# Effect of Freezing and Thawing on Unconfined Compressive Strength of Lime-Stabilized Soils

RICHARD D. WALKER and CETIN KARABULUT
Respectively, Associate Professor of Civil Engineering and Graduate Student, Virginia Polytechnic Institute

The effect of a closed-system freezing-and-thawing test on the confined compressive strength of a lime-stabilized silt and a clay soil was the object of this study. The clay soil was classified as A-7-5(18) and the silt soil as A-5(8). The percentages of hydrated lime used were 0, 5 and 10 by dry weight of soil. All specimens were wrapped in aluminum foil, sealed with paraffin, and cured for 48 hr at 120 F.

In one series of tests, the specimens were frozen in a standard deep-freeze unit to a temperature of 0 F and then thawed in a 100 percent humidity room at 70 F. All specimens were kept sealed in aluminum foil until tested in unconfined compression. The compression tests were run at the end of 0, 5, and 10 cycles of freezing and thawing. In a second series of tests, automatic equipment was used to freeze and thaw specimens alternately between 0 and 40 F. These specimens were tested at the end of 29 cycles of freezing and thawing.

Results showed that the strength of clay soil was greatly increased by the addition of lime but suffered large decreases in strength when exposed to freezing and thawing. The strength of the silt soil was affected very little by the addition of lime or by alternate cycles of freezing and thawing. With the untreated soils, the clay lost most of its strength after freezing and thawing, and the silt lost little of its strength.

Attention is given to the possible role of an activity similar to that described by Powers' hypothesis for concrete, taking place in the stabilized soil during freezing and thawing. A discussion of closed-system and open-system types of freezing-and-thawing tests is also included.

•IN VIRGINIA, as well as in other parts of the country, increasing quantities of hydrated lime are being used to improve subgrade materials under primary highways. Improvement of subgrade strength is becoming recognized as one of the most important factors in a successful pavement design.

Although results of previous investigations have shown that lime changes the plasticity and increases the unconfined compressive strength, the durability of lime-soil mixtures when exposed to freezing and thawing has not been studied to a very great degree. Those previous studies that have been accomplished have indicated that lime-soil mixtures may be susceptible to deterioration due to freezing and thawing. Thus, if a pavement design is to be based on an improved strength value, the expected loss in strength due to freezing and thawing must be known.

The effect of a closed-system freezing-and-thawing test on the unconfined compressive strength of a lime-stabilized silt and clay soil was the main object of this study.

Paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization and presented at the 43rd Annual Meeting.

A closed-system test prevents the ingress and egress of moisture and differs from the more common freezing-and-thawing tests where the specimen is permitted to draw up water by capillarity and, thus, often fails by ice segregation within the specimen. The closed-system test might be more appropriate, especially for plastic clays of low permeability, where the amount of water that could be brought up by capillarity would be very small.

An attempt is made to show how the freezing-and-thawing process in lime-stabilized soils might be similar to that in concrete as described by Powers' hypothesis (8). This would be a destructive process caused by hydraulic pressures rather than by ice segregation.

## FREEZING AND THAWING TESTS

### Open and Closed Systems

It is generally believed that detrimental effects of freezing and thawing on soils are caused by the formation of segregated ice or ice lenses. Since the belief has been prevalent that soils in the field generally behave as open systems, most freezing-and-thawing studies have been made with specimens in contact with water and with moisture absorption allowed.

Soil systems can be classified as open or closed systems. An open system is the one which has a water supply from outside. A closed system has only the water within itself and water is not gained or lost. Tabor (10), thinking that very impermeable soils behave as closed systems, conducted laboratory tests on clays containing bentonite. He found that segregation of ice does not occur in closed systems.

### Freezing and Thawing of Concrete

Powers (8) developed a theory to explain the freezing-and-thawing action in concrete. Concrete is believed to act somewhat as a closed system. Powers' hypothesis rests mainly on the premise that the destruction of concrete by freezing is caused by hydraulic pressure generated by the expansion accompanying freezing of water rather than by direct crystal pressure developed through growth of bodies of ice crystals. If the destructive action of freezing is due to hydraulic pressure, the resistance to movement of water must be the primary source of pressure, since all concrete contains enough air-filled space to accommodate water-to-ice expansion. The intensity of the hydraulic pressure developed during the freezing depends on degree of saturation, pore size, and permeability characteristics.

By using the test data of this study and by deductive reasoning, an attempt is made to rationalize this concept to lime-stabilized soils.

### Testing of Stabilized Soils Exposed to Freezing and Thawing

The most commonly used tests fall in one of the following three categories:

1. Loss in weight of specimens which is produced by brushing;
2. Percent change in unconfined compressive strength; and
3. Change in velocity of pulse propagation.

There are several objections to the brushing test. It can generally be used only on well-stabilized granular materials. Also, the results depend somewhat on the amount of pressure applied by the brusher and on the condition of the brush. The unconfined compression test has the advantage of being relatively free from operator influence and has been used extensively by Davidson (4), Whitehurst and Yoder (13), and several others. Even though pulse velocity measurements have been used for many years, the method is still in the experimental stage and is not as accurate as the compression test. However, it has the advantage of being a nondestructive test.

The unconfined compression test is used exclusively in this study.

## Freezing-and-Thawing Durability of Lime-Stabilized Soils

Probably most of the work on the freeze-thaw durability of lime-stabilized soils has been done at the Iowa Engineering Experiment Station (4, 5, 7). Yoder, at Purdue University, has also done considerable work in this field (13, 14). General conclusions of this past work can be listed as follows:

1. Soil texture appreciably affects durability;
2. Increase in percent lime generally increases soil durability; and
3. Durability is increased by longer curing before freeze-and-thaw cycles.

## Importance of Freeze-Thaw Durability in Southwest Virginia Area

Southwestern Virginia is generally located in the Ridge and Valley and Appalachian Mountain physiographic provinces. The climate is severe from the standpoint of the number of alternate cycles of freezing and thawing, and plastic clay residual soils are in abundance. The Virginia Department of Highways is using lime to stabilize these soils on all important highway projects and, thus, it would seem to be important to discover how permanent the strength gains are.

All of the previous research cited dealt with open-system tests on granular to silty-clay soil textures. Little or no attention has been given to the more impermeable plastic clay which may act more as a closed system.

# MATERIALS

## Soil

The clay soil was reddish-brown in color with a liquid limit (L. L.) of 77, a plastic limit (P. L.) of 53, and a plasticity index (P. I.) of 24. It had about 59 percent finer than 0.002 mm and was classified according to the AASHO system as A-7-5(18). The silt soil was brown with plasticity characteristics as follows: L. L. = 41, P. L. = 32, and P. I. = 9. It had about 31 percent finer than 0.002 mm and was classified according to the AASHO system as A-5(8).

## Lime

The hydrated lime used in all tests was manufactured by the Ripplemead Lime Co. X-ray analysis of the lime from the bag used after all tests were completed showed that the $CaCO_3$ content was as much as 60 percent. Since all the tests were run within a relatively short period of time, this should not have had significant effect on the variability of the results. However, it does point out the importance of checking the lime source for percent of calcium hydroxide.

# LABORATORY TEST PROCEDURES

## Density Tests

Density tests were performed on air-dry samples with the Harvard miniature compaction apparatus. Experience had shown that this device loaded with a 40-lb spring with 25 blows on each of three layers of soil gave similar results to those obtained by the standard AASHO procedure. Moisture-density curves were obtained for both soils, containing 0, 5 and 10 percent of lime, to determine optimum moisture content for each condition.

## Fabrication of Specimens

All specimens were compacted using the Harvard miniature apparatus. The samples were molded at the optimum moisture contents of the soils for 0, 5 and 10 percent of lime. All specimens after compaction were extruded from the mold, immediately wrapped with aluminum foil, and coated with paraffin to preserve the molding moisture content during curing and freezing and thawing.

Curing

All specimens were cured for 2 days at 120 F. This procedure was developed by Anday (1) and is roughly equivalent to 60 to 65 days of simulated field curing during a summer at Charlottesville, Va.

Freezing and Thawing

Two different methods of freezing and thawing were tried.

1. Four specimens were prepared for each of the 0, 5 and 10 percent combinations of lime with silt and clay, giving a total of 24 specimens. All specimens after 2 days of curing were placed in a copper container (3 by 3 by 15 in.) with about ⅛ in. of water in the bottom and the container was placed on a freezing plate. (The purpose of the water was merely to aid in conducting heat in and out of the specimens.) The specimens then underwent 29 cycles of freezing and thawing at a rate of 8 cycles per day. The temperature in adjacent cans which contained concrete specimens alternated from 0 and 40 F. The automatic equipment was designed for the freezing and thawing of concrete specimens according to ASTM Designation: C 290 and is described in an article by Cordon (3).

2. Four specimens were prepared for each combination of lime with silt and clay. After 2 days of curing, the specimens were frozen in a deep-freeze unit for 8 hr and thawed in a moist room at 70 F and 100 percent RH for 16 hr. (The main purpose of the moist room was to afford constant temperature.) Half of the specimens were subjected to 5 cycles of freezing and thawing and the other half to 10 cycles.

Twenty-four additional specimens were fabricated as controls and were tested after the 2-day curing period without undergoing freezing and thawing.

Unconfined Compressive Strength Tests

The unconfined compressive strength of all specimens was determined using a loading rate of 0.05 in./min. Altogether, 72 specimens were prepared for testing. The maximum compressive strength was determined, as well as a secant modulus which was determined by dividing the strain at the time maximum stress was reached into maximum stress.

## RESULTS

Standard Atterberg limit tests and Harvard miniature compaction tests were run on both soils with lime at 0, 5 and 10 percent. The results of these tests are given in Table 1. The results obtained are similar to those obtained by other researchers in that the P.I. of the plastic soil was greatly reduced with the addition of lime and that of the silt was not. Also, both soils showed a reduction in optimum density and an increase in optimum moisture content with an increase in lime content.

Figures 1 and 2 and Tables 2 and 3 present the results of the unconfined compressive strength tests for all the specimens in this durability study.

TABLE 1

ATTERBERG LIMIT AND DENSITY TEST RESULTS

| Soil | Lime (%) | L.L. | P.L. | P.I. | Opt. Moist. Cont. (%) | Opt. Dry Density (pcf) |
|---|---|---|---|---|---|---|
| Clay | 0 | 77 | 53 | 24 | 32 | 89 |
| | 5 | 70 | 55 | 15 | 35 | 85 |
| | 10 | 67 | 56 | 11 | 36 | 83 |
| Silt | 0 | 41 | 32 | 9 | 17 | 103 |
| | 5 | 42 | 33 | 9 | 22 | 99 |
| | 10 | 43 | 34 | 9 | 23 | 97 |

## DISCUSSION OF RESULTS

Effect of Lime on Soil Strength

Figure 1 and Tables 2 and 3 illustrate the great increase in compressive strength of the plastic clay by addition of lime. With the silt, the compressive strength was slightly decreased. However, Table 3 indicates that the secant modulus did increase when lime was added to the silt. Thus, although total capacity is not increased, the slope of the stress-strain

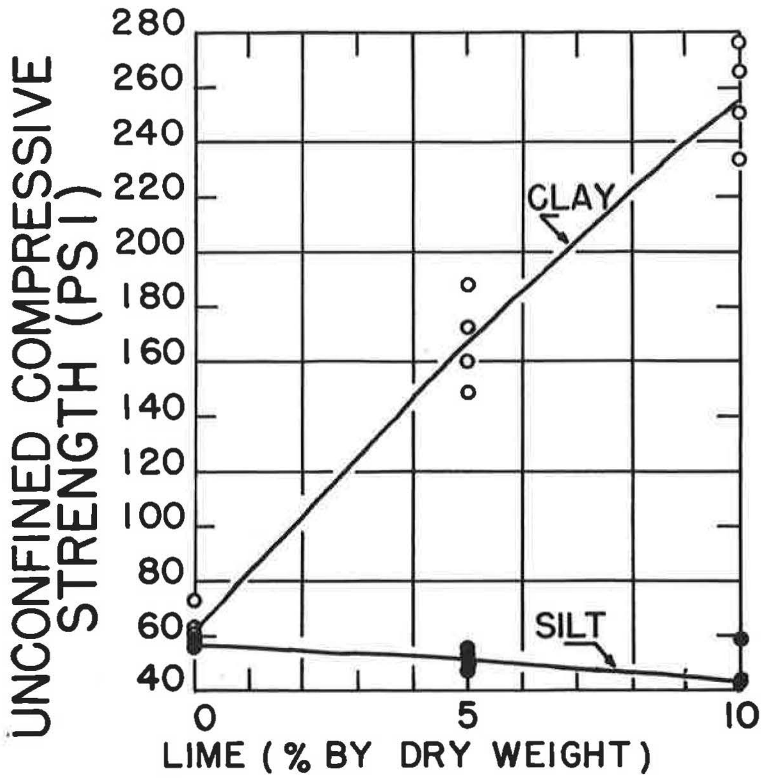


Figure 1. Strength vs percent lime in clay and silt.

curve was made steeper. Apparently the cementing action generated in the silt was broken down at a relatively low compressive stress. Both the secant moduli and compressive strengths were considerably higher for the clay-lime than for the silt-lime mixtures.

The significance of the increase in secant modulus for the silt-lime mixtures cannot be overemphasized. Whatever the cause of the increase (perhaps a weak $CaCO_3$ cement), it can result in lower pavement deflections, providing a certain stress is not exceeded. Heretofore, most silts were not considered likely subjects for lime stabilization, but actually great benefits may be derived. Anything that can reduce deflections in a flexible pavement is bound to be beneficial.

## Effect of Freezing and Thawing on Soil-Lime Mixtures

The comparison of the unconfined strengths after freezing and thawing among the various combinations of soil-lime mixtures can be made from Figure 2 and Table 2. In the clay-lime mixtures, all specimens showed a drastic decrease in strength after being exposed to 5 cycles of freezing and thawing. There was no appreciable difference between the strengths after 5 and 10 cycles, indicating that the loss in strength mainly occurred in the first few cycles. In the silt-lime mixtures, initial strength was low and freezing and thawing produced at the most only slight decreases in strength. In some cases, strength was higher after 10 cycles of freezing and thawing; this could be due to additional curing of the specimens.

The effectiveness of lime in resisting the effects of freezing and thawing can be compared by using a resistance value similar to that proposed by Davidson et al. (4):

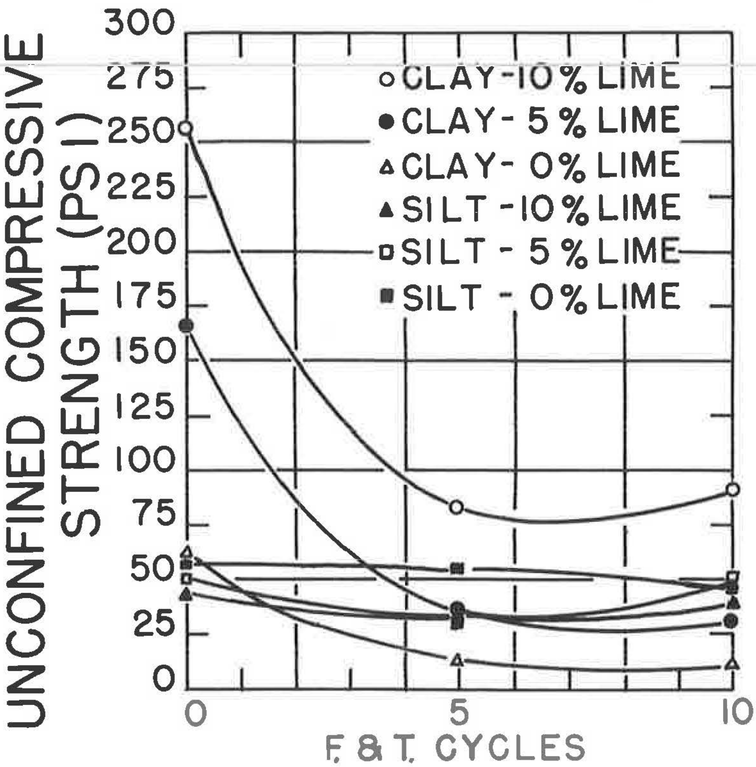


Figure 2. Strength vs freezing-and-thawing cycles, lime-soil mixtures.

$$R_f = p_f/p_o \tag{1}$$

where

$R_f$ = resistance factor,
$p_o$ = compressive strength at 0 cycles of freezing and thawing, and
$p_f$ = compressive strength after 5 or 10 cycles of freezing and thawing.

Resistance values calculated from this equation and given in Table 4 indicate that with a larger percentage of lime, a larger percentage of original strength can be retained.

Although lime-treated clays lost strength after freezing and thawing, they still had higher strengths than the untreated soil at a given number of cycles. In fact, clay soil with 10 percent lime, after freezing and thawing, had more strength than untreated clay soil not subjected to freezing and thawing.

The effect of freezing and thawing on the secant modulus of the silt soil (Table 3) should be noted. As with the control specimens, increases in lime content did bring about an increase in strength. More significantly, relatively large decreases in secant moduli occurred with the untreated silts when subjected to freezing and thawing, but little if any decrease occurred in the lime-treated silts. This would indicate that the durability of the lime-silt mixtures was improved by the addition of lime. Therefore, the deflection-resistance properties of the lime-stabilized soils would not be impaired by freezing and thawing.

It should also be noted that the cycles of freezing and thawing produced no visible distortion of the specimens.

TABLE 2

UNCONFINED COMPRESSIVE STRENGTHS OF CLAY-LIME AND SILT-LIME MIXTURES BEFORE AND AFTER FREEZING AND THAWING

| Soil | Lime (%) | Specimen No. | Strength (psi) | | | |
|---|---|---|---|---|---|---|
| | | | Cycles of Freezing and Thawing | | | |
| | | | 0 | 5 | 10 | 29[a] |
| Clay | 0 | 1 | 72.1 | 13.1 | -- | --[b] |
| | | 2 | 62.7 | 15.2 | -- | --[b] |
| | | 3 | 59.3 | -- | 11.0 | --[b] |
| | | 4 | 56.0 | -- | 11.7 | --[b] |
| | | Avg | 62.5 | 14.2 | 11.4 | |
| | 5 | 1 | 160.0 | 38.0 | -- | 19.3 |
| | | 2 | 148.2 | 32.7 | -- | 19.1 |
| | | 3 | 171.9 | -- | 29.8 | 20.2 |
| | | 4 | 188.0 | -- | 31.1 | --[b] |
| | | Avg | 167.0 | 35.4 | 30.5 | 19.6 |
| | 10 | 1 | 250.5 | 90.5 | -- | 65.8 |
| | | 2 | 234.0 | 79.1 | -- | 71.9 |
| | | 3 | 277.0 | -- | 94.5 | --[b] |
| | | 4 | 266.0 | -- | 84.3 | --[b] |
| | | Avg | 256.9 | 84.8 | 89.4 | 68.9 |
| Silt | 0 | 1 | 57.0 | 58.3 | -- | 66.0 |
| | | 2 | 62.6 | 50.6 | -- | 63.1 |
| | | 3 | 56.4 | -- | 45.0 | --[b] |
| | | 4 | 52.0 | -- | 45.8 | --[b] |
| | | Avg | 57.0 | 54.5 | 45.4 | 64.6 |
| | 5 | 1 | 55.0 | 33.7 | -- | 46.7 |
| | | 2 | 47.0 | 32.5 | -- | 43.2 |
| | | 3 | 53.0 | -- | 51.1 | 54.5 |
| | | 4 | 47.6 | -- | 43.6 | --[b] |
| | | Avg | 50.5 | 33.1 | 47.4 | 48.1 |
| | 10 | 1 | 49.1 | 29.6 | -- | 33.3 |
| | | 2 | 40.2 | 35.6 | -- | 35.5 |
| | | 3 | 40.7 | -- | 37.2 | 37.9 |
| | | 4 | 42.8 | -- | 41.8 | 62.6 |
| | | Avg | 43.2 | 32.6 | 39.5 | 42.3 |

[a]Specimen in automatic freeze-thaw apparatus.
[b]Sample destroyed during freezing and thawing because of entrance of water to wrapped specimen.

TABLE 3

SECANT MODULUS OF CLAY-LIME AND SILT-LIME MIXTURES BEFORE AND AFTER FREEZING AND THAWING

| Soil | Lime (%) | Specimen No. | Secant Modulus (psi) | | |
|---|---|---|---|---|---|
| | | | Cycles of Freezing and Thawing | | |
| | | | 0 | 5 | 10 |
| Clay | 0 | 1 | 1,100 | 316 | -- |
| | | 2 | 1,067 | 338 | -- |
| | | 3 | 1,710 | -- | 318 |
| | | 4 | 1,350 | -- | 275 |
| | | Avg | 1,350 | 327 | 347 |
| | 5 | 1 | 9,250 | 2,440 | -- |
| | | 2 | 7,140 | 2,100 | -- |
| | | 3 | 5,250 | -- | 1,720 |
| | | 4 | 7,780 | -- | 1,495 |
| | | Avg | 8,105 | 2,270 | 1,608 |
| | 10 | 1 | 12,050 | 7,450 | -- |
| | | 2 | 15,000 | 3,270 | -- |
| | | 3 | 13,300 | -- | 6,050 |
| | | 4 | 11,000 | -- | 3,480 |
| | | Avg | 12,840 | 5,360 | 4,765 |
| Silt | 0 | 1 | 1,180 | 800 | -- |
| | | 2 | 1,645 | 697 | -- |
| | | 3 | 1,250 | -- | 810 |
| | | 4 | 1,500 | -- | 825 |
| | | Avg | 1,394 | 749 | 818 |
| | 5 | 1 | 3,180 | 1,085 | -- |
| | | 2 | 2,260 | 1,343 | -- |
| | | 3 | 1,915 | -- | 2,460 |
| | | 4 | 2,760 | -- | 1,800 |
| | | Avg | 2,524 | 1,214 | 2,130 |
| | 10 | 1 | 2,820 | 1,224 | -- |
| | | 2 | 2,330 | 2,940 | -- |
| | | 3 | 1,960 | -- | 2,150 |
| | | 4 | 1,545 | -- | 3,020 |
| | | Avg | 2,164 | 2,082 | 2,585 |

## Mechanism of Disintegration Due to Freezing and Thawing

No water was lost or gained during the curing process or the freezing-and-thawing tests, as indicated by weighing the specimen just after molding and just before compression testing. Therefore, it is considered that the specimens behaved as a closed system, similar to that of concrete. If the destructive action of freezing is due to hydraulic pressure, as it is with concrete, then the resistance to movement of water is the primary source of pressure. The intensity of the hydraulic pressure depends on the pore size and rate of freezing. Resistance to freezing and thawing is largely affected by degree of saturation and pore characteristics.

It is known that the durability of concrete is greatly affected by pore characteristics of both the mortar and the aggregate it surrounds. The problem of concrete durability in a freezing-and-thawing environment is summarized by Powers (8, 9) and Verbeck and Landgren (12). Water permeability has been used as a measure of pore characteristics of the mortar and the aggregates that make up concrete. It is interesting to compare these permeabilities to values generally applied to different soils. In Table 5 are given typical permeability values for some chert and dolomite aggregates that present durability problems. Also given are typical ranges of values for concrete mortar and for silt and clay soils. It may be seen that clay soils fall in the general range of permeabilities for the components of concrete. If, by the addition of lime, sufficient strength was available to supply resistance to the flow of water, the loss of strength of the specimen in this study may well have been due to excessive hydraulic pressures rather than to crystal growth.

TABLE 4

RESISTANCE VALUES OF MIXTURES OF CLAY AND LIME[a]

| Lime (%) | Freeze-Thaw Cycles | | | |
|---|---|---|---|---|
| | 0 | 5 | 10 | 29 |
| 0 | 100 | 22.7 | 18.3 | -- |
| 5 | 100 | 21.2 | 18.2 | 11.7 |
| 10 | 100 | 31.5 | 34.9 | 27.0 |

[a]Calculated from Eq. 1.

TABLE 5

TYPICAL PERMEABILITY VALUES

| Material | Permeability (cm/sec) |
|---|---|
| Concrete mortar[a] | $1$ to $300 \times 10^{-10}$ |
| Dolomite[a] | $300 \times 10^{-10}$ |
| Chert[a] | $1 \times 10^{-10}$ |
| Clay[b] | $< 1,000 \times 10^{-10}$ |
| Silt[b] | $\leq 10,000 \times 10^{-10}$ |

[a]From Verbeck and Landgren (12).
[b]From Terzaghi and Peck (11).

Studies have shown that the critical degree of saturation for concrete exposed to freezing and thawing is about 0.85 (6). The clay-lime specimens in this study had degrees of saturation ranging from 0.86 to 0.89. This also supports the possibility of hydraulic pressure being in action.

Both clay- and silt-lime mixtures showed a decrease in strength after 5 cycles of freezing and thawing. The decreases in clay-lime mixtures were much greater, but then they had more strength to lose and offered greater resistance to water flow, making possible greater hydraulic pressures. In these tests the bond between particles must have been broken in the first few cycles, since beyond 5 cycles no further loss in strength was produced.

The results presented here do not constitute a proof that Powers' hypothesis operates in clay-lime mixtures, but it is hoped that further study of the problem can lead to better understanding of the deterioration or loss of strength in lime-stabilized soils exposed to freezing and thawing.

## SUMMARY


The most important results of this study are as follows:

1. A smaller percentage of strength was lost during freezing and thawing when lime content was increased up to 10 percent.
2. Decrease in strength due to freezing and thawing occurred in the first 5 cycles for all the soil-lime mixtures.
3. Decreases in unconfined compressive strength due to freezing and thawing are much greater in clay-lime mixtures than in silt-lime mixtures.
4. In the closed systems used in this study, disintegration in lime-stabilized soils due to freezing and thawing might be caused by hydraulic pressures generated by the movement of unfrozen water in the pores as a result of expansion of water by freezing.
5. If the hydraulic pressure theory was operating, then greater pressures probably developed in the clay-lime than in the silt-lime mixtures due to smaller pore sizes and much better cementation in the clay-lime mixtures.


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## *Discussion*

MANUEL MATEOS, Torán y Compañía, Madrid, Spain. —The writer was impressed by the very small number of specimens used in this work which, together with the miniature size of the specimens, the accelerated curing, and the accelerated freezing and thawing, makes him wonder about the reliability of the results.

The writer has used "open systems" in the freeze-thaw tests of lime-stabilized soils (15) to submit the specimens to the worst conditions which could be found in the field. Since it appears that the prevalent belief among soil engineers is that the open system reproduces the worst conditions likely to occur in the field, the paper would have been of greater value if it had had a comparative study of open and closed systems.

The established philosophy in research work is that when one of the materials used is spoiled or adulterated, all work affected by these materials should be repeated. The authors used a lime which contained 60 percent calcium carbonate. This is a very high degree of carbonation and, consequently, this lime should not have been used in research work.

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M.C. ANDAY, Highway Research Engineer, Virginia Council of Highway Investigation and Research. —The authors are to be complimented for pointing out that some of the

TABLE 6

SOILS TESTED

| Soil | Description | HRB Class. | Passing Sieve (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | No. 10 | No. 40 | No. 200 | L. L. | P.I. |
| A | Clay from Valley and Ridge | A-7-5(16) | 99.2 | 93.0 | 83.1 | 55 | 19 |
| B | Sand clay from Piedmont | A-4(4) | 97.6 | 81.5 | 53.1 | 26 | 9 |
| C | Micaceous silt from Piedmont | A-5(8) | 97.9 | 93.1 | 70.2 | 45 | N. P. |

properties imparted to soil by treatment with lime are subject to detrimental change by the forces of nature. They have chosen freezing and thawing as a test of durability, since this is one of the two most commonly used methods of simulating the forces of nature.

The studies conducted at the Virginia Council of Highway Investigation and Research since 1962 have been, by choice, based on the wetting of stabilized soils after treatment and curing. It is believed that though the ground surface temperatures might indicate several cycles of freezing and thawing, the stabilized layers might not freeze or thaw for long periods of time. Therefore, at least in Virginia, the number of freeze-thaw cycles at the ground surfaces might constitute too severe a criterion of durability.

It is interesting to note, however, that some of the results obtained by the authors are very similar to the ones obtained by the writer. With the hope that the readers might have a combined view of the effects of the detrimental forces of nature, the following data are offered in support of Messrs. Walker and Karabulut's findings.

The studies at the Virginia Council of Highway Investigation and Research involve soils from 13 projects in Virginia, most of which have been under traffic for several years. Since the overall data are very similar, only those for a few soils are illustrated here. A complete report will be available in the near future.

TABLE 7

EFFECT OF SOAKING

| Soil | Lime (%) | Laboratory Cured Strength (psi)[a] | | | | Secant Modulus (psi) | | $R_f$ (%)[c] |
|---|---|---|---|---|---|---|---|---|
| | | As Cured | V[b] | Cured and Soaked for 5 Days | V[b] | As Cured | Cured and Soaked for 5 Days | |
| A | 8.0 | 320 ± 10 | 5.7 | 201 + 5 | 4.6 | 28,700 | 20,330 | 63 |
| B | 5.0 | 230 ± 20 | 15.7 | 153 ± 8 | 9.4 | 18,170 | 15,000 | 67 |
| C | 5.0 | 91 ± 2 | 4.6 | 66 ± 3 | 7.0 | 3,017 | 2,266 | 73 |

[a]Cured for 2 days at 120 F.
[b]Coefficient of variation in percent (10 samples per test).
[c]Resistance factor ($R_f$) = $\frac{\text{compressive strength after soaking}}{\text{compressive strength as cured}}$.

It might be beneficial to note that the procedures used by the authors and myself were very similar. The main difference was that in my work the Harvard mold-size specimens, after curing for 2 days at 120 F, were soaked for 5 days instead of being subjected to freezing and thawing.

Some of the physical properties and the classification of the soils are given in Table 6. The strength of specimens before and after soaking, their secant moduli and their resistance factors are given in Table 7. Comparison of the resistance factors given in Table 7 with those presented by Walker and Karabulut might indicate that soaking is a less severe test than freezing and thawing and that caution should be exercised in the choice of the durability test; prevailing climatic conditions should be considered.

RICHARD D. WALKER and CETIN KARABULUT, Closure.—This discussion deals with points brought up by Mr. Mateos. It is true that the results of this study were based on a small number of specimens, i.e., as few as two specimens (one specimen from each of two different mixes) for each design consideration. However, the trend shown by these few specimens is unmistakably clear. An example of this can be seen by looking at Table 2. By taking the 5 percent lime case for the clay soil as an example and comparing the lowest zero-cycle strength to the highest 5-cycle strength, a range of 110.2 psi is found (148.2 psi for zero cycles vs 38.0 psi for 5 cycles). Similar comparisons can be made in any direction in the table. Although we emphatically agree that it is always desirable to have a statistically designed experiment, lack of such a design does not negate the large differences exhibited by the data shown. It is agreed, however, that in order to say that anything was significant concerning the silt soil, an adequate statistically designed experiment would have to be made.

The authors agree with Mr. Mateos that a comparative study of open- and closed-system tests would have been desirable. Such a project is being planned for the near future.

Concerning the fact that the hydrated lime was partially carbonized, it should be restated that this should not have affected the variability of the results. Perhaps it should have been stated with greater emphasis that the results were obtained with a lime that has undergone carbonation. We believe the effect of such carbonation should be more thoroughly investigated because there is no doubt that there are many cases in the field where lime is used which contains significant quantities of calcium carbonate.