tensely manipulated, as with a Sauerman bucket, it takes on the property of viscous flow and becomes absolutely unstable. Again, because of thixotropy if the soil is allowed to rest, it will regain its property of resisting erosion. (The above described phenomena have actually been observed on this project.)

While in principle it is possible to build high embankments with this material, in practice there are certain difficulties that are almost overwhelming. One is the almost constant rainfall. Another is the limitations of compacting equipment which makes it impossible to compact the lower lifts to a density high enough so that there is no further consolidation as a result of the dead weight of material above. Hence unless a high embankment is built very, very slowly, sudden settlements are likely to occur, especially along the side slopes resulting in slides because of unbalanced horizontal forces.

The most expeditious method of constructing high embankments (in excess of 20 to 25 ft. is to build only the central core of Pepeekeo ash, using some type of stable borrow material for the sides. This type of embankment construction has proved successful.

The various tests, physical and chemical, made by the PRA proved invaluable throughout the construction of this project, and the writer wishes to acknowledge his indebtedness to the results reported by Mr. Willis and his co-workers. While not used directly, the triaxial test results were especially valuable in providing at least some estimate of stability where previously there was none.

A last thought. Judging from the literature "Pepeekeo" ash must be similar in some respects to the volcanic clay of Mexico City. It is hoped that a direct comparison of the two can some day be made.

LABORATORY EXPERIMENTS WITH LIME-SOIL MIXTURES

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SYNOPSIS

This paper reports the results of laboratory research conducted by the Engineering Experiment Station of Purdue University and sponsored by the National Lime Association. Mr. Jean E. Hittle, formerly soils engineer, on the staff of the University, planned the details of the project and directed most of the laboratory work reported here.

The experiments were organized in three broad parts on the basis of soil types used. The tests in Part I were run on fine-grained soils by Mr. Lu I Cheng, a graduate student. Tests in Part II were performed on naturally-occurring gravels and those in Part III on synthetic gravel-binder mixes.

Atterburg limit tests were run on 25 fine-grained soils. The plastic indexes of silty soils were increased slightly by additions of 2 and 5 percent of hydrated lime but the PI's of clay soils were lowered appreciably by the lime additive. Comparable tests on a few soils with lime dust as the additive gave higher values for the PI than were obtained with lime. Tests were run on several of the soils at 7 and 14 days after the lime and water were mixed with the soil but the curing time appeared to have little consistent effect on the results.

Proctor compaction curves were plotted for 11 of the fine-grained soils with 0, 2, and 5 percent of lime. With but two exceptions, the addition of lime was accompanied by decreases in maximum density. The changes varied from an increase of 1.2 percent to a decrease of 5.5 percent of the corresponding maximum density obtained with the raw soil. Plots of penetration resistance quite consistently showed increased resistance to penetration with successive amounts of lime.

Compaction curves were plotted for five natural gravels to determine optimum moisture contents, and CBR specimens were molded at or near this moisture content with 0, 2, and 5 percent of lime. CBR tests were made on each combination of soil and lime, following three different curing procedures: (1) as molded; (2) after seven days of capillary saturation; and (3) after drying to constant weight at 140 F. and seven days saturation. Additions of lime produced increased strength in most specimens. In most cases, the period of drying before wetting added to the strength at the time of testing if lime had been added to the soil.

The synthetic gravel-binder mixes used in Part III were formed by using 0, 5, and 10 percent, by weight of total sample, of material passing the No. 200 sieve. Compaction tests were run on each combination and CBR specimens were molded with 0, 2, and 5 percent of lime. Tests were made on different samples after the three periods of curing described above. The same trends in strength, as measured by the CBR tests, were observed in these specimens as in the natural gravels.

One of the oldest of construction materials but one which has not received much attention from modern road builders is hydrated lime Some of the early research in the use of lime was reported by Dean McCaustland of the University of Missouri in 1925 (*1*)[1] and the highway research literature contains only scattered articles mentioning lime for the following 20 years. Engineers of the Texas Highway Department in their search for materials to stabilize highly plastic subgrade materials have recently done considerable work with lime, and the department has reported gratifying success (*2*, *3*).

The laboratory program to study lime-soil mixtures was sponsored by the National Lime Association and carried on in cooperation with the Engineering Experiment Station of Purdue University.

The work of the project was divided into three parts on the basis of the soils used. Part I covered a wide range of fine-grained soils; Part II was conducted with naturally occurring gravels; and Part III used synthetic gravel-binder mixes. Part I contained a plastic index series and a compaction test series. Also included in the program of Part I, but not at this time sufficiently complete to be reported, was a series of absorption-strength tests. Parts II and III consisted essentially of strength determinations after varied curing conditions.

SOILS AND PROCEDURES

The 25 fine-grained soils varied in texture from sand to clay, in plastic index from 3 to 40, in formation from residual to wind-blown, and in geographic source from North Dakota to Virginia and Texas. Ten of the soils were residual from bedrock areas, eight were glacial drift soils, three were coastal plain deposits, and the remaining four were wind or water deposited. Table 1 lists the formation and location of the soils used and Table 3 shows the liquid and plastic limit as well as plastic index of each.

Liquid limit and plastic limit tests were performed and plastic index determinations were made for each of the 25 soils with no admixture, and with 2 and 5 percent of hydrated lime. In each case, the test was begun immediately after adding water to the soil. The lime in each instance was mixed dry with the soil. The results of these tests are reported in Table 3.

To determine whether time of standing would have any effect upon the plastic index or change the effect of the lime added, 16 of the soils were tested at 7 and 14 days after water was added to the raw soil or to the lime-soil mixture. An amount of water about equal to the moisture content at the plastic limit was added to the soil, or to the lime-soil mixture, and was thoroughly mixed in. The samples were then covered and plastic index determinations were made on one of each type at the end of 7 days and on a companion specimen of each type at the end of 14 days. The results of the determinations are listed in Table 5.

To determine the comparable effect of lime dust, plastic index determinations were made on three selected soils with 2 percent and with 5 percent of ground limestone added. These results are reported in Table 7.

The compaction-test series on the fine grained soils used the 11 soils which are listed with their results in Table 8. Using standard Proctor procedure, moisture-density curves were obtained for each of the 11 soils. Similar

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[1] Italicized numbers in parentheses refer to the references listed at the end of the paper.

curves were made from results of compaction of the soil with 2 percent of hydrated lime added and again with 5 percent of lime. Penetrometer readings were taken on all compacted specimens.

Five natural gravels were used in Part II of the project. They came from Texas, Ohio, and Virginia and are listed in Table 1. Consistency limits of the material passing the No. 40 sieve and the grain-size distribution of each are tabulated in Table 2 and grain-size is plotted in Figure 1.

TABLE 1
LOCATION, FORMATION, AND ORIGIN OF SOILS USED

Soil No.	Soil Name	Location	Formation	Origin
664	Crosby	Central Indiana	Ground moraine	Wisconsin drift
666	Brookston	Central Indiana	Ground moraine	Wisconsin drift
669	Miami	Central Indiana	Ground moraine	Wisconsin drift
683	Switzerland	Southeast Indiana	Residual	Limestone and shale
692	Clermont	Southeast Indiana	Ground moraine	Illinoian drift
712	Zanesville	Southcentral Indiana	Residual	Sandstone and shale
718	Hagerstown	Southcentral Indiana	Residual	Limestone
727	Frederick	Southcentral Indiana	Residual	Limestone
837	Lake Charles	Texas Gulf Prairie	Coastal plain	Limey clay
889	Memphis	Southeast Mississippi	Loess	Loess
916	Ruston	Southwest Arkansas	Coastal plain	Sands and clays
920	Houston	Northeast Texas	Coastal plain	Chalk and marl
1005	Upshur	Southeast Ohio	Residual	Shale
1130	Fargo	Eastern North Dakota	Glacial lake bed	Wisconsin drift
2124[a]		Central Texas	Residual	Igneous Rock
2125[a]		Central Texas		
2126[a]		Southern Ohio	Terrace	
2127[a]		Western Virginia	Tertiary	
2128		Western Virginia	Residual	Limestone
2129		Northeast Virginia	Coastal Plain	Sand and marl
2130[a]		Northeast Virginia	Coastal Plain	Terrace
2131		Northeast Virginia	Residual	Diabase
2132		Northeast Virginia	Residual	Shale
2133		Northeast Virginia	Residual	Micaceous schist
2134		Northeast Virginia	Residual	Granite
2135	Crosby	West Central Indiana	Ground moraine	Wisconsin drift
2136	Brookston	West Central Indiana	Ground moraine	Wisconsin drift
2148		Northern Indiana	Terminal moraine	Wisconsin drift
2149		Northern Indiana	Glacial lake bed	Wisconsin drift
2150		Central Indiana	Ground moraine	Illinoian drift

[a] These soils were the natural gravels used. All others were fine-grained.

Using a modified compaction procedure and CBR molds, compaction curves were obtained for all of the samples with no admixture. Limited size of samples made it impossible to make additional compaction runs with lime added. The optimum moisture thus obtained provided a basis for estimating the amount of water to add when molding strength specimens. Maximum dry densities obtained and the moisture contents used are tabulated in Table 2.

Companion CBR specimens were molded using the raw soils and soils with 2 and 5 percent of lime added. Companion specimens of each mixture were cured under three different procedures· (1) One specimen of each mixture was tested as molded; (2) One specimen was tested after seven days in a water bath; and (3) One specimen was tested after drying to constant weight at 140 F. followed by seven days in a water bath. The bottom of the specimen while in the water bath rested on filter paper on a perforated plate and was supported a fraction of an inch above the bottom of the water tank. The sides of the mold extended 3 in. above the top of the specimen and the level of the water was held between 1 and 2 in. below the top of the mold. As a result, water gained access to the specimen only through the bottom. A perforated plate and surcharge weight rested on the top of the specimen and swell readings were taken daily. Shrinkage readings were also taken during drying.

The penetration test of the specimen was made with the standard piston and at the standard rate, using a surcharge. Readings of load were taken at 0.1-in. increments of penetration to 0.5 in. Before testing, the molds were removed from the water, allowed to drain freely for ten minutes, wiped off, and weighed. They were then returned to a water bath and tested under conditions comparable to those to which they had been subjected while soaking

Mixing, curing, and testing procedures in

Part III were the same as in Part II. The lime in all cases was mixed dry with the soil and tests were begun as soon as the water was added. Lime contents are expressed in terms of the air-dry weight of the soil. A Wabash Valley terrace gravel occurring in large quantities near Lafayette was used for Part III. Sufficient quantities of fine material were added so that the mixtures would meet, within reasonable tolerances, the specifications tabulated in Table 2 and plotted in Figure 2. Consistency limits of the portion finer than the No. 40 sieve are also given in Table 2.

TABLE 2
PHYSICAL TEST DATA ON COARSE-GRAINED SOILS

	Consistency Limits			Grain Size Distribution, percent					Compaction Data	
	Liquid Limit	Plastic Limit	Plastic Index	Plus No. 4	Passing No. 4, Plus No. 10	Passing No 10, Plus No 40	Passing No 40, Plus No. 200	Passing No 200	Max Dry Density	Moisture content Used
									lb per cu ft.	%
Gravel Binder Mixes										
0% Binder	—	—	—	50	18	17	15	0	134	5.5
5% Binder	18.4	—	—	50	18	17	10	5	141	7.0
10% Binder	31.5	18.2	13.3	50	18	17	5	10	140	7.5
Natural Gravels										
Soil 2124	27.6	—	—	38	27	24	9	2	136	9.5
Soil 2125	25.7	20.7	5.0	60	14	14	9	3	139	8.5
Soil 2126	—	—	—	0	17	30	51	2	121	12.5
Soil 2127	37.2	21.8	15.4	23	31	27	16	3	118	15.5
Soil 2130	39.7	22.7	17.0	0	24	38	31	7	123	12.5

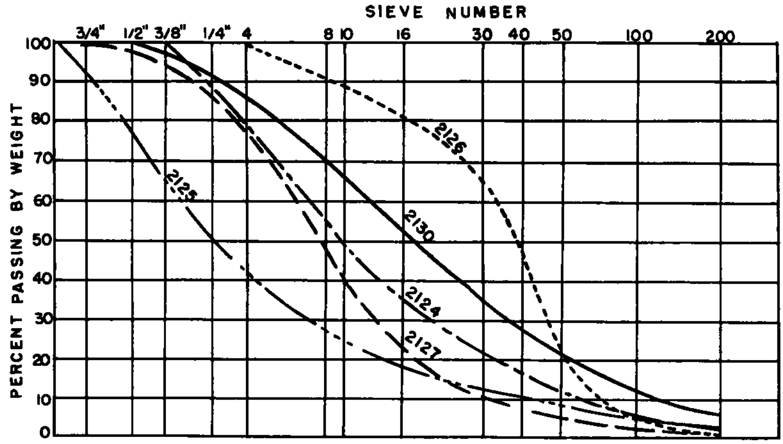

Figure 1. Grain Size Distribution of Natural Gravels

Compaction curves were determined for each of the three mixtures and specimens of each were formed with 0, 2, and 5 percent of lime. Moisture contents used in compacting the specimens are tabulated in Table 2 for all coarse-grained soils. These moisture contents are slightly less than the optimum. The specimens were cured under the conditions described above and tested with the California Bearing Ratio procedure.

RESULTS

Consistency Tests

Results of the consistency tests on the 25 fine-grained soils are tabulated in Table 3 and are briefly summarized in Table 4. For the purpose of the summary, the soils were divided into two groups on the basis of the PI of the raw soil. The ten soils with a PI under 15 were grouped together and the remaining 15 considered as another group. There is no rational basis for dividing the groups at a PI of 15 but the data grouped better with that dividing line; and, if a division were to be made between silt and clay soils on the basis of PI, it probably would not be far from 15.

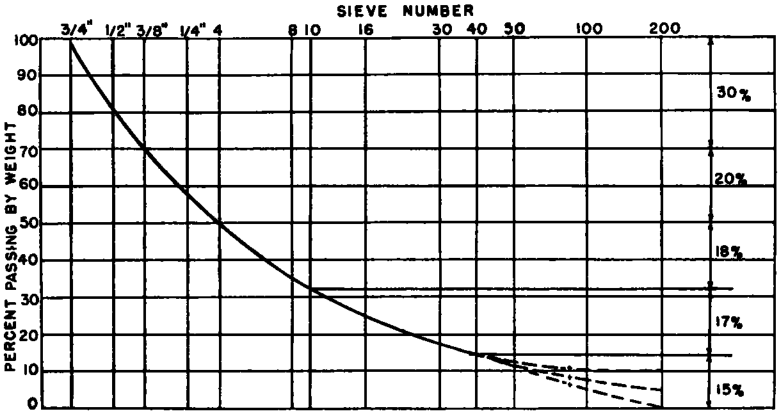

Figure 2. Grain Size Distribution of Gravel-Binder Mixes

TABLE 3
RESULTS OF CONSISTENCY TESTS ON 25 FINE-GRAINED SOILS

Soil No.	0% Lime			2% Lime			5% Lime		
	LL	PL	PI	LL	PL	PI	LL	PL	PI
664	34	19	15	33	23	10	32	22	10
666	42	24	18	39	29	10	37	27	10
669	33	18	15	34	22	12	34	24	10
683	36	19	17	35	23	12	36	24	12
692	25	15	10	28	17	11	27	17	10
712	31	18	13	34	22	12	35	23	12
718	34	19	15	38	22	16	36	23	13
727	63	23	40	58	30	28	52	35	17
837	40	17	23	38	23	15	38	26	12
889	23	19	4	23	18	5	25	17	8
916	19	13	6	22	17	5	24	18	6
920	53	26	27	49	31	18	46	32	14
1005	47	23	24	52	29	23	47	29	18
1130	64	35	29	66	41	25	59	42	17
2128	60	34	26	58	34	24	58	36	22
2129	61	36	25	60	36	24	55	38	17
2131	32	23	9	35	27	8	36	30	6
2132	50	23	27	52	24	28	51	32	19
2133	36	29	7	36	28	8	36	29	7
2134	48	38	10	48	34	14	49	37	12
2135	20	17	3	22	18	4	22	17	5
2136	51	27	24	53	32	21	55	35	20
2148	29	17	12	31	16	15	33	20	13
2149	24	14	10	26	15	11	29	15	14
2150	34	18	16	33	22	11	34	21	13

Examination of Table 3 will show, and Table 4 will confirm, that the plastic indexes of the soils whose initial PI's were 15 or above were decreased by additions of lime. Soils with PI's below 15 showed slight but nevertheless consistent increases in PI resulting from additions of lime. The ten soils with PI's ranging from 13 down to 3 had an average PI of 8.4. The average PI of the ten soils when mixed with 2 percent of lime was 9.0 and when mixed with 5 percent of lime was also 9.0, an increase of about 7 percent from the PI with no lime. On the other hand, the 15 soils whose PI's ranged from 15 to 40, with an average of 22.7, had an average PI of 18.4 with 2 percent of lime and 14.9 with 5 percent of lime, decreases of 19 and 34 percent respectively.

TABLE 4
SUMMARY OF CONSISTENCY TESTS ON 25 FINE-GRAINED SOILS

	0% Lime	2% Lime	5% Lime	Percent Change with	
				2% Lime	5% Lime
				%	%
Average of 10 Silty Soils, PI < 15					
Liquid Limit	28.7	29.9	30.6	+4.2	+6.6
Plastic Limit	20.3	20.9	21.6	+3.0	+6.4
Plastic Index	8.4	9.0	9.0	+7.1	+7.1
Average of 15 Clayey Soils, PI ≥ 15					
Liquid Limit.	46.8	46.5	44.7	−0.6	−4.5
Plastic Limit.	24.1	28.1	29.8	+16.6	+23.6
Plastic Index	22.7	18.4	14.9	−18.9	−34.4

Table 4 shows that for the silty soils, both the liquid and plastic limits were increased slightly following the additions of lime, The liquid limit increased slightly more than the plastic limit with the result that the plastic index was increased slightly. With the more plastic soils, however, the liquid limit was slightly decreased with lime while the plastic limit was increased very appreciably, resulting in a decided drop in plastic index.

TABLE 5
RESULTS OF CURING-TIME SERIES ON 16 FINE-GRAINED SOILS

Soil No.	Days	0% Lime			2% Lime			5% Lime		
		LL	PL	PI	LL	PL	PI	LL	PL	PI
669	0	33	18	15	34	22	12	34	24	10
	7	39	22	17	38	25	13	37	25	12
	14	40	20	20	39	25	14	43	30	13
692	0	25	15	10	28	17	11	27	17	10
	7	23	16	7	26	18	8	33	23	10
	14	23	15	8	26	17	9	33	22	11
727	0	63	23	40	58	30	28	52	35	17
	7	65	26	39	59	33	26	56	44	12
	14	60	26	34	61	32	29	74	47	27
920	0	53	26	27	49	31	18	46	32	14
	7	57	26	31	48	33	15	64	45	19
	14	56	27	29	57	27	30	67	50	17
1130	0	64	35	29	66	41	25	59	42	17
	7	67	34	33	67	41	26	75	51	24
	14	68	36	32	67	40	27	76	51	25
2128	0	60	34	26	58	34	23	58	36	22
	7	62	27	35	56	30	26	55	34	21
	14	61	27	34	55	27	28	55	34	21
2129	0	61	36	25	60	36	24	55	38	17
	7	60	33	27	64	35	29	56	35	21
	14	59	31	28	62	37	25	57	36	21
2131	0	32	23	9	35	27	8	36	30	6
	7	34	23	11	35	27	8	41	31	10
	14	35	23	12	36	26	10	42	33	9
2132	0	50	23	27	52	24	28	51	32	19
	7	48	22	26	53	27	26	51	32	19
	14	49	21	28	53	26	27	53	31	22
2133	0	36	29	7	36	28	8	36	29	7
	7	36	28	8	37	28	9	34	25	9
	14	35	27	8	36	29	7	35	28	7
2134	0	48	38	10	48	34	14	49	37	12
	7	47	33	14	49	36	13	51	38	13
	14	48	34	14	47	33	14	55	39	16
2135	0	20	17	3	22	18	4	22	17	5
	7	20	17	3	21	17	4	20	17	3
	14	20	17	3	21	18	3	20	17	3
2136	0	51	27	24	53	32	21	55	35	20
	7	55	30	25	54	33	21	55	36	19
	14	56	29	27	53	34	19	54	34	20
2148	0	29	17	12	31	16	15	33	20	13
	7	30	16	14	31	16	15	32	18	14
	14	30	16	14	31	17	14	32	18	14
2149	0	24	14	10	26	15	11	29	15	14
	7	24	13	11	26	14	12	29	15	14
	14	25	14	11	27	14	13	28	15	13
2150	0	34	18	16	33	22	11	34	21	13
	7	36	18	18	32	21	11	38	25	13
	14	36	17	19	33	20	13	41	28	13

Table 5 is the complete tabulation of the results of the curing-time series on 16 of the fine-grained soils. The results tabulated for a curing time of 0 days are those given in Table 3 but are repeated here for ready comparison. The results tabulated for 7 and 14 days curing time are those obtained from tests run on specimens 7 and 14 days after they had been mixed with water and covered. Seven of these 16 soils had PI's under 15, varying from 12 to 3 with an average of 8.7. The remaining nine, averaging 25.4, ranged from 15 to 40 in PI. The results of this series are summarized in Table 6.

It will be observed that allowing the soil to stand for a period of time after wetting tends to cause a slight increase in the PI. This trend is apparent with the raw soil as well as with that to which lime has been added.

TABLE 6
SUMMARY OF TIME SERIES ON 16 FINE-GRAINED SOILS

Time of Curing	Percent of Lime		
	0%	2%	5%
	Seven Silty Soils, PI < 15		
days			
0	8.7	10.1	9.6
7	9.7	9.8	10.4
14	10.0	10.0	10.4
	Nine Clayey Soils, PI ≥ 15		
0	25.4	21.2	16.6
7	27.9	21.0	20.0
14	27.9	23.6	19 9

The tendency of the more plastic soils to show markedly decreased plasticity with additions of lime, as observed in Table 4, is repeated in Table 6 for the 0 days curing time. If the data for 7 days curing time and 14 days curing time are examined it will be seen that the same property is evidenced. The PI noticeably decreased with additions of lime. The curing time makes little difference in the effect of the lime on the plasticity of the soil.

The silty soils also evidence a slight increase in plasticity with a period of curing. This tendency may be stronger in the raw soil than in that to which lime has been added. The tendency of the PI to increase with additions of lime is somewhat less strongly evidenced by the 7-day and 14-day data than by the 0-day data. However, the variations shown in this table are too slight to be taken as a positive indication.

These data are shown graphically by Figure 3 which shows the plotted data for five soils of the group. The Miami and Fargo soils most ideally represent the data for the more plastic soils. They show slight increases in plastic index with curing time but fairly consistent decreases in PI with additions of lime in spite of time. The Houston and Frederick soils show the trend but not as ideally. The Clermont soil is fairly typical of the silty soils, showing slight increases in PI with lime and not much change as a result of curing time.

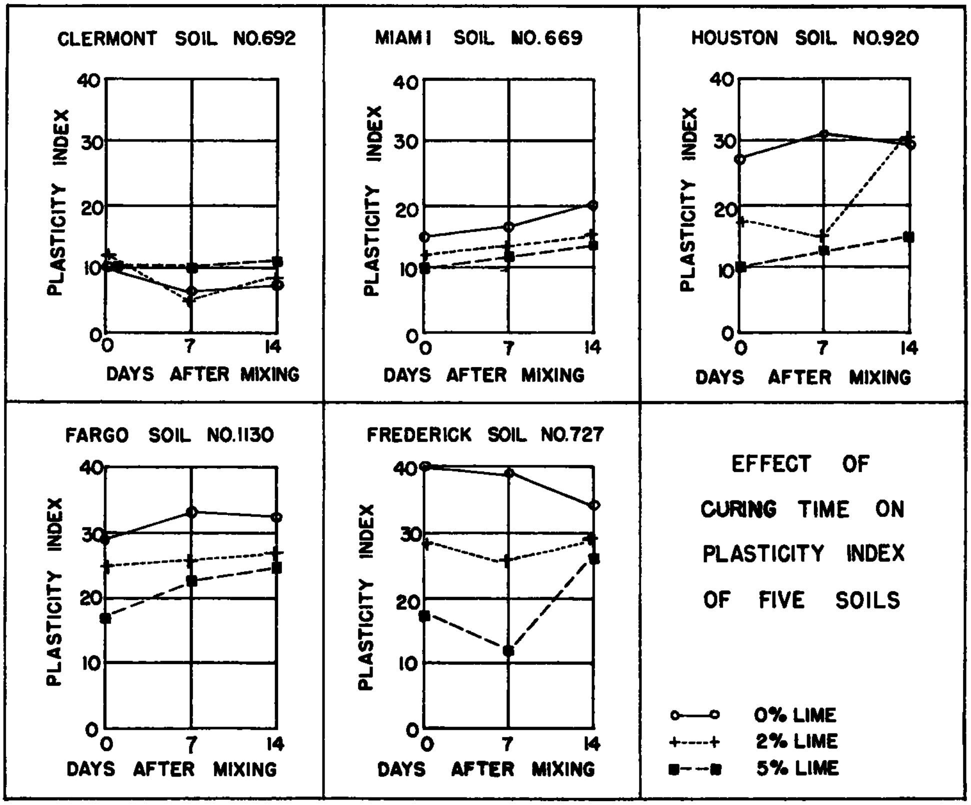

Figure 3

TABLE 7
RESULTS OF TESTS WITH LIME AND LIME DUST ON THREE FINE-GRAINED SOILS

Soil	0%			2%						5%					
				Lime			Dust			Lime			Dust		
	LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI
699 Miami	33	18	15	34	22	12	37	21	16	34	24	10	38	20	18
727 Frederick	63	23	40	58	30	28	62	27	35	52	35	17	57	26	31
920 Houston	53	26	27	49	31	18	54	28	26	46	32	14	54	24	30

The results of tests on three soils to determine the comparative effect of lime dust are tabulated in Table 7 and shown graphically in Figure 4. The data for the raw soils and those using lime are taken from Table 3. In Figure 4, the total height of the zero-percent bar is the PI of the raw soil. The total heights of the bars at two and at five percent are the values of the PI using lime dust. The lime dust led to an increase in PI for two of the soils and to decreases in the Frederick soil. The height of the cross-hatched bar represents the PI using lime, showing that hydrated lime was much more effective in reducing the PI of these soils than was the powdered limestone.

density with 2 and 5 percent of lime in terms of the maximum dry density obtained with no lime.

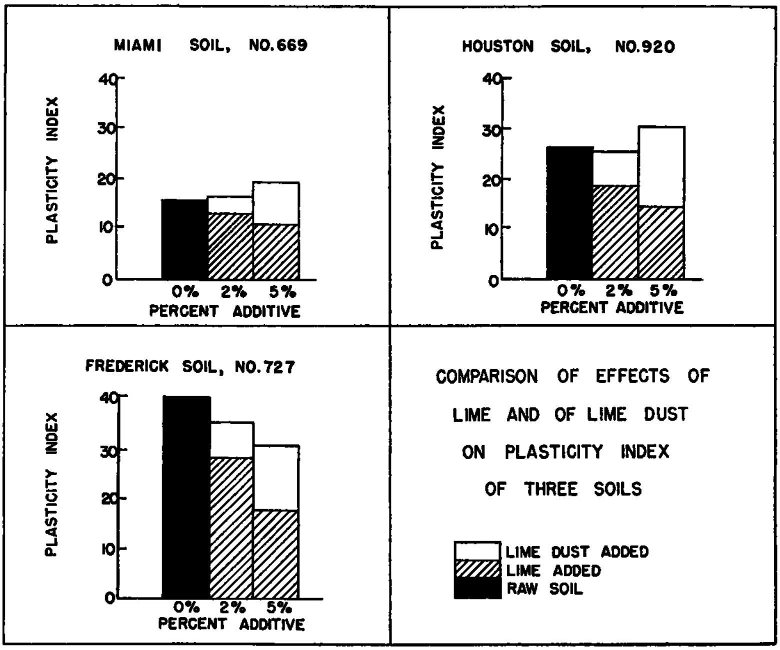

Figure 4

TABLE 8
RESULTS OF PROCTOR COMPACTION OF 11 FINE-GRAINED SOILS WITH AND WITHOUT LIME

Soil		Plastic Index	0% Lime		Dry Density		Per cent Change in Dry Density	
No.	Type		Optimum Moisture	Max. Dry Density	2% Lime	5% Lime	2% Lime	5% Lime
				pcf.	*pcf.*	*pcf.*		
2128	Limestone Residual	26	29.2	89.4	88.7	87.2	−0.8	−2.5
2129	Coastal Plain Sand & Marl	25	23.5	95.3	94 2	93.1	−1.2	−2.3
2131	Weathered Diabase	9	17.1	113.9	114.6	115.1	+0.6	+1.1
2132	Triassic Shale	27	20.0	101.6	101.9	102.8	+0.3	+1.2
2133	Micaceous Schist	7	19.3	100.2	96.3	94.7	−3.9	−5.5
2134	Granite Residual	10	24.4	95.2	93.6	94.3	−1.5	−0.9
2135	Wisconsin Drift—Crosby	3	14.8	109.6	109.3	106.4	−0.3	−2.9
2136	Wisconsin Drift—Brookston	24	21.5	93.7	92.1	91.6	−1.7	−2.2
2148	Clay—Shale Moraine	12	16.0	110.0	107.7	107.2	−2.1	−2.5
2149	Lakebed Clayey Sand	10	14.7	111.8	107.7	107.2	−3.7	−4.1
2150	Illinoian Drift	16	16.5	109.2	107.1	105.4	−1.9	−3.5

Compaction

A summary of the results from the Proctor compaction of the 11 fine-grained soils is given in Table 8. This table gives the optimum moisture content and maximum dry density obtained with the raw soil, as well as the dry density obtained. Also tabulated are the percentage changes in maximum dry

Nine of the soils showed decreases in maximum dry density, varying from 0.3 to 3.9 percent with 2 percent of lime and from 0.9 to 5.5 percent with 5 percent of lime. The remaining two soils showed slight increases, up to 1.2 percent, in maximum dry density with increases in lime. The plastic indexes of these soils varied from 3 to 27 and the densities from 89.4 to 113.9 lb. per cu. ft. One of the soils, No. 2131, which showed an increase in density with lime was the one with raw density of 113.9 lb. per cu. ft. The other soil which showed an increase in density had an original density of 101.6. There is no apparent correlation between change in density with lime and either plasticity or dry density. The only evident trend is a lowering of maximum dry density with additions of lime. As the family of curves for each soil takes the usual form, the lowered maximum density is accompanied by a slightly higher optimum moisture content.

Curves of penetration resistance readings on all compactions were plotted. Figure 5 shows the plots for two of the soils. Soil 2131 is the most dense of the soils used and is one of the two soils which showed increased densities using lime. Soil 2133 is the soil which evidenced the greatest drop in density with additions of lime.

Insofar as the resistance to the penetration of the needle is a measure of the strength of the specimen, the penetration plots indicate that the additions of lime add to the strength of the soil even though the density is less. Nine of the eleven soils used evidenced increased resistance to penetration resulting from the use of lime at all moisture contents used. The remaining two soils showed some variation at the lower moisture contents but appeared stronger with lime at the optimum moisture content.

Since the optimum moisture contents with lime were generally higher than with no lime, a comparison of strengths at the optimum moisture contents – or at the respective maximum densities – in some instances showed approximately equal or even lower strengths with added lime. For example, soil No. 2133 as indicated in Figure 5 had moisture contents for the three mixtures as shown by the dotted line. This indicates about the same penetration resistance for each mixture of soil and lime at its own maximum density. On the other hand, soil No. 2131 showed much higher penetration resistance for the lime mixes at their maximum densities.

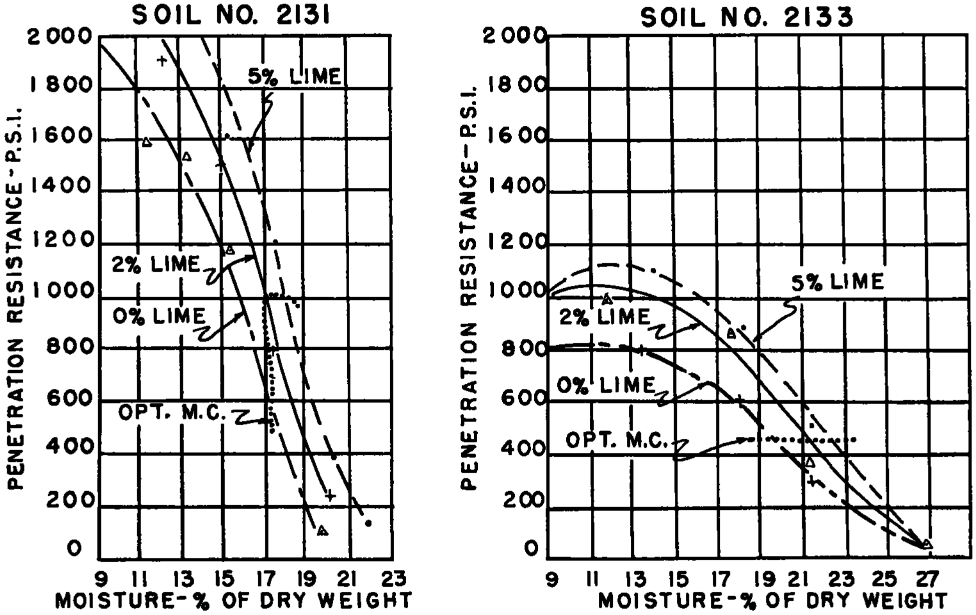

Figure 5. Effect of Lime on Penetration Resistance

Natural Gravels

The bar graphs of Figure 6 show a representative part of the results of the California Bearing Ratio tests on one of the natural gravels (No. 2125). These results and those for the other gravels are given in tabular form

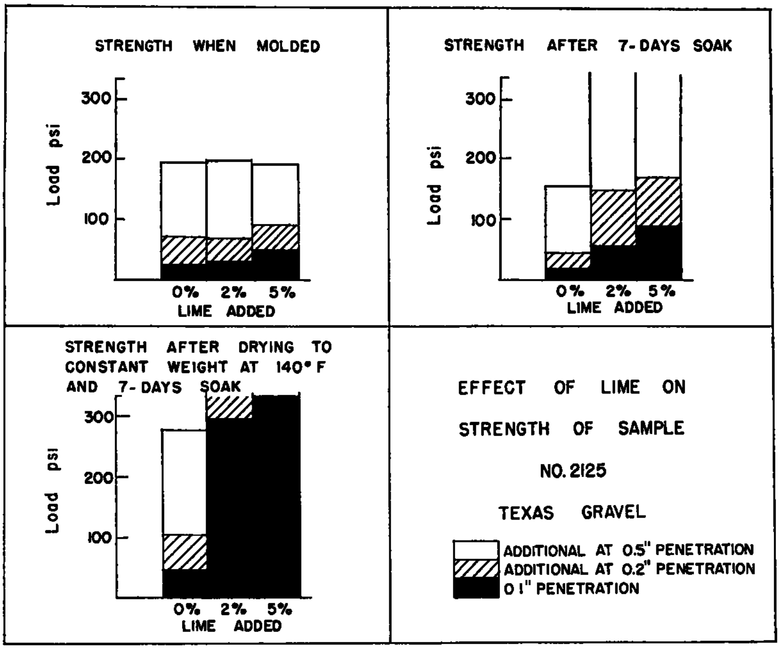

Figure 6

TABLE 9
PARTIAL RESULTS IN POUNDS PER SQUARE INCH OF CBR TESTS ON NATURAL GRAVELS

Soil	Per cent Lime	Tested as Molded			Tested After 7 Days Soak			Tested After Dried and Soaked		
		0.1"	0.2"	0.5"	0.1"	0.2"	0.5"	0.1"	0.2"	0.5"
2124	0	30	63	127	87	111	160	48	85	155
	2	53	105	213	63	130	198	167	[a]	[a]
	5	54	92	168	67	139	257	[a]	[a]	[a]
2125	0	25	73	193	18	45	155	47	105	277
	2	29	69	195	55	147	[a]	295	333	[a]
	5	50	90	190	89	169	[a]	[a]	[a]	[a]
2126	0	9	16	17	8	15	17	8	13	15
	2	10	18	24	7	15	27	57	88	85
	5	.7	15	26	9	15	39	53	96	110
2127	0	24	36	53	9	13	20	4	6	13
	2	30	41	60	12	16	22	16	23	35
	5	28	40	62	34	44	63	70	103	144
2130	0	18	28	47	11	19	32	10	17	31
	2	36	49	63	33	39	60	42	65	113
	5	14	25	45	17	31	62	228	[a]	[a]

[a] Penetration not reached within capacity of machine, 335 psi.

in Table 9. The bearing value obtained, in pounds per square inch using a piston with an end area of 3 sq. in., is plotted for each percentage of lime used. The height of the black bar is the bearing value obtained at a penetration of 0.1 inch. The ordinate of the top of the cross-hatched bar is the bearing value obtained at a penetration of 0.2 inch and the ordinate at the top of the white bar is the value of 0.5-inch penetration. The capacity of the machine used was about 335 psi. so that some of the bars are not closed off at the top, indicating that the corresponding penetration was not reached within the load limits of the machine.

Comparison of the heights of the black bars will give an indication of the relative strengths obtained at 0.1-inch penetration with 0, 2, and 5 percent of lime. Similarly the tops of the hatched bars compare strengths at 0.2-inch penetration and the white bars the values at 0.5-inch penetration.

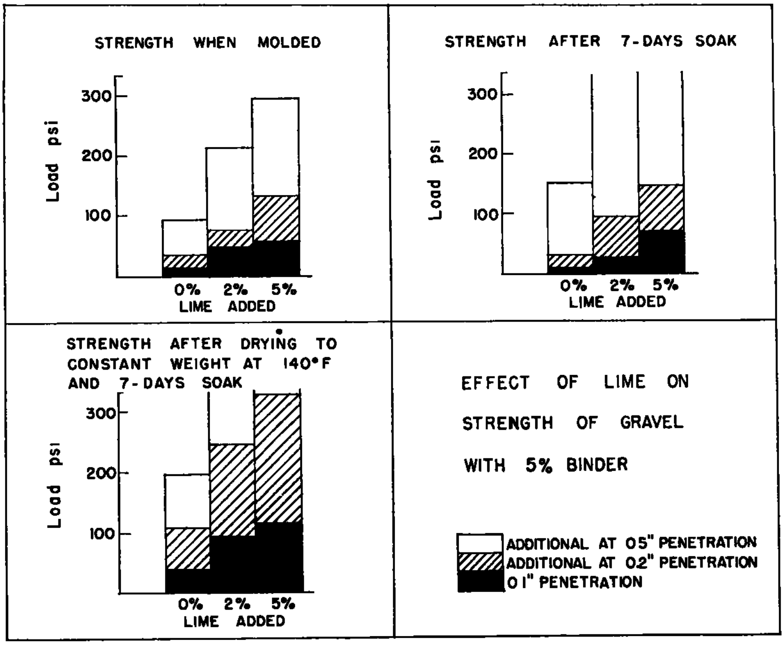

Figure 7

TABLE 10

PARTIAL RESULTS IN POUNDS PER SQUARE INCH OF CBR TESTS ON GRAVEL-BINDER MIXES

Soil	Per cent Lime	Tested as Molded			Tested after 7 days Soak			Tested after Drying and 7 Days Soak		
		0.1″	0.2″	0.5″	0.1″	0.2″	0.5″	0.1″	0.2″	0.5″
Gravel with 0% Binder	0	40	57	80	14	29	47	30	50	65
	2	100	110	113	37	94	90	184	219	178
	5	69	117	179	42	118	206	273	[a]	[a]
Gravel with 5% Binder	0	11	33	92	10	33	151	40	108	195
	2	22	74	213	27	94	[a]	93	246	[a]
	5	57	132	293	71	146	[a]	115	328	[a]
Gravel with 10% Binder	0	13	40	88	5	27	170	7	24	140
	2	20	65	236	26	111	[a]	84	240	[a]
	5	30	104	220	42	125	[a]	222	222	[a]

[a] Penetration not reached within capacity of machine, 335 psi.

The molded strengths of these five gravels (Table 9) show no significant changes as a result of adding lime. In most instances, however, the additions of lime to the soil were accompanied by noticeable increases in strength following a curing period. In all cases addition of five percent of lime to the soil produced higher strength even after seven days of soaking than was obtained with the lime and no curing, whereas the soil with no lime after seven days soaking was generally weaker than when molded. Two of the raw soils, No. 2124 and No 2125, were stronger after the combined drying-and-soak curing than they were as molded, but the other three soils showed a lower strength after the curing cycle. On the other hand, all the soils showed a greatly increased strength with the addition of five percent of lime after the combined curing cycle and all but one showed greater strengths with two percent of lime.

It will be observed that additions of lime in general tend to increase the strength of the gravels with the two methods of curing used and that use of five percent of lime resulted in much higher strengths than two percent of lime.

Gravel Binder Mixes

Partial results of the CBR tests on the gravel-binder mixes are tabulated in Table 10. The results for the 5-percent binder mix are illustrated graphically in Figure 7. In every instance, additions of lime to the soil resulted in increased strength, and in all but a few cases the higher percentage of lime led to higher strengths than were obtained with two percent of lime. The strength of the raw soils after curing varied both above and below the strengths obtained when molded. Strengths after the seven days of soaking with both two percent and five percent of lime with the soils containing binder were greater than were obtained with the same gravel-binder-lime mixtures when molded. This was not true of the gravel with no binder. All three gravel-binder mixes with both two and five percent of lime showed greatly increased strengths following the combined curing cycle. It will be seen with all eight coarse-grained samples used that the additions led to a greatly increased strength with the drying-and-soaking cycle as compared to the soaking cure. This increase in strength is not evident in the samples with no additive so that it appears that the lime is the direct cause of the added strength observed following the combined curing cycle. No correlation was found between the increase in strength resulting from the combined curing and the moisture content—or change in moisture content—at the time of testing.

CONCLUSIONS

The results of the tests reported here lead to the following conclusions for the range of soils used:

1. Additions of two and five percent of lime reduce the plasticity of the more plastic soils very markedly but cause little significant increase and may lead to a decrease of the plastic index of soils with plastic indexes under 15.

2. A period of moist curing of a sample before running the consistency tests may cause a slight increase in PI but makes no significant change in the comparative effect of lime upon the plastic index.

3. Lime dust added to plastic soils is less effective in lowering the plastic index than is hydrated lime.

4. Additions of two and five percent of lime in general will contribute to lowered maximum Proctor densities, but resistance to penetration is increased at a given moisture content by the additions of lime.

5. Additions of lime to natural gravels and gravel binder mixes lead to increases in strength as measured by the California Bearing Ratio test. This increase in strength occurs after a period of wet curing and even more strongly after a period of dry curing followed by wet curing.

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