VACUUM SATURATION METHOD FOR PREDICTING FREEZE-THAW DURABILITY OF STABILIZED MATERIALS

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A study was conducted to determine if vacuum saturation could be used as a rapid and economical method for accurately predicting the freeze-thaw durability of materials such as soil-cement, lime-fly ash, and lime-soil mixtures. Except where the effect of reduced density on soil-cement and lime-fly ash mixtures was to be studied, the stabilized specimens were compacted at optimum moisture content and maximum dry density. Soil-cement and lime-fly ash mixtures at reduced stabilizer contents and lime-soil mixtures cured for different time periods were also tested. Vacuum saturation was accomplished by allowing specimens that had previously been exposed to a vacuum pressure of 24 in. of mercury for 30 minutes to soak in water for 1 hour at atmospheric pressure. Unconfined compressive strength and moisture content measurements were used to evaluate the durability of the stabilized materials. Comparisons were made with results from an extensive freeze-thaw durability test program conducted at the University of Illinois. Linear regression analyses of the data indicated that there was a significant correlation between vacuum saturation strength and cyclic freeze-thaw strength. A significant correlation was also found to exist between vacuum saturation moisture content and cyclic freeze-thaw moisture content. It was concluded that vacuum saturation provides a rapid and economical method for accurately predicting the freeze-thaw durability of stabilized materials.

•A MAJOR effect of frost action on pavement systems constructed with stabilized materials such as soil-cement, lime-fly ash, and lime-soil mixtures can be a loss of strength and integrity after thawing. This loss of strength and integrity results from the deterioration of the cementitious matrix and the presence of excess water in the stabilized material after thawing has occurred.

Freeze-thaw, wet-dry, and extended soaking tests have been used to determine the durability of stabilized materials. The standard wet-dry and freeze-thaw tests for soil-cement mixtures are described in AASHO T-135 and T-136 (ASTM D559 and D560) respectively. Lime-fly ash mixtures are generally tested according to ASTM C593. Thompson (1) has found a reasonable correlation between cyclic freezing and thawing and extended soaking for determining the durability of lime-soil mixtures.

Dempsey and Thompson (2) have developed a freeze-thaw test that relates very well to the field temperature conditions in Illinois. This test includes the effects of geographical location, climate, and position in the pavement system. Although the freeze-thaw test developed by Dempsey and Thompson (2) provides a rational approach to durability testing, it is a slow testing procedure (48 hours are needed for each freeze-thaw cycle), and it requires special testing equipment. A description of the freeze-thaw testing equipment can be found in previous work by Dempsey (3).

It has been noted for the various durability tests that there is normally a water content increase in the specimens at the end of the test. Considerable experimental work

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has been completed to describe the mechanisms causing moisture transfer during freezing, and it has been found that soil moisture will translocate from points of high temperature to points of low temperature as a result of a thermal gradient. Several investigators (4, 5, 6) have indicated that the porosity and density have considerable influence on the freezing behavior of soils since these factors influence moisture movement.

An extensive freeze-thaw durability testing program on stabilized materials conducted at the University of Illinois has indicated that a rapid and inexpensive testing method that induces moisture changes in test specimens similar to those caused by freezing and thawing or wetting and drying might be used as an alternate procedure for evaluating durability. Herrin, Manke, and George (7) have conducted studies to determine how different soaking methods (total immersion, one-half immersion, and vacuum saturation) influenced the moisture content of bituminous mixtures. From the study they found that the vacuum saturation method provided a more uniform distribution of water within the test specimens and required less time. A chief advantage of the vacuum saturation method was that soaking time and pressure could be controlled to obtain the amount of moisture desired in the test specimens.

The purpose of this study was to determine if a vacuum saturation procedure could be used as a rapid method for predicting the durability of stabilized materials such as soil-cement, lime-fly ash, and lime-soil mixtures.

PREPARATION OF TEST SPECIMENS

Materials

Soils—Representative soils were sampled for inclusion in the program. Information and data concerning the soils are given in Table 1. A wide range of materials, from fine-grained soils to well-graded aggregates, was included.

Stabilizers—Table 1 gives the stabilizers (lime, lime-fly ash, and cement) that were used with the various soils. A commercial grade hydrated, high-calcium lime containing 96 percent available $Ca(OH)_2$ with 95 percent passing the No. 325 sieve was used. The cement (type I) was also a commercially available product. The fly ash, distributed by the Chicago Flyash Company, was finely divided, with approximately 100 percent passing the No. 30 sieve and 92 percent passing the No. 200 sieve.

Mixture Design and Preparation

Lime—The amount of lime added to the soil was the optimum percentage (dry weight of soil basis) determined from previous strength studies by Thompson (8). Only the portion of the soil that passed the No. 4 sieve was used in the test mixtures. The required amount of soil and lime was initially dry-mixed in a Lancaster mortar mixer to ensure uniform distribution of the lime throughout the soil. After dry-mixing, enough water was added to the mixture to bring it to optimum moisture content (AASHO T-99), and mixing was 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 the test specimens were compacted.

Cement—Both coarse- and fine-grained soils were used in test mixtures with cement; however, only the portion passing the ¾-in. sieve was used in the coarse-textured soil-cement mixtures. The optimum additive percentage (dry weight of soil basis) was determined using Portland Cement Association soil-cement criteria (9). Test data were developed in accordance with either Method A or Method B of AASHO procedure T-136, depending on the soil texture. Mixture designs for reduced cement contents were also developed. The required amounts of soil and cement were initially dry-mixed with a Lancaster mortar mixer for approximately 1 minute. After dry-mixing, enough water was added to the mixture to bring it to the optimum moisture content (AASHO T-134), and mixing continued for approximately 3 minutes. Compaction of the soil-cement mixture proceeded immediately after mixing was completed.

Lime-Fly Ash—Lime-fly ash stabilization was restricted to the coarser soils, which included the fine sands through the coarse aggregates. A lime-to-fly ash ratio of 1:4, as used in previous studies (10), was selected.

The optimum percentage (total dry weight of mixture basis) of lime and fly ash was determined in accordance with ASTM C593. Mixture designs for reduced lime-fly ash contents were also determined. The lime and fly ash were dry-mixed with the soil for approximately 1 minute in a Lancaster mortar mixer. Sufficient water was added to bring the mixture to optimum water content (ASTM C593), and mixing was continued for approximately 3 minutes. Compaction proceeded immediately upon completion of the mixing process.

Mixture Design Summary—Design stabilizer contents and compaction data for the optimum mixtures included in the laboratory program are given in Table 2.

Compaction Procedures

Two sizes of compaction molds were used for preparing the durability test specimens, depending on the gradation of the soil. The soils that contained material larger than the No. 4 sieve were classified as coarse soils. Most of the soils were finer textured, with approximately 100 percent passing the No. 4 sieve.

The standard Proctor size mold (4-in.-diameter by 4.59-in.), in conjunction with the appropriate hammer weight, drop height, and compaction effort (AASHO T-134 for soil-cement and ASTM C593 for lime-fly ash), was mainly used for the coarse soil-stabilizer mixtures. A study of the effect of reduced density was also conducted that required specimens to be molded at approximately 95 percent and 90 percent of the maximum dry density found by AASHO T-134 and ASTM C593 methods.

The finer grained soil-stabilizer mixtures were compacted in 3 equal layers in 2-in.-diameter by 4-in. steel molds. The compaction hammer utilized a 4-lb weight falling freely through a distance of 12 in. The surface between layers was scarified to a depth of ¼ in. to ensure a good bond. A blow-count correlation was performed to achieve the same density in the 2-in.-diameter by 4-in. specimens, as obtained by AASHO T-99 for lime-soil mixtures, AASHO T-134 for soil-cement mixtures, and ASTM C593 for lime-fly ash-aggregate mixtures. Reduced density studies for the soil-cement mixtures and lime-fly ash-aggregate mixtures were conducted at approximately 95 percent and 90 percent of maximum dry density.

The compaction moisture contents were maintained within ±1 percent of the appropriate optimum value, and the dry densities were maintained within ±3 pcf of the desired dry density.

Specimen sizes used in the study for the various mixtures are given in Table 2.

Curing Procedures

Immediately after compaction, all specimens were removed from the molds, marked, and weighed. The lime-soil specimens were sealed in plastic bags to prevent moisture loss during curing and placed on shallow metal trays to prevent damage during handling. The lime-soil specimens were cured for a period of 48 hours or 96 hours at 120 F.

The soil-cement specimens were placed on metal screens in a 100 percent relative humidity room at 77 F to cure for 7 days. The curing procedure used was that recommended by AASHO T-136.

The lime-fly ash specimens were sealed in plastic bags and cured 7 days at 100 F in a forced-air circulation cabinet, the procedure recommended in ASTM C593.

TESTING PROCEDURE

To determine if vacuum saturation could be used to predict the durability of stabilized soils, it was necessary to make comparisons with results from an extensive freeze-thaw durability test program conducted at the University of Illinois (2).

Freeze-Thaw Durability Test

The freeze-thaw testing procedure used to provide data for this study was developed from quantitative frost-action data generated by a special heat-transfer model. A detailed description of the model and its application can be found in previous investigations by Dempsey and Thompson (11) and Thompson and Dempsey (12).

The standard freeze-thaw cycle is shown in Figure 1. The temperatures are programmed into the top and bottom chambers of a specially developed freeze-thaw testing unit by means of a photoelectric-curve-following programmer and a controller-recorder (3). All stabilized mixtures were subjected to 5 freeze-thaw cycles and in some cases 10 cycles. Each cycle required 48 hours for completion.

Vacuum Saturation Test

A detailed description of the vacuum saturation testing method is given in the Appendix to this paper. For each stabilized material, 4 specimens were selected at random from the cured specimens to be used in the freeze-thaw test and placed in a vacuum vessel (Fig. 2) that was specially constructed for the project. The stainless-steel vessel was of welded construction with a 1-in. thick Plexiglas lid. The specimens were placed in an upright position on a perforated Plexiglas plate so that water could enter the soil from all surfaces. After closing the lid, the vessel was evacuated to 24 in. of mercury (about 11.8 psi) for 30 minutes. The reason for the 30-minute period under vacuum was to decrease the pressure in the stabilized soil specimens as much as possible. Upon completion of the vacuum treatment, de-ionized water was allowed to flood the vessel and cover the specimens. The vacuum was removed after the chamber was flooded, and the specimens were allowed to soak for 1 hour. After the saturation period the water was drained, and the specimens were immediately tested for unconfined compressive strength and moisture content.

EVALUATION METHODS

Unconfined compressive strength and moisture content measurements were used to evaluate the durability of the stabilized materials. Unconfined compressive strength has been found to be a sensitive indicator of the durability of stabilized soils (2). The change of moisture content in test specimens that have been subjected to one-directional freezing may be a measure of porosity and capillarity and may indicate the susceptibility of a stabilized material to heave and strength loss.

Unconfined compressive strength and moisture content measurements were conducted after vacuum saturation and following 5 and 10 freeze-thaw cycles. Specimens tested immediately after the curing period were used for controls. Generally, 4 specimens were tested for unconfined compressive strength and moisture content during various phases of the test program when 2-in.-diameter by 4-in. specimens were used. Three specimens were normally tested when Proctor-sized specimens (4-in.-diameter by 4.59-in.) were required. All strength tests were conducted at a loading rate of 0.05 in. per minute, and moisture contents were determined for the middle layer of the specimens.

FREEZE-THAW AND VACUUM SATURATION DATA

Average values for the data collected from the extensive laboratory testing program are given in Tables, 3, 4, and 5. Unconfined compressive strength and moisture content data for lime-soil mixtures cured for different time periods are given in Table 3. Similar strength and moisture data for soil-cement and lime-fly ash mixtures compacted at different densities and with different stabilizer contents are given in Tables 4 and 5.

DEVELOPMENT OF VACUUM SATURATION PROCEDURE

In developing the vacuum saturation test for stabilized materials, three important variables were considered:

1. The amount of time that the vacuum is applied to the test specimens;
2. The magnitude of the vacuum pressure; and
3. The amount of time the specimens soak in water after the release of the vacuum pressure.

Herrin et al. (7) found that little change in moisture content occurred in bituminous mixtures after 16 minutes of pressure time. In this study a vacuum was maintained on the specimens for a period of 30 minutes.

ble 1. Materials included in testing program.

Soil	Sample Location	Description	AASHO Classification	Atterberg Limits		Percent Passing No. 200 Sieve	Percent <2μ Clay	Stabilizing Agents		
				LL	PI			Lime	Cement	Lime-Fly Ash
Ava B	Williamson County	B horizon of profile developed in highly weathered loess over Illinoian age drift	A-6(10)	35	16	99	30	X	X	
Clarence C	Livingston County	Wisconsinan clay till	A-7-6(17)	54	24	93	69	X		
Drummer B	Champaign County	B horizon of humic-gley profile developed in loess over till	A-7-6(18)	52	28	99	38	X	X	
Illinoian till	Sangamon County	Calcareous loam till of Illinoian age	A-4(4)	21	6	55	18	X	X	
Wisconsinan till	Champaign County	Calcareous loam till of Wisconsinan age	A-4(7)	23	7	72	24	X	X	
Plainfield sand	Cass County	Outwash deposit in Illinois river bottom	A-3(0)	NP	NP	6	2		X	X
Ridgeville sand	Iroquois County	B horizon of profile developed in fine sandy outwash material	A-4(0)	25	7	36	17		X	X
CA-10	Champaign County	Outwash deposit in front of Champaign moraine	A-1-a(0)	NP	NP	8	—		X	X
CA-6	Will County	Crushed limestone	A-1-a(0)	NP	NP	11	—		X	X
Pit-run gravel	Lawrence County	Outwash deposit in Wabash River Valley	A-1-b(0)	19	4	13	—		X	X

Table 2. Optimum design stabilizer contents and compaction data.

Soil	Freeze-Thaw Specimen Size (diameter by length), in.	Lime-Soil Mixtures			Soil-Cement Mixtures			Lime-Fly Ash Mixtures		
		Additive[a] (percent)	Dry Density[b] (pcf)	Optimum Moisture[b] (percent)	Additive[a] (percent)	Dry Density[c] (pcf)	Optimum Moisture[c] (percent)	Additive[a] (percent)	Dry Density[d] (pcf)	Optimum Moisture[d] (percent)
a B	2 × 4	5	101.0	20.6	10.5	104.8	19.2	—	—	—
rence C	2 × 4	5	93.8	25.6	—	—	—	—	—	—
rummer B	2 × 4	5	96.0	23.5	14	98.8	22.0	—	—	—
Illinoian till	2 × 4	3	121.0	13.0	5	121.5	12.0	—	—	—
Wisconsinan till	2 × 4	3	120.0	11.5	6	116.0	14.5	—	—	—
Plainfield sand	2 × 4	—	—	—	7.5	110.7	11.5	23	123.6	8.8
Ridgeville sand	2 × 4	—	—	—	8	114.8	14.3	11	120.4	12.3
CA-10	4 × 4.59	—	—	—	4	134.9	8.2	10	137.0	6.4
CA-6	4 × 4.59	—	—	—	4	141.5	7.8	10	142.6	6.3
Pit-run gravel	4 × 4.59	—	—	—	4	131.5	9.0	10	135.2	7.0

[a] Percent dry weight of soil basis (total dry weight basis for lime-fly ash). [b] AASHO T 99 procedure. [c] AASHO T 134 procedure. [d] ASTM C 593 procedure.

Figure 1. Standard freeze-thaw cycle for Illinois.

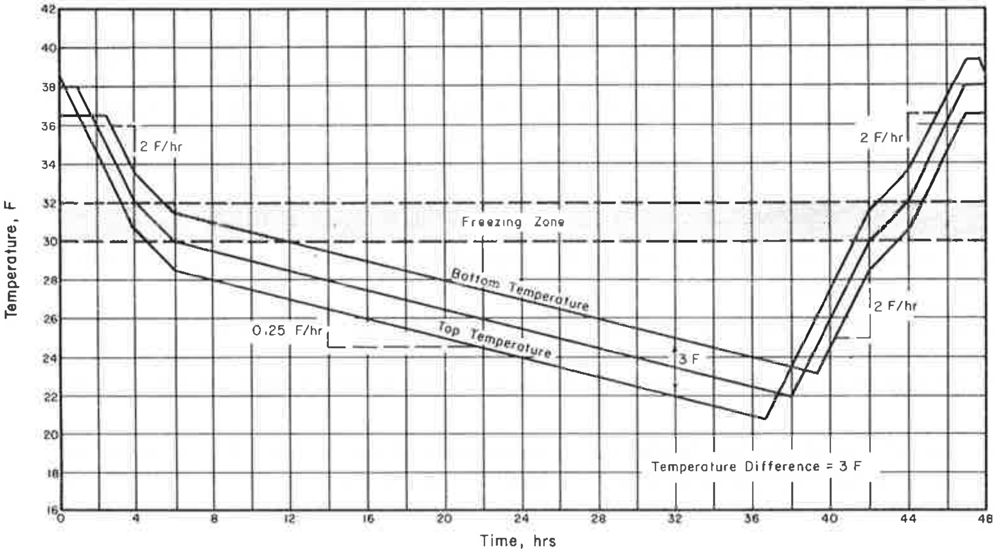


Figure 2. Vacuum saturation equipment.

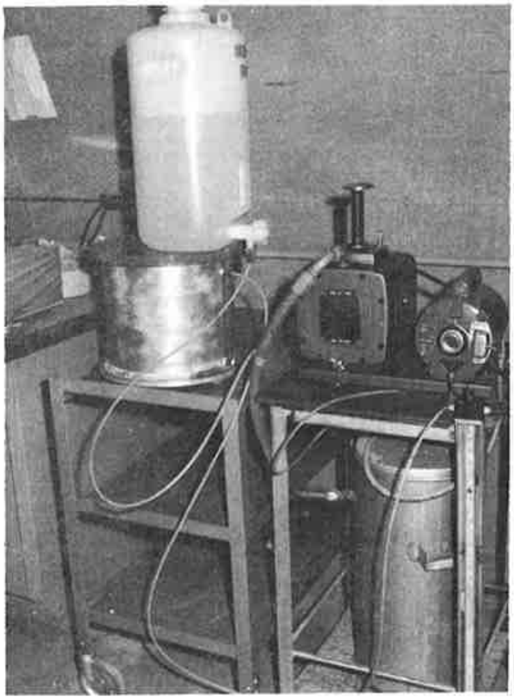


Table 3. Strength and moisture data from freeze-thaw and vacuum saturation tests conducted on lime-soil mixtures.

Soil	Lime, Percent	Curing Period, Hours	After Curing		5 Freeze-Thaw Cycles		10 Freeze-Thaw Cycles		Vacuum Saturation	
			q_u, psi[a]	w, Percent[b]	q_u, psi[a]	w, Percent[b]	q_u, psi[a]	w, Percent[b]	q_u, psi[a]	w, Percent[b]
Ava B	5	48	106	19.1	0	25.1	9	25.6	56	23.7
		96	149	18.5	5	23.7	—	—	82	22.9
Clarence C	5	48	312	23.6	39	22.5	30	27.3	63	27.8
		96	313	23.2	122	24.8	—	—	107	26.5
Drummer B	5	48	326	18.1	162	21.1	99	24.5	214	24.4
		96	395	20.6	155	23.5	—	—	264	25.8
Illinoian till	3	48	354	11.0	105	13.0	89	14.6	181	13.5
		96	446	11.8	194	12.9	—	—	253	14.3
Wisconsinan till	3	48	254	10.9	18	16.8	23	17.5	95	16.4
		96	247	10.2	16	16.2	—	—	101	17.0

[a] Unconfined compressive strength determined at a deformation rate of 0.05 in. per minute.

[b] Moisture content taken at middle of specimen.

Table 4. Strength and moisture data from freeze-thaw and vacuum saturation tests conducted on soil-cement mixtures.

Soil	Cement, Percent	Dry Density, pcf	After Curing		5 Freeze-Thaw Cycles		10 Freeze-Thaw Cycles		Vacuum Saturation	
			q_u, psi^a	w, Percent^b	q_u, psi^a	w, Percent^b	q_u, psi^a	w, Percent^b	q_u, psi^a	w, Percent^b
Ava B		104.8^c	449	16.6	359	17.4	395	18.5	362	19.2
	10.5	99.6	265	17.6	242	21.4	—	—	265	23.8
		94.0	225	15.1	175	24.1	—	—	213	24.3
	8	103.5	387	12.2	358	17.0	—	—	294	20.4
Drummer B		98.8^c	772	19.0	684	19.2	686	18.9	584	22.1
	14	93.3	444	20.0	270	24.0	—	—	357	25.8
		89.0	228	25.0	223	26.9	—	—	246	26.4
	10	103.4	628	19.3	457	19.4	—	—	386	21.0
Illinoian till		121.5^c	645	11.0	480	11.3	488	11.1	501	13.9
	5	116.1	310	14.4	223	14.6	—	—	254	16.6
		109.8	266	10.0	122	16.8	—	—	168	18.1
	3	123.1	424	11.5	291	11.4	—	—	247	13.6
Wisconsinan till		116.0^c	642	12.1	385	12.2	295	13.7	406	14.5
	6	110.4	381	13.0	219	15.8	—	—	238	17.5
		105.5	252	12.8	124	18.1	—	—	195	20.1
	4	117.0	325	13.5	233	14.6	—	—	262	15.0
Plainfield sand		110.7^c	375	9.3	369	9.5	370	10.1	328	17.0
	7.5	105.0	245	10.7	346	12.3	—	—	234	18.8
		100.0	216	11.2	244	12.8	—	—	193	23.9
	6	110.0	195	10.4	232	10.2	—	—	175	17.2
Ridgeville sand		114.8^c	798	11.9	603	12.0	510	13.2	572	15.2
	8	109.4	452	13.1	265	15.6	—	—	374	17.0
		103.3	319	12.8	231	18.5	—	—	236	19.1
	5	115.4	472	13.4	295	14.0	—	—	414	15.9
CA-10		134.9^c	749	7.0	719	7.9	735	8.2	633	8.8
	4	—	—	—	—	—	—	—	—	—
		—	—	—	—	—	—	—	—	—
	2	134.0	286	7.6	252	8.1	—	—	232	8.7
CA-6		141.5^c	844	6.3	733	7.1	664	7.3	685	8.7
	4	132.3	559	6.9	543	6.9	—	—	514	9.0
		128.7	507	6.7	524	—	—	—	485	8.6
	2	136.9	331	6.9	263	6.9	—	—	275	7.9
Pit-run gravel		131.5^c	643	7.7	656	8.0	674	7.6	571	8.3
	4	126.5	442	8.8	496	8.1	—	—	434	10.7
		117.5	265	9.0	298	12.1	—	—	255	9.4
	2	133.5	237	8.7	130	9.2	—	—	197	9.3

[a] ASTM D 1633 procedure. [b] Moisture content taken at middle of specimen. [c] Maximum dry density, AASHO T 134 procedure.

Table 5. Strength and moisture data from freeze-thaw and vacuum saturation tests conducted on lime-fly ash mixtures.

Soil	Lime-Fly Ash, Percent	Dry Density, pcf	After Curing		5 Freeze-Thaw Cycles		10 Freeze-Thaw Cycles		Vacuum Saturation	
			q_u, psi^a	w, Percent^b	q_u, psi^a	w, Percent^b	q_u, psi^a	w, Percent^b	q_u, psi^a	w, Percent^b
Plainfield sand		123.6^c	1,094	7.5	916	7.1	1,081	7.1	850	9.0
	23	116.8	1,072	8.1	782	7.8	—	—	519	14.8
		111.7	695	8.0	395	12.8	—	—	384	16.7
	14	123.5	595	6.8	436	7.1	—	—	366	11.0
Ridgeville sand		120.4^c	461	11.1	375	11.2	248	11.8	271	14.1
	11	112.8	364	11.0	219	12.8	—	—	239	16.9
		108.2	303	10.1	101	15.9	—	—	170	18.5
	7	117.1	371	10.7	201	13.0	—	—	187	15.4
CA-10		137.0^c	705	6.0	835	6.6	811	6.5	692	7.1
	10	—	—	—	—	—	—	—	—	—
		—	—	—	—	—	—	—	—	—
CA-6		142.6^c	1,119	5.5	1,010	6.1	1,180	5.8	1,062	6.4
	10	135.5	911	5.2	1,016	6.5	—	—	895	7.0
		127.9	853	5.3	718	5.2	—	—	687	9.8
	6	141.2	584	3.8	519	5.9	—	—	547	7.1
Pit-run gravel		135.2^c	338	6.4	304	6.9	234	7.4	232	9.5
	10	127.7	356	6.3	170	6.3	—	—	170	12.0
		122.6	279	5.7	172	8.6	—	—	170	13.9
	6	133.1	228	7.5	166	8.0	—	—	147	10.0

[a] ASTM C 593 procedure. [b] Moisture content taken at middle of specimen. [c] Maximum dry density, ASTM C 593 procedure.

Moisture content and strength studies were conducted on stabilized specimens that had been subjected to different vacuum pressures (Figs. 3 and 4). In both the Illinoian till stabilized with lime (Fig. 3) and the Plainfield sand stabilized with lime-fly ash (Fig. 4) there is some indication that the rate of moisture change decreases as the vacuum pressure increases. Herrin et al. (7) have indicated that the distribution of moisture in test specimens subjected to vacuum saturation becomes more uniform as the vacuum pressure is increased.

After vacuum-saturating the specimens, several moisture-tension tests were conducted with an Aquapot osmotic tensiometer. A soil moisture tension of zero was observed for those specimens vacuum-saturated at 24 in. of mercury. This would indicate that close to 100 percent saturation had been achieved.

Figures 3 and 4 also show the influence of vacuum saturation on the strength of stabilized specimens. The figures indicate that the strength did not change appreciably at vacuums greater than approximately 16 in. of mercury.

Based on the limited study of the influence of vacuum pressure on moisture content and strength of stabilized specimens, it was concluded that a large vacuum pressure would give the best results. Therefore a vacuum pressure of 24 in. of mercury was used throughout the study.

Herrin et al. (7) found that after the vacuum pressure is released the specimens will soak up water quite rapidly and then, as the time of soaking is allowed to continue, there will be little increase in moisture in the specimen. They found that after approximately 20 minutes of soaking there was very little additional moisture increase. In this investigation it was felt that a soaking period of 1 hour would be adequate for the moisture contents of the test specimens to reach equilibrium.

ANALYSIS AND DISCUSSION OF TEST DATA

Figures 5 and 6 show the relationships between vacuum saturation strength and 5-cycle and 10-cycle freeze-thaw strengths respectively. Figure 5 was developed from data that included the influence of density and stabilizer content for cement and lime-fly ash materials and the influence of curing period for lime-soil mixtures. Density, stabilizer-content, and curing-period effects were not included in the relationship between vacuum saturation strength and 10-cycle strength (Fig. 6). Linear regression analyses of the data indicated significant correlations ($\alpha = 0.01$) among the data. The regression equations for the data are shown in Figures 5 and 6.

It is apparent from the correlation coefficients that the regression equations shown in Figures 5 and 6 are highly representative of the relationships between vacuum saturation strength and cyclic freeze-thaw strengths. The standard error of estimate was 64 psi for the linear relationship shown in Figure 5 and 68 psi for that in Figure 6. From the linear regression analyses it would appear that vacuum saturation strength is indicative of strength in stabilized materials after 5 or 10 freeze-thaw cycles.

Figures 7 and 8 show respectively the relationships between vacuum saturation moisture content and 5-cycle and 10-cycle freeze-thaw moisture contents. Density, stabilizer-content, and curing-period effects were only included in the comparison of vacuum-saturation moisture content with 5-cycle freeze-thaw moisture content. As in the strength comparisons, linear regression analyses of the data indicated significant correlations ($\alpha = 0.01$) among the data.

In Figures 7 and 8 it is shown that the regression equations are representative of the relationships between vacuum-saturation moisture content and cyclic freeze-thaw moisture content. The standard error of estimate was 2.5 percent for the linear relationship shown in Figure 7 and 2.0 percent for that in Figure 8.

The linear regression analyses indicated that moisture contents in stabilized materials after vacuum saturation can be related to the moisture contents after cyclic freezing and thawing.

Figure 9 shows the effect of density on the strength of cement-stabilized Ridgeville sand after curing, following freeze-thaw cycles, and after vacuum saturation. Figures 10 and 11 show similar data for Ridgeville sand and a pit-run gravel treated with lime-fly ash. It is evident from these figures that the strength of stabilized materials after

Figure 3. Influence of vacuum pressure on the moisture content and strength of Illinoian till stabilized with lime.

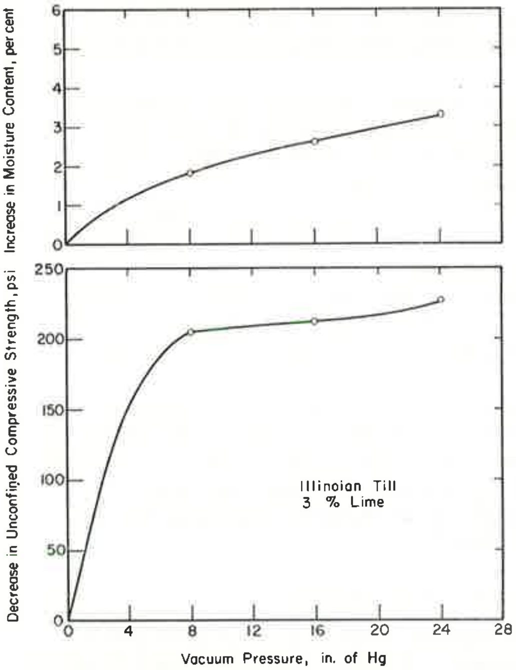


Figure 4. Influence of vacuum pressure on the moisture content and strength of Plainfield sand stabilized with lime-fly ash.

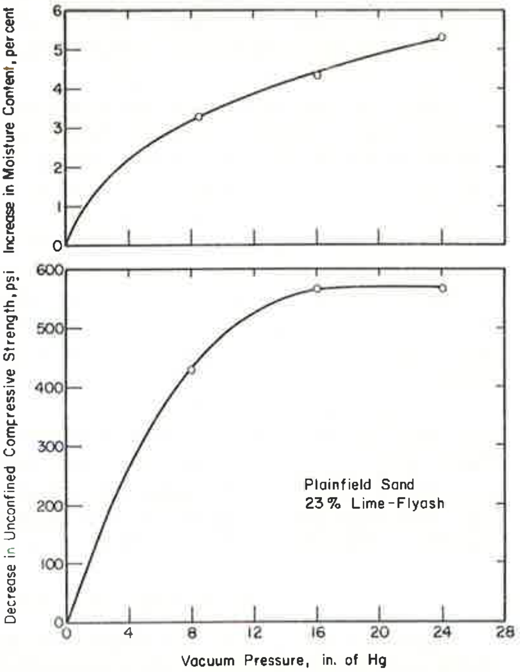


Figure 5. Relationship between vacuum saturation strength and 5-cycle freeze-thaw strength (all data adjusted to equivalent l/d = 2 strengths).

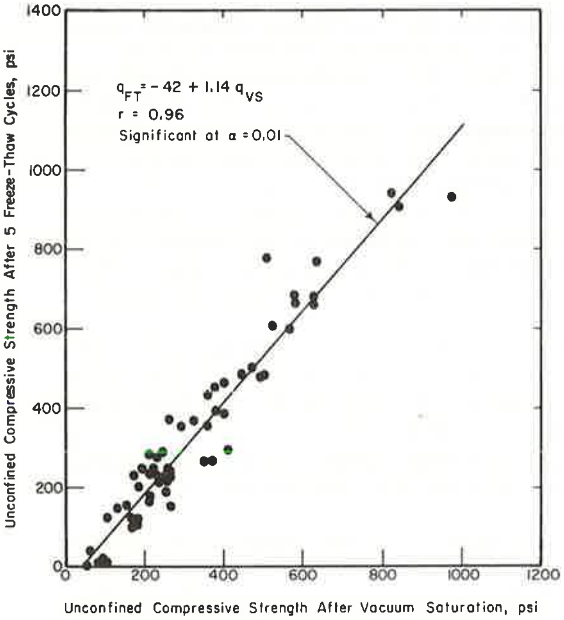


Figure 6. Relationship between vacuum saturation strength and 10-cycle freeze-thaw strength (all data adjusted to equivalent l/d = 2 strengths).

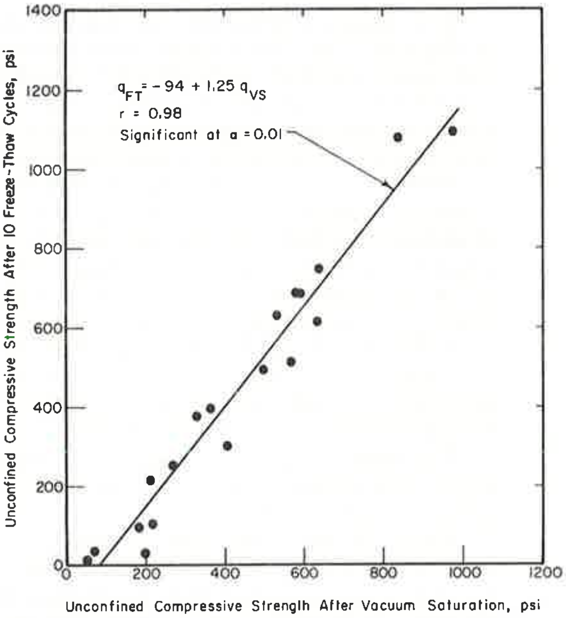


Figure 7. Relationship between vacuum saturation moisture content and 5-cycle freeze-thaw moisture content.

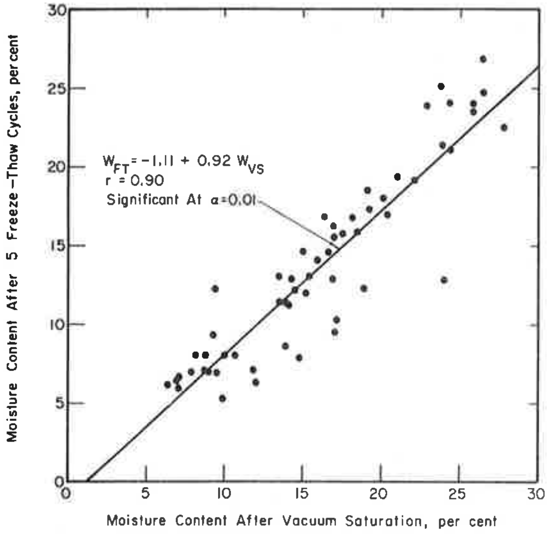


Figure 8. Relationship between vacuum saturation moisture content and 10-cycle freeze-thaw moisture content.

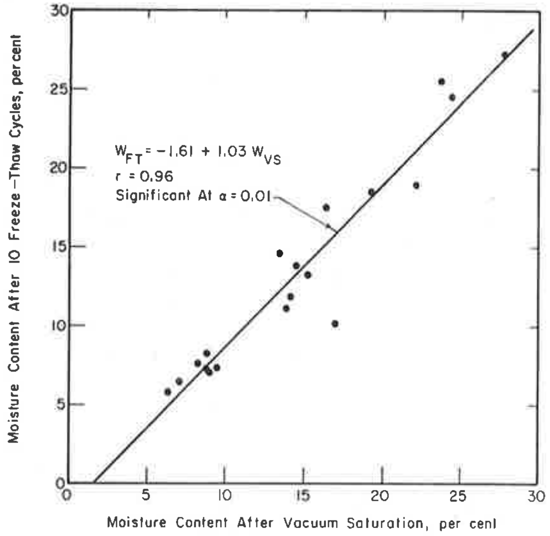


Figure 9. Effect of density on the strength of Ridgeville sand stabilized with cement.

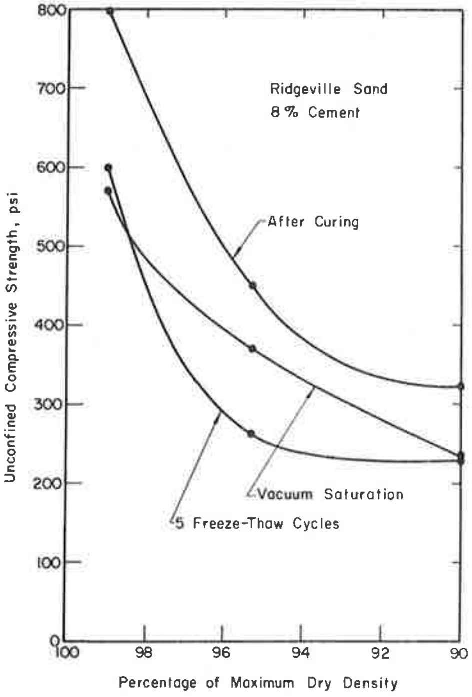
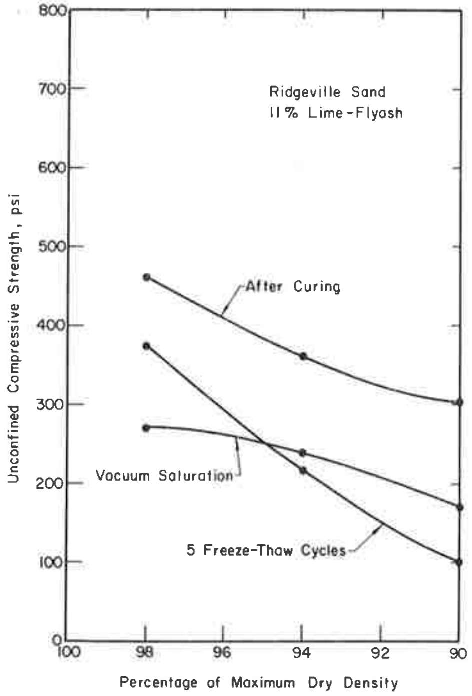


Figure 10. Effect of density on the strength of Ridgeville sand stabilized with lime-fly ash.



curing, vacuum saturation, or cyclic freezing and thawing can be substantially influenced by density.

To further analyze the influence of vacuum saturation on freeze-thaw durability, a pilot study was conducted to determine if freeze-thaw cycles had any effect on stabilized materials after they had been initially vacuum-saturated. Figures 12 and 13 show the influence of 12 subsequent freeze-thaw cycles on moisture content and strength changes in materials stabilized with lime and cement respectively.

Analyses of variance tests indicated that changes in the moisture content of the two stabilized materials after initial vacuum saturation were not significantly influenced ($\alpha = 0.05$) by freeze-thaw cycles. However, strength changes in both materials were significantly influenced ($\alpha = 0.05$) by freeze-thaw cycles after initial vacuum saturation. Although significantly different, it should be noted in Figure 12 that the strength changes with freeze-thaw cycles do not vary more than 50 psi from the strength change after vacuum saturation. For the cement-stabilized Ridgeville sand (Fig. 13), the Duncan multiple-range test showed that only the strength change after 9 freeze-thaw cycles was significantly different ($\alpha = 0.05$) from the strength change after vacuum saturation. Although the reasons for the relationship shown in Figures 12 and 13 are not fully understood at this time, it is evident that vacuum saturation considerably influenced the subsequent freeze-thaw durability response of the stabilized materials considered.

SUMMARY AND CONCLUSIONS

An extensive laboratory program was conducted to determine if vacuum saturation could be used as a rapid method for predicting the freeze-thaw durability of materials such as soil-cement, lime-fly ash, and lime-soil mixtures. The soils used in the stabilized mixtures were representative of those found in Illinois.

Except where the effect of reduced density on soil-cement and lime-fly ash mixtures was to be studied, the stabilized specimens were compacted at optimum moisture content and maximum dry density. Soil-cement and lime-fly ash mixtures at reduced stabilizer contents and lime-soil mixtures cured for different time periods were also tested.

Vacuum saturation was accomplished by allowing specimens that had previously been exposed to a vacuum pressure of 24 in. of mercury for 30 minutes to soak in water for 1 hour at atmospheric pressure. Measurements of unconfined compressive strength and moisture content were used to evaluate the durability of the stabilized materials.

To determine the feasibility of using the vacuum saturation test to predict the freeze-thaw durability of stabilized materials, strength and moisture content comparisons were made.

From the results of this study the following conclusions were established:

1. The vacuum saturation testing procedure can be used to predict the freeze-thaw durability of stabilized materials such as soil-cement, lime-fly ash, and lime-soil mixtures.
2. The vacuum saturation procedure is a fast and inexpensive test method.
3. An excellent correlation exists between the vacuum saturation strength and moisture content and the strength and moisture content after 5 and 10 freeze-thaw cycles.
4. Considerable strength loss in stabilized materials can be caused by vacuum-saturation-induced moisture increases.
5. Density has substantial influence on the strength and durability of cement- and lime-fly ash-stabilized materials.

Although the vacuum-saturation testing procedure can be used to predict the freeze-thaw durability of stabilized materials, a rationally based freeze-thaw test should be used for evaluating freeze-thaw durability when more precise durability property data are required and justified.

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Figure 11. Effect of density on the strength of pit-run gravel stabilized with lime-fly ash.

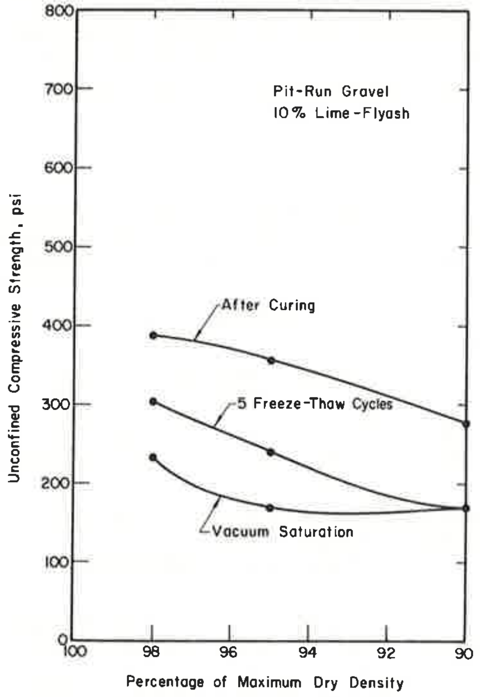


Figure 12. Influence of vacuum saturation and subsequent freeze-thaw cycles on the moisture content and strength of Illinoian till stabilized with lime.

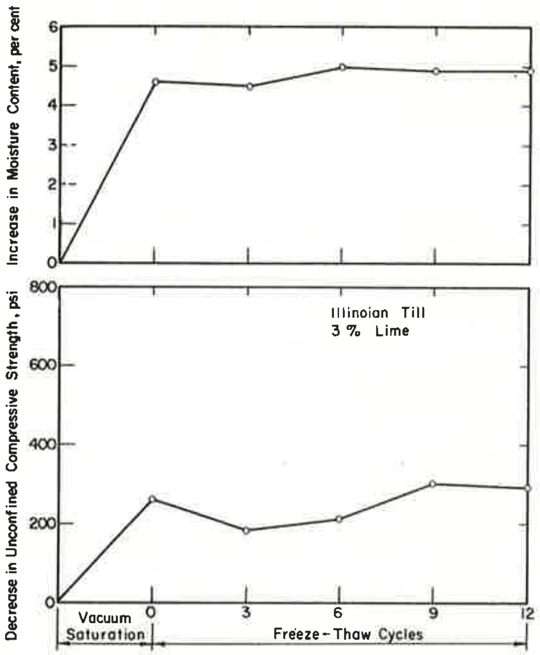
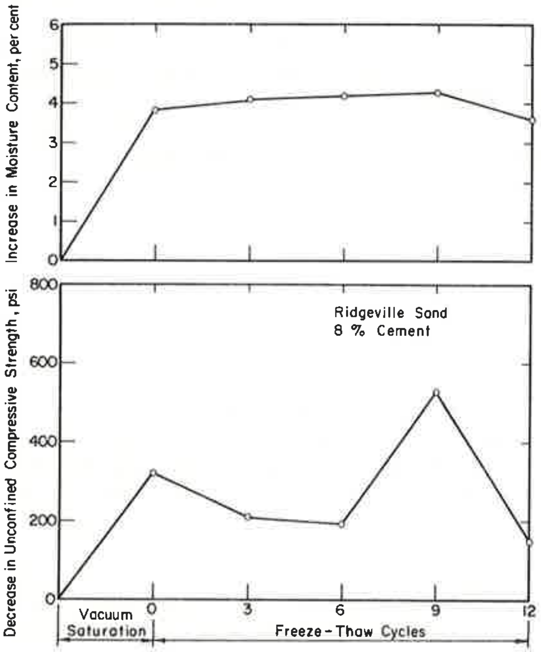


Figure 13. Influence of vacuum saturation and subsequent freeze-thaw cycles on the moisture content and strength of Ridgeville sand stabilized with cement.



Civil Engineering, in the Engineering Experiment Station, University of Illinois at Urbana-Champaign, in cooperation with the Illinois Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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APPENDIX

VACUUM SATURATION PROCEDURE

1. At the end of the curing period the specimens were removed from the curing room and allowed approximately 2 hours to reach equilibrium with room temperature. The specimens, which were cured in plastic bags, remained sealed in the bags during the 2-hour equilibration period to prevent moisture loss. The soil-cement specimens were cured at a temperature very close to room temperature and therefore did not require the equilibration period.

2. The specimens were placed in an upright position within the vacuum vessel, and the chamber was evacuated to 24 in. of mercury for 30 minutes. The specimens were placed on a perforated Plexiglas plate so that all surfaces would be equally exposed to

the chamber environment. The objective of this step was to remove the air from the voids in the specimens.

3. After the 30-minute de-airing period, the vacuum vessel was flooded with deionized water to a depth sufficient to cover the soil specimens. The vacuum was removed, and the specimens were soaked for 1 hour at atmospheric pressure.

4. At the end of the soak period, the specimens were removed from the water and allowed to drain for approximately 2 minutes on a nonabsorptive surface. With the free surface water drained away, the specimens were immediately tested for unconfined compressive strength at a loading rate of 0.05 in. per minute.

5. With compressive strength determined, the specimens were broken into 3 layers from the top to the bottom. The layers were then placed in moisture-content cans, weighed, and the information was recorded for moisture-content determination by weight. The moisture samples were dried in an oven at 110 C for 24 hours.