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EFFECTS OF FREEZE-THAW PARAMETERS ON THE DURABILITY OF STABILIZED MATERIALS

by
B. J. DEMPSEY
and
M. R. THOMPSON

A Report of the Investigation of
Durability Testing of
Stabilized Materials
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BARRY J. DEMPSEY and MARSHALL R. THOMPSON

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EFFECTS OF FREEZE-THAW PARAMETERS ON THE DURABILITY OF STABILIZED MATERIALS

Barry J. Dempsey and Marshall R. Thompson,
Department of Civil Engineering, University of Illinois

A study was conducted to evaluate the effects of various frost-action parameters on the freeze-thaw durability of stabilized materials and to determine which parameters could be modified so that a characteristic freeze-thaw cycle could be adapted to laboratory use. The parameters studied were cooling rate, freezing temperature, length of freezing period, and thawing temperature. The cooling rate was found to be an important factor affecting the freeze-thaw durability of stabilized soils. Lower cooling rates (0.2 to 2.0 F/hr) that correlated best with quantitative field data were generally the most detrimental to durability. A sustained freezing study revealed that the length of the freezing period did not have to be greater than that required to accomplish complete freezing of the test specimen. The study further indicated that freezing and thawing temperatures should be representative of those for in-service pavement systems. Thawing temperatures for some stabilized materials are important because strength increase caused by a pozzolanic reaction is possible at high temperatures. The number of cycles used in a laboratory freeze-thaw test should be related to geographical location, climatic conditions, and position of the stabilized layer in the pavement system. For Illinois climatic conditions, a laboratory freeze-thaw cycle representative of field conditions would require a completion period of 48 hours.

•STABILIZED materials such as soil-cement, lime-fly ash, and lime-soil mixtures are used extensively as base and subbase layers in pavement construction. In areas where frost action occurs, these materials must retain their integrity and maintain adequate residual strength at all times in order to provide adequate structural performance.

The laboratory testing procedure used to evaluate the freeze-thaw durability of stabilized soils and materials should be representative of field conditions. In an effort to develop a rational durability testing procedure, Thompson and Dempsey (1) used a pavement heat-transfer model to generate quantitative data for describing frost action in pavement systems.

A characteristic freeze-thaw cycle for central Illinois is shown in Figure 1 and includes all of the important frost-action parameters as follows: cooling rate, freezing temperature, length of freezing period, warming rate, thawing temperature. length of thawing period, and number of freeze-thaw cycles. Illinois frost-action parameter data (1) showed substantial variability as related to the effects of geographical location, climate, and position in the pavement system.

When an accelerated freeze-thaw durability test is developed, it may be desirable to change some of the frost-action parameters so that the period of time to complete a freeze-thaw cycle can be shortened for laboratory use. However, any changes made in the cycle should not substantially alter its representation of the frost action that actually occurs in field pavement systems.

The purpose of this study was to evaluate the effects of various frost-action parameters on the freeze-thaw durability of stabilized materials and to determine which parameters can be modified so that the characteristic field frost-action cycle can be adapted to laboratory use.

PREPARATION OF TEST SPECIMENS

Materials

The frost-action parameter study was limited to 2 typical Illinois soils that can be effectively stabilized with various stabilizing agents. These soils included Illinoian till and Ridgeville fine sandy loam. Table 1 gives the natural properties of the soils used in the parameter study. A hydrated high calcium lime containing 96 percent available $Ca(OH)_2$ with 95 percent passing the No. 325 sieve was used to stabilize the Illinoian till. A Type 1 portland cement was used to treat the Ridgeville fine sandy loam.

Mixture Design

Currently recognized strength and freeze-thaw durability testing procedures were utilized to establish the mixture designs. The amount of lime added to the Illinoian till consisted of the optimum percentage (dry-weight basis) determined from previous strength studies by Thompson (2). The soil-cement was prepared and tested according to AASHO T135 and T136 procedures, and Portland Cement Association criteria were employed to establish the design cement content for the Ridgeville fine sandy loam. Table 1 gives the specimen sizes, curing periods, mixture designs, and density properties for the stabilized materials used in this study.

Compaction Procedures

All freeze-thaw test specimens were molded in 2-in. diameter by 4-in. steel molds in 3 equal layers. Each layer was scarified to ensure 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. The compactive efforts for the lime- and cement-stabilized materials were established to produce average densities equivalent to those obtained by AASHO T99 compaction procedures.

Curing Procedures

Immediately after compaction, the test specimens were removed from the molds, marked, and weighed. The lime-soil specimens were cured in sealed plastic bags for 48 hours at 120 F. The soil-cement specimens were cured for 7 days in a room having a relative humidity of 100 percent and a temperature of 77 F. The accelerated curing periods used in the laboratory have generally been found to approximate field curing.

FREEZE-THAW TESTING PROCEDURE

The parameter study was conducted with a specially designed freeze-thaw durability testing unit that can be programmed to accurately control both the top and the bottom temperatures on a specimen. Either closed- or open-system moisture conditions can be provided. A more detailed discussion of the testing unit can be found in previous work by Dempsey (3).

In the parameter study the freeze-thaw test consisted of a combination of open and closed conditions depending on whether the free water near the base of the specimens was in a frozen or an unfrozen condition. The test specimens were supported on ½-in. porous stones that were in contact with the free water surface.

The freezing gradient in the test specimens was one dimensional and proceeded from the top to the bottom during freezing. A temperature differential between the top and bottom of the 4-in. specimens was maintained at approximately 3 F in all of the test series, based on the results of pavement heat-transfer model studies of typical Illinois pavements.

The freeze-thaw cycle programmed into the testing unit was variable depending on the frost-action parameter being investigated. Cooling rates of 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 F/hr were studied. The cooling rate was defined as the rate of temperature change at the surface of the test specimens. The minimum freezing temperatures were 25 F for the 0.2 F/hr cooling rate and 18 F for the remaining cooling rates. The time required for the temperature to cool from 30 F to the minimum freezing temperature

Figure 1. Characteristic frost-action cycle for central Illinois.

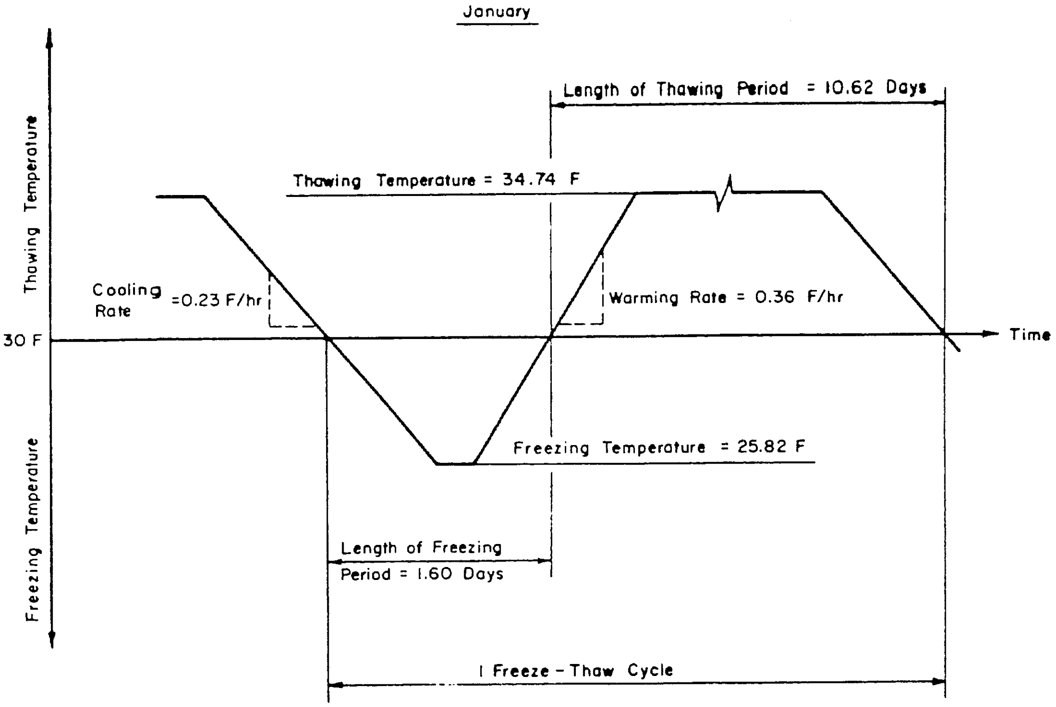

Table 1. Natural and mixture properties of samples.

Property	Illinoian Till	Ridgeville Fine Sandy Loam
Natural Properties		
Location	Sangamon County	Iroquois County
Description	Calcareous loam till of Illinoian age	B-horizon of profile developed in fine sandy outwash material
AASHO classification	A-4(4)	A-4(1)
Atterberg limits		
Liquid limit, percent	21	25
Plasticity index, percent	6	7
<200 sieve, percent	57	37
<2-μ clay, percent	18	17
Mixture properties		
Specimen size, in.	2 by 4	2 by 4
Stabilization agent	lime	cement
Content, percent	3	8
Curing	48 hours at 120 F sealed	7 days at 77 F in 100 percent relative humidity
Dry density, lb/ft^3	121.0	114.8
Water content, percent	13.0	14.3

ranged from a maximum of 24 hours for the slowest cooling rates (0.2 F/hr and 0.5 F/hr) to approximately 1 hour for the fastest cooling rate (10 F/hr). The freezing period lasted about 30 hours for the slowest cooling rates and 12 hours for the fastest cooling rate. A warming rate of 2 F/hr was used in all of the tests. The thawing temperature was set at 40 F. The length of time to complete 1 freeze-thaw cycle in the laboratory varied between 24 and 48 hours. A maximum of 6 freeze-thaw cycles was considered sufficient to determine whether there was a significant influence of a particular parameter.

At the end of the sixth freeze-thaw cycle a freezing duration study was conducted. A sustained freezing period of 96 hours was used to determine whether prolonged freezing influenced the durability of stabilized materials.

EVALUATION METHODS AND TEST DATA

Unconfined compressive strength change, moisture content change, and unit length change were used to assess the freeze-thaw durability of the stabilized materials during cyclic freezing and thawing and sustained freezing. Generally, evaluation tests were conducted on specimens at the end of 3 and 6 freeze-thaw cycles and specimens subjected to sustained freezing for periods of 48 or 96 hours after the sixth freeze-thaw cycle.

The average values for the data collected from the freeze-thaw parameter study are given in Table 2. The data listed are for 2 stabilized mixtures that were subjected to different freeze-thaw environments.

Unconfined Compressive Strength Change

Changes in unconfined compressive strength were determined by testing 4 specimens at various times during the freeze-thaw period. Specimens tested immediately after the cure period (0 freeze-thaw cycles) were used as the reference for determining strength change.

Moisture Content Change

Townsend and Klym (4) and Dempsey and Thompson (5) have indicated that the relative increase in moisture content and moisture distribution in lime-soil mixtures may be related to freeze-thaw 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 that can influence heave and associated strength loss. In this study, the effects of freeze-thaw cycles on moisture content changes in the stabilized specimens were analyzed. Moisture content determinations were made for the middle layer of 2 unconfined compressive strength specimens after they had been tested.

Unit Length Change

Length changes in 2 specimens were continuously monitored by use of linear motion potentiometers that had been calibrated to record relative length changes on a strip chart. The total specimen length change was measured to the nearest 0.001 in. The unit length change was determined as the inches of length change per inch of specimen height.

ANALYSIS AND DISCUSSION OF FROST-ACTION PARAMETERS

Earlier studies by Thompson and Dempsey (1) have indicated that cooling rate, freezing temperature, and length of freezing period are the most significant parameters influencing cyclic freeze-thaw deterioration. Kaplar (6) has indicated that the cooling rate is a major factor influencing the rate of heave in soils. Work at the University of Illinois has shown that the thawing temperature is also an important parameter in freeze-thaw durability studies of stabilized materials that gain strength through a pozzolanic reaction.

Frost-action literature generally shows that the number of freeze-thaw cycles has a substantial influence on the durability of pavement materials. In freeze-thaw durability testing it is important that the number of freeze-thaw cycles used be related to the geographical location, climatic conditions, and the depth in the pavement system where the stabilized material is placed.

Cooling Rate

The rate at which a stabilized material cooled during freezing was expected to have considerable influence on freeze-thaw durability. Figure 2 shows the influence of cooling rate on the moisture change, unit length change, and unconfined compressive strength change of soils stabilized with lime and cement after 3 freeze-thaw cycles. Figure 3 shows a similar plot for the stabilized soils after 6 freeze-thaw cycles. The slower cooling rates (0.2 to 2.0 F/hr) generally have the most detrimental influence on freeze-thaw durability. This fact is important because quantitative frost-action data based on heat-transfer model studies (1) show that cooling rates in Illinois generally vary between 0.2 and 1.0 F/hr.

Table 3 gives data from the statistical analyses of the influence of cooling rate on moisture change, unit length change, and unconfined compressive strength change after 3 and 6 freeze-thaw cycles. Moisture change in the middle layer of the lime-soil specimens was significantly influenced ($\alpha = 0.05$) by cooling rate. Although the data were not significantly different, the soil-cement did show substantial moisture increases at the lower cooling rates. Cooling rate did not significantly influence the unit length change in the stabilized soils. However, inspection of the data indicates that cooling rate appears to have some effect on the unit length change. The soil-cement generally experienced greater unit length changes at the lower cooling rates. Unconfined compressive strength change was significantly influenced ($\alpha = 0.05$) by cooling rate. In some cases it would appear that greater strength losses occurred during the slower cooling rates.

The stabilized materials used in the study were designed to be durable mixtures. It is probably for this reason that significant influences of cooling rate were not evident for some of the methods used for evaluating freeze-thaw durability. It is apparent that unconfined compressive strength change was a valid indicator of the freeze-thaw deterioration of these stabilized soils.

Freeze-thaw durability evaluation of stabilized soils and materials has shown that the data are highly variable and the variability tends to increase with the number of freeze-thaw cycles. Unpublished data at the University of Illinois have indicated that the coefficient of variation of unit length change data for a stabilized soil after 6 freeze-thaw cycles often exceeds 20 percent. Similar findings are true for moisture change and unconfined compressive strength change. Because of the substantial variability in freeze-thaw durability evaluation, statistically significant differences are difficult to establish but important qualitative trends can be discerned.

Freezing Temperature

The freezing temperature used in the study ranged from 18 to 25 F depending on the cooling rate. These temperatures are realistic for frost-action analysis in Illinois. It must be emphasized that the magnitude of the freezing temperature is dependent on factors such as geographical location, climatic conditions, pavement composition, and position in the pavement system.

Length of Freezing Period

The length of time that specimens should remain in a frozen condition is an important parameter in the development of an accelerated freeze-thaw test. In this study a sustained 96-hour freezing period was used after the specimens had been frozen for the sixth cycle. It was hypothesized that, once freezing of a specimen had occurred, additional freezing time would not have a detrimental effect on durability.

Table 4 gives the results of a statistical evaluation of the influence of sustained freeze-thaw durability. Unconfined compressive strength change, unit length change,

Figure 2. Effect of cooling rate on moisture change, unit length change, and unconfined compressive strength change after 3 freeze-thaw cycles.

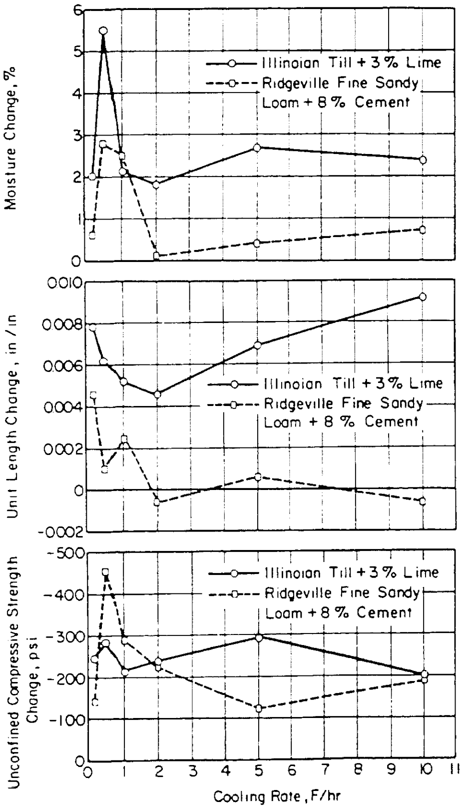

Figure 3. Effect of cooling rate on moisture change, unit length change, and unconfined compressive strength change after 6 freeze-thaw cycles.

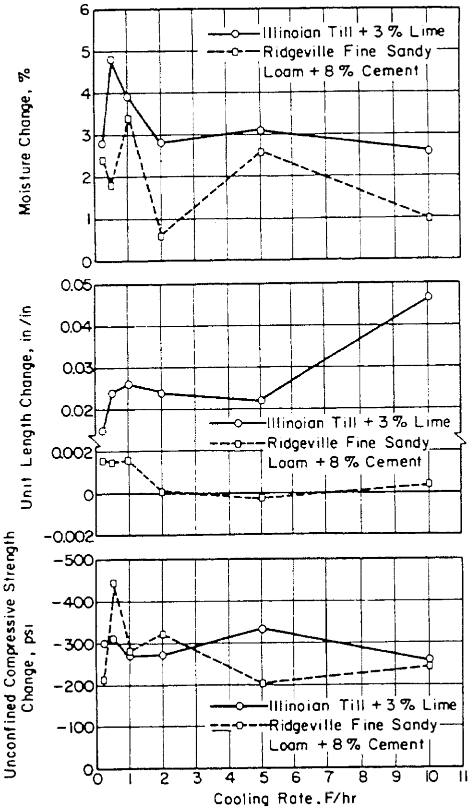

Table 2. Average data for frost-action parameters.

Stabilized Material	Cooling Rate (F/hr)	Unconfined Compressive Strength Change (psi)					Moisture Content Change at Middle Layer (percent)					Unit Length Change (in./in.)			
		Freeze-Thaw Cycles			Hours of Sustained Freezing		Freeze-Thaw Cycles			Hours of Sustained Freezing		Freeze-Thaw Cycles		Hours of Sustained Freezing	
		0	3	6	48	96	0	3	6	48	96	3	6	48	96
Illinois till + lime	0.2	410	166	110	140	140	10.6	12.6	13.4	13.4	13.2	+0.0078	+0.0150	+0.0150	+0.0150
	0.5	386	102	76	103	82	9.7	15.2	14.5	—	—	+0.0062	+0.0237	+0.0231	+0.0231
	1.0	354	141	85	—	—	11.4	13.5	15.3	—	—	+0.0052	+0.0260	—	—
	2.0	382	145	109	—	—	11.2	13.0	14.0	—	—	+0.0046	+0.0232	—	—
	5.0	408	116	74	63	17	10.1	12.8	13.2	14.9	16.1	+0.0069	+0.0221	+0.0425	+0.0554
	10.0	321	122	63	67	63	11.1	13.5	13.7	14.5	13.9	+0.0092	+0.0465	+0.0466	+0.0431
Ridgeville sand + cement	0.2	634	492	421	486	458	12.9	13.5	15.3	16.0	14.1	+0.0046	+0.0016	+0.0016	+0.0004
	0.5	893	438	450	446	489	11.7	14.5	13.5	14.3	14.1	+0.0010	+0.0015	+0.0000	+0.0001
	1.0	704	418	425	—	—	11.7	14.2	15.1	—	—	+0.0025	+0.0016	—	—
	2.0	737	513	415	558	468	12.9	12.8	13.5	14.0	14.7	-0.0006	+0.0001	-0.0001	-0.0001
	5.0	579	451	376	458	405	12.5	12.9	15.1	16.0	15.0	+0.0006	-0.0002	-0.0015	-0.0005
	10.0	673	388	431	547	514	13.2	14.0	14.2	13.6	14.6	-0.0006	+0.0004	+0.0000	-0.0001

Table 3. Results of statistical analysis of effect of cooling rate.

Evaluation Method	Stabilized Material	Freeze-Thaw Cycles	Test	Cooling Rate (F/hr) 0.2	0.5	1.0	2.0	5.0	10.0	F (calculated)	F (α = 0.05)	Difference[a]
Avg unconfined compressive strength change, psi	Illinois till + lime	3	A[b]	-244	-284	-213	-237	-292	-199	10.15	2.77	Y
			D[c]	-292	-284	-244	-237	-213	-199			
		6	A	-300	-310	-269	-273	-234	-258	10.79	3.03	Y
			D	-334	-310	-300	-273	-269	-258			
	Ridge. sand + cement	3	A	-142	-455	-286	-224	-128	-285	14.60	2.81	Y
			D	-455	-286	-285	-224	-142	-128			
		6	A	-213	-443	-279	-322	-203	-242	7.86	2.81	Y
			D	-443	-322	-279	-242	-213	-203			
Avg moisture content change at middle layer, percent	Illinois till + lime	3	A	+2.0	+5.5	+2.1	+1.8	+2.7	+2.4	77.66	4.39	Y
			D	+5.5	+2.7	+2.4	+2.1	+2.0	+1.8			
		6	A	+2.8	+4.8	+3.9	+2.8	+3.1	+2.6	8.50	4.39	Y
			D	+4.8	+3.9	+3.1	+2.8	+2.8	+2.6			
	Ridge. sand + cement	3	A	+0.6	+2.8	+2.5	-0.1	+0.4	+0.8	3.90	4.39	N
		6	A	+2.4	+1.8	+3.4	+0.6	+2.6	+1.0	1.72	4.39	N
Avg unit length change, in./in.	Illinois till + lime	3	A	+0.0078	+0.0062	+0.0052	+0.0046	+0.0069	+0.0092	1.41	4.39	N
		6	A	+0.0150	+0.0237	+0.0260	+0.0236	+0.0221	+0.0465	3.00	4.39	N
	Ridge. sand + cement	3	A	+0.0046	+0.0010	+0.0025	+0.0006	+0.0006	+0.0006	2.17	4.39	N
		6	A	+0.0016	+0.0015	+0.0016	+0.0001	-0.0002	+0.0004	0.45	4.39	N

[a] N = no significant difference; Y = significant difference.

[b] Analysis of variance.

[c] Duncan's multiple range. Any 2 means underscored by same line are not significantly different; any 2 means not underscored by same line are significantly different.

Figure 4. Effect of curing temperature on change in unconfined compressive strength.

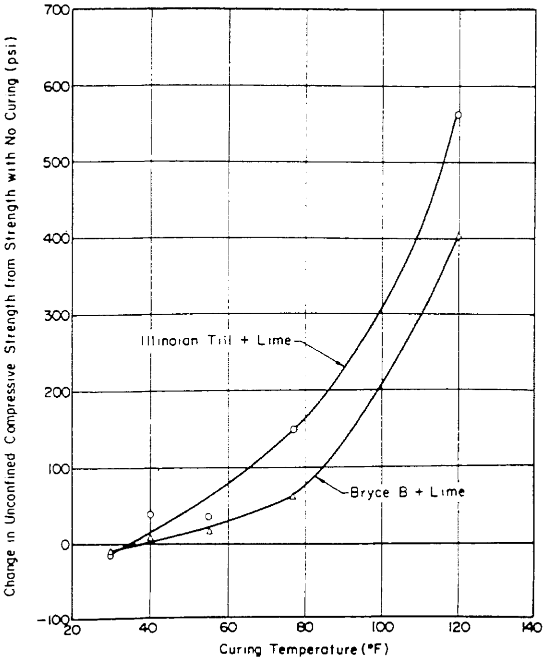

Table 4. Results of statistical analysis of effect of sustained freezing.

Stabilized Material	Evaluation Method	Cooling Rate (F/hr) 0.2	0.5	1.0	2.0	5.0	10.0
Illinois till + lime	Unconfined compressive strength change	N	N	—	—	N	N
	Unit length change	N	N	—	—	Y	N
	Moisture content change at middle layer	N	—	—	—	Y	N
Ridgeville sand + cement	Unconfined compressive strength change	N	N	—	N	N	Y
	Unit length change	N	N	—	N	N	N
	Moisture content change at middle layer	N	N	—	N	N	N

Note: α = 0.05. N = no significant difference; Y = significant difference; and — = no data.

and moisture content change at the end of the sixth freeze-thaw cycle are compared with data for continuous freezing periods of 48 and 96 hours. Regardless of the cooling rate, an increase in the length of the freezing period generally (23 out of 26 cases) did not significantly influence ($\alpha = 0.05$) the freeze-thaw durability of the stabilized materials tested.

Thawing Temperatures

Work by Thompson and Dempsey (1) indicated that thawing temperatures in stabilized materials are considerably lower than those specified in the standard freeze-thaw durability testing procedures. Generally, thawing temperatures ranging from 35 to 45 F are common in Illinois, depending on geographical location, climatic conditions, and depth in the pavement system (1).

The durability of stabilized materials such as lime-soil mixtures and lime-fly ash-aggregate mixtures that gain strength through a pozzolanic reaction can be substantially influenced by the magnitude of the thawing temperature. Figure 4 shows the effect of curing temperature on the change in unconfined compressive strength of 2 reactive soils stabilized with lime. It is shown that strength increases with an increase in curing temperature. At temperatures below approximately 40 F the strength increase with curing time essentially ceases.

If realistic durability evaluation is to be ensured, it is apparent that the thawing temperature used in a freeze-thaw durability test for stabilized materials should be representative of the thawing temperatures in the field.

SUMMARY AND CONCLUSIONS

Frost-action parameters that were expected to influence the development of a laboratory freeze-thaw durability test for stabilized soils and materials were studied. Although the data showed substantial variability, cooling rate was found to be an important factor affecting the freeze-thaw durability of stabilized soils. The lower cooling rates, which correlate best with quantitative field data, were generally the most detrimental to durability.

Data analyses for the frost-action parameter study indicate that a rational laboratory freeze-thaw durability test for typical Illinois climatic conditions should have the following characteristics:

1. A slow cooling rate, possibly between 0.2 and 1.0 F/hr;
2. Freezing and thawing temperatures similar to those of the in-service pavement system;
3. A freezing period not necessarily greater than that required to accomplish complete freezing of the test specimen; and
4. Number of cycles related to geographical location, climatic conditions, and position of the stabilized layer in the pavement system.

The laboratory freeze-thaw cycle now being used to test stabilized materials at the University of Illinois requires 48 hours to complete. This length of time was necessary because it was found that, for Illinois climate, the cooling rate in pavement systems is quite low (approximately 0.25 F/hr). Although the length of time to complete a freeze-thaw cycle is quite long, it is believed that the laboratory testing procedure is representative of field temperature conditions.

ACKNOWLEDGMENTS

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