Shear Strength and Elastic Properties of Lime-Soil Mixtures

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•THE SHEAR strength properties of a material are essential for the rational analysis and design of a flexible pavement structure. McCleod (1), Hewitt (2), and others have used shear strength parameters for evaluating the load-carrying capacity of flexible pavements. Many flexible pavement design procedures are based on the shear strength properties of the pavement materials. The Texas and Kansas triaxial design techniques and procedures are among the most renowned. McDowell (3) has shown excellent correlation between the Texas triaxial procedures and the performance of the flexible test sections at the AASHO Road Test.

If lime-soil mixtures are to be effectively used as paving materials, it is necessary to develop information concerning their shear strength properties. This information is required for determining the structural behavior of the material in addition to its usefulness in triaxial design procedures.

INVESTIGATION

The objectives of this study were (a) to investigate the shear strength and elastic properties of typical lime-soil mixtures, (b) to evaluate the influence of soil type and curing time on these properties, and (c) to determine the relationships, if any, between shear strength properties and unconfined compression test results.

Materials

Four typical Illinois soils were used in the testing program. Previous laboratory experience with these soils indicated that they reacted very satisfactorily with lime. These soils display a wide range of such properties as clay content, mineralogy, and plasticity. Selected soil properties, the lime treatments used, and the percent of dry weight of soil, are given in Table 1.

A commercially produced, high-calcium hydrated lime was used throughout the study. The lime contained 96 percent $Ca(OH)_2$, and 95 percent passed the No. 325 sieve.

Specimen Preparation

Mixing. —Proper quantities of lime and air-dry soil were thoroughly blended in a Lancaster mixer. The amount of water required to bring the lime-soil mixture to optimum moisture content was then added, and mixing continued for approximately 2 min. Following mixing, the lime-soil mixture was covered and allowed to stand 1 hr before specimens were compacted.

Compaction. —All specimens were compacted at approximately optimum moisture content as determined by a moisture-density test. This test was conducted in a manner similar to AASHO T99-57 except that 2-in. diameter by 4-in. high molds were used and the compactive effort was applied through 20 blows of a 4-lb hammer having a 12-in. drop. This compactive effort produces maximum dry densities and optimum moisture contents similar to those obtained from Method A of AASHO T99-57 test for moisture-density relations of soils. Optimum moisture contents and maximum dry densities for the various soils and lime-soil mixtures are given in Table 2.

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TABLE 1

SELECTED SOIL PROPERTIES

Soil	AASHO Class.	< 2μ Clay (%)	L. L. (%)	P. I. (%)	Carbonates (%)	Predom. Clay Mineral	Lime Treat. (%)
Bryce B	A-7-6 (18)	52	53. 1	28. 8	NC[a]	Illite	5
Illinoian till	A-6 (6)	14	25. 5	11. 0	18. 6	Illite	3
Fayette C	A-6 (8)	21	31. 9	10. 1	20. 0	Montmorillonite	5
Wisconsinan loam till	A-4 (8)	18	24. 5	7. 8	13. 8	Illite	3

[a]Noncalcareous.

TABLE 2

COMPACTION PROPERTIES

Soil	Lime (%)	Max. Dry Density (pcf)	Opt. Moist. (%)
Bryce B	0	101. 9	20. 5
	5	97. 3	25. 8
Illinoian till	0	125. 3	11. 3
	3	121. 0	13. 0
Fayette C	0	110. 5	18. 1
	5	108. 6	18. 3
Wisconsinan loam till	0	122. 4	12. 0
	3	120. 0	12. 0

A series of sixteen 2-in. diameter by 4-in. high specimens was prepared for each test condition, i. e., lime percentage, soil type, and curing period. The specimens were molded in three equal layers with each layer receiving a compactive effort of 20 blows of a 4-lb hammer dropping 12 in. Each layer was scarified to provide bond between the adjacent layers. After proper trimming, the specimens were extruded from their molds and cured.

Curing. --After compaction, trimming, and extrusion, the specimens were placed in 1-gal metal cans, and the can lids sealed with Perma-Tex. The lime-soil specimens were then placed in a 120 F curing cabinet for periods of 1, 2, 4, or 6 days. These curing conditions produce strengths that are comparable to those developed under field curing conditions (4).

The natural soil specimens were allowed to cure for 7 days at ambient room temperature to allow for thixotropic effects.

Testing Procedures

At the termination of the prescribed curing period, the specimens were allowed to cool to room temperature and then tested in triaxial compression (unconsolidated-undrained test).

The 16 specimens were divided into four equal-sized groups and one specimen from each group was selected at random to be tested at a given air-confining pressure (σ_3) of 0, 5, 15, or 35 psi. The samples were loaded at a constant rate of deformation of 0. 05/ in./min., and periodic readings of applied load and total deformation of the specimen were recorded until maximum load was achieved.

Samples taken from representative specimens following testing indicated that the specimens were at approximately the same moisture content as at the time of preparation.

Determination of C and ϕ

The cohesion intercept, C, and angle of shearing resistance, ϕ, were determined statistically by a process used by Herrin (5). The procedure is described below.

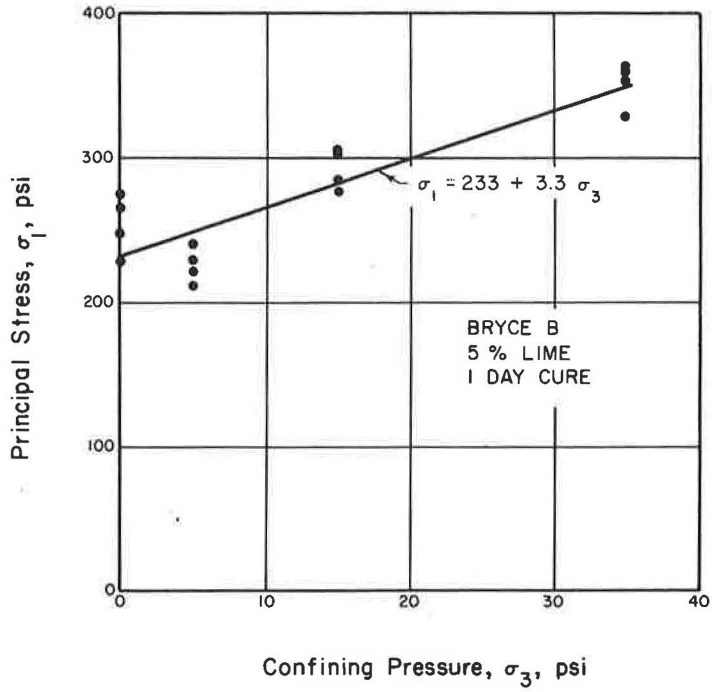

Figure 1. Influence of confining pressure on maximum principal stress.

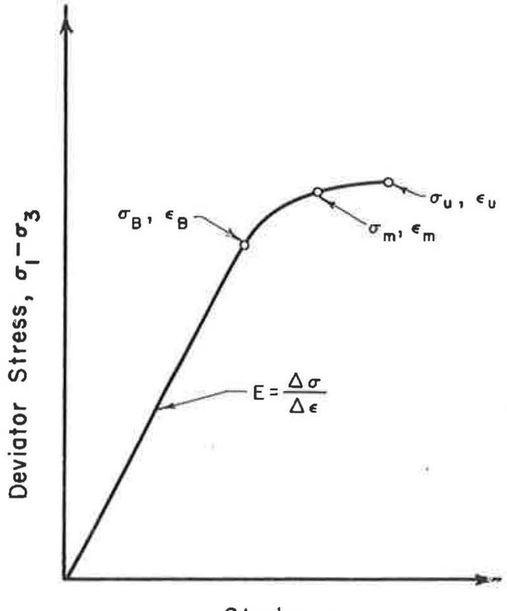

Figure 2. Composite stress-strain curve.

1. A plot of σ_1, maximum normal stress applied, vs σ_3, confining pressure, was prepared (Fig. 1).

2. The best least-squares regression equation for the data was determined. The equation (Fig. 1) was of the form $\sigma_1 = a + b\,\sigma_3$.

3. C and ϕ were calculated from the following relationships:

$$C = \frac{a}{2\sqrt{b}} \qquad \sin\phi = \frac{b-1}{b+1}$$

Evaluating Elasticity Properties

A composite or average stress-strain relationship was established for each series of four lime-soil specimens tested at a given confining pressure, σ_3. The composite relation (Fig. 2) was developed using the technique described in the appendix.

ANALYSIS OF TEST RESULTS

Shear Strength Properties

Pertinent shear strength properties for the natural soils and the lime-soil mixtures included in the investigation are

TABLE 3

SHEAR STRENGTH DATA

Soil	Lime (%)	Shear Strength: 7 Days at 73 F C (psi)	ϕ	E (ksi)[a]	1 Day at 120 F C (psi)	ϕ	E (ski)[a]	2 Days at 120 F C (psi)	ϕ	E (ski)[a]	4 Days at 120 F C (psi)	ϕ	E (ski)[a]	6 Days at 120 F C (psi)	ϕ	E (ksi)[a]
Bryce B	0	39	11.5	5.70												
	5				64	32.5	29.0	158	13.4	54.0	178	32.7	81.3	159	21.2	73.0
Illinoian till	0	60	13.0	8.60												
	3				94	34.2	28.4	113	35.5	63.5	129	32.1	56.7	250	27.0	87.5
Fayette C	0	22	17.6	6.50												
	5				108	14.5	52.5	93	37.0	63.0	149	43.7	115.0	386	14.2	160.0
Wisconsinan loam till	0	48	7.5	5.25												
	3				105	25.0	48.0	139	13.0	58.3	184	27.4	77.8	164	36.8	91.9

[a]E computed at 15 psi confining pressure.

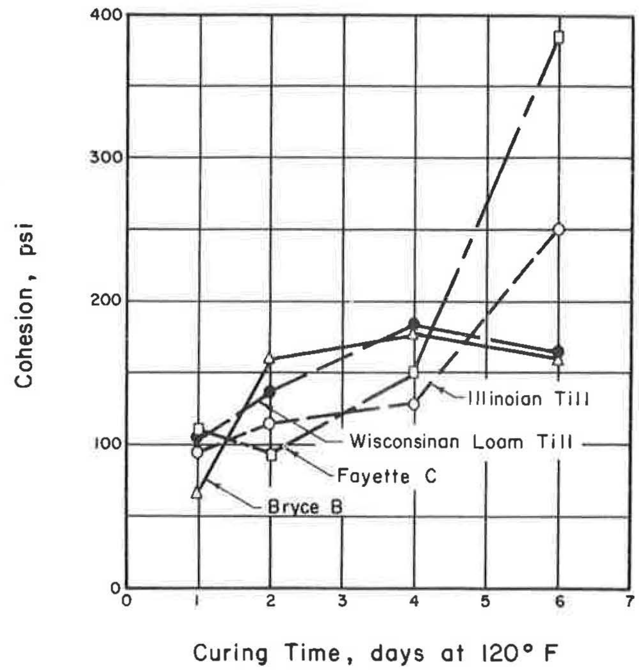

Figure 3. Influence of curing time on cohesion of lime-soil mixtures.

TABLE 4

COHESION (C)-UNCONFINED COMPRESSIVE STRENGTH (q_u) LINEAR REGRESSION ANALYSIS SUMMARY (Analysis of Variance[a])

Source of Variation	Degrees of Freedom	Sum of Squares	Variance	F
Total	15	87,145		
Regression	1	77,089	77,089.0	107.3[b]
Residual	14	10,056	718.3	

[a]Regression equation: C (psi) = 9.3 + 0.292 q_u (psi).
[b]Significant at α = 0.01.

given in Table 3. The lime treatment greatly improved the shear strength of the soils.

Substantial cohesion increases were obtained with every soil, the magnitude of the increase depending on the soil type and length of curing period. For the 1-day curing periods, the cohesion values of the lime-soil mixtures were 1.5 to 5 times larger than the cohesion of the untreated soils. Longer curing periods generally produced further increases in cohesion (Fig. 3). Cohesion values for the 6-day curing period varied from 159 to 386 psi.

Statistical analysis of the unconfined compressive strength and cohesion values for the lime-soil mixtures indicated a highly significant linear regression relation (Table 4). The regression equation, C (psi) = 9.3 + 0.292 q_u (psi) is shown in Figure 4.

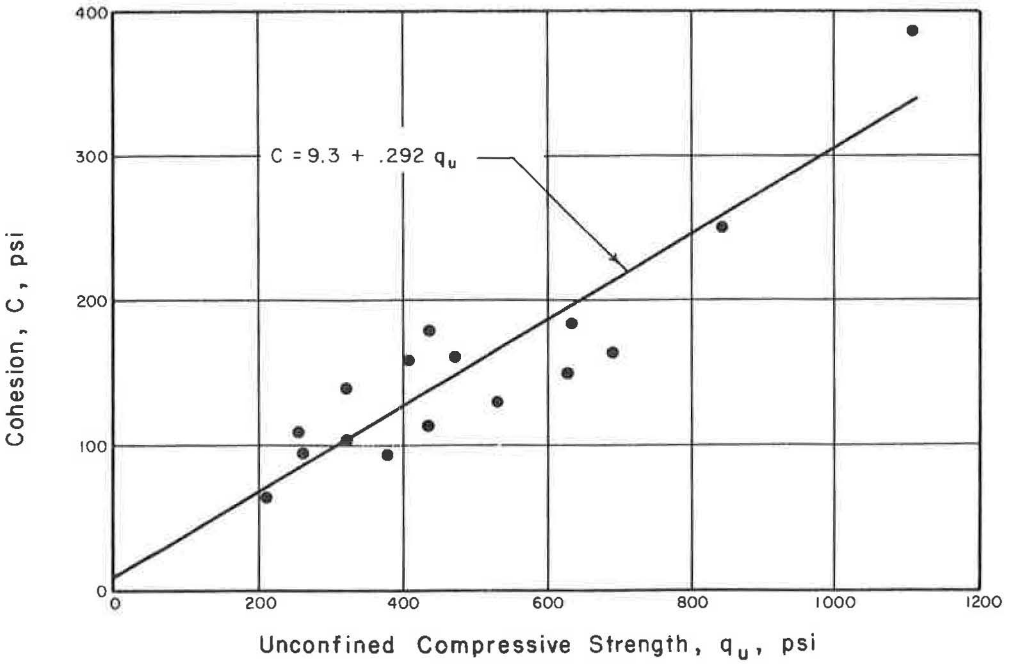

Figure 4. Cohesion vs unconfined compressive strength of lime-soil mixtures.

In every case except two, the cured lime-soil mixtures displayed a larger angle of shearing resistance, ϕ, than the untreated soil. The majority of the ϕ values for the lime-soil mixtures ranged from 25 to 35 deg. The data do not indicate any apparent trend between ϕ and curing time or soil type.

It is very difficult to evaluate ϕ effectively for materials such as lime-soil mixtures, which are characterized by very high cohesion. In this study, the cohesion was so large that small specimen-to-specimen variations in cohesion may have negated the effect of the low confining pressures, 0 to 35 psi, used. More realistic determinations of ϕ would require extremely high confining pressures for eliminating the influence of cohesion variations. Considering the very high cohesion of lime-soil mixtures and the low confining pressures normally assumed to exist in a flexible pavement structure, extremely elaborate high-pressure triaxial tests to obtain a more precise determination of ϕ may not be justified.

Elasticity Properties

A summary of pertinent stress-strain properties (E, ϵ_B, ϵ_u, σ_B, σ_u) for the natural soils and the lime-soil mixtures is given in Table 5. Figure 5 shows typical stress-strain curves.

The modulus of elasticity, E, of the cured lime-soil mixtures ranged from 28,000 to 160,000 psi, and the range was from 5,200 to 8,600 psi for the natural soils. Longer curing periods for the lime-soil mixtures generally produced an increase in E (Fig. 6). Increased confining pressure had little effect on E, the value remaining essentially constant for all magnitudes of confining pressures used.

The increase in E with longer curing periods is similar to the strength vs curing-time relation for lime-soil mixtures. Figure 7 shows the relation between E determined for a confining pressure of 15 psi and the unconfined compressive strength of the lime-soil mixtures. Linear regression analysis of the data indicated a highly significant regression between the variables (Table 6). The regression equation, E (ksi) = 9.98 + 0.1235 q_u (psi) is shown in Figure 7.

TABLE 5

SUMMARY OF STRESS-STRAIN PROPERTIES

Soil	Lime (%)	Curing (days at 120 F)	Confining Pressure (psi)	E (ksi)	ϵ_B (%)	ϵ_u (%)	σ_B (psi)	σ_u (psi)	σ_B/σ_u
Bryce B	0	–[a]	0	4.9	1.24	3.04	61	93	–
			5	4.8	1.73	3.58	83	104	–
			15	5.7	1.30	3.41	74	108	–
			35	5.0	1.92	3.12	96	110	–
	5	1	0	27.5	–	1.00	–	210	–
			5	31.1	0.65	1.08	203	254	0.80
			15	29.0	0.73	1.34	211	276	0.76
			35	30.1	0.76	1.59	229	318	0.72
	5	2	0	62.8	0.50	0.89	313	410	0.76
			5	57.6	0.47	1.03	273	403	0.68
			15	54.0	0.53	1.02	288	401	0.72
			35	59.6	0.53	0.96	315	428	0.74
	5	4	0	72.5	0.41	0.86	300	441	0.68
			5	64.6	0.52	0.90	333	440	0.76
			15	81.3	0.41	0.95	335	491	0.68
			35	71.3	0.50	1.16	354	520	0.68
	5	6	0	93.6	0.37	0.68	348	473	0.74
			5	80.1	0.41	0.79	328	461	0.71
			15	73.0	0.46	0.93	335	470	0.71
			35	67.1	0.50	1.21	335	506	0.66
Wisconsinan loam till	0	–[a]	0	6.4	1.48	2.93	95	133	–
			5	2.3	2.67	4.00	61	78	–
			15	5.2	1.33	3.06	70	111	–
			35	4.4	2.43	3.44	108	125	–
	3	1	0	47.5	0.55	0.96	262	322	0.81
			5	57.1	0.53	0.83	304	365	0.83
			15	48.0	0.57	1.03	274	376	0.73
			35	57.1	0.48	0.88	271	363	0.75
	3	2	0	58.1	0.41	0.71	238	322	0.74
			5	55.4	0.54	0.91	299	379	0.79
			15	58.3	0.38	0.94	221	365	0.61
			35	59.0	0.39	0.96	228	364	0.63
	3	4	0	86.1	0.59	0.90	508	637	0.80
			5	83.4	0.55	0.92	455	629	0.72
			15	77.8	0.63	1.06	492	644	0.76
			35	75.7	0.69	1.18	521	684	0.76
	3	6	0	98.3	0.55	0.88	542	692	0.79
			5	91.9	0.48	0.82	533	637	0.84
			15	91.9	0.55	1.04	506	710	0.71
			35	95.0	0.59	1.15	556	759	0.73
Fayette C	0	–[a]	0	4.3	1.16	1.92	50	63	–
			5	3.6	1.39	2.04	50	59	–
			15	6.4	0.92	1.60	60	77	–
			35	6.8	1.02	1.82	69	90	–
	5	1	0	41.6	0.44	0.73	185	258	0.72
			5	48.9	0.40	0.96	198	320	0.62
			15	52.5	0.36	0.77	189	290	0.65
			35	54.4	0.37	0.81	199	300	0.66
	5	2	0	60.0	0.50	0.78	303	378	0.80
			5	67.4	0.42	0.83	282	406	0.70
			15	63.0	0.46	0.95	292	422	0.69
			35	78.3	0.36	1.00	283	465	0.61
	5	4	0	155.0	0.34	0.50	523	630	0.83
			5	113.3	0.44	0.84	493	750	0.66
			15	115.0	0.43	0.86	492	770	0.64
			35	124.7	0.47	0.91	582	830	0.70
	5	6	0	187.7	0.41	0.75	770	1110	0.69
			5	153.0	0.58	0.92	885	1180	0.75
			15	160.0	0.58	0.92	935	1210	0.77
			35	205.0	0.40	0.74	832	1162	0.72
Illinoian till	0	–[a]	0	10.8	1.05	2.15	113	148	–
			5	8.1	1.12	2.51	91	132	–
			15	8.6	1.16	2.25	100	134	–
			35	10.9	0.92	2.58	100	152	–
	3	1	0	29.4	0.71	1.13	210	265	0.79
			5	35.6	0.55	1.11	196	279	0.70
			15	28.4	0.70	1.47	200	308	0.65
			35	38.3	0.63	1.36	243	352	0.69
	3	2	0	–	–	–	–	435	–
			5	63.1	0.52	0.97	328	463	0.71
			15	63.5	0.51	1.00	325	460	0.71
			35	71.6	0.53	1.03	379	541	0.70
	3	4	0	55.0	0.71	1.24	392	532	0.74
			5	54.7	0.64	1.18	348	502	0.69
			15	56.7	0.59	1.22	332	517	0.64
			35	55.9	0.75	1.24	420	540	0.78
	3	6	0	104.1	0.63	1.01	658	845	0.78
			5	91.4	0.70	1.07	640	787	0.81
			15	87.5	0.63	1.13	550	798	0.69
			35	89.2	0.80	1.25	713	908	0.78

[a]Cured 7 days at room temperature.

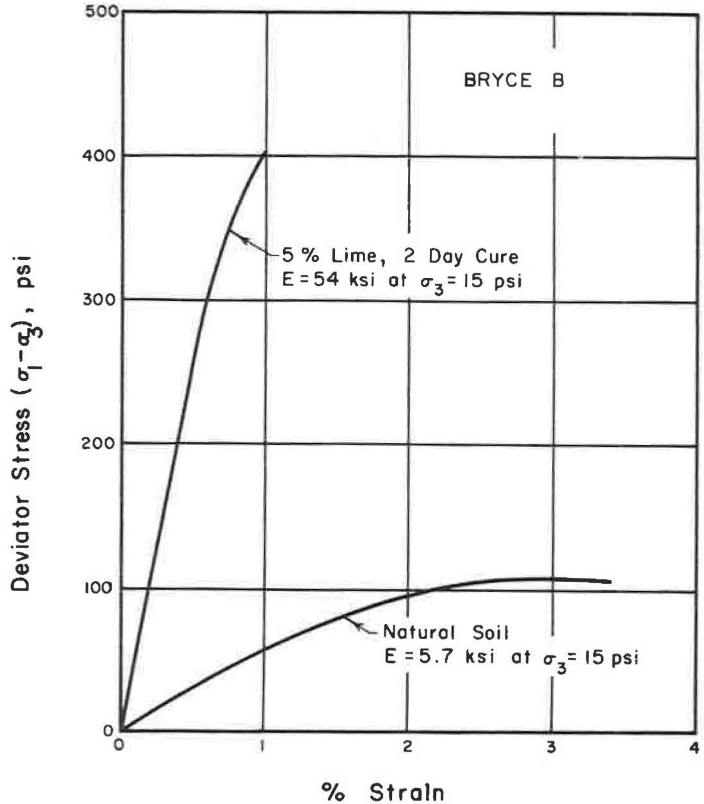

Figure 5. Typical stress-strain curves for natural and lime-treated soil.

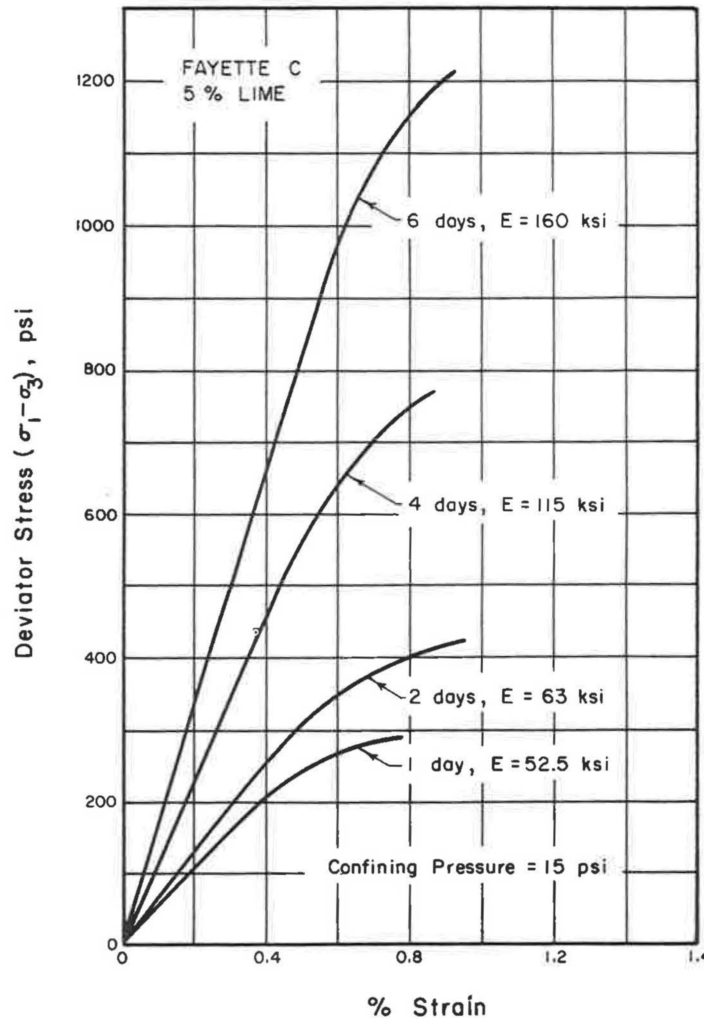

Figure 6. Influence of curing time on stress-strain properties of lime-soil mixture.

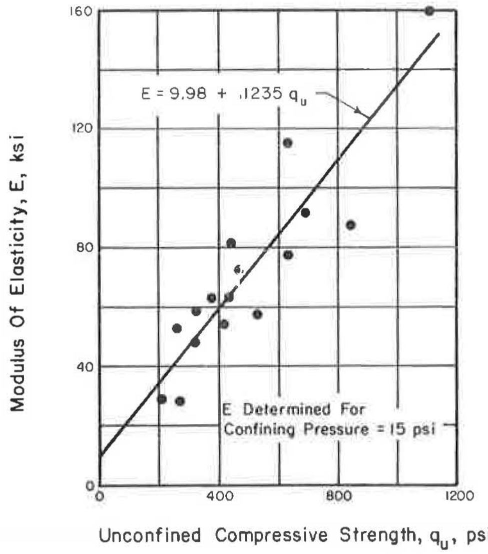

Figure 7. Modulus of elasticity vs unconfined compressive strength of lime-soil mixtures.

TABLE 6

MODULUS OF ELASTICITY (E) - UNCONFINED COMPRESSIVE STRENGTH (q_u) LINEAR REGRESSION ANALYSIS SUMMARY (Analysis of Variance[a])

Source of Variation	Degrees of Freedom	Sum of Squares	Variance	F
Total	15	15,951		
Regression	1	13,252	13,252	68.7[b]
Residual	14	2,699	192.8	

[a]Regression equation: E (ksi) = 9.98 + 0.1235 q_u (psi).
[b]Significant at $\alpha = 0.01$.

The failure strains, ϵ_u, for the lime-soil mixtures were decreased in relation to those exhibited by the natural soils (Fig. 5). Typical failure strains for the lime-soil mixtures were approximately 1 percent, compared to 2 or 3 percent for the untreated soils. Completely randomized design statistical analyses (Table 7) of the lime-soil mixture failure strains at different confining pressures indicated that for one-half of the mixes an increase in confining pressure produced larger failure strains. For the remainder of the mixtures there was no statistically significant influence of confining pressure on ϵ_u.

To evaluate the influence of soil type and curing period on failure strains, the average failure strains at a confining pressure of 15 psi for the various lime-soil mixtures and curing periods were statistically analyzed in a randomized complete block design. The analysis indicated that there was no statistically significant difference among the failure strains, regardless of soil type or curing period (Table 8). The average failure strains, ϵ_u, for all of the lime-soil mixtures analyzed was 1.02 percent.

TABLE 7

INFLUENCE OF CONFINING PRESSURE (σ_3) ON FAILURE STRAINS (ϵ_u)
(Statistical Summary of Completely Randomized Designs[a])

Soil	Lime (%)	Curing (days at 120 F)	Treatment[b] Variance	Variance	F
Bryce B	5	1	28.35	2.0	14.2[c]
		2	2.0	2.5	0.8
		4	6.33	1.42	4.46[c]
		6	19.33	0.58	33.2[c]
Illinoian till	3	1	7.33	4.1	1.79
		2	0.5	1.62	0.31
		4	0.0	4.1	0.0
		6	2.0	4.9	0.41
Fayette C	5	1	3.67	0.82	4.5[c]
		2	4.0	1.8	2.22
		4	10.67	0.91	11.7[c]
		6	3.67	1.36	2.7
Wisconsinan loam till	3	1	2.0	5.73	0.35
		2	6.33	0.33	19.0[c]
		4	6.33	1.18	5.36[c]
		6	8.0	1.09	7.34[c]

[a]In all analyses degrees of freedom were 3 for treatment and 12 for error.
[b]Treatment corresponds to various confining pressures.
[c]Significant at $\alpha = 0.05$ level.

TABLE 8

INFLUENCE OF SOIL TYPE AND CURING PERIOD ON AVERAGE FAILURE STRAINS OF LIME-SOIL MIXTURES AT σ_3 OF 15 psi

(a) Statistical Summary of Randomized Complete Block Design

Curing Period (days at 120 F)	Lime-Soil Mixture			
	Bryce B	Illinoian Till	Fayette C	Wisconsinan Loam Till
1	13.5[a]	11.2	7.7	10.5
2	10.3	10.1	9.8	9.5
4	9.6	12.3	8.6	10.5
6	9.3	11.3	9.3	10.4

(b) Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Variance	F[a]
Total	15	29.1		
Curing period	3	1.4	0.47	0.27
Lime-soil mixture	3	12.3	4.1	2.40
Error	9	15.4	1.71	

[a]Average strain values are × 10^{-3} in./in.
[b]F values not significant at $\alpha = 0.05$.

TABLE 9

INFLUENCE OF CONFINING PRESSURE (σ_3) ON ϵ_B (Statistical Summary of Completely Randomized Designs[a])

Soil	Lime (%)	Curing (days at 120 F)	Treatment[b] Variance	Error Variance	F
Bryce B	5	1	0.43	1.30	0.33
		2	0.67	1.17	0.57
		4	1.33	0.34	3.88[c]
		6	1.17	0.33	3.6[c]
Illinoian till	3	1	1.0	5.5	0.18
		2	0.0	0.73	0.0
		4	5.67	8.8	0.64
		6	3.0	1.8	1.67
Fayette C	5	1	1.07	1.63	0.66
		2	1.37	0.79	1.73
		4	1.13	0.42	2.69
		6	4.07	0.65	6.3[c]
Wisconsinan loam till	3	1	0.9	1.9	0.47
		2	1.93	0.72	2.68
		4	1.37	0.85	1.61
		6	0.1	0.43	0.23

[a]In all analyses degrees of freedom were 3 for treatment and 12 for error.
[b]Treatment corresponds to confining pressure.
[c]Significant at $\alpha = 0.05$

TABLE 10

INFLUENCE OF SOIL TYPE AND CURING PERIOD ON AVERAGE ϵ_B

(a) Statistical Summary of Randomized Complete Block Design

Curing Period (days at 120 F)	Lime-Soil Mixture			
	Bryce B	Illinoian Till	Fayette C	Wisconsinan Loam Till
1	7.2[a]	6.9	4.1	5.7
2	5.2	5.2	4.4	4.3
4	4.6	6.4	4.2	6.2
6	4.4	7.0	5.0	5.7

(b) Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Variance	F[b]
Total	15	41.9		
Curing	3	3.0	1.0	0.29
Lime-soil mixture	3	7.7	2.56	0.74
Error	9	31.2	3.47	

[a]Average strain values are $\times 10^{-3}$ in./in.
[b]F values not significant at $\alpha = 0.05$.

TABLE 11

INFLUENCE OF SOIL TYPE AND CURING PERIOD ON AVERAGE σ_B/σ_u RATIO

(a) Statistical Summary of Randomized Complete Block Design

Curing Period (days at 120 F)	Lime-Soil Mixture			
	Bryce B	Illinoian Till	Fayette C	Wisconsinan Loam Till
1	0.76[a]	0.66	0.71	0.78
2	0.72	0.70	0.71	0.69
3	0.70	0.71	0.71	0.76
6	0.71	0.73	0.77	0.77

(b) Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Variance	F[b]
Total	15	2.13		
Curing	3	0.0	0.0	0.0
Lime-soil mixture	3	0.84	0.28	1.96
Error	9	1.29	0.143	

[a]Average σ_B/σ_u ratio based on all specimens.
[b]F values not significant at $\alpha = 0.05$.

The strains at which the stress-strain curves departed from a linear relation, ϵ_B, were analyzed to determine if confining pressure, soil type, or curing period influenced the value. Completely randomized design statistical analyses of the data indicated that for 13 of the 16 lime-soil mixtures there was no significant difference for ϵ_B at different confining pressures (Table 9). Thus, ϵ_B for a given lime-soil mixture and curing period could be averaged to provide a representative ϵ_B. Statistical analysis of the average ϵ_B values indicated that there was no significant difference among the various lime-soil mixtures (Table 10). The overall average of ϵ_B, regardless of soil type, confining pressure, or curing period, was 0. 54 percent.

The data suggest that σ_B, the deviator stress corresponding to the strain ϵ_B, varies in relation to σ_u, the ultimate deviator stress. Close analysis of the data indicates that for a given lime-soil mixture and curing period the σ_B/σ_u for all confining pressures was therefore taken to be representative of a lime-soil mixture cured for a particular period. Table 5 gives the average σ_B/σ_u values for the various mixtures, curing periods, and confining pressures. Statistical analysis of the data indicates no significant difference among the σ_B/σ_u ratios, regardless of soil type and curing period (Table 11). The overall average, 0. 72, is therefore the best estimate of σ_B/σ_u for these lime-soil mixtures.

DISCUSSION

Shear Strength

The major effect of lime on the shear strength properties of a reactive fine-grained soil is to produce a substantial increase in cohesion, with some minor increase in ϕ. At the low confining pressures normally considered to exist in a flexible pavement structure, the cohesion increase is of the greatest significance.

McCleod (1) has demonstrated the value of cohesion to the ultimate bearing capacity of a flexible pavement structure. He stated, "The important contribution that the existence of cohesion, C, in any layer, surface, base, or subbase makes to the ultimate strength of a flexible pavement is one of the major conclusions indicated. . . . " Using McCleod's ultimate strength approach, it can be shown that if the lime-soil mixtures studied in this investigation were used in pavement components of normal thicknesses, the ultimate strength would be much larger than required for normal wheel loading and traffic conditions.

Theoretical analyses of shear stresses in pavement systems have been conducted by many investigators. In some instances, the maximum shearing stress is taken as one-half the difference of the principal stresses (6), but Mehta and Veletsos (7) evaluated the vertical shear stress component at various points in a layered system. Although the maximum shear stress in a pavement is dependent on the properties and characteristics of the particular pavement system and wheel loading condition, the maximum theoretical shear stress is substantially less than the tire contact pressure if the pavement is of normal thickness, greater than 6 to 8 in.

Assuming a simple pavement system similar to that in Figure 8, and using analytical procedures recommended by McDowell (6) and Mehta and Veletsos (7), the maximum shearing stresses in such a system are less than approximately 50 psi. Shear stresses of this magnitude would not cause shearing failure in any of the materials investigated in this study.

Modulus of Elasticity

The large E increase produced by lime treatment of a fine-grained soil has important implications regarding pavement system behavior. If a subgrade soil is stabilized, the modular ratio, $E_{lime\text{-}soil}/E_{subgrade}$, will be much larger than unity. Inasmuch as the modulus of elasticity of the lime-soil mixture increases with curing time, the effective modular ratio for the pavement system also varies. For the materials in this investigation the modular ratios for different mixtures ranged from approximately 3 to 25. Theoretical analyses have shown that in such a layered pavement system, substantial flexural stresses are developed in the layer containing the lime-soil mixture.

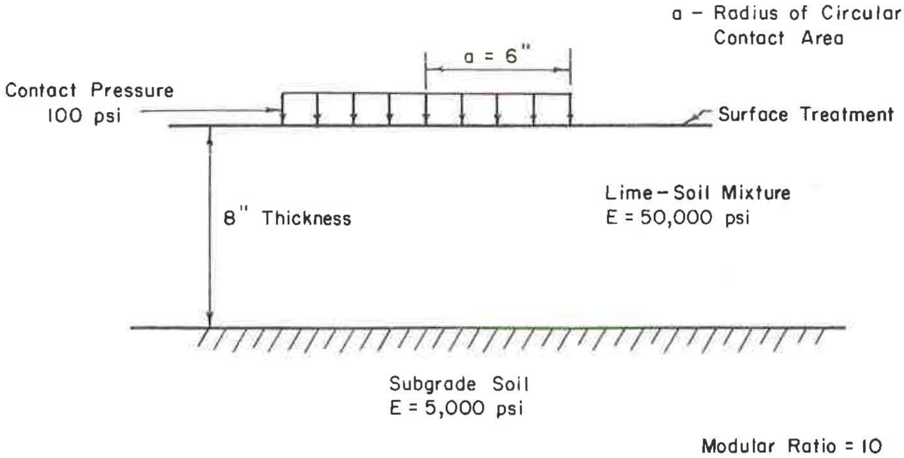

Figure 8. Typical lime-soil pavement section.

Thompson's work (8) indicated that lime-soil mixtures possess tensile-strength properties capable of resisting the flexural stresses developed. The behavior of the lime-soil layer over the untreated subgrade is therefore dissimilar from a typical flexible pavement due to the slab action which can be developed by the lime-soil mixture. The slab action of lime-soil mixtures has been considered by McDowell (3) in the Texas triaxial design procedure, and reductions in pavement layer thicknesses are permitted if the material has a substantial tensile strength as measured by the cohesiometer test.

Stress-Strain Properties

The typical stress-strain curves (Figs. 5 and 6) show that lime-soil mixtures under compressive states of stress at low confining pressures are fairly brittle materials and display a limited amount of inelastic yielding.

A significant finding of the study is that the ultimate strain, ϵ_u, at 15 psi confining pressure, is not significantly different for the various mixtures included in the study, although a large range of ultimate strengths, σ_u, were obtained. The finding suggests that the stress-strain properties of lime-soil mixtures are primarily determined by the hydrated calcium silicate and calcium aluminate cementing agents produced by lime treatment. Because the same basic cementing agents are present in all of the lime-soil mixtures, when the critical limiting strain for the cementing agents is achieved, failure occurs. Similarly, increased moduli of elasticity and strengths for the various mixtures and curing periods are due to the formation of larger quantities of the cementing agents and more cemented contact points in the material. The 1 percent ultimate strain, ϵ_u, may be an important design consideration because it suggests a limiting strain failure criteria. This behavior can be explained partially by the close positive correlation between E and the strength of the lime-soil mixtures.

As statistical analysis of the stress-strain data indicated that ϵ_u at 15 psi confining pressure, ϵ_B, and σ_B/σ_u were not significantly different for the various lime-soil mixtures, pertinent stress-strain characteristics can be defined for a wide strength range. Average values for these parameters as determined from this study, are

ϵ_u at 15 psi confining pressure = 1.02 percent;
ϵ_B = 0.57 percent; and
σ_B/σ_u = 0.72

General

The foregoing discussion indicates that in the rational design of a lime-soil mixture pavement layer, the shear strength of the mixture is probably not critical. The high modular ratios and mixture tensile-strength properties result in the generation of substantial flexural stresses in the lime-soil layer. These flexural stresses are probably the controlling factor in any rational design considerations if subgrade stresses are within an allowable range. The foregoing comments are based on the assumption that the lime-soil mixture is durable and retains its strength and integrity throughout its service life.

SUMMARY AND CONCLUSIONS

The shear strength and stress-strain properties of four soils and four lime-soil mixtures were evaluated. Curing periods for the lime-soil mixtures varied from 1 to 6 days at 120 F. Unconsolidated-undrained type triaxial tests with total deformation measurements were conducted on the cured samples. The test results suggest the following conclusions:

1. Lime treatment substantially increases the shear strength of lime-reactive soils. This improvement is primarily due to a large increase in cohesion with small increases in the angle of shearing resistance, ϕ.
2. The moduli of elasticity, E, of the lime-soil mixtures were much larger than the E of the untreated soils. Modular ratios, $E_{lime-soil}/E_{soil}$, of 3 to 25 were obtained for the materials studied.
3. Increased curing periods normally produced lime-soil mixtures with higher shear strengths and moduli of elasticity.
4. The cohesion, C, and modulus of elasticity, E, of the cured lime-soil mixtures investigated can be predicted based on unconfined compression test results.

$$C\,(psi) = 9.3 + 0.292\, q_u\,(psi)$$
$$E\,(ksi) = 9.98 + 0.1235\, q_u\,(psi)$$

5. Ultimate failure strains for the lime-soil mixtures were decreased in relation to the untreated soils. For the mixtures studied, the failure strains at 15 psi confining pressure were not significantly different for the various lime-soil mixtures and curing periods. The average ultimate strain was approximately 1 percent.
6. The strains at which the lime-soil stress-strain curves departed from a linear relation, ϵ_B, were not significantly different for the mixtures studied. The average value for ϵ_B was 0.54 percent.
7. The stress, σ_B, corresponding to ϵ_B was equal to approximately 0.72 σ_u for the different lime-soil mixtures, irrespective of soil type and curing period.
8. In typical flexible pavement structures the shear shear strengths of the mixtures studied were sufficient to prevent shear failure of the lime-stabilized layer. Flexural stresses in the stabilized layer will probably be the controlling factor in a rational design procedure for lime-soil mixtures of a quality comparable to those included in this investigation.

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Appendix

METHOD FOR DETERMINING COMPOSITE STRESS-STRAIN RELATION

1. Graphs of deviator stress, $\sigma_1 - \sigma_3$, vs strain were prepared for each specimen.

2. An initial tangent modulus of elasticity (E_1, E_2, E_n, etc.) was evaluated for each specimen from the straight-line portion of its stress-strain curve. An average modulus of elasticity, E, was determined by $E = E_1 + \ldots + E_n/n$.

3. The deviator stress at which the stress-strain curve departed from a linear relation was designated σ_{B1}, σ_{B2}, σ_{Bn}, etc. An average stress corresponding to this point was determined by $\sigma_B = \sigma_{B1} + \ldots + \sigma_{Bn}/n$. A strain value for σ_B was evaluated by $\epsilon_B = \sigma_B/E$.

4. The maximum deviator stresses for the four stress-strain curves σ_{u1}, σ_{u2}, σ_{un}, etc., were averaged to provide an average ultimate strength, σ_u.

5. An average ultimate strain value, ϵ_u, corresponding to σ_u was evaluated by averaging, for the four specimens, the magnitude of the strains that occurred between σ_{Bn} and σ_{un} and adding this average strain increment to ϵ_B.

6. An intermediate deviator stress value (σ_m) for the strain, ϵ_m, corresponding to the point midway between ϵ_B and ϵ_u was determined by averaging, for the four specimens, the stresses occurring at the strain halfway between the strains associated with σ_{Bn} and σ_{un}.

7. Utilizing the values computed above, E, σ_B, ϵ_B, σ_u, ϵ_u, σ_m, and ϵ_m, the composite stress-strain curve was plotted (Fig. 2).