EFFECT OF FREEZING AND THAWING ON UNCONFINED COMPRESSIVE STRENGTH OF CLAY-LIME MIXTURE WITH AND WITHOUT AIR ENTRAINING AGENT

by

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Dedicated

To my wife and two children

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INTRODUCTION

The rapid increase of air and highway transportation requires a rapid improvement in the physical properties of soil, especially soil strength. A large number of processes of soil stabilization using admixtures are known to exist; most, although in common use, are still undergoing extensive laboratory experimentation. Portland cement, bitumen, calcium chloride, lime and many others are included among these additives in actual field use or still in laboratory investigation.

Since hydrated lime is the main additive used in highway construction, it has been extensively used in the United States for the purpose of improving as well as strengthening the subgrade on which the pavement rests. It has been experimentally shown that the strength of the lime-stabilized soil can be greatly affected by freezing and thawing. The main question for which an answer has not yet been found is, "How much strength does the lime-stabilized soil lose when subjected to cycles of freezing and thawing, and why?" An answer to this question will enable the highway engineer to control the pavement thickness which in turn results in monetary savings.

Wide research programs have been carried out in the United States for the purpose of discovering a way to control this freezing and thawing problem. Since the soils in southwest Virginia are mostly plastic clays and are subject to freezing and thawing, and since limestone ($CaCO_3$) from which hydrated lime is derived is extensively available, considerable research has been done on this subject in Virginia.

Extensive studies of soil stabilization are being carried on by the Civil Engineering Department of Virginia Polytechnic Institute, particularly in the area of stabilizing plastic clay soil with hydrated lime.

Soil systems may be classified as open systems and closed systems. An open system is free to take on or lose water while a closed system is prevented from gaining or losing moisture. Since plastic clays are rather impermeable, it is possible that they behave mostly as a closed system in the field. Therefore, the closed system was used in this work, where the specimens were wrapped and sealed in aluminum foil and cured for two days at 120°F in the oven. Freezing and thawing tests were made by placing the sealed specimens in a zero °F deep freezer for six hours and in a 70°F environment for 18 hours. Specimens were tested for unconfined compressive strength after five and ten cycles, the percentage of lime used being between zero and 20 percent by dry weight.

Air entrainment was also used in an attempt to improve the lime-clay mixture resistance against freezing and thawing.

REVIEW OF THE LITERATURE

What Is Meant by Lime

Lime is calcium oxide (CaO), obtained by crushing and heating limestone ($CaCO_3$) to drive off its carbon dioxide (CO_2), leaving the calcium oxide or quicklime (3). Also there is the lime obtained by burning dolomite $CaMg(CO_3)_2$ which is a carbonate rock very similar to limestone. In this case the resulting lime is calcium oxide plus magnesium oxide, and it is called dolomitic quicklime. There are then two chemical types of quicklime, calcitic (CaO), and dolomitic (CaO + MgO).

When water is added to calcitic quicklime, the chemical reaction gives calcium hydroxide ($Ca(OH)_2$) plus heat. Calcium hydroxide is called hydrated lime or calcitic hydrated lime.

Water added to dolomitic quicklime gives the product known as dolomitic monohydrated lime ($Ca(OH)_2 + MgO$). Under steam and pressure the magnesium oxide (MgO) can be converted and the result is calcium hydroxide and magnesium hydroxide ($Ca(OH)_2 + Mg(OH)_2$) or dihydrate dolomitic lime.

The degree to which a lime is calcitic or dolomitic can be expressed by the calcium magnesium ratio Ca/Mg. Calcitic limes present a very large Ca/Mg ratio whereas with dolomitic lime this ratio is small, on the order of less than 2:1 (18).

Most of the lime used for road stabilization to date has been hydrated lime, although quicklime has been used with success. Hydrated lime has been applied both in powder and slurry forms. Quicklime has been applied only in the powder form but has been known to burn workmen who were not properly protected (3).

What Happens When Lime is Added to the Soil

This short discussion will cover only a few of the many chemical reactions which take place in soil-lime mixtures.

Ion exchange and flocculation. When lime and a moist cohesive soil are mixed together and allowed to cure in a loose condition for a period of time, the soil becomes friable and attains a silty-like condition, and the plasticity is lowered. This is due to one of two conditions. In one, the strong calcium cations of lime replace the weaker metallic ions, such as sodium and hydrogen. Another process is the crowding of additional calcium cations of the lime onto the surface of the clay. Both processes change the number of electrical charges on the surface of the clay particles. Clay particles then become electrically attracted to one another and they tend to flocculate to one another. (13,15)

Pozzolanic action. The calcium in the lime reacts with certain soil minerals to form new compounds. Usually, aluminous and silicious minerals in the soil react with the lime to produce a gel of calcium silicates and aluminates that tends to react with lime to produce a cementing compound known as a pozzolan. This reaction, known as "pozzolanic action", is a long term reaction and one that results in greater strengths, if the lime soil mixtures are cured for a period of time (13, 14).

Carbonation. The third important reaction is carbonation of lime by absorbing carbon dioxide (CO_2) from the air. The carbon dioxide reacts with calcium hydroxide forming calcium carbonate. These carbonates form weak cements which some investigators believe to be deleterious to overall strength gains (13).

Effect on density. It is generally recognized that the optimum unit dry weight of the compacted soil is decreased by the lime admixture, although the soils will show increase in strength. The optimum moisture content also varies with addition of lime to the soils, in most cases showing small increase of the order of two or three percent.

Freezing Phenomena in Soil

For the purpose of this discussion it is necessary to divide the freezing phenomena of soil into two distinctive parts. One part is where ice segregation takes place in a frost susceptible soil, due to a water supply being available and to slowly depressed freezing temperature, which results in frost heave. Frost susceptible soils fall mostly into the categories of silt and silty clays. A second part is the effect of alternate cycles of freezing and thawing on a relatively impermeable clay soil which is not normally susceptible to much frost heave.

Frost heave. Silt and silty clay soils, when frozen under natural conditions, generally behave as an open system with respect to water, i.e., they have a water supply from the outside. Taber (4) states that excessive heaving in this system is always accompanied by the segregation of some of the water to form layers or lenses of more or less pure ice. Taber found that ice segregation does not occur in a closed soil system. The factors which chiefly affect ice segregation, according to Taber, are texture of soil, composition of soil, supply of water, rate of removal of heat and surface load.

Effect of freezing and thawing. Since it is thought that the soils out of doors generally behave as open systems, most freezing and thawing studies have been made with specimens in contact with water and moisture absorption allowed (17). However, in many instances, very impermeable plastic clays are used which may operate more as a closed system.

Concrete also behaves as a closed system, and Powers (6) has developed a hypothesis describing the action of freezing and thawing on such a system. It is thought possible that such a hypothesis might also apply to impermeable soils.

Powers' hypothesis rests mainly on the premise that when ice begins to form in the outside of specimens, the unfrozen water will be displaced toward the center. If the water were free to move without resistance, no hydraulic pressure whatever would develop. However, since the water is required to move through a fine-textured porous substance, the force causing the movement will give rise to a corresponding frictional resistance and gradients of hydraulic pressure will be present during the movement of the water according to the laws of hydraulic flow.

If this reaction against the force displacing the water inward is sufficiently high, then it can be regarded as being capable of damaging the specimen.

Powers also states that resistance to freezing and thawing is largely affected by degree of saturation and permeability characteristics.

Walker and Karabulut (20) stated a comparison of some permeability values of chert and dolomite aggregates, silt and clay soils, and concrete mortar. These values are presented in the table below.

Typical Permeability Values

Concrete Mortar (12)	1 to 300 x 10^{-10} cm per sec
Dolomite (12)	300 x 10^{-10} cm per sec
Chert (12)	1 x 10^{-10} cm per sec
Clay (11)	less than 1000 x 10^{-10} cm per sec
Silt (11)	no more than 10,000 x 10^{-10} cm per sec

Freezing and Thawing Effects on Lime-Stabilized Soil

Work on freezing and thawing effects has been carried on by many investigators who have approached the problem in many different directions.

Hoover, Handy and Davidson (7), experimented with an open system of freezing and thawing on a Texas coastal plain clay. They used three compactive efforts: 1) between standard and modified Proctor density, 2) equivalent to modified Proctor, and 3) above modified Proctor. The criteria used to evaluate the effect of increased density on durability of the specimens after various cycles of freezing and thawing were unconfined compressive strength, moisture absorption and average increase in height of the specimens.

The conclusion was that high density does improve durability of soil-lime-flyash mixtures to the extent that after an initial moist cure, clay soils gained strength even more rapidly during freeze-thaw cycles than they did in continued moist cure condition. The strength of clay specimens during cycles of freeze-thaw correlated well with moisture absorption. Clay showed a drastic increase in absorption up to 5 cycles, after which the specimens slowly lost water. The strength dropped about 50 percent from the first to the fifth cycle, after which there was a slow gain.

Corte (8) in his study showed how a particle-size sorting occurs in saturated granular soils due to freezing and thawing cycling. The laboratory experiments and field studies indicated that there was a tendency for a heterogeneous mixture of grains to become vertically sorted under repeated freeze-thaw action, when adequate moisture was present, thereby increasing the volume of the mixture. This phenomenon was observed when the freezing and thawing plane moved from the top or from the bottom. The fact that the particles moved upward as a result of freezing and thawing from the top indicated that vertical sorting must take place in granular heterogeneous seasonally frozen soil outside the permafrost area if adequate moisture is available.

E. A. Whitehurst and E. J. Yoder (10) studied three soils with addition of 0, 2, 5, and 10 percent of lime. After fabrication, the specimens were permitted to cure in a moist room for various periods of time, one to thirty-six weeks. At the end of the curing period some of the specimens were subjected to 12 cycles of freezing and thawing. Their conclusions were as follows:

1) The texture of the soil has an appreciable effect upon the resistance of the lime-soil mixture to freezing and thawing.

2) For a given lime content, increased compaction, or greater density, results in increased resistance to freezing and thawing.

3) Lime in quantities of 5 percent or more, by weight of the soil, greatly increased the durability of the lime-soil mixtures; the greater the lime content the greater the durability.

4) Two percent lime did not appreciably alter the durability characteristics of the soil.

5) In general moist curing proved very beneficial to the lime-soil mixtures.

Air Entrainment

Air entrainment is the process of installing a quantity of air through the soil for the purpose of providing greater resistance to freezing and thawing. This process has been studied widely and used by many investigators in the field of concrete, but no work has yet been done in the field of soil mechanics. It has been found experimentally that the ability of concrete to resist freezing and thawing will be greatly improved by using five to six percent of entrained air.

The effect of air entrainment on plastic clay soil mixed with different percentages of lime and subjected to freezing and thawing was studied in this project, and in general, proved to be of some benefit.

PURPOSE AND SCOPE

The purpose of this study was to determine the effect of freezing and thawing on the loss in strength of lime-stabilized soil, and to investigate the effect of the addition of an air entraining agent on the freezing and thawing durability of lime-soil mixtures.

The effect of freezing and thawing on the strength of lime-soil mixtures was evaluated by means of unconfined compressive strength tests. Freezing and thawing conditions were limited to freezing and thawing in air, with the temperatures of 0°F and 70°F being used for freezing and thawing respectively. Harvard miniature apparatus was used to determine moisture-density relationships, using different percentages of lime, with and without air entrainment. This apparatus was also used to fabricate unconfined compressive strength specimens. All specimens were cured two days at 120°F. Control specimens were placed in the 70°F environment for ten days while companion specimens underwent freezing and thawing.

MATERIALS AND PROCEDURES

Soil

The plastic clay soil used in this project was selected from the roadside of a cut location near the northwestern city limits of the town of Blacksburg, Virginia. It was reddish-brown clay soil having a liquid limit (LL) of 80 percent, a plastic limit (PL) of 48 percent, and a plasticity index (P.I.) of 32 percent. Classification of the clay soil according to the AASHO system is A-7-5 with a group index of 20.

Lime

The hydrated lime ($Ca(OH)_2$) used in this study was manufactured at Kimballton, Virginia, by the National Gypsum Company of Buffalo, New York. The percentage of calcium carbonate ($CaCO_3$) was found to be 6.53 percent. This was determined by placing a sample of the lime in an oven at 900°C for about three hours in order to drive off all water and carbon dioxide.

Laboratory Procedures

Grain Size Analysis. Grain size analysis of the clay soil was performed essentially according to ASTM D422-54T. The results are shown in Figure 1.

Atterberg Limits. Liquid limit tests on the air dried sample of natural soil were performed in accordance with

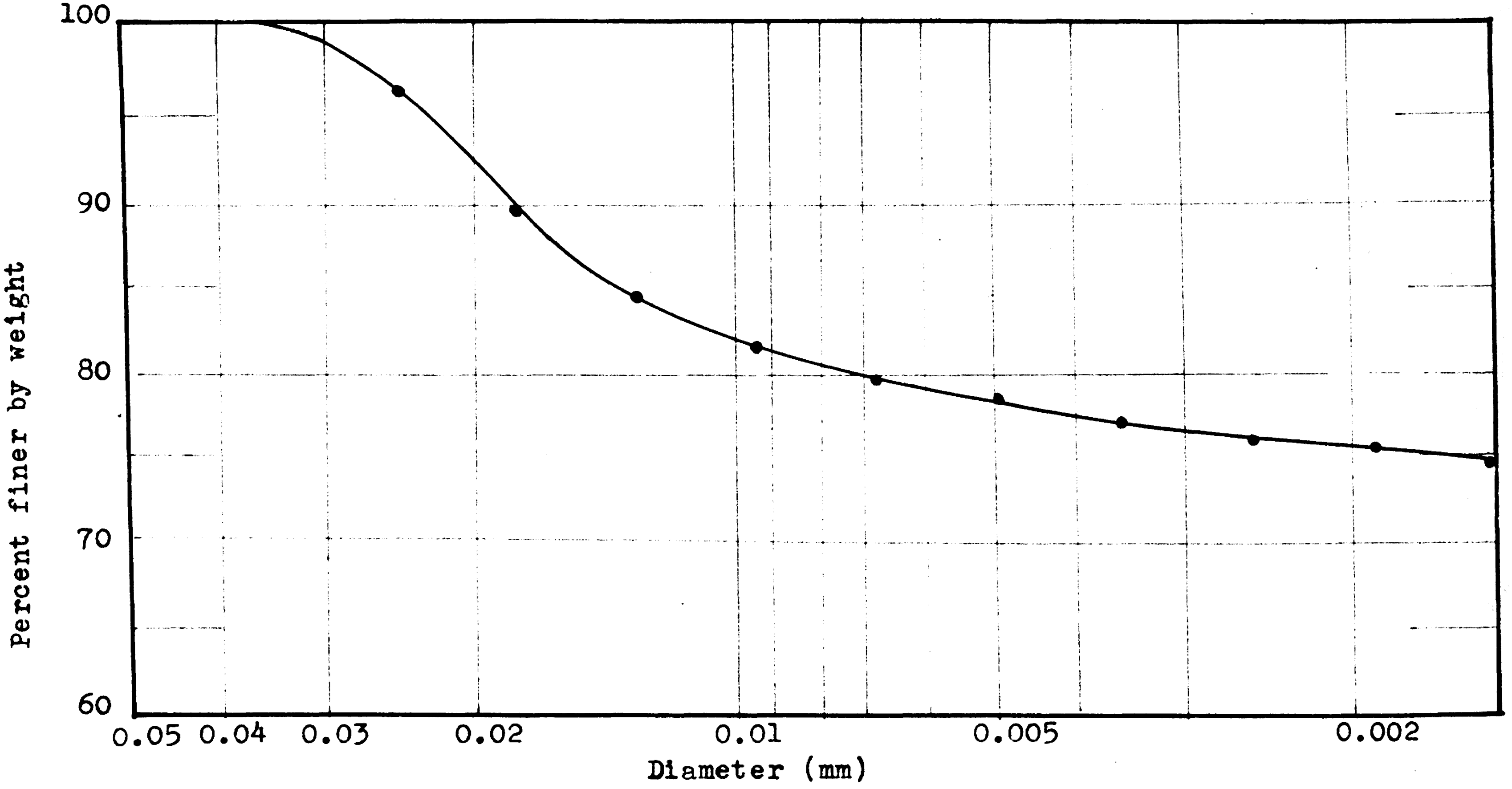

Figure 1. Grain Size Distribution Curve

ASTM D423-54T except for the following modifications: the soil was molded in Harvard miniature apparatus and wrapped with aluminum foil to preserve the moisture for a period of 48 hours before performing the test. Plastic limit tests on the air dried sample of natural soil were performed in accordance with ASTM D424-54T with the same modifications used in the liquid limit tests.

Density Tests. Standard density tests were run on the air dried sample of natural clay soil with the Harvard miniature compactive apparatus using a 40 pound spring plunger with 25 blows each on three uniform layers. Baig and Broberg (11, 12) found that the dry density obtained by this method was equal to the dry density obtained by standard AASHO method (ASTM 698-58T Method A). When passing the optimum moisture content, some difficulty was found in compacting the clay soil uniformly with the spring loaded device, due to the sticking of the clay soil to the plunger, preventing the clay from being compacted uniformly. It is recommended that a drop hammer be used instead of the spring as described by Anday (9).

Fabrication of Specimens. All specimens were 1.32 in. in diameter by 2.813 in. in height and were compacted by Harvard miniature apparatus in three layers. The compactive efforts applied were 25 blows per layer, with the compaction device using a 40 pound spring. The optimum moisture content for each of the conditions was used for molding the specimens. The specimens were wrapped with aluminum foil and immediately sealed with paraffin in order to preserve the molding moisture content during curing, freezing and thawing. Representative samples of the mixtures were taken from the mixing bowl for moisture content determinations.

Air Entrainment. In an attempt to improve the resistance of lime clay mixtures against freezing and thawing, Darex AEA manufactured by the Dewy-Almy Corporation was used as an air entrainment agent. Specimens containing five percent lime were treated with 4, 6, 8, 10 and 12 drops of air entrainment agent for each two specimen batch, while those containing zero and ten percent were treated with 4, 7, 10, 15 and 20 drops. The Darex was placed in the mixing water.

Curing. After the specimens were wrapped in aluminum foil and sealed with paraffin, they were placed in an oven at a constant temperature of 120°F for a period of 48 hours, plus or minus two hours. Experience has indicated that this is a realistic procedure and approximately equal to 45 days of field curing near Charlottesville, Virginia. (9)

Freezing and Thawing. Freezing and thawing tests were made by freezing the sealed specimens in a 0°F deep freezer for six hours, then thawing the specimens in a 70°F moist room for 18 hours. After either 5 or 10 cycles of freezing and thawing, the specimens were tested in unconfined compression.

Unconfined Compressive Tests. The unconfined compressive strength of compacted and cured specimens was determined by loading them at a rate of 0.05 inches deformation per minute. The maximum compressive stress was taken as the peak load, divided by the corrected cross-sectional area. A secant modulus was also calculated by dividing the maximum stress by the strain at the point where maximum stress occurred.

DESIGN OF EXPERIMENT

The experiments were designed as shown in Tables 1 and 2.

Table 1. Experiment A (without air entrainment)

	Unconfined Compressive Strength Test				
	No. of specimens tested				
Lime %	As cured	After 5 cycles F & T	After 10 cycles F & T	After 10 days in moist room	Total Specimens
0	3	3	3	3	12
5	3	3	3	3	12
10	3	3	3	3	12
15	3	3	3	3	12
20	3	3	3	3	12

Table 2. Experiment B (with air entrainment)

Unconfined Compressive Strength Test				
Lime %	No. of drops per (2) specimen batch	No. of specimens tested		Total Specimens
		As cured	After 5 cycles of F & T	
0	4	1	1	12
	7	2	2	
	10	1	1	
	15	1	1	
	20	1	1	
5	4	1	1	12
	6	1	1	
	7	1	1	
	8	1	1	
	10	1	1	
	12	1	1	
10	4	1	1	12
	7	2	2	
	10	1	1	
	15	1	1	
	20	1	1	

Grand total of specimens tested were 96.

RESULTS AND DISCUSSION

RESULTS

Atterberg Limits Tests

Results obtained from these tests are summarized in Table 3 and represented by the plot of Figure 2. Examination of Table 3 and Figure 2 show that the L.L., P.L., and P.I. of the clay soil were affected by the addition of lime.

Table 3. Atterberg Limits

Lime %	Clay		
	L.L.	P.L.	P.I.
0	80.0	48.0	32.0
5	70.5	51.20	19.30
10	67.4	57.50	9.90
15	70.8	59.7	11.10
20	73.5	62.2	11.3

Dry Density Tests

Table 4 and Figure 3 represent the results obtained from the dry density tests. Examination of Table 4 and Figure 3 show that the difference in the percentage of the lime added to the clay soil results in the difference in optimum moisture and the difference in the dry density.

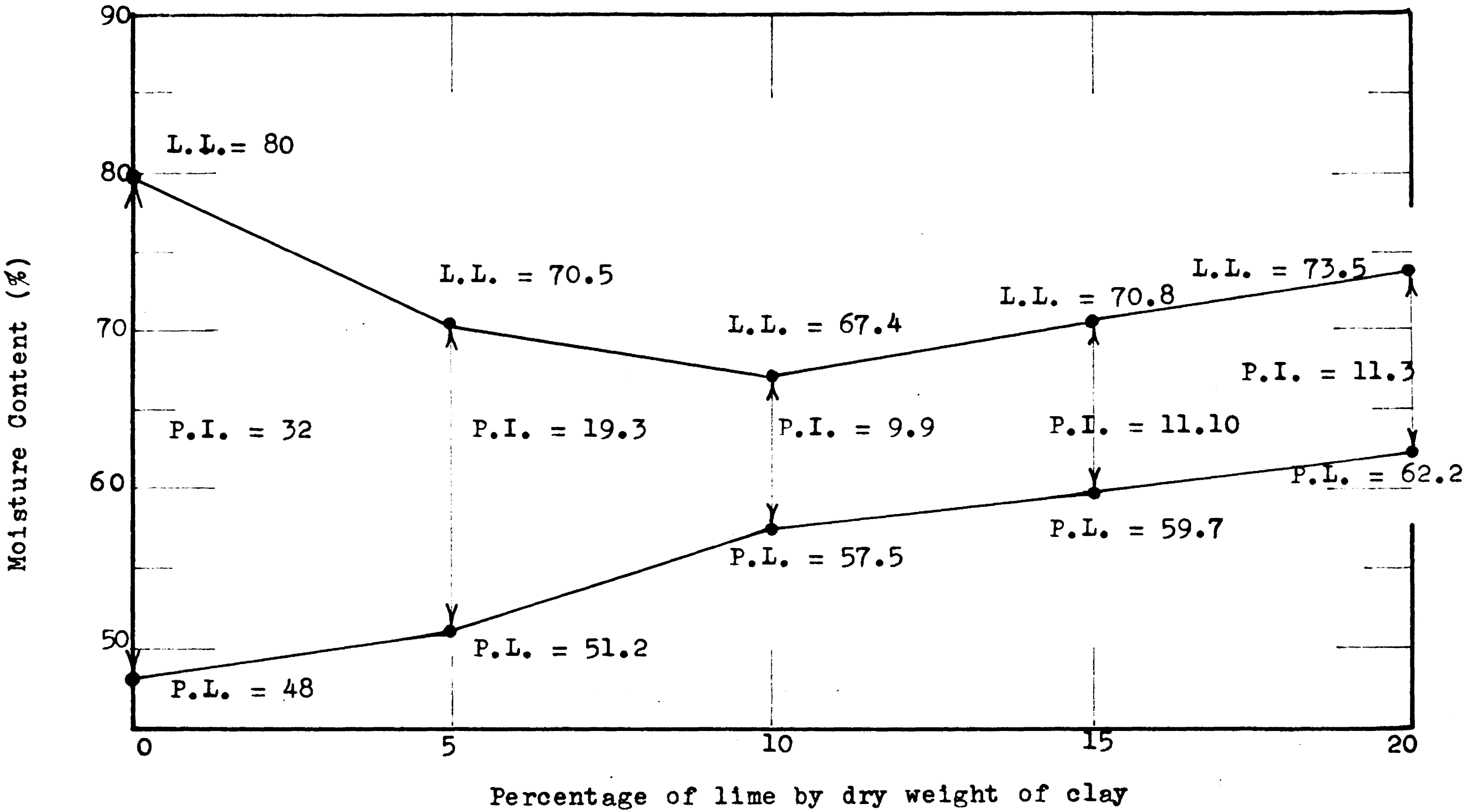

Figure 2. Atterberg Limits of Lime-Soil Mixtures.

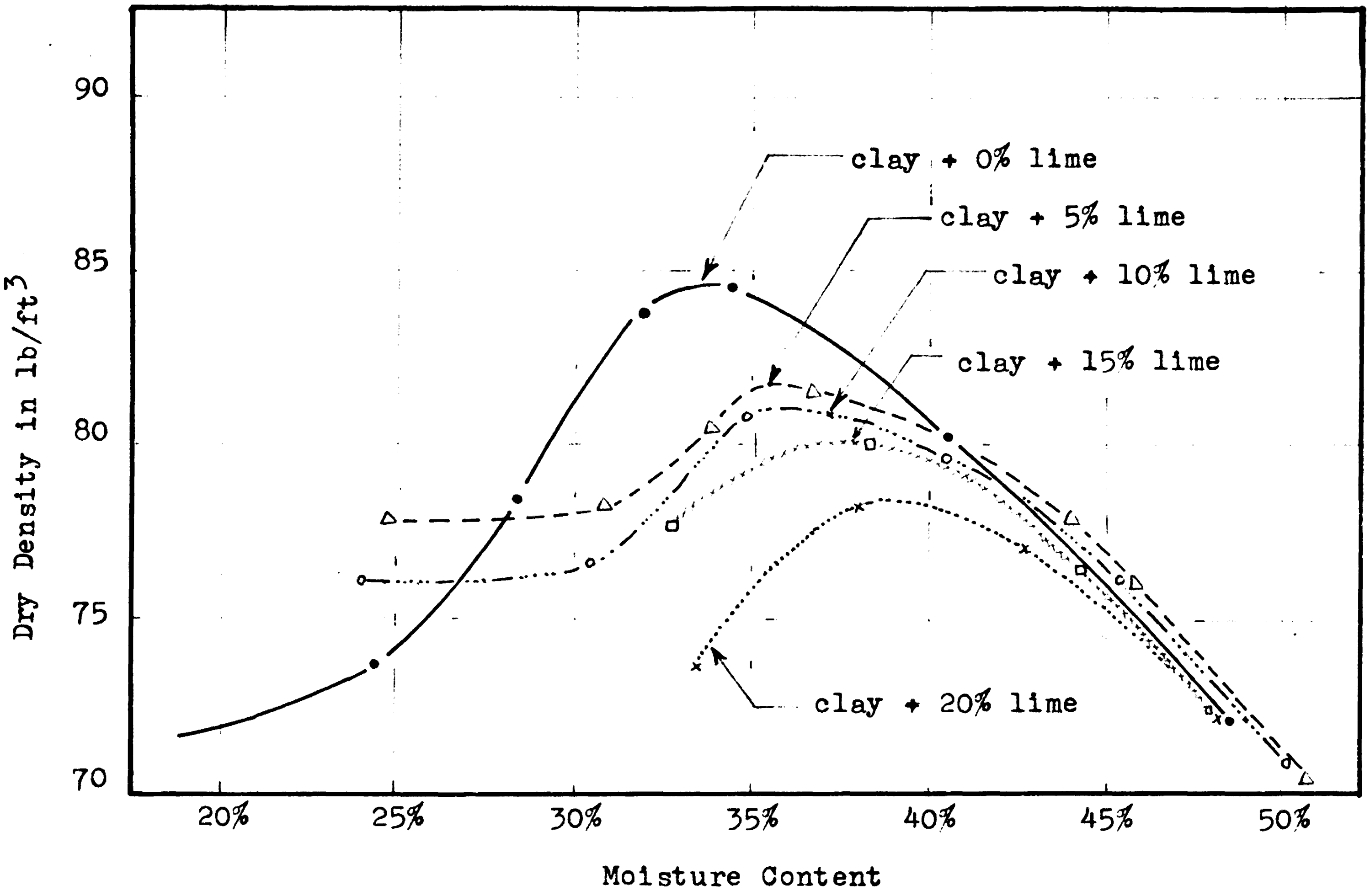

Figure 3. Standard Miniature Compaction Curves of Clay-Lime Mixtures.

Table 4. Dry Density Tests

Lime %	Clay	
	Optimum Density	Optimum Moisture
0	84.6 lb/ft^3	33.8 %
5	81.7 "	35.8 "
10	81.0 "	36.5 "
15	80.1 "	38.0 "
20	78.5 "	39.3 "

Unconfined Compressive Strength

The results of the unconfined compressive strength tests of the non-air-entrained soil-lime mixtures are shown in Tables 5 and 6 and Figures 4, 5, and 6.

The results of the unconfined compressive strength tests on the air-entrained specimens are summarized in Table 7 and presented in Figure 7.

Specimens treated with 0, 5, and 10 percent of lime were prepared in duplicate and then treated with 7 drops of air entraining agent. The first of these samples was tested immediately after curing, while the second was tested after 5 cycles of freezing and thawing. The results of these tests are summarized in Table 8 and presented in Figure 8. The secant modulus of all the air-entrained specimens was determined and presented in Tables 9 and 10. The quantity of air present inside each specimen after treating it with specific amounts of air entraining agent was determined and is shown in Table 11.

Table 5. Unconfined Compressive Strength (psi) of Clay-Lime Mixture, After Curing, Freezing and Thawing, and Kept in a Moist Room.

	Cycles of Freezing and Thawing			Days in a Moist Room
Lime %	0	5	10	10
0	79.2	11.0	10.3	57.2
	62.8	18.2	10.3	47.0
	65.8	11.1	10.5	52.2
	69.3 Avg.	13.4 Avg.	10.4 Avg.	52.1 Avg.
5	100.8	60.5	51.3	133.0
	85.3	42.2	51.4	76.5
	143.1	95.8	100.0	112.5
	109.7 Avg.	66.2 Avg.	67.6 Avg.	107.3 Avg.
10	166.0	143.0	126.8	179.0
	169.5	149.0	139.5	175.5
	203.0	174.8	159.0	192.5
	179.5 Avg.	155.8 Avg.	141.8 Avg.	182.3 Avg.
15	184.0	173.0	169.0	203.0
	200.0	180.0	185.5	213.0
	206.5	195.0	175.5	213.0
	196.8 Avg.	182.7 Avg.	177.3 Avg.	209.7 Avg.
20	200.0	185.0	188.5	208.5
	183.5	172.6	169.5	200.0
	199.0	180.0	175.0	198.0
	194.2 Avg.	179.2 Avg.	177.7 Avg.	202.2 Avg.

Table 6. Secant Modulus of Clay and Lime Mixture, After Curing, Freezing and Thawing, and Kept in a Moist Room.

Lime %	Cycles of Freezing and Thawing			Days in a Moist Room
	0	5	10	10
0	854	281	241	925
	870	338	224	860
	755	311	428	976
	826 Avg.	310 Avg.	298 Avg.	920 Avg.
5	7600	2430	2880	7350
	5330	1740	1450	5430
	8050	4800	4680	5370
	6993 Avg.	2990 Avg.	3003 Avg.	6050 Avg.
10	9330	5030	8075	8380
	9520	9380	7150	12400
	11400	10900	6385	9000
	10083 Avg.	8437 Avg.	7203 Avg.	9927 Avg.
15	10400	8100	6850	8150
	6240	4600	10350	9985
	7230	5050	7220	7470
	7957 Avg.	5917 Avg.	8140 Avg.	8535 Avg.
20	6980	5120	7400	4190
	8580	6440	6850	5085
	3970	4210	4500	5550
	6510 Avg.	5257 Avg.	6250 Avg.	4942 Avg.

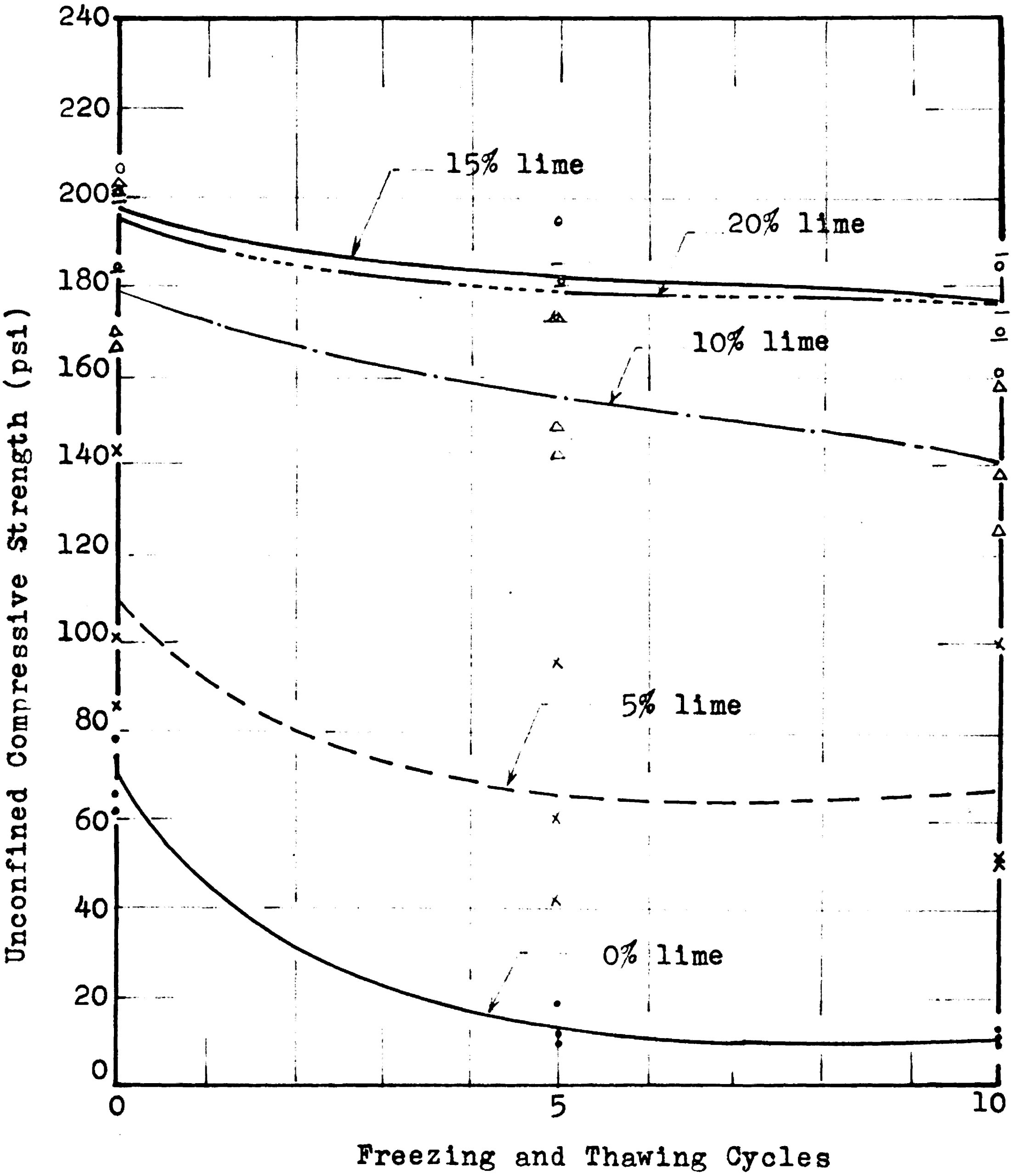

Figure 4. Compacted Strength - Freezing and Thawing Cycles Relationship of Clay-Lime Mixture.

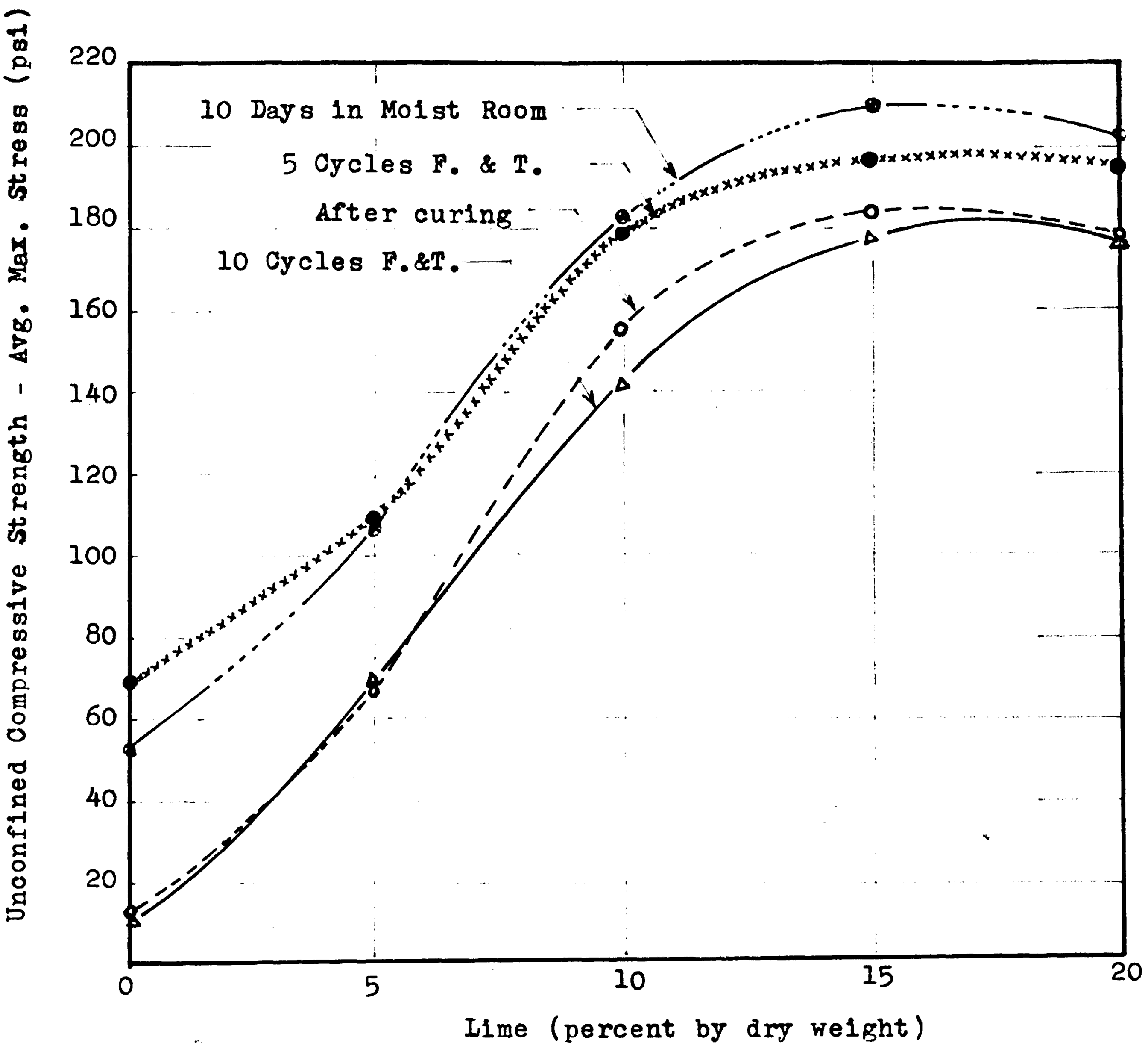

Figure 5. Compacted Strength - Lime Relationship of Clay Soil.

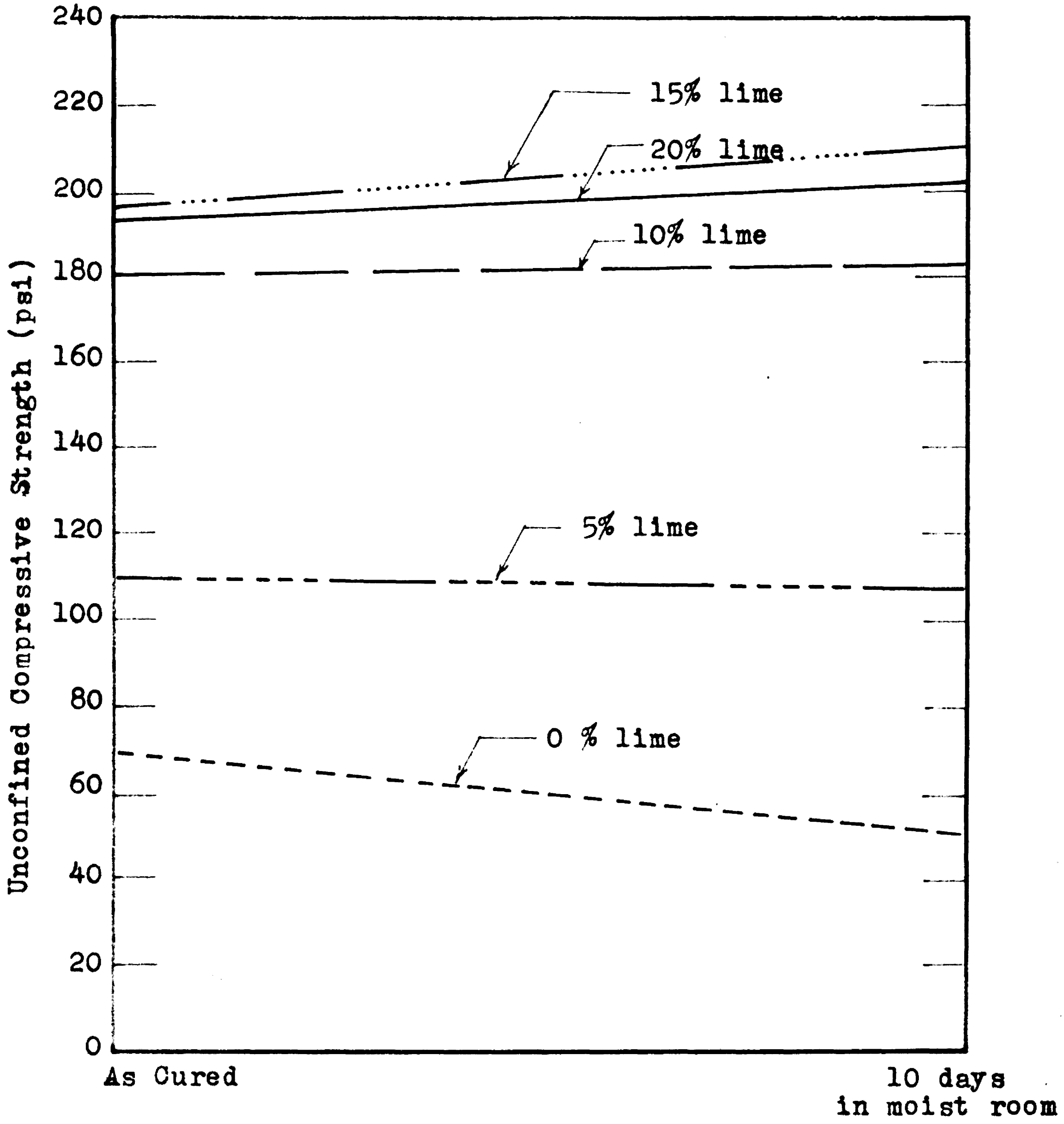

Figure 6. Compacted Strength - Lime Relationship of Clay Soil After Ten Days in a Moist Room.

Table 7. Unconfined Compressive Strength (psi) of Air-Entrained Clay-Lime Mixture After Curing and Five Cycles of Freezing and Thawing

Lime %	No. of Drops	2 Days Curing	5 Cycles of Freezing and Thawing
	4	60.2	22.9
	7	74.5	26.5
0	10	56.9	21.0
	15	48.2	18.4
	20	43.8	17.6
	4	105.5	76.8
	6	116.0	76.3
5	8	115.0	81.9
	10	101.5	75.2
	12	103.0	67.4
	4	157.5	109.7
	7	167.5	112.0
10	10	158.0	99.5
	15	155.5	101.0
	20	151.0	100.2

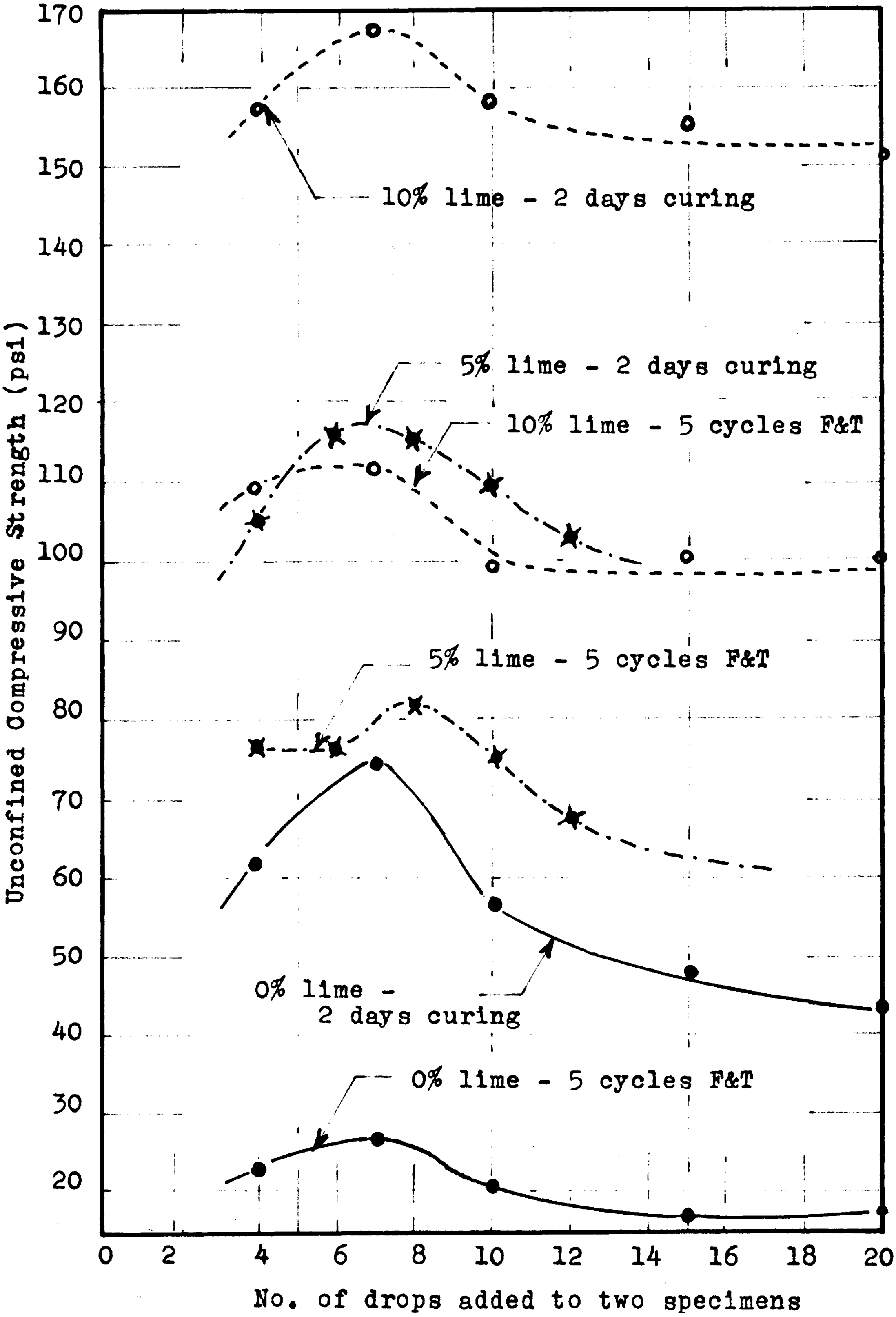

Figure 7. Effect of Air Entraining Agent on Compressive Strength.

Table 8. Unconfined Compressive Strength (psi) of Clay-Lime Mixture Treated with Seven Drops of Air-Entraining Agent Per Two Specimens Batch.

Lime %	No. of Drops	2 Days Curing	5 Cycles of Freezing and Thawing
0	7	69.3	31.2
5	7	115.0	65.2
10	7	165.5	131.5

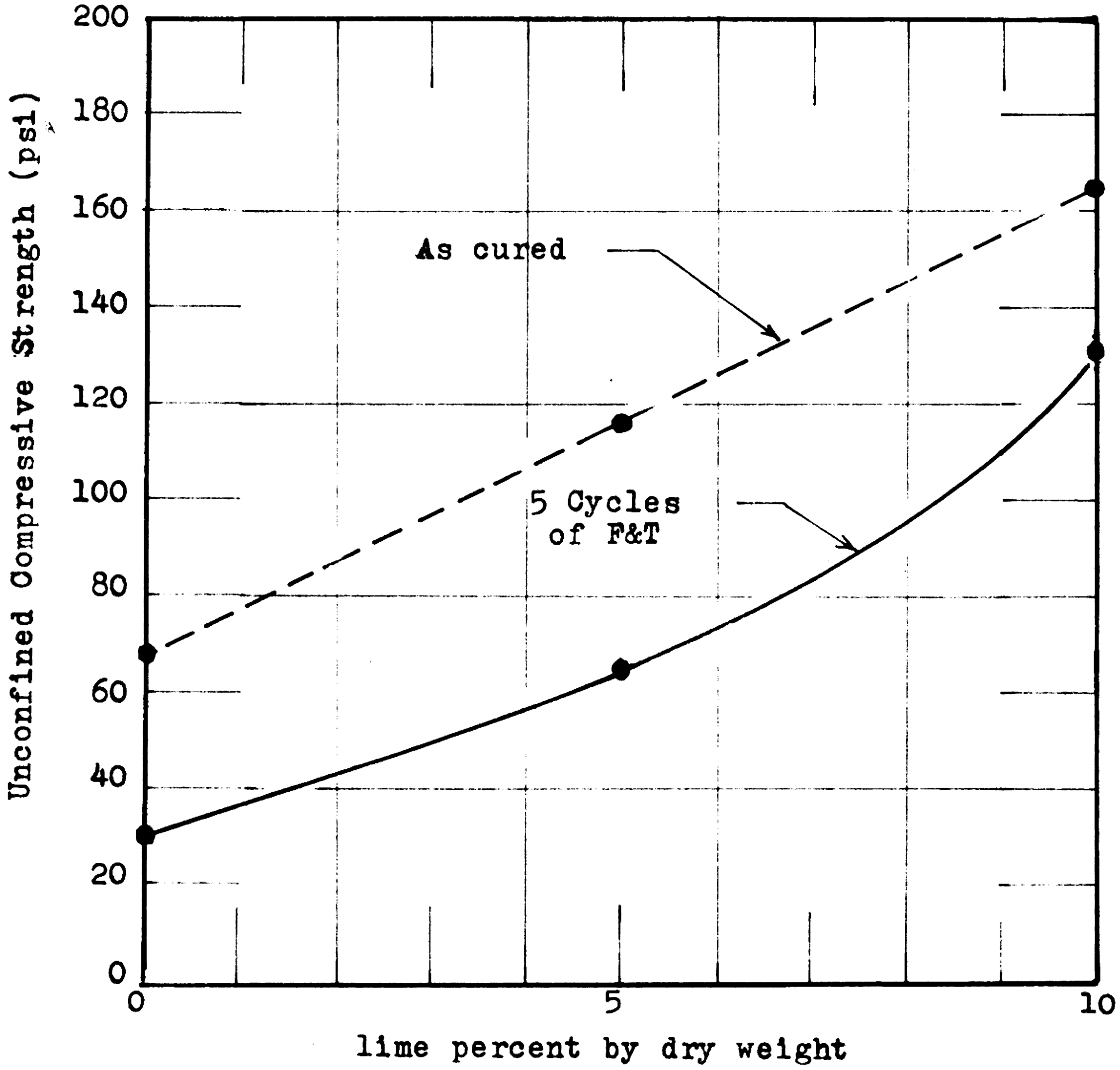

Figure 8. Effect of Seven Drops of Air Entraining Agent on Compressive Strength.

Table 9. Secant Modulus of Air Entrained Clay-Lime Mixture After Curing and Freezing and Thawing.

Lime %	No. of Drops	2 Days Curing	5 Cycles of Freezing and Thawing
0	4	818	428
	7	822	496
	10	1300	537.6
	15	1125	362
	20	1210	440
5	4	4950	4300
	6	4680	3510
	8	5420	3840
	10	4410	3140
	12	4830	3160
10	4	6275	4400
	7	6200	3420
	10	5800	2000
	15	6050	4550
	20	8395	3100

Table 10. Secant Modulus of Air-Entrained Clay-Lime Mixture Treated with Seven Drops per Two Specimen Batch.

Lime %	No. of Drops	2 Days Curing	5 Cycles of Freezing and Thawing
0	7	1645	1075
5	7	6450	1835
10	7	4200	6175

Table 11. Quantity of Air in Specimens Treated with Specific Number of Drops of Air-Entraining Agent.

Lime %	No. of drops	Percentage of air
0	0	2.2
	4	2.7
	5	3.8
	10	4.3
	15	4.4
	20	5.3
5	0	3.0
	4	3.4
	6	5.2
	8	6.6
	10	6.7
	12	7.7
10	0	2.7
	4	2.9
	7	3.1
	10	3.6
	15	3.8
	20	4.5

DISCUSSION

Atterberg Limits

Results of the liquid limit experiment at different percentages of lime (Figure 2) indicate that the liquid limit was inversely related to percentage of lime up to the ten percent level, which verifies the results of Karabulut (5) and Kotehne (19). However, when the lime concentration increased beyond ten percent, the liquid limit was found to increase rather than decrease, a result that has not previously been verified. On the other hand, the plastic limit was found to increase with the increase in concentration of lime within the limits used in this experiment. These results are in complete agreement with those obtained by Yoder (14), Karabulut (5) and Kotehne (19). As a result of this variation of the liquid and plastic limit, the plasticity index was found to decrease between 0 and 10 percent lime while it increased above that lime concentration.

Dry Density Test

Results of dry density tests, presented in Figure 3, show that the maximum densities decreased and the optimum moisture contents increased with the increase in percentage of lime added. These results are in complete agreement with those obtained by Yoder (14) and others.

Air Entrainment

The results of the comparison of the unconfined compressive strength of air-entrained clay-lime mixtures after curing as well as after five cycles of freezing and thawing show that there was no gain in strength due to the air entraining agent. Figure 7 shows that the drop in percentage of strength after five cycles of freezing and thawing was greater in the specimens with zero percent of lime. Figure 7 also shows that the maximum strength of the clay-lime mixture was obtained by using seven drops of air-entraining agent. Figure 8 shows the unconfined compressive strength of clay-lime mixture specimens molded with seven drops of air-entraining agent. Those specimens which were tested as cured were found to be linearly related to the lime concentration.

Five and Ten Cycles of Freezing and Thawing

The comparison of the unconfined compressive strength of the specimens after five and ten cycles of freezing and thawing among the various combinations of clay-lime mixtures is shown in Figures 4 and 5. Table 12 shows the percentage rise in strength of specimens subjected to five and ten cycles of freezing and thawing at different lime concentration. Examination of Table 12 shows that the percentage rise in the strength increased with the increase in lime concentration for both five and ten cycles of freezing and

Table 12. Effect of Lime on Compressive Strength.

Lime %	Increase in Strength (percent) 5 Cycles	Increase in Strength (percent) 10 Cycles
0	0	0
5	393	550
10	1065	1265
15	1260	1600
20	1230	1610

thawing. However, this percent increase in the strength was found to be higher for the ten cycles of freezing and thawing than that for five cycles. Also shown is that the maximum percent rise in the strength was found to be between five and ten percent of lime for both five and ten cycles.

Results presented in Figure 5 show that the increase in the concentration of lime resulted in the increase in strength of the clay-lime mixture for different methods of treatment. This figure also shows that maximum strength was obtained while the specimens were treated for ten days in a moist room. The greater strength for all different types of treatments was estimated to be at a lime concentration of about 17 percent. Table 13 summarizes the percent drop in strength after five and ten cycles of freezing and thawing for all specimens tested. Examination of this table indicates that the percent

Table 13. Effect of Freezing and Thawing Cycles on the Strength of Clay-Lime Mixture.

	Decrease in Strength (percent)		
Lime %	First Five Cycles	Second 5 Cycles	First 10 Cycles
0	80.5	4.5	85.0
5	39.7	-1.3	38.4
10	13.2	7.8	21.0
15	7.2	2.7	9.9
20	7.7	0.8	8.5

drop in strength for the first five cycles of freezing and thawing was much higher than that for the last five cycles of freezing and thawing.

Ten Days in a Moist Room

Results of the unconfined compressive strength for specimens treated ten days in a moist room were presented in Figure 6. This figure shows that strength was affected by the lime concentration. Furthermore, in a moist room specimens with a high lime concentration were found to gain more strength than those with a lower lime concentration. These results are summarized in Table 14. This seems to indicate the possibility of the moist environment having some effect on the specimens, despite the fact that they were wrapped and sealed in aluminum foil.

Table 14. Effect of Moist Room on Compressive Strength of Clay-Lime Mixture.

Lime %	Difference in Strength (percent)			
	As Cured	Ten Days in a Moist Room	Decrease in %	Increase in %
0	69.3	62.1	10.4	
5	109.7	107.3	2.2	
10	179.5	182.3		1.6
15	196.8	209.7		6.6
20	194.2	202.2		4.1

CONCLUSIONS

1. Moisture-density relationship was affected by the lime admixture. Maximum dry density was found to decrease while the optimum moisture increased.
2. The addition of lime changed the plasticity properties of the soil as follows:
    a. Increased the plastic limit
    b. Decreased the liquid limit with the increase of lime up to ten percent, above which it started increasing
    c. Decreased the plasticity index.
3. The compressive strength of clay-lime mixture increased with the increase in lime concentrations within the limits tested in this study.
4. The maximum percent increase in the strength of clay-lime mixtures was found to occur at about ten percent lime.
5. About 17 percent lime was estimated to give maximum strength.
6. The decrease in strength due to freezing and thawing was greatest during the first five cycles.
7. Seven drops of air entraining agent gave maximum strength of the air-entrained specimens.

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ABSTRACT

EFFECT OF FREEZING AND THAWING ON UNCONFINED COMPRESSIVE STRENGTH OF CLAY LIME MIXTURE WITH AND WITHOUT AIR ENTRAINING AGENT

The main objective of this study was twofold:

1. To determine the effect of freezing and thawing on the loss in strength of lime-soil mixture.

2. To investigate the effect of the addition of an air entraining agent on the freezing and thawing durability of lime-soil mixtures.

For the first part, twelve specimens were prepared for each of 0, 5, 10, 15 and 20 percent combination of lime-clay mixture, giving a total of 60 specimens.

For the second part, twelve specimens were prepared for each of 0, 5 and 10 percent of lime, giving a total of 36 specimens. Those containing five percent were treated with 4, 6, 8, 10 and 12 drops of air entraining agent for each two specimen batch, while those containing 0 and 10 percent were treated with 4, 7, 10, 15 and 20 drops. All specimens were wrapped with aluminum foil and immediately sealed with paraffin and cured for two days at 120°F. Control specimens were placed in the 70°F environment for ten days while companion specimens underwent five and ten cycles of freezing and thawing.

The results of this study indicated the following:

1. Addition of lime increases the strength of clay soil.

2. Maximum percent increase in durability of clay soil found to occur with addition of ten percent lime.
3. The decrease in strength due to freezing and thawing mainly occurred during the first five cycles.
4. Seven drops of air entraining agent gave maximum strength of air entrained specimens.