STATIC AND IMPACT COMPACTION
OF A LATERITIC SOIL

By

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CHAPTER I

INTRODUCTION

Laterite is a residual soil found in tropical terrains which have pronounced wet and dry seasons. The soil is formed by the weathering of basalt, granite, gneiss, breccia and conglomerates (1). Generally, in situ laterite and lateritic soils possess a granular structure due to the complete removal of the silica, alkali, and alkaline earths, and the concentration in the hydrated form of iron and aluminum oxides (sesquioxides).

The granular structure of lateritic soils is largely responsible for the desirable engineering properties that these soils display in the unremolded state. However, previous work (2, 3, 4) indicates that the desirable engineering properties, such as the high bearing capacity, low plasticity, and high permeability are lost or reduced upon remolding or "working" of the soil. The term, "working," refers to mixing, compaction, or any extensive manipulation of the soil by mechanical means; predominantly in the presence of moisture. Townsend (2) recommended the development of modifications to the standard testing procedures that would reduce or minimize the remolding of the soil. With regard to compaction procedures, he suggested that static compaction rather than the standard impact compaction might be more advantageous when dealing with lateritic soil.

Problem

Due to the alteration of the engineering properties of lateritic soils upon remolding, Fruhauf (3), Townsend (2), and Winterkorn (4) suggested that standard compaction methods be modified or changed so as to minimize the remolding action. Such modified compaction procedures should, however, yield densities comparable to those obtained by the impact method of compaction, i.e., Standard Proctor Compaction. Knowledge in this area could possibly be of some assistance to engineers working with this particular type of soil.

Scope of Investigation

A static compaction procedure and equipment, utilizing a hydraulic testing machine and a Harvard Miniature mold, were developed. Standard Proctor tests were made on the raw and lime stabilized, worked and unworked lateritic soil. Static pressure-density tests were also made on the same mixtures. Lime was used in proportions of 2 1/2, 5, 10 and 20 percent by weight of the dry soil.

Specimens were compacted using both static and impact methods of compaction, and the unconfined compressive strengths of these specimens were determined. The raw specimens were tested immediately. The stabilized specimens were cured for various periods of time before being tested for their unconfined compressive strengths. Curing periods of 7, 28, and 60 days were used for these lime stabilized specimens.

CHAPTER II

REVIEW OF LITERATURE

Lateritic Soils

In 1807, Buchanan (5), an observant Scotsman, was in India. He was impressed by the sight of Hindu laborers excavating the redbrown tropical clay, shaping it into bricks, and using them for building material after hardening in the sun. Because this tropical clay could be used so readily as a construction material, he called it laterite from the Latin work "latere," or brick.

Laterite soils are usually found in tropical areas such as India, Indonesia, Indo-China, Malaya, Burma, Western Australia, Madgascar, Central Africa, the Guianas, Brazil, Panama, and Cuba.

Laterite is a soil in which most of the silica, alkali, and alkaline earths have been leached out, and in which hydrated iron and aluminum oxides have been formed. The formation of laterites involves the factors of climate, elevation, rainfall, ground water fluctuation, parent rock, and age.

Laterite Profile

Nixon and Scipp (6) reported that a typical laterite profile has the following upward sequence of strata:

1) parent rock

2) a zone of decomposed parent rock boulders and clay

3) a reddish or yellowish clayey layer (kaolinite, montmorillonites and micaceous clays)

4) a gray zone rich in sesquioxides with small iron nodules or concretions in the upper layers

5) an indurated crust.

According to Mohr (7), the formation of this type of profile is dependent upon the following factors:

Climate - It is essential that the climate be quite humid. The soil must be moist for the leaching of the silica and alkaline earths, and there must be alternating wet and dry seasons for the hardening of the sesquioxides.

Rainfall - Frequent rainfall and good drainage are necessary conditions for leaching of the silica to take place. Silica is soluble in meteoric water that is slightly alkaline or neutral. Such waters are typical of tropical climates.

Ground Water Fluctuations - Chemical weathering takes place during the wet season as the gound water level rises. At this time, the parent rock is attacked and new minerals are formed. As the soil becomes saturated, seepage occurs, thus removing or leaching the minerals that have dissolved.

The weathering cycle is reversed during the dry season. The soil solutions advance to the upper layers, by capillary action, where they aerate and thus allowing the soil minerals to oxidize freely. This oxidation is responsible for the hardening process which forms the concretions and the indurated crust typical of many lateritic soils.

The gray layer generally found in laterite profiles is an indication of the extent of ground water fluctuations during the wet and dry seasons. The top of this layer indicates the height to which the water table rises. The ground water is responsible for carrying the iron and alumina-oxides to the upper horizons.

Parent Rock - The iron richness of the parent rock is related to the thickness of the laterite profile. Poor acid rocks usually produce thin layers, whereas basic rocks, such as basalt, usually produce thick layers. The sesquioxides content is relative to the type of rock. If the rock is highly ferrous, a larger iron and aluminum content would be observed. The brick red color associated with laterites is produced by basic rocks. Laterites have been known to occur over basalt, granite, gneiss, volcanic breccia, tuff and conglomerates (1).

Age - Age is an important factor that governs the characteristics of laterite formations. Well developed laterites are old formations in which the soil has gone through the leaching of the silicates and the concentration in the hydrated form of sesquioxides.

Because of the wide variations of the forementioned factors throughout the world, laterite occurs in a variety of forms from a friable soil to almost hard rock. This variation has created much controversy concerning the nomenclature of laterite and lateritic soils. Bawa (1) reported that there has been no general agreement to date regarding nomenclature and definitions for the terms relating to laterite and lateritic soils. A classification criterion was suggested by Martin and Doyne (8) in which the ratio of the silica to alumina content of the material was the basis for classification. This classification is presented in Table I.

TABLE I

SOIL CLASSIFICATION BASED ON THE
SILICA-ALUMINA RATIO

Soil Type	SiO_2/Al_2O_3
Laterite Soil	1.33 or less
Lateritic Soil	1.33-2.00
Non-Lateritic Soil	2.00 and over

However, since the presence of iron in laterite soils is an important factor that influences their engineering properties, a more appropriate classification based on the silica-sesquioxides (Fe_2O_3 + Al_2O_3) ratio has been suggested (4) and is presented in Table II.

TABLE II

SOIL CLASSIFICATION BASED ON THE
SILICA-SESQUIOXIDES RATIO

Soil Type	SiO_2/R_2O_3
Laterite Soil	1.33 or less
Lateritic Soil	1.33-2.00
Non-Lateritic Soil	2.00 and over

Physical Properties

Due to their existence in a variety of forms the properties of laterites vary from locality to locality, depending primarily on their age. For example, the characteristics of the hard indurated crust differ considerably from that of the friable soil. The following is a discussion of some of the properties associated with lateritic soils.

Specific Gravity - The specific gravity of laterites generally ranges from 2.70 to 3.50 (1). Zipkes (9) reported that the iron crusts of India exhibit a specific gravity slightly higher than 3.0, while those of lateritic soils are below 3.0. The higher specific gravities exhibited by the hard crusts are a result of the high iron content.

Atterberg Limits - The Atterberg limits of lateritic soils vary with the degree of remolding or working of the sample as reported by Newill (10). A deviation of ± 15% in the liquid limit, depending upon treatment, was noticed on soil samples taken from the Sasamua Dam area in Kenya (1). Winterkorn and Chandrasekharan (4) also observed a change in liquid limit from 46% to 53% depending upon the amount of remolding; however, there was no observed change in the plastic limit.

Lateritic soils generally exhibit values in the following range:

TABLE III

ATTERBERG LIMITS OF LATERITIC SOILS

Type & Location	LL	PL	PI	Source
Porous Red Clay - Brazil	53	10	43	Vargas (12)
Dark Red Laterite Soil - Cuba	53	31	22	Winterkorn (4)
Hydrated Lithomarge - Kenya	87	54	33	Terzaghi (11)
Lateritic Soil - Mocambique	69	31	38	Nascimento (13)
Lateritic Soil - India	51.5	16.5	35	Ramachandran (14)

<u>Grain Size</u> - The grain size of laterite and lateritic soils vary from gravel to clay depending upon the degree of laterization. The older deposits are usually composed of larger aggregates, while the younger lateritic soils possess larger percentages of clay.

<u>Permeability</u> - Generally, unremolded laterites exhibit a granular structure which accounts for excellent drainage and porosity. The permeability generally runs from 10^{-2} to 10^{-1} cm/sec depending upon the amount of aggregation (1). Remolding or working the soil will alter the granular structure and cause the soil to become plastic and thus lower the permeability.

<u>Swelling</u> - Swelling tendencies in lateritic soils are minor compared with clay soils of comparable Atterberg limits. Zipkes (9) reported that tests on lateritic cubes revealed swelling was limited to only a few hundredths of one percent.

Compaction

History

Early records of intentional compaction date back to the great road construction eras of the Babylonian, Pharaonic, and Roman Empires. Cylindrical shaped stone rollers, drawn by slaves, were used to compact earth embankments. Many of these roads are still in existence. Herds of sheep, cattle, and goats were also used as a mean to achieve compaction.

Although soil compaction has been utilized since ancient times, the fundamental principles of soil compaction, i.e., moisture content, unit weight, and compactive effort relationships, were not understood until the early 20th Century. During the construction of the Silvan Dam in Australia in the 1930's, Kelso (15) performed experiments that yielded data on soil moisture content - unit weight relationships. However, this idea didn't receive wide attention until R. R. Proctor (16) published a series of four articles on this subject in 1933.

Theory

When the unit weight of the soil is artificially increased it is said to be "compacted." The process could be done in the form of pressing, ramming, or vibrating the soil particles into a closer state of contact.

The extent to which a soil mass can be compacted depends on (17):

1) The nature of the soil and its compactibility;

2) The nature of the compactive effort;

3) The moisture content at which the soil is compacted.

Influence of Moisture Content

Figure 1 shows the moisture content-dry density relationship, resulting from a laboratory compaction test, for a given soil and compactive effort. Examination of the curve shows that the moisture content determines the state at which the maximum dry density occurs. At low moisture contents, the soil is stiff and difficult to compress, and as a result low values of dry densities are obtained. As the moisture content is increased, the added water acts as a lubricant causing the soil to soften and become more workable, resulting in a higher dry density and a lower air content. The optimum moisture content at which the maximum dry density is obtained is the moisture content at which the soil has become sufficiently workable so that, under the compactive effort used, the soil particles are packed so closely as to expel most of the air. As the moisture content is increased above optimum, the soil becomes increasingly more workable but the increased moisture content and the remaining unexpelled air fill the soil voids and prevent closer packing thus causing a drop in the densities.

Influence of Compactive Effort

It should be understood that optimum moisture content is not a constant value but rather varies with the compactive effort. An increase in the energy applied per unit volume of soil results in an increase in the maximum unit weight and a decrease in the optimum moisture content. Thus, for each compactive effort applied per unit volume of a given soil, there is a corresponding optimum moisture content and maximum unit weight.

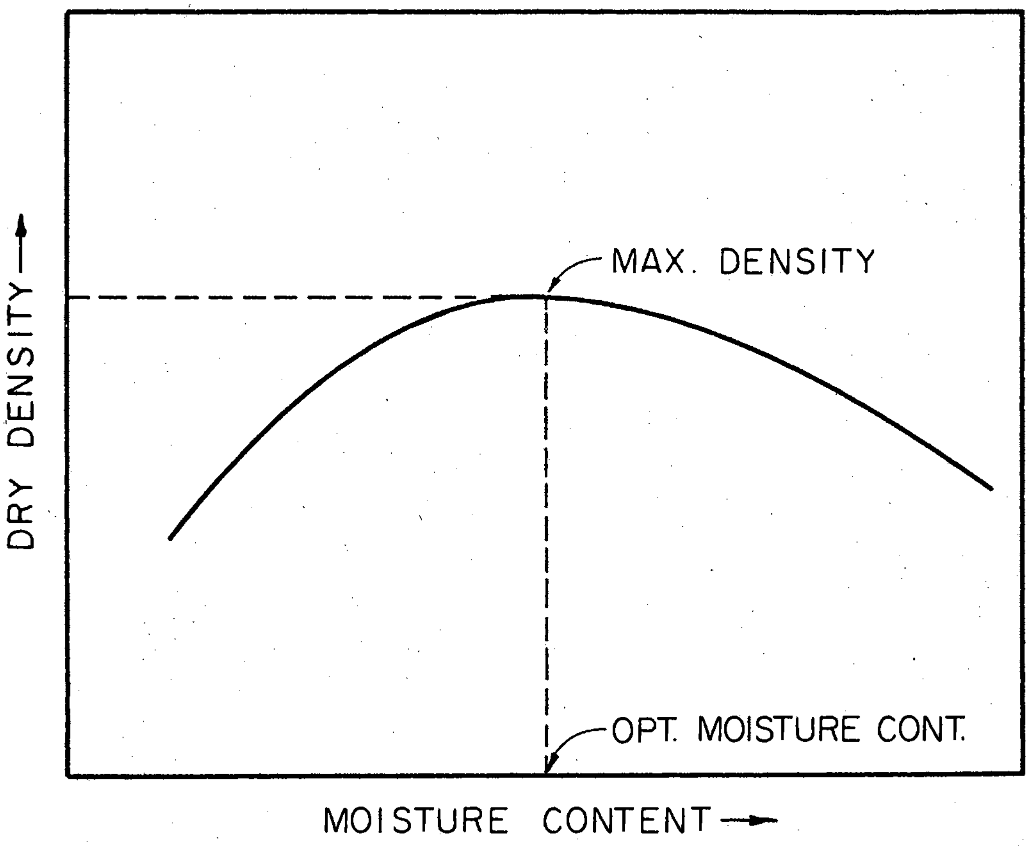

Figure 1. Dry Density - Moisture Content Relationship
(After Proctor)

Effect of Soil Type

Maximum unit weights and optimum moisture contents obtained under a given compactive effort may differ widely for different soil types, depending on the shape of the soil grains, their size distribution, specific gravity, and their plastic properties. Soils composed of sharp, angular particles exhibit higher unit weights than soils of rounded particles. Compaction of poorly graded soils results in low maximum unit weights and high optimum moisture contents. At the other extreme, well graded soils show high maximum unit weights. Usually, soils with low plasticity result in higher unit weights than soils with high plasticity.

Structure and Strength of Compacted Clay Soil

Convincing evidence of the type of structure developed in compacted clays and the influence of structure on soil properties has been presented in recent papers by T. W. Lambe (18, 19). Figure 2 illustrates the effect of compaction on the soil structure. At point A, the small amount of water present results in a high concentration of electrolyte which prevents the diffuse double layer of ions surrounding each clay particle from fully developing. The reduced double layer leads to low inter-particle repulsion, resulting in a tendency towards flocculation of the colloids and in turn a low degree of clay particle orientation in the compacted soil. This type of structure is referred to as "flocculated" arrangement of soil particles. If the moisture is increased to point B, the electrolyte concentration is reduced, resulting in an expansion of the double layer, increased repulsion between

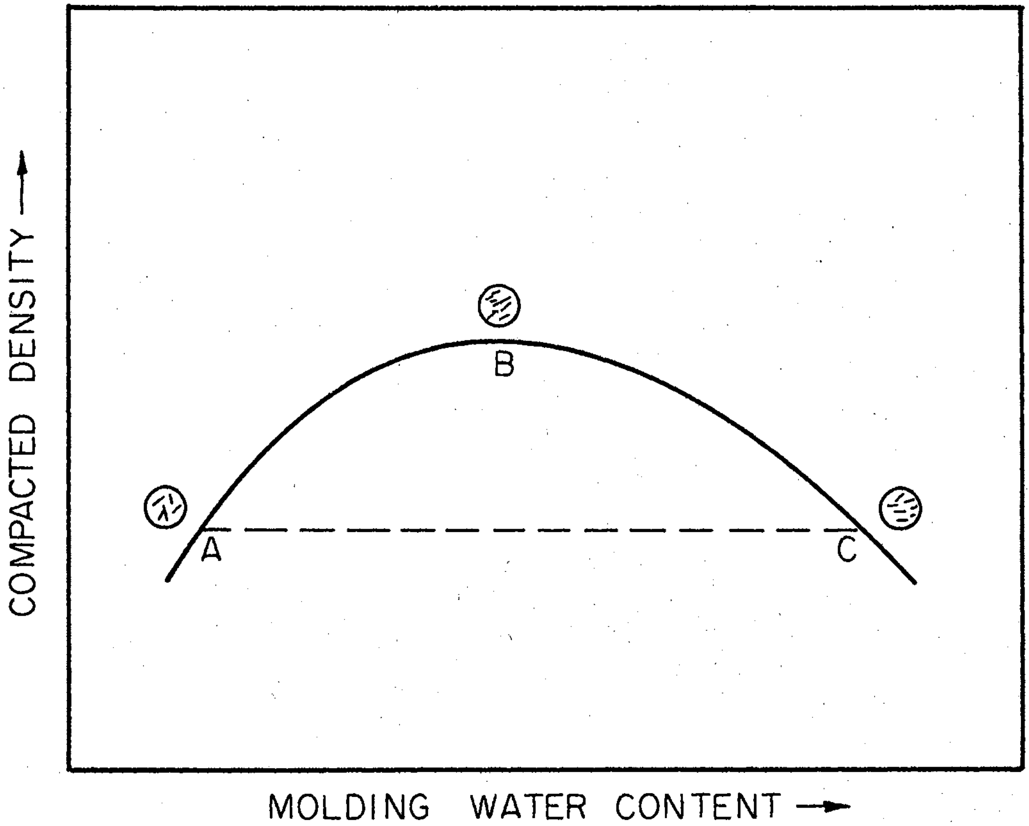

Figure 2. Effect of Compaction on Soil Structure
(After Lambe)

particles and a low degree of flocculation; that is, an increased degree of particle orientation. Further increase in water content at point C results in a still greater increase in particle orientation.

The parallel arrangement, which is approached at point C, is referred to as a "dispersed" system. Thus, in general it may be stated that the dry side of optimum of the moisture-density curve tends to produce a flocculated arrangement of particles, while the wet side of optimum of the same curve tends to produce a dispersed arrangement of particles. Pacey (20) obtained similar data from compacted samples of kaolin clay by using optical techniques.

Strength tests, at varying moisture contents and different compaction procedures, were performed by Seed and Chan (21) in an attempt to correlate strength with the particle orientation. They showed that the effect of method of compaction has little effect on the strength of clay samples compacted dry of optimum, with kneading compaction yielding higher strengths than impact compaction. For samples compacted wet of optimum the influence of method of compaction was considerable at about 5% strain. Wet of optimum strengths of samples of the same composition increased in the following order with regard to compaction procedure: kneading, impact, vibratory, and static. According to Lambe (18, 19), this seems to indicate that the degree of clay particle orientation decreases with the same order of compaction so that the more flocculated structure gives the highest strength.

However, it is noteworthy to mention at this point, that recent work in this area by Sloane (22) and Tice (23), showed that static compaction yields a higher degree of particle orientation than either the impact or the kneading procedures. In 1965, Sloane and Kell (22) studied the structure of compacted kaolinite clay by the use of the electron microscope. They concluded that a slight amount of orientation observable in kaolin at 3% below optimum moisture content showed an increase in the following order: kneading compaction, impact compaction, static load compaction. Based on their recommendations, Tice (23) used the x-ray defraction method to study the structure of compacted kaolinite. He concluded that the degree of particle orientation showed an increase in the following order at all moisture contents: kneading compaction, impact compaction, static load compaction.

Compaction Characteristics of Laterites

Compaction of laterites is greatly influenced by the remolding of the soil. Heavy construction equipment tends to transform the soil into a highly plastic clayey material. It has been reported that primitive manual compaction, which minimizes the remolding of the material, has yielded better airfields than compaction of the same soil by heavy equipment (4).

Bawa (1) related the compacted densities to the specific gravity of the solids. He stated that, in general, high compacted densities would be expected due to the high specific gravity of the solids. These densities are possibly true in the case of laterite or older lateritic soils. However, in many cases, densities of young lateritic soils are quite low in comparison with their high specific gravities. Townsend (2) believed that this phenomenon is caused by the popcornball-like clusters of microaggregates which provide a granular structure in the soil and thus a lower density when the soil is compacted.

The optimum moisture content is usually close to or slightly below the plastic limit; however, during the wet season, the natural moisture content of lateritic soils may be slightly above the plastic limit. For this reason, quite often it is necessary to dry the soil prior to placement for compaction (11).

The following table presents density values (Standard Proctor) and the corresponding optimum moisture contents for various lateritic soils:

TABLE IV

DENSITY AND OPTIMUM MOISTURE CONTENTS OF LATERITIC SOILS

Type & Location	Gs	Dry Density	Opt. M.C.	PL	Source
Lateritic Soil Guinea, Africa	----	113	10.3	----	Winterkorn (4)
Lateritic Soil Matanzas, Cuba	2.90	88	30	31.2	Winterkorn (4)
Lateritic Soil Morocco, Africa	2.87	126	13.9	22.7	Remillion (24)
Hydrated Lithomarge Kenya, Africa	2.83	79	50	54	Terzaghi (11)
Laterite India	2.70	121	12	16	Ramachandran (14)
Lateritic Soils Brazil	2.68	81-90	30	31	Grizienski (25)

Lime Stabilization of Lateritic Soils

Various admixtures such as lime, portland cement, chemicals, asphalt, and sand have been employed to stabilize laterites and lateritic soil. However, none of these additives is universally successful due to the varying nature of the soil.

It has been reported that lime stabilization was successful in French West Africa (26). In this case, three percent lime was found to reduce the plasticity index from 30 to 8 percent due to base exchange. Ten percent was sufficient to stabilize the red clays from the Sasamua Dam project in Kenya (10). Although lime stabilization was successful in those areas, failures have been reported in Cuba (4).

A summary of various lateritic soils and stabilizing admixture (lime) is shown in the following table:

TABLE V

UNCONFINED COMPRESSIVE STRENGTH OF LIME-STABILIZED LATERITIC SOILS

Stabilizer & %	Location	Compressive Strength	Source
Lime 8-18% (Wet-Dry)	Cuba	Failed	Winterkorn (4)
Lime 14% (Immersed)	Cuba	52 psi	Winterkorn (4)
Lime 18% (Immersed)	Cuba	41.0 psi	Winterkorn (4)
Lime 5%	Kenya	130 psi	Newill (10)
Lime 10%	Kenya	340 psi	Newill (10)

CHAPTER III

INVESTIGATIVE PROCEDURES

Materials

Soil

The lateritic soil used in this investigation was obtained from Curundu, Panama Canal Zone. The samples were taken at random depths varying from the surface to 17 feet. Permission to import the soil was obtained by Permit S-688 from the U.S. Department of Agriculture, Plant Quarantine Division.

Some of the soil properties are shown in Table VI.

TABLE VI

PHYSICAL PROPERTIES OF WORKED AND UNWORKED LATERITIC SOIL

Property	Worked		Unworked	
	N.A.	L.S.	N.A.	L.S.
Atterberg Limits				
Liquid Limit	69.6%	53.2%	60.5%	46.5%
Plastic Limit	40.1%	31.7%	39.5%	40.0%
Plasticity Index	29.5%	21.5%	21.0%	6.5%
Specific Gravity	2.8	--	2.80	--

N.A. - No Additive
L.S. - Lime Stabilized

Lime

The pelletized quick lime used in this study was obtained from a source in Eastern Oklahoma. The chemical composition of this particular lime is shown in Table VII.

TABLE VII

CHEMICAL COMPOSITION OF LIME

Constituent	Content % by Wt.
Calcium oxide	97 1/2
Magnesium oxide	1/2
Aluminum oxide	0.15
Silica dioxide	0.2
Iron	0.3
Sulfur	0.01-0.008
Arsenic	Trace
Phosphorous	Trace

Sample Preparation

General

Remolding of the soil was accomplished by grinding the soil to pass the U.S. No. 10 sieve, mixing the ground soil with a sufficient quantity of water to surpass the liquid limit, and manipulating the soil-water mixture with a spoon or a spatula.

The unworked material was obtained by gently hand sieving the soil through a U.S. No. 10 sieve.

Mixing

Due to the friability of the lateritic materials, it was necessary to use new material for each point of the Proctor curve and the static pressure-density curve. The raw, worked and unworked, soil samples were placed in tare pans, sprinkled with the desired amount of water for optimum moisture, and sealed in a plastic bag for at least twenty-four hours to assure a uniform distribution with the added moisture.

The stabilized test specimens were made by incorporating 2 1/2, 5, 10 and 20 percent by weight of quick lime. The following combining procedure was used for the soil-lime mixtures:

1) The soil and lime were hand mixed.

2) The soil-lime mixture was spread at a depth of about two inches in a shallow pan.

3) A predetermined large amount of water (approximately 50% by weight) was sprinkled over the mixture. The large amount of water was added to assure the cationic exchange.

4) The mixture was allowed to air dry until the moisture content

dropped considerably (approximately 4 days).

5) The dry mixture was hand stirred to break up any soil-lime agglomerates.

6) The moisture content of the dry mixture was determined.

7) The mixture was then brought to the desired optimum moisture content for molding.

Compaction of Test Specimens

Impact Compaction

The specimens were compacted in a Harvard Miniature compaction apparatus which had a diameter of 1 5/16 inches and a height of 2.8 inches (Figure 3). The soil was compacted in three layers, 25 blows per layer, by a drop hammer of 0.825 lbs. weight, with a face diameter of 0.70 inches and a drop height of 6 inches to get a compactive effort equivalent to the Standard Proctor compaction test.

Static Compaction

Static samples were compacted by the use of a hydraulic testing machine. An extension collar and a piston were designed and made to fit the purpose. The extension collar was used as a link between the head of the machine and the proving ring used to measure the applied load. The piston made had a height of 6 inches and was fitted to the proving ring (Figure 4).

The samples were compacted in three layers in a Harvard Miniature mold. The load was applied at a rate of 0.75 inch per minute. Once attained, the desired pressure was maintained for a period of 60 seconds, before release, to allow the escape of any entrapped air. The

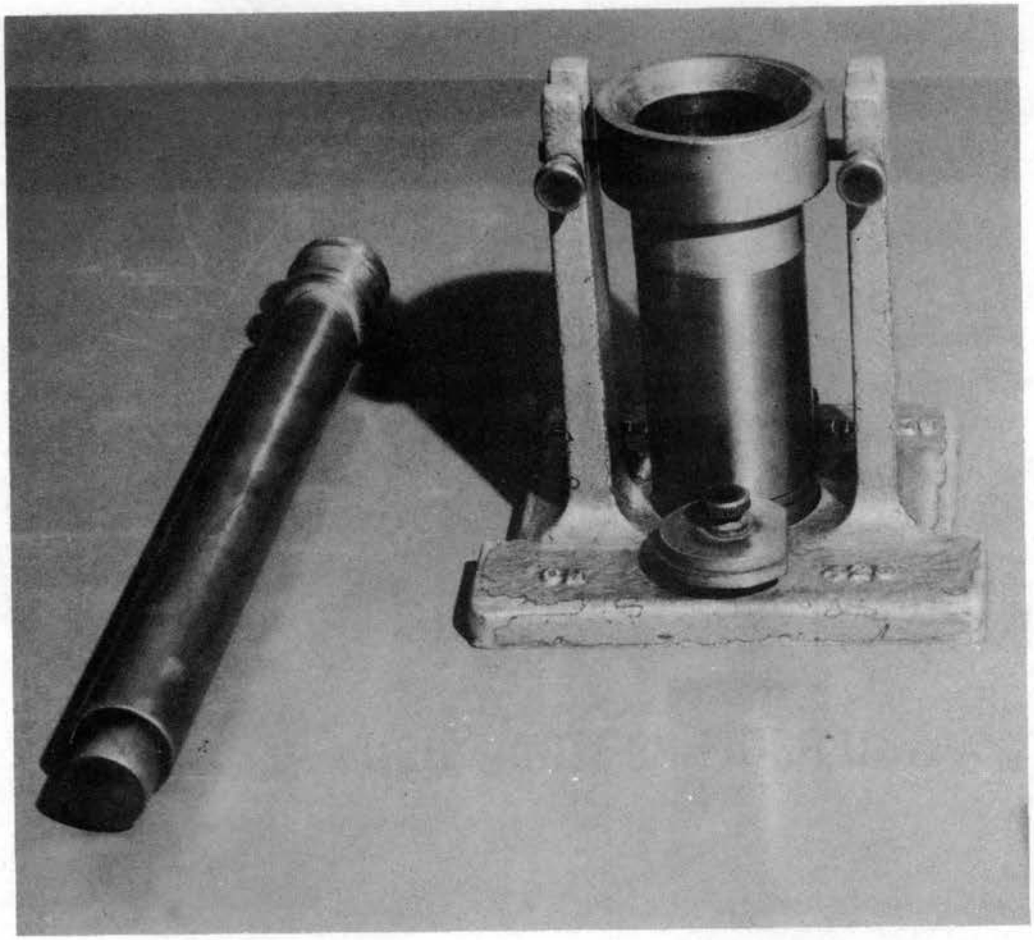

Figure 3. Harvard Miniature Compaction Apparatus

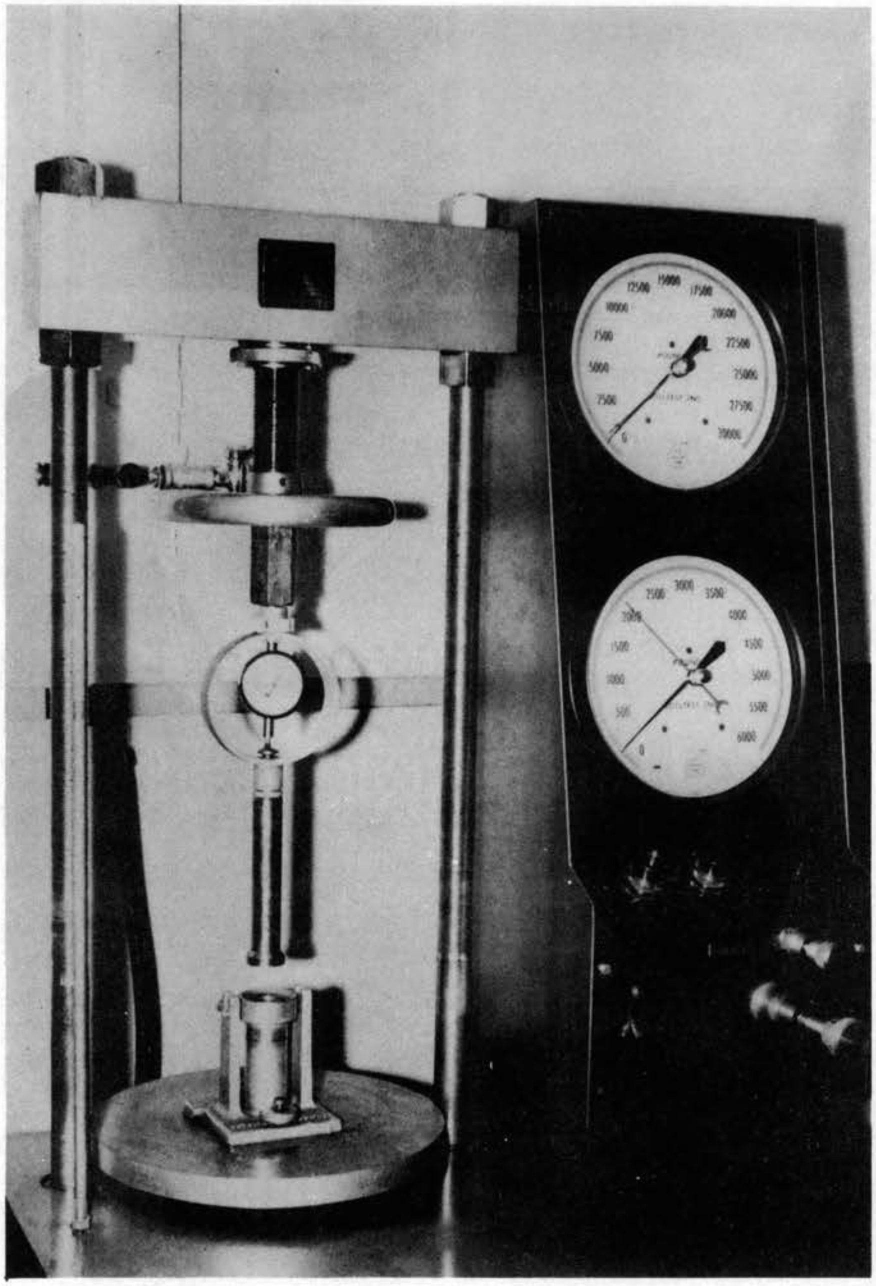

Figure 4. Static Compaction Apparatus

whole process consumed about 15 minutes per specimen.

In order to properly compare the strength values resulting from the two compaction procedures, i.e., static and impact, it was necessary that specimens be compacted to the same density and at the same moisture content. Prior to compacting the test specimens, Standard Proctor compaction tests were made on the worked and unworked, raw and lime stabilized soil samples. Results are shown in Table VIII.

TABLE VIII

PRELIMINARY COMPACTION DATA

Mixture	Maximum Density	W_{opt}
Worked + no additives	83.0	34.5%
Unworked + no additives	84.5	35 %
Worked + 2 1/2% lime	82.5	35 %
Unworked + 2 1/2% lime	81.6	35 %
Worked + 5% lime	82.0	34 %
Unworked + 5% lime	80.5	35 %
Worked + 10% lime	78.3	34.3%
Unworked + 10% lime	78.2	35 %
Worked + 20% lime	77	35 %
Unworked + 20% lime	76	34 %

All specimens were compacted at maximum density and at optimum moisture content for purposes of strength determination.

To obtain comparative densities at the same moisture contents by the static load method, it was necessary to run pressure-density tests for all mixtures to obtain the pressure at which the desired densities could be achieved (Figures 5, 6, 7, 8, 9, 10, 11, 12, 13, 14).

Curing of Test Specimens

After compaction, the soil-lime specimens were wrapped in Saran Wrap, waxed and stored in a moist room to cure (Figure 15). Three curing periods of seven, twenty-eight, and sixty days were used.

Testing Equipment and Procedures

Unconfined Compression Tests

At the specified curing age, the samples were stripped of their wax coatings, and their unconfined compressive strength was determined (Figures 16, 17). The tests were carried out at a constant deformation rate of 0.05 inches/minute on a Karol Warner compression machine (Model 550) (Figure 18). The peak stress was chosen to represent failure. Moisture contents of the tested samples were determined to insure that testing was done approximately at optimum moisture content. The reported results are an average of three tests.

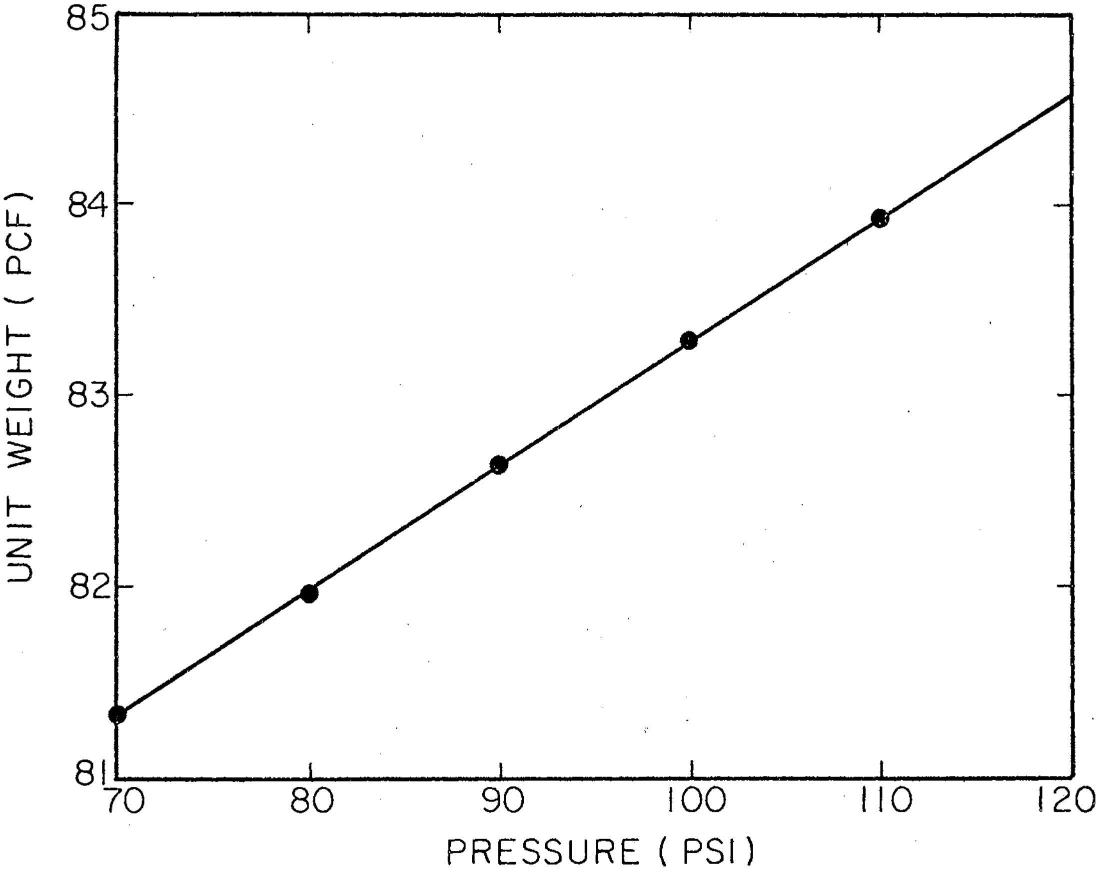

Figure 5. Pressure-Density Relationships, Worked + No Additives, W = 35%

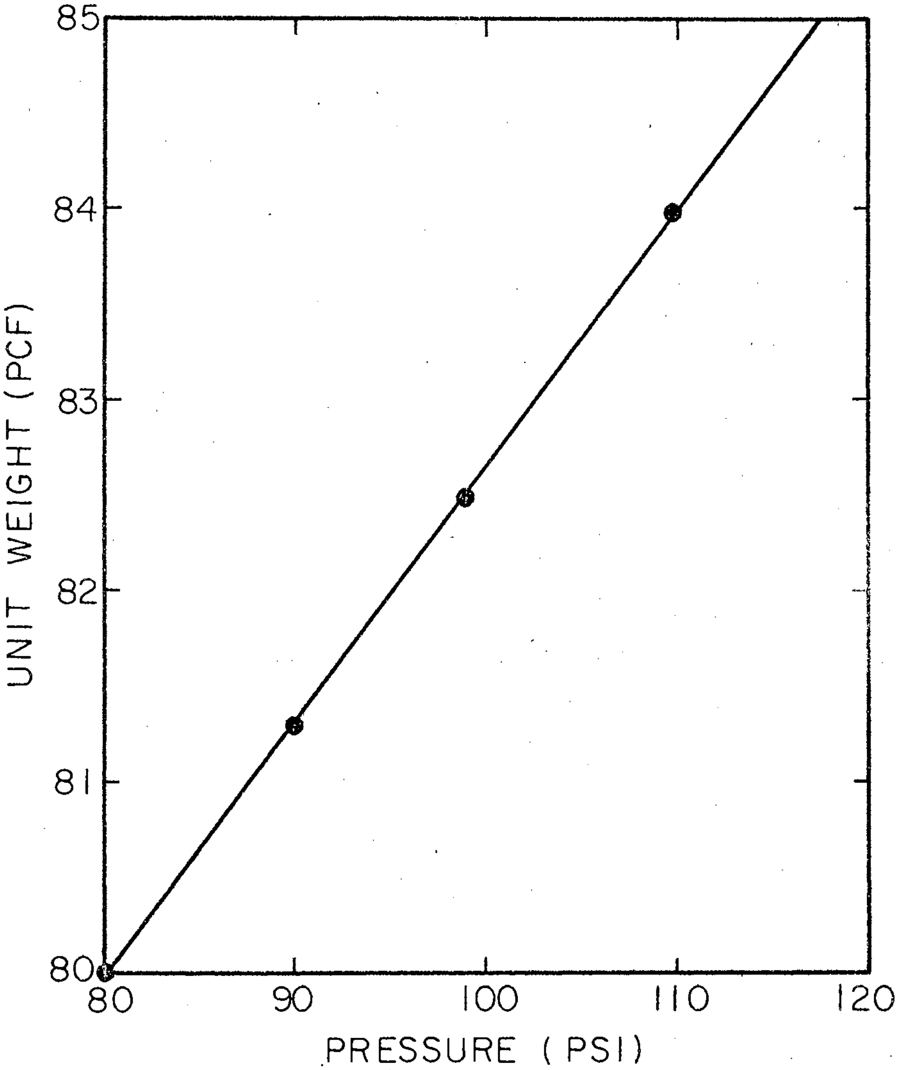

Figure 6. Pressure-Density Relationships, Unworked + No Additives, W = 35%

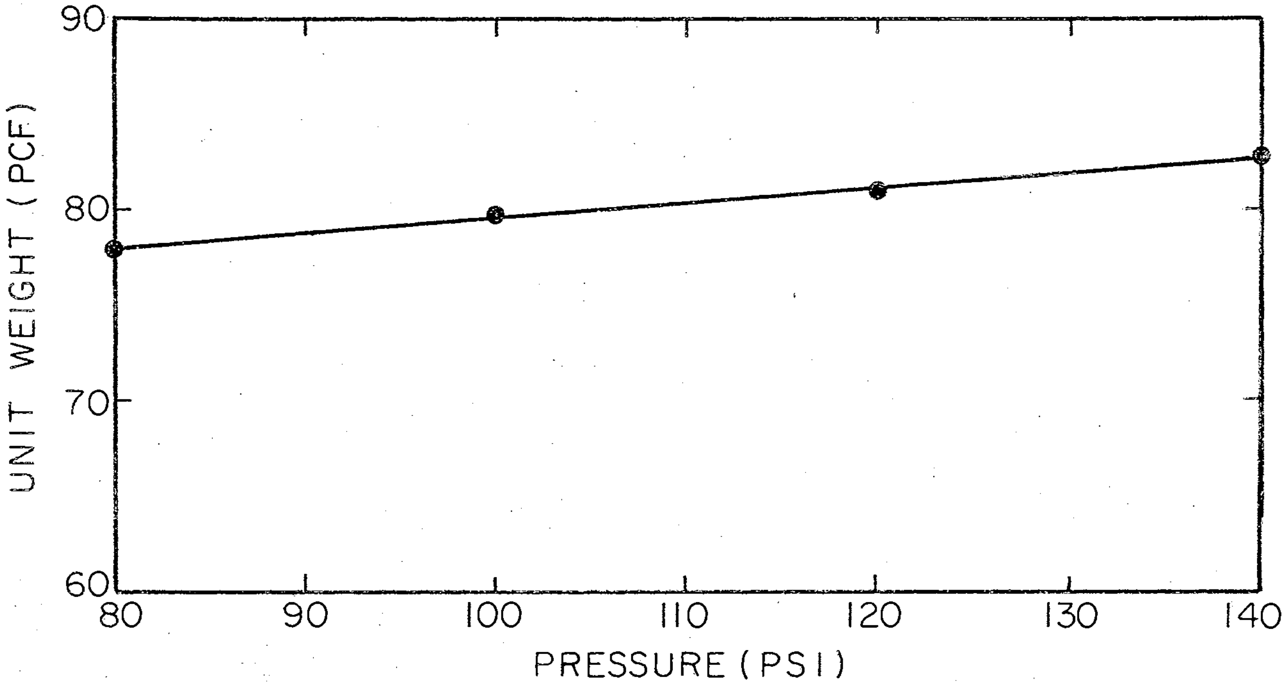

Figure 7. Pressure-Density Relationships, Worked + 2 1/2% Lime, W = 35%

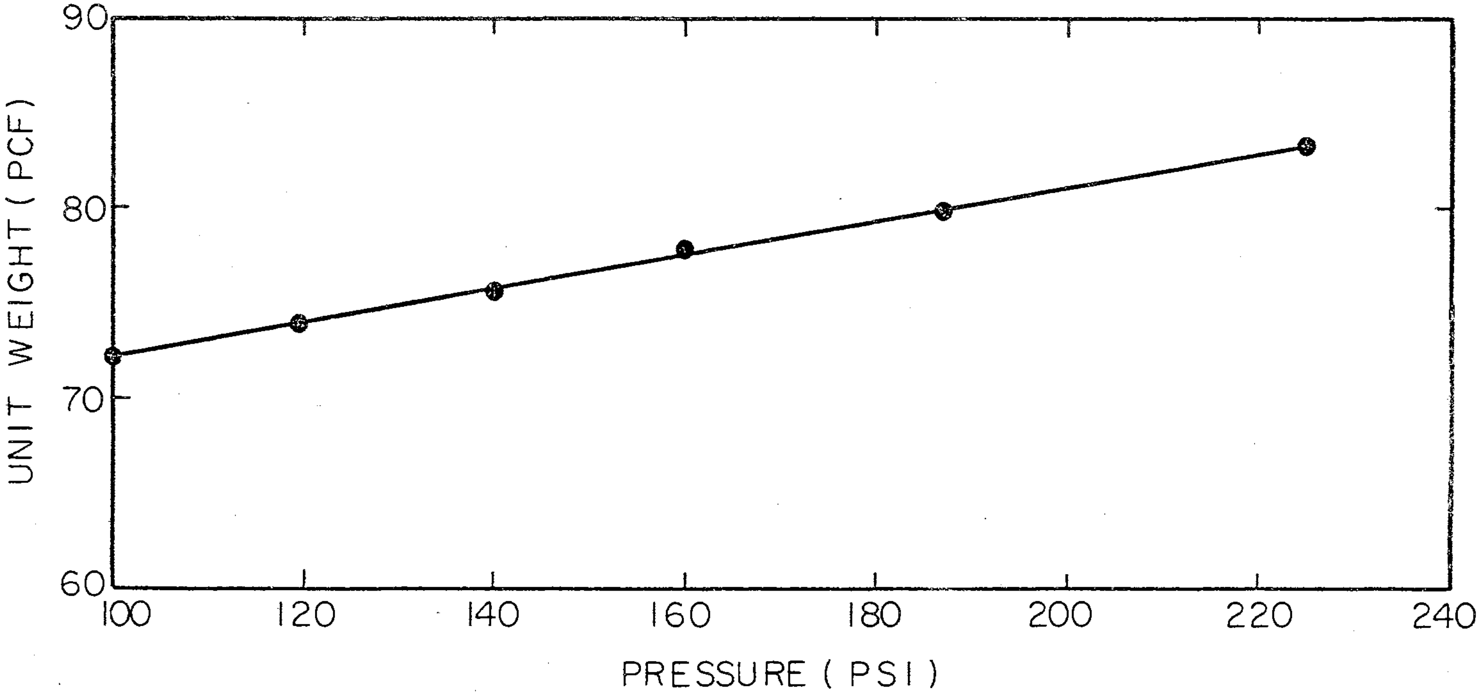

Figure 8. Pressure-Density Relationships, Unworked + 2 1/2% Lime, W = 35%

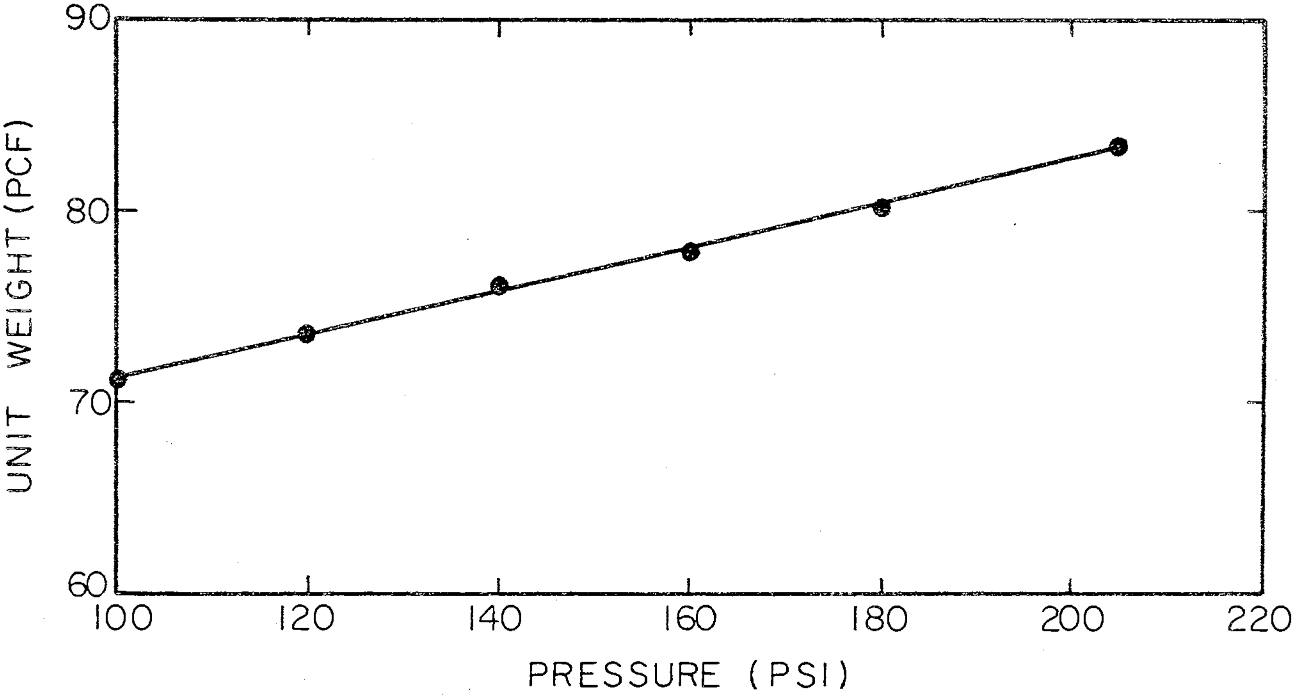

Figure 9. Pressure-Density Relationships, Worked + 5% Lime, W = 34%

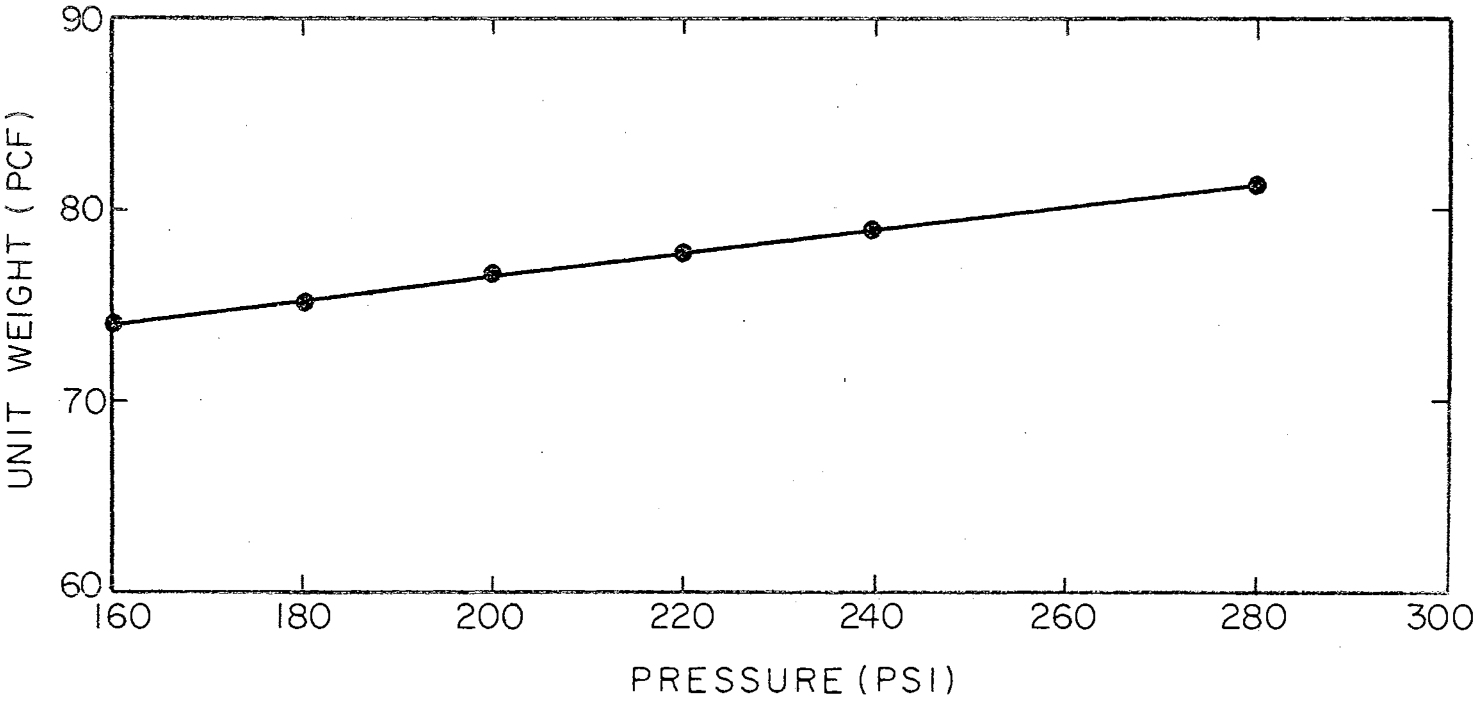

Figure 10. Pressure-Density Relationships, Unworked + 5% Lime, W = 35%

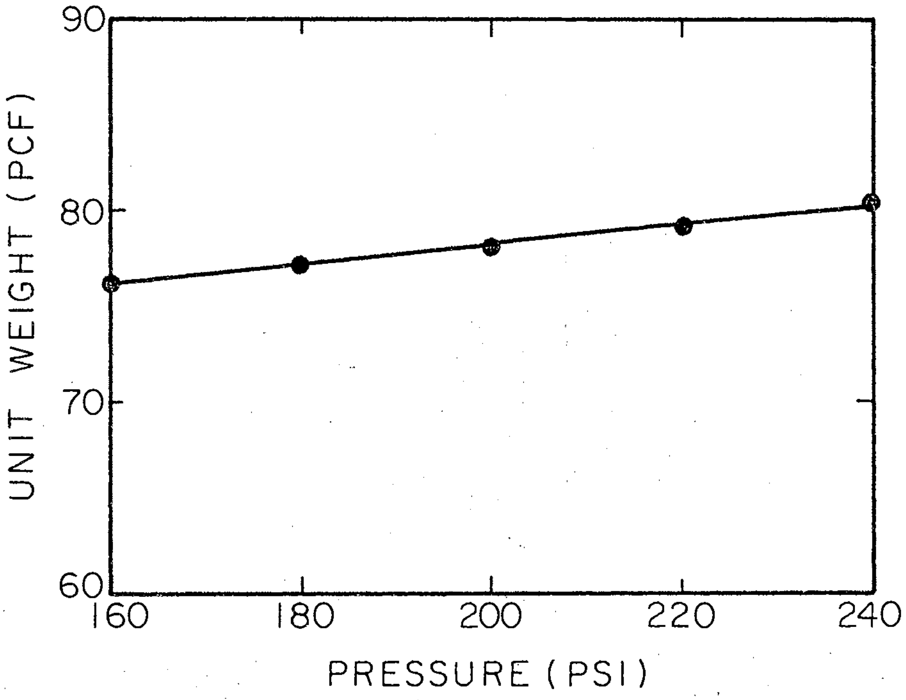

Figure 11. Pressure-Density Relationships, Worked + 10% Lime, W = 34.3%

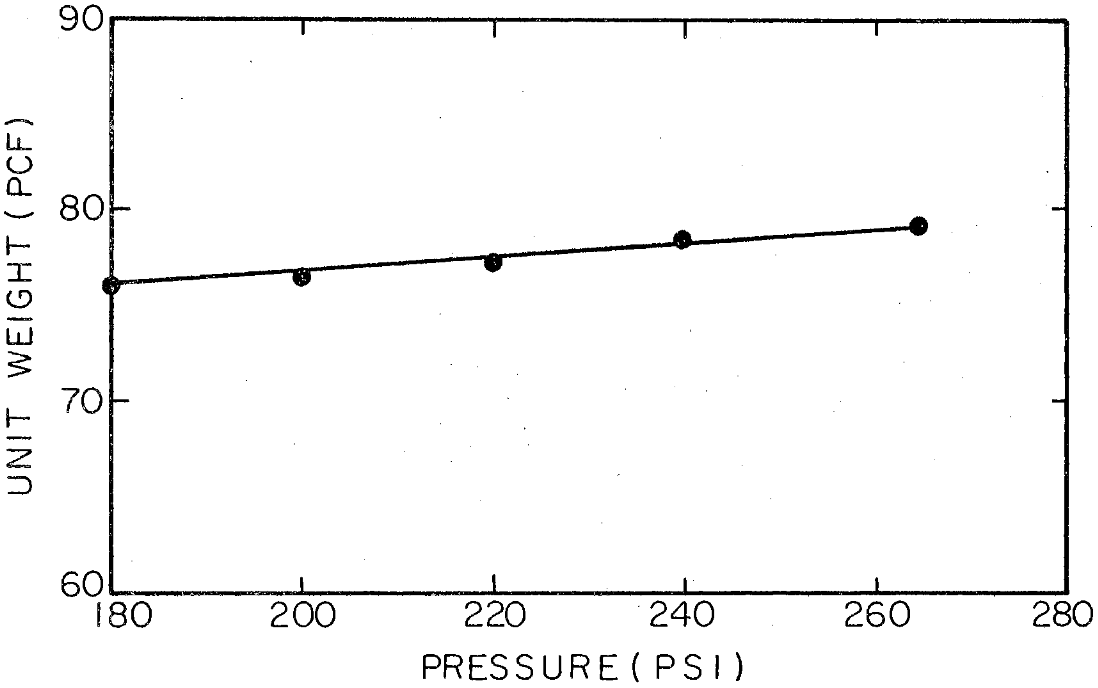

Figure 12. Pressure-Density Relationships, Unworked + 10% Lime, W = 35%

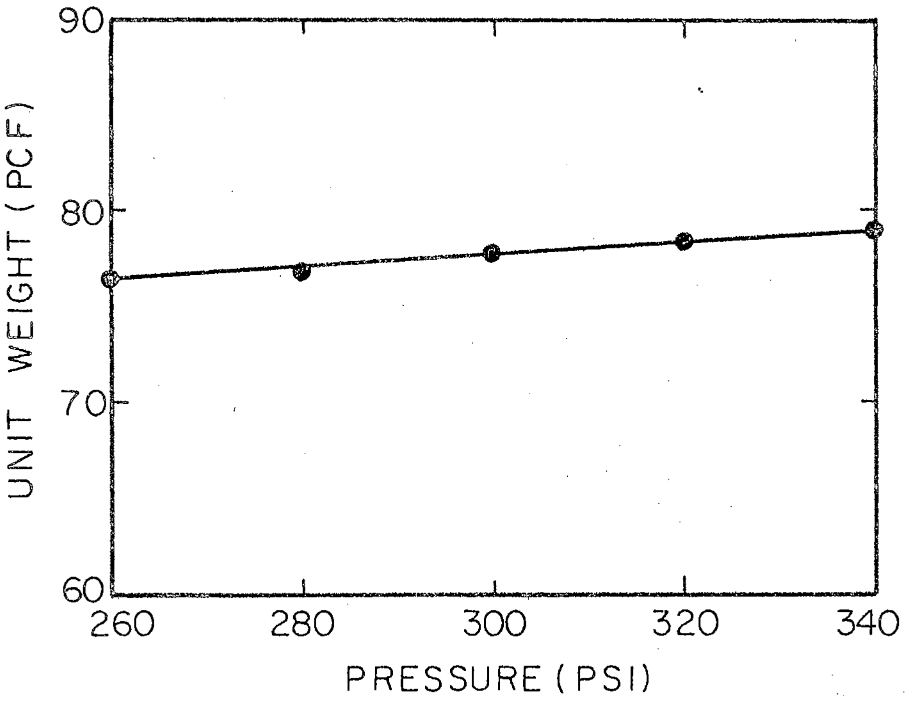

Figure 13. Pressure-Density Relationships, Worked + 20% Lime, W = 35%

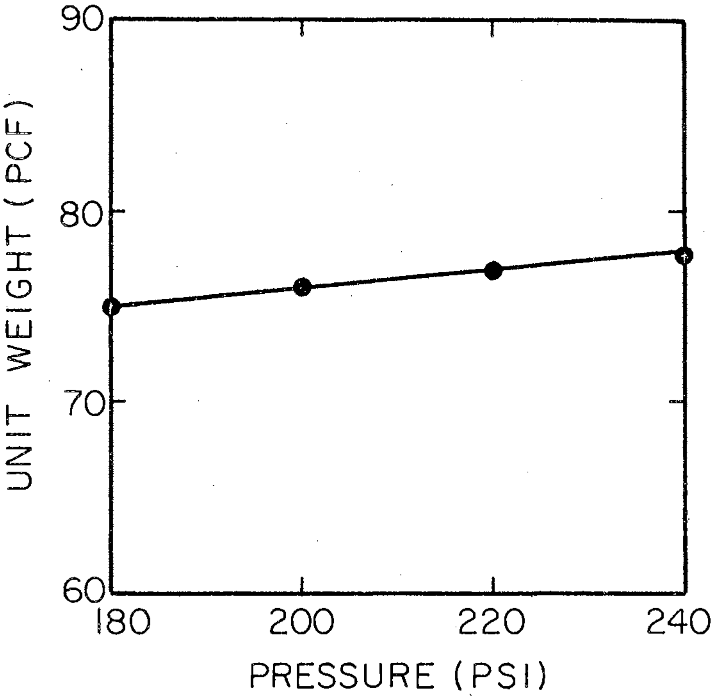

Figure 14. Pressure-Density Relationships, Unworked + 20% Lime, W = 34%

Figure 15. Waxed Specimens

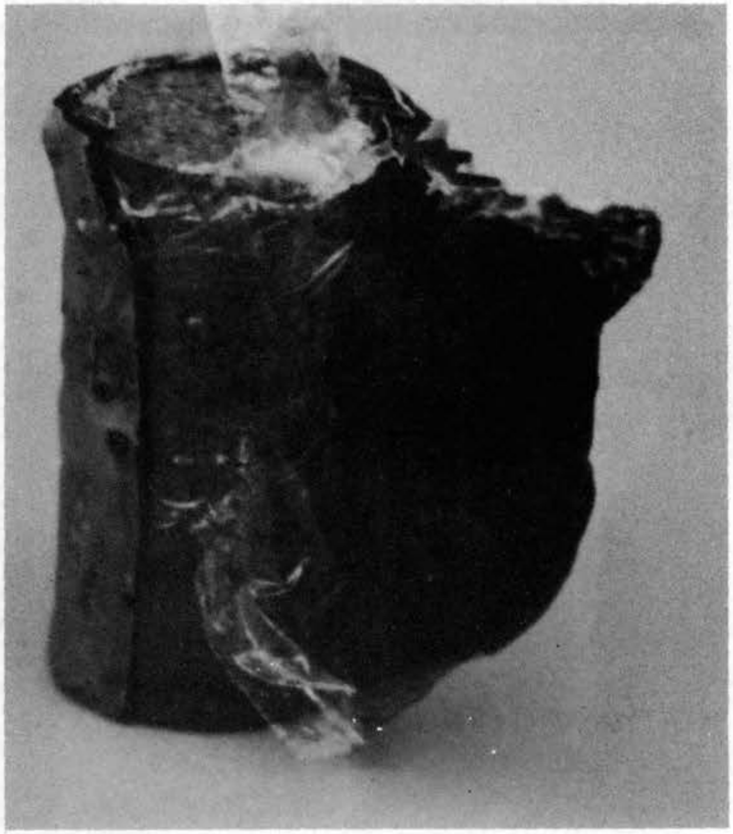

Figure 16. Waxed Coating Partially Stripped From Specimen

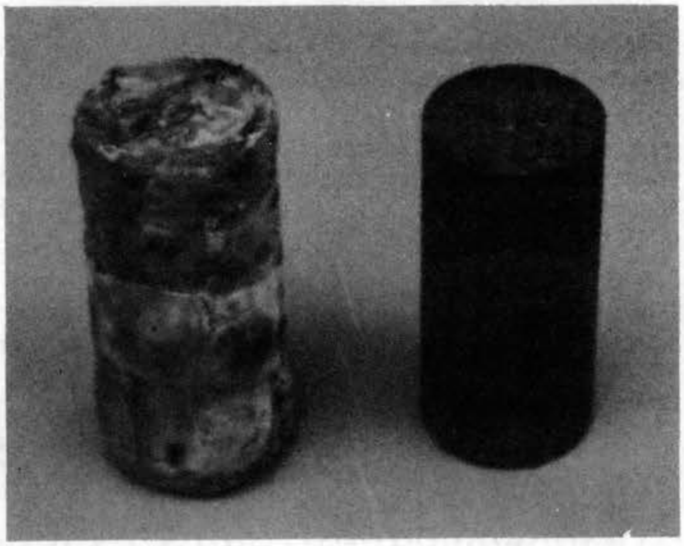

Figure 17. Specimens With and Without Protective Wax Coating

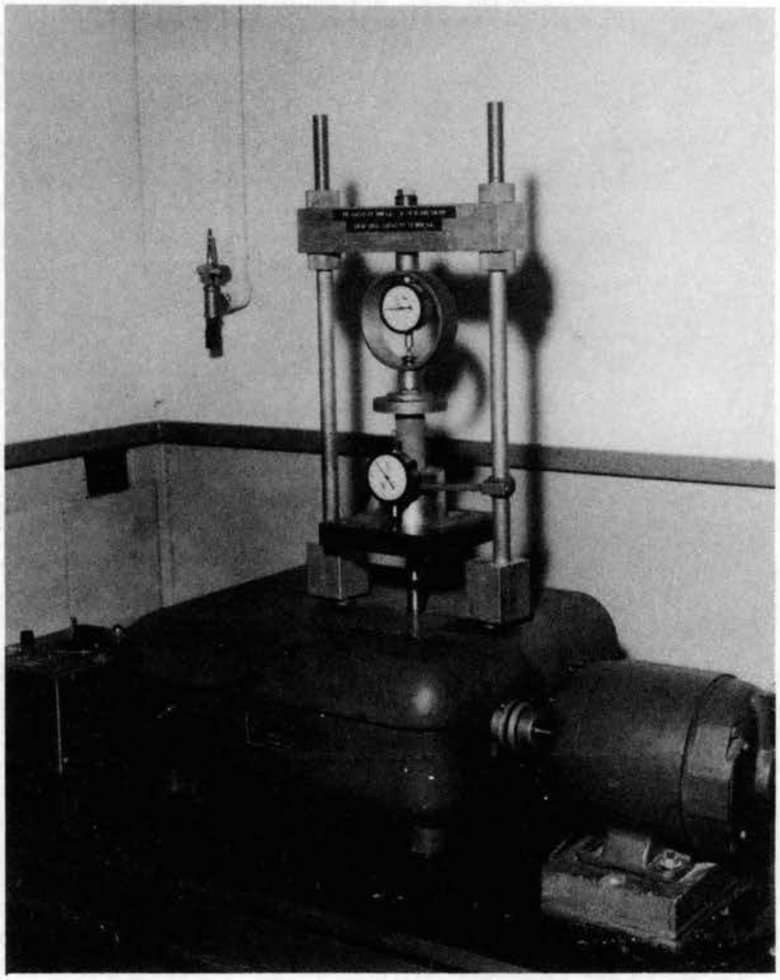

Figure 18. Karol Warner Compression Machine

CHAPTER IV

RESULTS AND DISCUSSION

Impact Compaction

The density values obtained by Standard Proctor compaction were presented previously in Table VIII. These values are very low compared to normal clays of temperate regions with similar Atterberg limits. Compared with the unworked soil, the worked soil showed a slight decrease (1.5 pcf) in maximum density; however, the moisture contents remained essentially the same. This is considered indicative of the increase in "effective" clay content of the soil due to the breakdown and stripping away of the sesquioxide coatings caused by mechanical manipulation. For the stabilized samples, there was a decrease in the maximum densities with an increase in the lime content. This is an indication of the granulating effect (base exchange) that takes place in the soil-lime mixtures.

Static Compaction

Prior to compaction of the static specimens, pressure-density tests were made to find the pressures that would achieve densities comparable to those obtained by the impact method. The results of the tests were presented graphically in Figures 5 through 14 and are listed tabularly in the following table:

TABLE IX

DENSITY-PRESSURE RELATIONSHIPS

Mixture	Density (pcf)	Pressure (psi)
Worked + no additives	83	95
Worked + 2 1/2% lime	82.5	135
Worked + 5% lime	82	195
Worked + 10% lime	78.3	205
Worked + 20% lime	77	277
Unworked + no additives	84.5	114
Unworked + 2 1/2% lime	81.6	216
Unworked + 5% lime	80.5	265
Unworked + 10% lime	78.2	240
Unworked + 20% lime	76	200

For the worked soil, higher static loads were needed to compact the specimens with increasing lime contents, even though the required densities were decreasing with increasing lime content. This is due to the granulation effect in the soil-lime mixture. For the unworked soil, the static loads required to achieve the desired densities increased for the 2 1/2 and 5 percent lime contents and then dropped for the 10 and 20 percent lime content specimens. Quite possibly, there was enough exposed clay particles (silicates) in the unworked soil to react with the smaller percentages of lime and cause base exchange. In the case of the higher lime contents, i.e., 10 and 20 percent, only a small portion of the lime could react with the silicates present and the rest remained as fines permitting the desired densities to be achieved at lower static pressures.

Unconfined Compressive Strength

Raw Soil

The results of the unconfined compression tests for the raw soil are shown in Table X. Each value is an average of three tests. The stress-strain characteristics of the remolded (worked) and unremolded (unworked) raw soils are shown graphically in Appendix.

TABLE X

UNCONFINED COMPRESSIVE STRENGTHS OF
THE RAW LATERITIC SOIL

Compaction Procedure	Unconfined Compressive Strength (psi) Worked	Unconfined Compressive Strength (psi) Unworked
Impact	23	22
Static	13	11

The results show that the difference in the strength values are negligible, between the worked and the unworked soil, for a given compaction procedure. However, the results cannot be compared directly because of the difference in densities of the respective specimens.

Impact compaction resulted in higher strengths than static compaction for both the worked and unworked soils. These results contradict the findings of Lambe (18, 19) and Seed and Chan (21). This discrepancy in results is attributed to the characteristics of this particular type of soil.

The worked soil has a higher clay content initially and subsequent compaction by impact procedures tends to increase the effective clay content through additional mechanical breakdown. This increase in the amount of effective clay particles in the material requires more moisture to satisfy the double water layer and thus causes an increase in the "optimum moisture content" for the compacted material. That is, the worked soil was brought to its optimum moisture content prior to compaction, however, due to the increase in effective clay content, resulting from the compaction procedure itself, some of the molding moisture is in effect removed by these additional exposed clay particles. Thus, the material is actually compacted on the dry side of optimum and apparently yields a more flocculated type of structure in the compacted specimen which in turn results in higher unconfined compressive strength.

On the other hand, the static compaction procedure does not tend to increase the initial effective clay content of the compacted material, and the optimum moisture content of the worked soil remains essentially the same. Therefore, static compaction at optimum molding moisture content apparently results in a dispersed soil structure in the specimens. Upon loading, the oriented soil particles tended to slide past one another very easily causing failure at strengths lower than those achieved by the impact compacted specimens. These results substantiate those obtained by Sloane (22) and Tice (23).

The same thing occurred in the case of the unworked soil, that is, the increase in the effective clay content upon impact compaction, caused an increase in the optimum moisture content. Compaction of specimens at a molding moisture below optimum resulted in a flocculated structure which in turn yielded higher unconfined compressive strengths.

On the other hand, static compaction caused little or no increase in the effective clay content. Therefore the specimens were compacted at optimum moisture content, and thus resulted in a more oriented structure than those compacted by the impact method. Upon loading, the oriented soil particles tended to slide easily past one another resulting in low unconfined compressive strengths.

Another possible reason for the higher strengths obtained by the impact method for the unworked soil could be a result of the change in cohesion. Static compaction caused negligible or no breakdown in the granular structure. On the other hand, impact compaction could have possibly caused a breakdown in the structure of some of the soil particles, thus causing an increase in the cohesion. This increase in cohesion could possibly be responsible for the higher strengths obtained by the impact method.

Stabilized Soil

The results of unconfined compression tests of the various soil-lime mixtures are tabulated in Table XI. The comparison of stress-strain characteristics of the worked and unworked stabilized soils are shown graphically in Appendix.

TABLE XI

UNCONFINED COMPRESSIVE STRENGTH OF LIME STABILIZED LATERITIC SOIL

Lime Content %	Curing Time (days)	Unconfined Compressive Strength (psi) Worked Impact	Worked Static	Unworked Impact	Unworked Static
2 1/2	7	13	17	12	15
	28	21.5	24	19	39
	60	41.5	56.5	46	51
5	7	42	50	32	44
	28	74	96	68	90
	60	140	168	212	290
10	7	27	34	25	32
	28	100	110	70	80
	60	195	223	227	283
20	7	28	45	36	28
	28	56	67	58	52
	60	100	180	80	128

Note: Worked and unworked cannot be compared directly because of difference in densities.

Static compaction resulted in higher strengths in all cases except for the unworked 20% lime content specimens cured for 7 and 28 days. The lower strengths exhibited by the impact compacted specimens are attributed to the breakdown of the soil particle aggregations resulting from the base exchange reactions.

Curing Time

Examination of Figures 19, 20, 21, and 22 indicates that in all cases the strength of the lime stabilized soil increased with prolonged curing times. This increase in strength is primarily a result of (1) base exchange reactions, i.e., the replacement of sodium and hydrogen ions by the stronger calcium cations, and (2) pozzolanic reactions. Pozzolanic reactions are the formations of calcium silicates (cementing compounds) by the reaction of lime with free silica and alumina in the soil (27). The latter phenomenon takes place at the same time but at a much slower rate than in the base exchange reactions.

Because of the crisscross tendency of the curves for the worked and unworked soils little can be interpreted from these plots regarding a comparison of the respective strength gains with curing time. However, these graphs indicate that for each type of soil there is an optimum lime content for maximum strength gain and that the method of compaction directly and in some cases drastically influences the strengths of the specimens. This is particularly true for extended curing times.

Specimens of both soils containing 5 and 10% lime exhibited the greatest strength gains with curing time (Figures 20 and 21). It is particularly interesting to note the general parallelism of the static and impact curves for each type of soil and the rather abrupt increase in rate of strength gain exhibited by the unworked soil after the 28 day curing period.

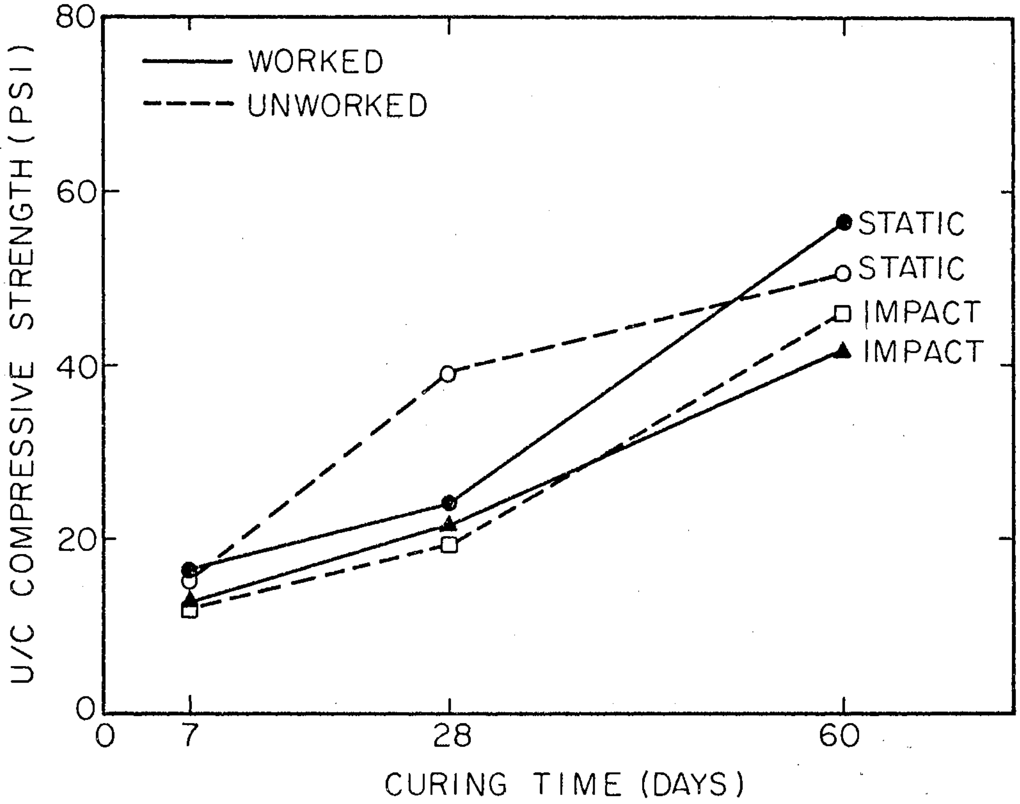

Figure 19. Effect of Curing Age on Unconfined Compressive Strength, Laterite + 2 1/2% Lime

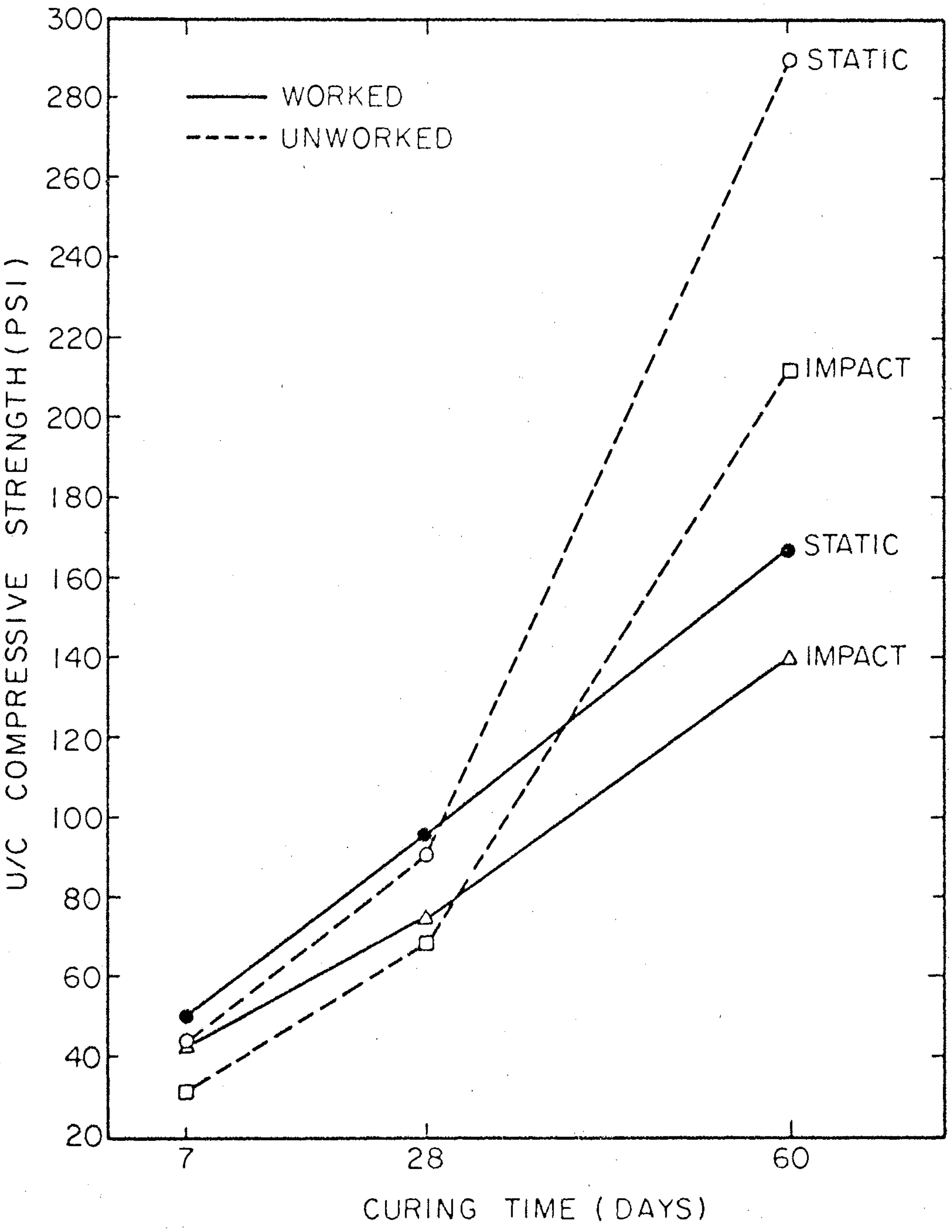

Figure 20. Effect of Curing Age on Unconfined Compressive Strength, Laterite + 5% Lime

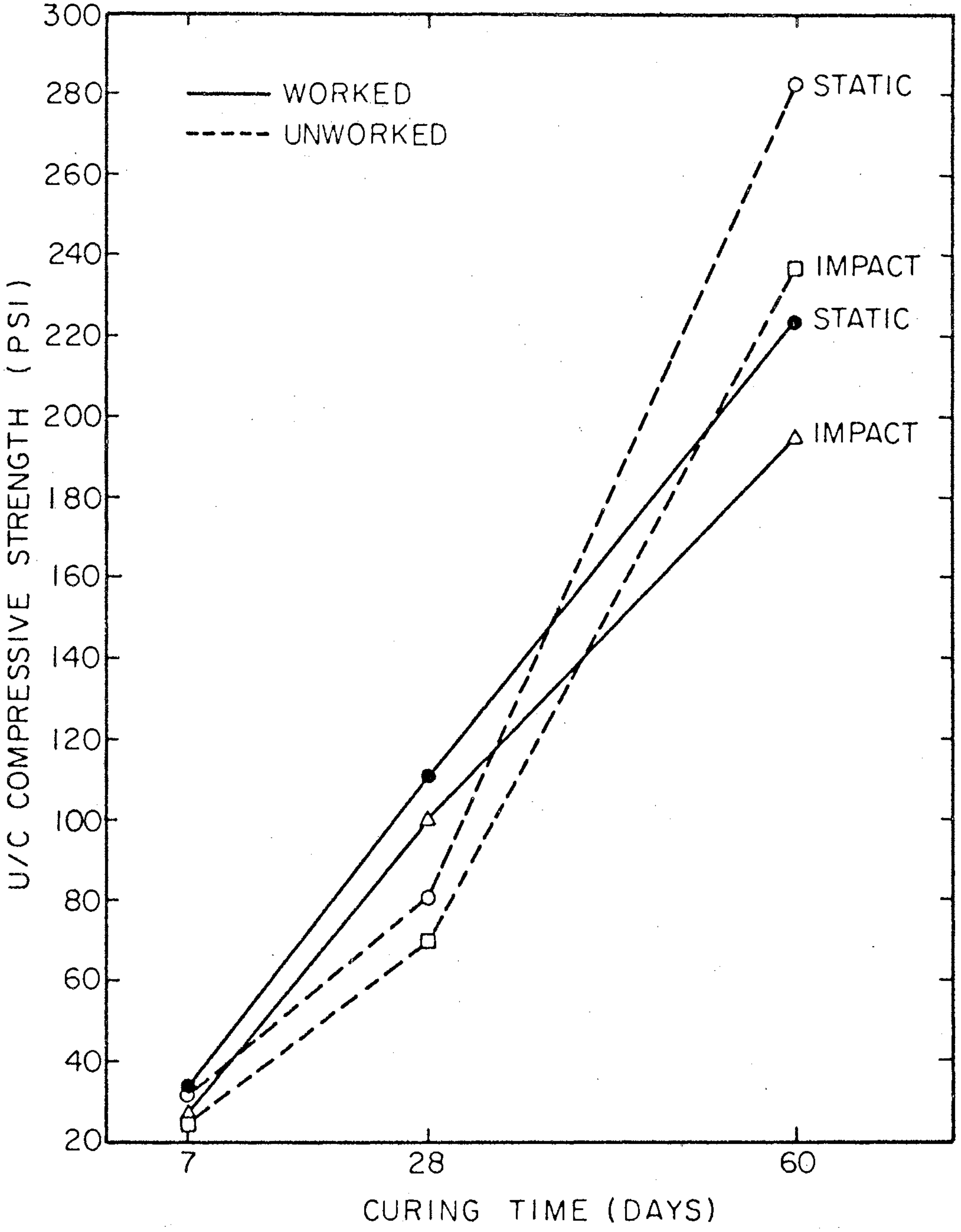

Figure 21. Effect of Curing Age on Unconfined Compressive Strength, Laterite + 10% Lime

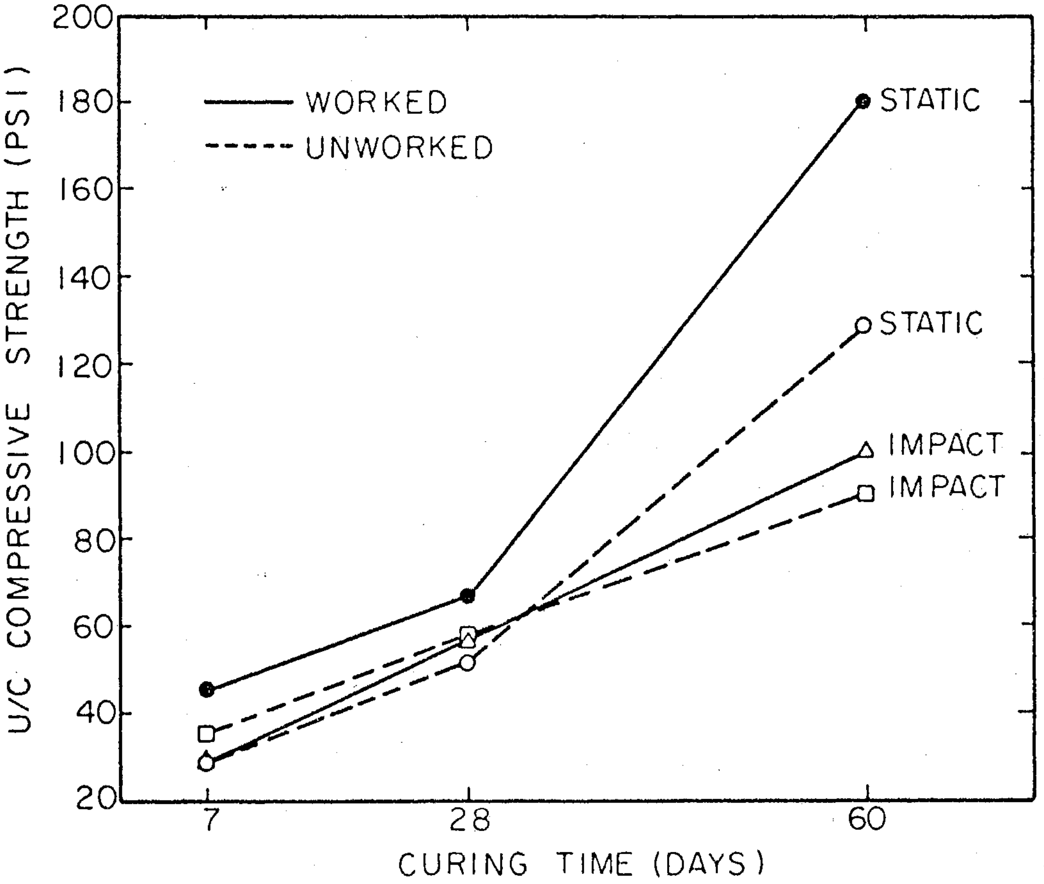

Figure 22. Effect of Curing Age On Unconfined Compressive Strength, Laterite + 20% Lime

Lime Content

Figures 23, 24, and 25 show the effect of lime content on the unconfined compressive strengths of the soils after various periods of curing.

In Figure 23, the optimum lime content for the seven day curing period appears to be at 5 percent. The increase in strength between 2 1/2 and 5 percent lime contents is caused by the increase in aggregation due to base exchange. The drop in strengths at 10 percent lime is due to overliming; i.e., there is an excess of lime above that required for base exchange reactions with the exposed silica. However, if the curing period was longer, the strengths would have been higher than those attained at 5 percent due to pozzolanic reaction as was the case in the 28 and 60 days curing periods (Figures 24, 25). No explanation can be offered for the increase in strengths by the worked soil compacted statically, and the unworked soil compacted by the impact method at 20 percent lime content (Figure 23).

For the 28 days curing period, the optimum lime content of the unworked soil, compacted statically, appears to be at 5 percent. On the other hand, the optimum lime content of the worked samples (static and impact), and the unworked samples compacted by the impact method, appears to be at 10 percent. The increase in the optimum lime content is caused by the higher number of exposed clay particles in the latter cases. The drop in strengths at 20 percent lime is again caused by overliming.

The results obtained from the 60 days curing period (Figure 25) are a duplicate of those for 28 days as far as optimum lime contents

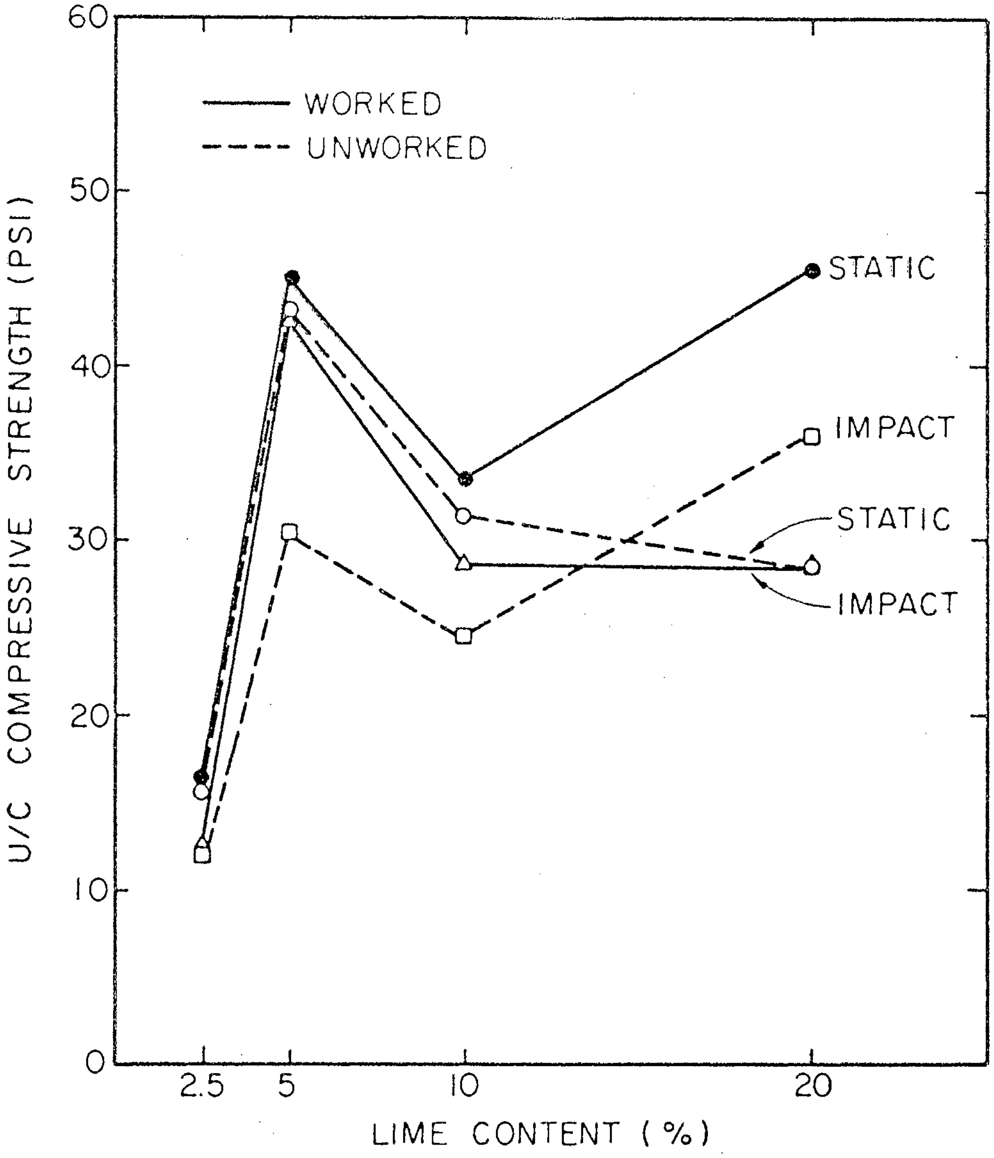

Figure 23. Effect of Lime Content on Unconfined Compressive Strength, 7 Days Cure

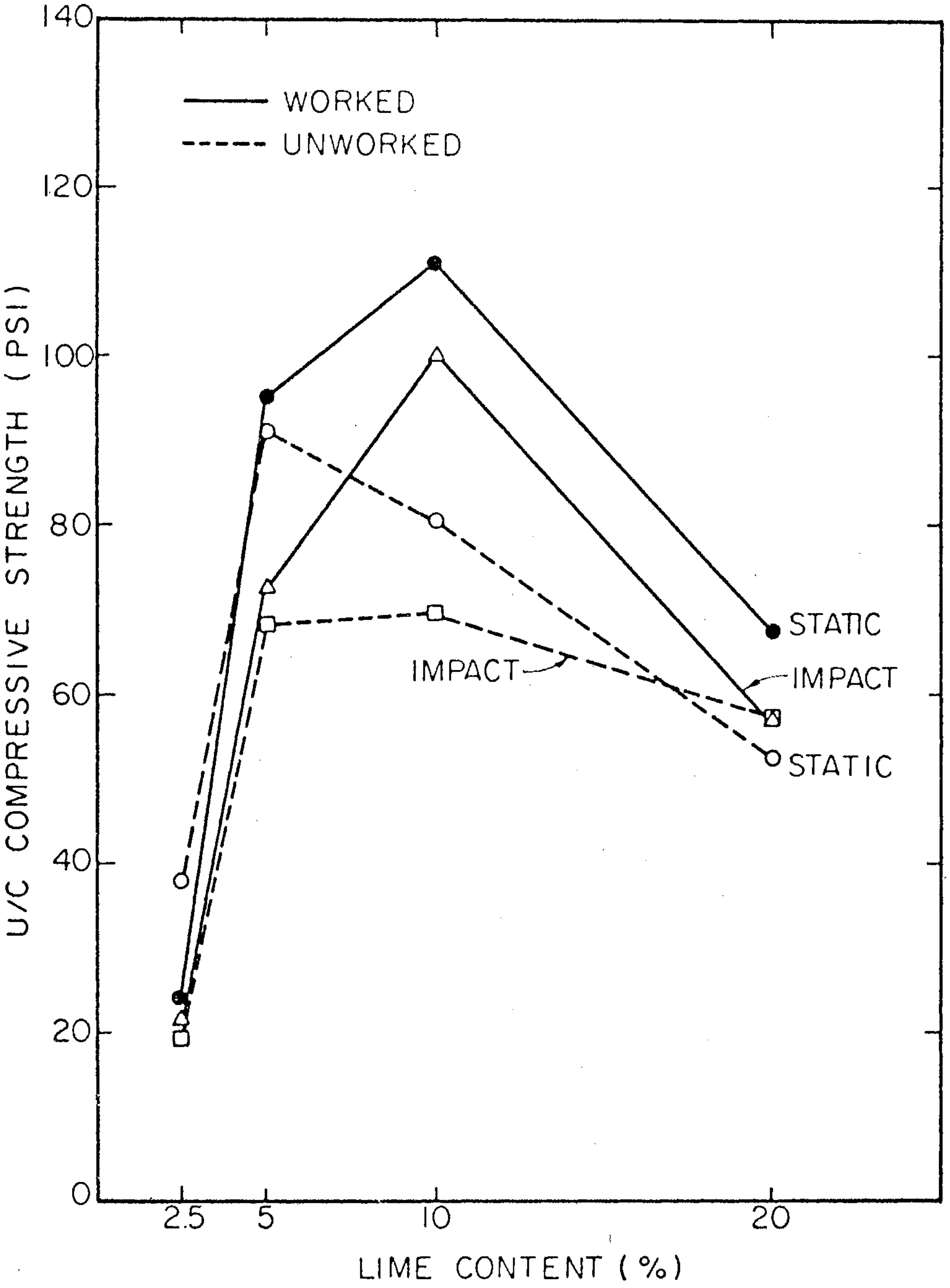

Figure 24. Effect of Lime Content on Unconfined Compressive Strength, 28 Days Cure

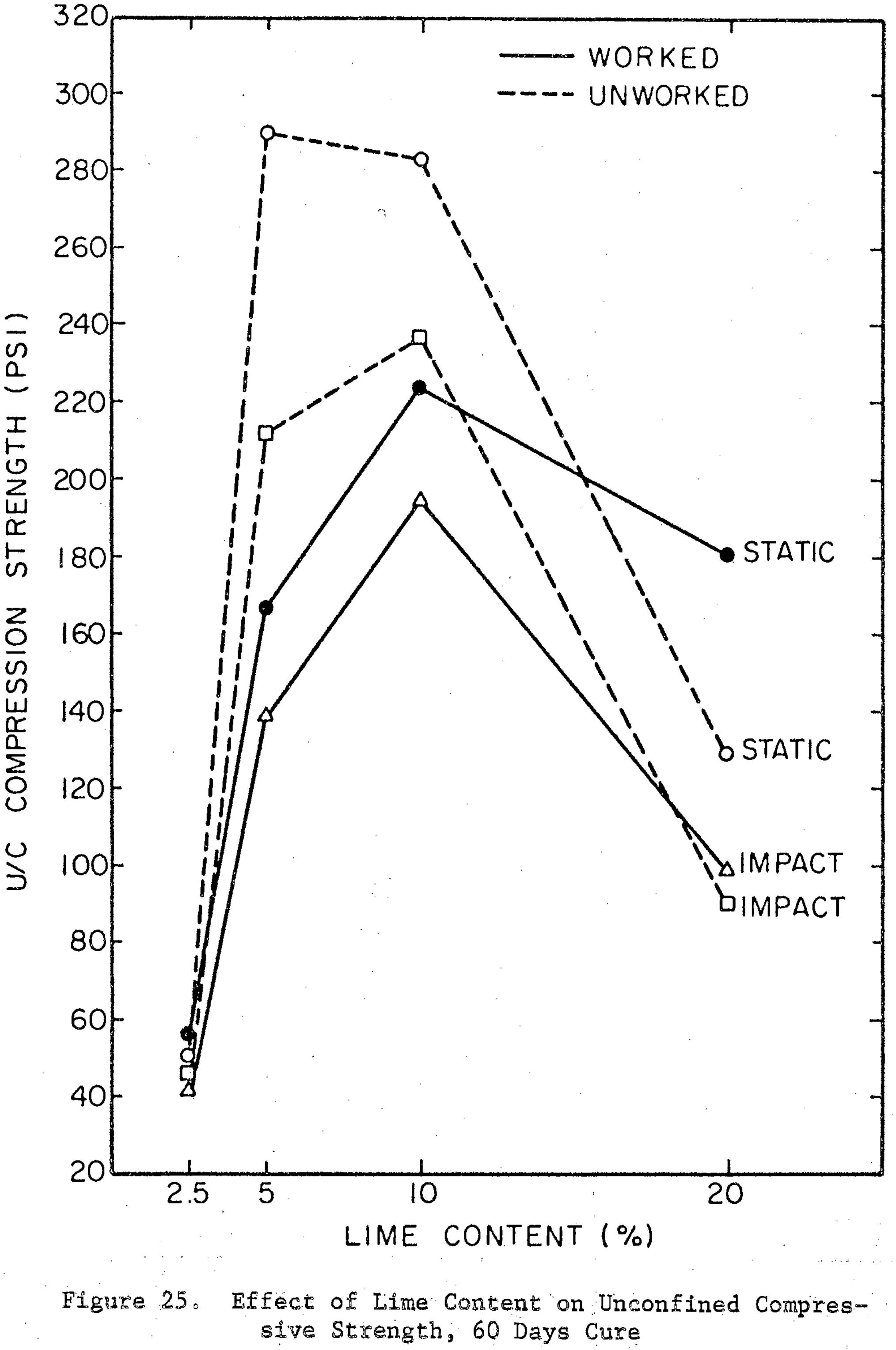

Figure 25. Effect of Lime Content on Unconfined Compressive Strength, 60 Days Cure

are concerned. However, there was a considerable gain in the strength values.

Comparison of the curves in Figures 24 and 25, at 10 percent lime content, show some interesting aspects, i.e., the reversal in maximum strengths of the worked soil at 28 days curing and the unworked soil at 60 days. Since most of the free silica has been leached from lateritic soils, very little base exchange occurs in the lime-unworked soil, and the only factor contributing to strength is the pozzolanic reaction resulting from the reaction of lime and the alumina in the sesquioxide coatings. On the other hand, the worked soil, with the coatings partially removed by working action, presents greater amounts of exposed clay particles. These exposed clay particles, combined with the lime have a twofold reaction; base exchange and pozzolanic reaction.

At 28 days curing (Figure 24), the worked soil gained strength by base exchange and pozzolanic reaction. At 60 days curing time, the same reactions took place. But since the lime reacted mostly in one way with the unworked soil, and the curing time was sufficient for pozzolanic reaction, higher strengths were obtained due to the cementing compounds that were formed. In the worked soil, the amount of lime was not sufficient to cause the same degree of pozzolanic reaction because most of the lime was used up for base exchange. It would appear that pozzolanic reaction contributes more to strength than base exchange for the longer curing periods.

Although the gains in strength were interpreted on the basis of chemical reactions in the soil, this author feels that the particle orientation has a great influence in the resulting strengths.

CHAPTER V

CONCLUSIONS

This investigation was a study of the effect of two compaction procedures on a Panamanian lateritic soil and of the influence of different lime contents. The following conclusions can be drawn, limited to the type of soil and testing procedures employed:

1. Mechanical working causes a breakdown of the granular structure possessed by the soil and increases the effective clay content.

2. Static compaction can be employed effectively and eliminates the breakdown of the granular structure, while impact compaction tends to cause a breakdown of the granular structure.

3. Impact compaction resulted in higher strengths in the case of the raw soil. On the other hand, static compaction proved to be superior in the stabilized soil.

4. Lime is an effective stabilizer for this type of soil and reacts with both the worked and unworked soils.

5. The optimum lime content is not a constant value, but rather, it varies with the length of the curing periods used, the method of compaction, and the nature of the soil, i.e., whether worked or unworked.

6. Length of the curing period is a critical factor. The strengths of the stabilized soil increase with prolonged curing periods.

Recommendations for Research

The following are suggestions for further research on lateritic soils:

1. An investigation of the effect of kneading compaction on the strength properties of lateritic soils.

2. Effects of immersion of the specimens on the strength values.

3. Triaxial tests to determine the effective strength parameters of lateritic soils based on measurement of the pore water pressure.

4. A study of the particle orientation, to determine the effect of compaction procedure on the soil structure.

5. An investigation of the effect of lime stabilization using longer periods of curing time.

6. An investigation similar to this study, using lateritic soils from other parts of the world. Such an investigation would determine if the conclusions of this study are applicable to a wide variety of lateritic soils.

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APPENDIX

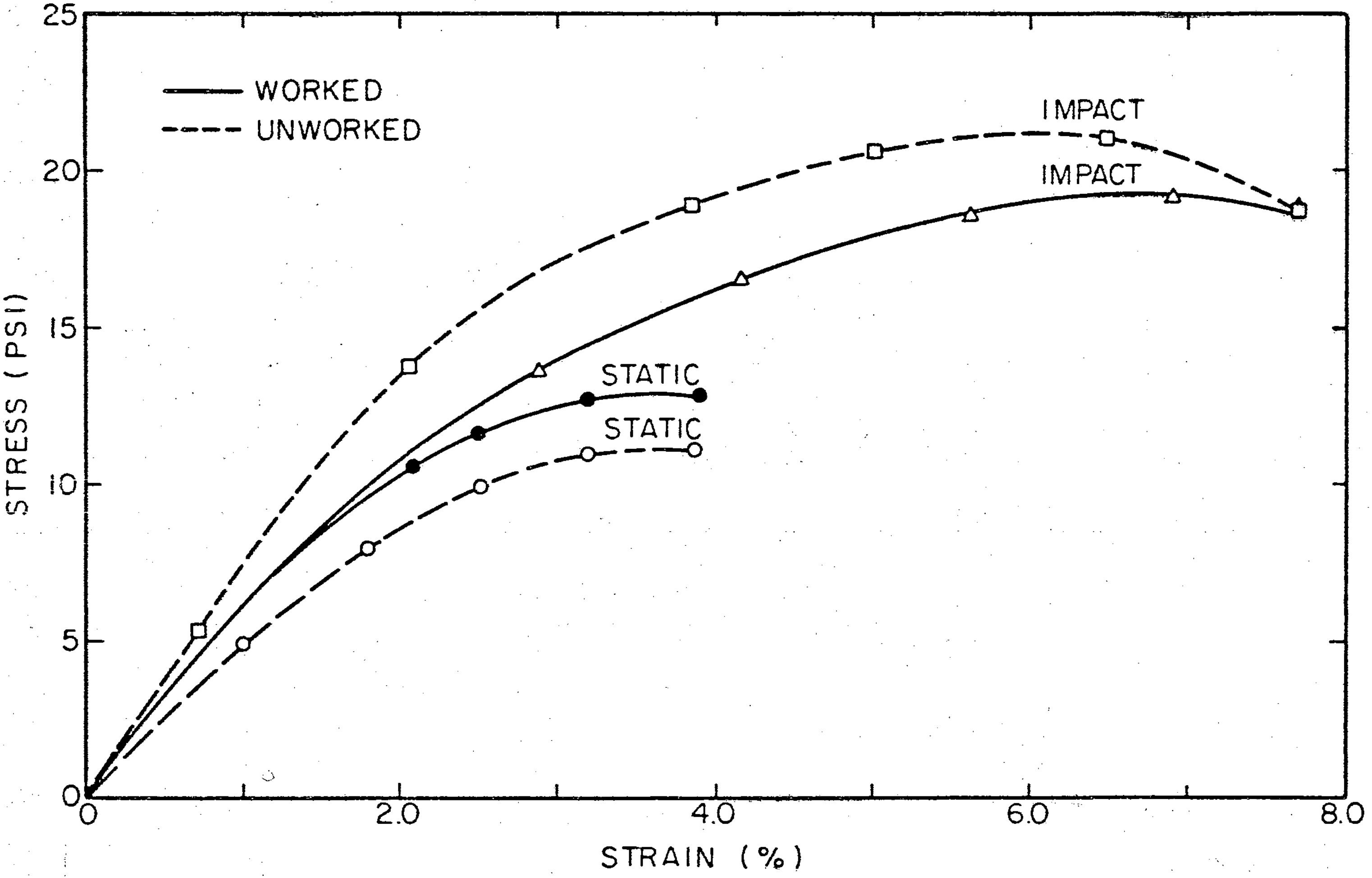

Figure 26. Stress-Strain Characteristics, Laterite + No Additives

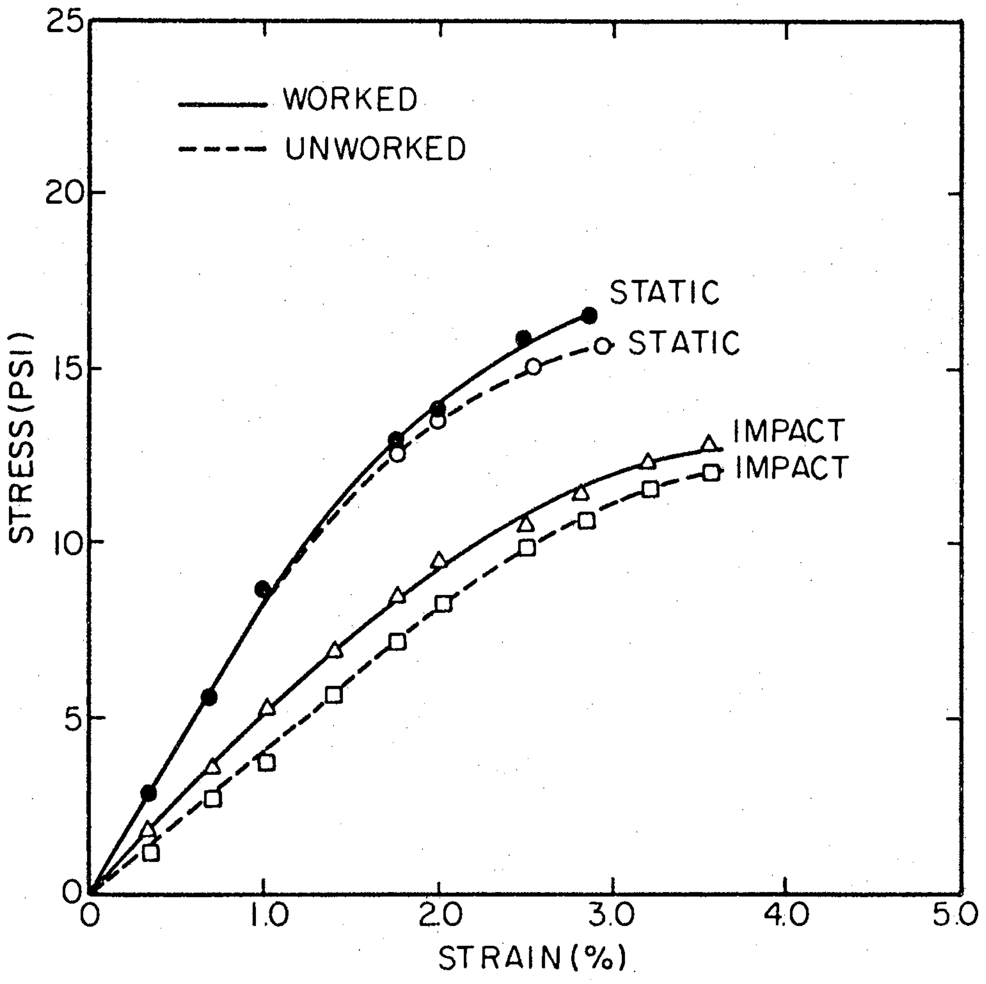

Figure 27. Stress-Strain Characteristics, Laterite + 2 1/2% Lime, 7 Days Cure

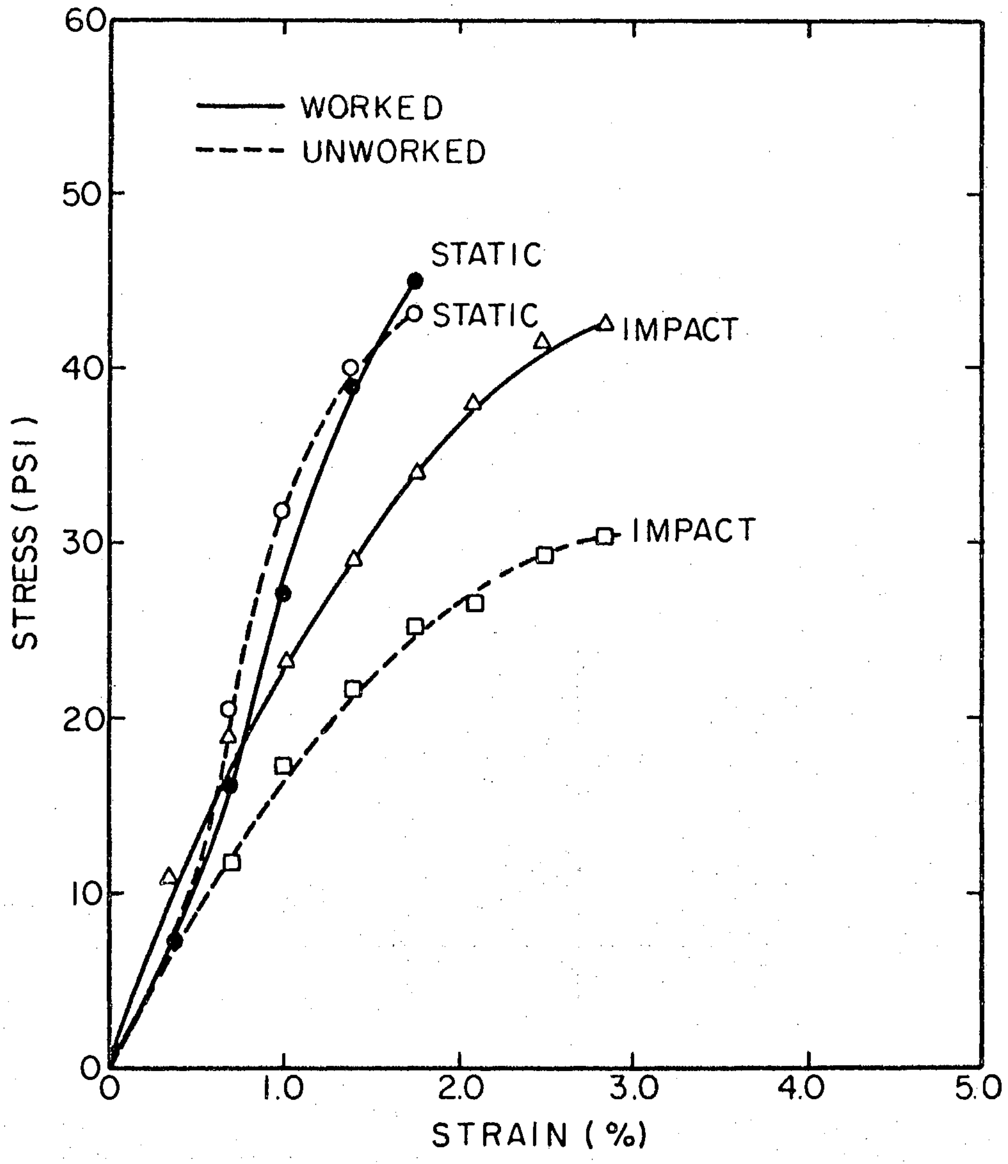

Figure 28. Stress-Strain Characteristics, Laterite + 5% Lime, 7 Days Cure

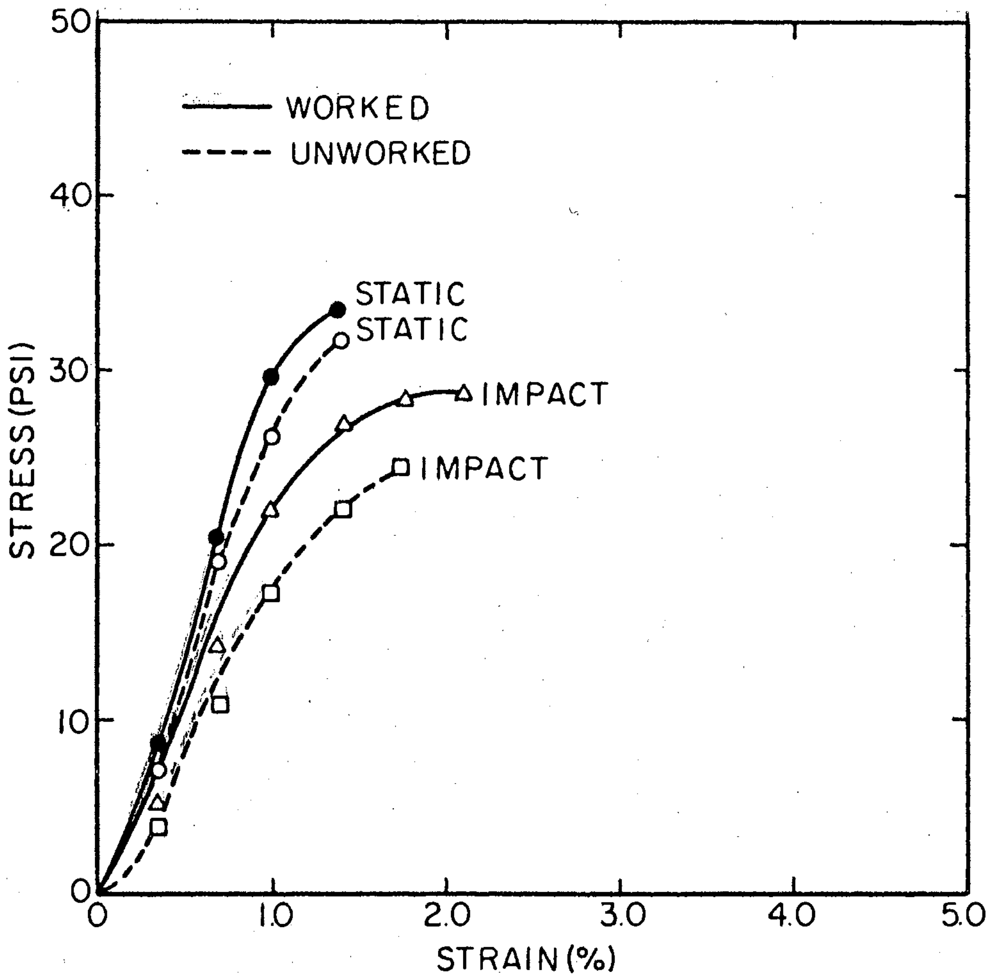

Figure 29. Stress-Strain Characteristics, Laterite + 10% Lime, 7 Days Cure

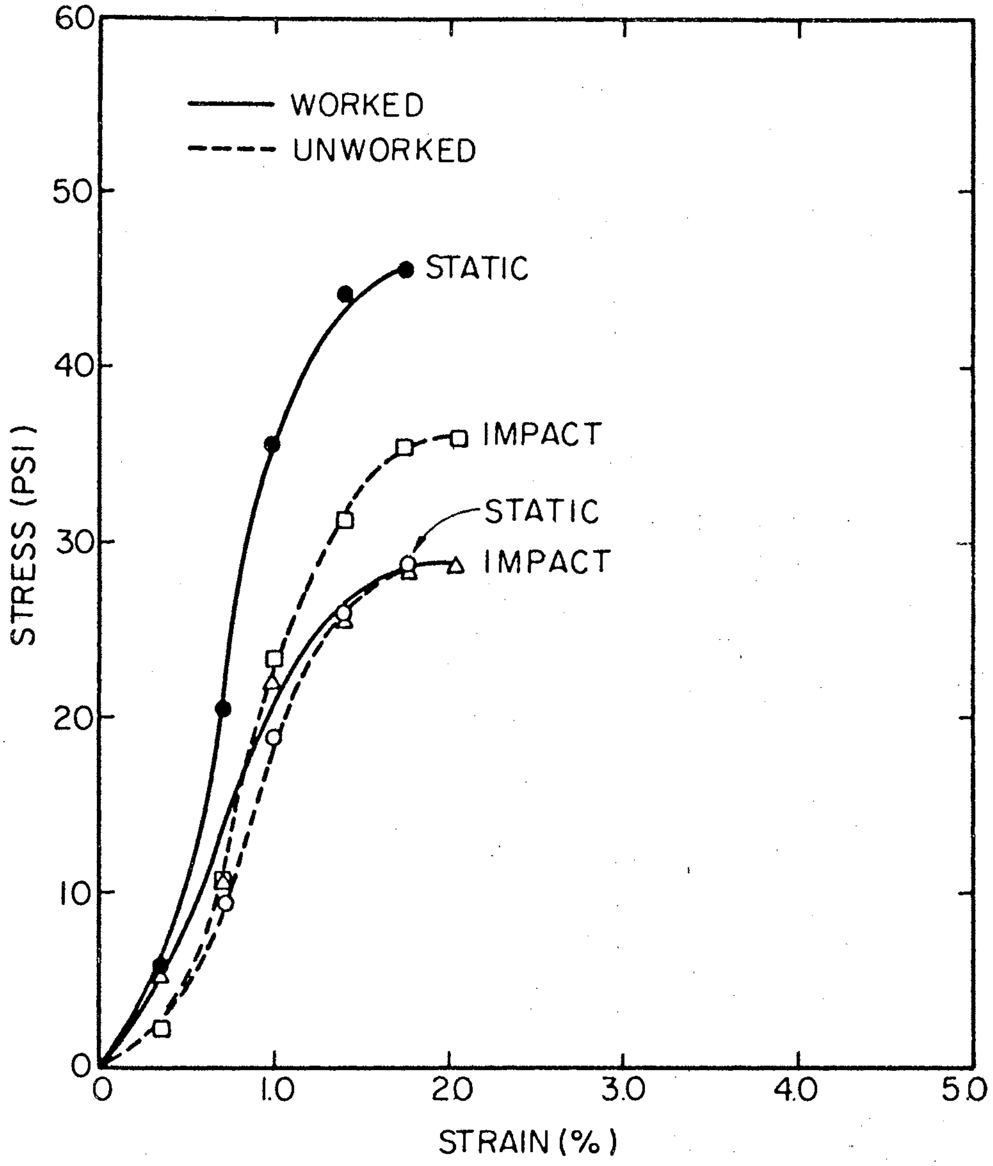

Figure 30. Stress-Strain Characteristics, Laterite + 20% Lime, 7 Days Cure

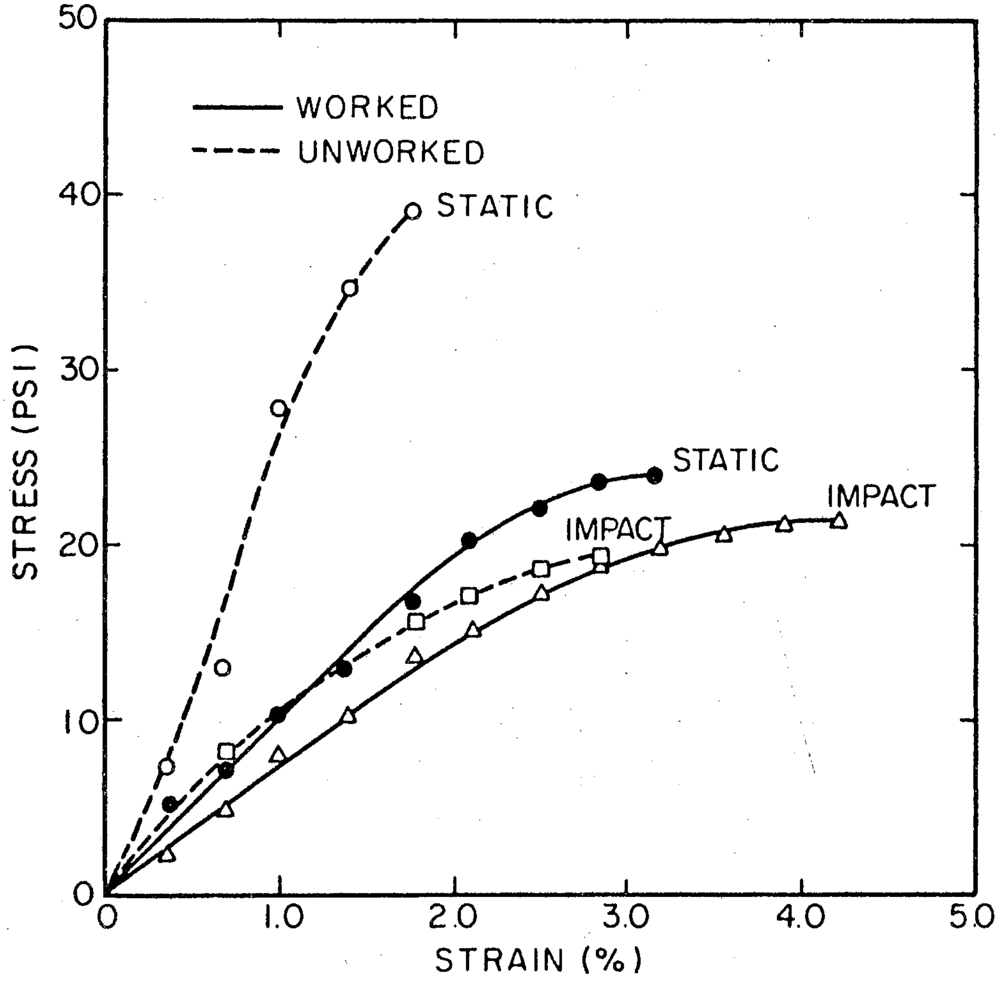

Figure 31. Stress-Strain Characteristics, Laterite + 2 1/2% Lime, 28 Days Cure

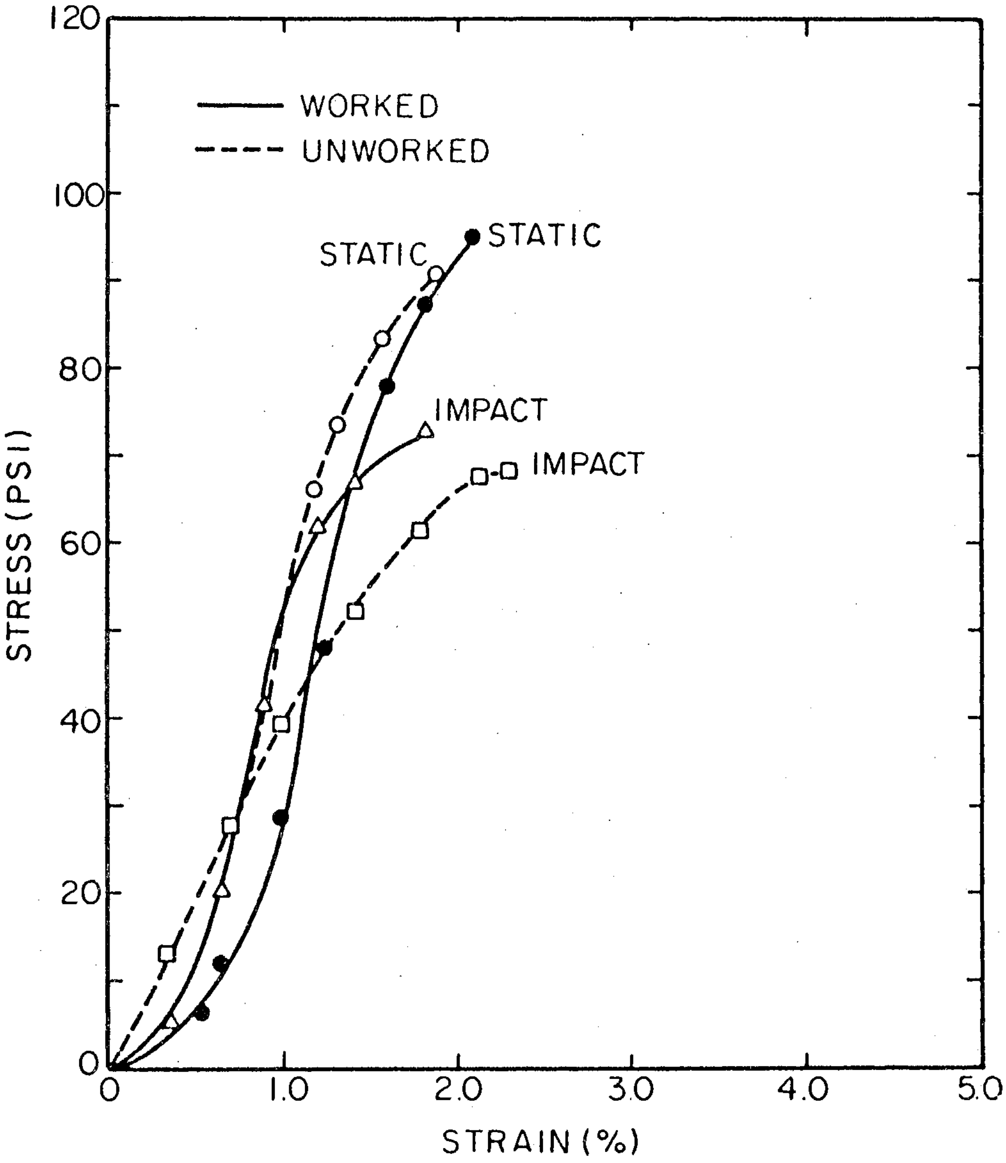

Figure 32. Stress-Strain Characteristics, Laterite + 5% Lime, 28 Days Cure

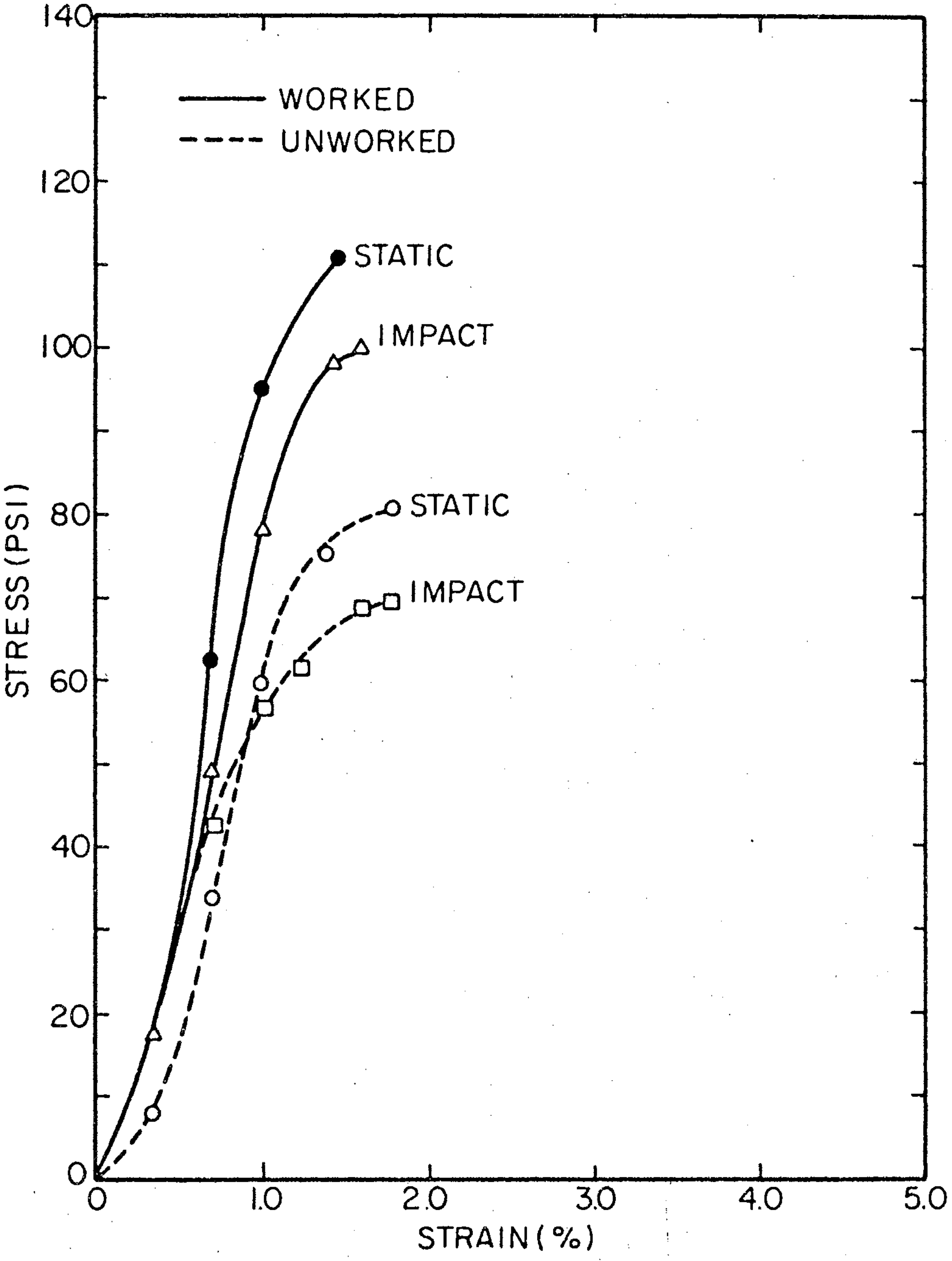

Figure 33. Stress-Strain Characteristics, Laterite + 10% Lime, 28 Days Cure

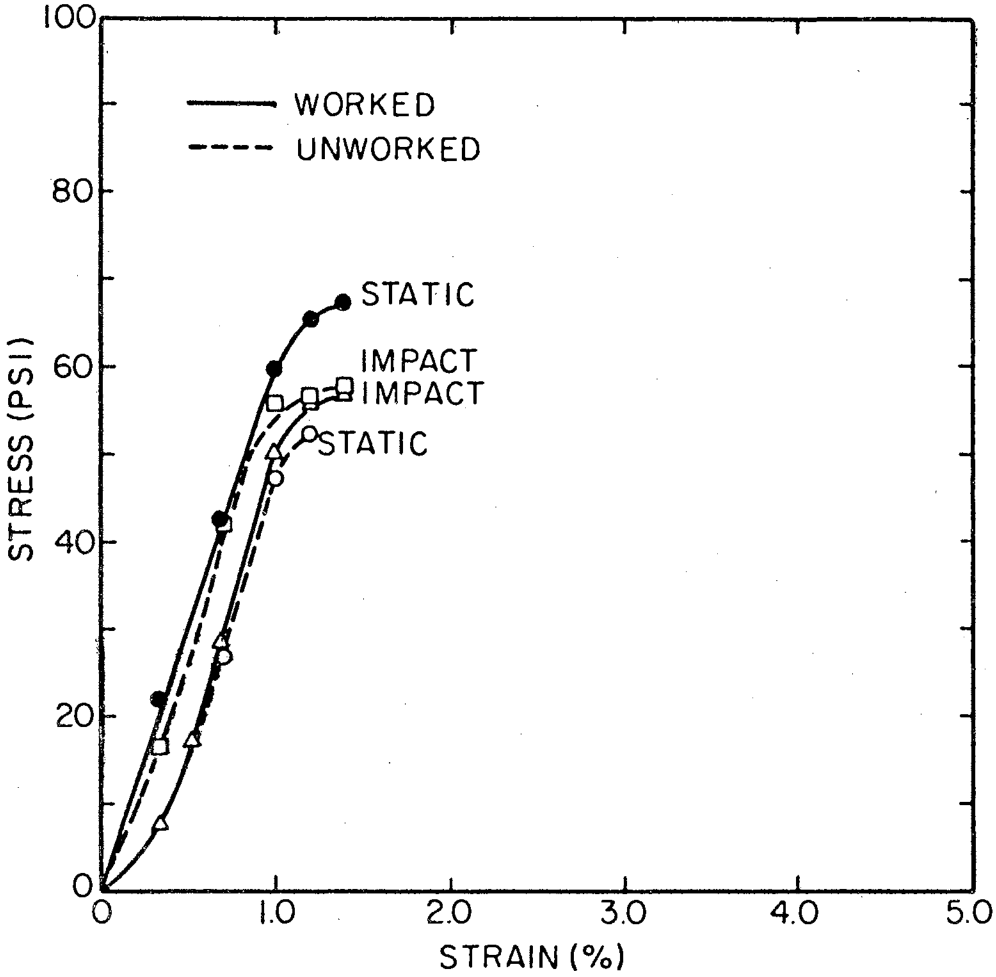

Figure 34. Stress-Strain Characteristics, Laterite + 20% Lime, 28 Days Cure

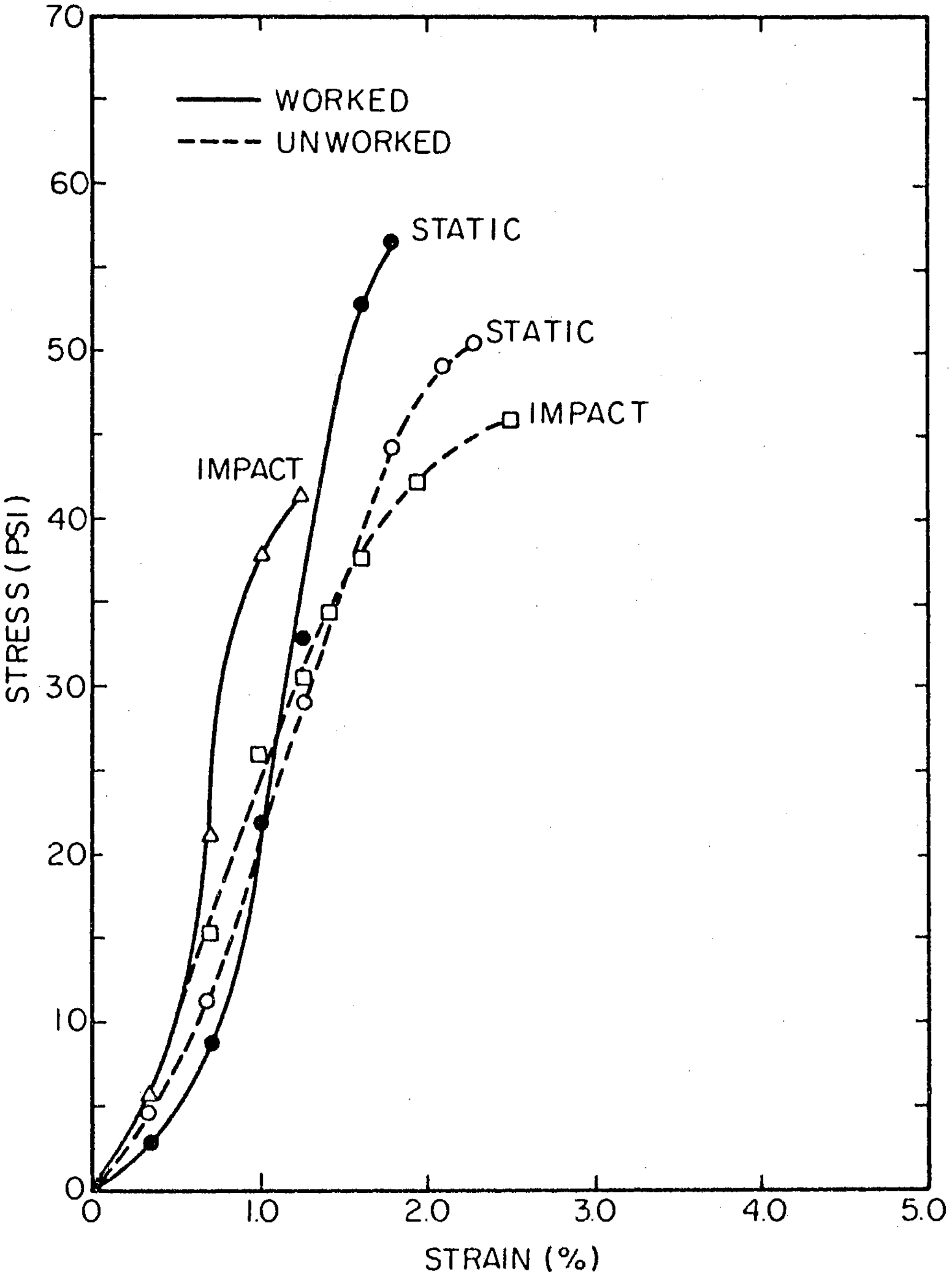

Figure 35. Stress-Strain Characteristics, Laterite + 2 1/2% Lime, 60 Days Cure

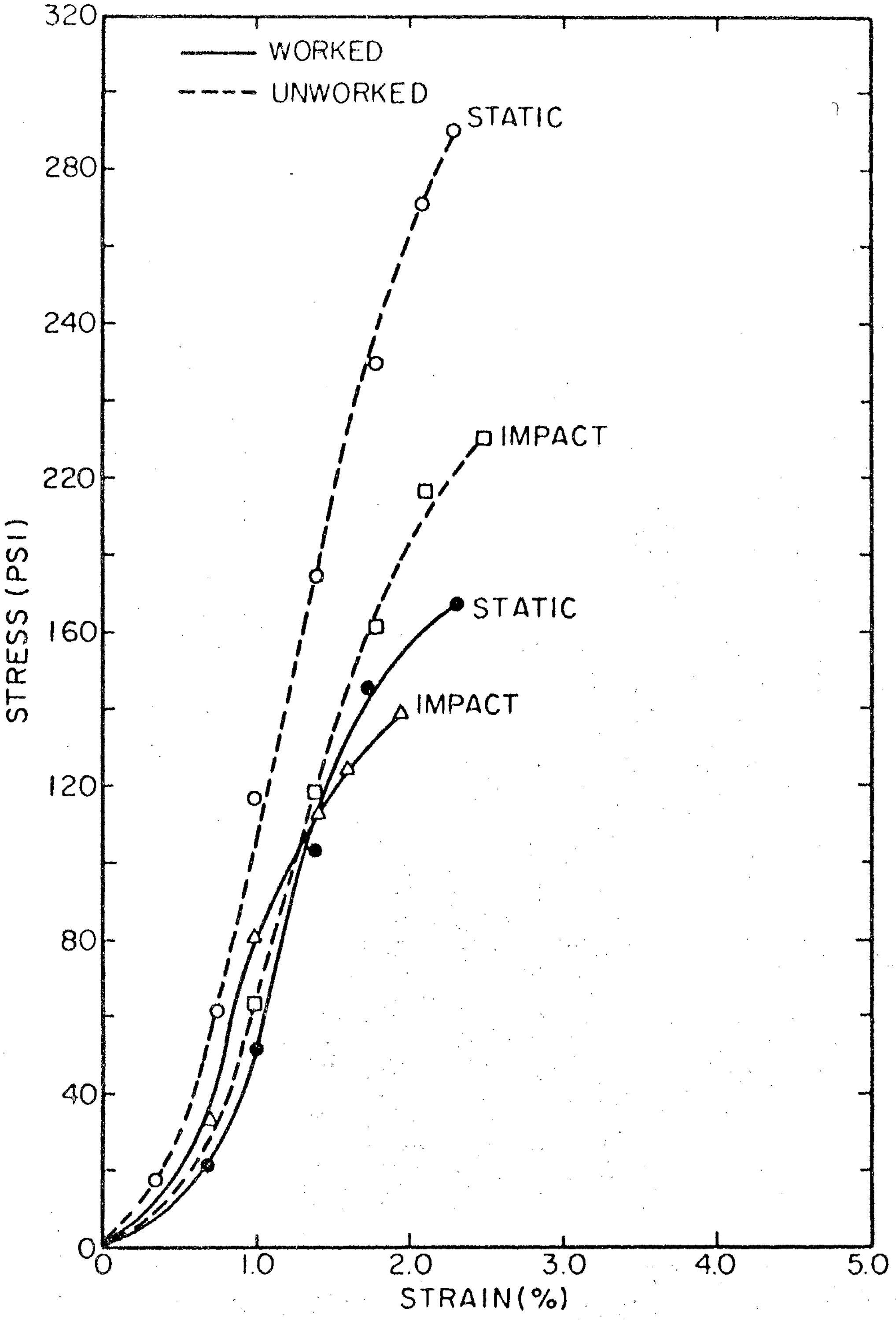

Figure 36. Stress-Strain Characteristics, Laterite + 5% Lime, 60 Days Cure

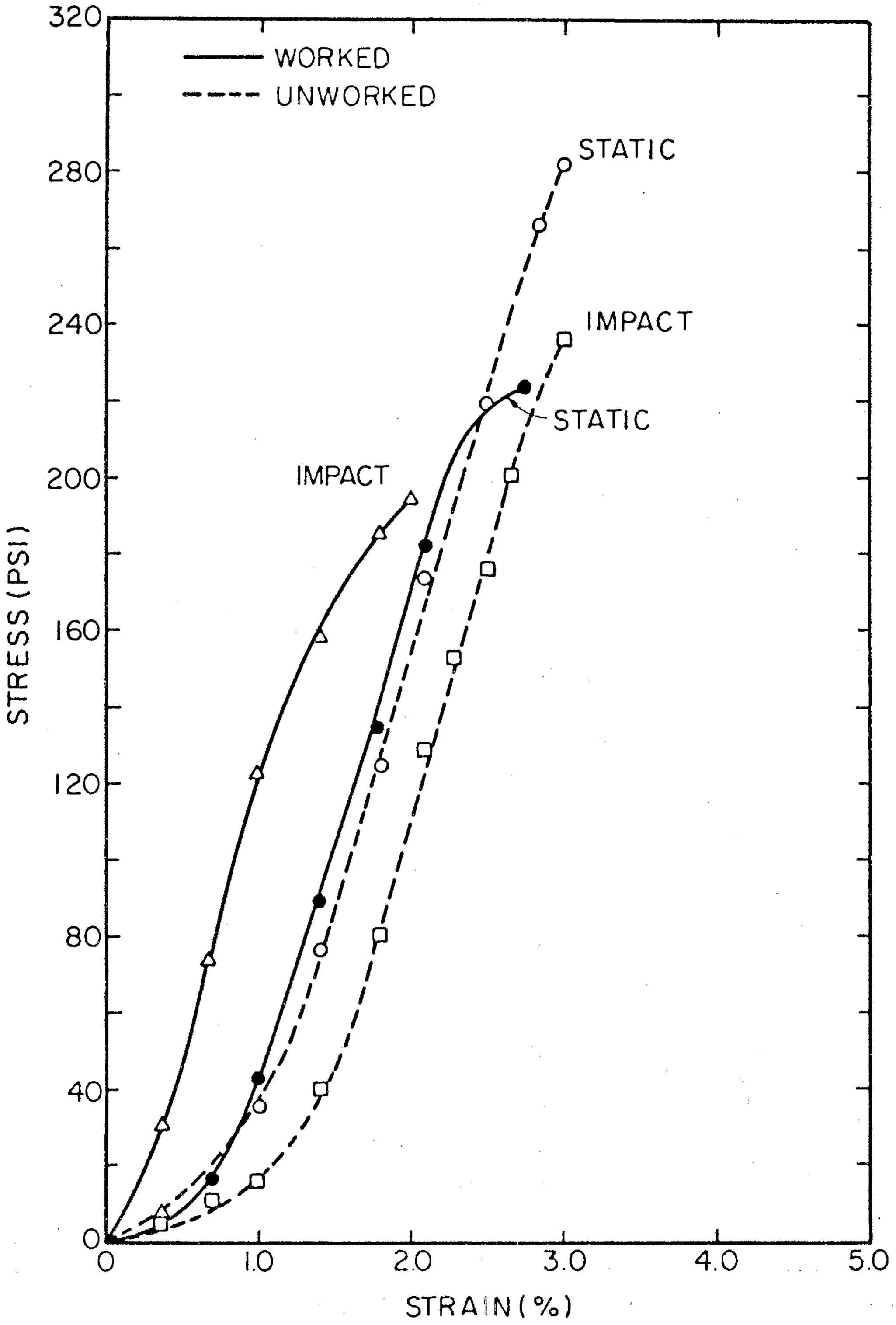

Figure 37. Stress-Strain Characteristics, Laterite + 10% Lime, 60 Days Cure

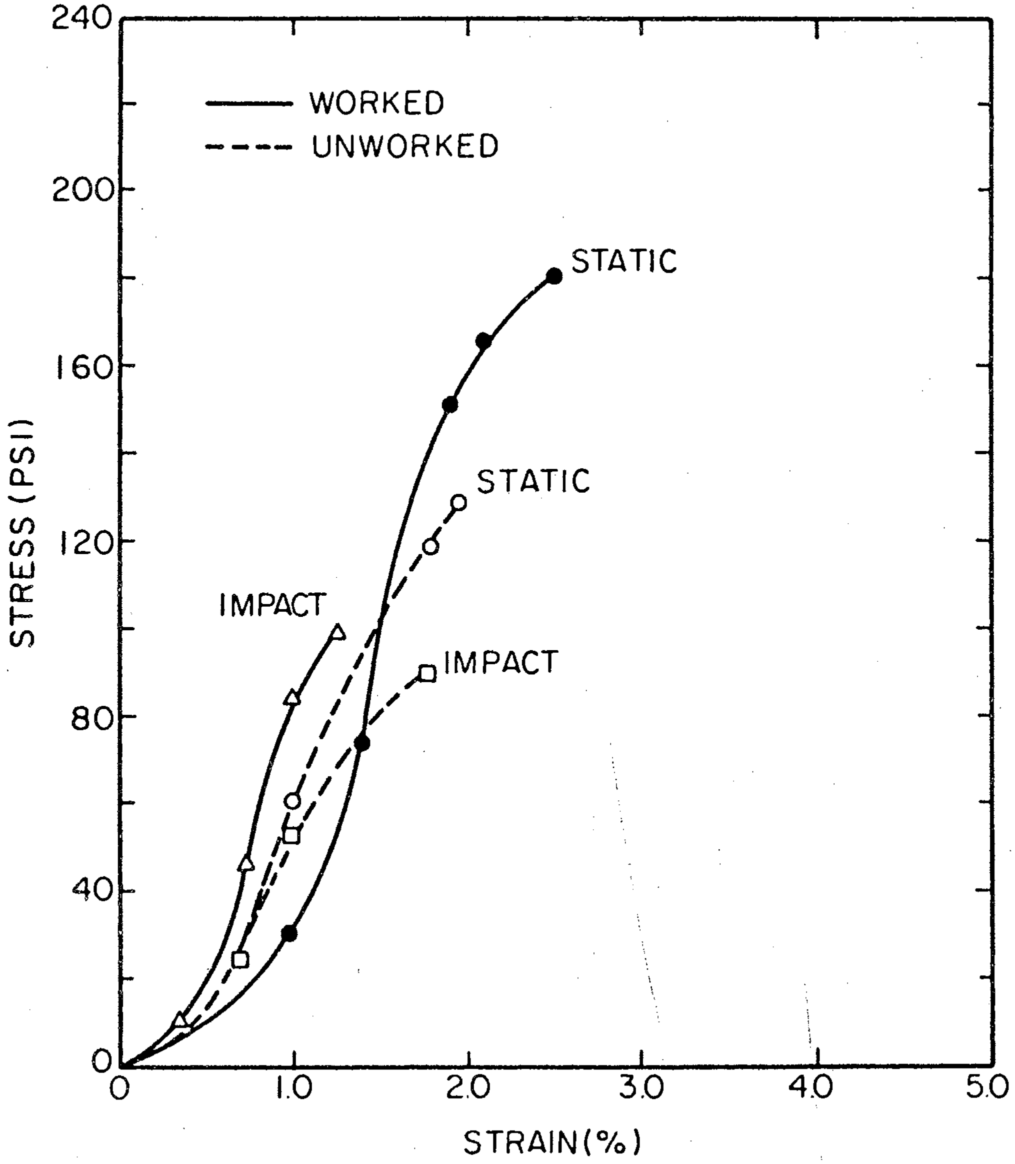

Figure 38. Stress-Strain Characteristics, Laterite + 20% Lime, 60 Days Cure

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