MICA STABILIZATION WITH LIME, PORTLAND CEMENT AND LIME-CALCIUM CARBONATE

by

Tai-Chou Hsieh

Thesis submitted to the Graduate Faculty of the

Virginia Polytechnic Institute

in candidacy for the degree of

MASTER OF SCIENCE

in

Civil Engineering

February 1964

Blacksburg, Virginia

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Soil is one of the oldest construction materials and is widely used in civil engineering. One of its most important usages is in the construction of fill. Fill serves many purposes. Long narrow fill, termed an embankment, may carry a railroad or highway across a low area or act as a dam or levee to impound or confine water. Fill serving as foundation or supporting soil for a highway or airport pavement is termed subgrade.

With the rapid increase in vehicle numbers and vehicle miles traveled there is a need for more highways. With the available supply of high quality soil for highway subgrade construction rapidly diminishing in many areas, the highway engineer is confronted with the problem of transporting suitable soil to construction sites or artificially producing a high quality soil by mixing the available soil with an admixture, which procedure is termed chemical stabilization. From an economic point of view, stabilization with additives is often favored over long-distance hauling.

Stabilization is the process of improving soil so that it can meet the requirements, such as strength and compressibility, imposed by the need for stable subgrade and embankment materials. Admixtures that have been used in chemical stabilization work include cementing agents, modifiers, waterproofing agents, water retaining agents, water retarding agents, and miscellaneous chemicals (24). Each type of admixture behaves differently from the others, each has its particular use, and, accordingly, each has its specific limitations.

Among the cementing agents that may be used as chemical stabilizing agents are portland cement and lime. Portland cement has been used with great success to improve existing gravel roads and to stabilize granular soils, silty soils, and lean clays (7). This success can be attributed to the strength gains that cement-treated soil shows over the natural material. The addition of lime to soil may also cause strength gains. Lime is more especially suited to clayey soils, which it often makes more workable, less plastic, and stronger in bearing (8 and 20).

Stabilization has proven its worth (13 and 20), but a problem that remains in many areas is the quantity and type of additive necessary to transform a low quality soil into a quality subgrade material. Unstable soils may be of many types, such as highly plastic, organic, or highly micaceous. Little work has been done on the stabilization of highly micaceous soils even though these are not uncommon in the Appalachian Piedmont Province of the Southeastern United States. The problem is unique in that mica is both inorganic and nonplastic, but responds poorly to stabilization by purely mechanical means and yields spongy or resilient subgrades. Work on stabilization of mica by additions of sand has given largely negative results (2).

This study is concerned with the effect of amount and type of common stabilizing agents on the unconfined compressive strength of a compacted granular mica soil. Particular attention is given the reaction of calcium hydroxide (lime) with mica and the influence of calcium carbonate-calcium hydroxide mixtures on the strength of compacted mica soil. The results are compared to strength gains given by portland cement stabilization.

II. PREVIOUS WORK ON LIME STABILIZATION

Most work (5, 17 and 20) has shown positive results with the stabilization of various soils using hydrated lime. Additions of lime generally change such physical properties as plasticity index, potential volume change, optimum moisture content, and maximum dry density, consequently improving the engineering properties of the soils.

One of the physical changes that may occur immediately with the addition of lime to a fine-grained soil is flocculation or agglomeration of clay particles. This process makes a soil appear more friable. As an example, it was found (17) that a clay having 10 percent lime as additive underwent so much apparent change in gradation that after 14 days of curing it was subsequently classified as a sandy loam and, after 240 days, the clay aggregates gave the soil the appearance of sand. In such reactions, the fine particles are more active than larger ones and tend to react readily with the lime. In many cases, aggregation takes place within the mixture of fine clay particles and chemical to form aggregate that will not readily pass a 200 mesh sieve. The amount of such agglomeration is determined by a number of factors, one of the most important being soil character. Plastic soils more readily agglomerate than sandy or silty soils. Also, agglomeration is affected by lime quantity, being roughly proportional to the amount of lime added to the soil. Type of lime may influence the amount of agglomeration; quicklime induces more reaction than hydrated lime.

The effect of lime in changing soil plasticity is a phenomenon noticed in almost every investigation on lime stabilization (4, 5 and 8). With the addition of lime to soil, liquid limit normally decreases and plastic limit usually increases. However, in some soils, liquid limit is increased by adding lime. Whether or not the liquid limit increases or decreases, the increase in plastic limit with the addition of small quantities of lime frequently reduces plasticity index.

Strengths of lime-soil mixtures generally are increased after the addition of lime to soils. It has been shown (11) that the addition of two percent lime to Georgia kaolin increases the strength of the clay by a factor of two. With this clay, strength was found to increase with lime contents up to eight percent by weight, with an increase of five fold at eight percent lime. In 1962, Davidson and Pietsch (5) reported on the beneficial effects of lime on the unconfined compressive strength of 20 soils from various parts of Iowa. Some of these soils showed a 28-day dry compressive strength of no less than 520 psi with four percent lime as an admixture. Reports on field work also show strength increases with lime stabilization (17).

The unconfined compressive strength of lime-soil mixtures is commonly used as a rough measurement of the effectiveness of lime stabilization. To date, investigators have found that there are many factors affecting the strength of lime-treated soils (20). Among these factors are soil type, lime content, type of lime, density of the compacted lime-soil mixtures, and time and type of curing. The strength gains that can be obtained by the addition of lime to a soil depend largely on the amount of pozzolans in the soil. When the required amount of pozzolans is available, higher strengths occur with lime addition than when there is a pozzolan deficiency. Normally, clays contain large amounts of pozzolans and are very reactive with lime. In some cases, only a small quantity of clay is required in a soil to provide significant strength increases with lime addition (20). Also, the amount of strength increase in a soil is related to the amount of lime added; with generally increasing strengths as the amount of added lime is increased (17, 18 and 19). Strength is influenced by the type of lime also; higher strengths being obtained with mixtures of dolomitic lime than with high calcium lime in the case of plastic soils (6).

Environment influences the strength of lime-treated soil. The strength is a function of curing time and environment. It increases with curing time, especially during the first few hours of curing, after which rate of strength increase diminishes with time (20). Conditions of curing such as temperature and moisture are important. The strength of mixtures cured at low temperatures is lower than those cured at high temperatures (20). Temperature also affects the speed of strength gain. It was found (6) that the strength of mixtures cured at 140°F. for 10 days was the same as that of mixtures cured at 70°F. for three to four months. Also, samples cured at a low humidity gain more strength than those cured at a high humidity. In a few instances, the reverse results may be obtained. Compactive effort is important in achieving strength gains through its influence on as-compacted density. Even though lime-soil mixtures are usually stronger than the soil alone, the as-compacted dry density is often less. Still, strength of the admixtures can be augmented by increasing compactive effort and, hence, as-compacted density.

The beneficial effects of lime are generally attributed to the interaction of lime and soil clay minerals. The reactions mentioned most often in the literature (21) are 1) aggregation caused by flocculation of clay particles, 2) cation exchange phenomena, 3) cementing or bonding action of indefinite character, and 4) reaction of lime and carbon dioxide to form calcium carbonate and thereby cement the soil particles together.

When lime and a moist cohesive soil are mixed together and cured in a loose state for a period of time, the soil becomes friable and behaves like a silt, which has a low plasticity or cohesion. This phenomenon is due to one of two conditions or possibly to a combination of them. Firstly, a base-exchange reaction occurs with strong calcium cations of the lime replacing weaker metallic ions, such as sodium and hydrogen, on the surface of the clay particle. Another process is the crowding of additional calcium cations of the lime onto the surface of the clay. Both processes act to change the electric-charge density around the clay particles. Clay particles then become attracted to one another, causing flocculation or aggregation. Aggregation takes place rather quickly and is caused by addition of only one or two percent lime.

Another important lime-soil reaction produces a cementing action between the soil particles. 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 tend to cement the soil particles in a manner similar to that produced by the hydration of portland cement. The minerals in the soil that react with lime to produce a cementing compound are known as pozzolans. Pozzolanic reactions are greatly accelerated by heat or by the addition of certain chemicals.

Another reaction which occurs in lime plaster is carbonation of lime by carbon dioxide from air, producing calcium carbonate. Not only do these carbonations form weak cementing materials but also deter pozzolanic action and prevent normal strength gains.

It is recognized that the effect of lime on clay soils is governed in part by the properties of the clay minerals in the soils. Mineralogically, soil clays may be divided into three broad groups: montmorillonite, illite, and kaolinite. The properties of the groups vary one from the other because of differences in the physico-chemical activity of the clays. Montmorillonite is most active, whereas kaolinite generally shows the least activity. This variation in activity can be attributed to the influence of the location and magnitude of the ionic charges carried by the particles, the nature of their surrounding moisture films, the character of the exchange ions present, and the crystalline structure of the mineral particles (8).

Eades and Grim (11) investigated and compared the reactions between lime and different clay minerals and reported that the strength of kaolin samples increased significantly with the addition of the first increment of lime, whereas for all the other clay minerals there is little increase in strength until four percent or more lime is added. It appears that kaolinite and lime react easily, and only small amounts of lime are required to start the reactions. On the other hand, for illite and montmorillonites, lime over and above a minimum amount must be added before there is a reaction accompanied by the development of strength. In the case of montmorillonites which have high cation exchange capacities, a certain amount of lime is required to drive the calcium ion into and onto the clay. Only after the clay apparently has been changed to a calcium variety does it develop strength. Therefore, the base exchange capacity of a clay soil may be considered as an index of favorable reaction of a soil with lime admixture. Grim (9) gives the base exchange capacity of the three basic members of the clay family as follows:

Montmorillonite	60 - 120 meq/100 gm.
Illite	20 - 40 meq/100 gm.
Kaolinite	3 - 15 meq/100 gm.

The reaction of lime and kaolinite leads to the formation of new crystalline phases, which are tentatively identified as calcium silicate hydrates on the basis of X-ray diffraction characteristics. This reaction seems to take place by lime eating around the edges of the kaolinite particles, with a new phase forming around the core of unaltered kaolinite. In contrast, the reaction of lime with the three-layered clay minerals begins by a replacement of the existing cations between the silicate sheets with calcium ions. Following the saturation of the interlayer positions with calcium, the whole clay mineral structure deteriorates without the immediate formation of substantial new crystalline phases. Later, and particularly with large lime additions, crystalline reaction products develop which are difficult to identify specifically, but undoubtedly are calcium silicate hydrates and calcium aluminum hydrates. For illite and montmorillonite, there is little strength developed until after the clay is saturated with lime and the destruction of the clay mineral is started. (9)

In 1962, Eades and Grim (10) reported that the formation of calcium silicate-hydrates occurs under field stabilization conditions. Also, they found that calcium carbonate is present in samples taken from some lime-stabilized subgrade soils. Since the subgrade soils did not contain calcium carbonate prior to stabilization, it could be concluded that carbonation took place under field conditions. The investigators studied untreated, laboratory-treated, and field-treated soil. After x-ray diffraction analysis, they found that neither calcium silicate-hydrates nor calcium carbonate was present at the untreated soil, calcium-silicate-hydrates were present at the laboratory-treated soil, and both calcium silicates-hydrates and calcium carbonate appeared in the field-treated soil.

Calcium carbonate that is the product of the carbonation of calcium hydrate by carbon dioxide from the air is regarded as a weak cementing material in some publications (4 and 20). Still, it was advised to prevent calcium hydrate from carbonation for the best strength to develop in both test samples and roads, since the quantity of calcium available for the formation of calcium silicate-hydrates, which is referred to as an important cementing matérial, will be reduced. However, some investigators (11) report that carbonation is a slow reaction and attribute to it strength gains of lime-soil mixtures over the long term.

III. THE CHARACTER OF MICA SOIL

Mica soil is important in the Piedmont Province of the Appalachian Highland in the southeastern United States (23). It generally contains quartz and kaolinite clay, but its properties are determined to a large extent by the large quantities of biotite or muscovite derived from the partial weathering of gneisses and schists. In some cases, the soil may be nearly 100 percent mica; mica contents of 20 to 30 percent are common (23). From the standpoint of highway subgrade materials, the mica is deleterious; yielding high void ratios (23), high compressibility, low strength, and poor response to compaction. These properties may be associated with any soil where mica behaves as the matrix material, which, according to Bhat (2), can occur in sand with less than 25 percent mica.

Micaceous sandy silts and silty sands are ordinarily not adapted to proper compaction (23). Maximum dry densities, as determined by the Standard Proctor Test, fall between 94 pcf. and 110 pcf. In general, the greater the percentage of mica and kaolins, the lower the maximum density. Optimum moisture contents typically range from 22 percent to 15 percent. The moisture-density curves usually have relatively sharp peak indicating that the soils are very sensitive to moisture content. In order to get favorable engineering properties, Sowers (23) emphasized that compaction of from 95 percent to 100 percent of the Standard Proctor maximum is necessary. As the compaction percentage falls below 95 percent, the properties of the compacted soil quickly become unfavorable.

Tate and Larew (25) have recently studied the structure of compacted micaceous silt. They found that the structure of a micaceous silt of the type studied does not necessarily follow the concept of compacted clay structure proposed by Lambe (15). Lambe's theory dictates an increasingly dispersed structure in compacted soil as the moisture content is increased during compaction. Micaceous silt discloses a more dispersed structure at or near the optimum moisture content and a more flocculated or random structure on the dry and wet sides of optimum. However, it should be noticed that a considerable difference exists between the colloidal clay particles considered in Lambe's studies and the very much larger mineral particles of micaceous silt.

Sowers (23) reports that the strength parameters, c and ϕ, obtained from quick triaxial shear tests of micaceous soils vary inversely with soil void ratio. Further, he suggested that a large part of the cohesion, c, is true cohesion or bonding among the soil particles. In the original rock the particles were all interlocked with certain physical bonds between them. Apparently, not all these bonds are broken during weathering, since many of the soils, especially those containing large amounts of mica, show appreciable cohesion. Sowers also states that the internal friction is true friction plus interlocking of the angular quartz and the mica flakes. He tested some remolded, dried soils at the same void ratio as undisturbed soils and found that the angles of internal friction were approximately the same as in the undisturbed samples. This suggests that the internal friction is not greatly dependent on the soil structure. Sowers made a few tests in comparing slow (drained) with quick (undrained) shear. The results show that the difference is negligible for a micaceous silty sand ($e = 1.4$) but may be very appreciable for the very silty soils or clayey soils when saturated.

According to Sowers' test results (23), micaceous soil consolidates fairly rapidly. In the partially saturated condition, a large percentage of the consolidation takes place immediately. When saturation is reached, the consolidation proceeds as would be expected from the Terzaghi Theory. The coefficient of consolidation is high for this type of soil. Smith's work (22) shows that the effect of mica content on increasing the rate of secondary compression is noticeable. He attributes this in part to the mica particles. Mica is noted for its platy cleavage and slippery quality. It possesses indexes of from two to three on the

Mohr's scale of hardness (12). Thus, mica may be rated as relatively unstable against shearing stress among the individual particles.

IV. MATERIALS AND METHODS

Soil

The soil used in this study is a naturally-occurring mica soil. It was obtained in Madison County, Virginia, in the Appalachian Piedmont. From the same source two shipments of soil samples were made at different times. The soil is dark yellow, highly micaceous saprolitic rock derived from sheared Lovingston granite. A particle size distribution analysis of the material is given by Bhat (2). His analysis shows 30 percent silt size and 8 percent of clay size. It is classed as SM by the unified soil classification system. X-ray diffraction analysis shows the material to be primary biotite mica with small amounts of poorly crystallized kaolinite. Differential thermal analysis shows similar results.

The soil was air dried and passed through a No. 10 sieve, with the portion retained on the sieve discarded.

Stabilizers

1) Portland cement

An air-entraining Lone Star portland cement type-1 was used in cement additive studies. This cement was manufactured by Lone Star Cement Corporation, Virginia.

2) Agriculture Lime

The lime used in this study was Mason General Purpose lime, manufactured by Ripplemead Lime Co., Inc., Ripplemead, Virginia. A weight loss determination showed that this lime contains about 43.5 percent of calcium carbonate due to carbonation in the laboratory.

3) Reagent grade lime and calcium carbonate

Other lime used in this study was a high calcium lime with an original content of CaO of more than 95 percent. Weight loss determination by burning at 900°C. showed the reagent lime to be essentially pure calcium hydroxide, due to hydration in the laboratory. Tests did not indicate the presence of significant carbonate. The reagent calcium carbonate is a pure chemical product containing less than one percent of impurities.

Methods

Unconfined compressive strength of specimens was used as a guide in determining the effectiveness of each additive added to the soil.

The samples were molded with the Harvard Miniature Compaction apparatus (16) having a 40 pound spring. Each sample was compacted in five soil layers with 25 hammer blows for each layer. This compaction effort is considered higher than that given by Standard AASHO test. Broberg (3) notes that compaction in the miniature device using a 40 pound spring with three soil layers and 25 hammer blows per layer is approximately the same as that with Standard AASHO compaction.

The samples were compacted at near optimum moisture content in the Harvard miniature apparatus, carefully extruded from the compaction mold and put into small jars that were capped tightly and sealed with grease in order to prevent evaporation of water. The samples were cured in an oven at 120° F. for two days. After curing, a constant strain test was conducted to determine the unconfined compressive strength of the samples.

The apparatus employed in determining the unconfined compressive strength of the treated soil is a standard strain-controlled triaxial compression testing machine. Size of the sample was 2.8 inches in length and 1.3 inches in diameter. There was no confining pressure, the axial load was applied at a strain-rate of 3.5 percent per minute, and the test was continued until the sample visibly failed or a load drop occurred.

X-ray diffraction tracings were made with a G.E. XRD-3 x-ray diffractions unit with a spectrogoniometer that plots the logarithum of x-ray intensity. Samples were prepared by grinding and smearing on a glass slide. Differential thermal analyses were made with a unit that advances the temperature of the calcined aluminum oxide reference at a rate of 12.5° C. per minute. The same temperature increase rate was employed for thermogravimetric analyses.

V. RESULTS AND DISCUSSION

Moisture-density characteristics

The moisture-density properties of compacted mixtures of mica soil and stabilizing agent are summarized in Figures 1 - 3. Figure 1 demonstrates that additions of agricultural lime has a marked effect on both maximum dry density and optimum moisture content of the compacted soil. Further, as shown in Figure 2, reductions in achieved compacted density with increases in lime content occur even when molding water content is held constant. This reduction is particularly pronounced at molding water contents dry of optimum. Similar results have been reported by Gallaway and Buchanan (8), who found that for compacted soils, lime admixtures caused dry unit weight to decrease and optimum moisture content to increase. The reduction in dry unit weight may be caused by the replacement of soil particles by water, which would also account for an increase in water content. Lime is a very fine powder. Hence, additions of lime amount to additions of fine particles with large surface areas for adsorption of water. Generally, the more fine-grained a soil, the lower its maximum dry density and the higher its optimum moisture content at any particular compactive effort.

Figure 3 shows that in the case of soil-portland cement mixtures, appreciable decreases in maximum dry density occur, but optimum moisture content appears to be little influenced

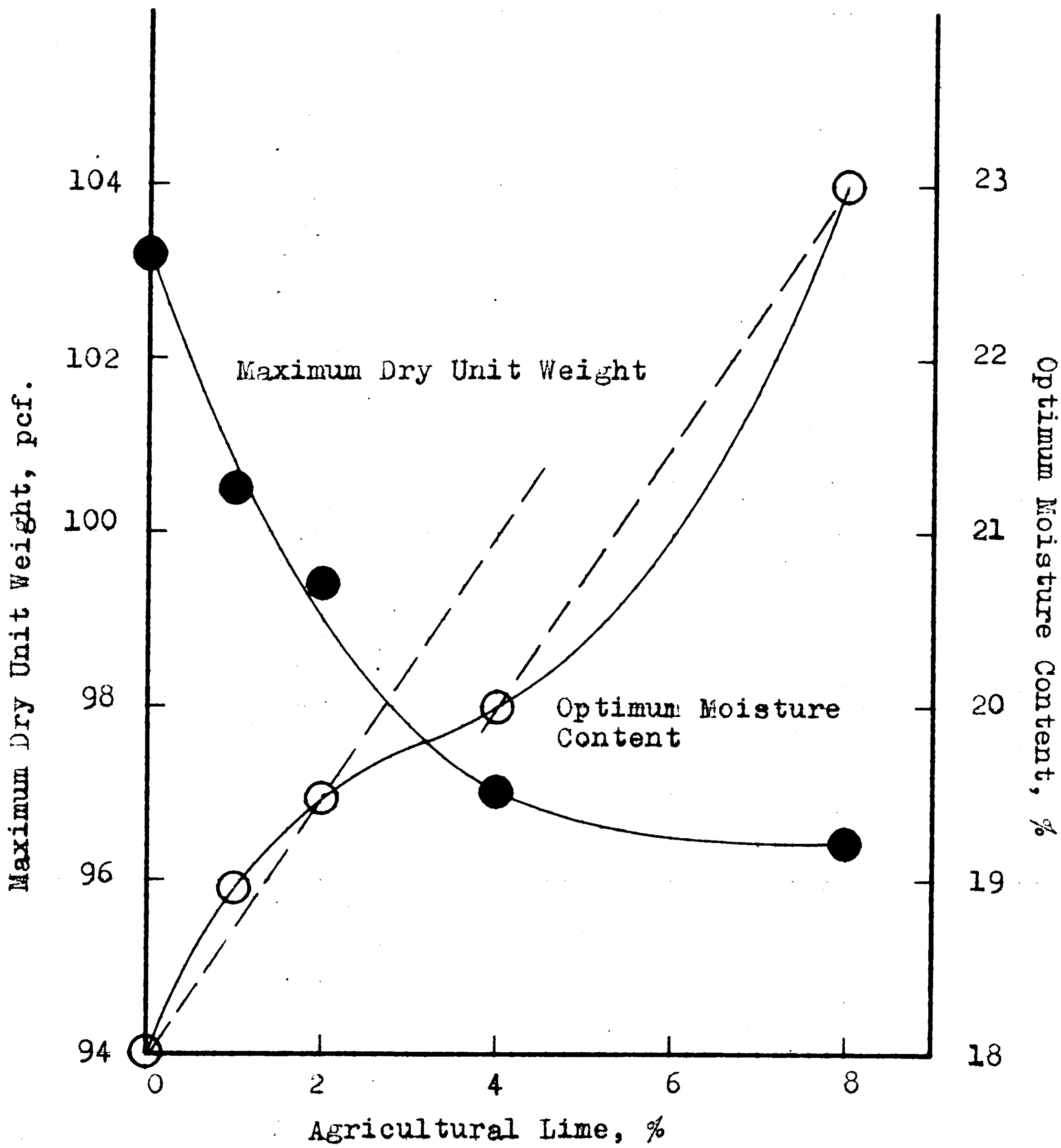

Figure 1. The maximum dry unit weight and optimum moisture content of compacted mixtures of mica soil and agricultural lime.

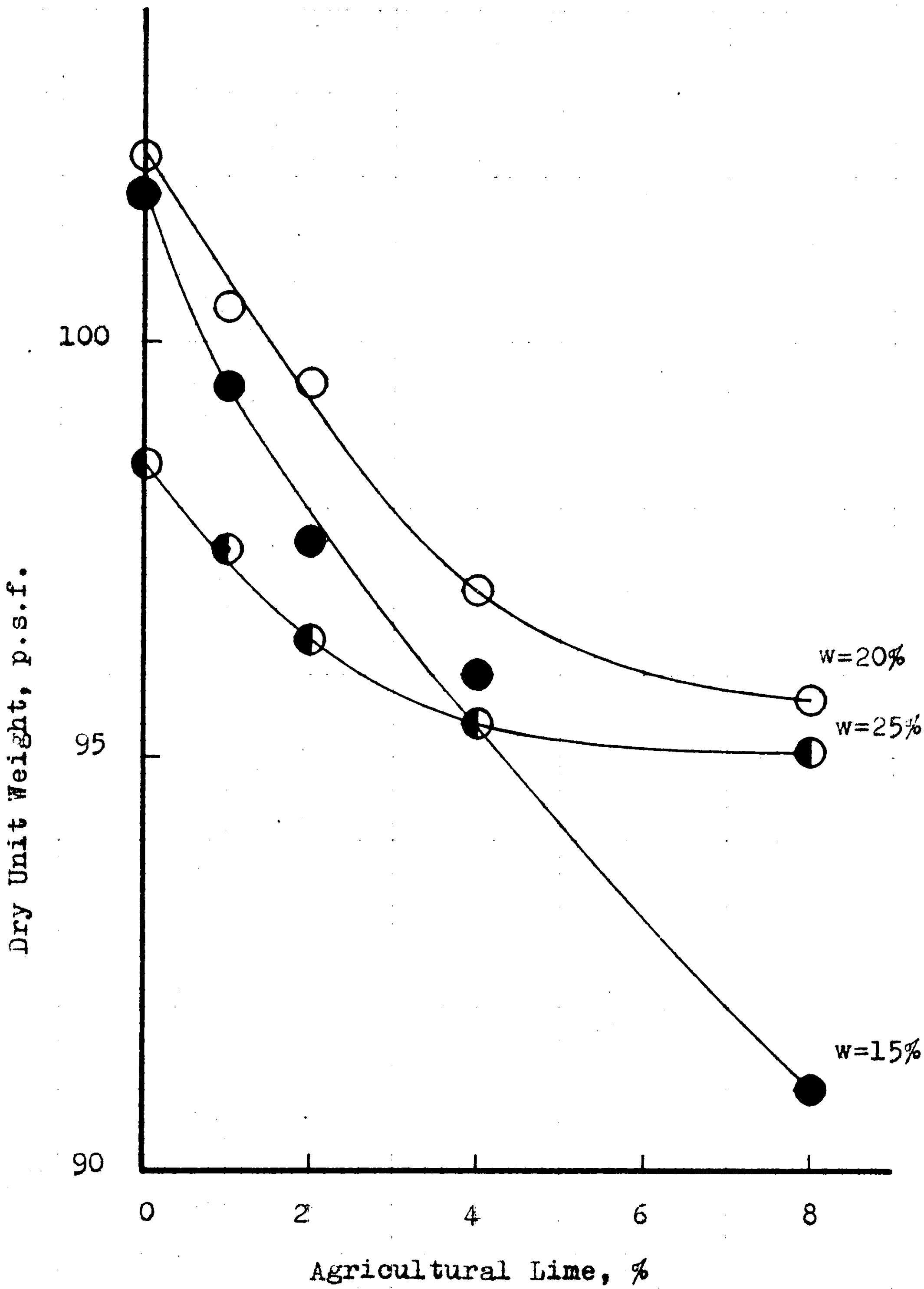

Figure 2. The dry unit weight of compacted mixtures of mica soil and agricultural lime.

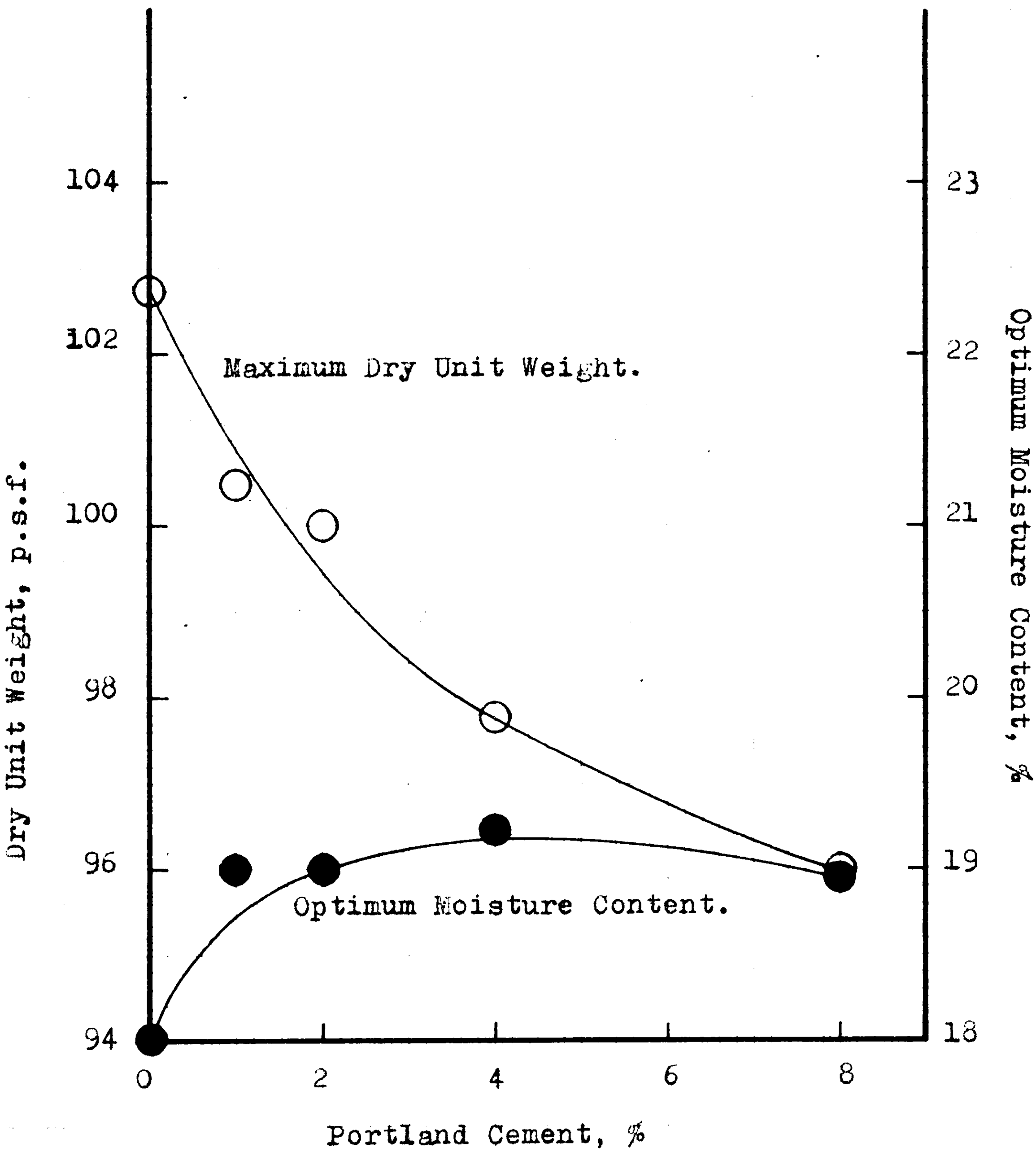

Figure 3. The dry unit weight and optimum moisture content of compacted mixtures of mica soil and portland cement.

by percent of stabilizing agent. This may signify the reaction of water with the stabilizing agent after compaction but before or during water content determination. There may have been, in effect, a high percentage of water in the soil during compaction, but during drying, much of this water may have reacted with the portland cement to form solid hydrates, like those formed during the cure of concrete, so that the water lost during the drying procedure of water content determination was much reduced.

Thinking in terms of water-stabilizer reaction versus increases in measured optimum water content with stabilizer addition, it is interesting to re-examine Figure 1. The slope of a line drawn between the points 0 percent lime, 18 percent water content and 2 percent lime, 19.5 percent water content is the same as that drawn between the points 4 percent lime, 20 percent water content and 8 percent lime, 23 percent water content. Using the reasoning applied to the case of the water content of portland cement-soil mixtures, this implies that between two percent and four percent lime, the molding water reacts with the stabilizing agent or some secondary product of soil-lime reaction to form hydrated compounds. As shown later, all gains in strength in the cured, compacted mixtures with additions of lime occur between lime contents of two percent and four percent.

Strength of portland cement-soil mixtures

The relationship between unconfined compressive strength and portland cement content is shown in Figure 4. The curve can be approximately divided into two parts, one with portland cement content less than one percent and another with portland cement content greater than one percent. The first part is almost horizontal, with strength gain approximately zero and unconfined compressive strength nearly constant. The second part has a steep slope with the unconfined compressive strength of the soil roughly proportional to the percentage of portland cement added. The strength gain is approximately 3,500 psf. for each percent of additional portland cement.

In compacted cement-treated soil the hydration of the different cement constituents occurs at different rates, providing cementitious amorphous and minutely crystalline hydration products responsible for characteristic early and long-term strength gains. The cementation is mainly chemical in nature and may be visualized as due to the development of chemical bonds or linkages among adjacent cement grain surfaces and among grain surfaces and exposed soil particle surfaces. These phenomena suggest that the unconfined compressive strength of soil treated with portland cement will increase as the percentage of portland cement added to soil increases.

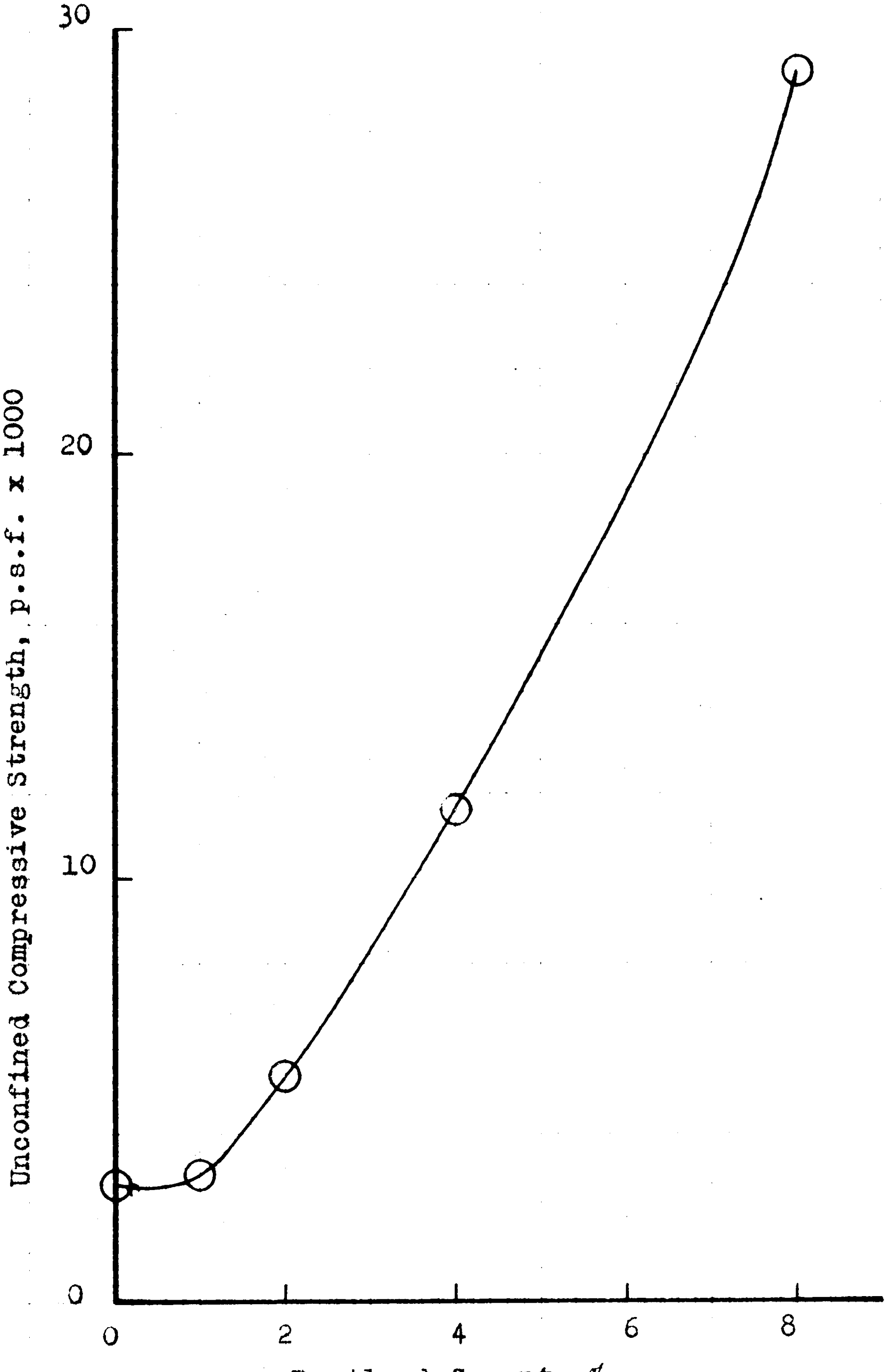

Figure 4. The unconfined compressive strength of compacted mixtures of mica soil and portland cement.

The results show that it is indeed possible to harden mica soil with small percentages of a cementitious material. Apparently, any cement introduced to the soil in quantities of greater than one percent will have observable effects on strength. This is important in terms of the quantity of lime-soil induced cement that must be generated, if any is generated at all, to increase strength.

<u>Strength of agricultural lime-soil mixtures</u>

The unconfined compressive strength of soil treated with agricultural lime (in this case 43.5 percent $CaCO_3$ and 56.5 percent $Ca(OH)_2$) is shown in Figure 5. When more than two percent of the lime is mixed with the soil, the unconfined compressive strength is increased. Strength gain with lime addition reaches a maximum at a lime content of four percent, and slightly decreases at higher percentages.

Possible mechanisms for the stabilization of soil with lime have been mentioned. It is suspected that flocculation or aggregation of soil particles occurs so as to make the soil more like a granular material. Such a reaction would be relatively fast, occur with very low percentages of lime, and have little significant effect on soils containing small percentages of clay, such as the soil in this study. Another reaction is the carbonation of hydroxide to form calcium carbonate as a weak cement. That at least some of the hydroxide does carbonate is very probable. However, one would

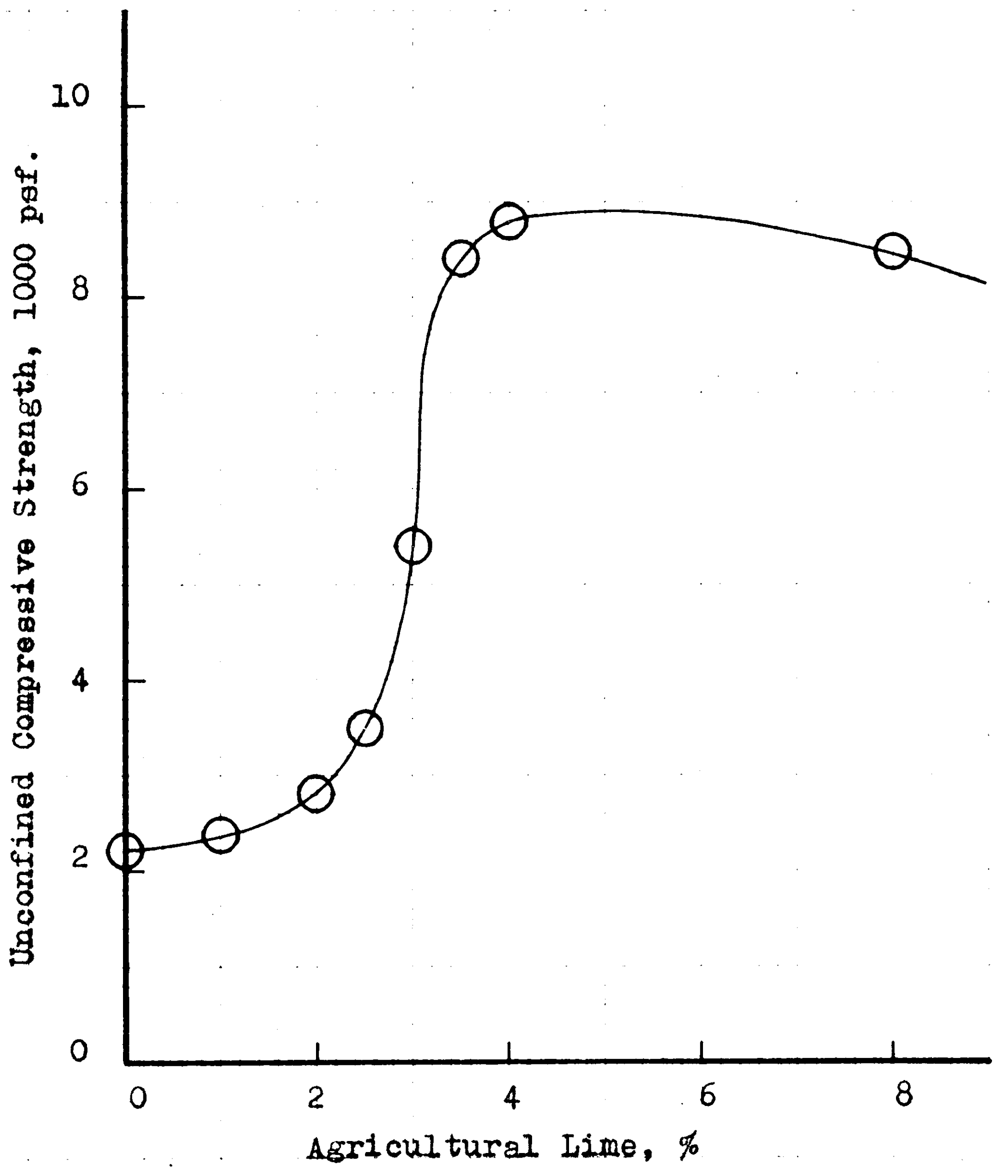

Figure 5. The unconfined compressive strength of compacted mixtures of mica soil and agricultural lime.

expect most of such carbonation to occur during the mixing stages of sample preparation rather than after compaction, since a free source of carbon dioxide is required. If this is the case, significant strength gains from such carbonation are difficult to visualize.

There is strong evidence that the formation of calcium silicate hydrates is the major source of the strength gain shown by the stabilized mica soil in this study. Firstly, the early portion of the strength-percent lime curve is much like the strength-percent portland cement curve, which indicates the same general type of cementing action. Perhaps it is significant that strength gain begins beyond a threshold value of one percent additive in the case of portland cement and a threshold value of two percent additive in the case of the agricultural lime, which is roughly one-half hydroxide. Secondly, Figure 1 indicates that the reaction which occurs is one involving the chemisorption of water, whereby hydrates are formed, analogous to the action of portland cement. It is probable that the reactions discussed by Eades and Grim (10 and 11) apply.

X-ray diffraction data, given in Figure 6, indicates the presence of calcium carbonate in the stabilized soil, but no calcium silicates hydrates were found and calcium hydroxide is conspicuous by its absence. However, small amounts of poorly crystalline material in a matrix of

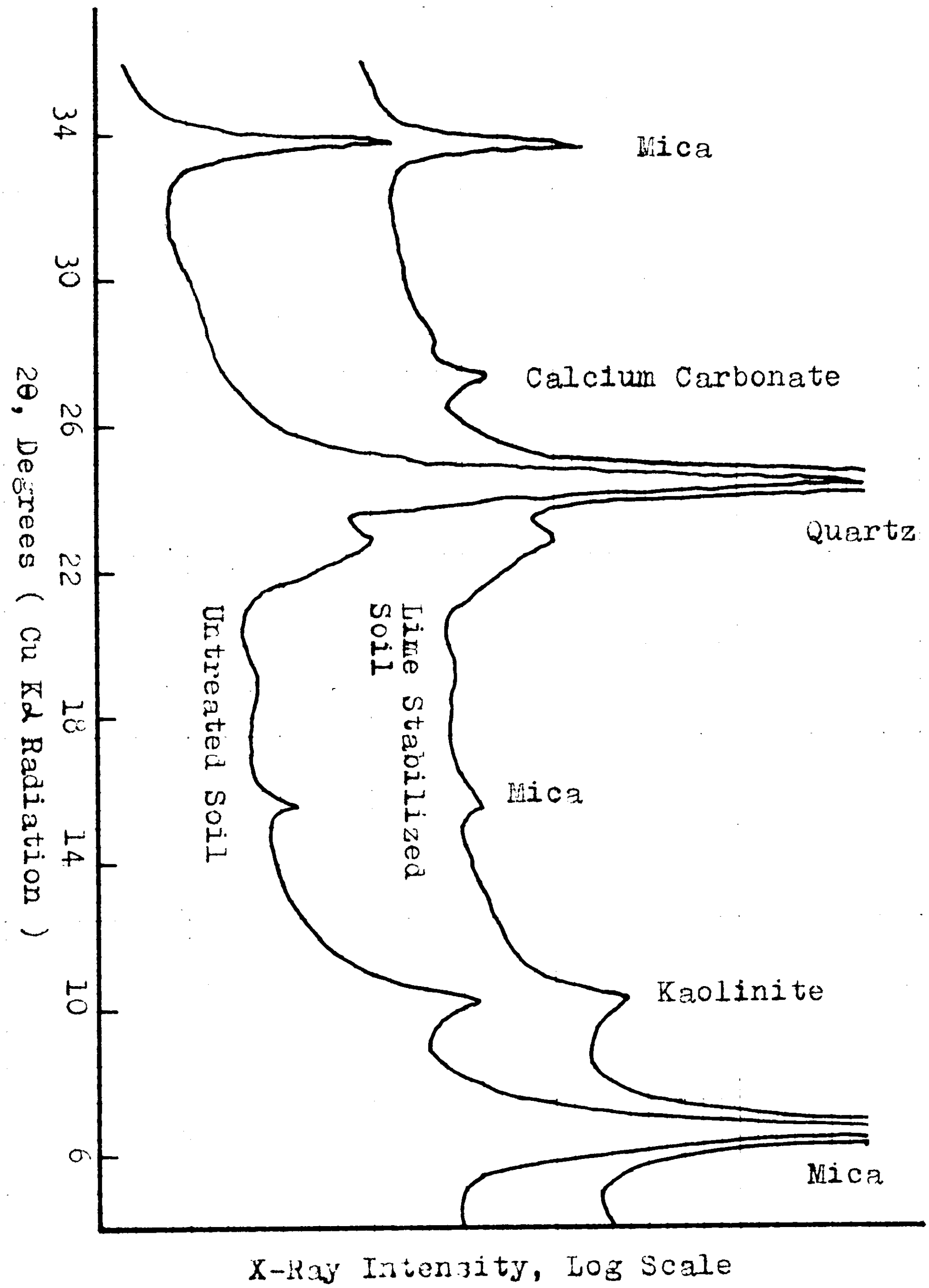

Figure 6. Smoothed x-ray diffraction tracings obtained for samples of mica soil compacted with and without four percent agricultural lime, cured, dried, and oriented on a glass slide with the aid of water.

well-formed mica and small particles of kaolinite would be exceedingly difficult to detect by the procedures used. D. T. A. data, given in Figure 7, are similar to those obtained by x-ray diffraction. The presence of calcium carbonate in the stabilized soil is clear, but there is no indication of the presence of hydroxide. Note that lime additions increased the size of the endotherm at 600° C., but had little influence on the 525° C. endotherm (kaolinite).

Thermogravimetric data, Figure 8, indicate the presence of both calcium hydroxide and calcium carbonate in soil stabilized with four percent lime, but do not positively show the presence of hydrates. Comparing the thermograms of untreated and lime-stabilized soil, it can be seen that the lime-stabilized soil lost about 1.2 percent more of its weight than the untreated soil. This differential occurred in two stages: 0.3 percent at about 400° C., suggesting a calcium hydroxide content of 1.2 percent, and 0.9 percent at about 700° C., suggesting a calcium carbonate content of 2.0 percent. Had the additive remained inert, the sample would show approximately 1.7 percent calcium carbonate and 2.3 percent calcium hydroxide. Accordingly, there occurred a slight gain in carbonate, 0.3 percent, which would account for a 0.2 percent loss in hydroxide, and a loss in hydroxide of about 1.1 percent, virtually none of which can be accounted for. Eades and Grim (10) also had difficulty

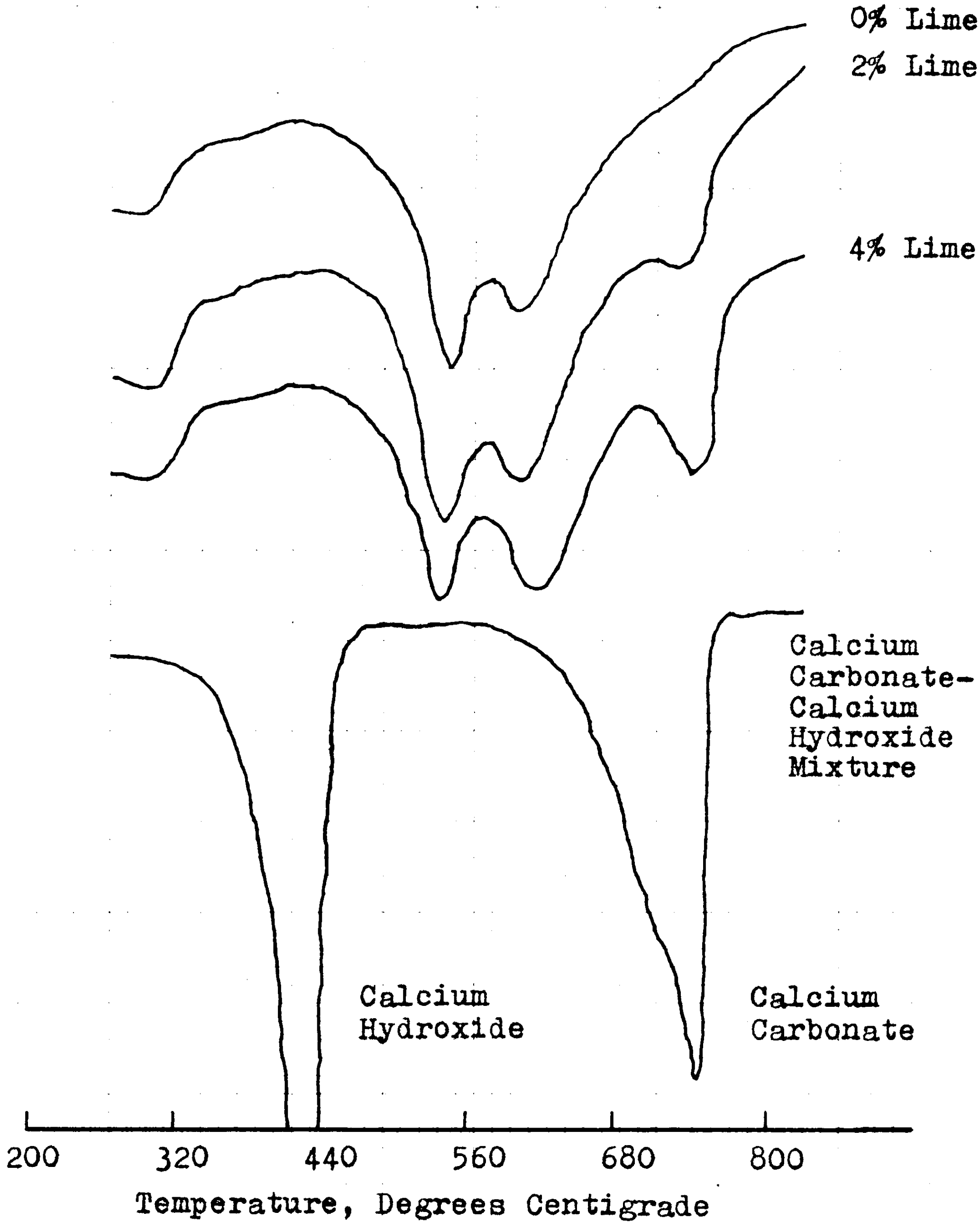

Figure 7. Differential thermal analysis tracings of mica soil compacted with and without stabilizing agent, cured, dried, and ground to a powder specimen. The $CaCO_3$-$Ca(OH)_2$ mixture tracing is for stabilizer alone.

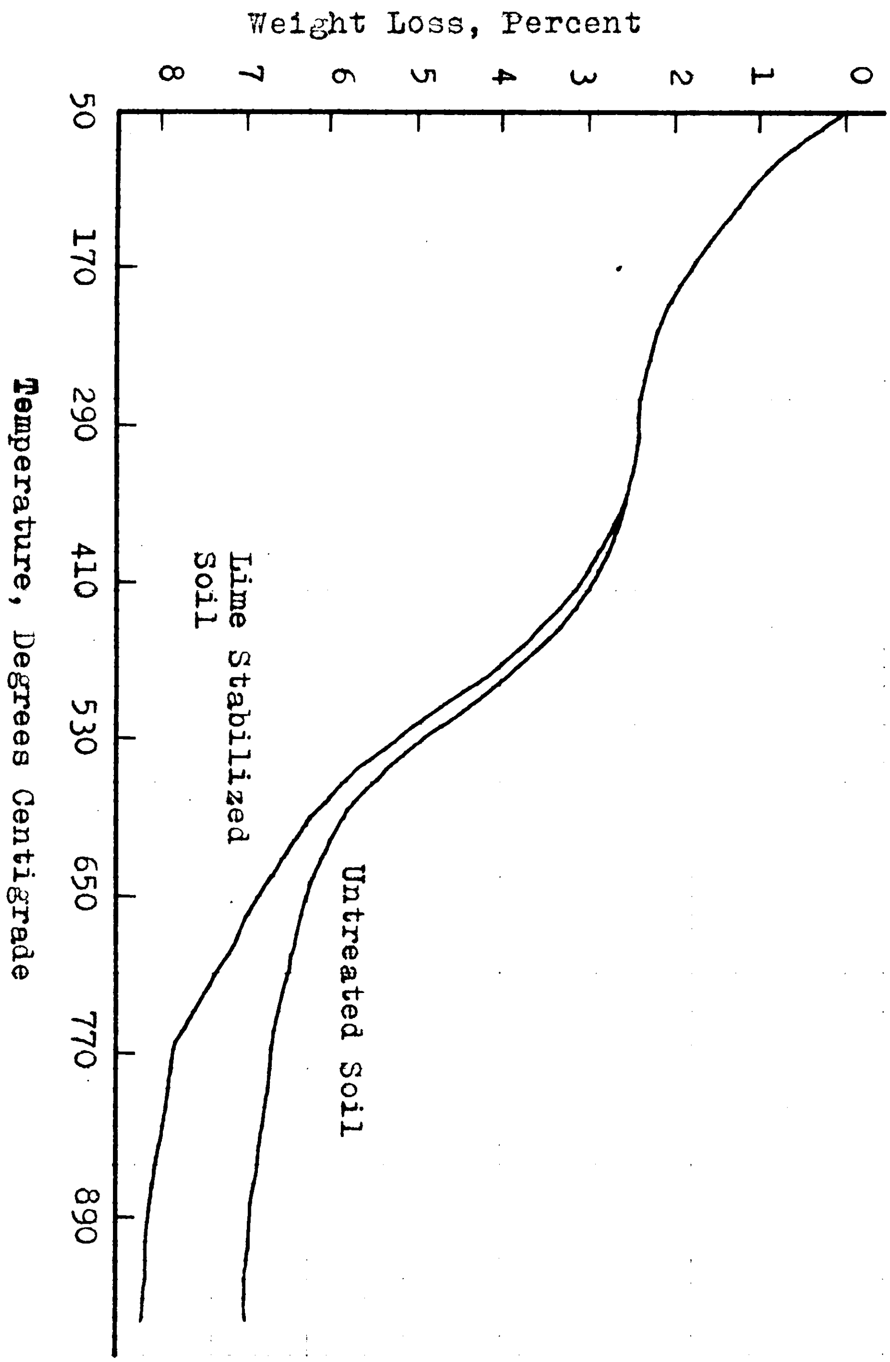

Figure 8. Thermogravimetric tracing of mica soil compacted with and without four percent lime, cured, dried, and ground to a powder specimen.

accounting for the apparent absence of calcium hydroxide in lime stabilized soils employed in their study. However, they concluded from indirect evidence that it was present even though not indicated by x-ray diffraction and differential thermal analyses. Their differential thermal analyses showed an endothermic peak at between 300 and 400° C., which they attributed to hydrated calcium silicate. Hence, it is possible that the 0.3 percent weight loss differential between 300 and 500° C. shown in Figure 8 is due to hydrated calcium silicate rather than calcium hydroxide.

It was suggested earlier during discussion on moisture-density characteristics that an appreciable amount of the molding water, as suggested by Figure 1, may be lost by hydrate formation during compaction and prior to curing. Although the thermograms were obtained for cured soil, which cannot be validly compared to uncured material, the weight loss data present a strong argument against the chemisorption of this large quantity of water; it simply does not appear during the burning of the samples. That it might in some way have been lost during the curing process is a remote possibility, but the data of Eades and Grim (10) suggest that, to the contrary, hydrate formation occurs during rather than prior to the curing process. Certainly something is happening to the hydroxide early in the stabilization procedure. If this were not so, more than a small percent would appear as carbonate after the extended period of sample preparation for thermogravimetric analysis. Also, one is faced with the fact that substantial gains in strength occurred.

Strength of soil stabilized with lime, carbonate mixtures

Given in Table 1 and Figure 9 are results obtained with the unconfined compression test on samples of mica soil stabilized with various percentages of mixtures of reagent grade calcium hydroxide and calcium carbonate. Note that when as much as four percent additive is mixed with the soil, the percent lime in the additive has a far greater influence on soil strength than the percent additive used. Accordingly, one must conclude that the presence of calcium carbonate in some way affects the stabilization of the mica soil. Still, this is contrary to the concept that calcium carbonate is a totally ineffectual stabilizing agent or is simply inert during stabilization.

There are two basic ideas that might be advanced to explain the action of calcium carbonate in the stabilization of the mica soil; 1) the carbonate acts as a cement and 2) the carbonate does not act as a cement, but has an influence on mixing and compaction efficiency. That the carbonate acts as a cement does not seem probable in view of the fact that the unconfined compressive strength of soil stabilized with carbonate alone is low regardless of the quantity of

Table 1 - Unconfined Compressive Strength (psf.) of Stabilized Mica Soil Treated with Calcium Hydroxide-Calcium Carbonate Mixtures

% Mix In Soil	% $Ca(OH)_2$ in Lime 100	75	50	25	0
2	6,500	4,200	2,600	2,600	3,300
4	13,600	18,500	8,600	3,000	3,200
6	14,550	18,575	17,050	4,500	3,450
8	13,800	18,200	15,000	8,300	3,400

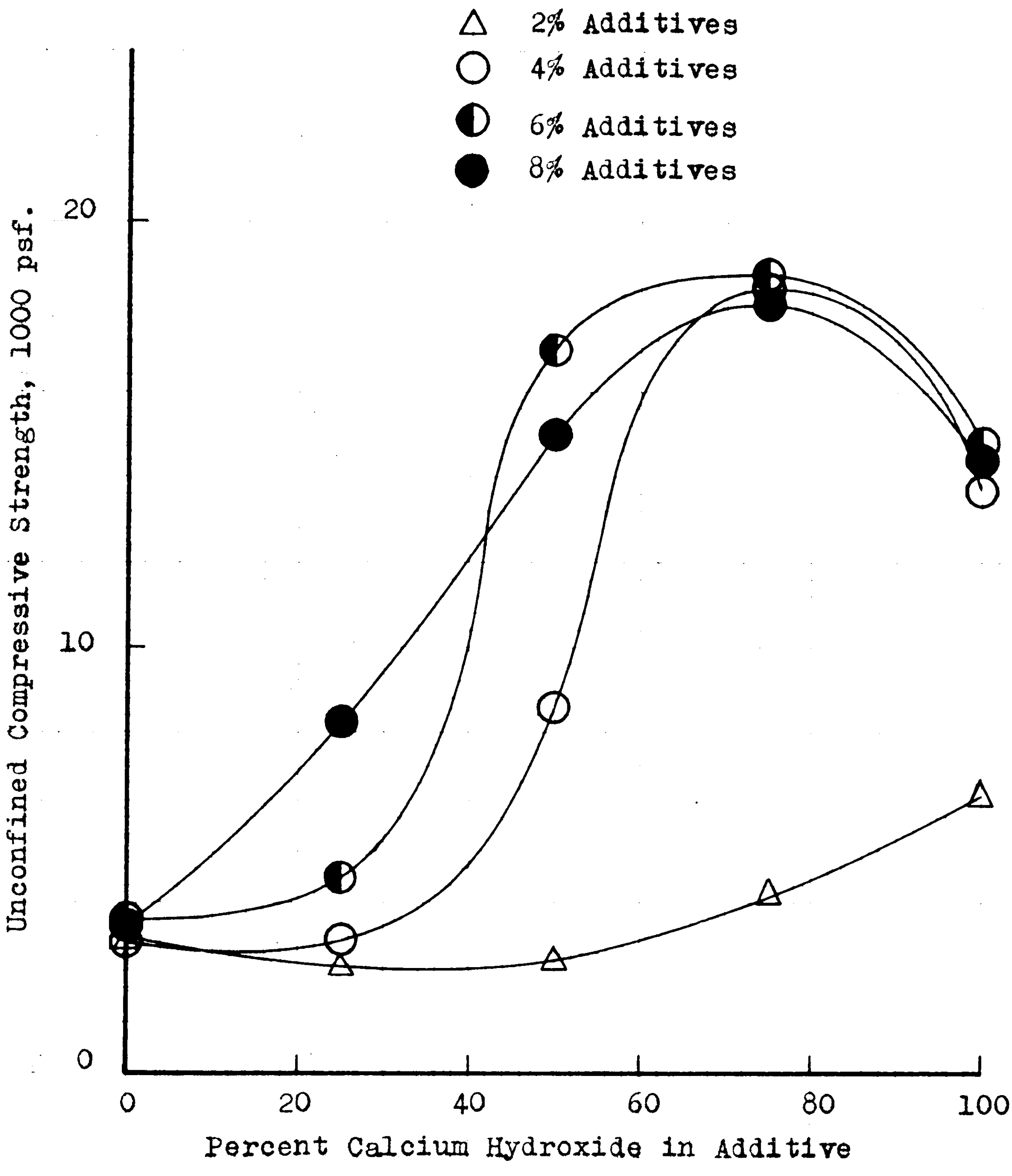

Figure 9. Unconfined compressive strength of stabilized mica soil treated with $Ca(OH)_2$-$CaCO_3$ mixtures.

carbonate employed. Simply adding carbonate by itself appears to do nothing toward increasing soil strength, either by way of cementation or increasing compaction efficiency. This makes paradoxical the fact that small amounts of carbonate increase strength when used with calcium hydroxide. It is unlikely that there is any carbonate-hydroxide reaction product or catalytic action on the part of the carbonate. The effect must be explained in physical terms; carbonate apparently enhances intimate mixing of the lime with the soil.

Figure 10 shows the relationship between stress and strain of soils treated with six percent of admixtures containing different percentages of calcium hydroxide. For the convenience of comparing the stiffness of each soil, all the curves are plotted in the same scale. The stiffest treated soil is the one with 6 percent of additives containing 75 percent of calcium hydroxide which is equal to 4.5 percent of pure calcium hydroxide in the treated soil. If a vertical line was drawn, it would reveal that in order to produce the same strain, it needs the highest stress for the soil containing 4.5 percent of pure calcium hydroxide; the soil containing zero percent of pure lime needs the lowest stress. The ratio of the stiffness of these two soils is roughly 10 to 1. The stiffer the soil is, the higher the unconfined compressive strength of the soil.

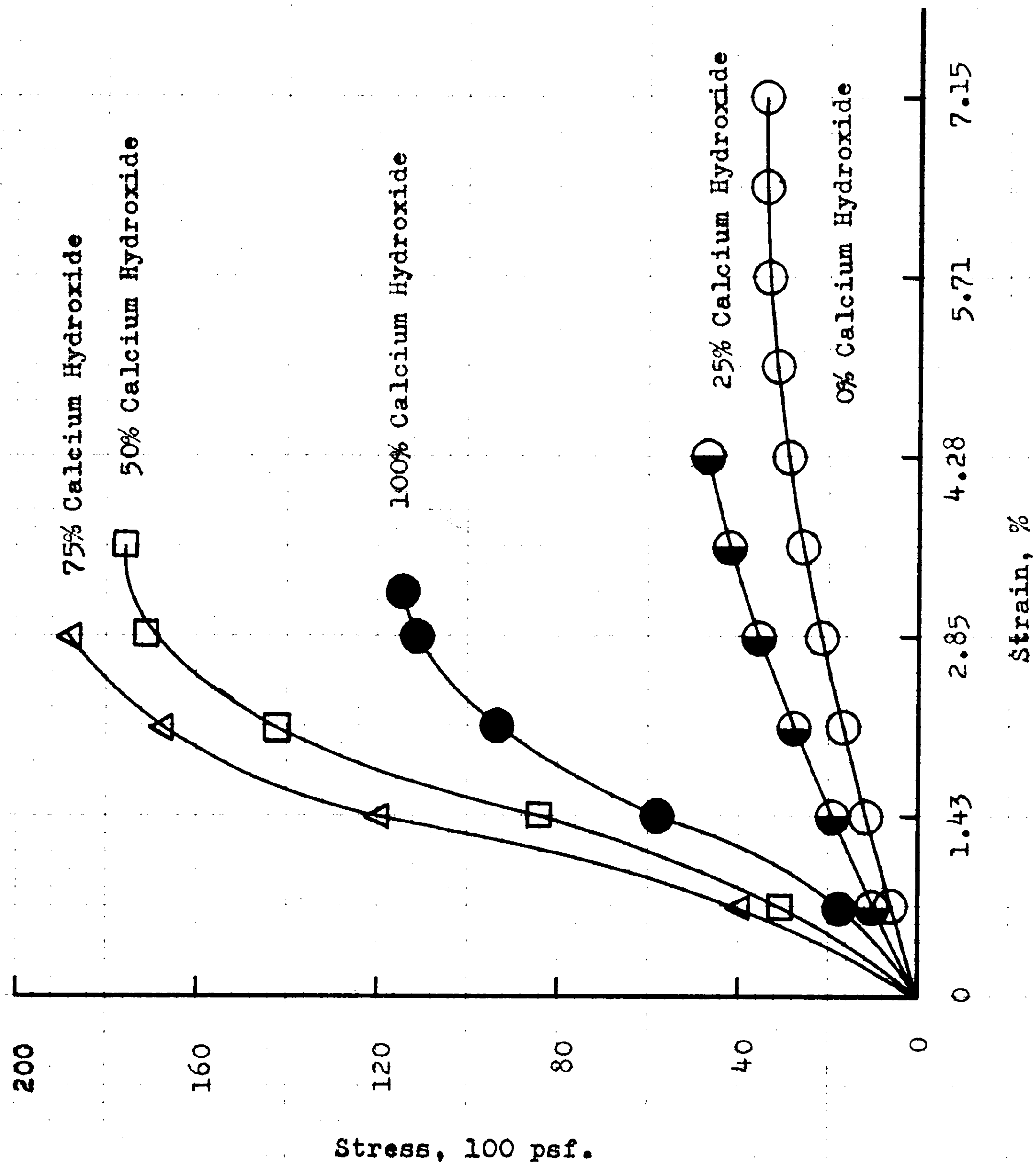

Figure 10. Stress-strain curves for stabilized mica soil treated with 6% $Ca(OH)_2$ -$CaCO_3$ mixtures.

According to the mechanisms of stabilization of the soil mentioned before, part of the calcium hydroxide might cause the flocculation or aggregation of soil particles, and another part produces calcium silicate hydrates that act as cementing materials. The calcium carbonate might act as fines to improve the gradation of the treated soil and to facilitate intimate mixing. Then the produced cementing materials bind the coarse and fine soil particles together to produce stiff treated soil. These three elements may be referred to as the main factors contributing to the stiffness of the treated soil. A soil treated with less than 75 percent of calcium hydroxide contained in the additives might not be able to produce sufficient calcium silicate hydrates, while the soil treated with more than 75 percent of calcium hydroxide contained in the additives might gain too many fine soil particles. Both of these two cases would reduce the stiffness of the treated soil.

In Figure 11, secant modulus of elasticity was plotted against the percentage of pure lime mixing in the additives. The secant modulus of elasticity increases rapidly after the lime content in additives is more than 25 percent and reaches its peak at 75 percent then decreases. It still suggests that four percent of lime is the optimum quantity to be added to the soil to obtain the highest strength.

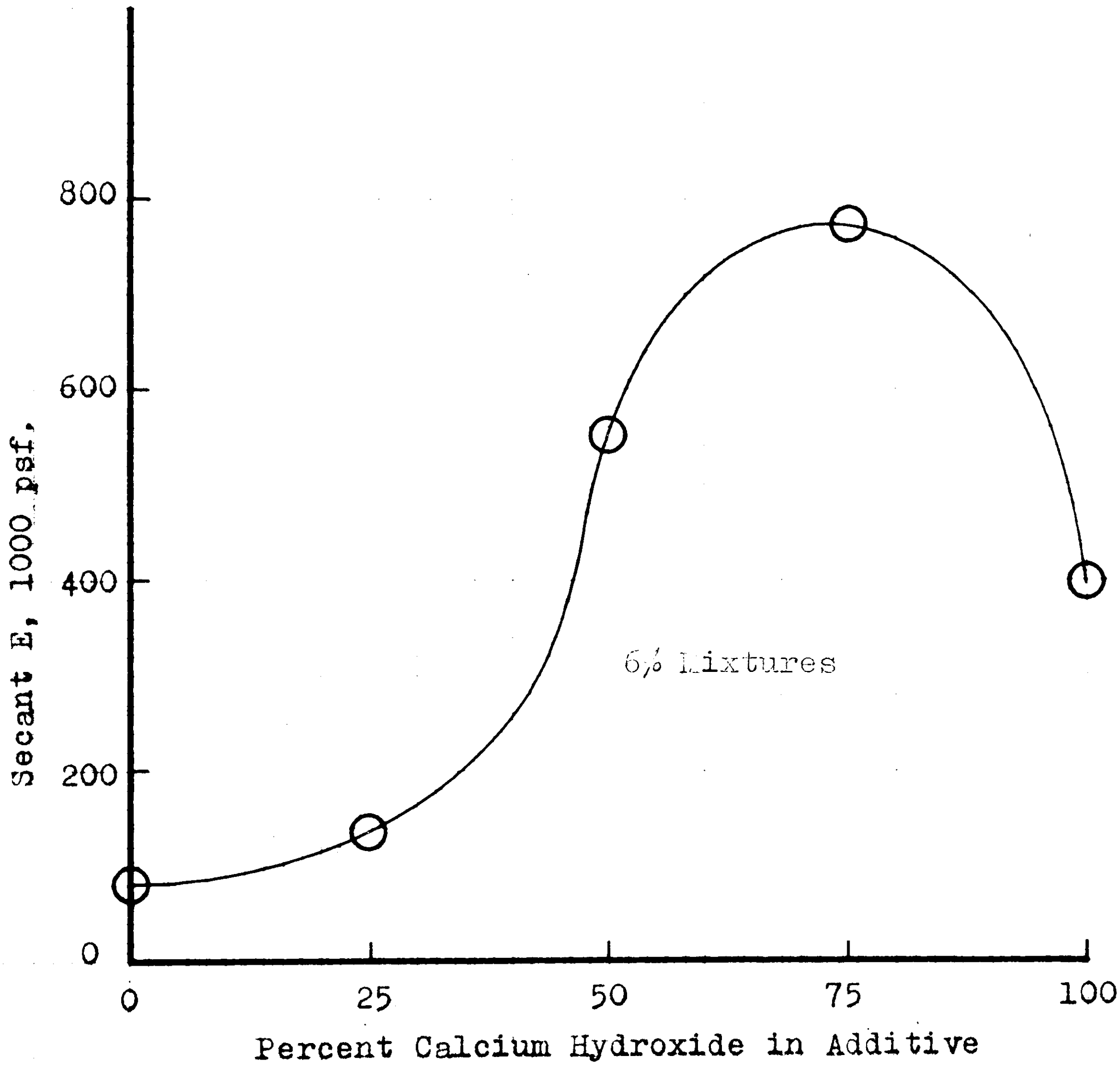

Figure 11. Secant modulus of elasticity (accumulative stress-accumulative strain ratio at one-half peak strength) for stabilized mica soil treated with $Ca(OH)_2$-$CaCO_3$ mixtures.

VI. CONCLUSIONS

From the results presented in this study, it is seen that all such additives used in this study as lime, portland cement, and calcium hydroxide-calcium carbonate admixtures have distinct effects on unconfined compressive strength of mica soil. Further, some important conclusions may be summarized from this laboratory study.

1. The optimum quantity of agricultural lime to be added to the mica soil for stabilization is four percent based on dry weight of soil. The highest strength was obtained when the soil was treated with four percent lime, and there is no observable increase in the strength of the soil if the content of stabilizer is higher than this quantity. The strength of soil treated with less than four percent lime is much lower than that of soil containing four percent stabilizer.

2. The unconfined compressive strength of soil stabilized with calcium hydroxide-calcium carbonate admixtures, as found in this study, is generally higher than that of soil treated with pure lime. The best ratio of the quantity of calcium hydroxide to calcium carbonate, based on weight, is 3 to 1. The optimum quantity of stabilizer to be added to the soil for development of strength is six percent based on dry weight of soil.

3. The effect of portland cement on strength of soil is different from that of lime and calcium hydroxide-calcium carbonate admixtures on the same soil. The strength of stabilized mica soil continues to increase with increasing amounts of portland cement, at least within the additive percentage range used in this study.

4. Comparing the strength of mica soil treated with the same quantity of different calcium stabilizers, the best quantity and additive is six percent of calcium hydroxide-calcium carbonate admixtures containing 75 percent of calcium hydroxide and 25 percent of calcium carbonate.

VII. REFERENCES

1. Anday, M. C., 1961, "Accelerated Curing for Lime Stabilized Soil." HRB Bulletin 304, p. 1 - 13.
2. Bhat, H. S., 1963, "Strength of Compacted Mica-Quartz Sand Mixtures." Master of Science Thesis, V.P.I.
3. Broberg, R. F., 1962, "Lime, Cement, and Lime-Cement Stabilization of a Clay Soil." Master of Science Thesis, V.P.I.
4. Davidson, D. T., 1960, "Soil Stabilization with Lime." Highway Engineering Handbook, Section 21, Part 4, K. B. Woods, Editor, McGraw-Hill Book Company, Inc. New York.
5. Davidson, D. T., and Pietsch, P. E., 1962, "Effect of Lime on Plasticity and Compressive Strength of Representative Iowa Soils." HRB Bulletin 335, p. 11-30.
6. Davidson, D. T., and Laguros, J. G., et al., 1956, "Evaluation of Lime for Stabilization of Loess." Proc. ASTM, 56:1301.
7. Davidson, D. T., 1961, "Soil Stabilization with Portland Cement." HRB Bulletin 292, p. 1-71.
8. Gallaway, B. M., and Buchanan, S. J., 1951, "Lime Stabilization of Clay Soil." Bulletin of the Agricultural and Mechanical College of Texas, No. 124.
9. Grim, R. E., 1962, Applied Clay Mineralogy. McGraw-Hill Book Company, Inc., New York.

10. Grim, R. E., Eades, J. L., and F. P. Nichols, Jr., 1962, "Formation of new minerals with lime stabilization as proven by field." HRB Bulletin 335, p. 31-39.

11. Grim, R. E., and Eades, J. L., 1960, "Reaction of hydrated lime with pure clay minerals in soil stabilization." HRB Bulletin 262, p. 51-63.

12. Krynine, D. P., and Judd, W. R., 1957, Principles of Engineering Geology and Geotechnics. McGraw-Hill Book Company, Inc., N. Y.

13. Lambe, T. W., 1962, "Soil stabilization." Foundation Engineering. Chapter 4, G. A. Leonards, Editor, McGraw-Hill Book Company, Inc., N. Y.

14. Lambe, T. W., Moh, Z. C., and Ladd, C. C., 1960, "Recent soil-lime research at M.I.T.." HRB Bulletin 262, p. 64-85.

15. Lambe, T. W., 1958, "The structure of compacted clay." Proc. ASCE, Journ. Soil Mechanics and Found. Div., Paper 1654, Vol. 84, No. SM2.

16. Lambe, T. W., 1951, Soil Testing for Engineers. John Wiley and Sons, Inc., New York.

17. Lund, O. L., and Ramsey, W. J., 1959, "Experimental lime stabilization in Nebraska." HRB Bulletin 231, p. 24-59.

18. McDowell, C., and Moore, W. H., 1948, "Improvement of highway subgrade and flexible bases by the use of hydrated lime." Proc. Second International Conf. on Soil Mechanics and Foundation Engineering, 5:260.

19. McDowell, C., 1959, "Stabilization of soils with lime, lime-flyash, and other lime reactive materials." HRB Bulletin 231, p. 60-66.

20. Moreland, H., and Henry, M., 1961, "Lime-soil mixtures." HRB Bulletin 304, p. 99-138.

21. National Lime Association, 1954, "Lime Stabilization of Roads." National Lime Association, Bulletin 323.

22. Smith, D. W., 1961, "Secondary Compression as Affected by Micaceous Constituents." Master of Science Thesis, V.P.I.

23. Sowers, G. F., 1954, "Soil problems in the Southern Piedmont Region." Proc. ASCE Journ. Soil Mechanics and Found. Div., Paper 416.

24. Sowers, G. B., and Sowers, G. F., 1961, <u>Introductory Soil Mechanics and Foundations</u>. The Macmillan Company, New York.

25. Tate, B. D., and Larew, H. G., 1963, "The effect of structure on rebound characteristic of soils in the Piedmont Province of Virginia." Paper presented at the 42nd Annual Meeting of the Highway Research Board, Washington, D. C.

VIII. ACKNOWLEDGMENTS

The author would like to express his deep appreciation and indebtedness to Dr. R. D. Krebs, his course and thesis advisor, for the invaluable guidance and assistance he gave during the laboratory testing and the completion of this thesis. Without his help, the differential thermal analysis, x-ray diffraction analysis and discussion in Section V would not have been possible.

The author wishes to extend his gratitude to Dr. H. M. Morris, Prof. W. W. Payne, Dr. W. A. Parsons, Dr. R. D. Walker and Prof. J. H. Hunter for their guidance and encouragement in the course of his study.

Sincere gratitude is due to the author's father and brothers for their encouragement during the period of his study.

In addition, the author would like to express gratitude to   for typing this thesis.

The vita has been removed from the scanned document

ABSTRACT

Research was conducted to study the unconfined compressive strength of a mica soil stabilized with various percentages of lime, portland cement, and combinations of calcium hydroxide and calcium carbonate. In order to trace the calcium carbonate and calcium hydroxide in the stabilized soil, x-ray diffraction analyses, differential thermal analysis, and thermagravimetric analyses were made. Results show the appearance of calcium carbonate and absence of calcium hydroxide.

It was found that all the stabilizers used in this study have an effect on both maximum dry unit weight and optimum moisture content. A significant increment in unconfined compressive strength does not occur until the amount of added stabilizer is more than one percent for portland cement and two percent for agricultural lime. When combined additives of calcium hydroxide and calcium carbonate were used, there was no strength gain until the content of calcium hydroxide in combined additives was more than 25 percent.

When more than one percent of portland cement is added to the mica soil used in this study, there is an approximate linear relationship between the soil strength and the percentage of added stabilizer, which exists within the percentage range used in this study. With agricultural lime, peak

strength was obtained with four percent of stabilizer. The unconfined compressive strength of the soil treated with combined calcium hydroxide-calcium carbonate additives was generally higher than that of soil treated with pure lime. The optimum quantity of combined calcium hydroxide-calcium carbonate additives for strength is six percent, in which the best calcium hydroxide-calcium carbonate ratio is 3 to 1. A possible explanation for this result is that the presence of calcium carbonate enhances intimate mixing of soil with hydroxide and improves the gradation of the soil.