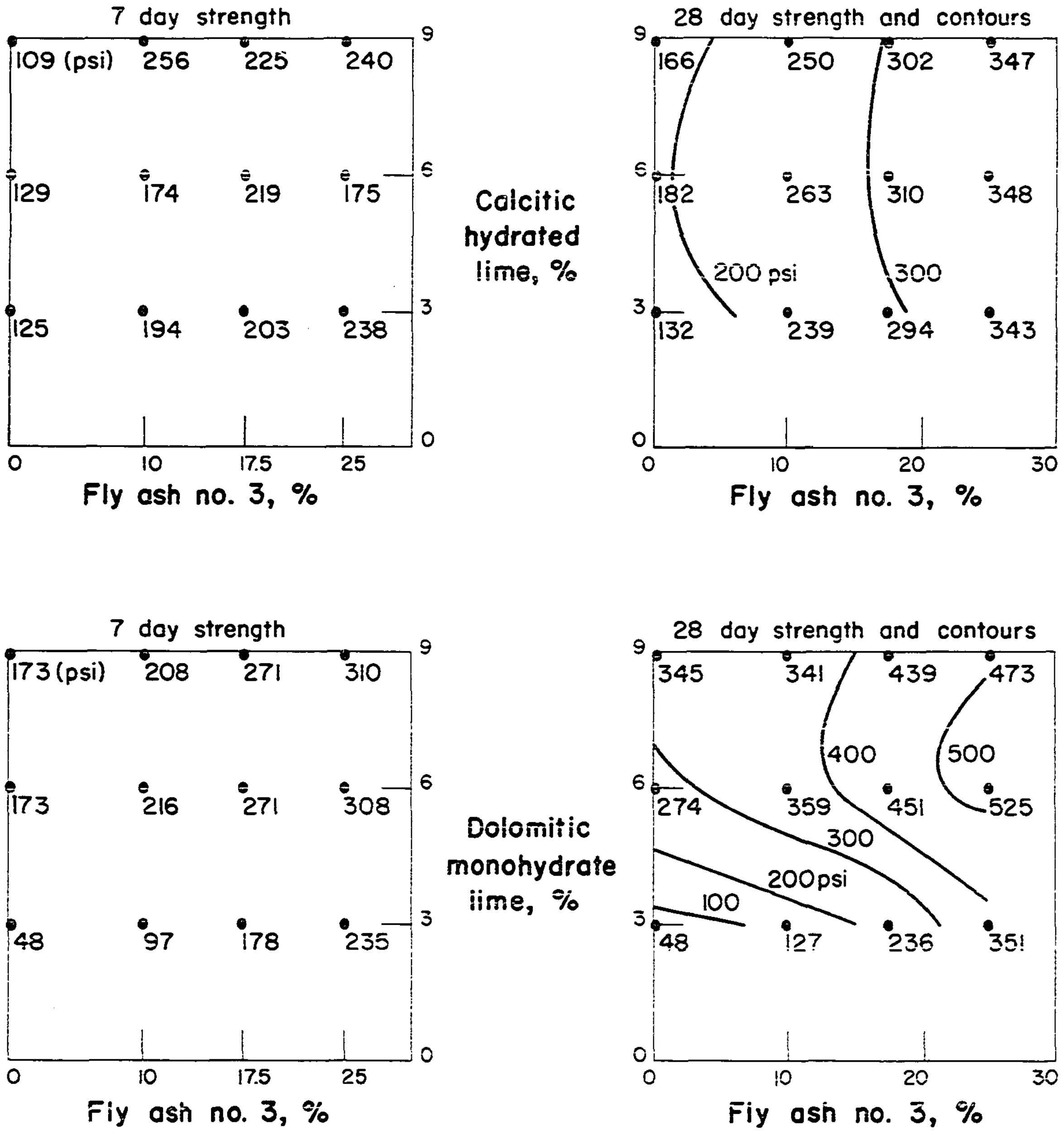


Figure 27. Immersed unconfined compressive strength values obtained for several combinations of alluvial clay, lime, and fly ash No. 3 for 7 and 28 day curing periods, and strength contour lines for 28 day results.

Materials

- alluvial clay
- lime
- fly ash no. 3



Density. No relationship was found between density and strength. The same statements made above on the relationship between specific gravity of fly ash and density of mixtures also apply here.

Lime. The calcitic hydrated lime gave better strengths than dolomitic monohydrate for the lowest amount of lime, 3 percent. The effectiveness is reversed for higher amounts. Without fly ash, 9 percent of plain dolomitic monohydrate lime may properly stabilize alluvial clay. Strengths of 173 psi after 7 day curing, and 345 psi after 28 days were obtained.

Fly ash. The overall effectiveness of fly ash No. 3 exceeded that of the other two fly ashes. Fly ash No. 1 was better than fly ash No. 2 with dolomitic monohydrate lime, but the effectiveness was reversed with calcitic hydrated lime; fly ash No. 2 was better than fly ash No. 1.

Strengths from 400 to 500 psi may be obtained with dolomitic lime and fly ash. This is an adequate strength level. Only fly ash No. 3 could be used with calcitic lime to stabilize alluvial clay. This is due to the low amount of calcitic hydrated lime required, although the strengths obtained, of the order of 350 psi, are rather low.

Discussion

Based on this study, no conclusions can be drawn as to the best ratio of lime to fly ash or as to the amount of lime and fly ash that could be used to stabilize any kind of soil.

Based on the results obtained with dune sand the amount of lime recommended for sandy or granular soils is from 3 to 6 percent and that of fly ash from 10 to 25 percent.

Unless fly ash is of a very high pozzolanic value, it should not be used with friable loess. If such a fly ash is available, 3 percent lime and 25 percent fly ash are recommended. The use of dolomitic monohydrate lime is favored.

The amounts of lime and fly ash best for both alluvial clay and gumbotil soils vary. For gumbotil, between 5 and 9 percent lime and between 10 and 25 percent fly ash are recommended. For alluvial clay, between 5 and 7 percent dolomitic monohydrate lime and between 10 and 25 percent fly ash are recommended. Lower amounts of lime may be used if it is a calcitic hydrated lime.

In general, dolomitic monohydrate limes give better strengths with fly ash than calcitic hydrated lime for the curing temperatures used (70°F). It should be pointed out that with one fly ash, No. 6, calcitic hydrated lime was more effective than dolomitic monohydrate lime. For low amounts of lime, the calcitic hydrated is more effective than the dolomitic monohydrate in the stabilization of clayey soils with lime and fly ash; at higher lime contents, dolomitic monohydrate gives better strengths than calcitic hydrated.

Fly ash, unless of a high quality, is detrimental in the stabilization of friable loess; in all other soils it was beneficial, giving better strengths than mixtures of soil-lime without fly ash.

In another report it was presented some work done at the Iowa Engineering Experiment Station on the pozzolanic behavior of fly ash (67). Twenty two fly ashes were studied in that report, among them those used in these tests. No new information is found here that might broaden our knowledge on the relation between pozzolanic activity of a fly ash and its physical or chemical characteristics.

The maximum dry density, for the same compactive effort, of soil, lime, and fly ash mixtures does not correlate with strength. Density varies with amounts and kind of lime and fly ash. Dolomitic monohydrate lime gives consistently greater densities in friable loess, lime and fly ash mixtures than calcitic hydrated lime. Fly ashes of low specific gravity produce lower densities than fly ashes of higher specific gravity.

Effect of Compactive Effort on Strength of Soil, Lime, and Fly Ash Mixtures

The present trend in compaction of earth embankments, subgrades and stabilized soils is towards compactive efforts greater than the standard Proctor. The Corps of Engineers specifies 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 (68,40) 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 with the alluvial clay and loess. Curing periods were carried up to 90 days. The results for different moisture contents may be seen in Figures 2 to 9, and the maximum strengths versus time are plotted in Figures 28 to 31, and given in Tables 9 to 12.

Discussion of results

In all the eight comparative studies made, the modified compaction gave strengths considerably greater than the standard compaction. This increase is appreciated in all curing periods, and ranges from a minimum of 50 percent increase to a maximum of 160 percent without any correlation whatsoever and depending on the kind of soil and fly ash and probably on the kind of lime also.

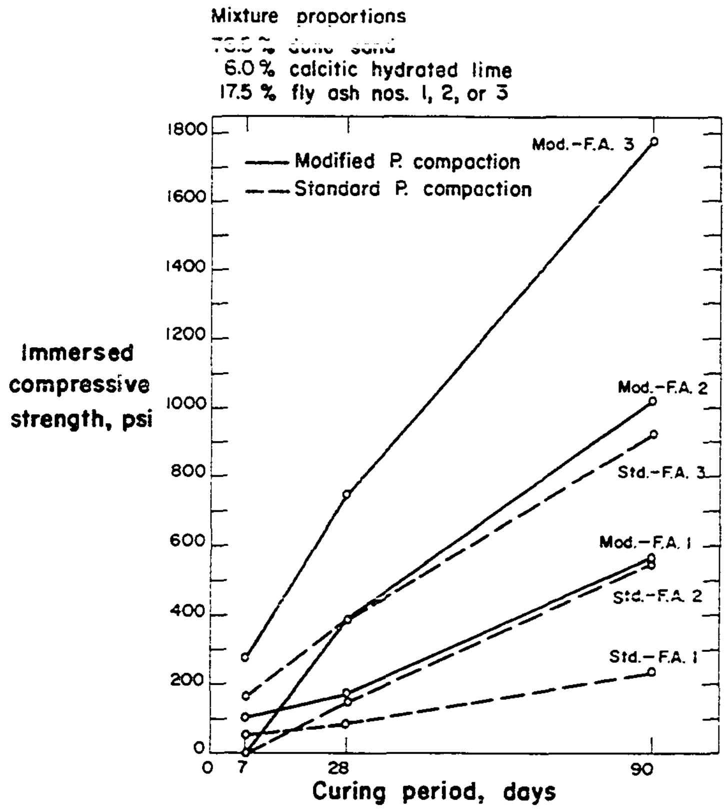
The rate of strength increase for 7, 28 and 90 days curing is almost a straight line relationship, except for those mixes made with the gumbotil. Greater rate of increase with time is found in the friable soils (dune sand and friable loess), in which there is not a break in the rate of increase up to the longest curing period used. After 90 days curing, all the mixtures show that the strength increase also takes place at longer curing periods.

The convenience of compacting the soil, lime and fly ash mixtures 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 strengths obtained with the modified compaction.

When lime and fly ash are used to stabilize friable soils, account for the steady increase in strength with time has to be made (Figures 28 to 31). 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.

Figure 28. Effect of compactive effort on strength of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash.

Figure 29. Effect of compactive effort on strength of a 76.5:6:17.5 mixture of gumbotil, calcitic hydrated lime, and fly ash.


Mixture proportions
6.0 % calcitic hydrated lime
17.5 % fly ash nos. 1, 2, or 3
Modified P. compaction
Standard P. compaction
Immersed compressive strength, psi
Curing period, days
Mod.-F.A. 3
Mod.-F.A. 2
Std.-F.A. 3
Mod.-F.A. 1
Std.-F.A. 2
Std.-F.A. 1
0
200
400
600
800
1000
1200
1400
1600
1800
0
7
28
90

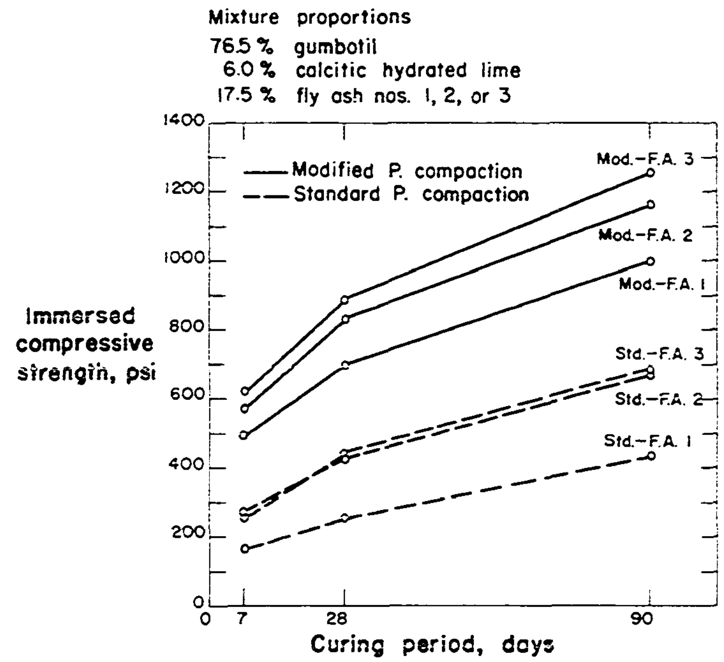
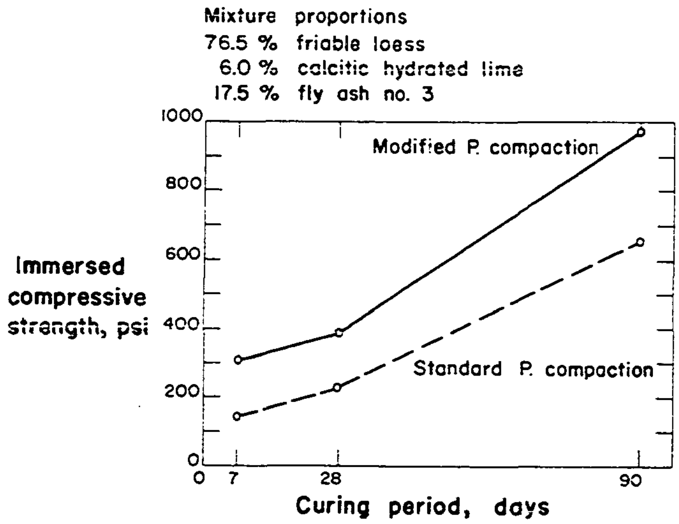

Mixture proportions
76.5 % gumbotil
6.0 % calcitic hydrated lime
17.5 % fly ash nos. 1, 2, or 3
Modified P. compaction
Standard P. compaction
Immersed compressive strength, psi
Curing period, days
Mod.-F.A. 3
Mod.-F.A. 2
Mod.-F.A. 1
Std.-F.A. 3
Std.-F.A. 2
Std.-F.A. 1
0
200
400
600
800
1000
1200
1400
0
7
28
90

Figure 30. Effect of compactive effort on strength of a 76.5:6:17.5 mixture of friable loess, calcitic hydrated lime, and fly ash No. 3.

Figure 31. Effect of compactive effort on strength of a 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3.


Mixture proportions
76.5 % friable loess
6.0 % calcitic hydrated lime
17.5 % fly ash no. 3
Modified P. compaction
Standard P. compaction
Immersed compressive strength, psi
1000
800
600
400
200
0
0
7
28
90
Curing period, days

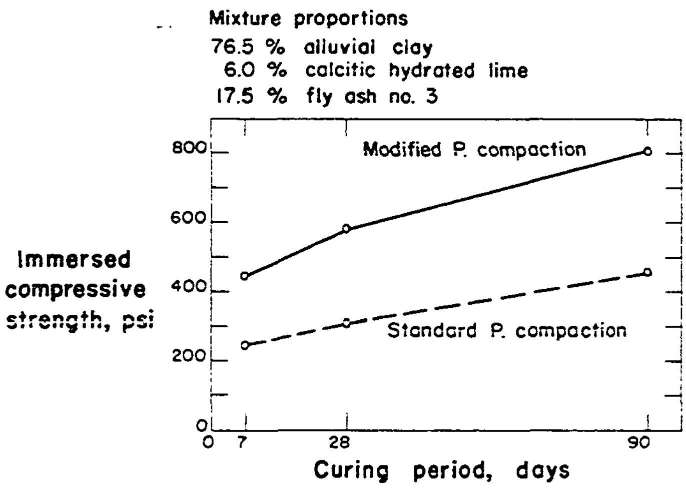

Mixture proportions
76.5 % alluvial clay
6.0 % calcitic hydrated lime
17.5 % fly ash no. 3
Modified P. compaction
Standard P. compaction
Immersed compressive strength, psi
800
600
400
200
0
0
7
28
90
Curing period, days

Table 9. Maximum strengths obtained at different curing periods for standard and modified Proctor compaction of 76.5:6:17.5 dune sand, calcitic hydrated lime and fly ash mixtures

Fly ash used, No.	Compaction	Maximum immersed unconfined compressive strength, psi		
		7 day	28 day	90 day
1	Standard	55	90	240
1	Modified	105	170	570
2	Standard	0	150	560
2	Modified	0	390	1025
3	Standard	165	390	930
3	Modified	280	750	1780

Table 10. Maximum strength obtained at different mixing periods for standard and modified Proctor compaction of a 76.5:6:17.5 friable loess, calcitic hydrated lime, and fly ash No. 3 mixture

Compaction	Maximum immersed unconfined compressive strength, psi		
	7 day	28 day	90 day
Standard	145	235	655
Modified	305	390	980

Table 11. Maximum strength obtained at different curing periods for standard and modified Proctor compaction of 76.5:6:17.5 gumbotil, calcitic hydrated lime, and fly ash mixtures

Fly ash used, No.	Compaction	Maximum immersed unconfined compressive strength, psi		
		7 day	28 day	90 day
1	Standard	170	260	440
1	Modified	490	700	1000
2	Standard	270	430	675
2	Modified	570	835	1170
3	Standard	255	445	685
3	Modified	620	890	1260

Table 12. Maximum strengths obtained at different curing periods for standard and modified Proctor compaction of a 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3

Compaction	Maximum immersed unconfined compressive strength, psi		
	7 day	28 day	90 day
Standard	240	310	460
Modified	445	585	810

Influence of Temperature of Materials at Time of Compaction

No reports have been published on the influence of temperature of the materials at time of compaction on soil, lime, and fly ash mixtures. The ambient temperature between two consecutive days in Iowa may in extreme cases be 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 60° F. This phase of the work was undertaken to determine the influence of extreme cases of ambient temperature during the working season on the strength of soil, lime, and fly ash mixtures.

The soils used were dune sand and gumbotil in mixes with 76.5 percent soil, 6 percent calcitic hydrated lime and 17.5 percent fly ash No. 3. A very reactive fly ash was used because it should accentuate the findings. A series of batches were 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, and fly ash mixtures were molded at several water contents, and then stored in the moist room at 70 ± 3° F. The maximum immersed unconfined compressive strength and density values obtained are reported in Table 13.

Discussion of Results

Although the data do not show a marked trend, mixing and compacting with hot materials may show a detrimental influence in clayey soils stabilized with lime and fly ash. The density and strength were somewhat reduced. No noticeable effects are seen in the tests made with sand.

According to the results, the basic reaction between lime and fly ash is not influenced by the temperature, in the range 54 - 104° F, of the materials at the time of mixing. This statement is based on the results obtained with sand, which may be considered as an aggregate inert to lime and fly ash. 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 prior to compaction.

Further tests were made in which the materials were mixed at the same temperatures as above, and then stored at the same temperatures of mixing for four hours before compaction. The specimens were cured in the moist room. Dune sand was the only soil used. The maximum results obtained, from batches made at different water moisture contents given in Table 14.

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

Table 13. Influence of mixing temperature of materials on the strength of a 76.5:6:17.5 mixture of soil, calcitic hydrated lime, and fly ash No. 3, with compaction after mixing

Soil	Temperature °F	Maximum immersed unconfined compressive strength, psi 7 day	28 day	90 day	Maximum dry density, pcf	Optimum M. C. for maximum density, %
Dune sand	54	154	422	1004	123.8	12
" "	70	165	390	930	124.2	12
" "	104	158	382	1010	124.2	12
Gumbotil	54	302	455	620	94.1	25
"	70	255	445	685	93.0	25
"	104	238	350	492	92.5	25

the time of mixing. The lime reacts in clayey soils in several ways with the clay particles, and some of these reactions may be activated by temperature, these reactions substract 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 on Strength of Soil, Lime, and Fly Ash Mixtures

Actual road construction is subject to many disturbances. When interruptions occur right after mixing of lime and fly ash with 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 to soil, lime and fly ash mixtures between wet mixing and compaction.

Selected mixes using dune sand or gumbotil, calcitic hydrated lime, and fly ashes Nos. 1, 2, or 3 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 hours in the moist room at 70° F and then specimens were compacted; and another set was stored for 24 hours in the same moist room before compaction of specimens.

Table 14. Influence of mixing temperature of materials in the strength of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 3, in which compaction was delayed four hours after mixing

Temperature °F	Maximum immersed unconfined compressive strength, psi			Maximum dry, density, pcf	Optimum M.C. for maximum 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

The maximum values for strength and density are given in Tables 15 and 16.

Table 15. 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	Maximum dry density, pcf	Maximum immersed unconfined compressive strength		
			7-day	28-day	90-day
1	Molded after mixing	121.2	55	90	240
1	Molded 4 hrs. after mixing	120.3	45	81	219
1	Molded 24 hrs. after mixing	118.6	41	60	210
2	Molded after mixing	112.3	0	150	560
2	Molded 4 hrs. after mixing	112.5	0	159	532
2	Molded 24 hrs. after mixing	110.8	0	141	417
3	Molded after mixing	124.1	165	390	930
3	Molded 4 hrs. after mixing	122.6	141	348	935
3	Molded 24 hrs. after mixing	122.6	118	243	945

Table 16. 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	Maximum dry density, pcf	Maximum immersed unconfined compressive strength, psi 7-day	28-day	90-day
1	Molded after mixing	Undefined	170	260	440
1	Molded 4 hrs. after mixing	Undefined	151	260	431
1	Molded 24 hrs. after mixing	Undefined	136	279	327
3	Molded after mixing	Undefined	255	445	685
3	Molded 4 hrs. after mixing	Undefined	260	405	596
3	Molded 24 hrs. after mixing	Undefined	173	244	351

<u>Dune sand</u>

Strength and density of the mixture with dune sand decrease slightly as the time between wet mixing and compaction increases. Regarding strength, the greatest decrease is found in mixtures made with fly ash No. 3, in which for 7 days curing it dropped from 165 psi for no delay in molding to 118 psi for a 24 hour delay; for 28 days curing the drop is from 390 to 243 psi; for 90 days curing there is no difference between the strength of specimens molded after mixing and of those molded after a 24 hour delay. With fly ash No. 2 specimens, after 90 days curing, there is also a great difference between the strengths of mixtures with no delay in compaction and those with 24 hours delay, the strength for these two cases being 560 and 417 psi respectively. With fly ash No. 1 the decrease is not very significant although it is steady with time of delay.

In general the decrease in strength is very slight in mixtures in which compaction was performed 4 hours after wet mixing. The decrease is more accentuated for the mixtures stored 24 hours 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 hour 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 hour 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, showing up in 7 and 90 day strengths but not in those of 28 days.

The density diminished consistently as delay of compaction increased. As the maximum dry density was undefined in mixtures with gumbotil, the moisture-dry density relationships are plotted for the range in moisture content in which the maximum strength were obtained (Figures 32,33). 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 hour delay and about 5 pcf for a 24 hour delay.

Discussion

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

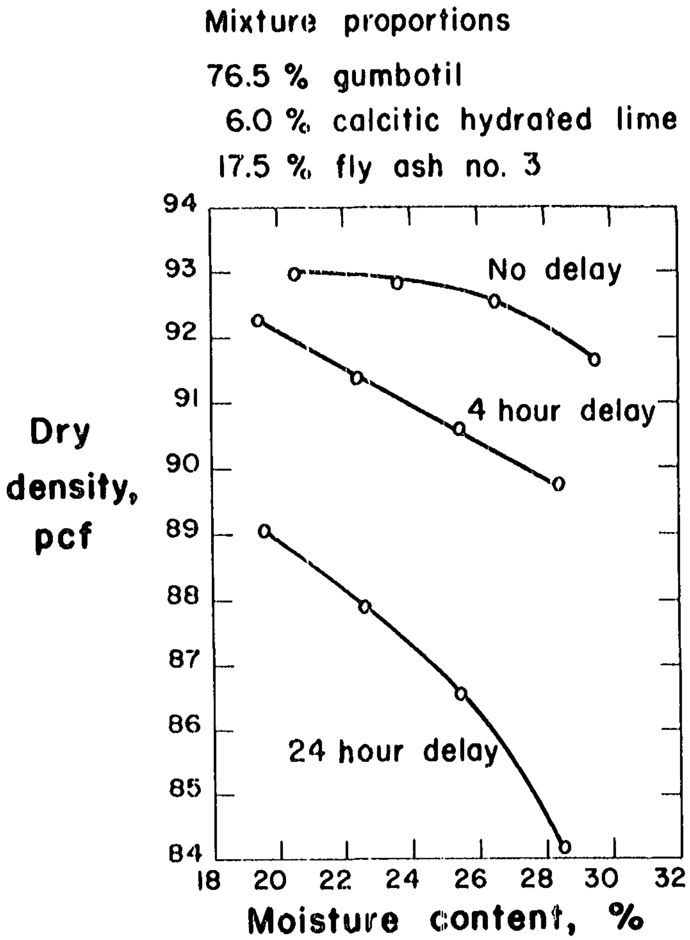
The lowering of strength and density may be for one or more of three different reasons:

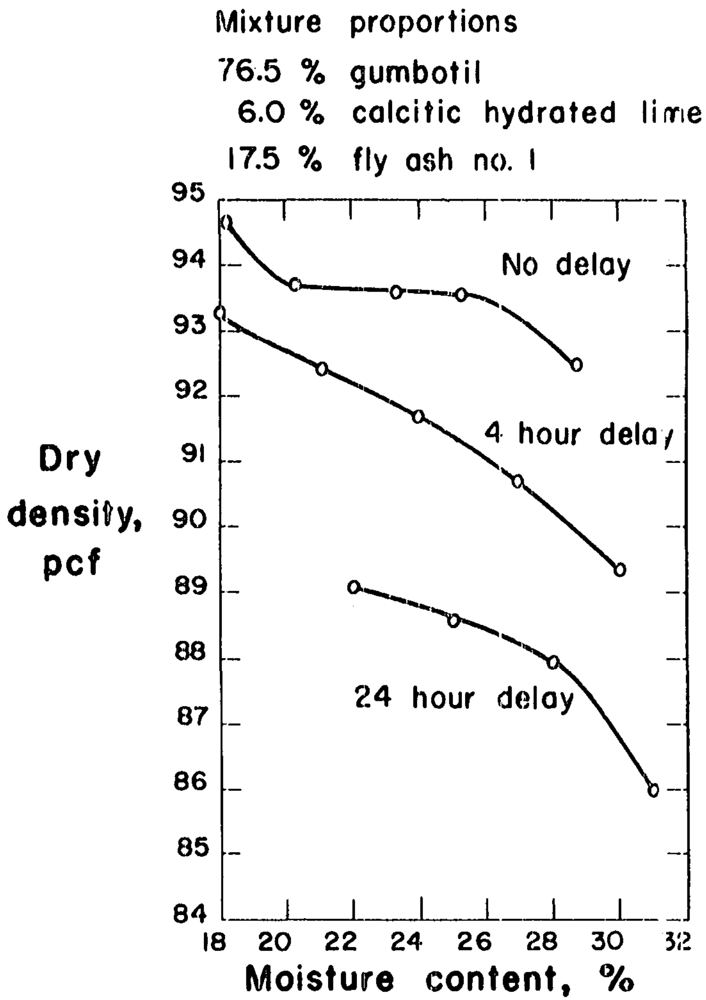
1. Formation of carbonates by chemical reaction between lime and the carbon dioxide of the atmosphere.

2. Pozzolanic reactions between lime and fly ash.

Figure 32. Moisture-density relationships of a 76.5:6:17.5 mixture of gumbotil, calcitic hydrated lime, and fly ash No. 3, in which compaction was carried at different intervals of time after wet mixing.

Figure 33. Moisture-density relationships of a 76.5:6:17.5 mixture of gumbotil, calcitic hydrated lime, and fly ash No. 1, in which compaction was carried at different intervals of time after wet mixing.


Mixture proportions
76.5 % gumbotil
6.0 % calcitic hydrated lime
17.5 % fly ash no. 3
No delay
4 hour delay
24 hour delay
Dry density, pcf
94
93
92
91
90
89
88
87
86
85
84
18
20
22
24
26
28
30
32
Moisture content, %


Mixture proportions
76.5 % gumbotil
6.0 % calcitic hydrated lime
17.5 % fly ash no. 1
No delay
4 hour delay
24 hour delay
Dry density, pcf
95
94
93
92
91
90
89
88
87
86
85
84
18
20
22
24
26
28
30
32
Moisture content, %

3. Reactions between lime and soil particles.

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

A very 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 the unlikeness of 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 soil particles are very important in clayey 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 follow wet mixing of clayey soil, lime and fly ash mixtures.

Effect of Temperature on Strength of Soil, Lime, and Fly Ash Mixtures

High temperature is known to accelerate the reaction between lime and fly ash. The knowledge of the rate of strength increase with temperature of curing is important as a determinant of the working season for lime and fly ash stabilization. It also may throw some light on the prediction of long-term strengths at ambient temperatures by curing for a short period of time at high temperatures.

Dune sand was used in these studies with calcitic hydrated lime and fly ashes Nos. 1, 2 or 3, or with dolomitic monohydrate lime and fly ash No. 3. The data are given in Tables 17 and 18 and the results are plotted in Figures 34 to 37.

Calcitic lime

The results point out the beneficial effects of high curing temperatures on the strength of soil, lime, and fly ash mixtures. The rate of strength increase varies with temperature. With calcitic lime the lowest increase in psi per degree F is found between 50°F and 70°F as seen by the small value of the tangent of the lines joining the strength values at 50°F and 70°F. The strength then increases at a higher rate between 70°F and 104°F. At 104°F there is a break in the rate of strength for specimens cured for 28 days. Between 104°F and 140°F, specimens cured for 3 and 7 days experience the highest rate of increase in psi per degree F; those cured for 28 days are still gaining strength, but the rate is a little lower than that at the previous range of temperatures. Between 140°F and 248°F the strength is still increasing; but the rate of increase, although still very important, is smaller than for some of the other temperature ranges. The shape of the curves indicate that the strength should still be increasing for curing temperatures over 248°F. Steam curing mixtures made with fly ash No. 3 at temperatures higher than 248°F may make them reach strengths of 4000 psi or over after a few hours curing.

Dolomitic lime

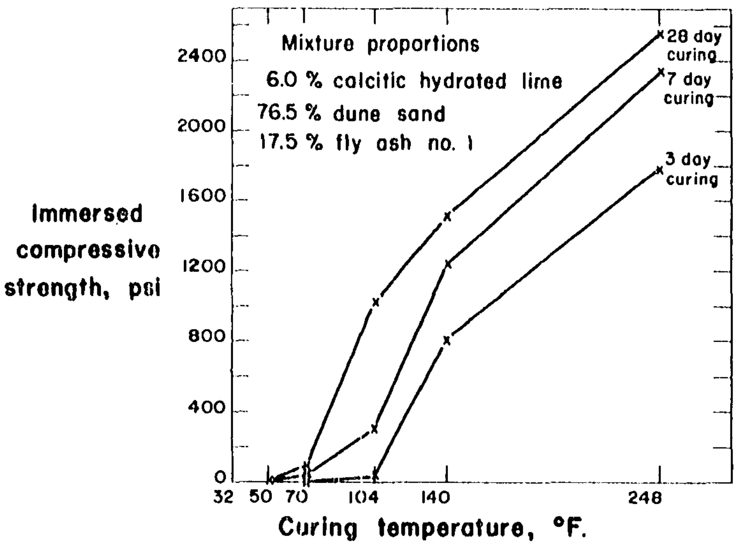
The pattern of strength increase for mixtures made with dolomitic monohydrate lime is very different from the one given by the mixtures made with calcitic hydrated lime (Compare Figure 36 with Figure 37). The rate of strength increase at low temperatures is greater than with calcitic lime, but at high temperatures it is not as great. At about 135°F the strengths are the same for both limes; dolomitic lime gave better strengths below that curing temperature; above that temperature calcitic lime was the best one.

Discussion

The pozzolanic activity between lime and fly ash is greatly influenced by temperature. After curing periods of 3 and 7 days, all specimens cured at 50°F failed during immersion, but those cured at 248°F developed strengths comparable with those of concrete. At ambient temperatures, dolomitic monohydrate lime gave higher strengths than calcitic hydrated lime, but at high temperatures calcitic lime was better than dolomitic.

Figure 34. Effect of temperature on strength of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 1.

Figure 35. Effect of temperature on strength of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 2.


Mixture proportions
6.0 % calcitic hydrated lime
76.5 % dune sand
17.5 % fly ash no. 1
28 day curing
7 day curing
3 day curing
Immersed compressive strength, psi
2400
2000
1600
1200
800
400
0
32 50 70 104 140 248
Curing temperature, °F.

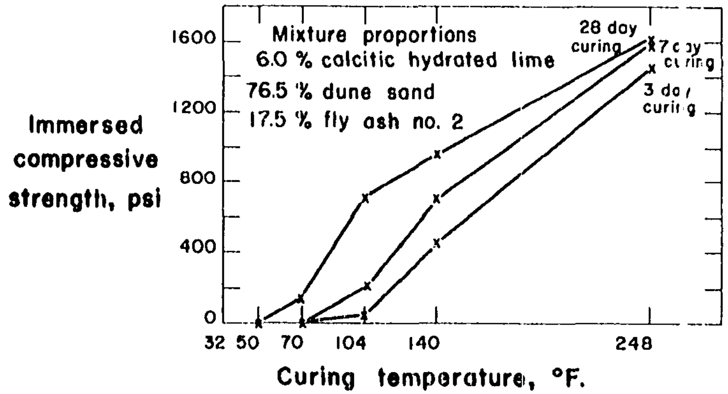
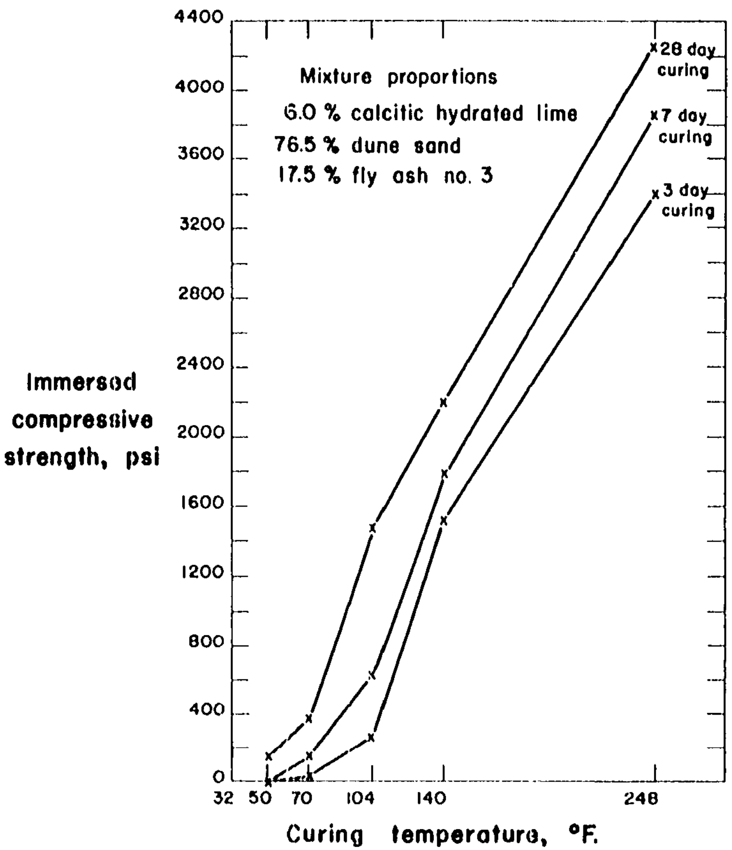

Mixture proportions
6.0 % calcitic hydrated lime
76.5 % dune sand
17.5 % fly ash no. 2
28 day curing
3 day curing
Immersed compressive strength, psi
1600
1200
800
400
0
32 50 70 104 140 248
Curing temperature, °F.

Figure 36. Effect of temperature on strength of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 3.

Figure 37. Effect of temperature on strength of a 76.5:6:17.5 mixture of dune sand, dolomitic monohydrate lime, and fly ash No. 3.


Mixture proportions
6.0 % calcitic hydrated lime
76.5 % dune sand
17.5 % fly ash no. 3
28 day curing
7 day curing
3 day curing
Immersed compressive strength, psi
4400
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
32 50 70 104 140 248
Curing temperature, °F.

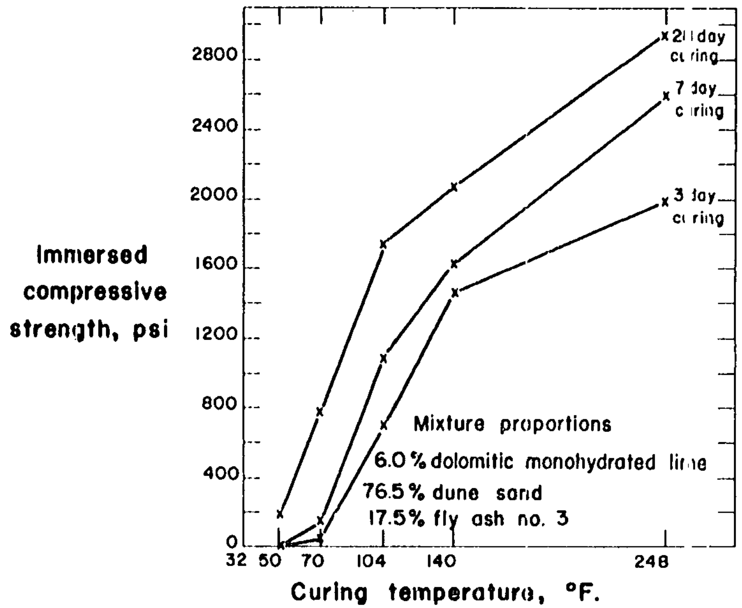

Mixture proportions
6.0 % dolomitic monohydrated lime
76.5 % dune sand
17.5 % fly ash no. 3
7 day
3 day
Immersed compressive strength, psi
2800
2400
2000
1600
1200
800
400
0
32 50 70 104 140 248
Curing temperature, °F.

Table 17. Effects of curing temperature on strength of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash

Fly ash No.	Curing temperature °F	Immersed unconfined compressive Strength, psi		
		3 day	7 day	28 day
1	50	0	0	0
1	70	0	42	78
1	104	41	295	1018
1	140	813	1216	1488
1	248	1783	2342	2572
2	50	0	0	0
2	70	0	0	141
2	104	43	208	718
2	140	449	712	971
2	248	1477	1595	1627
3	50	0	0	155
3	70	37	159	371
3	104	268	635	1496
3	140	1530	1789	2199
3	248	3407	3862	4263

Table 18. Effects of curing temperature on strength of a 76.5:6:17.5 mixture of dune sand, dolomitic monohydrate lime, and fly ash No. 3

Curing temperature °F	Immersed unconfined compressive strength, psi		
	3-day	7-day	28-day
50	0	0	193
70	52	145	783
104	717	1097	1755
140	1464	1622	2079
248	1997	2605	2947

The importance of high temperatures in the development of strength emphasizes the necessity for early summer construction when using lime-fly ash stabilization. The pavement courses will have time to cure for several weeks at temperatures high enough to aid in developing strength enough to withstand the adverse effects of winter freezing temperatures.

The strengths obtained for every temperature and curing period are in relation to the reactivity of the fly ash. Fly ash No. 3 is a good quality fly ash and the strengths obtained with it are in every case above those obtained with fly ashes Nos. 1 or 2. Fly ash No. 1 is considered of medium quality and generally performed better than fly ash No. 2, considered of poor quality. The inherent strength production, or quality, of a fly ash shows up on the unconfined compressive strength of its mixes with lime for any temperature of curing. The methods of selecting a fly ash as standardized by ASTM or the Corps of Engineers include a variety of tests cumbersome and expensive to make, and some do not select a fly ash properly. The selection of a fly ash must be made on the basis of its reactivity with lime, except when, as in cement-concrete, a gradation of the fine material is very important.

Although these tests are not statistically enough, it appears that the quality of a fly ash is reflected in the strength values of its mixtures with lime at any temperature, and it is possible that a fly ash might be selected on the basis of a simple strength test, three days after molding the specimens.

For instance, a fly ash mixed with calcitic hydrated lime and dune sand in the proportions used here, should be a good quality fly ash if after three days it gives strengths of 3000 psi cured at 248°F, 1400 psi cured at 140°F, and 220 psi cured at 104°. More studies of this kind should be made in order to establish a criterion for use in the selection of satisfactory fly ashes by the simple method of determining its reactivity with lime for short curing periods at high temperatures.

Some investigators have used a short curing period at high temperature to predict the strength that may be expected after long curing periods at ambient temperatures. To check for possible relationships of this kind, the strength after 90 days curing at 70°F has been compared with the strength-curing time relationship (Figure 38). The results indicate that strengths equal to those obtained after 90 days curing at 70°F may be obtained.

a) after 6 days curing at 104°F with fly ash No. 1 and calcitic lime

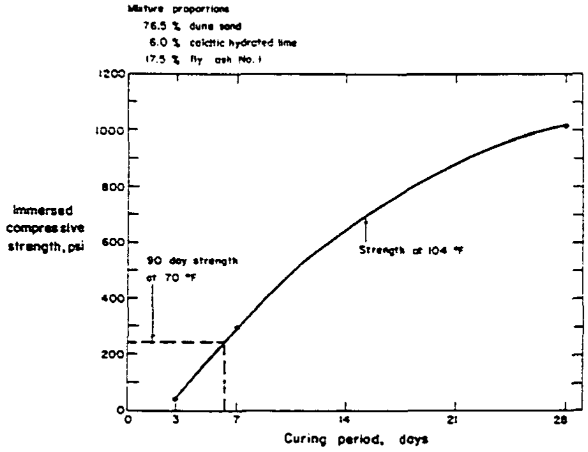
b) after 19 days curing at 104°F with fly ash No. 2 and calcitic lime

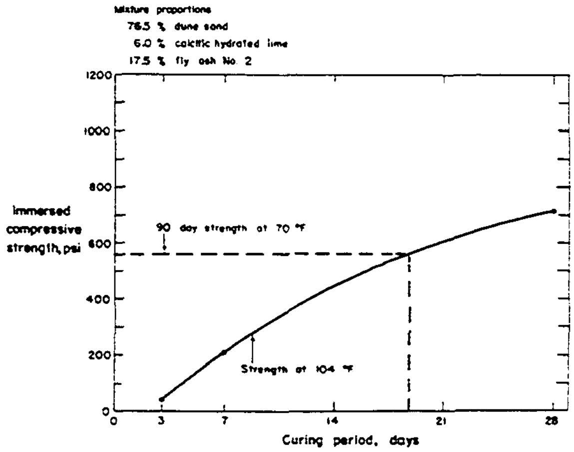
c) after 12 days curing at 104°F with fly ash No. 3 and calcitic lime

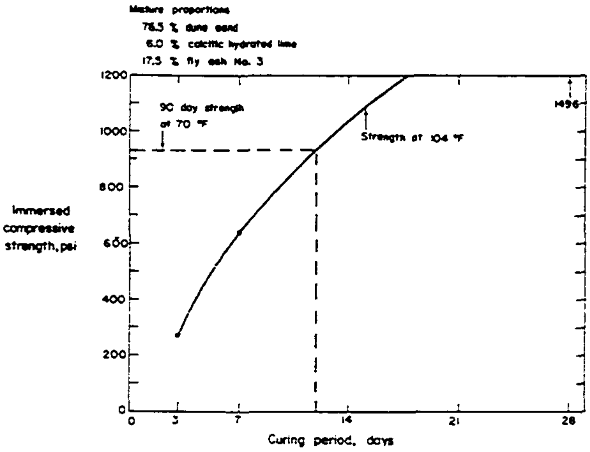
d) after 7 days curing at 104°F with fly ash No. 3 and dolomitic lime.

The range is from 6 to 19 days with both limes and even with calcitic lime only. This points out the difficulty of predicting long-term strengths at ambient temperatures by finding short-term strengths at high temperatures. Curing the specimens at temperatures higher than 104°F will give a less realistic correlation because of the probable formation of compounds different from those formed at ambient temperatures.

Figure 38. Time relationships between strength obtained after 90 days curing at 70°F and the same strength when curing at 104°F.


Mixture proportions
76.5 % dune sand
6.0 % calcitic hydrated lime
17.5 % fly ash No. 1
Immersed compressive strength, psi
90 day strength at 70 °F
Strength at 104 °F
Curing period, days


Mixture proportions
76.5 % dune sand
6.0 % calcitic hydrated lime
17.5 % fly ash No. 2
Immersed compressive strength, psi
90 day strength at 70 °F
Strength at 104 °F
Curing period, days


Mixture proportions
76.5 % dune sand
6.0 % calcitic hydrated lime
17.5 % fly ash No. 3
Immersed compressive strength, psi
90 day strength at 70 °F
Strength at 104 °F
1496
Curing period, days

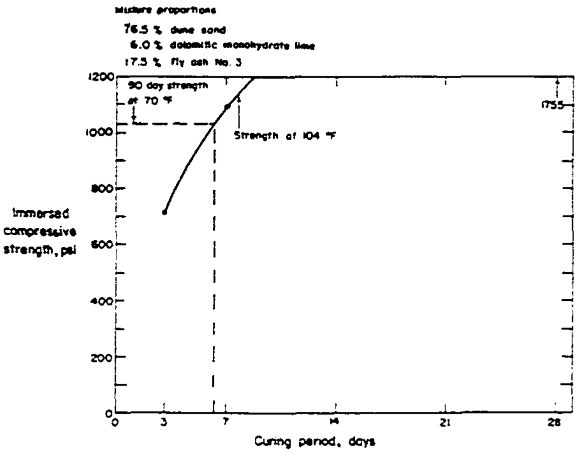

Mixture proportions
76.5 % dune sand
6.0 % dolomitic monohydrate lime
17.5 % fly ash No. 3
Immersed compressive strength, psi
90 day strength at 70 °F
Strength at 104 °F
1755
Curing period, days

Table 19. Effects of high-temperature curing on specimens previously cured at lower temperatures

Mixture	Curing	Immersed unconfined compressive strength, psi
76.5% dune sand	7 days at 120°C	2342
6.0% calcitic hydrated lime	28 days at 10°C + 7 days at 120°C	2104
	35 days at 10°C	40
17.5% fly ash No. 1		
	28 days at 40°C + 7 days at 120°C	2104
	35 days at 40°C	1079
	28 days at 60°C + 7 days at 120°C	1895
	35 days at 60°C	1336
76.5% dune sand	7 days at 120°C	1595
6.0% calcitic hydrated lime	28 days at 10°C + 7 days at 120°C	1915
	35 days at 10°C	0
17.5% fly ash No. 2		
	28 days at 40°C + 7 days at 120°C	1520
	35 days at 40°C	905
	28 days at 60°C + 7 days at 120°C	1204
	35 days at 60°C	1093

It should also be mentioned that the strength may be accelerated after the specimens have been cured for a lapse of time at a certain temperature by submitting them to higher temperatures. The lower the initial temperature of curing the higher the strength is boosted. Examples of this property are given in Table 19. These findings indicate that the strength of soil, lime, and fly ash mixtures may be increased at any time by submitting them to higher curing temperatures.

Steam Curing Soil Stabilized Mixtures

After the temperature curing studies were made, further investigation was made of the effect of steam curing on the strength of stabilized soil specimens.

In a recent report presented to the Highway Research Board (38) it was recommended that an additional 10 million dollars be spent exclusively in research on aggregates during the next four or five years. The same report suggested some research in the use of nuclear energy in highway construction. Based on the need for new sources of aggregates and the future use of nuclear energy, the study on steam curing of soil-lime-fly ash specimens was expanded to include soil-cement and soil-lime. This was done because of the concrete-like strengths obtained with soil, lime and fly ash mixtures, and to gather information on the effects of steam curing on other kinds of soil stabilization.

This was not approached as a systematic study since it is beyond the purpose of the lime, fly ash stabilization investigation.

Extensive research has been done on sand-lime bricks (23,27,29,43,57). These bricks are made by submitting the sand-lime paste to temperatures of 150-200°C (302-392°F) for about 8 hours in autoclaves with pressures from 5 to 10 atmospheres. The addition of clay has been tried, and about 10 percent clay has been found to increase the strength of sand-lime bricks (27,57,60). The treatment of cement concrete by steam is a well known process, and the curing of lime and fly ash mixtures at high temperatures has already been mentioned. A comparative study of the autoclaving of soil specimens stabilized with lime, cement, or lime, and fly ash at 248°F, 15 atm., was undertaken. The results, together with those obtained at 70°F are presented in Table 20.

Discussion

Soil specimens stabilized with lime and fly ash, lime, or cement may reach strengths of 1000 psi or higher by exposing them to high temperatures and steam.

A mixture of 76.5 percent sand, 6 percent calcitic hydrated lime and 17.5 percent fly ash No. 3, developed a concrete-like strength of 2548 psi after 24 hours in the autoclave (248°F, 15 atm.). After 7 days, the strength was 3662 psi. These strengths are many times higher than those obtained at ambient temperatures. A great increase was also obtained with the same fly ash and different lime percentages mixed with friable loess. Mixtures of dune sand, lime and fly ash No. 1 or No. 2 also gave very good strengths after curing in the autoclave, although they are much lower than strengths obtained with fly ash No. 3.

Addition of 6 percent calcitic hydrated lime to friable loess gave a 24 hour strength of 1792 psi, with a subsequent increase for longer curing periods. Dolomitic lime gave strengths lower than calcitic lime, either used alone or with fly ash. Sand-lime mixes that have practically no strength at ordinary temperatures, reached 1030 psi after 3 days in the autoclave.

Cement treated soils also benefit from the accelerated curing at high temperature, but not to the extent of those treated with lime or lime-fly ash. Maximum strengths with cement were lower than with lime or lime-fly ash.

An examination of the results shows that:

1. High-temperature curing with a supply of moisture in the form of steam enhances the strength of soils stabilized with lime, lime-fly ash or cement.

Table 20. Comparison of strengths of soil stabilized mixtures cured at 248°F and 70°F

Materials and proportions	Immersed unconfined compressive strength after steam-curing at 248°F		
	1 day	3 days	7 days
Sand			
+ 8% calc. lime	311	1030	ND[a]
+ 8% cement	654	968	1162
+ 6% calc. lime + 17.5% F.A. #1	1668	1783	2342
+ 6% calc. lime + 17.5% F.A. #2	1087	1477	1595
+ 6% calc. lime + 17.5% F.A. #3	2548	3407	3662
+ 6% dolo. lime + 17.5% F.A. #3	ND	2014	ND
Loess			
+ 3% calc. lime	630	654	ND
+ 3% dolo. lime	254	271	ND
+ 3% cement	366	420	ND
+ 6% calc. lime	1792	1977	2118
+ 6% dolo. lime	1396	1630	1561
+ 6% cement	955	1084	1244
+ 9% calc. lime	1441	1820	ND
+ 9% dolo. lime	1344	1524	ND
+ 9% cement	1140	1425	ND
+ 3% calc. lime + 17.5% F.A. #3	1432	1624	ND
+ 6% calc. lime + 17.5% F.A. #3	1780	1969	ND
+ 9% calc. lime + 17.5% F.A. #3	2063	2182	ND
Alluvial			
+ 9% calc. lime	921	969	1054
+ 9% dolo. lime	613	597	ND
+ 3% calc. lime _ 6% cement	717	715	711
Gumbotil			
+ 9% calc. lime	1188	1318	1350

[a] Not determined.

[b] Dolomitic monohydrate lime used.

Table 20. (Continued)

Table 20. (Continued)

Materials and proportions	Immersed unconfined compressive strength after moist-curing at 70°F		
	7 days	28 days	90 days
Sand			
+ 8% calc. lime	5	20	30
+ 8% cement	398	474	541
+ 6% calc. lime + 17.5% F.A. #1	55	90	240
+ 6% calc. lime + 17.5% F.A. #2	0	150	560
+ 6% calc. lime + 17.5% F.A. #3	165	390	930
+ 6% dolo. lime + 17.5% F.A. #3	145	783	1030
Loess			
+ 3% calc. lime	72	110	287
+ 3% dolo. lime	117	249	234
+ 3% cement	ND	ND	ND
+ 6% calc. lime	59	105	403
+ 6% dolo. lime	151	354	584
+ 6% cement	330	495	715
+ 9% calc. lime	78	158	499
+ 9% dolo. lime	174	400	621
+ 9% cement	423	566	1001
+ 3% calc. lime + 17.5% F.A. #3	140	226	ND
+ 6% calc. lime + 17.5% F.A. #3	142	225	655
+ 9% calc. lime + 17.5% F.A. #3	126	203	ND
Alluvial			
+ 9% calc. lime	109	166	218
+ 9% dolo. lime	173	345	336
+ 3% calc. lime _ 6% cement	328[b]	469[b]	501[b]
Gumbotil			
+ 9% calc. lime	125	215	386

[a] Not determined.

[b] Dolomitic monohydrate lime used.

2. The strength increases with length of curing, from which it is deducted that the strengths might be boosted to higher values by curing at higher temperatures than the one used here (248°F).

3. Compacted mixtures of soil, calcitic hydrated lime, and high quality fly ash develop concrete-like strengths after a few hours of steam curing.

4. Lime-fly ash gave best strengths followed by calcitic lime, dolomitic lime and cement in this order; although sand-lime mixes should be regarded as a special case requiring higher temperatures than those used here. Calcitic lime ranks better than dolomitic in steam cured soil, lime, and fly ash mixtures.

It is anticipated that the results shown by these experiments may have an impact in the future development of the technique of soil stabilization. The recommendations made to the Highway Research Board to promote research to study the applications of nuclear power in road construction are reinforced by the results reported herein. The development of a machine able to heat economically a 4 to 6 inch layer of compacted stabilized soil to temperatures in the range of 212 to 572°F (100 to 300°C) could revolutionize the practice of soil stabilization. If the application of heat to road courses is feasible, further work may determine such details as the amount of stabilizer to use with each soil, the time and temperature of application as related to the heat conductivity of soils and to the strength desired, feasibility of the use of steam, etc.

Preliminary Survey of Chemical Additives to Mixtures of Lime and Fly Ash

The preliminary survey was made using twelve chemicals in varying amounts to determine the minimum amount of each required for substantial improvement of the lime-fly ash reaction and to serve as the basis for selecting a smaller number of chemicals for more detailed studies. Ottawa sand was used as the soil component because its gradation and monomineralic composition, silica, may make it behave as an inert material at the curing temperatures used, thus minimizing the effect of the soil component on the lime-fly ash reaction. A calcitic hydrated lime was chosen because, although of reagent grade, it was representative of a great amount of commercial limes produced in the U. S. A medium quality fly ash from the Midwest (St. Clair Power Plant) was used as the pozzolan component. The Ottawa sand, lime, fly ash mix proportions were 75 percent, 5 percent, 20 percent, respectively, near optimum for these materials.

Specimens were molded at optimum moisture for strength.

Any or certain amounts of all the chemicals used increased the strength of the Ottawa sand lime, and fly ash mixture. Following is an analysis of each chemical evaluated.

Sodium carbonate

Even the smallest amount of sodium carbonate tried, 0.05 percent, increased the strength substantially. Seven and 28 day strengths were increased over thirty times with amounts of chemical greater than 0.5 percent. Some differences in strength are shown between the use of sodium carbonate in powder form or in liquid solution, but the great increase in strength warrants the use of the chemical in either form. The optimum amount is about 1.0 percent when used in powder form. The commercial price of this product, 35 to 65 dollars a ton, makes it a promising additive for lime-fly ash stabilization.

Sodium hydroxide

This chemical is also very effective. A noticeable improvement of strength started with amounts of sodium hydroxide as low as 0.03 percent. A recommended amount is about 1.0 percent. This chemical, priced at about 100 dollars a ton, may also be an economical activator of the pozzolanic reaction.

Figure 39. (a,b,c,d). Effect of amount of chemical additive on strength of 75:5:20 Ottawa sand, calcitic hydrated lime, and fly ash No. 1 mixture.

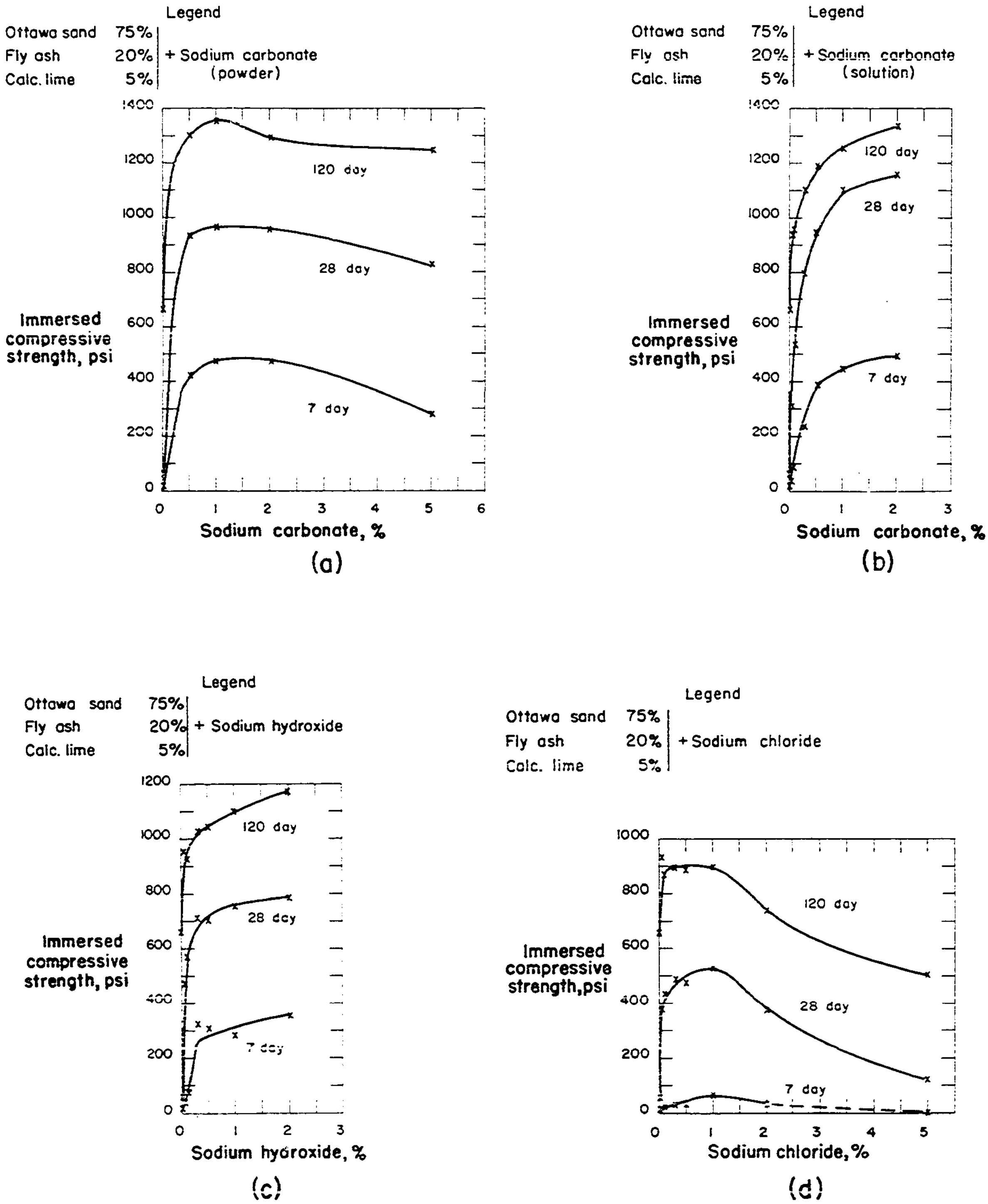
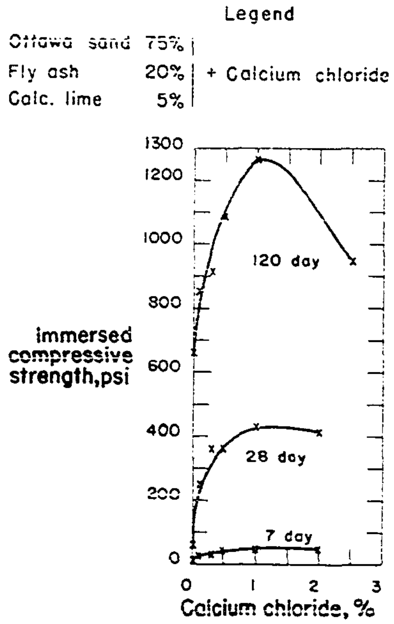
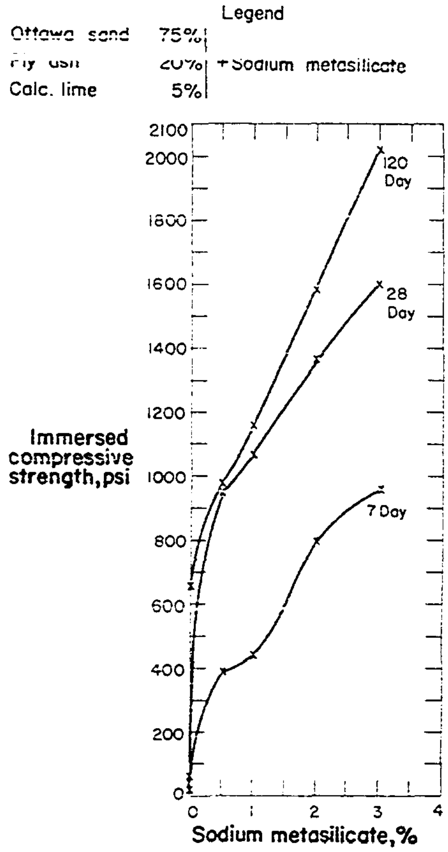

Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Sodium carbonate (powder)
Immersed compressive strength, psi
120 day
28 day
7 day
Sodium carbonate, %
(a)
Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Sodium carbonate (solution)
Immersed compressive strength, psi
120 day
28 day
7 day
Sodium carbonate, %
(b)
Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Sodium hydroxide
Immersed compressive strength, psi
120 day
28 day
Sodium hydroxide, %
(c)
Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Sodium chloride
Immersed compressive strength, psi
120 day
28 day
7 day
Sodium chloride, %
(d)

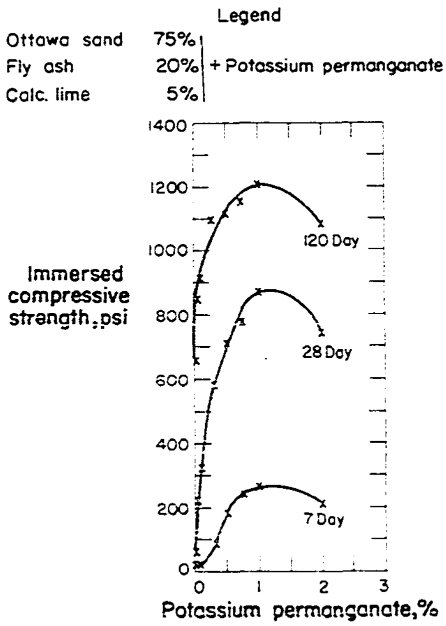
Figure 39. (e,f,g,h). Effect of amount of chemical additive on strength of 75:5:20 Ottawa sand, calcitic hydrated lime, fly ash No. 1 mixture.


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Calcium chloride
Immersed compressive strength, psi
120 day
28 day
7 day
Calcium chloride, %

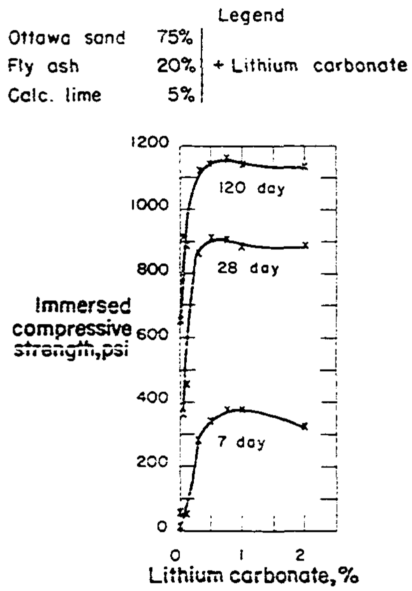
(e)


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Sodium metasilicate
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Sodium metasilicate, %

(f)

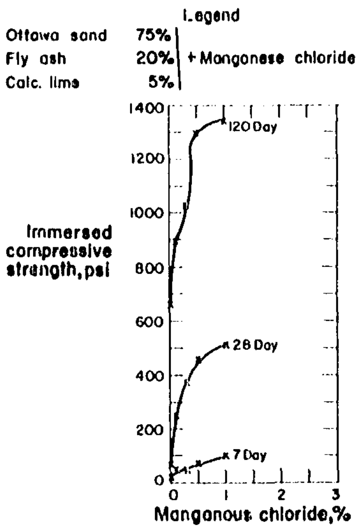

Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Potassium permanganate
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Potassium permanganate, %

(g)

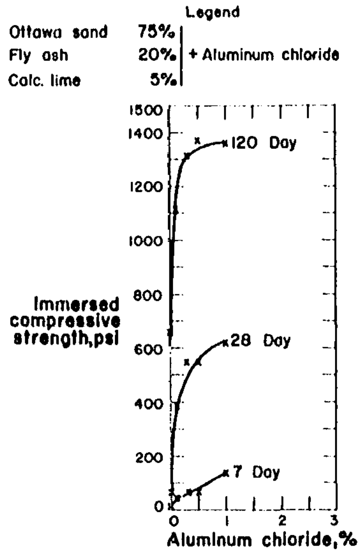

Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Lithium carbonate
Immersed compressive strength, psi
120 day
28 day
7 day
Lithium carbonate, %

(h)

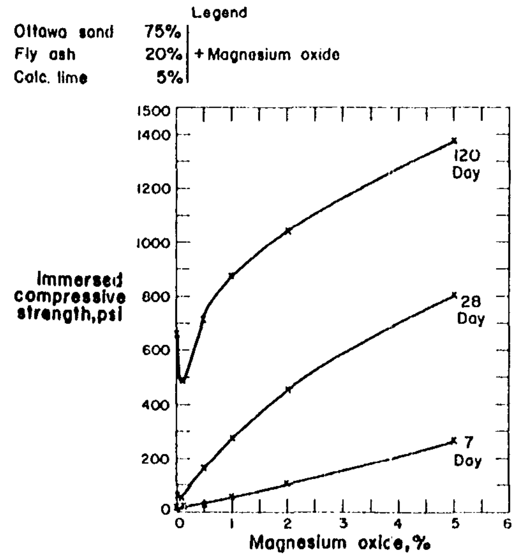
Figure 39. (i,j,k,l,m). Effect of amount of chemical additive on strength of 75:5:20 Ottawa sand, calcitic hydrated lime and fly ash No. 1 mixture.


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Manganese chloride
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Manganous chloride, %

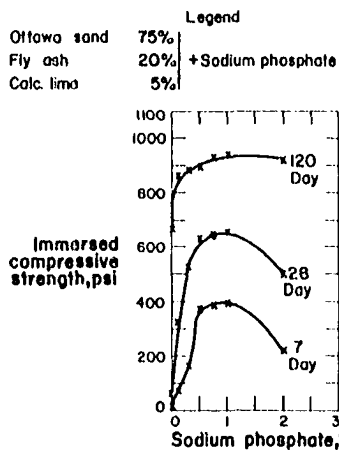
(i)


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Aluminum chloride
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Aluminum chloride, %

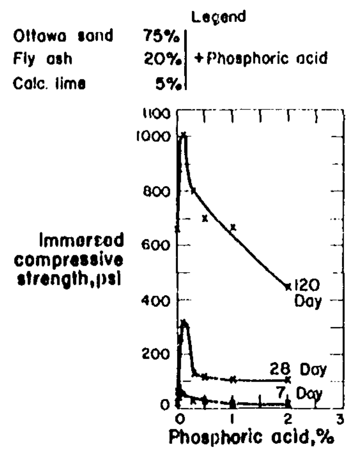
(j)


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Magnesium oxide
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Magnesium oxide, %

(k)


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Sodium phosphate
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Sodium phosphate, %

(l)


Legend
Ottawa sand 75%
Fly ash 20%
Calc. lime 5%
+ Phosphoric acid
Immersed compressive strength, psi
120 Day
28 Day
7 Day
Phosphoric acid, %

(m)

Sodium chloride and calcium chloride

The effects of these two additives are somewhat parallel. They gave little improvement to 7 day strength, but gave a substantial increase to 28 day and 4 month strengths even with small concentrations of chemical. The price difference, 20 dollars a ton for sodium chloride and 60 for calcium chloride, and the small amounts of sodium chloride required for a maximum increase in strength, makes sodium chloride the choice when improvement of long-term strengths is the main interest. Three-tenths of a percent of sodium chloride increased the 28 day strength by about ten times, and the optimum amount was about 1.0 percent.

Sodium metasilicate

This chemical increased the strength greatly, even in small amounts. The strength increase was more or less proportional to amount used; the optimum was above 3.0 percent. The strength of 1,000 psi was found after 7 days curing with the largest amount of sodium metasilicate tested, 3.0 percent. The commercial price of this chemical is about 120 dollars a ton on a dry basis, which makes it a promising chemical additive when used in small amounts.

Lithium carbonate, potassium permanganate, manganese chloride, aluminum chloride and sodium phosphate

These chemicals increase strengths, but the rate of increase, amounts required, and economical considerations make them less desirable.

Phosphoric acid

Although very small amounts of phosphoric acid improved soil strength, concentrations larger than 0.03 percent caused a decrease in strength. Its use is therefore not recommended.

Magnesium oxide

One of the components of dolomitic monohydrate (Type N) lime is magnesium oxide; consequently the effects on strength caused by addition of this chemical should give an indication on the effects of using dolomitic monohydrate lime instead of calcitic hydrated in lime-fly ash stabilization.

Small amounts, up to 0.5 percent, resulted in a slight decrease of strength, but increased amounts up to the largest amount tried, 5.0 percent, increased the strength (Figure 39, k). The results indicate that dolomitic monohydrate limes are more effective with the fly ash used here, but they are not as effective as calcitic hydrated lime plus treatment with some of the other chemical additives. The results also warranted an investigation on the effects of chemical additives to dolomitic lime and fly ash mixtures.

Extended Evaluation of Chemical Additives

To complement the tests made with Ottawa sand, the study was extended to include four natural soils: a dune sand, a friable loess, an alluvial clay and a gumbotil (Tables 1 and 2).

The evaluation of magnesium oxide indicated that dolomitic monohydrate lime might be more effective than calcitic hydrated lime, and that the use of dolomitic lime might make unnecessary the addition of chemicals; therefore the use of both limes, calcitic hydrated and dolomitic monohydrate, was evaluated. Commercial type limes were used.

Three fly ashes were selected to include such desired variations in their properties as coarseness, carbon content, specific surface, etc.

From the preliminary studies, four chemicals warranted further evaluation based on strength improvement and economics: sodium carbonate, sodium hydroxide, sodium metasilicate and sodium chloride.

The proportions of soil, lime, and fly ash used were 76.5 percent, 6 percent and 17.5 percent. The amount of chemical used was 1.0 percent in mixtures prepared with all soils, limes, and fly ashes, except that 0.5 percent was also used with dune sand and fly ash No. 1. The evaluation was not intended to be an economic comparison of lime-fly ash-chemical stabilization of soils with other methods of soil stabilization, but rather to be a check on the possible beneficial effects of the selected chemicals on soil, lime, and fly ash mixtures. Therefore, the mixture proportions are within the range commonly recommended for lime-fly ash stabilization, and the amount of chemical added is probably near the optimum amount, except for sodium metasilicate.

The molding moisture content for mixtures was deducted from the moisture-density and moisture-strength curves of soil, lime, and fly ash mixtures without chemical additives. With friable loess, maximum density and maximum strength occurred at the same moisture content, and this was considered the optimum. The moisture requirements for maximum density and maximum strength of mixtures with sand were not the same, and as the moisture content for maximum density gave very low strengths, the moisture content for maximum strength was used as the optimum. The molding moisture to get maximum strengths of mixtures with alluvial clay and gumbotil was about two percent above the optimum for maximum density.

Dune sand

The data of tests made with this soil and combinations of calcitic hydrated or dolomitic monohydrate lime and fly ashes Nos. 1, 2 and 3 are plotted as bar graphs in Figures 40 through 43.

Sodium carbonate, sodium metasilicate and sodium hydroxide in amounts of 1.0 percent increased 7, 28 and 90 day strengths of all dune sand-lime-fly ash mixtures considerably. Sodium chloride increased 28 and 90 day strengths of dune sand, calcitic lime, and fly ash mixtures to a great extent and also increased substantially the 90 day strength of dune sand, dolomitic lime, and fly ash mixtures except those made with fly ash No. 2, in which the strength increase was quite small.

The strengths obtained using 0.5 percent chemical in mixtures with fly ash No. 1 are smaller than those obtained with 1.0 percent chemical additive, but the strength increases follow the same trend for both amounts.

Friable loess

All four chemicals increased the strength of loess, calcitic lime, and fly ash mixtures except for 90 day strength of specimens made with sodium metasilicate and fly ash No. 2 (Figures 44 through 46). Loess, dolomitic lime, and fly ash mixtures were not appreciably benefited by the addition of the chemicals.

The use of sodium chloride, sodium carbonate or sodium hydroxide in mixtures of friable loess, calcitic hydrated

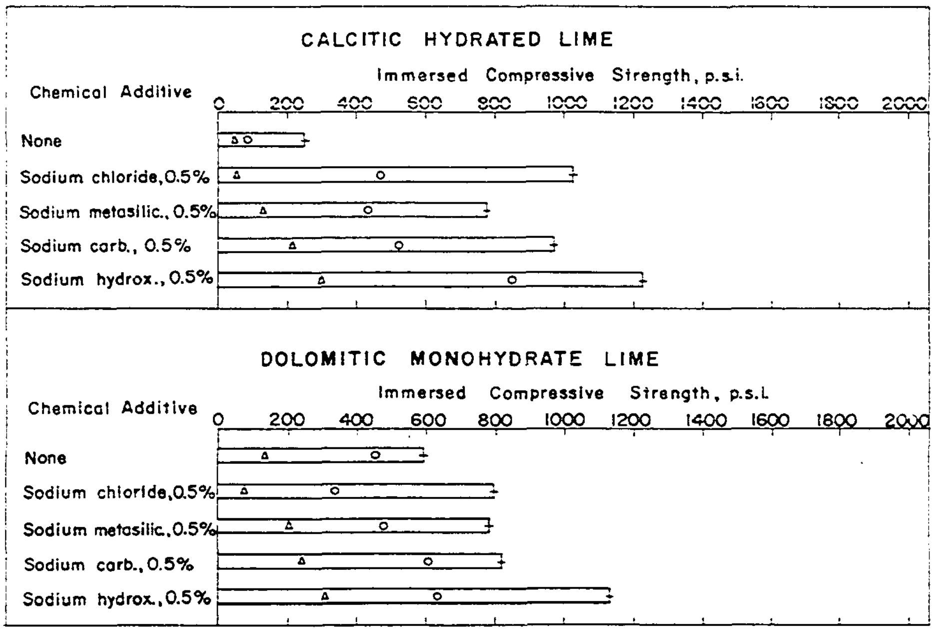
Figure 40. Effect of 0.5 percent chemical additive on strength of a 76.5:6:17.5 mixture of dune sand, lime, and fly ash No. 1.

Figure 41. Effect of 1.0 percent chemical additive on strength of a 76.5:6:17.5 mixture of dune sand, lime, and fly ash No. 1.

Mixture Proportions

76.5 % dune sand
6.0 % lime
17.5 % fly ash No.1

△ 7 day curing
○ 28 day curing
+ 90 day curing



Mixture Proportions

76.5 % dune sand
6.0 % lime
17.5 % fly ash No.1

△ 7 day curing
○ 28 day curing
+ 90 day curing

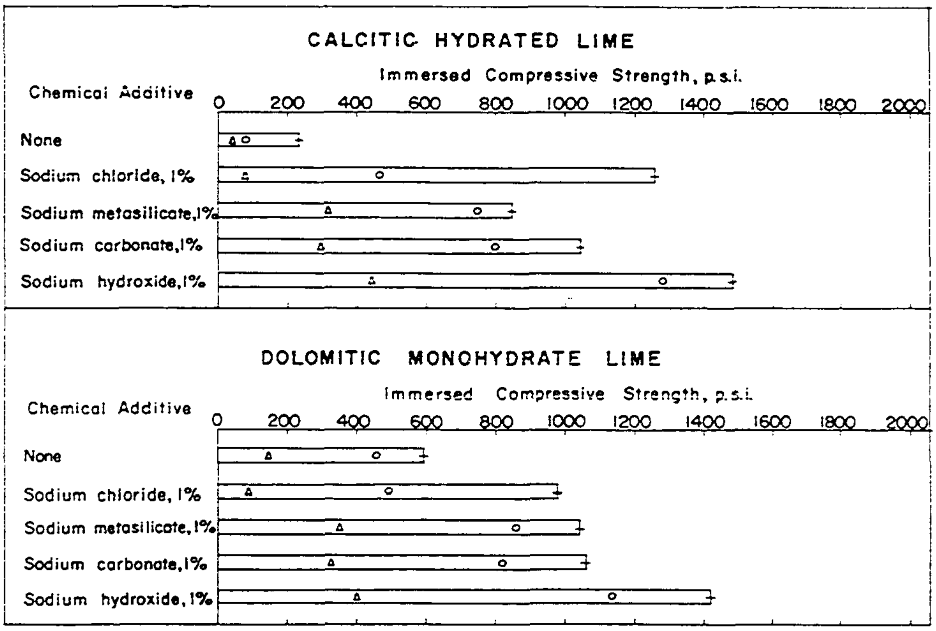


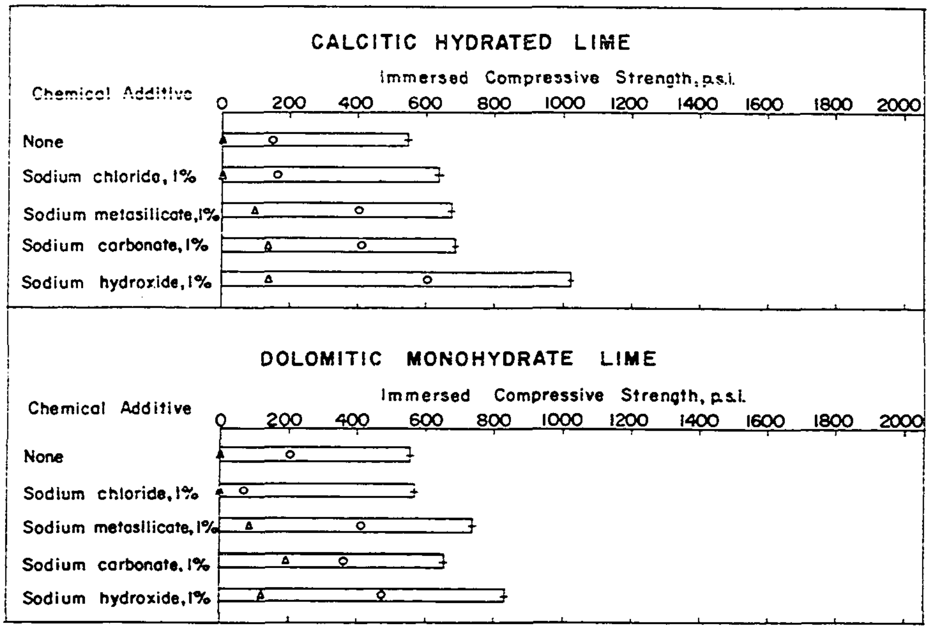
Figure 42. Effect of 1.0 percent chemical additive on strength of a 76.5:6:17.5 mixture of dune sand, lime, and fly ash No. 2.

Figure 43. Effect of 1.0 percent chemical additive on strength of a 76.5:6:17.5 mixture of dune sand, lime, and fly ash No. 3.

Mixture Proportions

76.5 % dune sand
6.0 % lime
17.5 % fly ash No.2

▵ 7 day curing
o 28 day curing
+ 90 day curing



Mixture Proportions

76.5 % dune sand
6.0 % lime
17.5 % fly ash No.3

▵ 7 day curing
o 28 day curing
+ 90 day curing

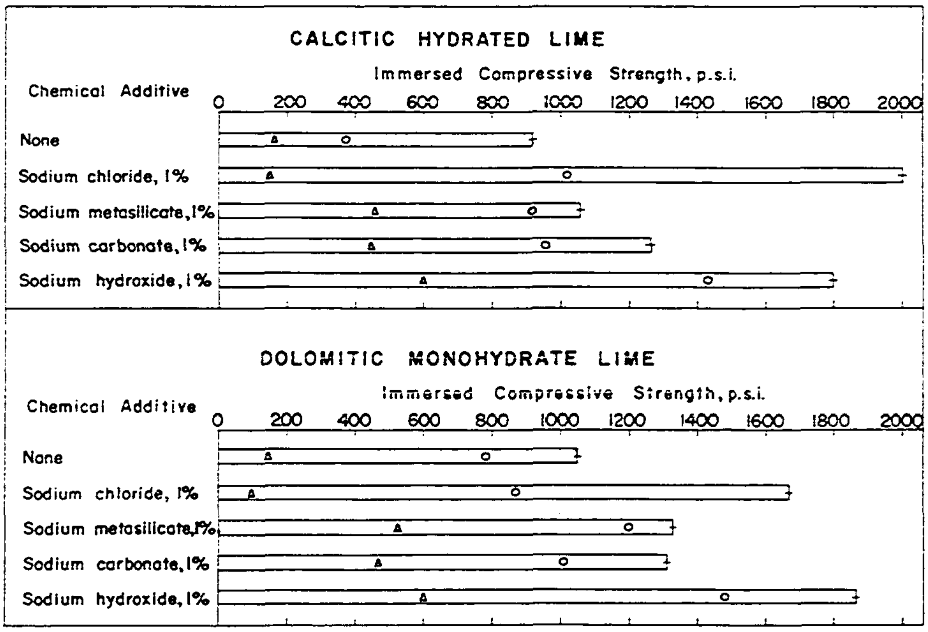


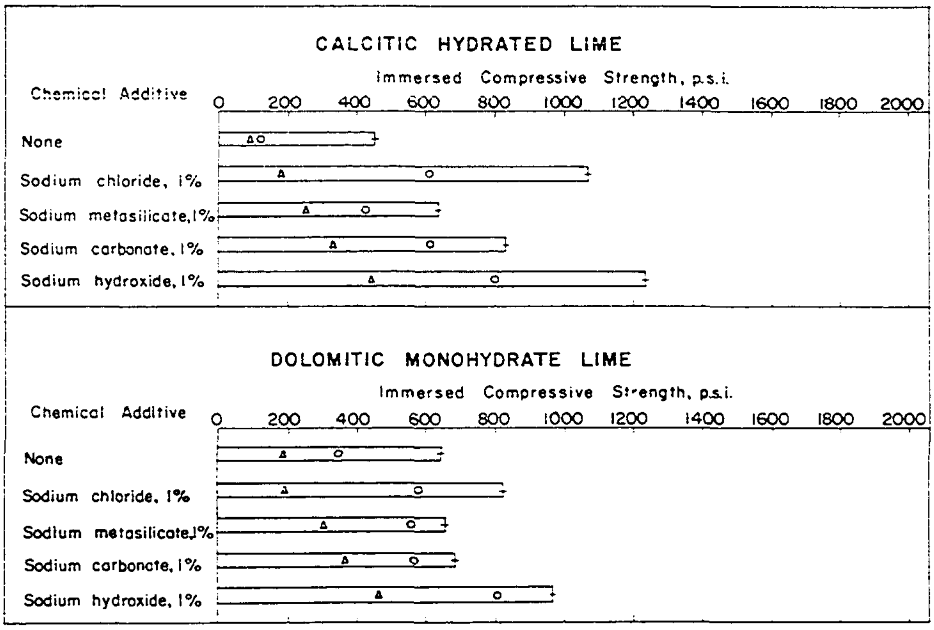
Figure 44. Effect of 1.0 percent chemical additive on strength of a 76.5:6:17.5 mixture of friable loess, lime, and fly ash No. 1.

Figure 45. Effect of 1.0 percent chemical additive on strength of a 76.5:6:17.5 mixture of friable loess, lime, and fly ash No. 2.

Mixture Proportions

76.5 % friable loess
6.0 % lime
17.5 % fly ash No.1

△ 7 day curing
○ 28 day curing
+ 90 day curing



Mixture Proportions

76.5 % friable loess
6.0 % lime
17.5 % fly ash No.2

△ 7 day curing
○ 28 day curing
+ 90 day curing

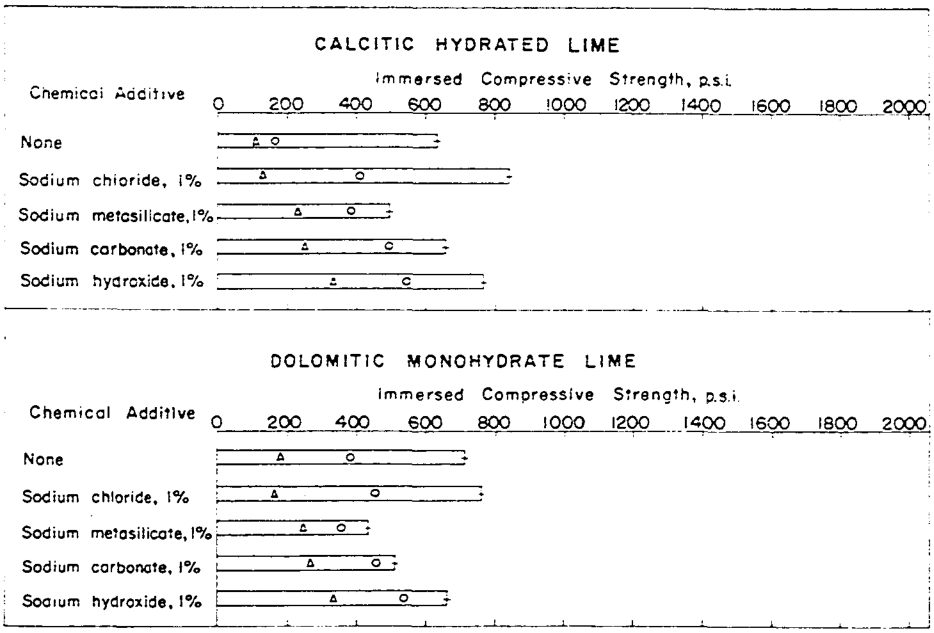
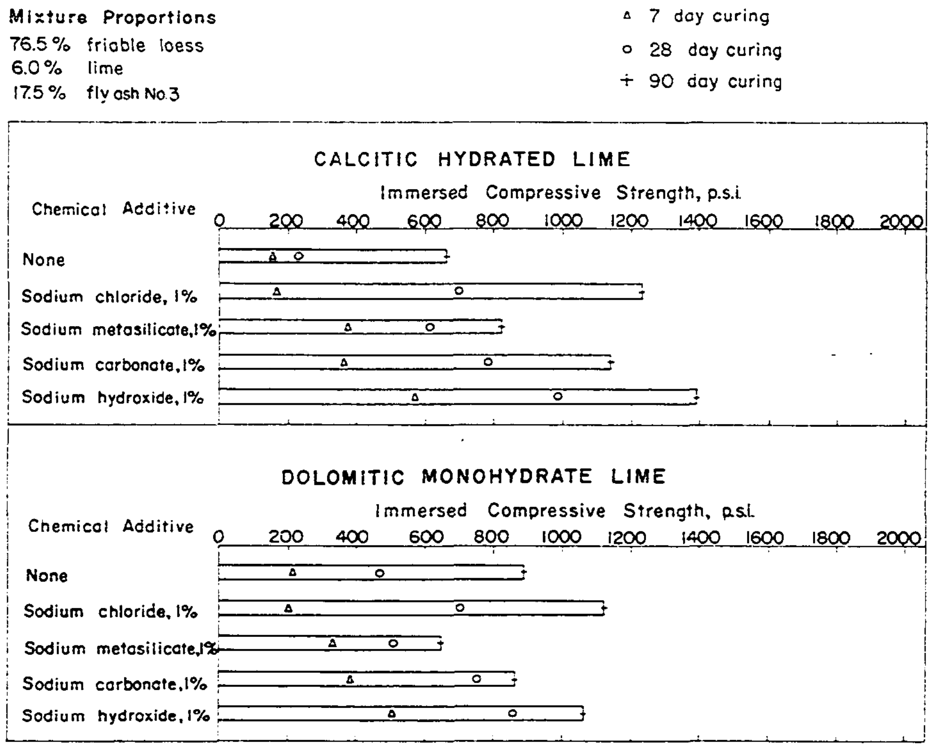


Figure 46. Effect of 1.0 percent chemical additive on strength of a 76.5:6:17.5 mixture of friable loess, lime, and fly ash No. 3.


Mixture Proportions
76.5 % friable loess
6.0 % lime
17.5 % fly ash No.3
△ 7 day curing
○ 28 day curing
+ 90 day curing
CALCITIC HYDRATED LIME
Immersed Compressive Strength, p.s.i.
Chemical Additive
0 200 400 600 800 1000 1200 1400 1600 1800 2000
None
Sodium chloride, 1%
Sodium metasilicate, 1%
Sodium carbonate, 1%
Sodium hydroxide, 1%
DOLOMITIC MONOHYDRATE LIME
Immersed Compressive Strength, p.s.i.
Chemical Additive
0 200 400 600 800 1000 1200 1400 1600 1800 2000
None
Sodium chloride, 1%
Sodium metasilicate, 1%
Sodium carbonate, 1%
Sodium hydroxide, 1%

lime and fly ash No. 1 or No. 3 could be recommended. The strengths produced by the addition of these chemicals in mixtures containing calcitic hydrated lime surpassed that of the similarly proportioned mixtures containing dolomitic monohydrate lime, with or without chemicals.

Alluvial clay and gumbotil

The effect of chemical additives on these clayey soils stabilized with lime and fly ash was nil and sometimes detrimental; consequently the results are not graphed. Specimens treated with sodium carbonate, sodium hydroxide or sodium metasilicate and cured for 90 days were so weakened during the 24 hour immersion period that strength testing was impossible, or strengths were much lower than the strengths of specimens made without treatment or with sodium chloride as the additive. Sodium carbonate, sodium hydroxide and sodium metasilicate are therefore not recommended for use as additives to montmorillonitic clay soils stabilized with lime and fly ash. Sodium chloride was neither harmful nor beneficial; so there appears no reason to use it as an additive.

Sodium carbonate

This chemical was very effective in the improvement of 7 and 28 day strengths of sandy soil, lime, and fly ash mixtures, regardless of the kind of hydrated lime used.

Ninety day strengths were also benefited, but to a lesser extent. Sodium carbonate also improved the early strength of friable loess, lime, and fly ash mixtures containing calcitic hydrated lime, but it did not improve the early strength of mixtures containing dolomitic monohydrate lime.

Owing to its relatively low cost, sodium carbonate in amounts of 0.5 to 1.0 percent is a most promising additive for sandy soils stabilized with lime and fly ash.

Neither sodium carbonate, nor sodium hydroxide or sodium metasilicate, are recommended as additives to montmorillonitic clay soil, lime, and fly ash mixtures because they reduce the long-term immersed strength, and do not affect early strength.

Sodium hydroxide

This chemical greatly improved the strength of sand and friable loess stabilized with hydrated lime and fly ash. The overall effectiveness was greater with calcitic hydrated lime than with dolomitic monohydrate lime. As an example of the strength increases possible, dune sand stabilized with calcitic hydrated lime and fly ash No. 1 showed the following strength improvements by the addition of 1.0 percent of sodium hydroxide:

Curing period	Untreated mixture	Treated with 1.0% NaOh	Increase
7 days	42 psi	443 psi	10.5 times
28 days	74 psi	1,291 psi	17.4 times
90 days	241 psi	1,493 psi	6.2 times

Its use is therefore recommended with these types of soils.

Sodium chloride

This chemical used as an additive increased the 90 day strength of dune sand, lime, and fly ash mixtures, in some to a considerable extent. Seven day strength was slightly reduced, and 28 day strength was sometimes greatly improved and sometimes was reduced. All 90 day strengths were increased by the addition of sodium chloride. The same trends were observed in mixtures with friable loess as a soil. Thus sodium chloride may be a promising additive to friable soils stabilized with lime and fly ash when long-term strengths are desired. The strength of montmorillonitic clay soil, lime, and fly ash mixtures was not affected by adding sodium chloride.

Sodium metasilicate

Sodium metasilicate in the amount of 1.0 percent increased the strength of the dune sand, lime, and fly ash mixtures. It can also improve friable loess, lime, and fly ash mixtures containing some fly ashes. For the percentage used, this chemical rates lower than sodium carbonate or sodium hydroxide. Greater amounts are suspected to improve greatly the strength of friable soils; they were not tried here for economic reasons.

Calcitic hydrated and dolomitic monohydrate limes

The dolomitic monohydrate lime used produced better strengths than the calcitic hydrated lime when the mixtures were not treated with chemicals. However, the calcitic lime mixture responded better to chemical treatments.

Effects of Additives at Low Curing Temperatures

The strengths obtained with lime and fly ash mixtures depend greatly on curing temperatures. When soils are stabilized with lime and fly ash in the late part of the summer in temperate climates, they may not develop sufficient strength to withstand the imposed stresses of the colder seasons. This may lead to failure of the pavement.

The effect of chemical additives at low temperatures was investigated. Dune sand and fly ash No. 1 were used with both calcitic hydrated and dolomitic monohydrate limes. The curing temperature was 43 ± 1 °F. Results for 7 and 28 day strengths are given in Figure 47.

Calcitic lime

The mixture of dune sand, calcitic hydrated lime and fly ash No. 1 without additive, cured for 7 days, failed during the period of immersion in water. The same happened with the mixture with 1.0 percent sodium chloride as additive. Additions of 1.0 percent sodium metasilicate, sodium carbonate or sodium hydroxide, however, gave strengths of about 100 psi.

After 28 days curing, the mixture without additive showed some immersed strength, 41 psi. This strength was increased five or sixfold by additions of 1.0 percent sodium metasilicate, sodium carbonate or sodium hydroxide. Sodium chloride produced a slight strength improvement.

Dolomitic lime

The untreated dune sand, dolomitic lime, and fly ash mixture did not show any immersed strength after 7 days curing. Additions of 1.0 percent sodium metasilicate gave a strength of 107 psi; 1.0 percent sodium carbonate gave 57 psi; and 1.0 percent sodium hydroxide gave 76 psi. Sodium chloride was not beneficial.

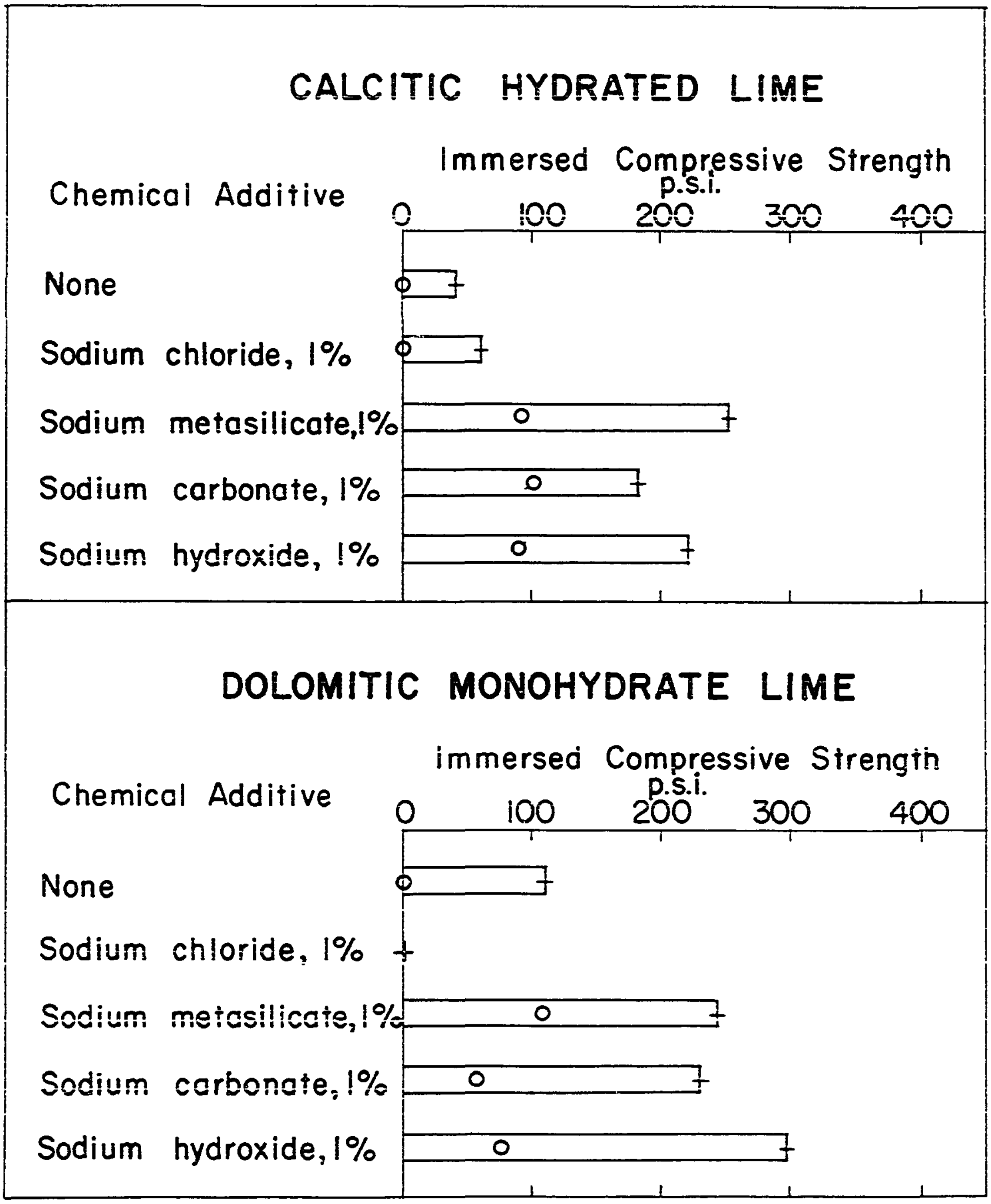
After 28 days, the untreated mixture had a strength of 111 psi. Additions of 1.0 percent sodium metasilicate or sodium carbonate more than doubled the strength. One percent sodium hydroxide increased the strength almost three times, to 298 psi. Specimens with sodium chloride did not show any immersed strength.

Figure 47. Effect of 1.0 percent chemical additives on strength of a 76.5:6:17.5 mixture of dune sand, lime, and fly ash No. 1 cured at a temperature of 43°F.

Mixture Proportions

76.5 % dune sand
6.0 % lime
17.5 % fly ash No.1

o 7 day curing
+ 28 day curing



Discussion

The beneficial effects of some additives to the lime-fly ash pozzolanic reaction are very important when low temperatures are expected during the curing period. Addition of promising chemicals may lengthen the working season for stabilization of soils with lime and fly ash.

The strengths obtained with dune sand, lime, and fly ash No. 1 mixtures cured at 43 ± 1 °F may be from 200 to 300 psi by the addition of a small amount of sodium metasilicate, sodium carbonate or sodium hydroxide. Those strengths may be sufficient in a base course to withstand the adverse effects of traffic and lower winter temperatures. Untreated sand, lime, and fly ash No. 1 mixtures after 28 days curing showed strengths of 100 psi or less, which are insuffient for a base course. The same beneficial effects may be expected with other fly ashes. Sand, lime, and fly ash mixtures made with either calcitic hydrated or dolomitic monohydrate lime increased in strength by the addition of sodium metasilicate, sodium carbonate or sodium hydroxide, but the data obtained herein were not sufficient to indicate which lime is more beneficial.

The chemical additives, as salts, also assist by lowering the freezing point of the free water in stabilized soil mixtures. By depressing the temperature at which the free soil water freezes, more time is allowed to gain strength; and the stabilized soil is exposed for shorter periods to the damaging effects caused by ice formation.

Mechanism of Chemical Additives in Lime, and Fly Ash Mixtures

A complete evaluation of the mechanism of the effects of chemical additives in lime and fly ash mixtures must involve extensive chemical analysis. Based on the strength data and on the assumption that strength is indicative of the extent of the pozzolanic reaction, an explanation of the mechanism is given herein.

The effects of chemical additives on lime and fly ash may be due to one or more of the three following:

1. Speeding up of the pozzolanic reaction;
2. Production of secondary cementitious products; and
3. Combination with the primary, or pozzolanic, cementitious products.

The first should probably be of a catalitic nature. It may show up particularly in the curve for 7 day strength versus additive content, with a sharp increase in strength for small amounts of chemical added.

In the second, the chemicals combine or react with lime to form cementitious products like $CaCO_3$, $Ca(PO_4)_2$, $Al(OH)_3$, etc.

In the third are included those chemicals that may combine or react with the pozzolanic cement produced, with the pozzolanic materials in fly ash or with the soil. This combination or reaction may be a complex one producing better cementitious materials or speeding up the reaction or be a reaction that activates some of the materials, increasing their pozzolanic value.

For a separate evaluation of the different chemicals, they may be grouped on the basis of their reactions - basic, neutral or acidic. Bases and basic salts, also known as alkalies and alkaline salts, produce hydroxyl ions in water solution to varying extents. Acid salts produce hydrogen ions in water solutions to varying extents. Neutral salts in water solution do not upset the natural balance of hydrogen and hydroxyl ions. Another group is formed with phosphoric acid, and magnesium oxide is in a miscellaneous group.

This evaluation is made based on the results obtained with mixtures with Ottawa sand as a soil in this and in a previous investigation (18,50). The characteristics of this sand make it, supposedly, an inert material in the lime-fly ash or lime-fly ash-chemical reactions.

Bases and basic salts

Alkaline additives increase the amount of available hydroxyl ions in the moistened Ottawa sand-lime-fly ash system. As a result the pozzolanic reaction may be accelerated by the increased solubility of the siliceous material caused by the alkalinity (30).

The base, sodium hydroxide, acts as a catalyst supposedly in the following way:

a) It first reacts with the siliceous material to produce intermediate sodium silicates;

b) The over-all reaction goes to completion when the intermediate sodium silicates subsequently react with lime (calcium hydroxide) to form sodium hydroxide and cementitious insoluble calcium silicates;

c) The sodium hydroxide is then free for further reaction with unreacted siliceous material.

In the alkaline salts, sodium carbonate very likely reacts with lime in the moist Ottawa sand, lime, and fly ash mixture to form calcium carbonate and sodium hydroxide in the following way,

$$Na_2CO_3 + Ca(OH)_2 \longrightarrow CaCO_3 + 2NaOH$$

The precipitated calcium carbonate contributes cementation to the system, and, as hypothesized in the preceeding paragraph, the sodium hydroxide acts as a catalyst.

The other alkaline salts used, sodium phosphate, sodium metasilicate and lithium carbonate, may act similarly to sodium carbonate. Sodium phosphate reacts with lime to form calcium phosphate, which may be cementitious, and sodium hydroxide, which acts as a catalyst. Sodium metasilicate forms highly cementitious calcium silicates with lime and releases also sodium hydroxide. Lithium carbonate reacts with lime and precipitates calcium carbonate releasing lithium hydroxide, an alkali that produces the same catalitic effects as sodium hydroxide in the lime-fly ash reaction.

Acid salts

Acid salts undergo a hydrolysis reaction with the precipitation of weak bases (hydroxides). With calcium hydroxide (lime) and aluminum chloride this reaction proceeds as follows:

$$2AlCl_3 + 3Ca(OH)_2 \longrightarrow 2Al(OH)_3 + 3CaCl_2$$

The weak base formed, $Al(OH)_3$, has some cementing properties that may be beneficial. The clacium chloride formed may also benefit through complex effects of the third category.

With calcium chloride, the principal long-term strength benefits obtained are thought due to a different type of chemical mechanism than discussed above, and that are included in the third category of effects. Calcium chloride being highly hygroscopic and deliquescent ensures a relatively high concentration of calcium ions over a long period of time by providing moisture for a solution. Since lime has a low solubility and a lower ionization constant than calcium chloride, the concentration of calcium ions from lime is lower than that from calcium chloride.

The other acid salt used, manganese chloride, probably produces effects analogous to those of calcium chloride.

Neutral salts

Sodium chloride, although a neutral salt, may act as does calcium chloride; but it gives less benefit to long-term strength, perhaps because sodium chloride is less hygroscopic and deliquescent than calcium chloride.

The mechanism of the action of potassium permanganate in lime and fly ash mixtures is also included in the third category. Potassium permanganate, a strong oxidizing agent, may oxidize the carbon in the fly ash with subsequent production of potassium carbonate and the precipitation of manganese dioxide. The potassium carbonate formed may then give rise to further reactions, of the first and second category, similar to those of sodium carbonate, previously discussed, which are beneficial to strength. Potassium permanganate may also clean the surface of fly ash by oxidation of possible organic matter. This may make the fly ash more reactive with lime.

Acid

Very small amounts of phosphoric acid somewhat improved the strength. This may be brought about by the formation of complex calcium phosphates or by the activation of fly ash (1,25). Increased amounts of acid caused a decrease in strength, due to the neutralization caused by the acid which reduced the alkalinity and subsequently the silica release.

Miscellaneous chemical

Magnesium oxide is supposed to react with lime and fly ash producing effects of the third category. It may enter into the pozzolanic reaction and form complex silicates of calcium and magnesium. The effectiveness of magnesium oxide, a component of dolomitic monohydrate lime, in calcium hydroxide and fly ash mixtures corresponds with the findings of previous research which indicated that dolomitic monohydrate lime gives better strengths than calcitic hydrated lime in soil, lime and fly ash mixtures cured at ambient temperatures.

Chemical additives in soil, lime, and fly ash mixtures

Four chemicals were evaluated with soils; sodium carbonate, sodium hydroxide, sodium metasilicate and sodium chloride. The greater benefits were obtained with the sandy soil; and the benefits decreased with the increase in the amount of clay in the soil.

With the available data it is difficult to evaluate the influence of the soil factor in soil, lime, fly ash, and chemical mixtures. The chemical additives used were beneficial in mixtures with friable soils and detrimental in mixtures with montmorillonitic clay soils. The decrease in strength in the clayey soils is likely brought about by the excess of sodium ions and high alkalinity in the pore fluid of the soil, lime and fly ash mixtures. Both factors introduce disruptive forces in the clay structures that are not overcome by the cementitious bond of the pozzolanic reaction.

Modification of Fly Ashes

The processing of fly ash to broaden its use or to improve its qualities has not been extensively tried. In the manufacture of lightweight aggregate, a fly ash is sintered by a process developed at the Building Research Station, Garston, England (61,5). By the sintering process spherical particles 1/8 to 1/2 inch in size are made. This is carried out at a temperature sufficient to cause the particles to adhere but not to fuse. The spherical uncompacted pellets produced contain about 40 percent voids with a density of about 42 pcf.

Some work is now being done on the modification of fly ash by grinding*. The results of this work show that it is possible to improve some of the properties of a fly ash, such as specific surface and specific gravity, strength of

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* Walter N. Handy, Inc. P.O. Box 549, Evanston, Illinois. Information on screening and pulverization of fly ashes. Private communication. September 8, 1960.

mortars with lime, etc.

The reaction between lime and fly ash is apparently a surface reaction, as the reactivity of a fly ash with lime is closely related to fineness and specific surface. It was supposed that by grinding or by scalping the coarse fraction, a fly ash might be improved for its use in soil stabilization. Consequently two low quality fly ashes, Nos. 2 and 4, were selected to be processed and used with dune sand and calcitic hydrated or dolomitic monohydrate lime.

The proportions used were 76.5 percent dune sand, 6 percent lime and 17.5 percent fly ash. The mixtures were run at several water contents and the maximum results are recorded (Tables 21 and 22).

Table 21. Comparative results obtained by the modification of the fly ash of a 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 2

Process of fly ash	Maximum dry density, pcf	Maximum immersed unconfined compressive strength, psi		
		7 day	28 day	90 day
As it is (unprocessed)	112	0	158	554
Ground to pass the #270 sieve	116	0	203	631
Discarded coarser than #270 sieve	118	0	175	633

Table 22. Comparative results obtained by the modification of the fly ash of a 76.5:6:17.5 mixture of dune sand, dolomitic monohydrate lime, and fly ash No. 4

Process of fly ash	Maximum dry density, pcf	Maximum immersed unconfined compressive strength, psi		
		7 day	28 day	90 day
As it is (unprocessed)	105	91	309	650
Ground to pass the #200 sieve	110.5	116	408	700
Discarded coarser than #200 sieve	126.5	103	506	892

Fly ash No. 2

This fly ash, with a 7.2 percent carbon content, was selected because it did not show any strength after 7 days curing for any combination of sand, lime and fly ash. The results show that neither grinding it to pass a #270 sieve nor the use of only the fraction passing the #270 sieve gave any improvements in 7 day strengths. For 28 and 90 days curing periods, the mixtures with the processed fly ash showed an increase in strength over the unprocessed, but this increase does not warrant the cost of processing this fly ash.

Fly ash No. 4

This fly ash was chosen because it has a very high content of carbon, 18.6 percent. A different lime, dolomitic monohydrate, was used with this fly ash, and the #200 was used as a selector sieve instead of the #270.

By grinding the coarse part to pass the #200 sieve there is a slight increase in strength. Discarding the material retained in the #200 sieve, the strength is increased 64 percent after 28 days curing and 40 percent after 90 days. The processing of this high-carbon fly ash may then be economical.

Discussion

The density of sand, lime, and fly ash mixtures increased greatly when the fly ash was modified by grinding or by scalping the coarse fraction. This increase in density is caused by an improvement in the gradation of the fly ash or by breaking down hollow spheres present in any fly ash. An increase in strength is brought about by the increase in density and through a closer contact and/or more contact points between the lime and fly ash. Using a finer fly ash there will be more surface area available for the pozzolanic reaction to take place, which also brings an increase in strength. It is apparent that the increase in strength was partly a contribution of the higher densities and of the greater surface area of the modified fly ashes.

A fly ash of high carbon content may be beneficially processed by sieving. The coarse material will contain most of the carbon, which is not reactive with lime and can be reused as a fuel. The fine material will be more reactive with lime and be used in soil stabilization or as a pozzolan in concrete.

The above tests show an opening to improve the quality of fly ashes by grinding and/or sieving, which will broaden their use as a construction material.

Lime Stabilization

It has been found in this investigation that the lime stabilization of some soils may sometimes not be appreciably benefited by the addition of fly ash. To obtain data to evaluate the use of lime or lime and fly ash, an extensive study of lime stabilization was made. Maximum strength up to 90 days were recorded, and up to 25 percent of lime was used. (Tables 23 to 26, and Figures 48 to 50).

Presentation and discussion of results

Dune sand. Though sandy soils do not benefit by the addition of small amounts of lime, it was suspected that large percentages of lime might impart some strength. Therefore quantities of lime up to 25 percent were studied in mixtures with dune sand. The test results are given in Table 23.

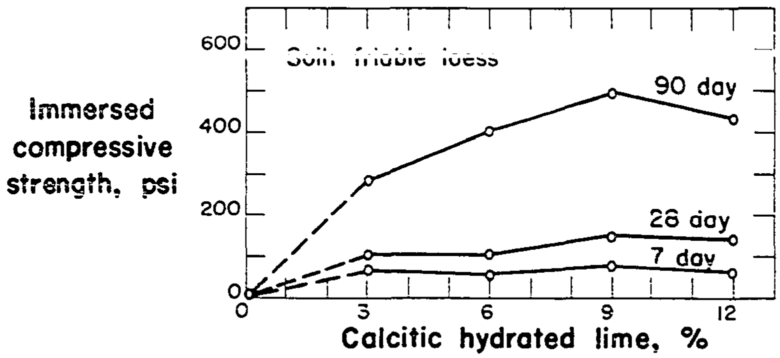
The large quantities of lime strengthened the dune sand; for instance a mixture of 25 percent dolomitic monohydrate lime and 75 percent sand, had 7 and 28 day strengths of 112 and 215 psi respectively. But the additions of such a great amount of lime is not economical. It was also observed that dolomitic monohydrate lime produced much higher strengths than calcitic hydrated lime. The strengths obtained with lime may be greatly increased by the addition of a fly ash.

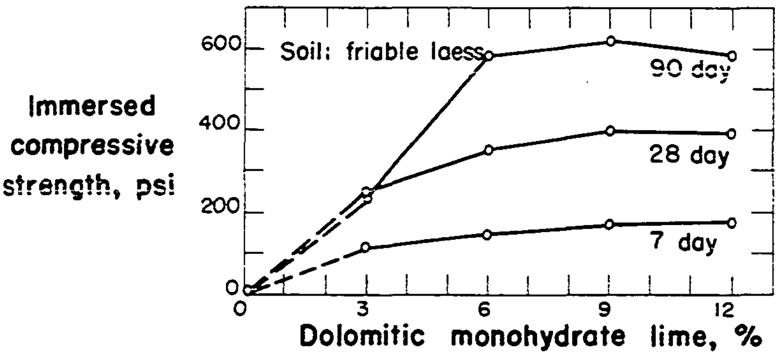
The added strength obtained by the addition of lime to sandy soils probably comes mainly from carbonation of the lime. But part of the strength may have been caused by the formation of calcium silicates, although this is not likely to have occurred at the curing temperatures used in this research.

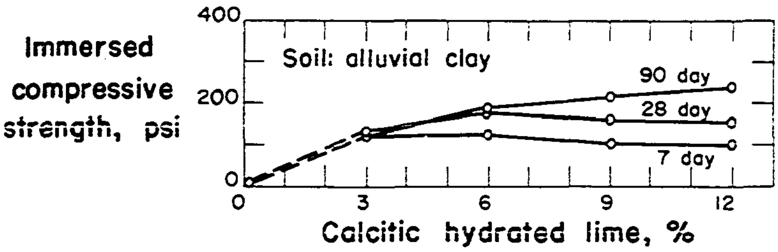
<u>Friable loess</u>. This soil shows a great pozzolanic activity with lime. It has been pointed out in another section, that based on 7 and 28 day curing periods the addition of some fly ashes actually diminishes the strength obtained with this soil and lime only, but the pozzolanic action between loess and lime continues and is important beyond 28 days (Figure 48). Very small amounts of lime are needed to develop the full strength that may be obtained by addition of lime. Six percent of dolomitic monohydrate lime

Figure 48. Strengths obtained by additions of different amounts and kinds of lime to friable loess.

Figure 49. Strengths obtained by additions of different amounts and kinds of lime to alluvial clay.


Immersed compressive strength, psi
600
400
200
0
Soil: friable loess
90 day
28 day
7 day
0
3
6
9
12
Calcitic hydrated lime, %


Immersed compressive strength, psi
600
400
200
0
Soil: friable laess
90 day
28 day
7 day
0
3
6
9
12
Dolomitic monohydrate lime, %


Immersed compressive strength, psi
400
200
0
Soil: alluvial clay
90 day
28 day
7 day
0
3
6
9
12
Calcitic hydrated lime, %

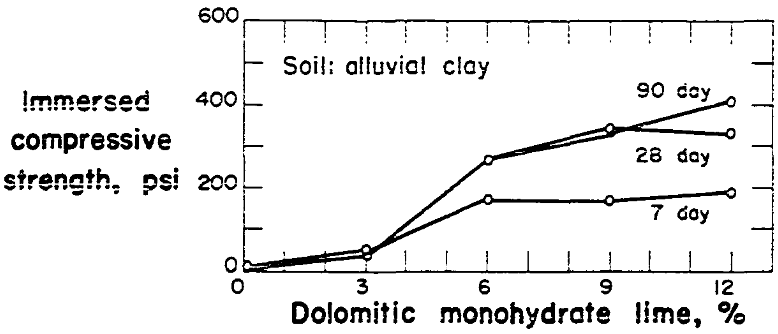

Immersed compressive strength, psi
600
400
200
0
Soil: alluvial clay
90 day
28 day
7 day
0
3
6
9
12
Dolomitic monohydrate lime, %

Figure 50. Strengths obtained by additions of different amounts and kinds of lime to gumbotil.

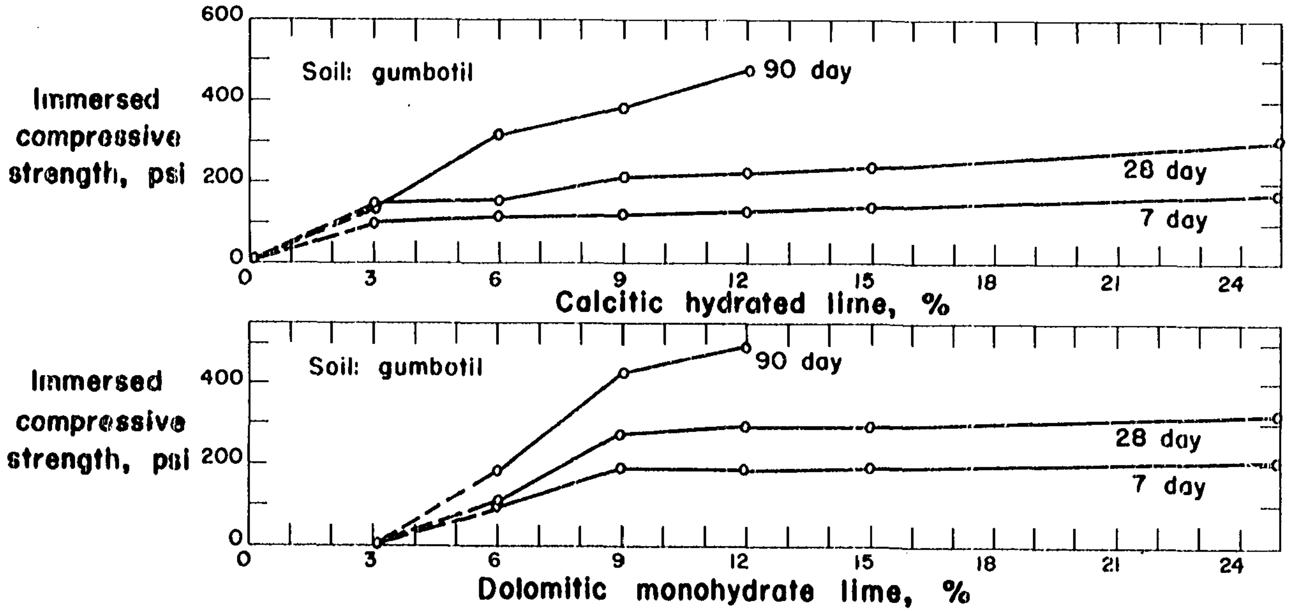

Soil: gumbotil
Immersed compressive strength, psi
600
400
200
0
0
3
6
9
12
15
18
21
24
90 day
28 day
7 day
Calcitic hydrated lime, %
Soil: gumbotil
Immersed compressive strength, psi
400
200
0
90 day
28 day
7 day
Dolomitic monohydrate lime, %

Table 23. Strengths of dune sand stabilized with lime

Lime Kind	%	Molding dry density, pcf	Immersed unconfined compressive strength, psi 7 day	28 day	90 day
Calcitic hydrated	3	110	0	11	11
"	6	113	0	11	12
"	9	117	8	25	31
"	12	119	19	30	42
"	15	120.5	30	51	ND*
"	25	112	64	73	ND
Dolomitic monohydrate	3	110	0	11	14
"	6	113	0	15	31
"	9	116.5	21	29	57
"	12	119	32	51	93
"	15	120.5	53	120	ND
"	25	120.0	112	215	ND

* Not determined.

Table 24. Strengths of friable loess stabilized with lime

Lime Kind	%	Molding dry density, pcf	Immersed unconfined compressive strength, psi 7 day	28 day	90 day
Calcitic hydrated	3	99.9	72	110	287
"	6	99.0	59	105	403
"	9	99.0	78	158	499
"	12	97.7	64	144	435
Dolomitic monohydrate	3	100.9	117	249	234
"	6	100.8	151	354	584
"	9	100.6	174	400	621
"	12	100.5	182	369	588

appears to be the best amount; use of greater percentages do not appear warranted.

Friable loess should not be stabilized with lime and fly ash, unless a very good quality fly ash is cheaply available. Six percent dolomitic monohydrate lime gave strengths of 150, 354 and 584 psi for 7, 28 and 90 days curing respectively. These strengths were actually lowered by the addition of a medium or low quality fly ash.

Gumbotil. In the experiments with gumbotil, lime was added in amounts up to 25 percent (Figure 50). In every curing period a percentage of lime was found above which there was no appreciable increase in strength. This "breaking" percentage tends to be higher for the longer curing periods. (This was also observed in the results with alluvial clay.)

At least 9 percent of either dolomitic or calcitic lime is recommended. With dolomitic lime, 200 and 300 psi may be obtained after 7 and 28 days curing respectively. These figures are rather low and may be increased by the addition of fly ash, or by substituting some lime for fly ash. Lime and fly ash may compete economically and strength-wise with the minimum amount of lime required.

Table 25. Strengths of gumbotil stabilized with lime

Lime Kind	%	Molding dry density, pcf	Immersed unconfined compressive Strength, psi 7 day	28 day	90 day
Calcitic					
hydrated	3	93.5	100	145	97
"	6	89.5	116	155	317
"	9	87.1	125	215	386
"	12	87.1	132	228	478
"	15	87.0	141	240	ND*
"	25	86.4	173	307	ND
Dolomitic					
monohydrate	3	93.8	0	0	0
"	6	92.5	89	104	188
"	9	92.3	191	274	429
"	12	92.3	190	298	495
"	15	89.8	197	296	ND
"	25	86.2	211	326	ND

* Not determined.

Alluvial clay. The strengths obtained with alluvial clay stabilized with lime were relatively low (Figure 49). The desirable value of 300 psi after 28 days curing may be obtained with 9 percent dolomitic lime, but for this amount the strength is not improved beyond 28 days. The extension of the curing period from 28 to 90 days shows that amounts of 9 percent or greater of calcitic hydrated lime and 12 percent or greater of dolomitic monohydrate lime are needed for the pozzolanic reaction to continue beyond 28 days.

A recommended amount of lime is 12 percent, but the strengths obtained with this amount may also be obtained with an economically competitive lime and fly ash admixture.

Discussion

These researches change the concept that in lime stabilization a small amount of lime added to soil is sufficient to obtain the maximum benefits of lime. It is possible that this concept was the result of a testing program limited in time. Observation of 7 and 28 day strengths may lead to that erroneous concept (Figures 48 to 50). But when curing periods were continued up to 90 days, the strength gain with time was found to be influenced by the amount of lime. For instance with friable loess (Figure 48) it might be concluded, based on 7 and 28 day strengths, that 3 percent lime is the best amount to stabilize this soil; higher amounts do not particularly add to strength. But a study of 90 day strengths shows that 6 percent should be the recommended amount of lime to stabilize the soil. Therefore the amount of lime needed to stabilize a soil should be determined on the basis of short as well as long curing periods. If it is desirable to obtain a high long-term strength, the highest economically possible amount of lime should be used.

It was also found (Figures 48 to 50) that calcitic hydrated lime was more effective than dolomitic monohydrate lime in low amounts of lime, of around 3 percent. Dolomitic monohydrate lime was more effective than calcitic hydrated in amounts of lime of 6 percent or higher. Consequently when small amounts of lime are used, the calcitic hydrated type should be favored. For high amounts, dolomitic monohydrate lime should be used.

Discussion of Moisture-Density Curves of Clayey Soils Treated With Lime

It has been observed that the moisture-density curves for gumbotil and alluvial clay treated with lime and fly ash had a peculiar shape (Figures 5,6,7 and 9). There was not a distinctive maximum density; it being undefined in many instances. Fly ash was found not to be the cause of this.

The shape of the curves of moisture-density relationships of a friable loess-lime mixture follow the concept of a maximum density at an optimum moisture content (Figure 51). This soil, friable loess, has a relatively low amount of clay, 17 percent. But for mixtures of gumbotil and lime or alluvial clay and lime there is not a defined maximum density for an optimum moisture content, and the drier the mixtures the greater the dry density obtained (Figures 52,53).

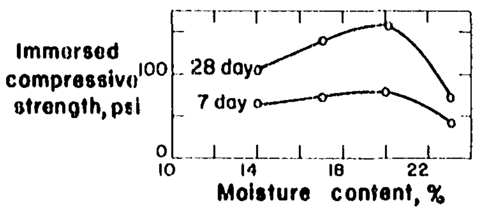
Both gumbotil and alluvial clay have a very high content about 70 percent, of montmorillonitic clay. It was suspected that high amounts of clay, at least of the montmorillonitic type, were the cause of the poorly defined shape of moisture-density curves.

To find if the soil without lime had the same shape of moisture-density curves, some comparative tests were made. For instance in Figure 54 are plotted moisture-density curves for alluvial clay with and without lime, compacted with the same compactive effort modified Proctor in this case only. A very wide range of moisture contents was used in these tests. The curve for straight soil shows a continuous increase in density, as the water content increases, up to a maximum density; higher amounts of water will then decrease the density. The curve for the soil-lime mixture shows a small increase in density with increase in water content for very low amounts of moisture; from then on, the density decreases with the increase in water content, slightly initiating a hump close to the point at which, theoretically, should be the maximum density. The addition of lime to soils of high content of montmorillonitic clay distorted the shape of moisture-density curves.

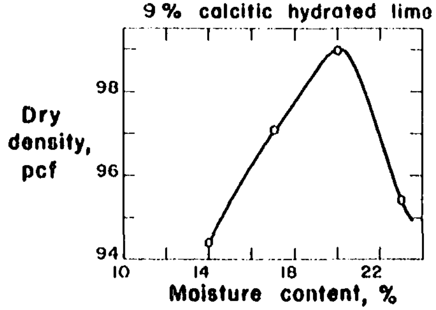
The moisture-density curves for montmorillonitic clay soils stabilized with lime are probably affected by the flocculating effects of lime. The lime alters the character-

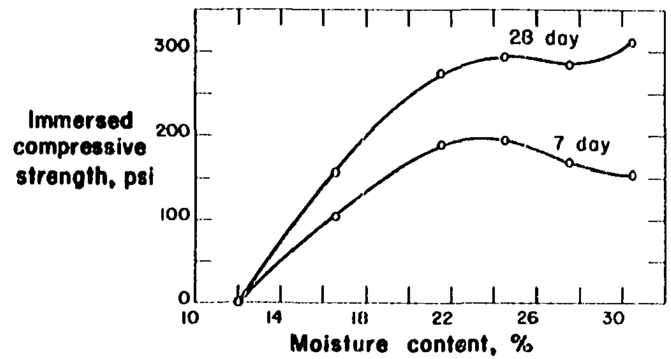
Figure 51. Moisture-density and moisture-strength relationships of a mixture of 91 percent friable loess and 9 percent calcitic hydrated lime, compacted at standard Proctor compactive effort.

Figure 52. Moisture-density and moisture-strength relationships of a mixture of 85 percent gumbotil and 15 percent dolomitic monohydrate lime, compacted at standard Proctor compactive effort.



Mixture proportions
91 % friable loess
9 % calcitic hydrated lime





Mixture proportions
85 % gumbotil
15 % dolomitic monohydrate lime

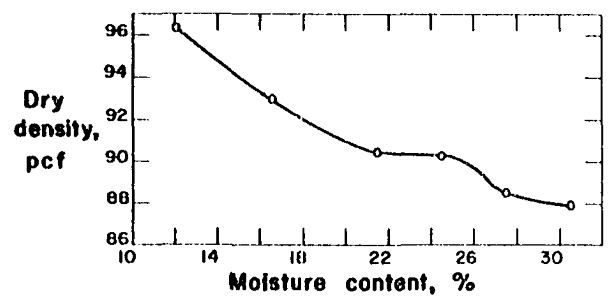
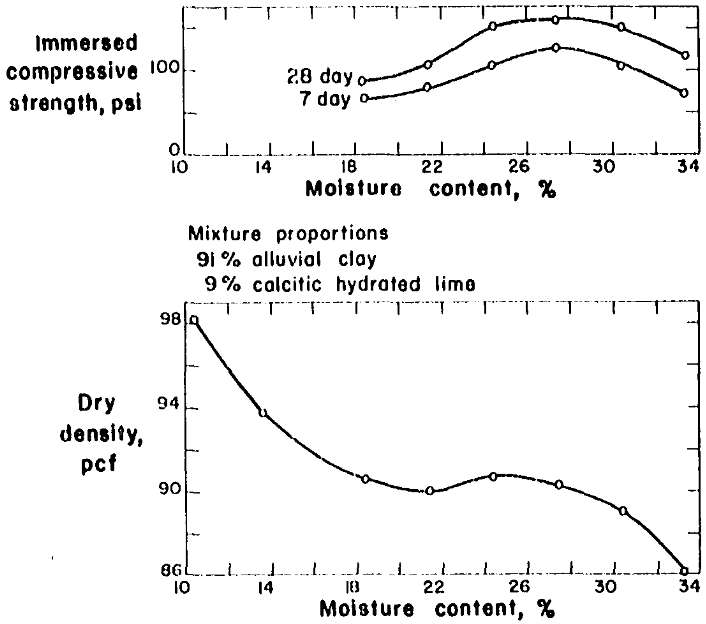
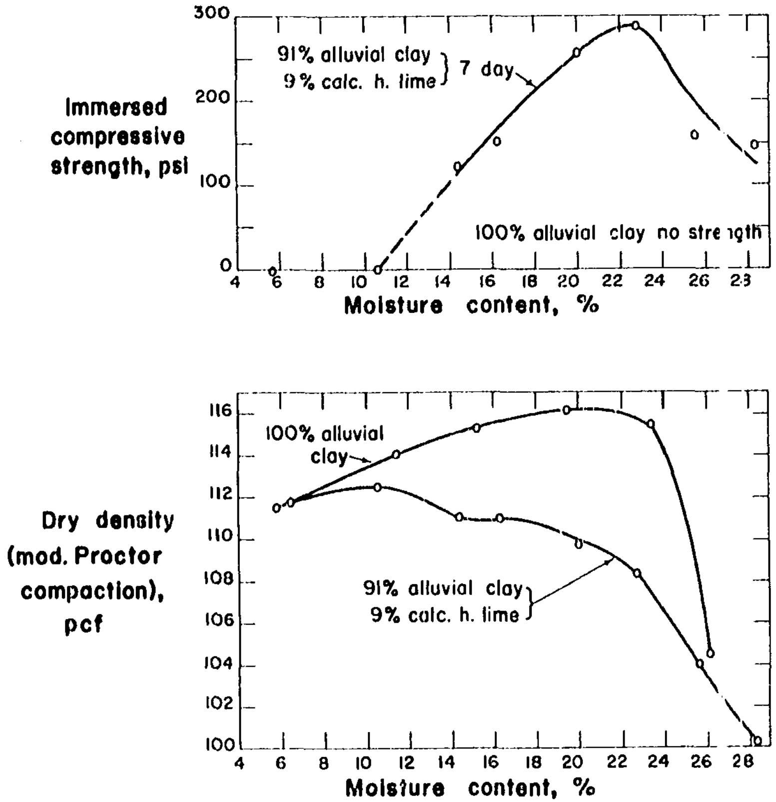


Figure 53. Moisture-density and moisture-strength relationships of a mixture of 91 percent alluvial clay and 9 percent calcitic hydrated lime, compacted at standard Proctor compactive effort.

Figure 54. Moisture-density and moisture-strength relationships of a mixture of 91 percent alluvial clay and 9 percent dolomitic monohydrate lime, compacted at modified Proctor compactive effort.


Immersed compressive strength, psi
28 day
7 day
Moisture content, %
Mixture proportions
91 % alluvial clay
9 % calcitic hydrated lime
Dry density, pcf
Moisture content, %


Immersed compressive strength, psi
91% alluvial clay
9% calc. h. lime
7 day
100% alluvial clay no strength
Moisture content, %
Dry density (mod. Proctor compaction), pcf
100% alluvial clay
91% alluvial clay
9% calc. h. lime
Moisture content, %

istics of clayey soils converting them into a material with the workability of friable soils. At low moisture contents the flocculating effects of lime impart to clayey soils a highly open structure. This facilitates the expulsion of air which becomes more important, in these soils with a void ratio of about 0.35 at the maximum density, to the increase of density than the lubricating effects of water. The free expulsion of air from a mass containing about one third void space can easily have a great influence on the final compacted dry density at low moisture contents.

As seen in Figures 52 through 54, the maximum strength does not occur at a point of maximum density. It is also observed in Figure 52 that for high moisture contents there is an initiation of a second point of maximum strength. This is more clearly seen in the 28 day strength curve. This points out the necessity of reviewing the present concept used in soil stabilization of compaction at the optimum moisture content for maximum dry density. As discussed above, regarding the molding or compaction moisture content of soils stabilized with lime and fly ash, the strength gain or hardening of these mixtures comes from the formation of cementitious products rather than from density. A high moisture content maintains a larger supply of water for the hydration process to proceed at a faster rate and/or for longer periods. It is therefore recommended that in the stabilization of soils with lime or lime and fly ash, the molding or compacting moisture content be chosen on the basis of the maximum strength rather than on the maximum density of the mixture.

Portland Cement Stabilization

An evaluation of lime-fly ash stabilization is not complete without a comparison of its effectiveness with that of cement stabilization. Strength results for several percentages of cement are presented and discussed here. A final comparison of lime-fly ash and cement stabilization will be given further in this paper after evaluating economically competitive mixes and their durability resistance.

Plastic soils to be stabilized with cement should be pre-treated with lime to flocculate the soil particles and thereby facilitate the mixing process. Alluvial clay and gumbotil are soils of high plasticity needing the lime pre-treatment. Consequently alluvial clay was treated with 3 percent lime and gumbotil with 4 percent in addition to cement. Both lime and cement were added together.

The same water content found optimum for soil-lime specimens was used here. The results are given in Table 27 and are presented in Figures 55 to 58.

Presentation and discussion of results

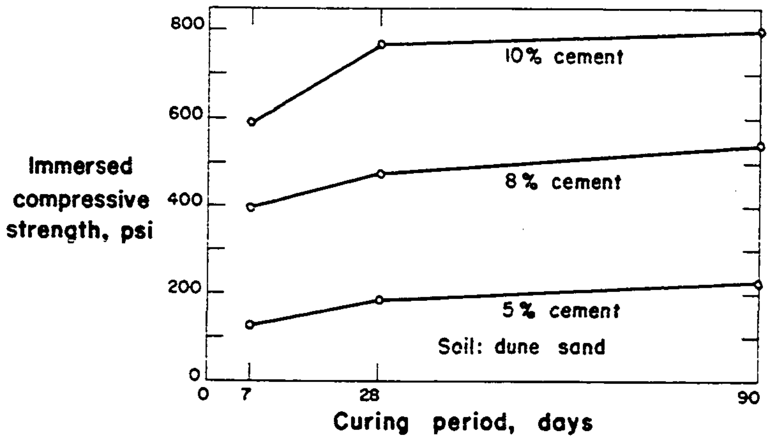
Portland cement in the proper amounts stabilized any of the four soils tested. Good strengths were obtained with at least 8 percent cement in dune sand, 6 percent in loess, 3 percent lime plus 6 percent cement in alluvial clay and 4 percent lime plus 5 percent cement in gumbotil. These mixes gave 7 day strengths over 300 psi.

Most of the final strength was developed in the first seven days. The rate of increase after seven days was not very pronounced, except with the loess. In the length of time needed to develop strength lies an important difference between cement and lime-fly ash stabilization (Compare Figure 55 with Figure 28; Figure 56 with Figure 29; Figure 57 with Figure 30 and Figure 58 with Figure 31). The early strengths for lime-fly ash were low, but the strength steadily increased with time at a fairly good rate. For long curing periods the strengths with lime-fly ash and cement tended to equalize; being in many instances greater for lime-fly ash than for cement-treated soils.

Both calcitic hydrated and dolomitic monohydrate limes were used with gumbotil to compare their effectiveness in the lime treatment to change the plasticity. The results were erratic and do not show consistently better improvements, based on strength, with one or the other lime (Table 27). Further tests should be conducted to compare the

Figure 55. Strength of dune sand cement mixtures.

Figure 56. Strength of friable loess cement mixtures.


800
600
400
200
0
Immersed compressive strength, psi
10% cement
8% cement
5% cement
Soil: dune sand
0
7
28
90
Curing period, days

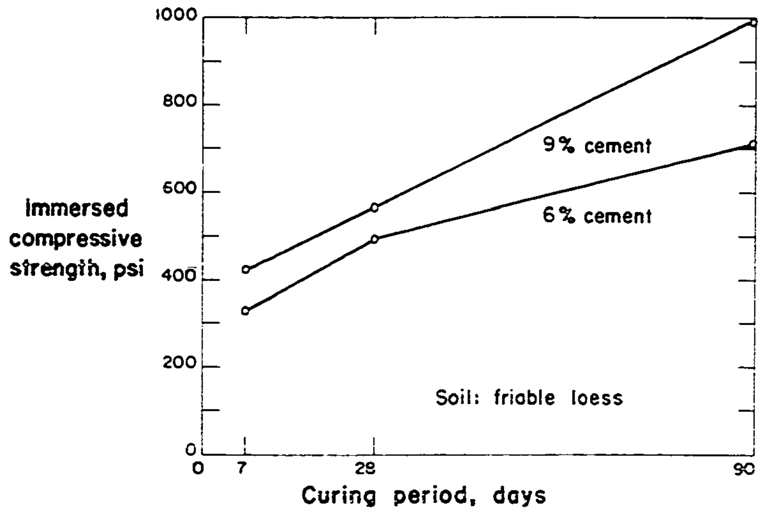
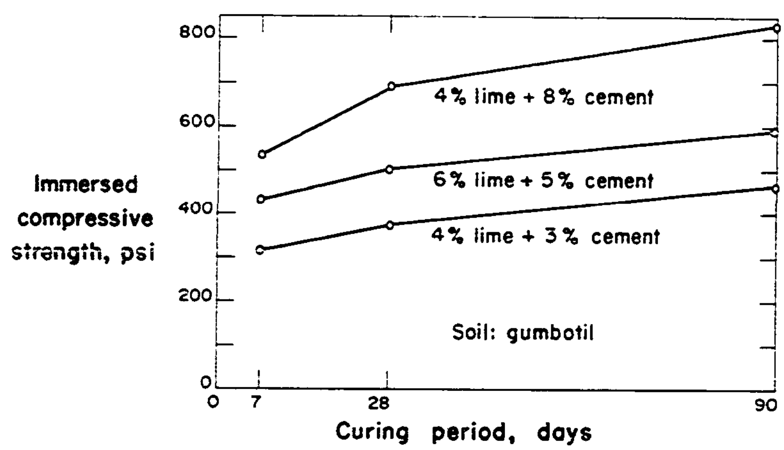

1000
800
600
400
200
0
Immersed compressive strength, psi
9% cement
6% cement
Soil: friable loess
0
7
28
90
Curing period, days

Figure 57. Strength of gumbotil cement mixtures.

Figure 58. Strength of alluvial clay cement mixtures.


800
600
400
200
0
Immersed compressive strength, psi
4% lime + 8% cement
6% lime + 5% cement
4% lime + 3% cement
Soil: gumbotil
0
7
28
90
Curing period, days

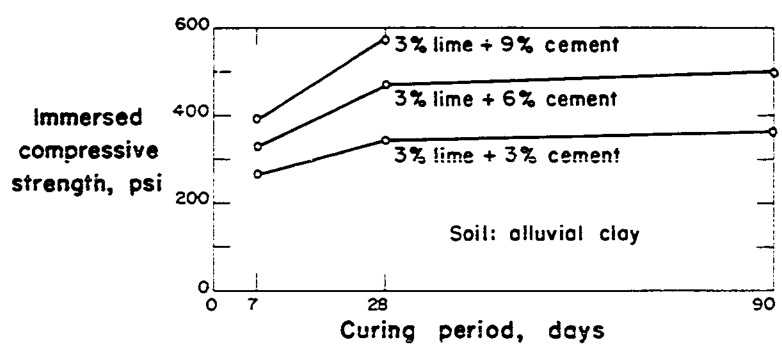

600
400
200
0
Immersed compressive strength, psi
3% lime + 9% cement
3% lime + 6% cement
3% lime + 3% cement
Soil: alluvial clay
0
7
28
90
Curing period, days

Table 26. Strengths of alluvial clay stabilized with lime

Lime Kind	Lime %	Density, pcf	Immersed unconfined compressive strength, psi 7 day	28 day	90 day
Calcitic hydrated	3	92.4	125	132	124
"	6	91.1	129	182	194
"	9	90.6	128	166	218
"	12	89.8	112	158	241
Dolomitic monohydrate	3	93.5	48	48	35
"	6	92.2	173	274	250
"	9	91.5	173	345	336
"	12	90.8	194	334	415

Table 27. Immersed unconfined compressive strength of mixtures of soil, stabilized with portland cement

Soil	Lime treatment % and kind	Cement %	Dry Density, pcf	Immersed unconfined compressive strength, psi		
				7 day	28 day	90 day
Dune sand	None	5	110.8	127	184	228
" "	None	8	112.7	398	474	541
" "	None	10	117.1	591	770	802
Friable loess	None	6	101.3	330	495	715
" "	None	9	103.5	423	566	1001
" "						
Alluvial clay	3, dol.	3	93.5	266	341	369
" "	3, dol.	6	94.0	328	469	501
" "	3, dol.	9	94.9	391	574	ND[a]
Gumbotil	4, calc.	3	94.2	317	376	463
"	4, calc.	5	93.4	440	493	687
"	4, calc.	8	94.4	515	586	870
Gumbotil	4, dol.	5	95.0	432	507	590
"	4, dol.	8	94.7	534	692	830
"						

[a] Not determined.

effectiveness of both limes in treatments for soil-cement stabilization. In the meantime the cheapest one available is recommended.

Durability Evaluation

The effectiveness of lime-fly ash stabilization was compared with that of other methods of soil stabilization. A few mixes were selected with the proper amount of lime and fly ash for each soil, to compare them with mixes in which lime and/or cement was the stabilizer. The comparison included freeze-thaw testing of selected mixes.

Dolomitic monohydrate lime and fly ash No. 3 were the most suitable lime and fly ash for stabilizing any of the four Iowa soils evaluated here. The addition of chemicals is highly recommended with sandy soils; therefore chemical additives were used in three mixes with dune sand. Sodium carbonate and sodium chloride were chosen as additives based on strength improvements, cost of the chemicals, and practicability of their use in field construction. The composition and proportions of the selected mixtures, which vary somewhat with each soil, are given in Tables 38 through 41.

The proportions used in the soil, lime and fly ash mixtures were calculated to compete with the required amount of cement and/or lime needed to stabilize the same soil.

Use was made of the Iowa State equal cost line method for soil-lime-pozzolan mix design (71).

It was assumed that:

a) Eight percent cement is required to stabilize dune sand.

b) Ten percent cement or 9 percent dolomitic monohydrate lime is required to stabilize friable loess.

c) Three percent lime and 9 percent cement are required to stabilize alluvial clay.

d) Four percent lime and 8 percent cement are required to stabilize gumbotil.

e) The cost of lime or cement is the same, about $22 a ton.

f) The cost of fly ash is one-sixth that of lime or cement.

g) The cost of handling two materials (lime and fly ash; lime and cement), instead of one if stabilized with cement or with lime only, is equal to the cost of one percent of cement.

h) The cost of sodium carbonate and handling this extra material is 2.5 times that of an equal amount of cement, and the cost of sodium chloride and extra handling is the same as one percent of cement.

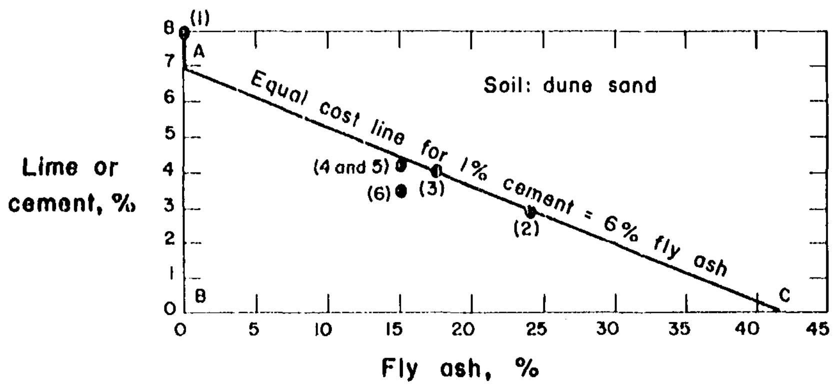
Dune sand

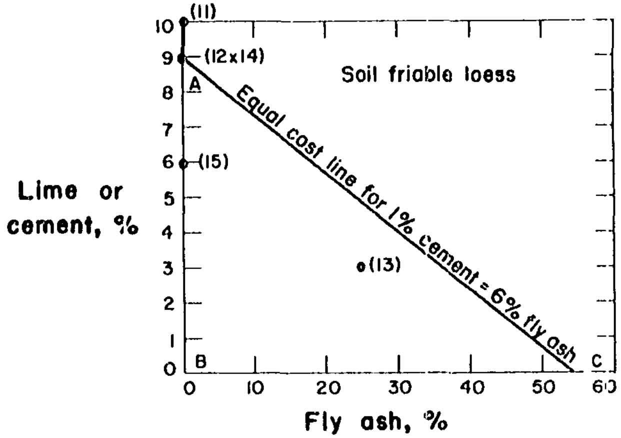
The sand-lime-fly ash equal cost line graph for the selected mixtures is given in Figure 59. All the mixtures within the triangle ABC, have the same cost or are cheaper than the required 8 percent of cement needed to stabilize dune sand.

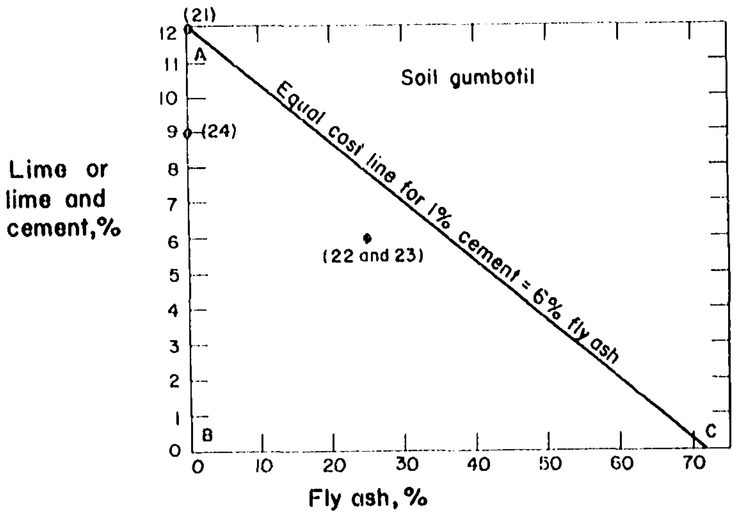
Based on 28 day strength requirements, lime and fly ash may be economically used to stabilize sandy soils (Table 28). Either lime and fly ash mixtures or lime and fly ash mixtures with chemical additives withstood the severity of freezing and thawing tests and had enough residual strength to be considered adequately stable. A good quality fly ash (No. 3) was used in these tests; these results may not be reproduced with all kinds of fly ash.

All five selected dune sand, lime, and fly ash mixtures gave 28 day strengths equal or greater than dune sand-cement for the same curing period. It has been estimated that after freezing and thawing, the stabilized soil specimens should yield a minimum strength of 250 psi (16). This value was surpassed by all mixtures (see column p_f Table 28). It is desirable that soil stabilized specimens show an index of resistance to the effects of freezing (R_f) of at least 80 percent to satisfactorily withstand Iowa climatic conditions (16). Only mixes Nos. 4 and 6 gave indexes of resistance lower than 80 percent; however, they had R_f values of 78 percent, which should be adequate, since the values of p_f and p_c are over 400 psi.

Figure 59. Equal-cost-line charts for soil stabilized with selected admixtures of lime-fly ash or lime-fly ash-chemical compared with mixtures of soil-lime-cement or soil-cement.


Lime or cement, %
Fly ash, %
Soil: dune sand
Equal cost line for 1% cement = 6% fly ash
(1)
A
B
C
(4 and 5)
(6)
(3)
(2)
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35
40
45


Lime or cement, %
Fly ash, %
Soil friable loess
Equal cost line for 1% cement = 6% fly ash
(11)
(12x14)
(15)
(13)
A
B
C
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60


Lime or lime and cement,%
Fly ash, %
Soil gumbotil
Equal cost line for 1% cement = 6% fly ash
(21)
(24)
(22 and 23)
A
B
C
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70

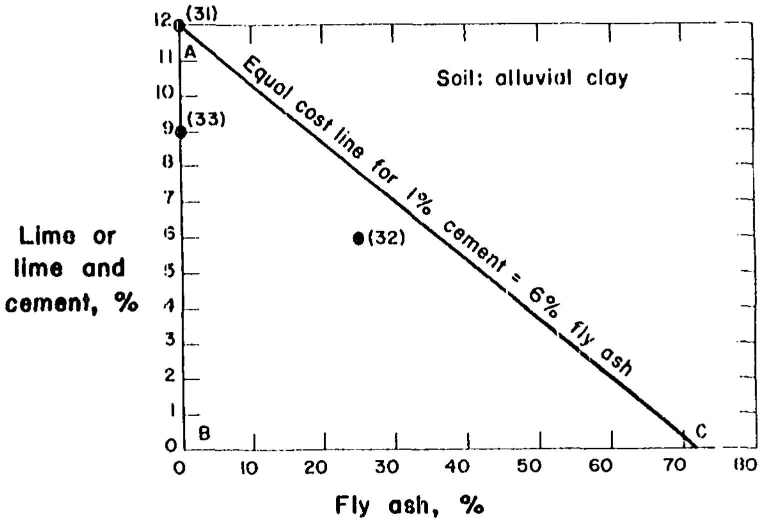

Lime or lime and cement, %
Fly ash, %
Soil: alluvial clay
Equal cost line for 1% cement = 6% fly ash
(31)
(33)
(32)
A
B
C
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80

Table 28. Durability evaluation of selected admixtures to stabilize dune sand

Mix No.	Proportions	As-molded dry density, pcf
1	92% sand, 8% p. cement	112.6
2	73% sand, 3% dol. lime, 24% fly ash No. 3	124.3
3	76% sand, 4% dol. lime, 17.5% fly ash No. 3	124.4
4	82% sand, 3% dol. lime, 15% fly ash No. 3 + 0.5% sodium carbonate	117.2
4A	82% sand, 3% dol. lime, 15% fly ash No. 3	123.8
5	82% sand, 3% calc. lime, 15% fly ash No. 3 + 0.5% sodium carbonate	116.1
6	82% sand, 3% calc. lime, 15% fly ash No. 3 + 0.5% sodium chloride	124.1
5A-6A	82% sand, 3% calc. lime, 15% fly ash No. 3	123.1

(Continued)

Table 28. (Continued)

Mix No.	Proportions	Unconfined compressive strength, psi			
		28 day[a]	P_f[b]	P_o[c]	R_f[d], %
1	92% sand, 8% p. cement	474	507	517	98
2	73% sand, 3% dol. lime, 24% fly ash No. 3	792	821	966	85
3	76% sand, 4% dol. lime, 17.5% fly ash No. 3	646	634	674	94
4	82% sand, 3% dol. lime, 15% fly ash No. 3 + 0.5% sodium carbonate	554	452	583	78
4A	82% sand, 3% dol. lime, 15% fly ash No. 3	390	ND[e]	ND	ND
5	82% sand, 3% calc. lime, 15% fly ash No. 3 + 0.5% sodium carbonate	644	596	570	104
6	82% sand, 3% calc. lime, 15% fly ash No. 3 + 0.5% sodium chloride	453	414	454	78
5A-6A	82% sand, 3% calc. lime, 15% fly ash No. 3	120	ND	ND	ND

[a] After 28 days curing and 24 hours immersion in distilled water.

[b] After 28 days curing, 24 hours immersion in distilled water and ten freeze-thaw cycles.

[c] After 28 days curing and 11 days immersion in distilled water.

[d] $R_f = \frac{100\, P_f}{P_o}$

[e] Not determined.

Some mixtures continued gaining strength during freezing and thawing cycles and/or during immersion. None of the mixtures showed any visible damage detriment from freeze-thaw, neither did they show any expansion.

The as-molded dry density of the several mixtures changed by as much as 12 pcf, but there was no relationship between density and strength values.

Friable loess. Only one loess, lime and fly ash mixture was considered to compete economically and on a strength basis with loess and cement or loess and lime mixtures. That loess, lime and fly ash mixture was 72 percent loess, 3 percent dolomitic monohydrate lime and 25 percent fly ash No. 3 (Table 29). It was compared with mixtures of the same soil stabilized with 9 percent dolomitic monohydrate lime or with 10 percent cement. The amount of 9 percent dolomitic lime was chosen based on a previous evaluation using different amounts of lime (Table 24). Ten percent cement was chosen based on the A.S.T.M. requirements to stabilize this kind of soil (3). Twenty-eight day results for mixtures with 6 and 9 percent cement are also included in Table 29.

Strengths of 400 psi were obtained with all selected mixtures after a curing period of 28 days. The mixtures exposed to 10 cycles of freezing and thawing showed a strength either close to 400 psi or well over this value, which is very adequate for a base course. The indexes of resistance were over the minimum of 80 percent desired.

Friable loess can be stabilized with cement, lime, or lime and fly ash for use as a road base course material. The 10 percent cement mixture gives strengths that are much higher than those obtained with mixtures with lime or with lime and fly ash. It appears that a lower amount of cement might also adequately stabilize friable loess. For instance, mixture No. 15 (Table 29), composed of 6 percent cement and 94 percent loess, gave a strength of 495 psi after 28 days. This strength is comparable to that obtained with the selected mixtures of loess-lime and loess-lime-fly ash. Therefore, it is possible that 6 percent cement would be an adequate amount to stabilize this soil. In this case, cement should preferably be used to stabilize friable loess rather than lime or lime and fly ash, unless the price of lime is much cheaper than that of cement or a high quality fly ash is cheaply available.

<u>Gumbotil</u>. Two fly ashes, No. 2 and No. 3, were used with dolomitic monohydrate lime to stabilize gumbotil and to make an evaluation of the durability of these mixtures. The proportions used, based on previous results, were 69 percent gumbotil, 6 percent lime and 25 percent fly ash (Table 30). The strengths previously obtained with lime and gumbotil were rather low (Table 24) and do not recommend the use of straight lime stabilization for base course con-

Table 29. Durability evaluation of selected admixtures to stabilize friable loess

Mix No.	Proportions	As-molded dry density, pcf	Unconfined compressive strength, psi			
			28 days[a]	P_f[b]	P_c[c]	R_f[d], %
11	90% loess, 10% cement	103.5	645	567	682	83
12	91% loess, 9% dol. mon. lime	100.8	396	387	428	90
13	72% loess, 3% dol. mon. lime, 25% fly ash No. 3	99.1	462	441	521	85
14	91% loess, 9% cement	103.5	566	ND[e]	ND	ND
15	94% loess, 6% cement	101.3	495	ND	ND	ND

[a] After 28 days curing and 24 hours immersion in distilled water.

[b] After 28 days curing, 24 hours immersion in distilled water and ten freeze-thaw cycles.

[c] After 28 days curing and 11 days immersion in distilled water.

[d] $R_f = \frac{100P_f}{P_c}$

[e] Not determined.

struction with gumbotil. Consequently the use of lime was not evaluated here. The amount of cement to stabilize gumbotil, based on A.S.T.M. requirements is about 12 percent (3). Therefore this was the amount used in the durability studies.

Without using lime it would be impossible to field mix gumbotil with cement, because gumbotil is an extremely plastic clay soil. Hence, four percent of the required amount of cement was replaced by lime to decrease the plasticity of the soil.

Both mixtures in which lime and fly ash was the stabilizing agent gave strengths comparable with that of the mixture of gumbotil stabilized with lime and cement. The stre strengths after 28 days curing were above 600 psi for both immersion periods and for all three mixes selected for the freeze-thaw studies. The strengths after freezing and thawing cycles were about 540 psi for the three mixes. These strengths are very good for this high-clay content soil, and warrant the use of these mixtures as a base course material. The indexes of resistance are adequate for mixes Nos. 21 and 22 (Table 30). Mix No. 23 had a rather low index of resistance of 68 percent. This index value is due to a substantial gain of strength during the 11 day immersion period. Provided that the strength after the Iowa freeze-thaw test is still 529 psi, gumbotil may be used in a base course when stabilized with the materials and proportions of

Table 30. Durability evaluation of selected admixtures to stabilize gumbotil

Mix No.	Proportions	As-molded dry density, pcf	Unconfined compressive strength, psi			
			28 day[a]	P_o[c]	P_f[b]	R_f[d], %
21	88% gumbotil, 4% dol. mon. lime and 8% cement	95.1	705	634	550	87
22	69% gumbotil, 6% dol. mon. lime and 25% fly ash No. 2	90.0	606	642	534	83
23	69% gumbotil, 6% dol. mon. lime and 25% fly ash No. 3	94.1	682	780	529	68
24	91% gumbotil, 4% dol. mon lime and 5% cement	93.3	534	ND[e]	ND	ND

[a] After 28 days curing and 24 hours immersion in distilled water.

[b] After 28 days curing, 24 hours immersion in distilled water and ten freeze-thaw cycles.

[c] After 28 days curing and 11 days immersion in distilled water.

[d] $R_f = \frac{100 P_f}{P_o}$

[e] Not determined.

mix No. 23; that is 69 percent gumbotil, 6 percent dolomitic monohydrate lime and 25 percent fly ash No. 3.

As evident by the strength obtained with mix No. 24, it is possible to obtain good strengths with lesser amounts of lime and cement. However, strengths equivalent of mix No. 24 may be also obtained with lesser amounts of lime and fly ash than those used in mix Nos. 21 and 22. Hence it may be concluded that gumbotil can be stabilized with lime and fly ash, competing economically and strength-wise with cement, or, for this plastic soil, with lime and cement.

It is necessary to point out that with gumbotil, the strengths obtained with the specimens prepared for the durability evaluation studies had greater strengths than specimens made with the same admixtures in previous studies. This lack of reproducibility of strength was only found with gumbotil. It is possible that specimens prepared for the durability studies were benefitted during curing by temperatures slightly higher than in the other studies, causing the strength differences noted.

Alluvial clay. About 12 percent cement is the least amount required for stabilizing alluvial clay according to A.S.T.M. tests (3). The lime-fly ash combinations that might give strengths comparable with those obtained with cement were those made with dolomitic monohydrate lime plus fly ash No. 3 (Table 31). Mixtures of alluvial clay and lime did not show high strength (Table 26), so they were not evaluated here.

Instead of using the full cement requirement of 12 percent, 3% lime and 9% cement were used. The lime was used primarily to give the soil friable characteristics which would allow better mixing with the cement. Lime also may counteract any adverse effects from the somewhat high organic matter content of the alluvial clay.

Both mixtures submitted to the freezing and thawing tests gave strengths of around 500 psi for any of the three testing treatments tried. The indexes of resistance were also above the minimum desired. It appears that alluvial clay stabilized with the proper lime and fly ash admixture may have strengths and durability comparable to alluvial clay stabilized with cement, and be economically competitive as. (See Figure 59).

Mix No. 33, was composed of 91 percent alluvial clay and 9 percent lime and cement, not evaluated in freezing and thawing but seemingly gave adequate 28 strength. It is also possible that mixtures containing smaller amounts of fly ash than mix No. 32 might give strengths as good as those of mix No. 33.

Table 31. Durability evaluation of selected admixtures to stabilize alluvial clay

Mix No.	Proportions	As-molded dry density, pcf	Unconfined compressive strength, psi			
			28 day[a]	P_f[b]	P_c[c]	R_f[d], %
31	88% alluvial clay, 3% calc. hyd. lime and 9% cement	94.9	574	498	527	94
32	69% alluvial clay, 6% dol. mon. lime and 25% fly ash No. 3	93.6	513	475	563	84
33	91% alluvial clay, 3% dol. mon. lime and 6% cement	94.0	470	ND[e]	ND	ND

[a] After 28 days curing and 24 hours immersion in distilled water.

[b] After 28 days curing, 24 hours immersion in distilled water and ten freeze-thaw cycles.

[c] After 28 days curing and 11 days immersion in distilled water.

[d] $$R_f = \frac{100\ P_f}{P_c}$$

[e] Not determined.

CONCLUSIONS

Based on this investigation the following conclusions are made:

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. With sandy soils, the compaction moisture for maximum strength 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, it is to the wet side. With other soils, such as friable loess, maximum strength and maximum density may occur at the same compaction moisture.

2. Maximum strength of soil-lime mixtures also may occur at a compaction moisture content different than the optimum moisture content for maximum density.

3. The required compaction moisture content to produce maximum strength changes with the curing period of soil, lime, and fly ash mixtures: the longer the curing period the greater the compaction moisture content needed for maximum strength.

4. Increasing the compactive effort from standard Proctor to modified Proctor increases the strength of soil, lime, and fly ash mixtures. The strength increase obtained is variable, but usually in the range of 50 to 160 percent.

5. There is not an optimum amount or ratio of lime and fly ash for stabilizing all soils. The amount and proportions of lime and fly ash to use depend greatly on the kinds of fly ash and soil, and somewhat on the kind of lime. For granular soils the amount of lime should be between 3 and 6 percent; the amount of fly ash between 10 and 25 percent. For clayey soils the amount of lime should be between 5 and 9 percent; the amount of fly ash between 10 and 25 percent.

6. Dolomitic monohydrate lime generally gives better strengths in soil, lime, and fly ash mixtures than calcitic hydrated lime for normal amounts of lime and using ambient curing temperatures.

7. At low lime contents, of the order of 3 percent, calcitic hydrated is more effective than dolomitic monohydrate for stabilizing clayey soils with or without fly ash; at higher lime contents, dolomitic monohydrate gives better strengths than calcitic hydrated.

8. The fly ashes used were beneficial to soil-lime mixtures for all soils except friable loess. With the friable loess, only a high quality fly ash was beneficial to loess-lime mixtures.

9. Heating of the materials to high temperature at the time of mixing lowers the compacted density and cured strength of clayey soil, lime, and fly ash mixtures.

10. 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. At the most, with clayey soils, wet mixing and compaction should be done the same day; but with sandy soils compaction could be delayed until the day after wet mixing without appreciable loss of strength.

11. Increase of temperature accelerates the lime-fly ash pozzolanic reaction and the strength of soil, lime, and fly ash mixtures may be greatly increased by moist curing at higher than ambient temperatures. Soil-lime and soil-cement mixtures are also benefited by high temperature moist curing.

12. Steam cured specimens of soil stabilized with lime, lime-fly ash, or cement after a few hours attain strengths comparable to concrete.

13. At ambient temperatures, dune sand or dune sand-fly ash stabilized with dolomitic monohydrate lime reaches generally higher strengths than when stabilized with calcitic hydrated lime, but at high temperatures (above 140°F) calcitic lime is better than dolomitic.

14. The quality of a fly ash for soil stabilization is reflected in the unconfined compressive strength developed in mixes with lime after curing at any temperature. A mixture made with a high quality fly ash will always show.

greater strength than a mixture made with a low quality one, regardeless of the curing temperature at which both mixtures were cured.

15. There is no correlation between long-term strength at ambient curing temperatures and short-term strength at elevated curing temperatures for soil, lime, and fly ash mixtures. The strength correlation depends on the kind of fly ash, the kind of lime, and probably also on the type of soil.

16. The quality of a fly ash can be improved by removing the coarse fraction and/or by grinding.

17, a). The strength attained with soil, lime, and fly ash mixtures may be increased by the addition of small amounts of some chemicals; sodium carbonate, sodium metasilicate and sodium hydroxide appear to be the most promising ones, as indicated by strength improvements and economic considerations. This benefit is greatest in mixtures with sandy soils followed by soils of low plasticity. Clayey soils stabilized with lime and fly ash do not benefit from the addition of sodium hydroxide, sodium carbonate or sodium metasilicate.

b). Although the increase of strength gained from the use of chemical additives occurs over the ordinary range of temperatures, the additives are especially needed at temperatures close to freezing when they may permit extending the working season of the soil-lime-fly ash stabilization.

c). Sodium carbonate is the chemical most highly recommended for use in sandy or silty soils stabilized with lime and fly ash. The addition of 0.5 percent sodium carbonate permits a reduction in the amounts of lime and fly ash needed to attain the same strength that may be obtained by using greater amounts of lime and fly ash.

18. The amount of lime needed to stabilize a soil should be determined on the basis of short as well as long curing periods. Small amounts of lime give early strengths equal to or higher than larger amounts of lime, but after long curing periods the larger amounts will produce the highest strengths.

19. The moisture-density curves of montmorillonitic clay soils stabilized with lime are affected by the flocculating effects of lime. Sometimes the curves do not show a maximum density.

20. Cement is a very effective stabilizer for most soils. The strength gain of soil-cement mixtures is rapid and a large percentage of ultimate strength is developed in a relatively short time. Contrarywise, compacted soil, lime, and fly ash mixtures gain strength slowly and full strength may not be developed for several years. The comparison of soil-cement and soil-lime-fly ash test specimens should be made on the basis of 28 day curing. After this

period, soil-cement should have developed about 90 percent of the ultimate strength, and soil-lime-fly ash only about 50 percent, depending on the soil, lime and fly ash used.

21. Selected compositions of dune sand, lime and fly ash; or dune sand, lime, fly ash and chemicals can compete in strength, freeze-thaw resistance and cost with mixtures of the same soil stabilized with cement.

22. Friable loess is most effectively stabilized with cement. If lime is cheap and a good quality fly ash is available, lime or lime and fly ash may compete with cement to stabilize friable loess.

23. Additions of fly ash are beneficial to gumbotil-lime mixtures. Selected gumbotil-lime-fly ash mixtures show good resistance to freezing and thawing, and may compete with gumbotil-cement stabilization.

24. Additions of fly ash are beneficial to alluvial clay-lime mixtures. Lime-fly ash stabilization of alluvial clay may compete economically and strengthwise with cement stabilization.

RECOMMENDATIONS FOR FURTHER STUDY

The following suggestions for further research are an outgrowth of this investigation:

1. Moisture-density and moisture-strength relationships be compared for mixtures of soil, lime, and fly ash, with the effect of molding moisture content on strength determined at curing periods up to one year. With clayey soils these studies should include specimens made with the highest moisture contents possible.

2. The same moisture-density and moisture-strength studies be made for mixtures of soil and lime.

3. Moisture-density and moisture-strength relationships be compared for mixtures of soil and cement, with the effect of molding moisture content on strength determined at different curing periods up to 90 days or longer.

4. A basic investigation be made to determine the products formed in the lime-fly ash reaction.

5. A basic investigation be made to determine the effects of lime in clayey soils in both compacted and uncompacted states and at different moisture contents.

6. A method be developed for finding the pozzolanic activity of a fly ash by curing lime-fly ash specimens for short curing periods at elevated temperatures.

7. A machine be designed able to heat economically layers of road courses built with stabilized soil. A portable nuclear reactor could be the source of cheap energy.

8. The effect of fineness of lime on strength of soil, lime, and fly ash mixtures be studied.

9. A further evaluation be made of the effect of chemical additives on the strength of soil, lime, and fly ash mixtures.

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APPENDIX

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Dune Sand,	97	Calc. hyd.,	3	– 0	0	110.0
" "	94	" "	6	–	0	113.0
" "	91	" "	9	–	0	117.0
Dune Sand,	87	Calc. hyd.,	3	No. 1,	10	119.7
" "	79.5	" "	3	"	17.5	121.6
" "	72	" "	3	"	25	119.8
Dune Sand,	84	Calc. hyd.,	6	No. 1,	10	121.2
" "	76.5	" "	6	"	17.5	120.9
" "	69	" "	6	"	25	120.3
Dune Sand,	81	Calc. hyd.,	9	No. 1,	10	122.6
" "	73.5	" "	9	"	17.5	120.8
" "	66	" "	9	"	25	119.0
Dune Sand,	87	Calc. hyd.,	3	No. 2,	10	114.6
" "	79.5	" "	3	"	17.5	112.4
" "	72	" "	3	"	25	107.1
Dune Sand,	84	Calc. hyd.,	6	No. 2,	10	115.7
" "	76.5	" "	6	"	17.5	112.5
" "	69	" "	6	"	25	107.2
Dune Sand,	81	Calc. hyd.,	9	No. 2,	10	116.4
" "	73.5	" "	9	"	17.5	112.1
" "	66	" "	9	"	25	106.1

Densities of soil-lime-fly ash mixtures

Soil Kind	Soil Amount, %	Lime Kind	Lime Amount, %	Fly ash Kind	Fly ash Amount, %	Molding dry density pcf
Dune Sand,	87	Calc. hyd.,	3	No. 3,	10	120.9
" "	79.5	" "	3	"	17.5	123.9
" "	72	" "	3	"	25	122.7
Dune Sand,	84	Calc. hyd.,	6	No. 3,	10	122.3
" "	76.5	" "	6	"	17.5	123.2
" "	69	" "	6	"	25	120.5
Dune Sand,	81	Calc. hyd.,	9	No. 3,	10	121.9
" "	73.5	" "	9	"	17.5	119.2
" "	66	" "	9	"	25	117.7
Dune Sand,	87	Calc. hyd.,	3	No. 4,	10	108.7
" "	79.5	" "	3	"	17.5	100.6
" "	72	" "	3	"	25	92.5
Dune Sand,	84	Calc. hyd.,	6	No. 4,	10	111.0
" "	76.5	" "	6	"	17.5	101.8
" "	69	" "	6	"	25	91.8
Dune Sand,	81	Calc. hyd.,	9	No. 4,	10	112.0
" "	73.5	" "	9	"	17.5	102.7
" "	66	" "	9	"	25	92.0
Dune Sand,	87	Calc. hyd,	3	No. 5,	10	115.1
" "	79.5	" "	3	"	17.5	117.7
" "	72	" "	3	"	25	118.9

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Dune Sand,	84	Calc. hyd.,	6	No. 5,	10	118.7
" "	76.5	" "	6	"	17.5	120.6
" "	69	" "	6	"	25	121.6
Dune Sand,	81	Calc. hyd.,	9	No. 5,	10	121.2
" "	73.5	" "	9	"	17.5	122.6
" "	66	" "	9	"	25	122.0
Dune Sand,	87	Calc. hyd.,	3	No. 6	10	118.4
" "	79.5	" "	3	"	17.5	122.3
" "	72	" "	3	"	25	122.8
Dune Sand,	84	Calc. hyd.,	6	No. 6	10	121.5
" "	76.5	" "	6	"	17.5	123.4
" "	69	" "	6	"	25	122.3
Dune Sand,	81	Calc. hyd.,	9	No. 6	10	121.9
" "	73.5	" "	9	"	17.5	123.0
" "	66	" "	9	"	25	121.6
Dune Sand,	87	Calc. hyd.,	3	No. 7	10	109.8
" "	79.5	" "	3	"	17.5	103.7
" "	72	" "	3	"	25	95.9
Dune Sand,	84	Calc. hyd.,	6	No. 7	10	112.4
" "	76.5	" "	6	"	17.5	104.0
" "	69	" "	6	"	25	95.5

<u>Densities of soil-lime-fly ash mixtures</u>

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Dune Sand,	81	Calc. hyd.,	9	No. 7,	10	112.0
" "	73.5	" "	9	"	17.5	102.6
" "	66	" "	9	"	25	93.8
Dune Sand,	87	Calc. hyd.,	3	No. 8,	10	116.6
" "	79.5	" "	3	"	17.5	118.8
" "	72	" "	3	"	25	117.7
Dune Sand,	84	Calc. hyd.,	6	No. 8,	10	119.0
" "	76.5	" "	6	"	17.5	120.0
" "	69	" "	6	"	25	118.0
Dune Sand,	81	Calc. hyd.,	9	No. 8,	10	120.9
" "	73.5	" "	9	"	17.5	120.1
" "	66	" "	9	"	25	117.6
Dune Sand,	97	Dol. mhy.,	3		0	110.0
" "	94	" "	6		0	113.0
" "	91	" "	9		0	116.5
Dune Sand,	87	Dol. mhy.,	3	No. 1,	10	120.1
" "	79.5	" "	3	"	17.5	122.6
" "	72	" "	3	"	25	121.2
Dune Sand,	84	Dol. mhy.,	6	No. 1,	10	121.0
" "	76.5	" "	6	"	17.5	122.0
" "	69	" "	6	"	25	122.1

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Dune Sand,	81	Dol. mhy.,	9	No. 1,	10	122.2
" "	73.5	" "	9	"	17.5	120.2
" "	66	" "	9	"	25	118.5
Dune Sand,	87	Dol. mhy.,	3	No. 2,	10	107.7
" "	79.5	" "	3	"	17.5	99.2
" "	72	" "	3	"	25	99.5
Dune Sand,	84	Dol. mhy.,	6	No. 2,	10	110.2
" "	76.5	" "	6	"	17.5	105.0
" "	69	" "	6	"	25	95.8
Dune Sand,	81	Dol. mhy.,	9	No. 2,	10	111.4
" "	73.5	" "	9	"	17.5	104.0
" "	66	" "	9	"	25	97.8
Dune Sand,	87	Dol. mhy.,	3	No. 4,	10	107.8
" "	79.5	" "	3	"	17.5	100.6
" "	72	" "	3	"	25	92.7
Dune Sand,	84	Dol. mhy.,	6	No. 4,	10	116,8
" "	76.5	" "	6	"	17.5	102.6
" "	69	" "	6	"	25	93.9
Dune Sand,	81	Dol. mhy.,	9	No. 4,	10	113.5
" "	73.5	" "	9	"	17.5	101.3
" "	66	" "	9	"	25	90.5

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density pcf
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	
Dune Sand,	87	Dol. mhy.,	3	No. 5,	10	115.6
" "	79.5	" "	3	"	17.5	115.7
" "	72	" "	3	"	25	116.9
Dune Sand,	84	Dol. mhy.,	6	No. 5,	10	119.1
" "	76.5	" "	6	"	17.5	117.3
" "	69	" "	6	"	25	118.5
Dune Sand,	81	Dol. mhy.,	9	No. 5,	10	121.7
" "	73.5	" "	9	"	17.5	119.2
" "	66	" "	9	"	25	121.0
Dune Sand,	87	Dol. mhy.,	3	No. 6,	10	119.2
" "	79.5	" "	3	"	17.5	124.2
" "	72	" "	3	"	25	124.0
Dune Sand,	84	Dol. mhy.,	6	No. 6,	10	121.5
" "	76.5	" "	6	"	17.5	123.9
" "	69	" "	6	"	25	123.8
Dune Sand,	81	Dol. mhy.,	9	No. 6,	10	122.7
" "	73.5	" "	9	"	17.5	124.3
" "	66	" "	9	"	25	121.6
Dune Sand,	87	Dol. mhy.,	3	No. 7	10	110.3
" "	79.5	" "	3	"	17.5	104.0
" "	72	" "	3	"	25	96.9

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Dune Sand,	84	Dol. mhy.,	6	No. 7,	10	110.5
" "	76.5	" "	6	"	17.5	104.9
" "	69	" "	6	"	25	96.1
Dune Sand,	81	Dol. mhy.,	9	No. 7,	10	113.8
" "	73.5	" "	9	"	17.5	105.0
" "	66	" "	9	"	25	95.4
Dune Sand,	87	Dol. mhy.,	3	No. 8,	10	116.4
" "	79.5	" "	3	"	17.5	118.7
" "	72	" "	3	"	25	117.5
Dune Sand,	84	Dol. mhy.,	6	No. 8,	10	119.2
" "	76.5	" "	6	"	17.5	120.4
" "	69	" "	6	"	25	119.8
Dune Sand,	81	Dol. mhy.,	9	No. 8,	10	122.5
" "	73.5	" "	9	"	17.5	120.1
" "	66	" "	9	"	25	120.0
Dune, Sand	87	Dol. mhy.,	3	No. 3,	10	121.4
" "	79.5	(U.S. Gypsum)	3	"	17.5	125.5
" "	72		3	"	25	125.3
Dune Sand,	84	Dol. mhy.,	6	No. 3,	10	123.1
" "	76.5	(U.S. Gypsum)	6	"	17.5	125.3
" "	69		6	"	25	122.7

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Dune Sand,	81	Dol. mhy. (U.S.Gypsum)	9	No. 3,	10	124.1
" "	73.5	" " (U.S.Gypsum)	9	"	17.5	120.4
" "	66	" " " " "	9	"	25	118.9
Dune Sand,	87	Dol. mhy. (U.S.Gypsum)	3	No. 3,	10	120.1
" "	79.5	" " " " "	3	"	17.5	123.4
" "	72	" " " " "	3	"	25	122.5
Dune Sand,	84	Dol. mhy. (U.S.Gypsum)	6	No. 3,	10	120.6
" "	76.5	" " " " "	6	"	17.5	123.3
" "	69	" " " " "	6	"	25	120.4
Dune Sand,	81	Dol. mhy. (U.S.Gypsum)	9	No. 3,	10	122.6
" "	73.5	" " " " "	9	"	17.5	122.5
" "	66	" " " " "	9	"	25	118.0
Dune Sand,	87	Dol. mhy. (Western)	3	No. 3,	10	120.5
" "	79.5	" " "	3	"	17.5	123.2
" "	72	" " "	3	"	25	121.7
Dune Sand,	84	Dol. mhy. (Western)	6	No. 3,	10	122.2
" "	76.5	" " "	6	"	17.5	122.3
" "	69	" " "	6	"	25	119.6
Dune Sand,	81	Dol. mhy. (Western)	9	No. 3,	10	122.8
" "	73.5	" " "	9	"	17.5	120.4
" "	66	" " "	9	"	25	117.6

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Friable Loess,	97	Calc. hyd.,	3	-	0	99.8
" "	94	" "	6	-	0	99.0
" "	91	" "	9	-	0	99.0
Friable Loess,	87	Calc. hyd.,	3	No. 1,	10	97.6
" "	79.5	" "	3	"	17.5	98.4
" "	72	" "	3	"	25	97.8
Friable Loess,	84	Calc. hyd.,	6	No. 1,	10	98.3
" "	76.5	" "	6	"	17.5	97.1
" "	69	" "	6	"	25	96.8
Friable Loess,	81	Calc. hyd.,	9	No. 1,	10	96.8
" "	73.5	" "	9	"	17.5	95.9
" "	66	" "	9	"	25	95.3
Friable Loess,	87	Calc. hyd.,	3	No. 2,	10	95.0
" "	79.5	" "	3	"	17.5	91.4
" "	72	" "	3	"	25	88.2
Friable Loess,	84	Calc. hyd.,	6	No. 2,	10	94.3
" "	76.5	" "	6	"	17.5	89.8
" "	69	" "	6	"	25	87.6
Friable Loess,	81	Calc. hyd.,	9	No. 2,	10	93.9
" "	73.5	" "	9	"	17.5	90.2
" "	66	" "	9	"	25	87.5

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Friable Loess,	87	Calc. hyd.,	3	No. 3,	10	99.1
" "	79.5	" "	3	"	17.5	99.9
" "	72	" "	3	"	25	96.9
Friable Loess,	84	Calc. hyd,	6	No. 3,	10	97.6
" "	76.5	" "	6	"	17.5	97.8
" "	69	" "	6	"	25	96.2
Friable Loess,	81	Calc. hyd.,	9	No. 3,	10	97.3
" "	73.5	" "	9	"	17.5	95.7
" "	66	" "	9	"	25	95.8
Friable Loess,	97	Dol. mhy.,	3	--	0	100.9
" "	94	" "	6	--	0	100.8
" "	88	" "	9	--	0	100.6
Friable Loess,	87	Dol. mhy.,	3	No. 1,	10	99.8
" "	79.5	" "	3	"	17.5	99.1
" "	72	" "	3	"	25	98.7
Friable Loess,	84	Dol. mhy.,	6	No. 1,	10	98.9
" "	76.5	" "	6	"	17.5	99.0
" "	69	" "	6	"	25	97.6
Friable Loess,	81	Dol. mhy.,	9	No. 1,	10	99.6
" "	73.5	" "	9	"	17.5	98.6
" "	66	" "	9	"	25	96.5

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Friable Loess,	87	Dol. mhy.,	3	No. 2,	10	96.0
" "	79.5	" "	3	"	17.5	92.0
" "	72	" "	3	"	25	88.2
Friable Loess,	84	Dol. mhy.,	6	No. 2,	10	95.1
" "	76.5	" "	6	"	17.5	92.2
" "	69	" "	6	"	25	88.9
Friable Loess,	81	Dol. mhy.,	9	No. 2,	10	95.7
" "	73.5	" "	9	"	17.5	92.4
" "	66	" "	9	"	25	89.3
Friable Loess,	87	Dol. mhy.,	3	No. 3,	10	100.3
" "	79.5	" "	3	"	17.5	99.4
" "	72	" "	3	"	25	99.5
Friable Loess,	84	Dol. mhy.,	6	No. 3,	10	100.7
" "	76.5	" "	6	"	17.5	98.5
" "	69	" "	6	"	25	97.9
Friable Loess,	81	Dol. mhy.,	9	No. 3,	10	99.3
" "	73.5	" "	9	"	17.5	98.3
" "	66	" "	9	"	25	97.4

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density pcf
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	
Gumbotil,	97	Calc. hyd.,	3	-	0	93.5
"	94	" "	6	-	0	89.5
"	91	" "	9	-	0	87.1
"	88	" "	12	-	0	87.1
Gumbotil,	87	Calc. hyd.,	3	No. 1,	10	93.7
"	79.5	" "	3	"	17.5	94.1
"	72	" "	3	"	25	94.6
Gumbotil,	84	Calc. hyd.,	6	No. 1,	10	92.2
"	76.5	" "	6	"	17.5	92.3
"	69	" "	6	"	25	92.0
Gumbotil,	81	Calc. hyd.,	9	No. 1,	10	90.2
"	73.5	" "	9	"	17.5	91.7
"	66	" "	9	"	25	91.9
Gumbotil,	78	Calc. hyd.,	12	No. 1,	10	90.7
"	70.5	" "	12	"	17.5	90.5
"	63	" "	12	"	25	92.0
Gumbotil,	87	Calc. hyd.,	3	No. 2,	10	92.5
"	79.5	" "	3	"	17.5	91.1
"	72	" "	3	"	25	89.9
Gumbotil,	84	Calc. hyd.,	6	No. 2,	10	91.3
"	76.5	" "	6	"	17.5	89.7
"	69	" "	6	"	25	88.7

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly Ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Gumbotil,	81	Calc. hyd.,	9	No. 2,	10	89.4
"	73.5	" "	9	"	17.5	89.6
"	66	" "	9	"	25	88.7
Gumbotil,	78	Calc. hyd.,	12	No. 2,	10	89.8
"	70.5	" "	12	"	17.5	89.6
"	63	" "	12	"	25	88.9
Gumbotil,	87	Calc. hyd.,	3	No. 3,	10	95.4
"	79.5	" "	3	"	17.5	95.0
"	72	" "	3	"	25	95.7
Gumbotil,	84	Calc. hyd.,	6	No. 3,	10	93.5
"	76.5	" "	6	"	17.5	93.8
"	69	" "	6	"	25	93.2
Gumbotil,	81	Calc. hyd.,	9	No. 3,	10	93.0
"	73.5	" "	9	"	17.5	95.1
"	66	" "	9	"	25	94.9
Gumbotil,	78	Calc. hyd.,	12	No. 3,	10	92.5
"	70.5	" "	12	"	17.5	91.8
"	63	" "	12	"	25	91.7

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Gumbotil,	97	Dol. mhy.,	3	-	0	93.8
"	94	" "	6	-	0	92.5
"	91	" "	9	-	0	92.3
"	88	" "	12	-	0	92.3
Gumbotil,	87	Dol, mhy.,	3	No. 1,	10	96.2
"	79.5	" "	3	"	17.5	97.1
"	72	" "	3	"	25	97.9
Gumbotil,	84	Dol. mhy.,	6	No. 1,	10	94.4
"	76.5	" "	6	"	17.5	93.6
"	69	" "	6	"	25	95.0
Gumbotil,	81	Dol. mhy.,	9	No. 1,	10	92.0
"	73.5	" "	9	"	17.5	92.8
"	66	" "	9	"	25	95.1
Gumbotil,	78	Dol. mhy.,	12	No.,1,	10	92.0
"	70.5	" "	12	"	17.5	92.2
"	63	" "	12	"	25	93.0
Gumbotil,	87	Dol. mhy.,	3	No. 2,	10	93.2
"	79.5	" "	3	"	17.5	91.4
"	72	" "	3	"	25	91.5
Gumbotil,	84	Dol. mhy.,	6	No. 2,	10	91.9
"	76.5	" "	6	"	17.5	90.1
"	69	" "	6	"	25	90.2

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Gumbotil,	81	Dol. mhy.,	9	No. 2,	10	91.3
"	73.5	" "	9	"	17.5	90.8
"	66	" "	9	"	25	89.2
Gumbotil,	78	Dol. mhy.,	12	No. 2,	10	90.9
"	70.5	" "	12	"	17.5	89.4
"	63	" "	12	"	25	88.6
Gumbotil,	87	Dol. mhy.,	3	No. 3,	10	94.2
"	79.5	" "	3	"	17.5	94.2
"	72	" "	3	"	25	95.3
Gumbotil,	84	Dol. mhy.,	6	No. 3,	10	93.2
"	76.5	" "	6	"	17.5	94.1
"	69	" "	6	"	25	94.1
Gumbotil,	81	Dol. mhy.,	9	No. 3,	10	94.2
"	73.5	" "	9	"	17.5	92.9
"	66	" "	9	"	25	92.9
Gumbotil,	78	Dol. mhy.,	12	No. 3,	10	91.5
"	70.5	" "	12	"	17.5	92.6
"	63	" "	12	"	25	92.6

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Alluvial clay,	97	Calc. hyd.,	3	-	0	92.4
" "	94	" "	6	-	0	91.1
" "	91	" "	9	-	0	90.6
Alluvial clay,	87	Calc. hyd.,	3	No. 1,	10	92.0
" "	79.5	" "	3	"	17.5	93.9
" "	72	" "	3	"	25	94.7
Alluvial clay,	84	Calc. hyd.,	6	No. 1,	10	92.9
" "	76.5	" "	6	"	17.5	93.2
" "	69	" "	6	"	25	94.4
Alluvial clay,	81	Calc. hyd.,	9	No. 1,	10	91.8
" "	73.5	" "	9	"	17.5	93.3
" "	66	" "	9	"	25	93.3
Alluvial clay,	87	Calc. hyd.,	3	No. 2,	10	90.7
" "	79.5	" "	3	"	17.5	89.8
" "	72	" "	3	"	25	89.1
Alluvial clay,	84	Calc. hyd.,	6	No. 2,	10	90.1
" "	76.5	" "	6	"	17.5	90.4
" "	69	" "	6	"	25	88.7
Alluvial clay,	81	Calc. hyd.,	9	No. 2,	10	90.5
" "	73.5	" "	9	"	17.5	89.8
" "	66	" "	9	"	25	86.8

Densities of soil-lime-fly ash mixtures

Soil		Lime		Fly ash		Molding dry density
Kind	Amount, %	Kind	Amount, %	Kind	Amount, %	pcf
Alluvial clay,	87	Calc. hyd.,	3	No. 3,	10	94.2
" "	79.5	" "	3	"	17.5	94.4
" "	72	" "	3	"	25	95.3
Alluvial clay,	84	Calc. hyd.,	6	No. 3,	10	93.7
" "	76.5	" "	6	"	17.5	93.8
" "	69	" "	6	"	25	93.9
Alluvial clay,	81	Calc. hyd.,	9	No. 3,	10	92.0
" "	73.5	" "	9	"	17.5	93.2
" "	66	" "	9	"	25	92.5
Alluvial clay,	97	Dol. mhy.,	3	-	0	93.5
" "	94	" "	6	-	0	92.2
" "	91	" "	9	-	0	91.5
Alluvial clay,	87	Dol. mhy.,	3	No. 1,	10	95.2
" "	79.5	" "	3	"	17.5	95.4
" "	72	" "	3	"	25	95.7
Alluvial clay,	84	Dol. mhy.,	6	No. 1,	10	93.2
" "	76.5	" "	6	"	17.5	93.8
" "	69	" "	6	"	25	94.1
Alluvial clay,	81	Dol. mhy.,	9	No. 1,	10	92.5
" "	73.5	" "	9	"	17.5	92.5
" "	66	" "	9	"	25	93.7

Densities of soil-lime-fly ash mixtures

Soil Kind	Soil Amount, %	Lime Kind	Lime Amount, %	Fly ash Kind	Fly ash Amount, %	Molding dry density pcf
Alluvial clay,	87	Dol. mhy.,	3	No. 2,	10	95.0
" "	79.5	" "	3	"	17.5	89.8
" "	72	" "	3	"	25	88.9
Alluvial clay,	84	Dol. mhy.,	6	No. 2,	10	91.2
" "	76.5	" "	6	"	17.5	89.8
" "	69	" "	6	"	25	88.1
Alluvial clay,	81	Dol. mhy.,	9	No. 2,	10	90.0
" "	73.5	" "	9	"	17.5	89.2
" "	66	" "	9	"	25	87.9
Alluvial clay,	87	Dol. mhy.,	3	No. 3,	10	93.5
" "	79.5	" "	3	"	17.5	94.0
" "	72	" "	3	"	25	94.7
Alluvial clay,	84	Dol. mhy.,	6	No. 3,	10	92.7
" "	76.5	" "	6	"	17.5	93.5
" "	69	" "	6	"	25	94.0
Alluvial clay,	81	Dol. mhy.,	9	No. 3,	10	91.8
" "	73.5	" "	9	"	17.5	93.1
" "	66	" "	9	"	25	93.5