Durability Properties of Lime-Soil Mixtures

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An open freeze-thaw durability test which simulated the freeze-thaw conditions in typical pavements was developed using four representative Illinois soils which reacted well with lime. Two accelerated curing periods, 48 and 96 hours at 120 F, were used. The durability test consisted of realistic freezing and thawing temperatures, a readily available source of water, a thermal gradient which was developed by using a vacuum flask, and repeated cycles of freezing and thawing. A large number of freeze-thaw cycles was used so that significant durability trends could be analyzed more fully.

The four methods used to evaluate the freeze-thaw durability of the lime-soil mixtures were unit length change, unconfined compressive strength, moisture distribution, and visual inspection. All four evaluation methods adequately assessed the freeze-thaw durability of the lime-soil mixtures. However, unit length change and unconfined compressive strength were the most informative of the four methods. Based on the evaluation methods, the rank of the four lime-soil mixtures in decreasing order of durability were Illinoian till (Sangamon County), Bryce B, Sable B, and Champaign County till.

•MANY engineering properties must be considered when evaluating lime-soil mixtures for use as paving materials. Durability, which can be defined as the ability of a material to retain stability and integrity over the years of exposure to the destructive forces of weathering, is one of the most important properties.

Since weathering is the major condition which causes deterioration, there are many factors which may contribute to durability failures in stabilized soils. The mechanisms of deterioration depend on both the properties of the stabilized soil and the intensity and nature of the exposure conditions. A survey of the durability literature indicated that freeze-thaw tests have adequately served for evaluating the durability of stabilized highway materials (soil-cement, lime-fly ash aggregate) which are similar to cured lime-soil mixtures.

The purpose of this study was to determine whether soils which react with lime to form substantially stronger materials are sufficiently durable for use in the construction of pavement bases and subbases. A three phase durability program was developed:

1. Establishment of realistic freeze-thaw laboratory testing procedures and methods;
2. Collection of laboratory data; and
3. Analysis and evaluation of laboratory results.

PREPARATION OF TEST SPECIMENS

Materials

The durability study was limited to four typical Illinois soils which react well with lime: Champaign County till, Illinoian till (Sangamon County), Bryce B, and Sable B.

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A hydrated high calcium lime containing 96 percent available $Ca(OH)_2$ with 95 percent passing the No. 325 sieve was used in all of the test mixtures. The natural properties and the lime-soil mixture properties for the four soils are summarized in Table 1.

Mixture Design and Preparation

Only that portion of the soil which passed the No. 4 sieve was used in the test mixtures. The amount of lime added to the soil consisted of the optimum percentage (dry weight basis) determined from previous strength studies by Thompson (1). The required amounts of soil and lime were initially dry mixed with a Lancaster mortar mixer to insure uniform distribution of the lime throughout the soil. After dry mixing, enough water was added to the mixture to bring it to the optimum moisture content (AASHO T-99) and mixing continued for approximately 3 minutes. After mixing, the lime-soil mixture was tightly covered to prevent moisture loss and allowed to mellow 1 hour before compaction.

Compaction Procedure for Test Specimens

The test specimens for the freeze-thaw test were prepared by compacting the lime-soil mixture into 2-in. diameter by 4-in. steel molds in 3 equal layers. Each layer was scarified to insure bonding between the layers. The compaction hammer had a 2-in. diameter base and the compactive effort was applied by a 4-lb weight falling freely through a distance of 12 in. In order to produce uniform densities in the compacted lime-soil specimens, the compactive effort was different for each layer (Table 1). This method of compaction produced average densities equivalent to those obtained from AASHO T-99.

Curing Procedures

Accelerated curing periods of 48 and 96 hours at 120 F were used. Studies by Anday (2) and unpublished results from the University of Illinois have indicated that compacted

TABLE 1

NATURAL SOIL AND LIME-SOIL MIXTURE PROPERTIES

Item	Soil			
	Champaign County Till	Bryce B	Sable B	Illinoian Till (Sangamon Count)
General description	A Wisconsinan loam till; typical throughout the Midwest.	A humic-gley (B horizon) derived from thin loess over Wisconsinan drift.	A humic-gley (B horizon) derived from loess.	Typical Illinoian t
Natural soil properties:				
AASHO classification	A-4-6	A-7-6(18)	A-7-6(16)	A-6(6)
< 2 μ clay, %	16	52	36	14
Liquid limit, %	22.5	53.1	50.7	25.5
Plasticity index, %	7	28.8	23.5	11.0
Carbonates	Calcareous	Noncalcareous	Noncalcareous	18.6%
pH	8.3	7.4	7.8	8.3
Predominant clay mineral	Illite-chlorite	Illite	Mixed Layer	Illite-chlorite
Lime-soil mixture properties:				
Lime treatment, %	3	5	3	3
Optimum water content, %	11.5	25.8	20.1	13.0
Maximum dry density, pcf	120	97.3	100	121
Compaction, blows/layer (top-middle-bottom)	26-20-14	45-30-15	60-40-20	60-35-10
Initial cure	48 hr at 120 F 96 hr at 120 F	48 hr at 120 F 96 hr at 120 F	48 hr at 120 F 96 hr at 120 F	48 hr at 120 F 96 hr at 120 F
Number of freeze-thaw specimens tested	20	20	20	20

lime-soil mixtures cured for 48 hours at 120 F attain strengths approximately equivalent to 30 to 45 days' curing at 70 F. This length of cure was therefore assumed to be representative of field conditions. The specimens were cured in plastic bags to prevent moisture loss.

DEVELOPMENT OF FREEZE-THAW TEST

British Standard Test 1924: 1957 (3) and a modified freeze-thaw test developed by George and Davidson (4) were used as guidelines for the development of the laboratory freeze-thaw durability test for lime-soil mixtures. These tests consisted of an open freeze-thaw system and simulated the freeze-thaw conditions in typical pavements. Such factors as a realistic freezing temperature, a readily available source of water, a thermal gradient, and repeated cycles of freezing and thawing were included.

Temperature Considerations

It was decided to adapt the freeze-thaw durability test for lime-soil mixtures to the climatic conditions of a specified area. Much of the pertinent data concerning the weather conditions which affect durability can be obtained from local weather stations. The average minimum air temperature in Champaign, Ill., during the months of November through March was chosen as a typical freezing temperature. Analysis of climatic data indicated that the average minimum air temperature was 22 F for the 5-month period (5). Analysis of soil temperature data for the Champaign area revealed that the average daily soil temperatures were 30 F at 4-in. depth and 31 F at 12-in. depth during the 5-month period (5). Therefore, during winter the top surface of a typical pavement would have an average temperature similar to that of the air (22 F) and the bottom surface would have an average temperature similar to that of the surrounding soil (30 to 31 F).

Approximate calculations showed that thawing temperatures for the Champaign area range from about 35 F to 45 F during winter. However, rapid and complete thawing, which is considered to be the type most detrimental to the strength of stabilized base course materials, generally occurs at higher temperatures; therefore, a high thawing temperature, greater than 60 F for example, may be reasonable for a freeze-thaw durability test.

Number of Freeze-Thaw Cycles

Freeze-thaw data from the AASHO Road Test indicated that 3 to 7 cycles of freezing and thawing occurred each year (6). However, 12 freeze-thaw cycles were chosen for the durability study to provide for more variable winter temperatures than those at the Road Test.

Test Procedure

The detailed test procedure used in the freeze-thaw study is presented elsewhere.[1] All specimens were soaked (complete immersion) in demineralized water at 77 ± 4 F for a period of 24 hours before testing. The durability tests consisted of 12 cycles of 16 hours' freezing and 8 hours' thawing. A vacuum flask was used to produce a thermal gradient between the top and bottom of the specimen. The bottom of each specimen was in contact with water during freezing and thawing.

The test temperatures were based on the values established for the Champaign area. During the freezing period, an air temperature of 22 ± 2 F was maintained at the tops of the specimens and an equilibrium temperature of about 32 F was reached at the bottoms of the specimens. The water at the bottoms of the specimens did not freeze. An air

[1]The original manuscript of this paper contained an appendix with supporting information given in detail. This appendix may be obtained from the Highway Research Board by special arrangement as to cost of reproduction and handling. Inquiries should refer to XS-16, Record 235.

temperature of 77 ± 2 F was used during thawing to insure rapid and complete thawing in the 8-hr period. The specimens were thawed outside of the vacuum flasks. Unit length change, unconfined compressive strength, moisture distribution, and visual ratings were used to evaluate the durability of the lime-soil mixtures.

EVALUATION METHODS

Unit Length Change

Packard and Chapman (7) have indicated that length change is a very sensitive and direct measure of deterioration in soil-cement during freeze-thaw testing. Similarly it was hypothesized that a unit length change measurement (inches of length change per inch of specimen height) would be an effective way to measure the deterioration in cured lime-soil mixtures.

Length changes in four specimens were measured with a comparator at the end of each freeze and each thaw cycle. All length changes were determined as the change from the initial reading taken after the 24-hr soak period and were recorded to the nearest 0.001 in. Due to the degree of scatter in the unit length change data, it was believed that a statistical regression analysis would be a realistic method for evaluating the trend of unit length change with freeze-thaw cycles. In the regression analysis, only the unit length changes at the end of the freezing cycles were used.

Unconfined Compressive Strength

Although unconfined compressive strength may not reflect the formation of all minute cracks or localized weaknesses, it is with adequate replication, a direct measure of deterioration.

Unconfined compressive strengths were determined initially after 24 hours' soaking (0 cycles) and at the end of 3, 6, 9, and 12 cycles for 4 specimens selected at random. A linear regression analysis was used to determine the relationship between unconfined compressive strength and cycles of freezing and thawing.

Moisture Distribution

Townsend and Klym (8) have indicated that, with cycles of freezing and thawing, the relative increase in moisture content and moisture distribution in lime-soil mixtures may be related to the durability. The vertical distribution of moisture and the rate of moisture movement in test specimens subjected to one directional freezing are indicative of permeability and capillarity. Furthermore, it is apparent that the amount of water drawn into the voids of a lime-soil mixture will influence the magnitude of heave during freezing and the associated strength decrease. The effects of freeze-thaw cycles on moisture distribution in the lime-soil specimens were analyzed after 0, 3, 6, 9, and 12 cycles.

Visual Evaluation

All of the unconfined compressive strength specimens were visually inspected before they were tested. Based on the general external appearance, the durability of each specimen was rated as poor (P), fair (F), good (G), or excellent (E).

The poor rating was given to lime-soil mixtures which displayed extensive surface deterioration and ice lensing with freeze-thaw cycles; the excellent rating to those which displayed little or no surface checking and no evidence of ice lensing; the fair or good rating to those in between.

ANALYSIS AND DISCUSSION OF FREEZE-THAW DATA

Several investigators (9, 10, 11) have presented theories to explain the freeze-thaw mechanism responsible for concrete deterioration. Cordon (10) has proposed that the mechanisms primarily responsible for deterioration of concrete are hydraulic pressure and crystal growth. Due to the similarity of the cementing agents it is possible that the freeze-thaw mechanisms suggested for concrete are applicable to lime-soil mixtures.

TABLE 2

FREEZE-THAW DATA
(Average Values)

Soil Type	Curing Time (hr)	Freeze-Thaw Cycle	Unit Length Change (in./in.)[a]		Unconfined Compressive Strength (psi)[a]	Moisture Contents in Layers (%)[b]			Visual Rating[a, c]
			Freeze	Thaw		Top	Middle	Bottom	
Campaign County till	48	0	—	—	64.3	—	13.0 14.2	—	G
		3	+ 0.0505	+ 0.0205	27.9	16.8	16.1 16.2	15.1	P
		6	+ 0.0384	+ 0.0186	22.2	18.0	18.0 16.0	14.7	P
		9	+ 0.0519	+ 0.0172	17.8	21.5	15.9 15.0	15.2	P
		12	+ 0.0472	+ 0.0201	15.4	20.2	17.1 16.1	16.2	P
	96	0	—	—	186.2	—	13.2	—	E
		3	+ 0.0234	+ 0.0122	108.0	15.6	13.4	13.0	F
		6	+ 0.0370	+ 0.0206	56.0	17.2	13.6	13.7	P
		9	+ 0.0436	+ 0.0225	26.8	17.9	16.1	13.6	P
		12	+ 0.0481	+ 0.0251	27.8	19.4	15.4	15.4	P
Bryce B	48	0	—	—	317.5	—	25.0	—	E
		3	+ 0.0006	+ 0.0009	236.5	24.8	24.8	23.0	G
		6	+ 0.0018	+ 0.0016	301.2	25.2	25.6	24.8	F
		9	+ 0.0036	+ 0.0026	163.5	26.4	25.4	25.6	F
		12	+ 0.0055	+ 0.0040	251.8	26.8	25.9	23.9	F
	96	0	—	—	486.0	—	24.8	—	E
		3	+ 0.0008	+ 0.0008	439.8	24.1	24.8	24.6	G
		6	+ 0.0046	+ 0.0030	336.0	—	26.9	—	F
		9	+ 0.0053	+ 0.0044	286.8	26.8	25.9	24.6	F
		12	+ 0.0096	+ 0.0064	260.2	26.5	26.3	25.0	F
Sable B	48	0	—	—	259.8	—	22.4	—	E
		3	+ 0.0026	+ 0.0020	310.5	22.6	22.4	21.6	E
		6	+ 0.0046	+ 0.0031	307.2	23.4	24.2	24.4	G
		9	+ 0.0055	+ 0.0040	188.8	23.7	24.7	24.3	G
		12	+ 0.0073	+ 0.0039	195.5	24.4	25.2	24.1	G
	96	0	—	—	299.0	—	22.8	—	E
		3	+ 0.0041	+ 0.0019	189.8	22.2	24.0	23.3	G
		6	+ 0.0118	—	209.0	22.8	23.8	22.8	G
		9	+ 0.0174	+ 0.0090	66.4	24.0	23.6	23.0	P
		12	+ 0.0223	+ 0.0134	60.8	24.7	23.7	23.2	P
Illinoian till (Sangamon County)	48	0	—	—	377.8	—	13.4	—	E
		3	+ 0.0001	+ 0.0001	388.5	13.3	14.2	14.3	E
		6	+ 0.0020	+ 0.0012	367.5	13.4	13.8	14.7	E
		9	+ 0.0067	+ 0.0044	293.0	13.4	13.6	13.7	G
		12	+ 0.0096	+ 0.0063	244.0	13.6	14.2	14.6	G-F
	96	0	—	—	519.2	—	13.8	—	E
		3	- 0.0001	- 0.0003	446.8	13.2	13.1	13.2	E
		6	- 0.0002	- 0.0002	455.8	13.6	13.8	14.0	E
		9	- 0.0002	- 0.0001	347.5	13.2	14.8	14.5	E
		12	+ 0.0044	+ 0.0019	337.5	13.4	14.2	14.2	G

[a] Four specimens were used in determining the average values.
[b] Two specimens were used in determining the average values.
[c] P = poor; F = fair; G = good; E = excellent.

The average values for the data collected from the freeze-thaw durability study are given in Table 2. The data are for 4 lime-soil mixtures and 2 curing periods. In the cases where linear regression analyses were used, individual data points were used in lieu of the average values.

Unit Length Change

The linear regression plots for unit length change with respect to cycles of freezing and thawing are shown in Figures 1 and 2. All of the regression plots show that the test specimens increased in length with freeze-thaw cycles.

Statistical t tests obtained for regression line slope comparisons of the different mixtures indicated that for a given curing period (48 or 96-hr curing) the slopes of the unit length change regression lines for all of the lime-soil mixtures, except 48-hr cured mixtures of Bryce B and Sable B, were significantly different ($\alpha = 0.05$). Thus, soil type significantly influenced the rate of unit length change with respect to cycles of freezing and thawing.

The t tests also revealed that the slopes of the unit length change regression lines for all of the lime-soil mixtures were significantly different ($\alpha = 0.05$) for 48 and 96-hr curing. Therefore, the length of curing period influenced the rate of unit length change with respect to freeze-thaw cycles. It was assumed that longer curing would increase the resistance of the lime-soil mixtures to frost heave. However, the regression line plots (Figs. 1 and 2) and the t test results indicated that the higher clay content lime-soil mixtures (Bryce B and Sable B) experienced significantly greater unit length changes with freeze-thaw cycles when they were cured for a longer period of time. Although the slope of the regression line for the Champaign County till mixtures was significantly greater for a longer curing time, the initial unit length change was less. Therefore, it appears that longer curing time was beneficial for this lime-soil mixture. For the Illinoian till mixture, additional curing significantly decreased the rate of unit length change with freeze-thaw cycles.

The detrimental effect which additional curing appears to have on Bryce B and Sable B mixtures may be due to those freeze-thaw mechanisms described previously. In considering the permeability of a cement paste, Kennedy (11) has pointed out that if hydraulic pressure freeze-thaw mechanisms are valid, improved durability may be attributed to increased permeability of the gel structure.

Since it is generally concluded that longer curing decreases the permeability of lime-soil mixtures (due to the formation of additional cementing agents), it is possible that greater hydraulic pressures will develop in the capillaries and pores of longer cured mixtures subjected to freezing and thawing. Therefore, the greater rates of unit length change noted for longer cured Bryce B and Sable B mixtures are assumed to be caused by decreased permeability associated with increased curing time.

The regression plots indicated that, except for the 96-hr cured lime-soil mixture with Sable B, the mixtures with Sable B and Bryce B soils displayed substantial resistance to unit length changes caused by cycles of freezing and thawing. Generally less than 0.01 in./in. unit length change was noted after 12 cycles of freezing and thawing.

The Champaign County till mixture experienced large unit length changes after 2 or 3 cycles of freezing and thawing and generally displayed poor durability regardless of curing period. Illinoian till which, except for slightly less silt-sized materials, has physical and chemical properties very similar to those of Champaign County till, reacts with lime to form a material which is very resistant to cyclic freeze-thaw deterioration. Even after 12 cycles of freezing and thawing the unit length changes of the Illinoian till specimens were less than 0.01 in./in. for 48-hr curing and less than 0.005 in./in. for 96-hr curing.

Unconfined Compressive Strength

The regression analysis results for the effect of freeze-thaw cycles on unconfined compressive strength are shown in Figures 3 and 4. The plots indicate that all of the lime-soil mixtures exhibited strength decreases with increased cycles of freezing and thawing.

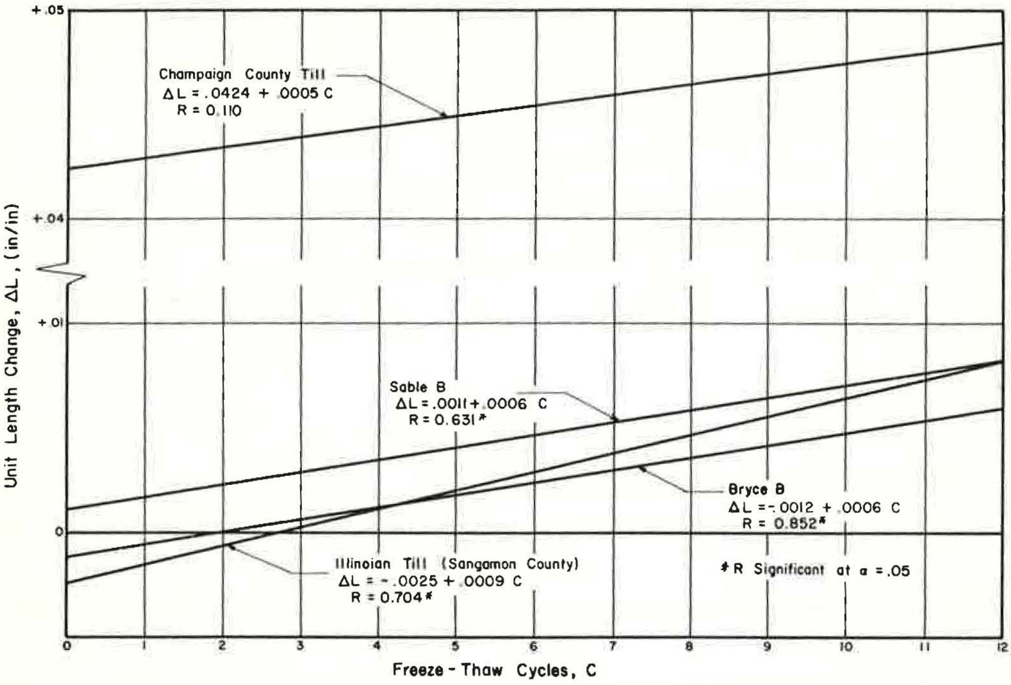

Figure 1. Influence of freeze-thaw cycles on unit length change (48-hr curing).

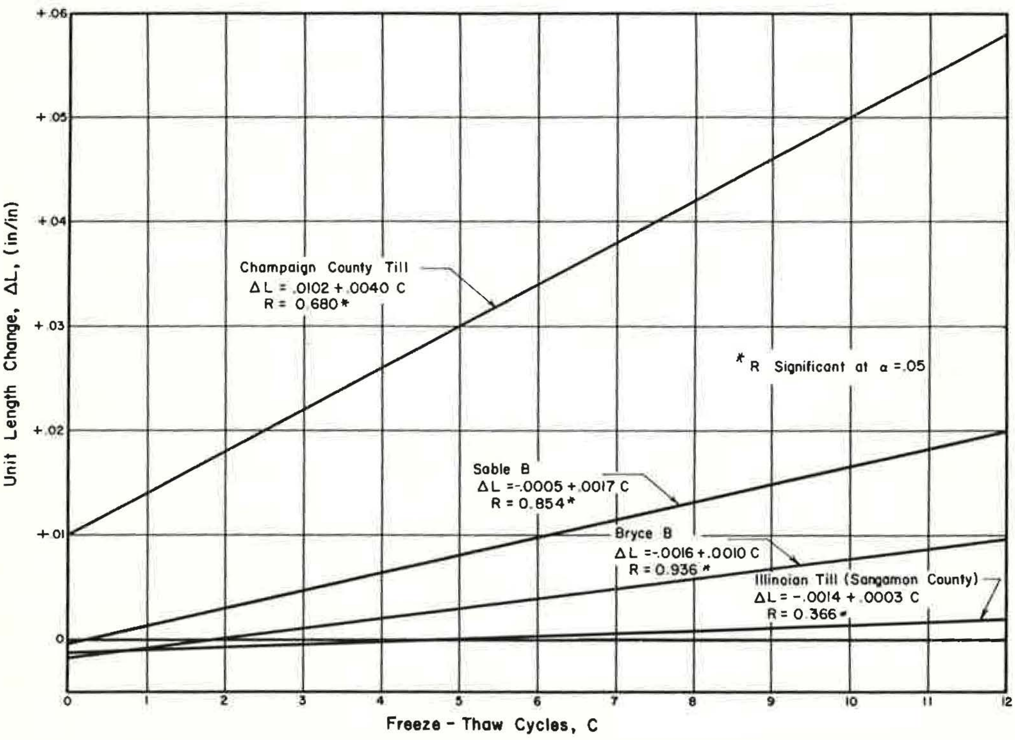

Figure 2. Influence of freeze-thaw cycles on unit length change (96-hr curing).

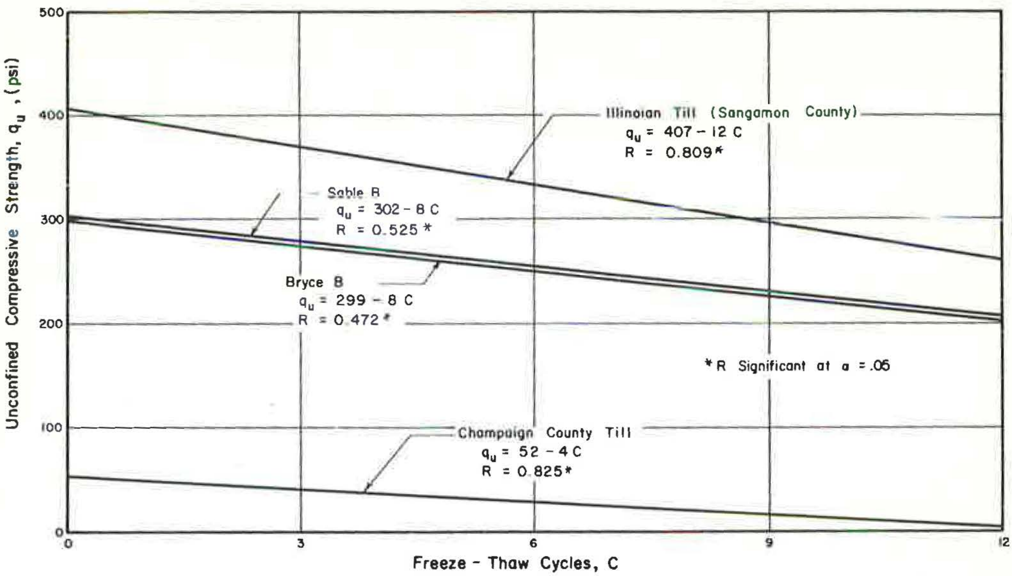

Figure 3. Influence of freeze-thaw cycles on unconfined compressive strength (48-hr curing).

Statistical comparisons (t tests) of the regression line slopes showed that for a given curing period all of the lime-soil mixtures, except 48-hr cured mixtures with Illinoian till and Champaign County till and 96-hr cured mixtures with Sable B and Champaign County till, displayed similar rates of strength loss with freeze-thaw cycles ($\alpha = 0.05$). Therefore, it was concluded that soil type generally did not significantly affect the rate

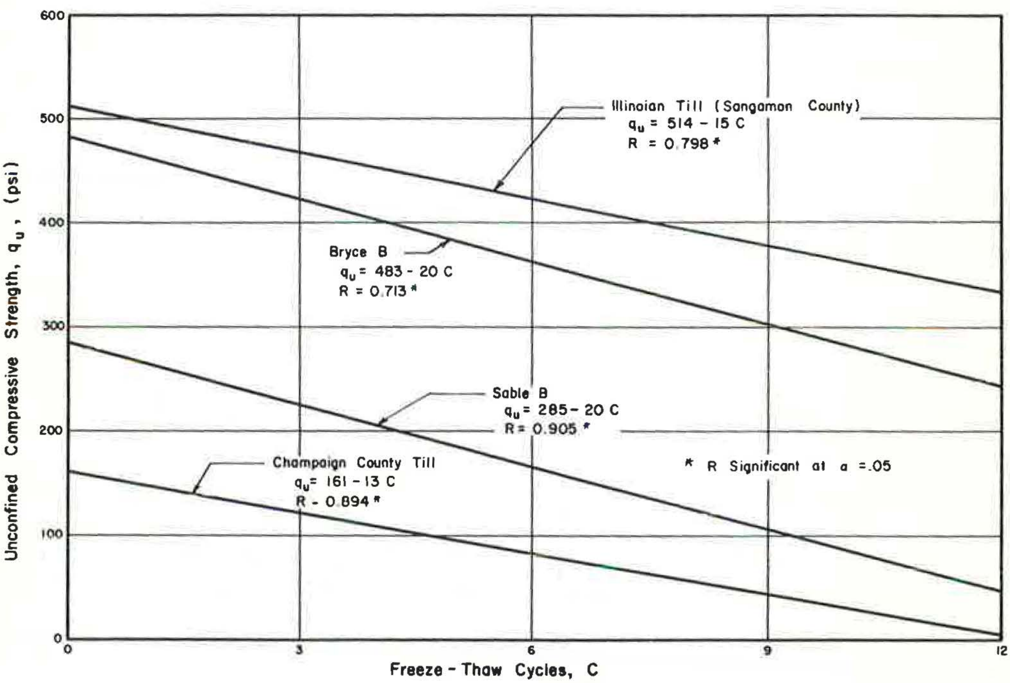

Figure 4. Influence of freeze-thaw cycles on unconfined compressive strength (96-hr curing).

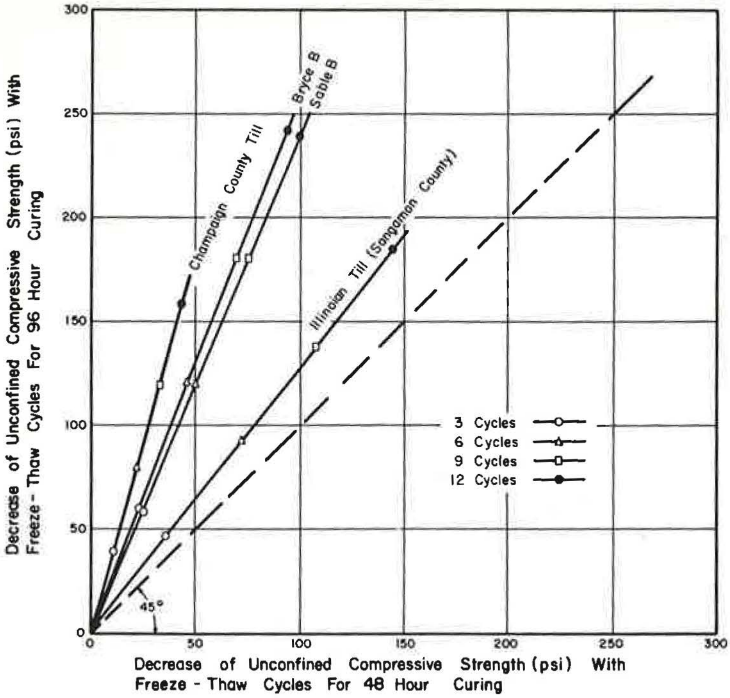

Figure 5. Effect of curing period on decrease of unconfined compressive strength with freeze-thaw cycles.

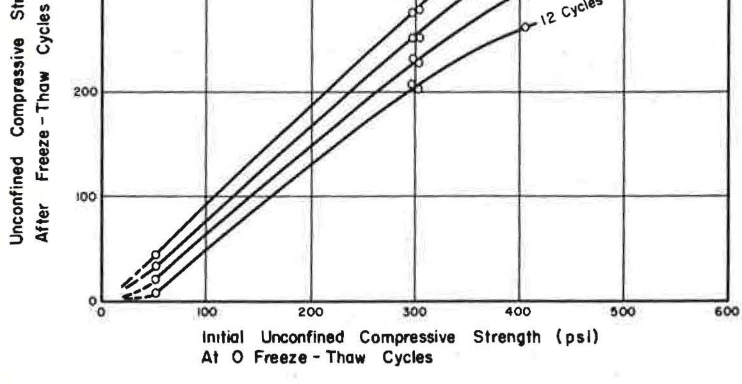

Figure 6. Influence of initial unconfined compressive strength on the residual strength after freeze-thaw cycles (48-hr curing).

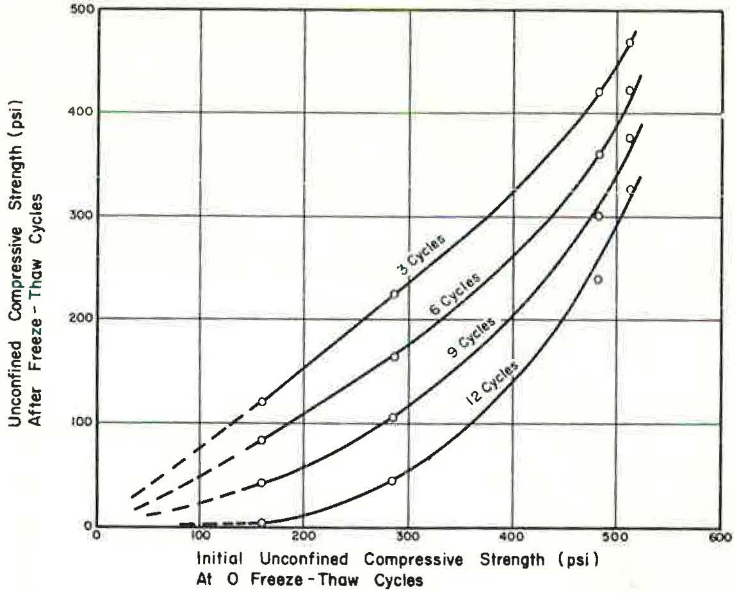

Figure 7. Influence of initial unconfined compressive strength on the residual strength after freeze-thaw cycles (96-hr curing).

of strength loss with freeze-thaw cycles. The average rates of strength loss (based on the three lime-soil mixtures that did not display significant differences) are 9.4 psi/cycle for 48-hr curing and 18. 5 psi/cycle for 96-hr curing. These values are conservative estimates of the rates of strength loss for the significantly different mixture (Champaign County till) which had strength losses of 3.2 psi/cycle for 48-hr curing and 13. 3 psi/cycle for 96-hr curing. Since soil type generally did not significantly influence the rate of strength loss for a given curing period, it is important to note that the residual strength of a lime-soil mixture after a specific number of freeze-thaw cycles can be estimated from the average strength loss per cycle and the initial unconfined compressive strength (0 cycles).

A comparison of Figures 3 and 4 indicates that, even though initial unconfined compressive strengths are in most cases substantially higher for the longer cured lime-soil mixtures, the rates of strength decrease with cycles of freezing and thawing are greater. This characteristic is shown in Figure 5. Statistical t test results also showed that, except for the Illinoian till mixture, the slopes of the regression lines for each 48-hr cured lime-soil mixture were significantly smaller ($\alpha = 0.05$) than the slopes for mixtures cured 96 hours. Thus it can be concluded that, with longer curing, the lime-soil mixtures generally experience greater initial strengths and greater rates of strength loss with freeze-thaw cycles.

Although the rate of strength loss increases with curing time, higher initial strength at 0 cycles many times offsets this effect. Except for the Sable B mixture, mixtures cured for 96 hours remained stronger than their 48-hr cured counterparts during freeze-thaw cycles (Figs. 3 and 4).

Figures 6 and 7 show the effects of the initial unconfined compressive strength on the durability of lime-soil mixtures, suggesting that high initial strength is indicative of good freeze-thaw resistance.

The freeze-thaw mechanisms responsible for the strength loss in lime-soil mixtures are presumed to be the same as those affecting unit length change. As would be expected, the increased rate of strength loss caused by additional curing, especially in the Bryce B and Sable B mixtures, was in agreement with the rate of unit length change noted. With additional curing time, freeze-thaw cycles appeared to destroy the cementitious bonds at a much faster rate.

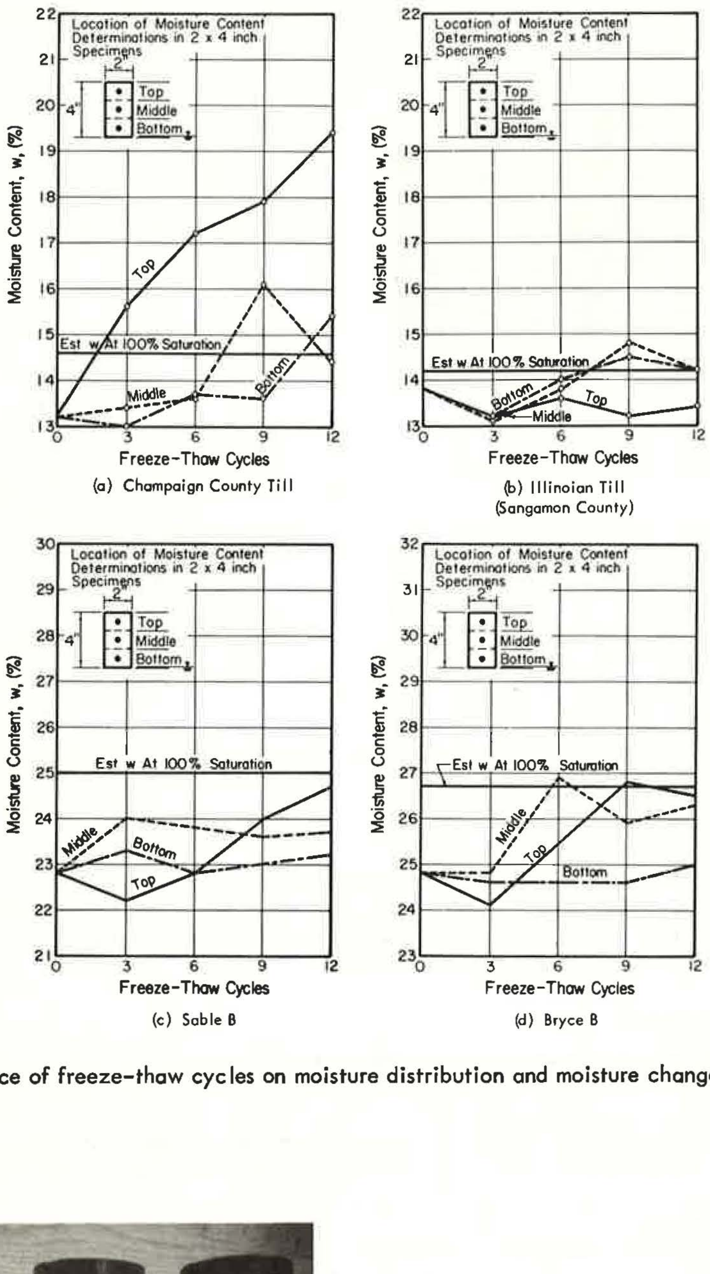

Figure 8. Influence of freeze-thaw cycles on moisture distribution and moisture change (96-hr curing).

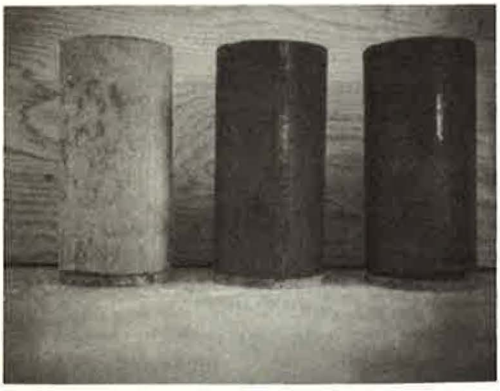

Figure 9. Illinoian till (Sangamon County) after 0, 3, and 12 freeze-thaw cycles (96-hr curing).

Figure 10. Champaign County till after 0, 3, and 12 freeze-thaw cycles (96-hr curing).

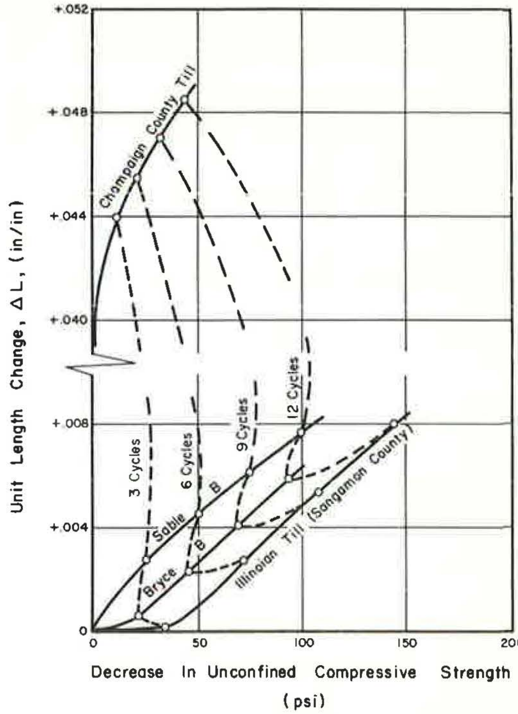

Figure 11. Relationship between unit length change and strength decrease with freeze-thaw cycles (48-hr curing).

Unconfined compressive strength appeared to be a meaningful measure of the freeze-thaw durability of the lime-soil mixtures. The high unconfined compressive strengths observed for the Illinoian till mixture during cycles of freezing and thawing indicated that this mixture was very durable. Bryce B and Sable B mixtures also displayed relatively high unconfined compressive strengths during freezing and thawing and appeared to be reasonably durable mixtures. The low unconfined compressive strength of the Champaign County till mixture, especially after 3 or 4 cycles of freezing and thawing, indicated that this lime-soil mixture was not durable. In general, the durability evaluations based on unconfined compressive strength agreed with the unit length change evaluations.

Moisture Distribution

Figure 8 shows the effects of freeze-thaw cycles on moisture distribution and moisture changes in the lime-soil mixtures cured for 96 hours. The length of curing time did not seem to have a pronounced effect on the rate or magnitude of moisture migration to the tops of the specimens since the trends for 48-hr curing were similar to those for 96-hr curing. Although the lime-soil mixtures studied were assumed quite impermeable, it was noted that moisture did migrate to the tops of the specimens as a result of cyclic freezing and thawing.

Moisture accumulated at a very high rate at the tops of Champaign County till specimens, indicating possible ice lensing and poor freeze-thaw resistance. Very little moisture change was noted in the top layers of the Illinoian till specimens, implying that little moisture migration and ice lensing had occurred. Sable B and Bryce B specimens, which possessed reasonably good durability properties, exhibited gradual and small moisture content increases in their top layers (less than 2 percent moisture increase after 12 cycles) with freeze-thaw cycles.

Moisture distribution and moisture changes in the lime-soil mixtures were indicative of the freeze-thaw durability. Fairly uniform moisture distributions and negligible moisture increases above the molding water contents were observed for the durable mixtures. The less durable mixtures exhibited large moisture content increases (especially in the top layers) and reached moisture contents substantially higher than their molding water contents. These mixtures also displayed low unconfined compressive strengths and large unit length changes.

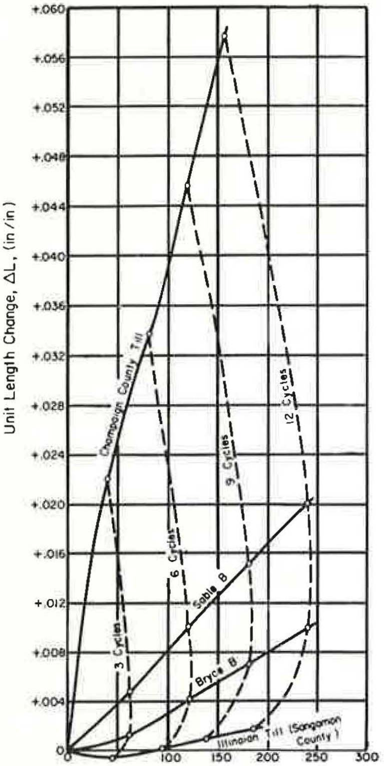

Figure 12. Relationship between unit length change and strength decrease with freeze-thaw cycles (96-hr curing).

Visual Inspection

Visual inspection of the lime-soil specimens after designated freeze-thaw cycles indicated qualitatively the amount of deterioration which had taken place. The specimens were rated according to their general external appearance prior to the compressive strength test. The average ratings are given in Table 2.

Figures 9 and 10 show typical lime-soil specimens after various freeze-thaw cycles. Disintegration progresses toward the bottoms of the specimens. Surface checking and ice lensing were readily observed in the Champaign County till specimens after 2 or 3 freeze-thaw cycles. In the Sable B, Bryce B, and Illinoian till specimens, surface checking usually did not become evident until after 5 or 6 freeze-thaw cycles and ice lensing usually did not occur until after 11 or 12 freeze-thaw cycles.

The lime-soil mixtures with poor freeze-thaw durability usually experienced more surface deterioration and, therefore, had lower visual ratings than the lime-soil mixtures with good freeze-thaw durability. The visual ratings generally reflect the mixture durabilities determined previously by the other evaluation methods.

Interrelationships

Figures 11 and 12 were developed from the regression relations for the effects of freeze-thaw cycles on unit length change and unconfined compressive strength. The Champaign County till mixture experienced much greater unit length change than the Illinoian till mixture for the same loss in unconfined compressive strength. Also, freeze-thaw specimens made with Champaign County till can undergo large unit length changes with little strength loss; however, due to the low initial strength for the mixture, each increment of strength loss is more critical since residual strength would be quite low. Further analysis indicates that, for a given curing period, Sable B and Bryce B mixtures decrease in strength similar amounts with each cycle of freezing and thawing but that the Sable B mixture undergoes greater unit length change than Bryce B for the same amount of strength loss.

The Illinoian till mixture displayed good freeze-thaw durability, and therefore, it might be assumed that small strength loss in addition to small unit length change are important for maintaining structural integrity and stability. Again, initial strength would be important in order to maintain adequate residual strength after several cycles of freezing and thawing. Generally, analysis of the interrelationships indicated that strength or unit length change criteria used alone may not fully describe the durability of lime-soil mixtures.

The effects of additional curing periods are also evident (Figs. 11 and 12). For a given unit length change, the mixtures cured the longest lose the most strength with freeze-thaw cycles. However, as discussed previously, the correspondingly higher initial strengths associated with longer curing offset the greater rates of strength loss and longer curing did normally produce higher residual strengths.

CONCLUSIONS

Unit Length Change

The unit length change was an effective method of measuring the deterioration of cured lime-soil mixtures. Regardless of the curing period, the unit length changes of all the mixtures increased with cycles of freezing and thawing. With the exception of 48-hr cured Bryce B and Sable B mixtures, soil type significantly influenced ($\alpha = 0.05$) the rate of unit length change with respect to freeze-thaw cycles for both curing periods (48 and 96-hr curing). The length of the curing period also influenced the rate of unit length change with respect to freeze-thaw cycles. In most cases, the slopes of the unit length change regression lines were significantly greater ($\alpha = 0.05$) for the longer curing period.

The Champaign County till mixture experienced large amounts of heave after the first 2 or 3 freeze-thaw cycles and displayed poor durability properties. Lime-soil mixtures composed of Sable B, Bryce B, and Illinoian till generally exhibited less than 1 percent heave after 12 freeze-thaw cycles for both curing periods.

Unconfined Compressive Strength

The freeze-thaw durability evaluation based on the unconfined compressive strength corresponded to the unit length change evaluation. All of the mixtures exhibited strength decreases with cycles of freezing and thawing. For a given curing period, soil type generally did not significantly ($\alpha = 0.05$) influence the rate of strength loss. The average rates of strength loss for the mixtures which were not significantly different were 9.4 psi/cycle for 48-hr curing and 18.5 psi/cycle for 96-hr curing. The longer cured mixtures generally exhibited substantially higher initial unconfined compressive strengths and higher rates of strength decrease. However, except for the Sable B mixture, mixtures cured for 96 hours remained stronger than their 48-hr cured counterparts.

Mixtures with high initial unconfined compressive strengths displayed high residual strengths after cycles of freezing and thawing and good freeze-thaw durability.

Moisture Distribution

Moisture changes were indicative of freeze-thaw durability since the durable lime-soil mixtures displayed fairly uniform moisture distributions and negligible moisture increases above their molding water contents. Rapid and high moisture content increases in the upper layers of a specimen during cycles of freezing and thawing were indicative of poor durability.

The length of the curing period did not appear to affect the rate or magnitude of moisture migration to the upper layers of the lime-soil specimens.

Visual Inspection

The amount of surface deterioration generally reflected mixture durability. Surface checking and ice lensing were readily observed in the Champaign County till specimens after 2 or 3 freeze-thaw cycles. In the Sable B, Bryce B, and Illinoian till specimens, surface checking usually did not become evident until after 5 or 6 freeze-thaw cycles and ice lensing usually did not become evident until after 11 or 12 cycles. Generally the number of cycles required to cause surface checking and ice lensing and the amount of ice lens growth were indicative of mixture durability.

Interrelationships

Both small unit length changes and small strength losses were important for maintaining structural integrity and stability in the mixtures. The unit length change criteria alone did not fully describe the freeze-thaw durability of the lime-soil mixtures since it was found that, for a given decrease in unconfined compressive strength, the unit length changes were remarkably different for the four mixtures.

General

Durable lime-soil mixtures can be obtained when reactive soils are stabilized with quality lime. The systems developed in this investigation show substantial merit for evaluating lime-soil mixture freeze-thaw durability.

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