EFFECTS OF EXTENDED CYCLES OF OPEN SYSTEM FREEZING AND THAWING ON A CLAY-LIME MIXTURE

by

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INTRODUCTION

In recent years, a large amount of research has been done and material written on the stabilization of soils with hydrated lime. It has been discovered that the addition of lime to a clay soil increases the strength of the soil and makes the soil more friable, thereby increasing its workability. Lime stabilized soils are being used with increasing frequency as subgrades beneath highway pavements and airfields. Many airfields and highway pavements are located in regions where freezing and thawing is a serious problem owing to the destruction of subgrades and subsequent deterioration of pavements. Pavement designs have been developed to minimize the deleterious effect of freezing and thawing, but most are expensive and not completely effective. On the other hand, lime stabilization may be an economical approach to the problem of freezing and thawing. Researchers are finding that the addition of lime to a soil increases the soil's durability, but how much the durability is increased is still an enigma. Research has been done to determine the effects of freezing and thawing after relatively few cycles of freezing and thawing, but data are lacking for long term freezing and thawing.

The purpose of this research is to investigate the behavior of a lime stabilized soil after extended periods of freezing and thawing.

Specimens were made containing 0 and 7 per cent lime. Half the specimens were cured for two days at 120°F and half the specimens were cured for four days at 120°F to determine if the length of curing time has any effect on the unconfined compressive strength of the soil before and after freezing and thawing. The specimens were subjected to 0, 5, 10, and 15 cycles of open system freezing and thawing, where one cycle consists of 24 hours in a deep freeze at 0°F and 24 hours in a 100 per cent humidity room at 70°F. An open system is a system in which the water is free to enter and leave the system from an external source. The unconfined compressive strength and the secant modulus were determined after freezing and thawing.

PROPERTIES OF LIME-CLAY MIXTURES

The addition of lime to a clay soil results in an amelioration of the clay characteristics of the soil. Lime affects the plasticity, strength, and swell characteristics of clay.

Atterberg Limits. Studies have shown that the addition of lime to a clay soil generally increases plastic limit and decreases liquid limit, resulting in a decrease in plasticity index. Reduction in plasticity index results in a more friable soil which is easier to handle. (1, 2, 3, 4, 5)

Strength. The strength of a clay soil is increased by the addition of lime.

Hilt and Davidson (5) found that the addition of lime increased the unconfined compressive strength of a montmorillonitic soil the largest amount. A kaolinitic soil had a large strength increase with the addition of lime, but an illitic-chloritic soil only showed a slight strength increase. They found the existence of a lime fixation point (the point at which additional lime does not increase the plastic limit) of three per cent lime, but they discovered that strength increased with the addition of lime beyond the lime fixation point.

Jan and Walker (1) discovered little change in plastic properties by adding more than three per cent lime, but with the addition of five per cent lime CBR soaked values increased more than 10 times.

Although the increase of strength in a clay soil with the addition of lime is apparent, there are several factors affecting the amount of increase in strength. The amount of $CaCO_3$ present in the lime affects the strength of a lime-soil mixture. The greater the amount of $CaCO_3$ present in the lime, the smaller the strength increase, since the $CaCO_3$ subtracts from the amount of calcium that can be used in long term pozzalanic strength reactions. The length of curing affects the strength of soil-lime mixtures. Anday (6), in studies at Charlottesville, Virginia, found that unconfined compressive strength increases with the length of field curing, but that two days curing at 120°F will predict, within reasonable limits, the unconfined compressive strength that can be developed by a soil at a time when it is needed, i.e. about 40 to 45 days after construction.

The time between mixing and compaction influences the strength of soil-lime mixtures. Taylor and Arman (7) discovered that lime has an initial reaction taking place during the first 48 to 72 hours after mixing, and a secondary reaction which starts after the initial reaction and continues indefinitely. They report that when a stabilized base is compacted within 48 hours after mixing, cementation takes place and the whole base becomes a homogenous slab, whereas delayed compaction densifies the friable material with no cementation and resulting strength loss.

Jan and Walker (1) discovered that increased compactive effort results in greater strength for a lime-clay mixture, and increases in compactive effort are more effective for stabilized than non-stabilized mixes.

Swell. The addition of lime to a clay soil decreases swell potential. Jones (8) found that the use of lime reduces expansive properties of soil generally in proportion to the admixture used.

Jan and Walker (1) state that the addition of hydrated lime to a clay soil reduces swell percentage appreciably. Herrin and Mitchell (4) obtained similar results.

Compaction and Optimum Moisture. When compacted with the same effort, a lime-soil mixture has a lower density than the same soil without lime, and as the lime content increases the density tends to decrease progressively.

Optimum moisture tends to increase upon addition of lime to soil (4, 12, 13).

MECHANISMS OF LIME-CLAY REACTIONS

There are three reactions that occur with the addition of lime to soil: carbonation, ion exchange, and pozzolanic reaction.

Carbonation. The calcium in the lime reacts with carbon dioxide from the air to form calcium carbonate, a weak cementing agent. This reaction subtracts from the amount of calcium which can be used for pozzolanic reaction, the source of long term strength, and may be deleterious to the overall strength of the mixture. Some researchers (24), however, have found a slight increase in the strength of a silt soil which they believed was caused by carbonation. (4, 9)

Ion Exchange. A base exchange reaction occurs with the strong calcium cations of the lime replacing the weaker metallic ions, such as sodium and hydrogen, on the surface of the clay particle (4). Ion exchange is said to cause flocculation of a clay soil and has been suggested as an explanation for the rapid amelioration effects of lime, e.g. lowering of the plasticity index, resulting in a more friable soil, increase in effective grain size, and reduction in swelling (11). A more modern hypothesis suggests the formation of calcium aluminates as the cause of the amelioration effects, since most soils in need of stabilization are naturally flocculated.

Pozzolanic Reaction. Diamond and Kinter (11) postulate that ameliorative effects of lime on clay are due to an almost immediate, but limited, chemical reaction at the points of contact between the edges and faces of primary clay particles within the flocs formed by the normal electrolyte effect of added lime. Lime reacts with hydrous alumina to form tetracalcium aluminate hydrate at the points of contact between the edges of one particle and the faces of adjacent particles in the card house structure of the flocs. Calcium silicate hydrate (tabermorite gel) also forms at these points but more slowly over a period of some hours. Formation of very small quantities of these cementing products at the points of contact is thought to be sufficient to stabilize the flocs and knit the particles together so that plasticity, shrinkage and swelling are inhibited. The flocs are bound together tightly enough to resist dispersion and act as single grains.

The calcium of lime reacts with silicates and aluminates in clay to form a calcium silicate hydrate and a calcium aluminate hydrate, and it is these two reactions which give the mixture its long term strength. (2, 4, 11)

FREEZING AND THAWING

Freezing and thawing can be put into two categories: open system and closed system. In open system action, water is free to enter and leave the soil. Pressure effects from freezing in open system are due to growth of ice crystals. Excessive heaving is caused by the segregation of water as it freezes. (14)

Closed-system freezing and thawing does not permit the flow of water from an external source into the system. Pressures in this system are thought to be generated by the resistance of small pores to the flow of water as ice growth forces water through pores. The susceptibility of soil to freezing is thought to be dependent upon size and distribution of pores and degree of soil saturation. This hypothesis is analogous to the one advanced by Powers (15) as the mechanism of freezing in concrete mortar.

Silt soils are thought to behave as an open system, whereas highly plastic clay soils, due to their impermeability are thought to behave as a closed system. The actual mechanism is probably a combination of both open and closed system action. (16)

Freezing Mechanisms in Lime-Soil Mixtures. Calcium silicates form in lime-soil mixtures as in portland cement (11). Townsend (17) suggests that lime-soil mixtures exhibit the same trends as those of cement mortars and suggests the following hypothesis:

1. Addition of lime causes flocculation. There are large pores adjacent to the flocs, and within the flocs the pores are exceptionally small.
2. Within the finer pores, as the calcium silicate reaction progresses there is an increase in the alkalinity of pore water due to the presence of sodium and potassium hydroxides, which depresses the freezing point below that normally encountered in highway conditions.
3. Larger pores between flocs enable fluid to flow more readily through the soil as manifested by increased permeability.
4. Complex calcium silicate reaction develops the usual cementing agents, which bind the pore walls together. This is a similar theory to that developed by Diamond and Kinter (11).
5. When the temperature is lowered below the depressed freezing point in the larger pores, ice formation begins the usual volume expansion as an ice crystal is formed and suction begins. The volume expansion places the remaining fluid under a hydraulic gradient, which can be dissipated through the increased permeability of the soil. The soil pore acts as a rigid container and immediate expansion does not take

place. Eventually, available pore space is filled with ice, excess water is dispersed to other parts of the system, and heaving is stopped as the ice water interface is destroyed.

6. If cementing action is not sufficiently developed, the hydraulic pressures generated may exceed the tensile strength of the pore structure. Due to rearrangement in pore geometry and loss of confinement of pore structure, the induced suction is increased. This leads to ice segregation, further volume expansion and deterioration.
7. The interrelationship between permeability and strength is modified by the degree of saturation of the sample and the freezing temperatures encountered. If an appreciable number of unfilled pores exists near the freezing front and the amount of water which may be transformed into ice is small, it will be easier for the hydraulic pressures to be dissipated.

Townsend's (17) theory suggests that if the mixture has adequate strength and permeability then it will be stable during freezing and thawing.

Properties of Lime-Soil Mixtures Subjected to Freezing and Thawing. The addition of lime to a soil increases the durability of the soil. Walker, Esmer, and Krebs (16) found that the largest strength loss suffered by stabilized specimens (60 psi for 10 per cent lime, five cycles, five day moist room treatment) resulted in a compressive strength roughly equivalent to non-stabilized specimens not exposed to freezing and thawing. Esmer (18) stated that the addition of lime greatly reduced the percentage strength loss of specimens exposed to either open or closed system freezing and thawing.

Whitehurst and Yoder (21) found that for a given lime content, increased compaction results in increased resistance to freezing and thawing. These results were confirmed by Hoover, Handy, and Davidson (19).

Hoover, et al (19) found that clay and silt soils gain strength more rapidly in freeze-thaw cycles than they do in a continued moist cure. Townsend (17) and Esmer (18), however, discovered that the strength of a lime-soil mixture decreased with increased cycles of freezing and thawing.

The porosity of a lime-soil mixture has a profound influence on its strength. Jumikis (20) states that the amount of soil moisture transferred upon freezing from ground water to the cold front is greater the less the porosity of the soil. Esmer (18) discovered that clay-lime mixtures decrease in strength as porosity increases.

Davidson, Mateos, and Barnes (22) introduced a resistance factor to measure the durability of a soil. The index of the resistance of the effect of freezing (R_f) was calculated from the formula:

$$R_f = \frac{100\ P_f}{P_c}\quad (\%)$$

where P_f is the unconfined compressive strength of the freeze-thaw specimen and P_c is the unconfined compressive strength of a specimen not subjected to freezing and thawing. A limiting resistance index (R_f) may be used as a design criteria.

MATERIALS AND PREPARATION

The soil was air dried, passed through a No. 10 sieve, placed in a Los Angeles Abrasion Machine for 20 minutes to break any large aggregates present, brought to a moisture of approximately 20 per cent, sealed in a Tupperware container, and allowed to cure overnight. If lime was to be added to the soil, it was then added, mixed thoroughly, and allowed to cure for three hours in a sealed Tupperware container.

Soil Properties. The soil used in this study was obtained from a site near the Virginia Tech Airport, near Virginia Polytechnic Institute, Blacksburg, Virginia. The soil was a highly plastic yellowish brown clay and its characteristics, with andwithout lime, are shown in Table I.

Except for soil preparation, density tests were performed according to ASTM D1557-58T, Method A; specific gravity test according to ASTM D854-58; and the plastic limit and plasticity tests according to ASTM D424-54T. The liquid limit tests were run according to ASTM D423-54T, with the exception that the tests were conducted from the wetter to the dryer condition of the soil and the soil was prepared as previously described.

The results of the density tests are illustrated in Figure 1. Figure 2 illustrates the effect of lime on the Atterberg limits of the soil.

Table I. Soil Characteristics

Soil Properties	Lime Content 0	7
Liquid Limit	89	72.5
Plastic Limit	46	50.9
Plasticity Index	43	21.6
AASHO Classification	A-7-5	-
Optimum Moisture	22%	26%
Maximum Dry Density	99.5 pcf	93.0 pcf
Specific Gravity	2.76	-

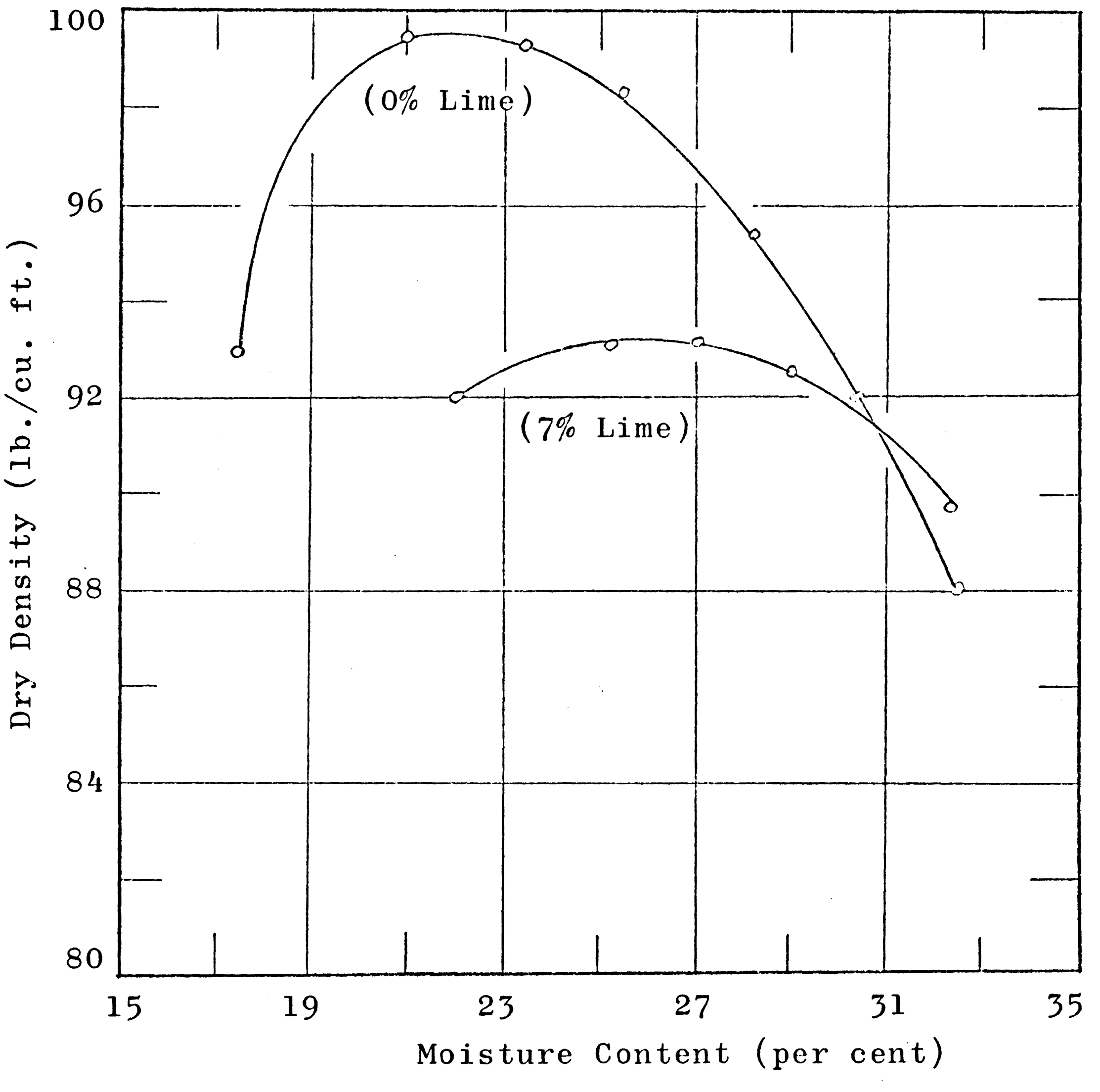

Figure 1. Compaction Curves.

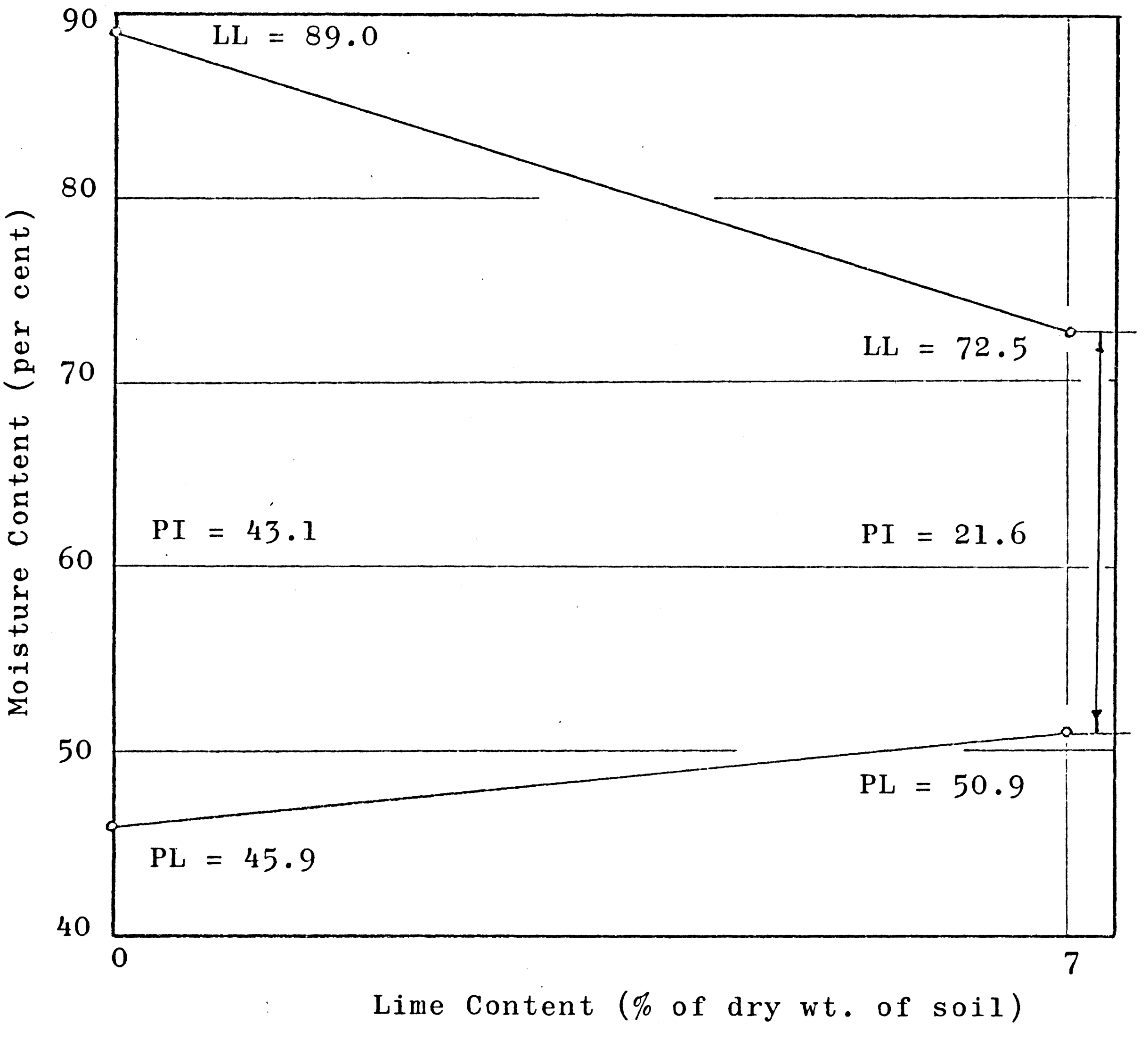

Figure 2. Atterberg Limits.

Lime. Hydrated lime ($CaOH_2$) was used in this study. The lime was manufactured by the National Gypsum Company at Kimballton, Virginia, and was sealed in double bags and kept in a dry location throughout the entire study to prevent the formation of calcium carbonate ($CaCO_3$).

PROCEDURES

The procedures used to manufacture, freeze, and thaw the specimens are explained in this section.

Manufacturing and Curing of Samples. The soil was prepared as previously described, and compacted according to Method A, ASTM D1557-58T. Moisture determinations were made from the shavings taken from the top of the compacted soil. The compacted soil was extruded from the mold, quartered, and trimmed on a soil lathe until the specimen had a diameter of approximately 1-3/8 inches. The specimen was then cut to the proper length (approximately 2-13/16 inches), and its length, weight, and diameter recorded. Saran wrap was used to seal the specimen, which was then coated with Protexo Cote, a strippable protective coating manufactured by Thermo Cote, Inc. The specimen was placed in a sealed Tupperware container and placed in an oven to cure at 120°F. Sixty-two specimens were made. Half the specimens were cured for two days, a time shown by Anday (6) to give results analogous to 40 to 45 days curing in the field, and half the specimens were cured for four days. Seven per cent lime by dry weight was added to 46 specimens and 16 specimens contained no lime.

Freezing and Thawing. Fifty specimens were subjected to freezing and thawing. Specimens were open at one end to provide the opportunity for open system freezing. The specimens were placed on a moist sand layer in a deep freeze unit for 24 hours immediately after curing, and were then thawed in a 100 per cent humidity room at 70°F. for 24 hours to complete one cycle of freezing and thawing. A fan was placed in the deep freeze unit so that air blew down on the specimens and they froze from the top down. This procedure is similar to that described by Walker, Esmer, and Krebs (32).

Sixteen specimens, containing 12 specimens with seven per cent lime and four specimens with no lime, were exposed to five cycles of freezing and thawing. Sixteen specimens of similar composition were subjected to ten cycles of freezing and thawing. Fourteen specimens, containing 10 specimens with seven per cent lime and four specimens without lime, were exposed to 15 cycles of freezing and thawing. Sixteen specimens were used as control specimens and tested immediately after curing. Half the specimens of each group were cured for 48 hours while the second half was cured for 96 hours.

Unconfined Compressive Strength. The unconfined compressive strength was determined for each specimen after 0, 5, 10 and 15 cycles of freezing and thawing. The strength was taken as the largest stress withstood by the specimen. Loading rate was 0.05 inches per minute. The secant modulus was obtained by dividing the peak stress by the corresponding strain.

RESULTS

Unconfined compressive strength tests were run on all specimens. The results presented here are in the form of unconfined compressive strength and secant modulus. Moisture content data and statistical analysis are also included.

Unconfined Compressive Strength. All specimens were tested for unconfined compressive strength after 0, 5, 10 and 15 cycles of freezing and thawing.

Table II shows the average unconfined compressive strength of specimens after various cycles of freezing and thawing. Lime increased the unconfined compressive strength of the soil as manifested in Table II and further illustrated in Figure 3, which includes values for both two and four day curing and is a plot of average unconfined compressive strength against per cent lime. The unconfined compressive strength increased from 263 psi to 326 psi, an increase of 24 per cent.

Specimens were cured for both two and four days, but a statistical analysis of variance (see Appendix A) showed that there was no appreciable difference in the unconfined compressive strength of the specimens cured for two or four days.

Figure 4, a plot of compressive strength against cycles of freezing and thawing, enables the reader to observe the effect of cycles of freezing and thawing on the specimens.

Table II. Average Unconfined Compressive Strength (psi) of Specimens Cured for Two and Four Days.

Days of Curing	Per Cent Lime	Cycles of Freezing and Thawing 0	5	10	15
2	0	266	0	0	0
2	7	276	45	0	0
4	0	260	0	0	0
4	7	376	63	0	0

Note: Each average value of 0 per cent lime was determined from two specimens, and each average value of 7 per cent lime was determined from six specimens, with the exception of the 15 cycle value which was determined from five specimens.

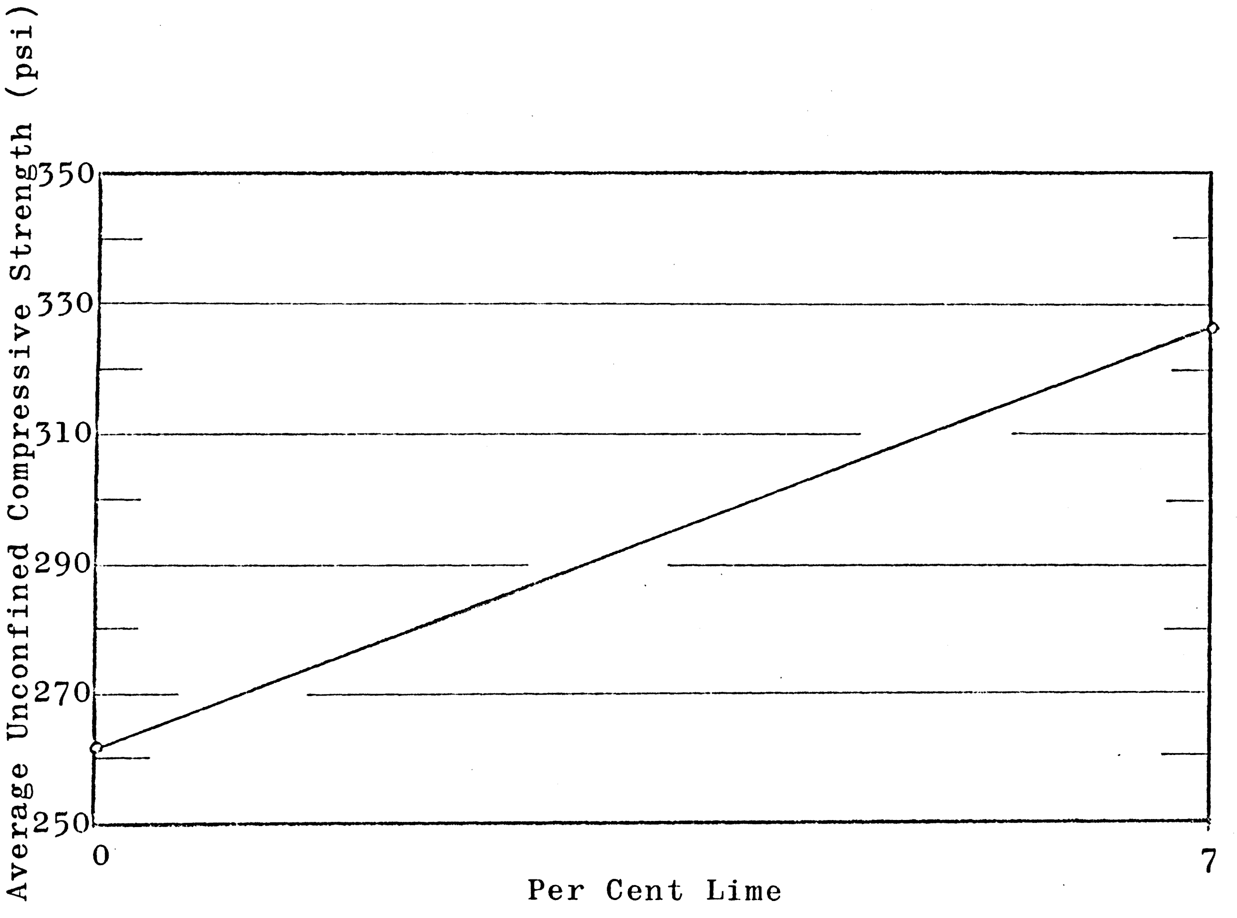

Figure 3. Effect of Per Cent Lime on Unconfined Compressive Strength of Soil Before Freezing and Thawing.

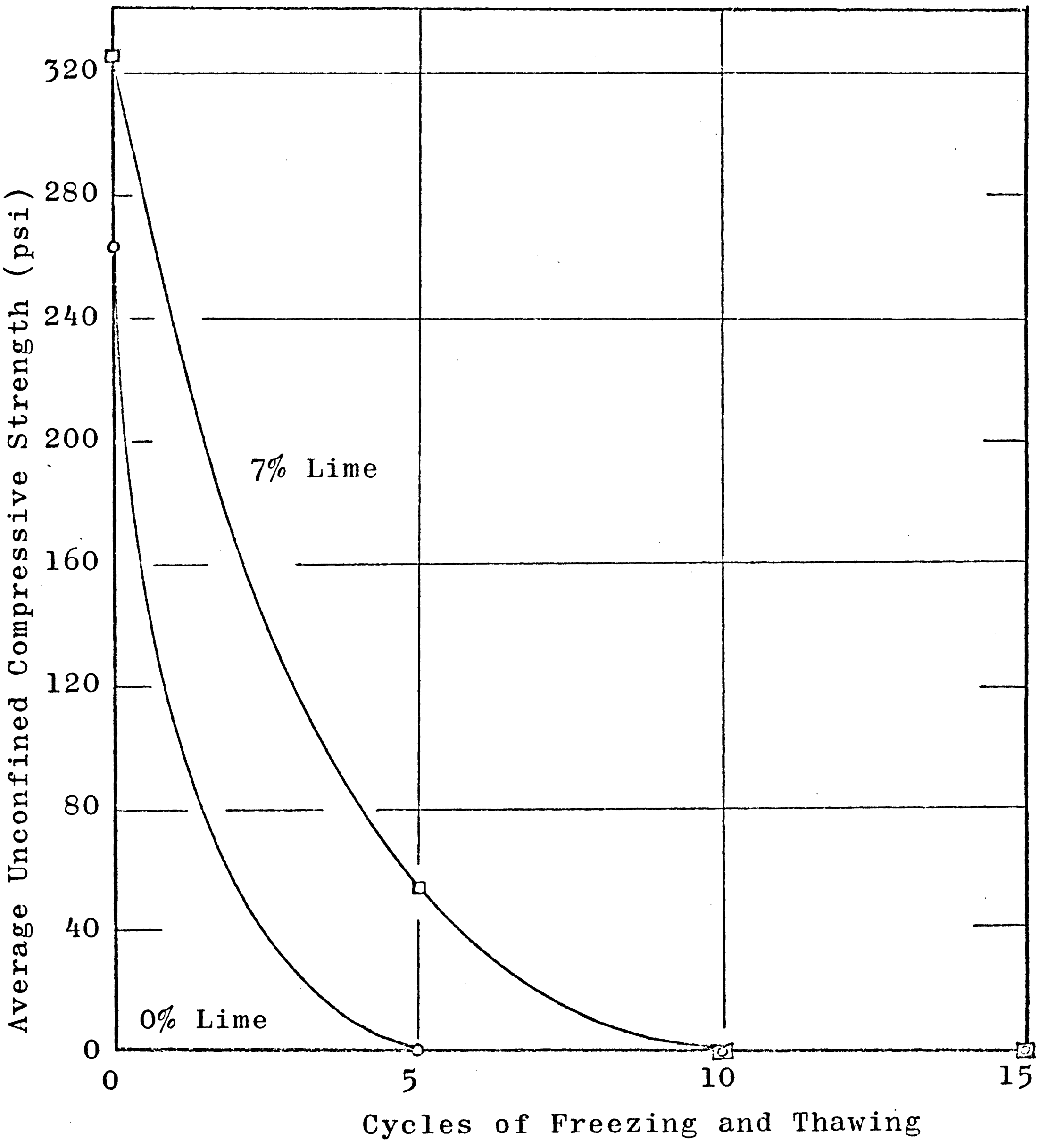

Figure 4. Effect of Cycles of Freezing and Thawing on Unconfined Compressive Strength.

Cycles of freezing and thawing have a profound influence on the unconfined compressive strengths of specimens. Soil containing seven per cent lime lost 83.6 per cent of its strength after five cycles of freezing and thawing. Soil without lime lost 100 per cent of its strength after five cycles of freezing and thawing. Ten cycles of freezing and thawing destroyed all strength of the seven per cent soil-lime mixture. Figures 5, 6, 7 and 8 show samples after various cycles of freezing and thawing. Although Figure 5 is a photograph of a specimen with seven per cent lime and two days curing, it may be taken as representative for all specimens as there was no visible difference in the specimens after curing. Figures 6 and 8 show a marked difference between seven per cent soil-lime mixtures after five and ten cycles of freezing and thawing. The seven per cent soil-lime mixture, after 10 cycles of freezing and thawing, had deteriorated to such a degree that the specimen could not hold its original shape (see Figure 8), whereas a similar mixture after five cycles of freezing and thawing held its original shape and manifested its only visible sign of deterioration in the form of a hairline fracture in the upper section of the sample, clearly visible in Figure 6. Obviously the lime-soil specimens failed completely between five and ten cycles of freezing and thawing, and it is recommended that additional work be done to determine the exact number of cycles for destruction. No photographs were taken of a specimen with zero

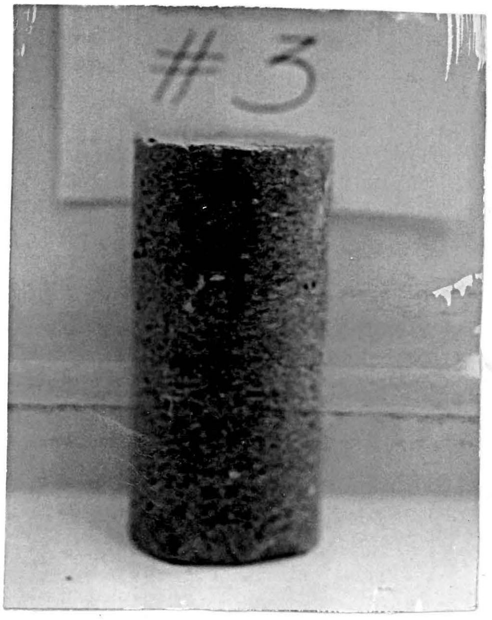

Figure 5. Specimen After Two Days Curing, Lime Content Seven Per Cent.

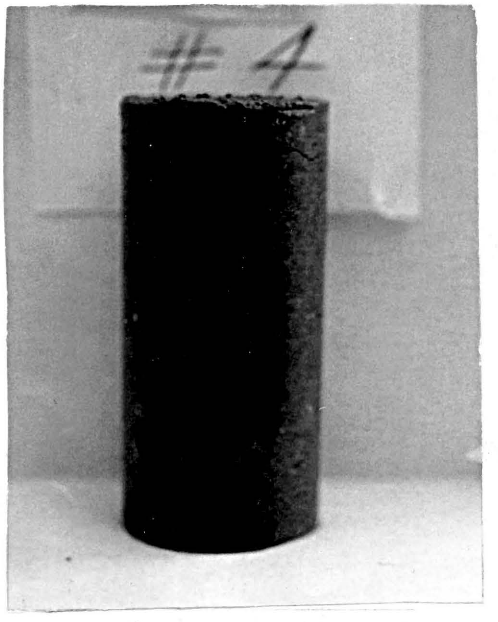

Figure 6. Specimen After Five Cycles of Freezing and Thawing, Lime Content Seven Per Cent.

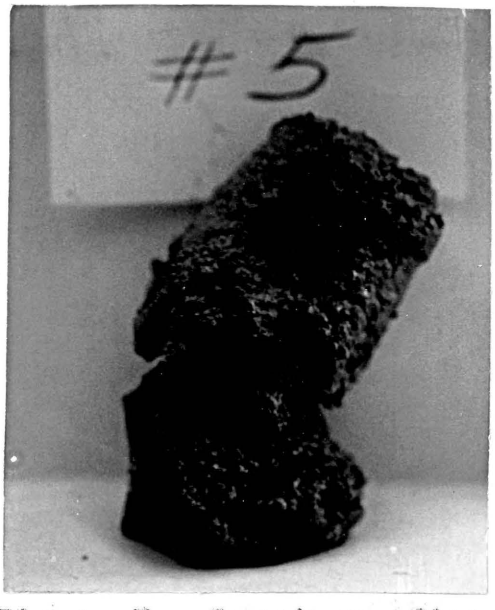

Figure 7. Specimen After Ten Cycles of Freezing and Thawing, Lime Content Zero Per Cent.

Figure 8. Specimen After Ten Cycles of Freezing and Thawing, Lime Content Seven Per Cent.

per cent lime after five cycles of freezing and thawing, but a great deal of deterioration was present and there was a vast difference between a sample with zero per cent lime, which could not be handled without falling apart, and a sample with seven per cent lime.

The addition of lime increased the durability of the soil. Specimens with seven per cent lime did not lose their strength until after five cycles of freezing and thawing, but specimens without lime failed between zero and five cycles of freezing and thawing. At five cycles of freezing and thawing, specimens containing seven per cent lime had an average unconfined compressive strength of 54 psi and specimens without lime had zero psi strength. These results are illustrated in Figure 9.

Secant Modulus. The secant modulus is a measure of soil stiffness, with the stiffer specimen having the higher secant modulus. A stiffer soil will deflect less than a soil with less stiffness, a property beneficial in subbases for rigid pavement, and for this reason the secant modulus of almost every specimen was computed. The results are presented in Table III.

Examination of Table III reveals that per cent of lime had a definite influence on the secant modulus of specimens. Figure 10, a plot of the average secant modulus against the per cent lime, shows that the addition of seven per cent

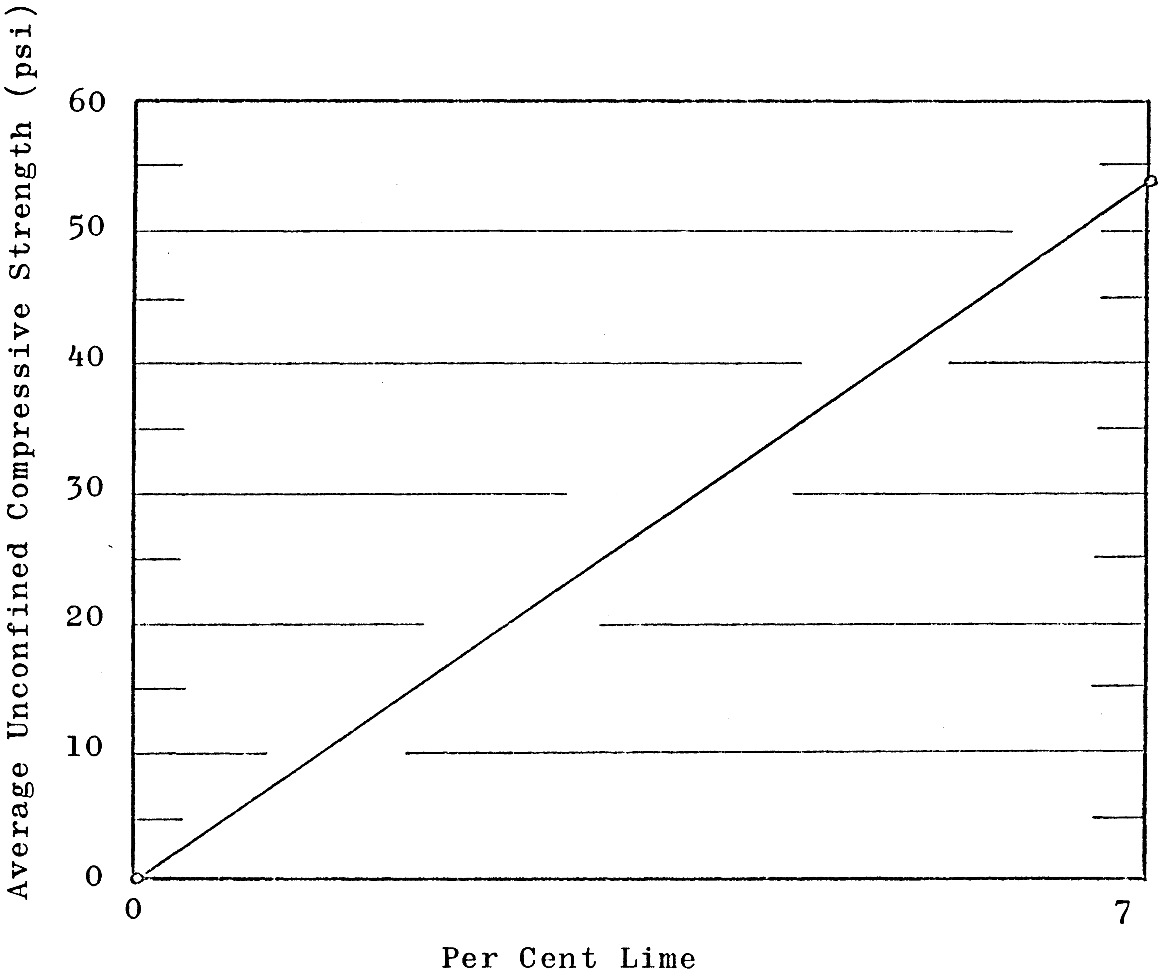

Figure 9. Effect of Per Cent Lime on Unconfined Compressive Strength of Soil After Five Cycles of Freezing and Thawing.

Table III. Average Secant Modulus (psi) of Specimens Cured for 48 Hours.

Days of Curing	Per Cent Lime	Cycles of Freezing and Thawing 0	5	10	15
2	0	1965	0	0	0
2	7	5452	1983	0	0
4	0	2197	0	0	0
4	7	9208	3224	0	0

Note: The average for zero per cent lime was computed from two values, the average for seven per cent lime at zero cycles of freezing and thawing was computed from six values, and the average for seven per cent at five cycles of freezing and thawing was computed from five values.

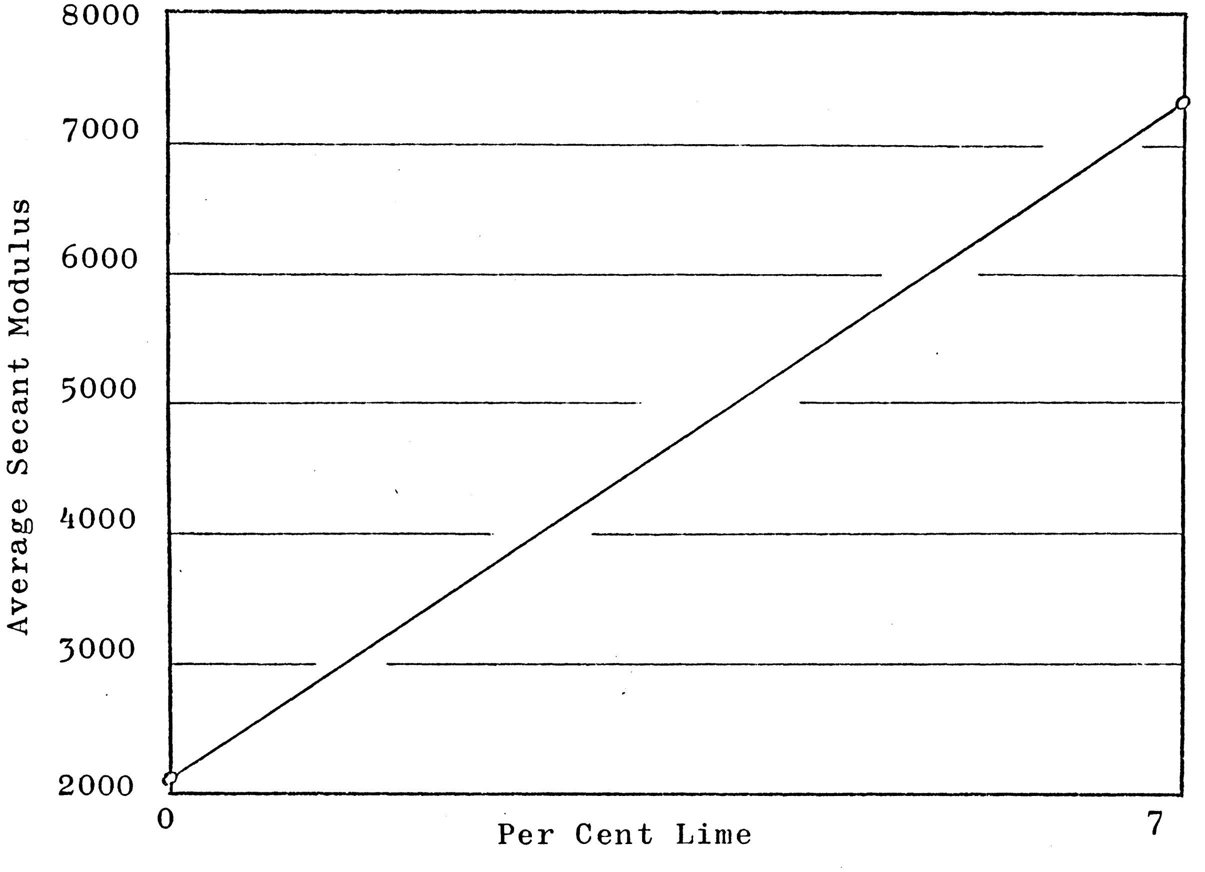

Figure 10. Effect of Per Cent Lime on the Secant Modulus After Curing.

lime raised the secant modulus from 2169 to 7330, an increase of 238 per cent. The results from four and two day curing were included in Figure 10.

There was no appreciable difference in secant modulus between unstabilized specimens cured for two or four days, but a statistical analysis of variance showed that length of curing might have an effect on secant modulus specimens containing seven per cent lime at a level of significance of 0.10 (see Appendix A). Examination of Table III reveals an increase in secant modulus with increased curing, and a decrease in secant modulus with increased cycles of freezing and thawing.

Moisture. Tables IV, V, and VI show results of moisture determinations. The tables reveal an increase in moisture with increased cycles of freezing and thawing. The exact amount of moisture increase could not be determined because the samples lost moisture during curing and moisture determinations could not be taken after curing except for the control specimens.

Table IV. Moisture Content (per cent) of Specimens Without Lime.

Cycles of Freezing & Thawing	Days of Curing	Moisture Content Before Curing	Moisture Content After Curing	Moisture Content After Freezing and Thawing
0	4	27.5	21.8	
	4	27.5		
	2	27.5		
	2	27.5		
5	4	27.1		39.2
	4	27.1		39.5
	2	27.1		
	2	27.1		
10	4	29.1		46.9
	4	29.1		42.6
	2	29.1		54.7
	2	29.1		52.3
15	4	24.9		
	4	24.9		
	2	24.9		
	2	24.9		

Table V. Moisture Content (per cent) of Specimens Containing Seven Per Cent Lime Cured for Two Days.

Cycles of Freezing and Thawing	Moisture Content		
	Before Curing	After Curing	After Freezing and Thawing
0	33.1	29.0	
	33.1	29.0	
	33.1	29.0	
	30.7		
	30.7		
	30.7		
5	29.2		31.7
	29.2		30.1
	29.4		31.4
	29.4		31.9
	29.4		30.6
	29.4		29.9
10	31.9		41.3
	33.0		52.8
	33.0		51.5
	33.0		53.8
	33.0		47.0
	33.0		47.1
15	28.0		
	29.5		
	29.5		
	29.5		
	28.0		

Table VI. Moisture Content (per cent) of Specimens Containing Seven Per Cent Lime Cured for Four Days.

Cycles of Freezing and Thawing	Moisture Content		
	Before Curing	After Curing	After Freezing and Thawing
0	29.7	27.7	
	29.7		
	29.7		
	31.8	29.3	
	31.8		
	31.8		
5	30.6		31.1
	30.6		31.8
	30.6		34.3
	30.6		32.8
	29.2		30.6
	29.2		30.6
10	34.6		42.4
	34.6		44.0
	34.6		52.6
	31.9		39.8
	31.9		48.5
	31.9		35.8
15	29.2		
	29.2		
	29.2		
	29.2		
	28.0		

POSSIBLE MECHANISMS OF DESTRUCTION DUE TO FREEZING AND THAWING

The unstabilized specimens probably behaved as an open system, i.e. ice lenses formed, attracted water and grew to such proportions that they destroyed the structure and strength of the specimens. The unstabilized specimens lost their strength before five cycles of freezing and thawing and showed a large increase in moisture after five cycles of freezing and thawing (see Table IV). The above facts suggest the rapid formation of ice lenses.

The stabilized specimens possibly deteriorated according to Townsend's (17) theory. Small flocs form with the addition of lime to a clay soil. There are large pores adjacent to the small pores within flocs, and when the temperature drops below the freezing point of water in the large flocs, ice begins to form. The ice formation creates hydraulic pressures as the pores resist the flow of water. If the hydraulic pressures exceed the tensile strength of the pore walls, the pore walls collapse and the pore is enlarged. An ice crystal begins to form, suction takes place, and ice segregation destroys the strength of the specimen. According to Townsend's theory, destruction is due to a combination of hydraulic pressures and ice segregation, and not just ice segregation alone. There is evidence to support this theory. A specimen after five cycles of freezing and thawing lost strength but still held its original shape as shown in Figure 6. Examination of Tables V and VI shows that the stabilized specimens did not gain much moisture after five cycles of freezing and thawing, but gained considerable moisture after ten cycles of freezing and thawing. The specimens lost all their strength after ten cycles of freezing and thawing as illustrated in Figure 8. The stabilized specimens may have lost strength at five cycles due to hydraulic pressures, since the specimens still retained their shape and did not gain much moisture. Sometime after five cycles of freezing and thawing, ice lenses began to form and a resulting increase in moisture and decrease in sample strength and shape occurred. Further study is needed to confirm whether or not Townsend's theory applies to this lime-soil mixture.

SUMMARY

The results obtained from this study are summarized as follows:

1. The addition of seven per cent lime to a lodi clay soil increased the plastic limit, decreased the liquid limit, lowered the plasticity index, raised the optimum moisture content and decreased the dry density with compaction.
2. There was no appreciable difference in unconfined compressive strengths between two or four day curing for either stabilized or unstabilized specimens.
3. Cycles of open system freezing and thawing had a profound influence on the unconfined compressive strength of the specimens. Specimens containing seven per cent lime by dry weight lost an average of 83.6 per cent of their strength after five cycles of freezing and thawing. Specimens without lime lost 100 per cent of their strength after five cycles of freezing and thawing.
5. The durability of the soil was increased by adding lime. Specimens containing seven per cent lime failed between five and ten cycles of freezing and thawing, but specimens without lime failed before five cycles of freezing and thawing.

6. The addition of lime increased the unconfined compressive strength of the compacted lodi clay soil after curing.
7. There was no appreciable difference in secant modulus between unstabilized specimens cured for two or four days, but a statistical analysis of variance showed that the length of curing may affect the secant modulus of stabilized specimens. Four day curing increased the secant modulus of stabilized specimens over values of specimens cured for two days.
8. Lime addition increased secant modulus.
9. Secant modulus decreased with increasing cycles of freezing and thawing for all specimens.
10. The samples, both stabilized and unstabilized, gained moisture with increasing cycles of freezing and thawing.
11. Since all specimens had access to water, unstabilized specimens possibly failed because of ice segregation, but stabilized specimens possibly failed because of a combination of hydraulic pressures and ice segregation according to Townsend's (17) theory.

BIBLIOGRAPHY

1. Jan, Mohammad Ashraf, and Walker, Richard D., "Effect of Lime, Moisture and Compaction on a Clay Soil," Highway Research Board No. 29, pp. 1-12, 1963.

2. Yoder, E. J., Principles of Pavement Design, Chapter 10, "Soil Stabilization," John Wiley and Sons, pp. 255-266, 1959.

3. Pietsch, Paul E., and Davidson, Donald T., "Effects of Lime on Plasticity and Compressive Strength of Representative Iowa Soils," Highway Research Board No. 335, pp. 11-30, 1962.

4. Herrin, M., and Mitchell, H., "Lime Soil Mixtures," Highway Research Board Bulletin 304, pp. 99-138, 1961.

5. Hilt, G. H., and Davidson, D. T., "Lime Fixation in Clay Soils," Highway Research Board Bulletin 262, pp. 20-32, 1960.

6. Anday, M. C., "Curing Lime-Stabilized Soils," Highway Research Board Record No. 29, pp. 13-26, 1963.

7. Taylor, W. H. Jr., and Arman, Ara, "Lime Stabilization Using Pre-Conditioned Soils," Highway Research Board Bulletin 262, pp. 1-11, 1960.

8. Jones, Chester W., "Stabilization of Expansive Clay with Hydrated Lime and with Portland Cement," Highway Research Board Bulletin 193, pp. 40-47, 1958.

9. McDowell, C., "Stabilization of Soils with Lime, Lime Flyash and Other Reactive Materials," Highway Research Board Bulletin 231, pp. 60-66, 1959.

10. Eades, James L., Nichols, Jr., F. P., and Grim, Ralph E., "Formation of New Minerals with Lime Stabilization as Proven by Field Experiments in Virginia," Highway Research Board Bulletin 335, pp. 31-39, 1962.

11. Diamond, Sidney, and Kinter, "Mechanism of Soil-Lime Stabilization: An Interpretive Review," Highway Research Record Number 92, pp. 83-96, 1965.

12. Karabulut, Cetin, "Effect of Freezing and Thawing on Unconfined Compressive Strength of Lime Stabilized Soils," Master of Science Thesis, Virginia Polytechnic Institute, Department of Civil Engineering, 1963.

13. Ladd, C. C., Moh, Z. C., and Lambe, T. W., "Recent Soil-Lime Research at the Massachusetts Institute of Technology," Highway Research Board Bulletin Number 262, pp. 64-85, 1960.

14. Taber, S., "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements," Public Roads, Vol. II, pp. 113-132, 1930.

15. Powers, T. C., "The Mechanism of Frost Action in Concrete," Stanton Walker Lecture Presented at the University of Maryland, 1965.

16. Walker, Richard D., Esmer, Erkan, and Krebs, Robert D., "Strength Loss in Lime-Stabilized Clay Soils When Moistened and Exposed to Freezing and Thawing," Paper Presented to the 46th Annual Meeting of the Highway Research Board, 17 pp., 1967.

17. Townsend, David L, and Klym, Tony W., "Durability of Lime Stabilized Soils," Highway Research Record Number 739, pp. 25-39, 1966.

18. Esmer, Erkan, "Comparison of Open and Closed System Freezing and Thawing Tests of a Lime Stabilized Clay Soil," Master of Science Thesis, Virginia Polytechnic Institute, Department of Civil Engineering, 1965.

19. Hoover, J. M., Handy, R. L. and Davidson, D. T., "Durability of Soil-Lime-Flyash Mixes Compacted Above Proctor Density," Highway Research Board Bulletin 193, pp. 1-11, 1958.

20. Jumikis, A. R., "Effective Soil Moisture Transfer Mechanism Upon Freezing," Highway Research Board Bulletin 317, pp. 1-8, 1961.

21. Whitehurst, E. A., and Yoder, E. J., "Durability Tests on Lime Stabilized Soils," Highway Research Board Proceedings, Vol. 31, pp. 529-540, 1952.

22. Davidson, D. T., Mateos, Manuel, and Barnes, H. F., "Improvement of Lime Stabilization of Montmorillonitic Clay Soils with Chemical Additives," Highway Research Board Bulletin 262, pp. 33-50, 1960.

23. "ASTM Standards - 1958," American Society for Testing and Materials, Philadelphia, Pennsylvania.

24. Walker, R. D., and Karabulut, Cetin, "Effect of Freezing and Thawing on Unconfined Compressive Strength of Lime-Stabilized Soils," Highway Research Board Record 92, pp. 1-11, 1965.

25. Jumikis, A. R., "Concerning a Mechanism for Soil Moisture Translocation in the Film Phase Upon Freezing," Highway Research Board Proceedings, Vol. 39, pp. 619-637, 1960.

26. Hoekstra, P., Chamberlain, E., and Frate, T., "Frost-Heaving Pressures," Highway Research Board Record 101, pp. 28-38, 1965.

27. Jumikis, A. R., "Vapor Diffusion in Freezing Soil Systems of Very Large Porosities," Highway Research Board Bulletin 331, pp. 28-45, 1962.

28. Shandaala, Abdul Ghani, "Effect of Freezing and Thawing on Unconfined Compressive Strength of Clay-Lime Mixture With and Without Air Entraining Agent," Master of Science Thesis, Virginia Polytechnic Institute, Department of Civil Engineering, 1964.

29. Laguros, Joakim G., "Lime-Stabilized Soil Properties and the Beam Action Hypothesis," Highway Research Board 92, pp. 12-20, 1965.

30. Means, R. E. and Parcher, J. V., Physical Properties of Soils, Charles E. Merrill Books Inc., Columbus, Ohio, 1963.

31. Jumikis, A. R., "Experimental Study on Soil Moisture Transfer in the Film Phase Upon Freezing," Highway Research Board Bulletin 331, pp. 21-27, 1962.

32. Walker, Richard D., Esmer, Erkan, and Krebs, Robert D., "Effect of Freezing and Thawing on the Strength, Permeability, and Pore Characteristics of Lime Stabilized Soils," Unpublished Paper to be presented at the Seventieth Annual Meeting of the American Society for Testing and Materials, June, 1967.

33. Bowker, Albert H., and Lieberman, Gerald J., Engineering Statistics, Chapter X, "Analysis of Variance," Prentice-Hall, Inc., 1959.

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APPENDIX A

Analysis of Variance to Determine if Length of Curing Has An Effect on Unconfined Compressive Strength

An analysis of variance test was performed on the data presented in Table VII to determine if there was an appreciable difference in unconfined compressive strength of specimens cured for two or four days. The results and procedure of this test are presented below:

$$Yij^2 = 1,382,199.70$$

$$\frac{G^2}{r\,C} = 863,332.32$$

$$\frac{Ti^2}{C} = 884,362.53$$

$$SS_{TOT} = Yij^2 - \frac{G^2}{rC} = 581,867.38$$

$$SS_{Treat} = \frac{Ti^2}{C} - \frac{G^2}{rC} = 21,030.21$$

where

r = Number of columns.

C = Number of rows.

Yij^2 = Sum of the squares.

G^2 = The sum squared.

Ti^2 = Sum of the columns squared.

The above symbols apply to the data presented in Table VII.

Table VII. Unconfined Compressive Strength (psi).

Two Days Curing	Four Days Curing
234	376
190	385
254	457
254	301
351	351
370	385
31	100
88	63
39	26
31	48
25	94
53	46

Table VIII. Analysis of Variance Table for Unconfined Compressive Strength.

Source	Sum of the Squares	Degrees Freedom	Mean Squared
Treat	21,030.21	1	21,030.21
Error	497,837.17	22	22,628.96
Total	518,867.38	23	

$$F_o = \frac{MS_{Treat}}{MS_{Error}} = \frac{21,030.21}{22,628.96} = .929$$

$$F_{.10,\ 1,\ 22} = 2.95$$

Since .929 is less than 2.95, there is no appreciable difference in the unconfined compressive strength due to length of curing. The level of significance used in this test was 0.10.

Analysis of Variance to Determine if Length of Curing Has an Effect on the Secant Modulus

An analysis of variance test was performed on the data presented in Table IX to determine if there was an appreciable difference in secant modulus of specimens cured for two or four days. The procedure and symbols are the same as used for the unconfined compressive strength test, and the results are presented below:

$$Yij^2 = 800,795,719$$

$$\frac{Ti^2}{C} = 628,140,056$$

$$\frac{G^2}{rC} = 590,592,553$$

$$SS_{TOT} = 210,203,166$$

$$SS_{Treat} = 37,547,503$$

Table X is the analysis of variance table and the final results derived from Table X are shown below:

$$F_0 = 4.35$$

$$F_{0.10,\ 1,\ 20} = 2.97$$

Since 4.35 is greater than 2.97 we conclude that there may be a difference in secant modulus at a level of significance 0.10 due to length of curing.

Table IX. Secant Modulus (psi).

Two Days Curing	Four Days Curing
3895	9394
4226	8554
4624	9143
6358	5466
5395	11,690
8211	10,998
1565	3340
2505	2505
1565	1925
2505	3758
1774	4591

Table X. Analysis of Variance Table for Secant Modulus.

Source	Sum of the Squares	Degrees Freedom	Mean Squared
Treat	37,547,503	1	37,547,503
Error	172,655,663	20	8,632,783
Total	210,203,166	21	

EFFECTS OF EXTENDED CYCLES OF OPEN SYSTEM FREEZING AND THAWING ON A CLAY-LIME MIXTURE

by

Raymond Stewart Tyler

Abstract

The purpose of this study was to evaluate effects of long term open system freezing and thawing on unconfined compressive strength of a lime-clay mixture and determine if length of curing has appreciable effect on strength and durability of the mixture.

Soil specimens were made by compacting the soil slightly above optimum moisture, quartering the extruded soil, using a lathe to bring the specimen to 1-3/8 inches diameter, and cutting specimens to 2-13/16 inches. Specimens were cured for two and four days, one half being curing for two days and the other half being cured for four days. Specimens containing zero and seven per cent lime were placed in open system freezing and thawing for 0, 5, 10 and 15 cycles of freezing and thawing, where one cycle consisted of 24 hours in a deep freeze unit and 24 hours in a 100 per cent humidity room at 70°F.

Unconfined compressive strengths were determined for all samples after freezing and thawing.

Results from the tests indicate the following:

1. Lime increased the strength of the clay soil used.

2. Lime increased the durability of the soil.
3. There was no appreciable difference in unconfined compressive strength for stabilized or unstabilized specimens cured for two or four days.
4. There was no appreciable difference in secant modulus between two or four day curing of unstabilized specimens, but prolonged curing increased the secant modulus of stabilized specimens.
5. Lime increased the secant modulus of specimens.