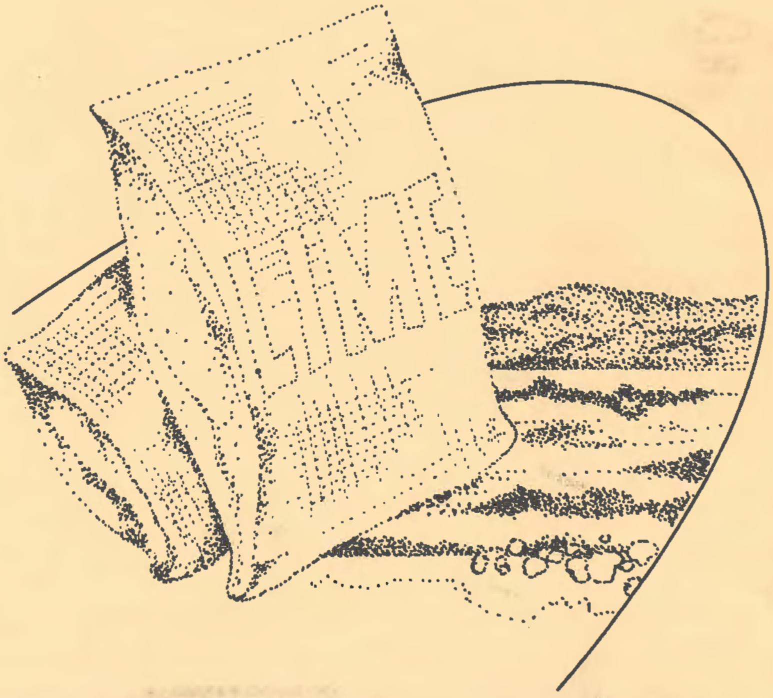
A PRELIMINARY STUDY OF SOIL STABILIZATION PROCEDURES



RESEARCH CONDUCTED BY
CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF ARKANSAS

ARKANSAS STATE HIGHWAY DEPARTMENT
PLANNING AND RESEARCH DIVISION
IN COOPERATION WITH
U.S. DEPARTMENT OF COMMERCE
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RESEARCH PROJECT 13

A PRELIMINARY STUDY OF SOIL STABILIZATION PROCEDURES

BY

EDWARD C. GRUBBS

Associate Professor of Civil Engineering

Civil Engineering Department
University of Arkansas
Fayetteville, Arkansas

ARKANSAS STATE HIGHWAY DEPARTMENT
DIVISION OF PLANNING AND RESEARCH

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CHAPTER I

INTRODUCTION

This report presents the results of research performed by the Civil Engineering Department of the University of Arkansas and sponsored by the Arkansas State Highway Commission and the Department of Commerce, Bureau of Public Roads. This project, entitled "Preliminary Study of Soil Stabilization Procedures", was designated Highway Research Committee Project No. 13.

Project 13 was approved in March, 1963, for direction by Mr. M. L. Odem, Principal Investigator. On June 1, 1963, Mr. Miller Ford assumed the temporary duties of the Principal Investigator. The direction of Highway Research Committee Project No. 13 was given to the writer on September 1, 1963.

The purpose of this report is: (a) to review the published work on soil stabilization and provide the Arkansas Highway Department with a summary of the information with suggestions and recommendations as to its applicability to Arkansas Highway Construction; (b) to investigate the possible use of several industrial by-products as economical additives for stabilizing Arkansas soils; and (c) to report the results of the above studies together with appropriate conclusions and recommendations to the Arkansas Highway Department.

CHAPTER II

PRESENT STATE OF KNOWLEDGE

Soil stabilization in its broadest sense may be defined as any regulated process of adding materials to a soil to result in changes in the characteristics of the soil, with increases in strength and volumetric stability being the most desired outcomes. Soil stabilization is, therefore, the name given to those methods used in construction in which soils are treated to provide for stronger and more durable roadbed, subbase and base courses. Thus the purpose of stabilization is the ultimate improvement of roadway materials so that they can carry the applied traffic loads under all normal environmental conditions for the economical service life of the roadway.

Soil stabilization is becoming increasingly important in highway construction due to the natural depletion of base material, the increased wheel loads which a road must carry, and the need for inexpensive all-weather secondary roads. With the advent of the Interstate Highway System, highways could no longer be located so as to by-pass poor foundation materials, nor could the location be governed solely on the availability of good road building materials. For these reasons the problems of poor foundations and poor building materials could not be by-passed, and had to be solved. Soil stabilization has been a valuable tool in helping to solve some of these problems.

2.1 Criteria for Evaluating Soil Additives

The effectiveness of an additive to stabilize a soil is most generally evaluated on the basis of comparative laboratory tests performed using treated and untreated soils. The tests generally performed include tests to determine the volumetric stability, compressive strength, freeze-thaw characteristics, plasticity changes, and absorption characteristics. Volumetric stability is usually determined by measuring the amount of shrinking and swelling that takes place in specimens prepared with various amounts of additives and the untreated soil. A reduction in the shrinking or swelling of the soil resulting from an additive indicates that the additive may be classified as a stabilizing agent. Compressive strength is usually determined by triaxial compression or unconfined compression tests, with the unconfined compression test being the most common. An increase in strength results in a high classification of the additive. Freeze-thaw tests are performed in some localities to provide an indication of the change in strength and volumetric stability as a result of the action of freezing and thawing. Plasticity changes are determined by performing the Atterberg limit tests on the untreated soil and on the soil altered by the addition of various amounts of additives. Absorption tests are performed to determine the increase or decrease in water absorption characteristics as a result of the additive.

2.2 Action of Stabilizing Additives

The success of an additive to act as a stabilizer when mixed with a soil depends on its ability to react with the soil. The types of reactions that take place are classified as chemical actions, mechanical actions, cementing actions, or a combination of any of the above. Although there are many sub-classifications of soil stabilization, these are ancillary to the main reactions.

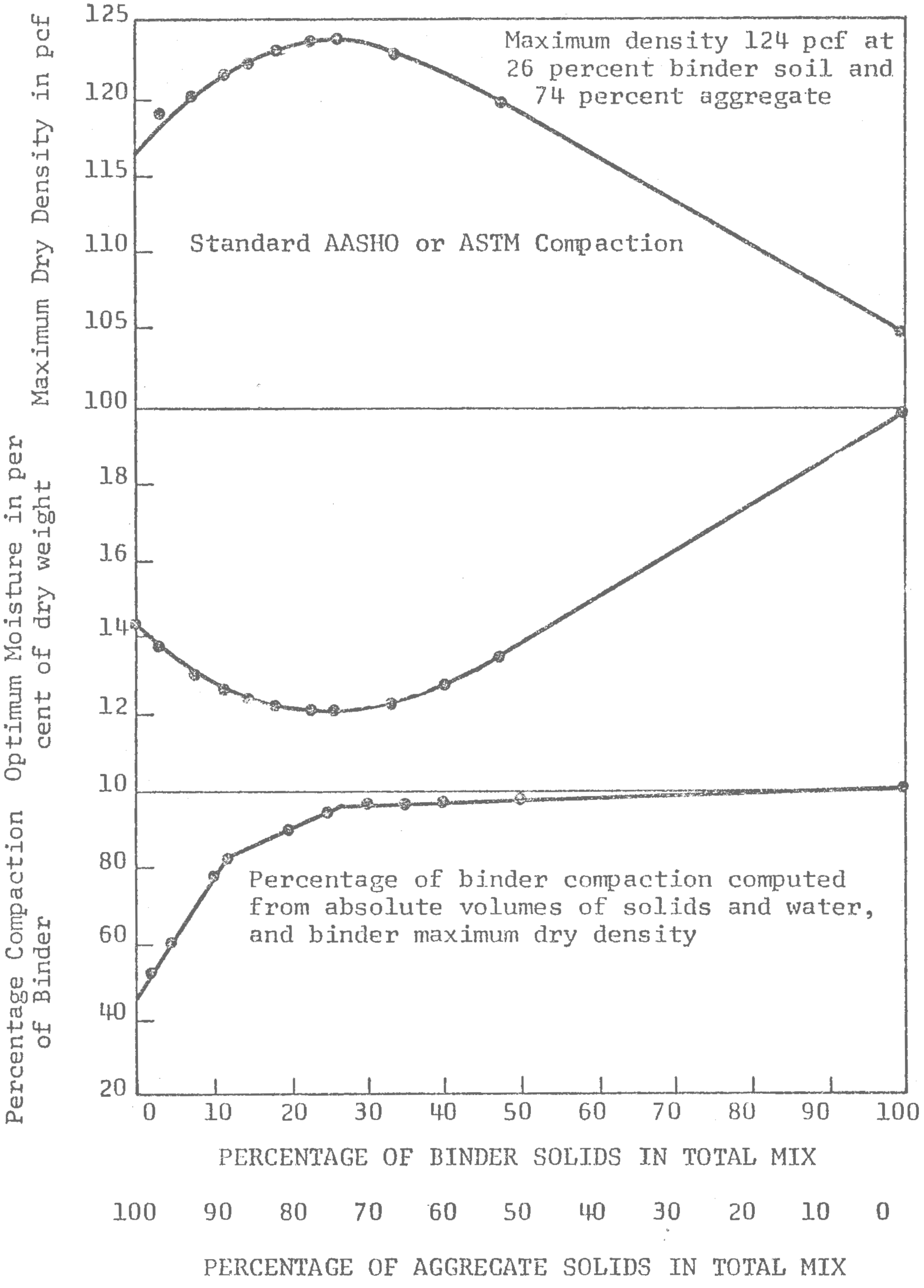
a. Mechanical stabilization. Mechanical stabilization is simply the addition of one or more soils to the parent soil to remedy a deficiency of the parent material. This type of stabilization is usually used to improve the gradations specifications of available materials. For example, Handy, et. al. (8), reported that mixing of a binder material with in-place Arctic beach sand in Alaska increased the soaked CBR tenfold. While the actual strength obtained in this case was not sufficient for all applications, it does demonstrate the benefit which can be derived from proper application of the principals of mechanical stabilization.

In other research on strength of soil-aggregate mixtures, Miller and Sowers (23) proposed a method of determining the best soil-aggregate mix. Briefly, this method is to compact aggregate and binder separately and to determine the weight of the binder required to fill the voids of the aggregate. The results indicate that the actual amount of binder specified may vary from 50 to 100% of the amount of binder required to fill the aggregate voids without materially affecting the resultant bearing capacity. The general effect of mixed proportions on water content and density is illustrated in Figure 1.

b. Cementing action. The need for greater strengths and increased durability of roadway foundation materials has led to the use of a large number of materials in soil stabilization. The primary function of one group of these materials is to form a cement bond connecting the individual soil particles or groups of particles. The actual nature of the bonds formed by the cementing agents differ. Some bonds, such as those occurring in portland cement are chemical. Other bonds, such as those found with asphalt additives, are mechanical.

FIGURE 1

MAXIMUM DENSITY, OPTIMUM MOISTURE, AND PERCENTAGE OF COMPACTION OF BINDER FOR VARIOUS PROPORTIONS OF BINDER SOIL AND AGGREGATE
(After Miller and Sowers, 1957 (23))



However, those materials whose functions are to increase the strength and volumetric stability of the admixtures by binding the soil particles together (by means other than electrochemical bonds) are classified as cementing additives. The effectiveness of some of the more important cement stabilizing additives will be discussed on the following pages.

c. Chemical stabilization. Chemical stabilization involves the use of various chemical additives in the process of soil stabilization. Although many chemicals have been used experimentally and in practice over the past 15 to 20 years to stabilize the less suitable soils encountered in highway and airfield construction, some have met with more success than others. An understanding of the chemical reactions involved in the process of soil stabilization is essential in selecting the proper additives for various soils. In general these reactions may be classified as ones of cation exchange, water-proofing and/or formation of weak cement.

(1). Cation Exchange: In a clay electrolyte system, the negatively charged clay particles attract both water molecules and hydrated cations. Following equilibrium, a diffused electro-double layer is formed adjacent to the clay surface. The forces holding the cations are a function of the distance from the clay surface to the ionic center of the hydrated cations, i.e., the larger effective cation radius will result in weaker force fields. For example, if an electrolyte in a clay system contains two cations of the same valence but with different effective radii, the cation with the smallest effective radius will approach the negatively charged clay surface more closely. If it completely satisfies the negative surface charge, the cation with the larger effective radius will no longer be attracted to the surface. This phenomena is termed "cation exchange".

Cation exchange is related to the zeta potential. Since clays with high zeta potentials are those that have absorbed cations at greater distances from their surfaces, they contain more readily exchangeable cations. These concepts, cation exchange and zeta potential, are useful in explaining terms familiar to engineers, namely, flocculation and dispersion. Dispersion implies that particles are separated, while flocculation suggests that they are held together. Clays having high zeta potentials are dispersed since their absorbed cations are further removed from their surfaces. Conversely, clays with low zeta potential should flocculate more readily. Thus, the zeta potential can be used to classify the exchangeability of the various cations in clay-electrolyte systems, as well as to indicate the ability of various cations to cause flocculation or dispersion.

The electro-double layer and the zeta potential theories are aids in explaining the distribution of the forces adjacent to clay mineral particles. According to these concepts, force fields exist in the vicinity of clay minerals and are reduced by the cations in the surrounding solution. The closer the cations are held to the charged surfaces, the greater is the reduction of the force field, the lower is the zeta potential, the more difficult it becomes to replace or exchange these cations with others and the more stable is the clay soil. Thus, one of the major methods of stabilizing clay soils for engineering purposes is to take advantage of the exchange properties of clays, in order to substitute more desirable cations for less desirable ones.

A measure of the activity of a clay is its ability to exchange cations. Generally, the cation exchange capacity of the clay minerals varies in the order of montmorillonite > illite > kaolinite. The replacing power of the more common cations, although not always the same, has been found to be $Na^+ < K^+ < Ca^{++} < Mg^{++} < NH_4^+$, which means simply that Ca^{++} will more easily replace Na^+ than Na^+ will replace Ca^{++}.

Since occasionally adverse effects can result from cation exchange, it is necessary for engineers to observe some caution. An example of difficulties that could be encountered by engineers in highway construction is: the difference in soil behaviors resulting from laboratory testing based on tap water, and the behavior of materials in place when water is obtained from nearby streams containing sufficient impurities to alter the engineering characteristics of the material.

(2). Waterproofing: One of the prime requirements for any stabilizer used in roadway construction is that the stabilized soil specimens should attain, or increase, their shear resistance even in the presence of saturating amounts of water. Chemical additives have been developed that can render the soil grains hydrophobic, thus improving their properties in the presence of water although they do not necessarily cement or bond the soil grains together. Most of these types of chemical additives developed contain large organic cations. Therefore, the initial reaction may be one of limited cation exchange, while the resultant product is a "waterproof" soil.

The advantages of waterproofing a soil are apparent when considering detrimental affects that a high water table, or poor drainage conditions can have on the decrease in strength of roadway foundations. A decrease in the fluctuation of subgrade moisture will result in higher strengths and greater volumetric stability.

(3). Secondary Cementation: While cementation is classified under a separate category than chemical stabilization, many chemical additives function as weak cements when mixed with soils. Generally, cementation resulting from chemical additives is a secondary effect, the primary purpose being the achievement of ion exchange or waterproofing. As will be discussed in subsequent paragraphs, the effectiveness of many chemical stabilizers is enhanced by this secondary cementation.

2.3 Important Soil Stabilizing Additives

Engineering publications abound with results of research on the use of potential soil stabilizers. From this multitude of research papers, it is easily observed that a practical, universal soil stabilizer has yet to be developed. Instead, certain additives are effective on one group of soils but are ineffective on others. However, as opposed to the embryonic days of soil stabilization, the present day engineer can usually select a material to suit his needs from the ever-increasing "library" of soil stabilizers. The following discussions are presented to point out a few of the additives selected from the stabilizer "library" which cover the range of stabilizers and could be of specific use in Arkansas.

a. Portland cement. Portland cement has been used as a soil additive for a number of years. The first recognized use of portland cement for making soil-cement was in 1915. (12). Since that time a voluminous amount of research has been carried out by a variety of agencies, including many state highway departments and the Portland Cement Association. The first extensive use of soil-cement was in airfield construction during World War II. After that time soil-cement began to be used more and more in highway construction until by 1960 the United States and Canada were using 46 million square yards of soil-cement annually.

Cement stabilization is achieved by mixing pulverized soil, measured amounts of portland cement, and water. Cement stabilization varies, in terms of degree of stabilization achieved, from cement-modified soil to soil-cement. A cement-modified soil has had its characteristics somewhat modified by the addition of cement but the quantity of cement added is less than that required to produce a stable material. Soil-cement implies certain hardness and durability characteristics. These characteristics and the method for testing and evaluating soil-cement are listed in ASTM. (1).

Cement can be used most effectively with sands, silts and clays of low plasticity. The use of cement with moderate to high plastic soils is marginal from an economic standpoint, principally because of the difficulties in obtaining proper distribution of the additive in the soil. The amount of cement required for effective stabilization increases with an increase in clay content (plasticity) (12). This is illustrated in Table 1.

The stabilization of soils by portland cement occurs in two ways. The first property change that occurs as cement is mixed with moist cohesive soils is a marked reduction in plasticity, probably caused by calcium ions released during the initial cement hydration reactions. The mechanism is basically one of a cation exchange. The second process is cementation. This is chemical in nature and may be visualized as the result of the development of chemical bonds or linkages between adjacent soil grain surfaces, so as to surround the exposed soil particles.

The degree of stabilization achieved depends on four main variables. The principal variable is the classification of soil to be stabilized i.e., sand, silt, or clay. The effect of cement on the plasticity and volumetric stability of various soils is illustrated in Figures 2 through 5. The second variable is the amount of cement added to the soil. In general the more volume of cement added the higher the effective stabilization becomes. However, in most instances the relation between quantity and stability tends to level out and an economical mixture can be determined. The addition of cement to soils improves

TABLE 1

CEMENT REQUIREMENTS BY AASHO SOIL GROUPS[a] (12)

AASHO Soil Group	Usual Range in Cement Requirement (% by vol)	Usual Range in Cement Requirement (% by wt)	Estimated Cement Content and That Used in the Moisture-Density Test (% by wt)	Cement Content for Wet-Dry and Freeze-Thaw Tests (% by wt)
A-1-a	5-7	3-5	5	3-5-7
A-1-b	7-9	5-8	6	4-6-8
A-2	7-10	5-9	7	5-7-9
A-3	8-12	7-11	9	7-9-11
A-4	8-12	7-12	10	8-10-12
A-5	8-12	8-13	10	8-10-12
A-6	10-14	9-15	12	10-12-14
A-7	10-14	10-16	13	10-13-15

[a] For dark gray to gray A-horizon soils, increase the above cement contents four percentage points, for black A-horizon soils six points.

FIGURE 2

EFFECT OF CEMENT CONTENT ON THE PLASTICITY INDICES OF THREE SOUTH CAROLINA SOILS (After Willis, E.A., 1947 (27))

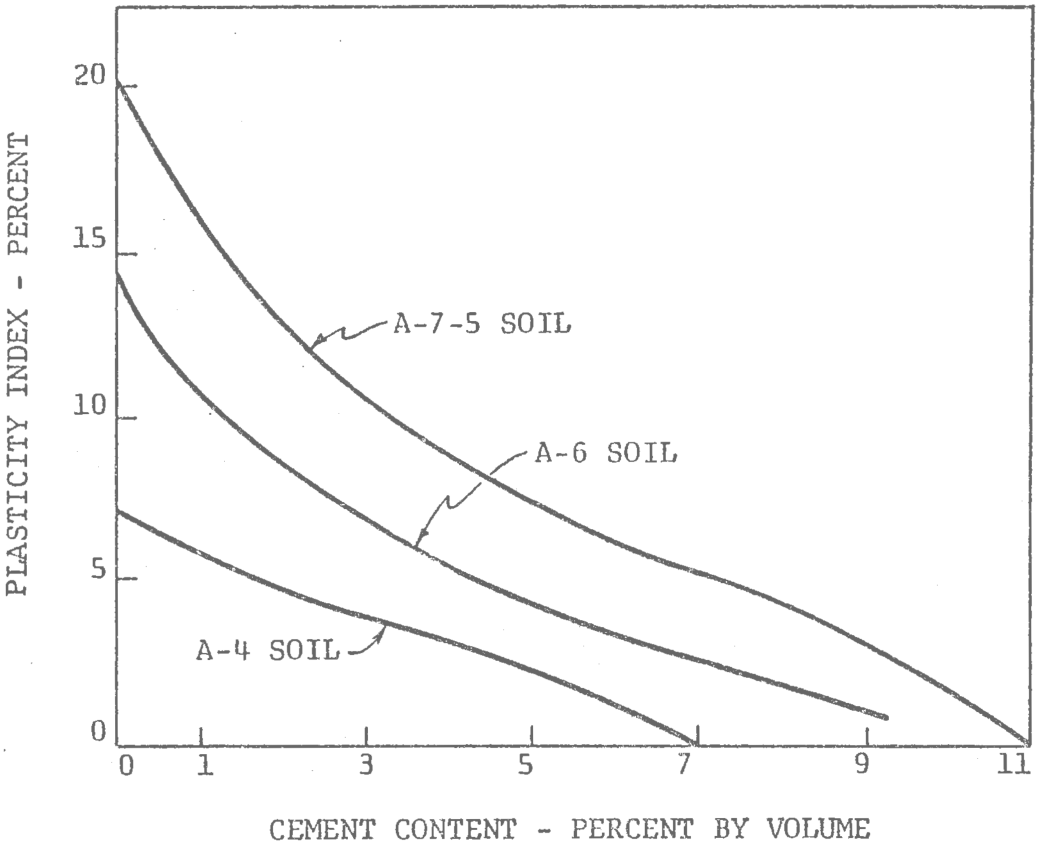
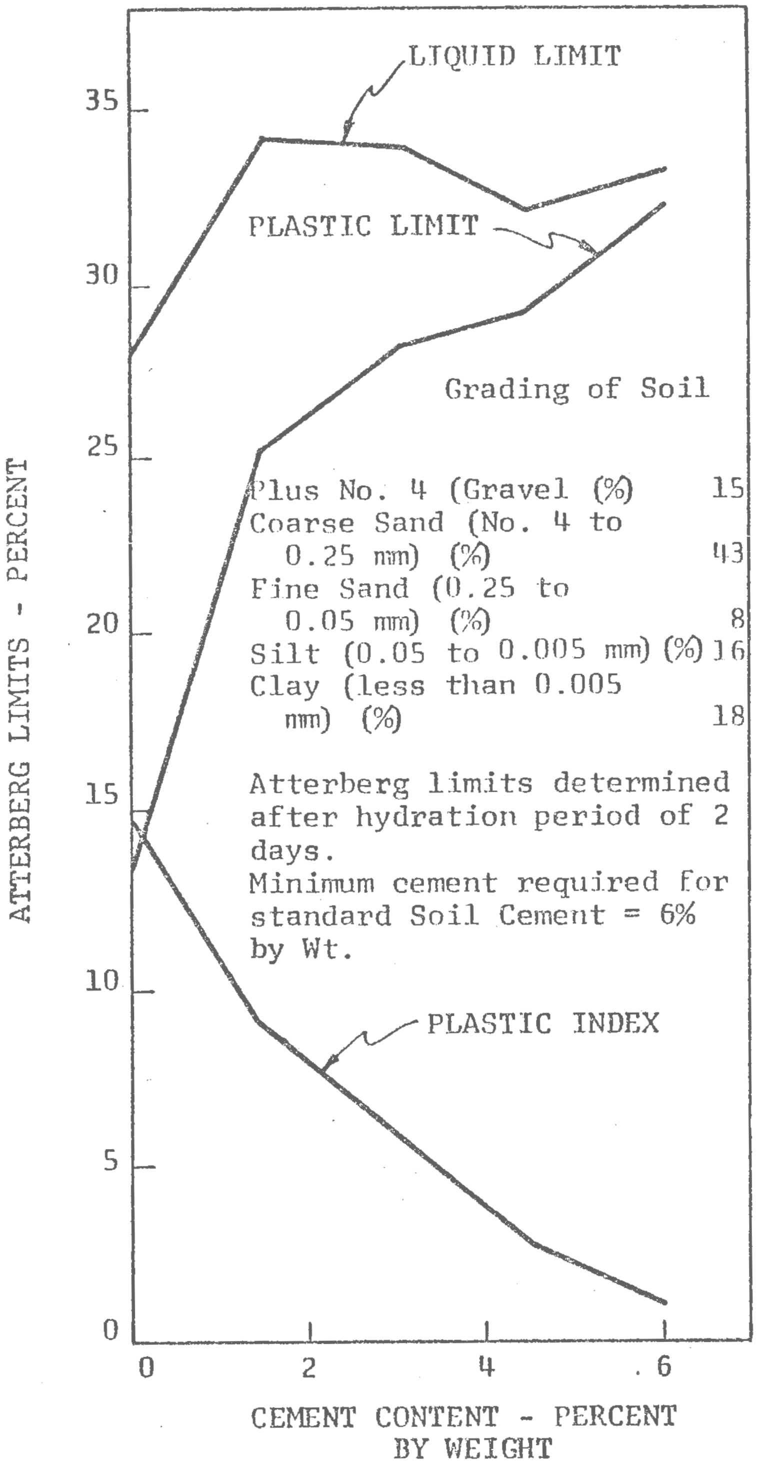


FIGURE 3

CEMENT - PLASTICITY RELATIONSHIPS FOR A PLASTIC GRAVELLY SAND
(After Felt, E.J., 1955 (6))



Grading of Soil

Plus No. 4 (Gravel (%)	15
Coarse Sand (No. 4 to 0.25 mm) (%)	43
Fine Sand (0.25 to 0.05 mm) (%)	8
Silt (0.05 to 0.005 mm) (%)	16
Clay (less than 0.005 mm) (%)	18

Atterberg limits determined after hydration period of 2 days.
Minimum cement required for standard Soil Cement = 6% by Wt.

FIGURE 4

EFFECT OF CEMENT CONTENT IN MODIFYING THE SHRINKAGE PROPERTIES OF A HEAVY CLAY SOIL
(After Jones, C.W., 1958 (14)

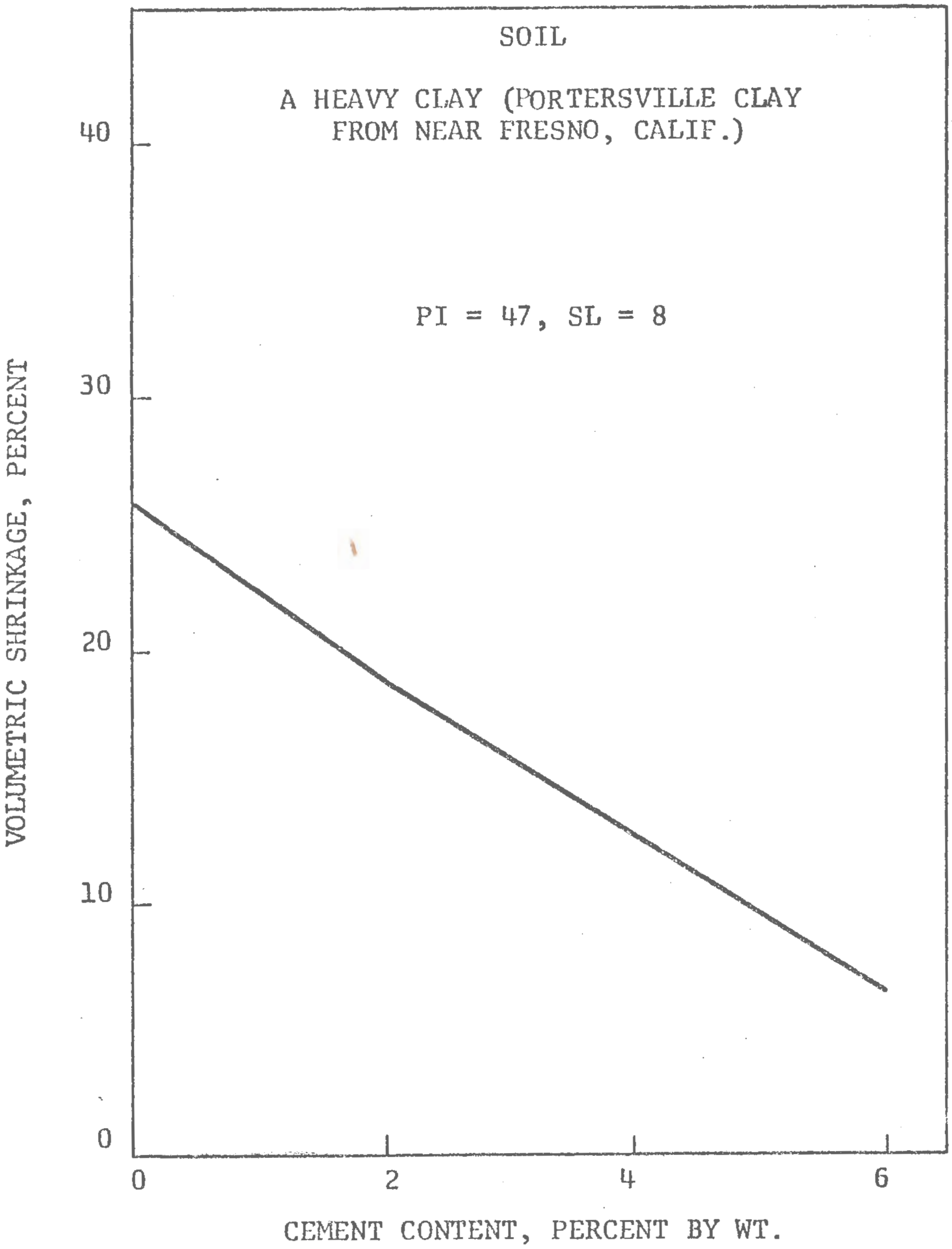
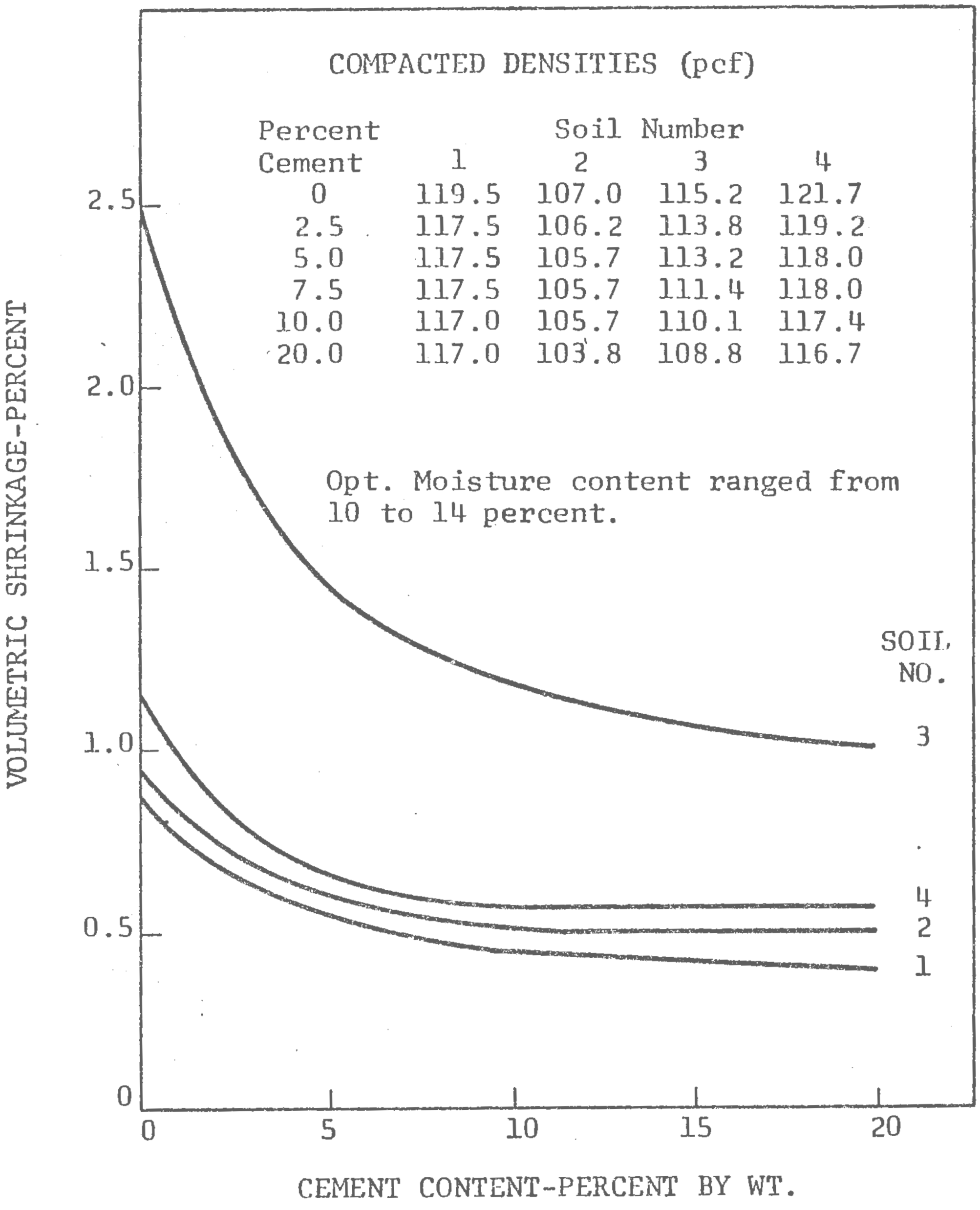


FIGURE 5

EFFECT OF THE ADDITION OF CEMENT ON THE SHRINKAGE OF SOILS
(After Mehra and Uppal, 1950-51 (20,21))



COMPACTED DENSITIES (pcf)

Percent Cement	Soil Number 1	2	3	4
0	119.5	107.0	115.2	121.7
2.5	117.5	106.2	113.8	119.2
5.0	117.5	105.7	113.2	118.0
7.5	117.5	105.7	111.4	118.0
10.0	117.0	105.7	110.1	117.4
20.0	117.0	103.8	108.8	116.7

Opt. Moisture content ranged from 10 to 14 percent.

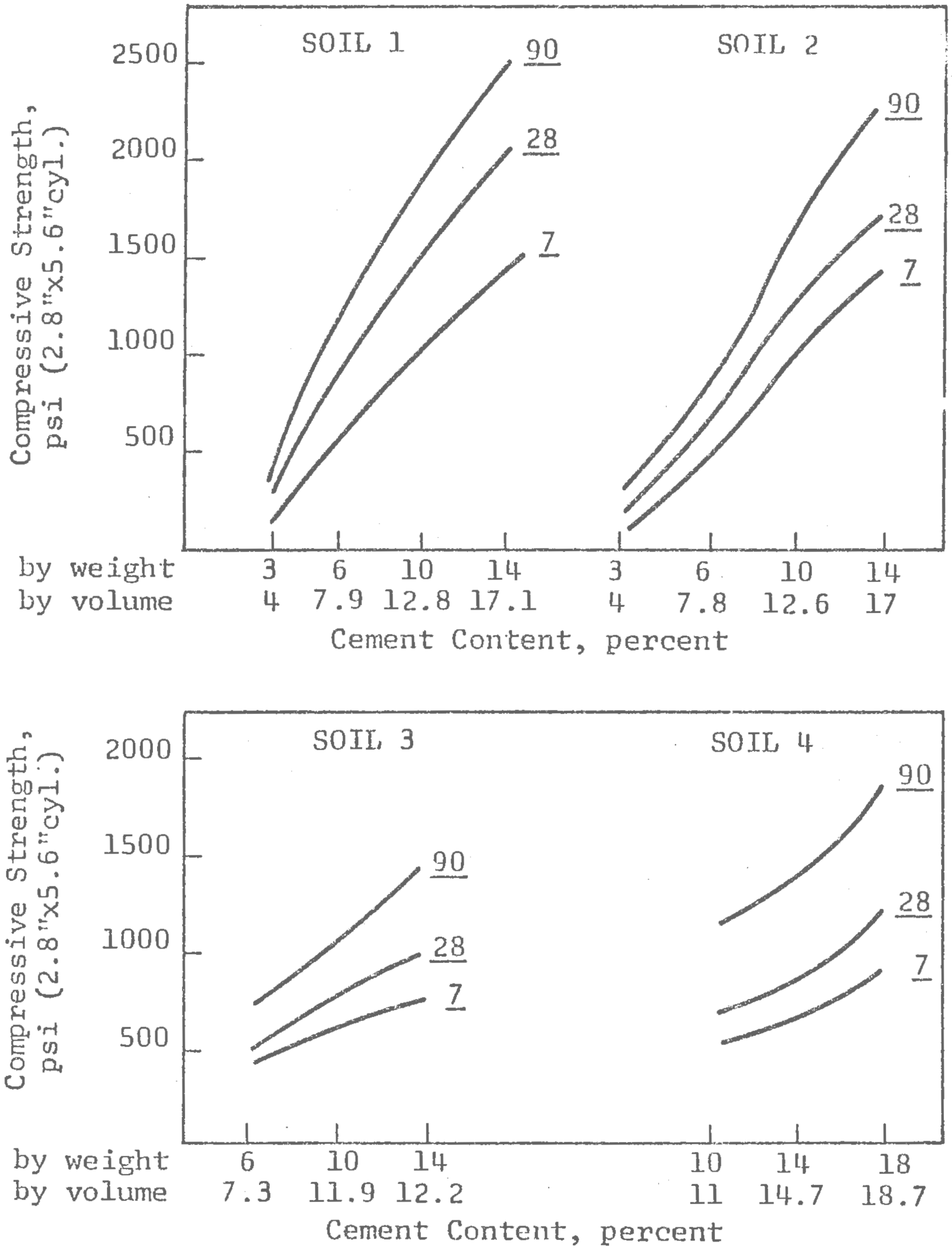
their strengths substantially. This is shown in Figure 6, which is a rather typical illustration of this effect. A third variable controlling the results obtained from cement stabilized soils is the amount of free water in the soil at the time of compaction. In this instance two criteria must be satisfied: (a) the correct water content to provide for adequate density and volumetric stability, and (b) enough water to react with the cement. Finally, the degree of densification attained at the time of compaction influences the degree of stabilization.

There are a number of secondary additives including lime, flyash and various alkali compounds which are used in combination with portland cement to improve various soil properties including compressive strength. Moh, et.al. (24) reports that the use of sodium additives materially improves the resistance of soil-cement to possible sulfate attack. Cordon (3) reports that sodium salts mixed with soil-cement increases the compressive strength and the resistance to the action of freezing and thawing. In general the addition of lime improves the soil-cement mixture. The amount of lime required is independent of the cement requirement and increases with clay content (25). Flyash is a beneficial secondary additive and seems to be most effective when used with poorly-graded, low clay content soils (4).

b. Lime. The addition of lime in the form of calcium hydroxide is beneficial to most all soils but most effective when used with the more plastic soils. The mechanisms of lime stabilization are ion exchange and the formation of weak cements. These mechanisms occur together so that it is difficult to separate them into a specific chronological sequence (11). As lime is mixed with a moist, cohesive soil and allowed to cure, the soil becomes friable and attains a silty-like condition readily apparent by its reduced stickiness. The cause of this apparent change in physical properties is due to an ion exchange. Researchers have discovered that most natural soil clays exhibiting high plasticity are at least partially saturated with sodium ions. These sodium clays tend to adsorb large volumes of water about their surfaces. The addition of lime to the soil results in a replacement

FIGURE 6

COMPRESSIVE STRENGTH, SOIL TYPE, CEMENT CONTENT AND AGE
(After Felt, E.J. and Abrams, M.S., 1957 (7))



Underlined numbers show days of moist cure prior to testing of sodium by calcium. This causes the soil clays to adsorb less water and serves to reduce the plasticity.

The addition of lime has been utilized by highway engineers to render a sticky, unworkable soil friable so that construction could proceed immediately after mixing. This reaction of lime and moist soils also makes lime valuable as a preconditioning additive in that it aids in mixing the soil with other desired additives such as portland cement.

The cementing action of lime is another important lime-soil reaction. This action is not yet fully understood but apparently the calcium in the lime reacts with various soil minerals to form new compounds. Usually these compounds are calcium silicates and aluminates which tend to cement the soil particles together similar to hydration of portland cement. These minerals which react with the lime are called pozzolans. The type and amount of pozzolans, and as a result, the reaction with the lime, vary from soil to soil. Soils with insufficient quantities and types of pozzolans exhibit little cementing action due to the lime additive. In such cases substitute pozzolanic materials, such as flyash, may be added to the lime-soil mixture to achieve the desired results. This is a slow reaction requiring a considerable time for completion which may run into years (11). Another mechanism of cementation observed in lime stabilized soils is carbonation. Lime, or calcium hydroxide, reacts with carbon dioxide in the air to form calcium carbonate. These carbonates form weak cements, deter pozzolanic action, and prevent normal rapid-strength gains. However, over a prolonged period of time the cementing action of calcium carbonate may contribute significantly to the soil strength.

It is generally agreed that lime influences the following physical characteristics of a soil: grain size distribution, plasticity, volumetric stability, swell pressure, compaction and optimum moisture content, strength and durability.

The influence on grain size distribution is a result of agglomeration or flocculation of the clay particles caused by the action of the lime. For example, a clay with 10 percent lime underwent a gradation change such that after curing 14 days it was classified as a sandy loam and after [illegible]0 days it was classified as a sand. This same phenomenon also resulted in a classification change in one instance from an A-7-6 (16) soil to an A-4 (6) soil (17). The soils that are most affected by this apparent change in size are fine clays.

A noticeable phenomenon resulting from the addition of lime to a soil is the change in plasticity. The plastic limit increases with increasing amounts of lime and the liquid limit normally decreases with increasing amounts of lime. However, there are some soils which exhibit a slight increase in liquid limit with the addition of lime. Regardless of the direction of change of the liquid limit, the overall result of the addition of lime to a plastic clay is a reduction in the plasticity index. This phenomenon is illustrated by the example of a clay with a liquid limit of 51 and a plasticity index of 30 which became non-plastic in two days with the addition of only 6 percent lime (17). Generally speaking the amount of reduction in the plasticity index is a function of soil type (11). The highly plastic soils exhibit a greater reduction than do the less plastic soils. This change takes place over a considerable length of time.

The addition of lime to soils also tends to increase the volumetric stability. As the lime content increases, the shrinkage limit increases and the shrinkage ratio decreases. This would seem to indicate that the plasticity index and the shrinkage limit are related to some degree. As the plasticity index decreases with lime content, the shrinkage limit tends to increase. Also, when there is little further change in the plasticity index with additional lime, there is little change in the shrinkage limit (11). As an example of this influence, specimens were placed under a load of 1 psi with excess water present. An originally highly plastic soil (PI=37) did not swell but actually consolidated about 1.5 percent (14).

There are optimum lime contents for each soil beyond which very little additional benefit can be expected. As might be anticipated, the greatest improvement in volumetric stability is encountered with those soils which exhibited large volume changes in the untreated condition (i.e. the highly plastic soils) (11) (14) (17).

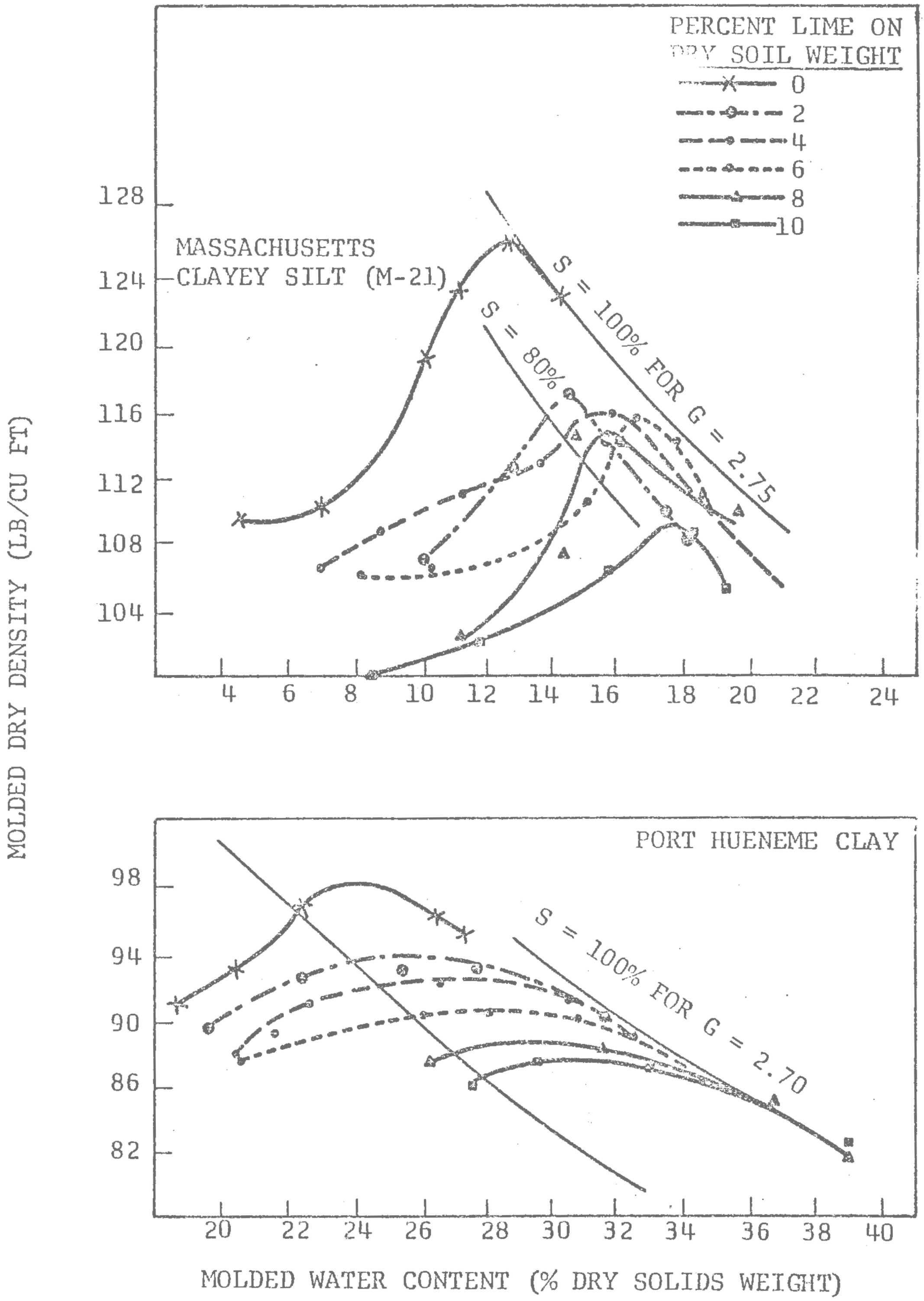
The limited amount of information available on the swelling pressure developed by a soil indicates that as the lime content increases the swell pressure decreases. One investigator reported that the swelling pressure in a predominantly montmorillonitic clay was reduced from approximately 7 psi to 1 psi with the addition of 8 per cent lime (17).

In general, a lime-soil mixture has a lower standard AASHO T-99 density than the untreated soil. Within limits, the trend continues with an increase in lime content. In most soils this decrease is relatively small and averages about 2.5 percent. This decrease in unit weight is accompanied by an increase in the optimum water content. The initial increase in optimum water content is fairly large and may increase by one-fourth with the addition of only 3 percent lime. Subsequent increases are smaller with increasing amounts of lime (11). This overall effect is shown in Figure 7.

Compaction of lime-soil mixtures are also influenced by the type of lime. Soils treated with quicklime usually have slightly higher optimum moisture contents than soils treated with hydrated

FIGURE 7

EFFECT OF LIME ON COMPACTION CHARACTERISTICS OF TWO SOILS
(After Ladd, C.C., et al., 1960 (16))



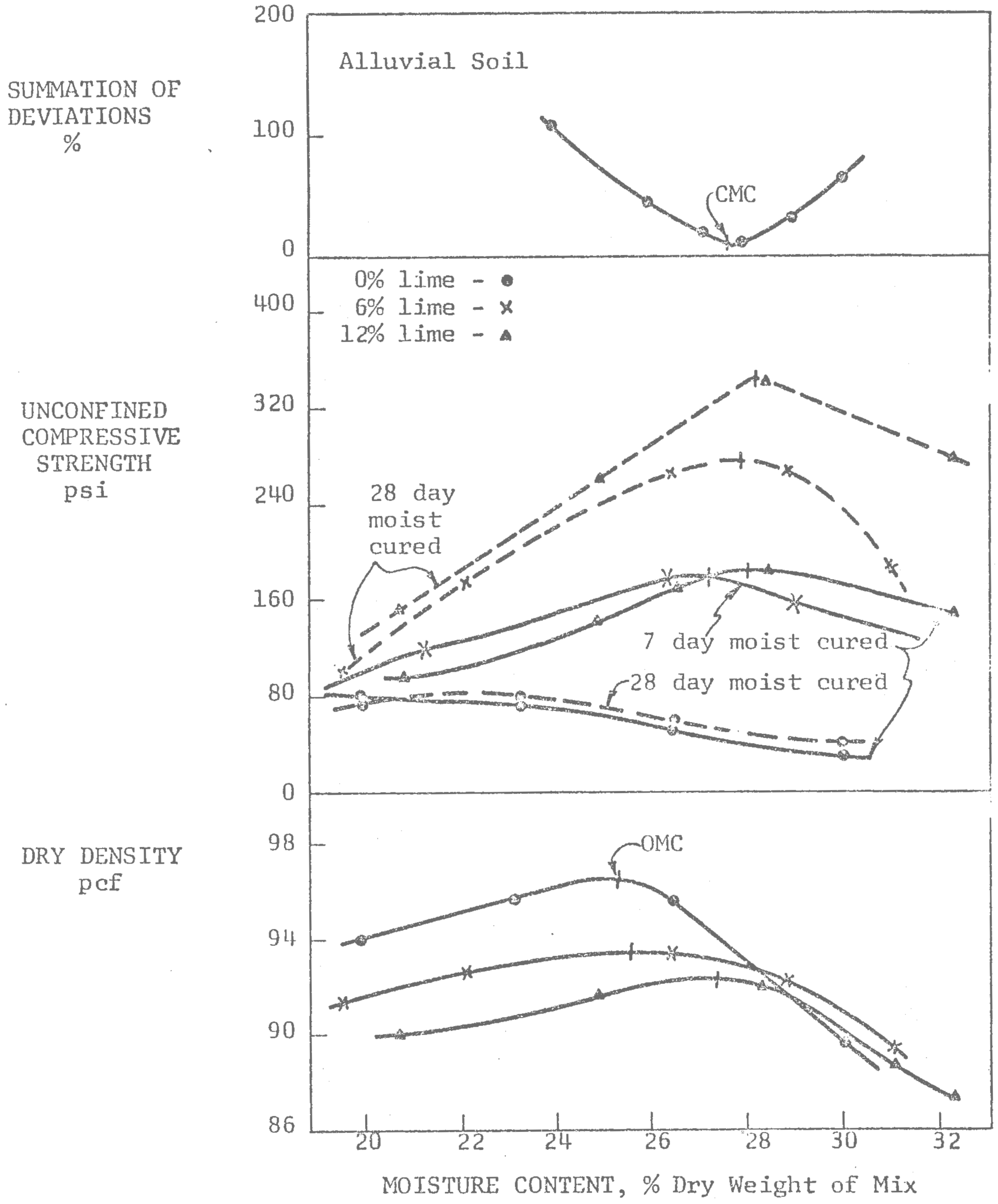
lime. However, this type of lime does not seem to affect the maximum density greatly (11). When an untreated soil is compacted at the optimum water content for a lime-soil mixture, the resulting unit weight will be less than that for a lime-soil mixture at the same compactive effort and moisture content. This indicates that the lime-soil mixtures have greater compactability than untreated soils at high water contents. However, lime-soil mixtures are less compactible at lower moisture contents and thus have lower unit weights than the untreated soil at the same moisture contents. This is illustrated to some degree in Figure 8.

It should not be assumed that a lower density (resulting from lime addition) necessarily indicates a lower strength. This may not be true, as illustrated in Figure 8. The curve shows that for an increase in lime content there was a corresponding increase in unconfined compressive strength although the unit weight decreased with the increasing lime content. There appears to be no optimum lime content that will produce a maximum strength in a lime-stabilized soil under all conditions. Some investigators have indicated that there is a definite optimum, but generally speaking these results were obtained for one soil and for one duration of cure.

The chief factors affecting the strength of lime-soil mixtures are lime content, type of lime, soil type, density and the time and type of curing. These factors are, of course, interrelated and except for specific cases no one factor is relatively more important than another (11). In general, the strength of lime-soil mixtures increases with an increase in lime content (see Figure 8). However the rate of increase tends to decrease as more and more lime is added. There are data available which indicate that some types of lime have more influence on strength

FIGURE 8

UNCONFINED COMPRESSIVE STRENGTHS, DRY DENSITIES, AND SUMMATIONS OF DEVIATIONS FOR ALLUVIAL SOIL MIXED WITH VARYING AMOUNTS OF LIME AT VARYING MOISTURE CONTENTS (After Pietsch, P.E., and Davidson, D.T., 1962 (14))



than others. Since the composition of lime varies somewhat depending on the deposit from which it was taken, it is recommended that the various available limes be tested with a particular soil to determine which lime product is the most effective. For example, data is available showing instances in which three times more of one lime product is required to produce the same strength as another product. (11).

The amount of strength increase that can be produced in a soil is a function of the amount and type of pozzolans in the soil. Usually clays are more reactive with lime than other soils and generally exhibit significant strength increases. There are some exceptions to this as noted in reference (11). Compaction is very important to achieving proper lime stabilization. The strength is increased substantially when the soil-lime mixture is compacted to a higher density with a greater compactive effort. Lime-treated soils tend to increase in strength with time. The greatest increase has been observed to occur at the beginning of the curing period. However, strength gains continue for a number of years (19). Various methods of curing lime-treated soils have been used. These include curing at various moisture conditions or relative humidities, and curing at normal or elevated temperatures. The rate of gain in strength has been found to be directly related to the curing temperature. However, the effect of curing moisture is indefinite. It is definitely subordinate to temperature in its influence on strength gains.

The determination of durability properties of a lime-soil mixture is a major problem since it is difficult to simulate in the laboratory the detrimental actions of repeated loads and elements of nature that are produced in the field. Some of the tests used include heating and cooling, wetting and drying, and freezing and thawing. Research has indicated that some of the factors affecting the durability of lime-soil mixtures are the amount and type of lime, initial compaction, curing time and the nature of the soil.

c. Phosphorus compounds. Study of phosphorus compounds in the area of soil stabilization began as far back as the early 1930's and perhaps earlier. Much of the information which has been useful to those investigators concerned with this area of soil stabilization has come from the field of agricultural chemistry, since phosphates are quite important to agriculture for their fertilization properties.

The reactions which take place between soils and phosphorus compounds are quite complex, resulting in conflicts of conclusions drawn by various investigators (18). Phosphorus compounds, due to the nature of the reaction, are most applicable to the stabilization of fine-grained soils. Most of the research, therefore, has been performed on soils whose dominant constituent was clay.

The addition of phosphate to a soil, either as an acid or as a salt, results in the formation of iron and aluminum phosphates in the soil. Generally speaking these phosphates are hard and highly insoluble. Due to the abundant availability of aluminum as compared to iron in the soils, the aluminum phosphates are formed in greater abundance (9). These phosphates have a cementing effect which results in stabilization.

Phosphorus compounds lower both the liquid limit and the plasticity index. (18). This general effect is illustrated in Table 2. Phosphorus compounds added to soils result in an increase in the compressive strength. The amount of increase depends on several variables, some of which are soil type, amount of phosphorus compound added, curing time after mixing and before compaction, curing time after compaction but before usage, compactive effort, and moisture content at compaction.

TABLE 2

EFFECT OF PHOSPHORIC ACID ON GROUP INDEX OF PUTNAM CLAY[a]

Treatment	% Passing No. 200 Sieve	Liquid Limit	Plasticity Index	Group Index
Untreated	85.3	75	55	20
1% H_3PO_4	79.7	51	24	16
2% H_3PO_4	68.4	47	19	11
3% H_3PO_4	60.4	45	17	8
4% H_3PO_4	60.3	47	18	9

[a] Compacted specimens humid-cured 5 days, immersed 2 days in water, air dryed, and repulverized. Samples moistened with water and held overnight before testing to insure equilibration. After Lyons, J. W., McEwan, G. J., Siebenthal, C. D., 1962. (18).

In general those soils which respond best to phosphorus compounds are those which are predominantly clay. Those soils whose predominant constituent is silt react quite slowly and require an economically infeasible amount of phosphorus compound for satisfactory stabilization.

Lyons and McEwan (18) reported that, for the soils tested, there was a continual increase in immersed unconfined compressive strength with an increase in phosphoric acid concentration. They found an optimum acid content beyond which very little additional strength gain was realized (for a given curing period). This is illustrated in Figure 9. They also concluded that the moisture content for maximum immersed strength and the moisture content for maximum density may not always be the same. Several examples of this are shown in Figure 10.

The lapse of time between mixing and compacting is quite important in phosphorus-treated soils. A high proportion of the reaction of the phosphorus compounds with the soil takes place soon after mixing. Therefore, it is important for compaction to take place as quickly after mixing as possible. The longer the delay in compaction, the higher the compactive effort required to achieve the desired density. This fact has strong implications for the engineer in the field. The length of curing time required after compaction for the development of near maximum strength varies (increases) with varying (increasing) amounts of phosphorus compound added, as illustrated by comparison of Figures 9, 11, and 12.

d. Asphalt. Asphalt is one of the older soil stabilizers. It has been used for years for purposes ranging from a dust retardant, to a membrane for enclosing an entire embankment against moisture uptake. There are two primary types of asphalts which are suitable for mixing with soils, i.e., cutback asphalts and asphalt emulsions. The cutback asphalts are those which have been reduced

FIGURE 9

STRENGTH VS PHOSPHORIC ACID CONCENTRATION--SAMPLES CURED AT 100 PERCENT R.H. AND ROOM TEMPERATURE 30 DAYS, IMMERSED IN WATER 2 DAYS: KEYPORT CLAY LOAM A-7-6(12); 2- BY 4-IN. CYLINDERS, 8 BLOWS PER EACH OF 4 LAYERS (After Lyons, J.W. and McEwan, G.J., 1962 (18))

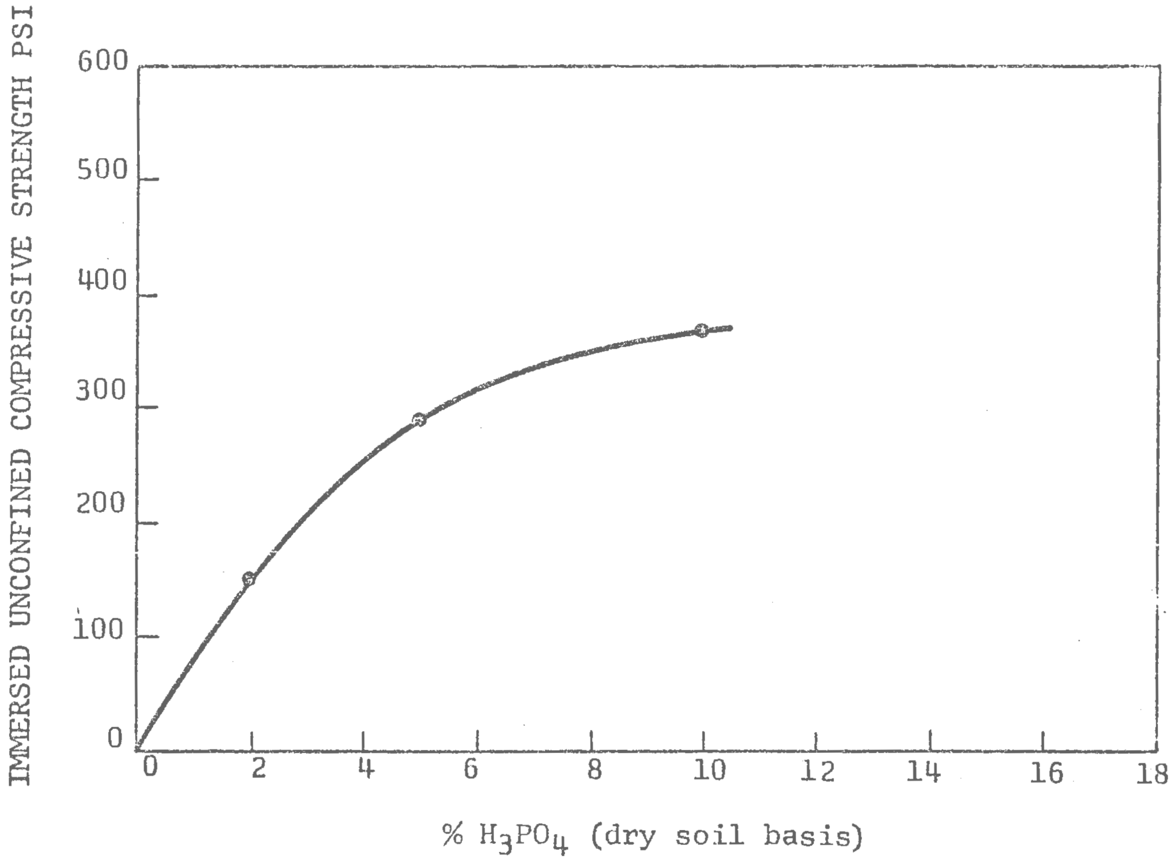
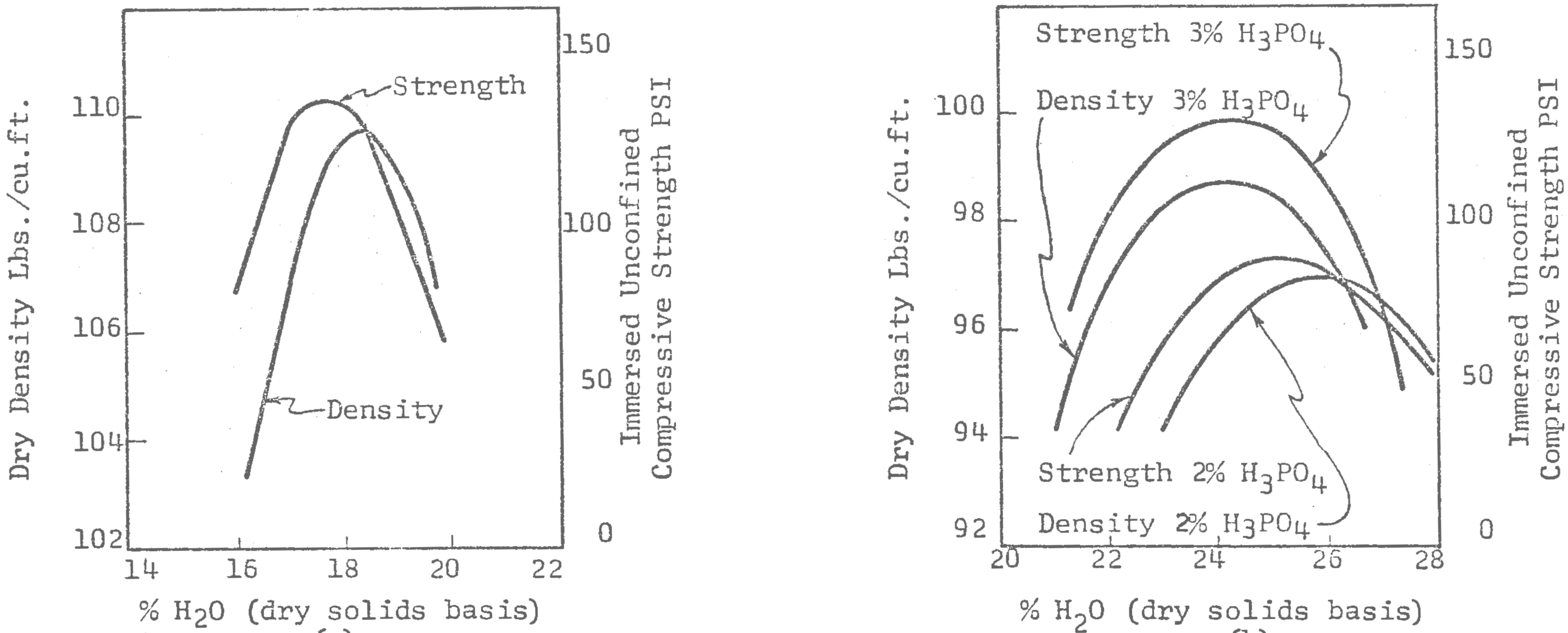


FIGURE 10

IMMERSED STRENGTH AFTER 5 DAY HUMID CURE AND DRY DENSITY VS MOLDING MOISTURE CONTENT FOR (a) CLAY FROM MARYLAND A-7-6(16) WITH 2 PERCENT H_3PO_4 AND (b) CLAY FROM MARYLAND A-7-6(20) (2- BY 4-IN. CYLINDERS, 8 BLOWS PER EACH OF 4 LAYERS (After Lyons, J.W. and McEwan, G.J., 1962 (18))



(a)

(b)

FIGURE 11

STRENGTH VS PHOSPHORIC ACID CONCENTRATION--SAMPLES CURED AT 100 PERCENT R. H. AND ROOM TEMPERATURE 5 DAYS, IMMERSED IN WATER 2 DAYS: KEYPORT CLAY LOAM A-7-6 (12); 2-BY 4-IN. CYLINDERS, 12 BLOWS PER EACH OF 4 LAYERS (After Lyons, J.W. and McEwan, G.J., 1962 (18))

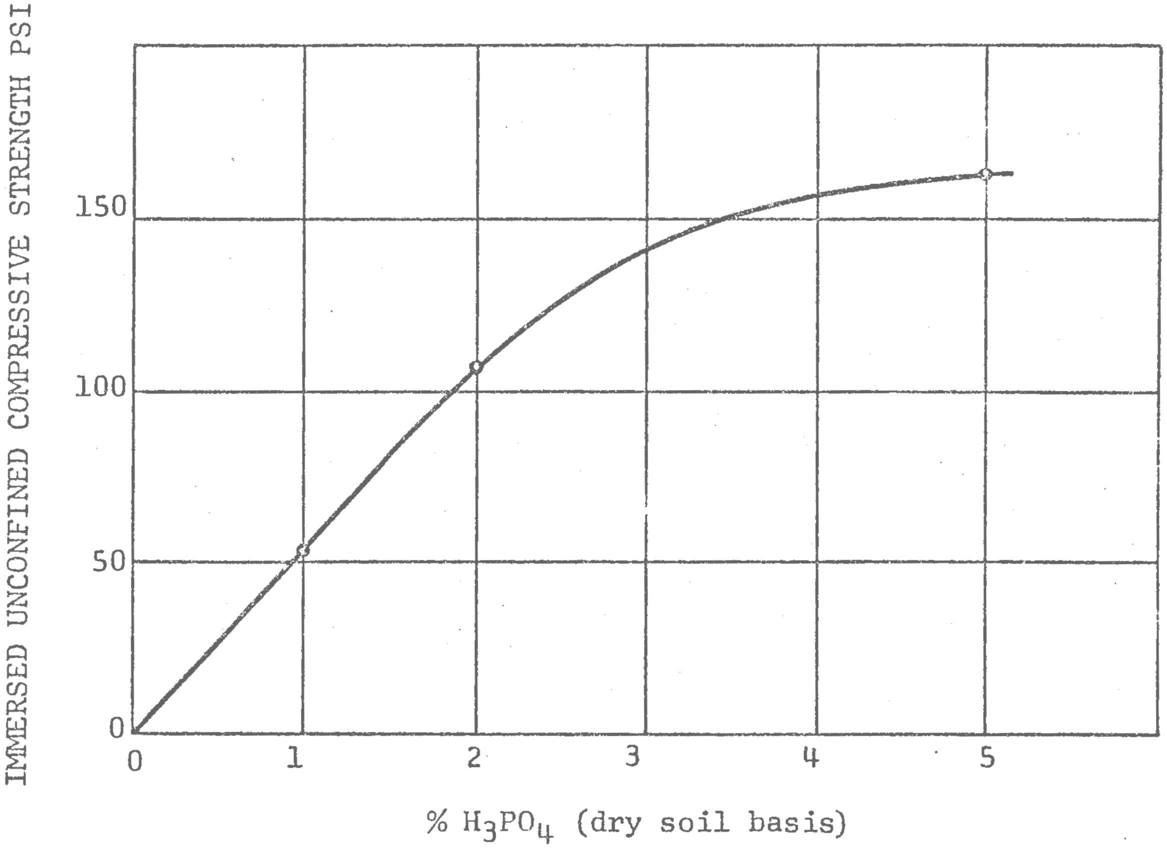
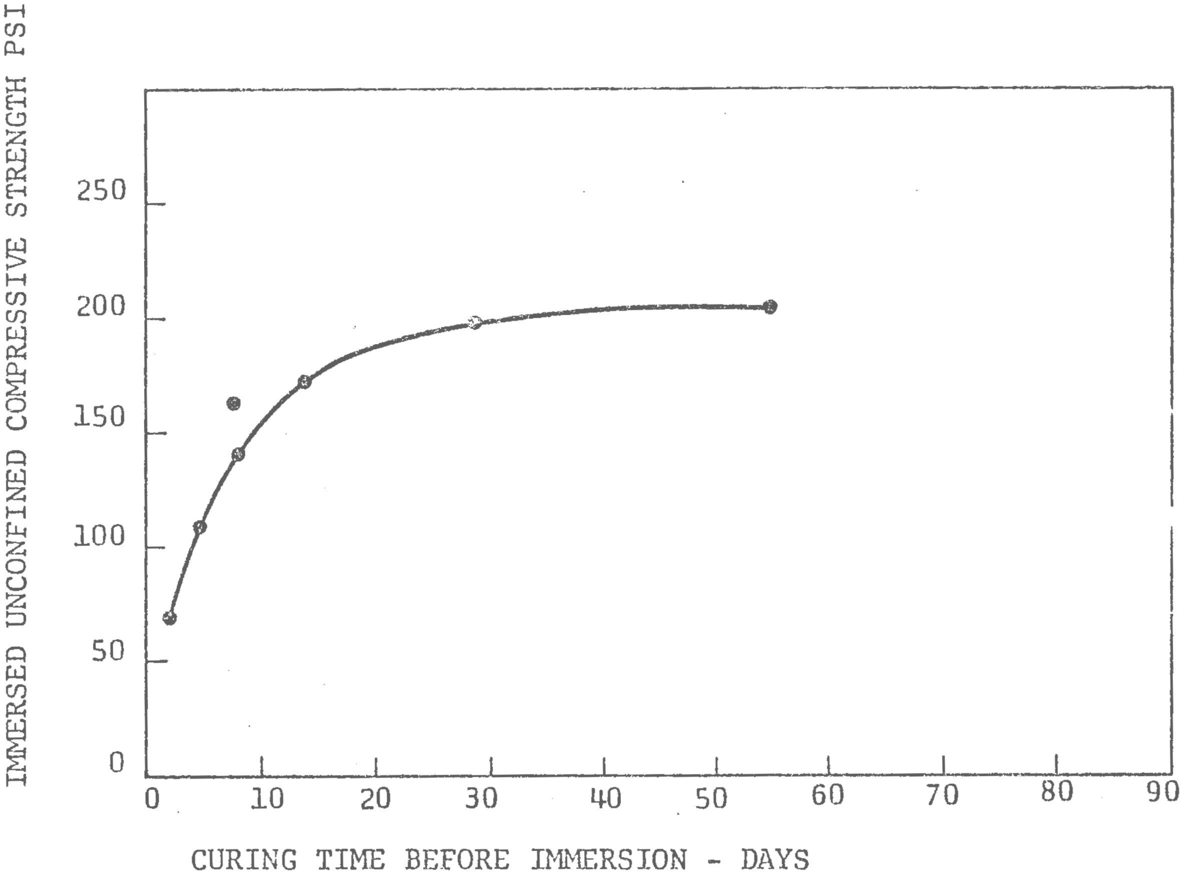


FIGURE 12

IMMERSED STRENGTH VS CURING TIME--SAMPLES CURED AT 100 PERCENT R.H. AND ROOM TEMPERATURE, THEN IMMERSED 2 DAYS: KEYPORT CLAY LOAM A-7-6 (12); 2 PERCENT H_3PO_4, 2- BY 4-IN. CYLINDERS 12 BLOWS PER EACH OF 4 LAYERS

(After Lyons, J.W. and McEwan, G.J., 1962 (18))



in viscosity by the addition of a solvent. The emulsions are those which have been reduced to colloidal size droplets and dispersed in water. The use of emulsions has been complicated by the fact that, when mixed with some clays or fine silts, the emulsions may "break" (i.e. asphalt may come out of suspension) before the mixing is completed. For this reason the cutback asphalt may be somewhat more practical for most soils and were mentioned almost exclusively in literature (15) (10) (22).

The types of cutback asphalts generally used are the MC-2 and 3 (medium-curing) and the RC-2 and 3 (rapid-curing). These cutbacks represent a compromise between ease of mixing and curing time required. Cutback asphalts are graded from MC (RC) - 0 to MC (RC) -5 depending on solvent content. Solvent content ranges from 50 percent (MC-0) to about 18 percent (MC-5). The grade of asphalt used depends on the soil type and climatic conditions (15).

Asphalt stabilizes soils in two ways; cementation and waterproofing. Which of the two mechanisms is more important depends somewhat on the type of soil. In the case of coarse-grained, non-cohesive soils (sands and silts) both mechanisms are rather important. The asphalt film first waterproofs the soil mass and, second, it binds the soil particles together and in so doing contributes to the strength of the stabilized soil. In the case of fine-grained cohesive soils, the principal function of the asphalt is to waterproof the compacted soil mass (22).

Definite benefits can be derived from the use of various secondary additives along with asphalt in soil stabilization. In general, the secondary additives strengthen the compacted soil mass and the asphalt then waterproofs it. Some additives which have been used are: ortho-phosphoric acid, hydrated lime and portland cement (22).

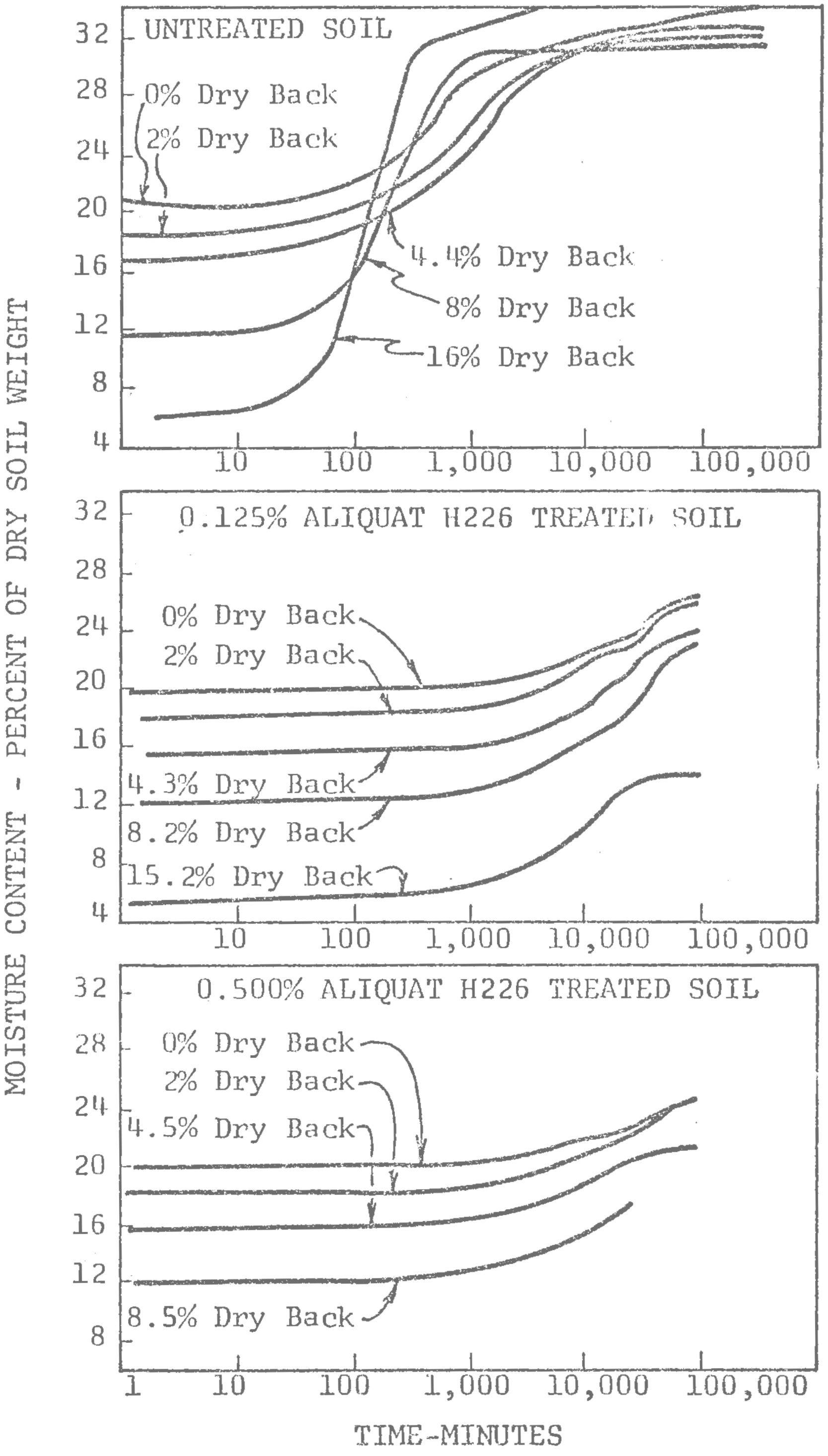
e. Organic chemicals. Many of the chemicals recently investigated are chemicals containing organic cations. The term organic, cationic chemical denotes a chemical, organic in nature, which dissociates in water to produce organic cations having exceedingly complex structures. The organic cations are very large when compared to the inorganic cations such as calcium, magnesium, hydrogen or sodium.

A characteristic of most of these organic cations is that one or more of the radicals are of a hydrophobic nature. When mixed with soil in proper amounts, the organic cations are adsorbed rather completely to the clay surfaces, replacing some of the more easily exchangeable inorganic cations. These cations thus adsorbed may be visualized as being oriented on the clay surface in such a manner as to place the hydrophobic part of the cation outward from the particle surface. Considerable areas of the clay particle surfaces thus repel water. The more completely the clay surfaces are covered by the adsorbed organic cations, the more hydrophobic a clay soil becomes.

Two of these chemicals which have been investigated are known commercially as Aliquat H226, a product of General Mills (5), and Arquad 2HT, a product of Armour and Company (13). These are both di-hydrogenated tallow di-menthyl amonium chlorides, differing essentially in commercial name only. An illustration of the waterproofing properties of these chemicals is shown in Figure 13.

FIGURE 13

RESULTS OF CAPILLARY ABSORPTION TESTS ON RF 251-109
(After Dunlap et al., 1962 (5))



CHAPTER III

SELECTION OF ADDITIVES AND SOILS

3.1 Soil Additives

The additives selected for investigation in this study included portland cement, lime, an aluminum smelter by-product, two forms (liquid and solid) of paper plant by-products and Sarabond, a Dow Chemical Company product. The criteria for selecting soil additives for this investigation were: availability of sufficient quantities of material for roadway construction, low cost of additives and preliminary evidence of some stabilizing qualities. Of the above enumerated additives, only Sarabond violates the first two criteria, as will be discussed below.

a. Lime and portland cement. Lime and portland cement were obtained from local suppliers. Caution was exercised to insure that a sufficiently fresh supply of each was used in the study. These two additives were selected because of their known high degree of effectiveness as soil stabilizers.

b. Aluminum by-products. Samples of aluminum smelter by-products were obtained from the Alcoa Plant, located near Benton, Arkansas, and the Reynolds Metal Company Plant, located near Bauxite, Arkansas. The materials from these two plants appeared to be very similar, having the same general characteristics. Since a large quantity was obtained from the Alcoa Plant, this material was used in the investigation.

The process of removing usable aluminum from bauxite ore is an electrolytic process and involves use of very high temperatures. In the course of treatment the aluminum by-product has been heated to approximately 2,000°F. Following extraction of the aluminum, the by-products are mixed with water and pumped into a reservoir as a liquid. However, the Alcoa sample was obtained at the plant before the mixing water was added.

A chemical analysis of the Alcoa Material, furnished by Alcoa, is shown in Table 3. This analysis will vary according to the composition of the ore being processed at the smelter. However, the variation will be slight, resulting in minor changes in the percentages of the material present and not the materials themselves. The specific gravity of the material is 2.96 as determined by the AASHO Test Designation T 100-60. The grain-size analysis was obtained by Mechanical Analysis Test, AASHO Test Designation T 88-57, and is shown in Table 4.

Examples of the use of this product as a construction material can be seen at both the Alcoa and Reynolds Plants. At both locations the construction consisted of access roads to the waste reservoirs and dams to form the reservoirs. Since facilities at both plants are similar, only those at the Reynolds Plant are described herein.

Reynolds' Dam, which is approximately 6,500 feet long, has a maximum height of about 30 feet and was constructed in 1955 using the by-product of the processing plant. The dam appears to be very stable and shows a high degree of resistance to erosion. The surface material on the downstream face of the dam has hardened and appears to be very water resistant. Furthermore, much of the material resembles sandstone, indicating some cementing action has occurred.

Table No. 3

Chemical Analysis of Alcoa By-Product

Constituent	Percent
Silicon	23
Iron Oxide	8
Titanium Oxide	3.5
Aluminum Oxide	5
Calcium Oxide	47
Sodium Oxide	4
Others	6

Table No. 4

Mechanical Analysis Alcoa By-Product AASHO T-88-57

Sieve Size	Grain Size	Percent Passing
60	0.25	80
100	0.174	56
200	0.074	43
---	0.05	37
---	0.01	4
---	0.005	3

Access roads at the Reynolds Plant were also constructed from the by-product. Although these roads have no surfacing or surface treatment and have been subjected to heavy wheel loads, they are apparently in good shape. The surfaces of the access roads are very hard and dust free. It was primarily these observations which led to the selection of the aluminum smelter by-product for this study.

c. Paper plant by-products. Two forms of the paper plant by-product, or waste material, were used in the testing program. These by-products were obtained from the Georgia-Pacific Corporation of Crossett, Arkansas. Both by-products are carried by water into large settling basins approximately 100 yards long, 30 yards wide and 4 feet deep.

The first of these materials used in the testing program consisted of the fiberous solids obtained at the settling basin just prior to cleaning of the tanks and, therefore, had a very high water content. The second by-product consisted of only the liquid portion of the waste material.

The road used by trucks in cleaning the settling basins at the Georgia-Pacific Plant was constructed using local soil and no surfacing. Georgia-Pacific reported difficulties with the road in wet weather in that it became very muddy and heavily rutted. In an effort to remedy this situation, gravel was added to the road. Since the trucks leave the road on a slight grade, the waste material was spread rather freely. Rather than remove this material at the time the gravel was placed on the road, the spilled material was mixed with the soil and gravel. Since that time the portion of the road on which the spillage was the greatest has performed more satisfactorily than the sections where little or no spillage had occurred. This section of the road has less ruts and shows better water resisting characteristics.

d. Sarabond. Sarabond (registered trademark), a Polymer solution, an experimental product of the Dow Chemical Company, was developed as an additive to increase the strength of portland cement mortar. Although this product violates the first two criteria set for investigation of a product, preliminary testing performed at the University of Arkansas indicated that Sarabond may have possibilities as a soil stabilizer. These preliminary tests, conducted by Dr. Charles W. Yantis, showed the use of Sarabond instead of mixing water in cement mortar greatly increased the strength of the mortar. On the basis of these earlier tests it was assumed that the use of Sarabond instead of water in a cement-modified soil may give added strength.

3.2 Test Soils

The criteria used in selecting the soils for this study were: availability of a sufficient quantity of material, range of Atterberg limits and percent of the sample passing a 200 mesh sieve. The four soils selected offer a range of engineering properties and characteristics and are given in Table 5.

Soil 1 was obtained from a borrow pit which was located about one-half mile north of the Champagolle Creek, South of Thornton, Arkansas, just 300 feet east of U. S. Highway 167. Soil 2 was obtained from the west ditch of U. S. Highway 167 about one mile south of the Champagolle Creek. Soil 3 was obtained from borrow areas used in construction of the Lincoln County Dam about 4 miles north of Lincoln, Arkansas. Soil 4 was obtained from Crowley's Ridge in the loess terrace region of Arkansas. This material was located one-quarter mile north of U. S. Highway 64, and two miles east of Wynne.

TABLE 5

PHYSICAL PROPERTIES AND CHARACTERISTICS OF TEST SOILS

	Soil 1	Soil 2	Soil 3	Soil 4
Classification	A4	A6	A 7-5	A4
Liquid Limit	20	40	82	31
Plastic Limit	17	23	37	23
Specific Gravity	2.69	2.68	2.80	2.70
Optimum Water Content, Percent	13*	19*	31*	12**
Maximum Dry Density, pcf	116*	105*	91*	118**
Minus 200 Fraction, Percent	47.9	70.5	91.1	97

* AASHO Test Designation T 99-57

** AASHO Test Designation T 180-57

CHAPTER IV

TESTING PROCEDURES

To evaluate the stabilizing effectiveness of the additives on the experimental soils the following tests were performed: unconfined compression tests, absorption tests, compaction tests and triaxial compression tests.

The standard density (AASHO T 99-57) was determined for each soil (See Table 5). In order to meet the geometric requirements for the performance of standard unconfined and triaxial compression tests, a Harvard Miniature compacting device was used to make all test specimens. This required calibration of the Harvard device so that it would produce, as nearly as possible, the standard moisture-density curve. Each additive combination slightly modifies the optimum water content and maximum density, but recalibration of the Harvard device for each of the combinations was not feasible in terms of the time required and results obtained. Therefore, the calibration was accomplished for only the untreated soils.

The unconfined compression test was selected because of its simplicity and because it may be performed rapidly. Due to the large number of samples tested, the time required for each test was an important consideration. In most cases the unconfined compression tests may be relied upon to yield qualitative if not quantitative results. All compressive strength tests were conducted using a controlled rate of strain. This was accomplished by using a hydraulic testing machine with which the desired rate-of-strain could be easily and accurately obtained. A rate-of-strain of 0.02 inches per minute was selected for all tests.

Three conditions of cure for specimens to be tested were selected to represent a wide range of possible field conditions. The initial in-place condition, Condition 1, is represented by specimens tested immediately after compaction. In Condition 2, soil specimens are allowed to cure 7 days at a temperature of 75°F. and in an atmosphere of 90 percent relative humidity. In Condition 3, test specimens are first allowed to cure 7 days at 75°F. and 90 percent relative humidity and then are submerged for 6 days prior to testing.

In general, the sequence of testing for unconfined compression tests of the various specimens was as follows:

1. Twelve samples of each additive combination were compacted.
2. Three of the samples were tested for strength using the unconfined compression test immediately after compaction (Cure Condition 1).
3. Nine samples were cured at 90 percent relative humidity and at 75°F. for seven days.
4. At the end of seven days, three of the nine samples were tested using the unconfined compression test. Three additional samples were immersed one-quarter inch in water for absorption tests (Cure Condition 2). These specimens were weighed at the end of 30, 60, 120 and 240 minutes, and then daily to determine the increase in weight for a period of two weeks or until they disintegrated.
5. The remaining three samples were totally immersed for six days. At the end of the six-day immersion, unconfined compression strengths were determined. (Cure Condition 3).

As stated above, nine of the test specimens were cured for seven days after compaction before various tests were accomplished. The curing conditions, 90 percent relative humidity at approximately

75°F., were the best obtainable with the equipment available. It is doubtful that any qualitative alteration of the results would have been obtained had the curing humidity been closer to 100 percent. The three samples were totally immersed since this is the most severe condition at which to evaluate the stabilizing effectiveness of various additives.

An absorption test was performed on specimens by immersing one-quarter inch of the specimen in a tray of water inside the humidity box. The specimens were resting on metal plates so that they could be easily lifted up out of the water tray for weighing. The specimens were weighed before immersion and at intervals of 30, 60, 120 and 240 minutes, and then daily to monitor the increase in weight (moisture content). These daily weights were continued for a period of 2 weeks or until the specimens disintegrated.

CHAPTER V

TEST RESULTS

5.1 Aluminum By-Product

The effectiveness of the aluminum by-product as a stabilizing additive was investigated by comparing the unconfined compression strengths of Soils 1 and 2 prepared with no additive with the strengths of specimens prepared with 5 and 10 percent additive. Absorption tests were also performed using specimens prepared from Soil 1 with no additive and specimens treated with 10 percent of the aluminum by-product.

Test results obtained using Soil 1 show that initial strength increases and density decreases with an increase in quantity of additive for the same compaction energy. After seven days of humid cure, Condition 2, the average compressive strengths of specimens treated with 5 percent additive increased from 2.02 to 4.6 tons per square foot with a decrease in water content from 12.3 to 11.3 percent. The average strengths of specimens prepared with 10 percent additive increased from 2.13 to 9.8 tons per square foot with a decrease in water content from 13.1 to 8.9 percent. With identical curing conditions the untreated soil increased in strength from 1.34 to 26.0 tons per square foot but this strength increase was accompanied by a decrease in water content from 12.1 to 3.8 percent. All specimens in this series of tests disintegrated when totally submerged in water prior to the end of the 6-day curing period, Condition 3. This data is presented in Table 6.

TABLE 6

RESULTS OF STABILIZATION STUDY OF SOIL 1

Additive Mixture	Dry Density	Unconfined Comp. Strength			Moisture Content		
	Initial Lbs/Ft^3	Initial Tons/Ft^2	7-Day Cure Tons/Ft^2	7-Day Cure + 6-Day Subm Tons/Ft^2	Initial %	7-Day Cure %	7-Day + 6-Day Subm %
Raw Soil	116.4	1.34	26.0	--	12.1	3.8	--
5%A	112.4	2.02	4.6	--	12.3	11.3	--
10%A	107.8	2.13	9.8	--	13.1	8.9	--

Classification: A-4
Liquid Limit: 20
Plastic Limit: 17

AASHO (T99-56)
Opt. Water Content: 13%
Max. Dry Density: 116 pcf

-- indicated specimen disintegrated during submerged cure.
A Aluminum smelter by-product
All values are average of three or more tests.

TABLE 7

RESULTS OF STABILIZATION STUDY OF SOIL 2

Additive Mixture	Dry Density	Unconfined Comp. Strength			Moisture Content		
	Initial Lbs/Ft^3	Initial Tons/Ft^2	7-day Cure Tons/Ft^2	7-Day Cure + 6-Day Subm Tons/Ft^2	Initial %	7-Day Cure %	7-Day + 6-Day Subm. %
Raw Soil	103.0	2.92	10.51	--	18.1	12.9	--
5%A	97.3	3.10	9.11	--	19.6	14.2	--
10%A	93.9	3.10	7.20	--	18.5	12.4	--

Classification: A-6
Liquid Limit: 40
Plastic Limit: 23

AASHO (T 99-57)
Opt. Water Content: 19%
Max. Dry Density: 105 pcf

-- indicates specimen disintegrated during submerged cure.
A Aluminum
All values are average of three or more tests

For the same compaction energy the addition of the aluminum by-product to Soil 2 resulted in lower densities for increasing amounts of additive as seen in Table 7. The strengths of the treated specimens were higher than those observed for the untreated specimens for the initial cure condition, Condition 1. However, after 7 days humid cure, Condition 2, the untreated specimens showed slightly higher strength gained than the treated specimens even though the loss in water contents during curing were approximately the same. Once again upon total immersion, Condition 3, the specimens all disintegrated.

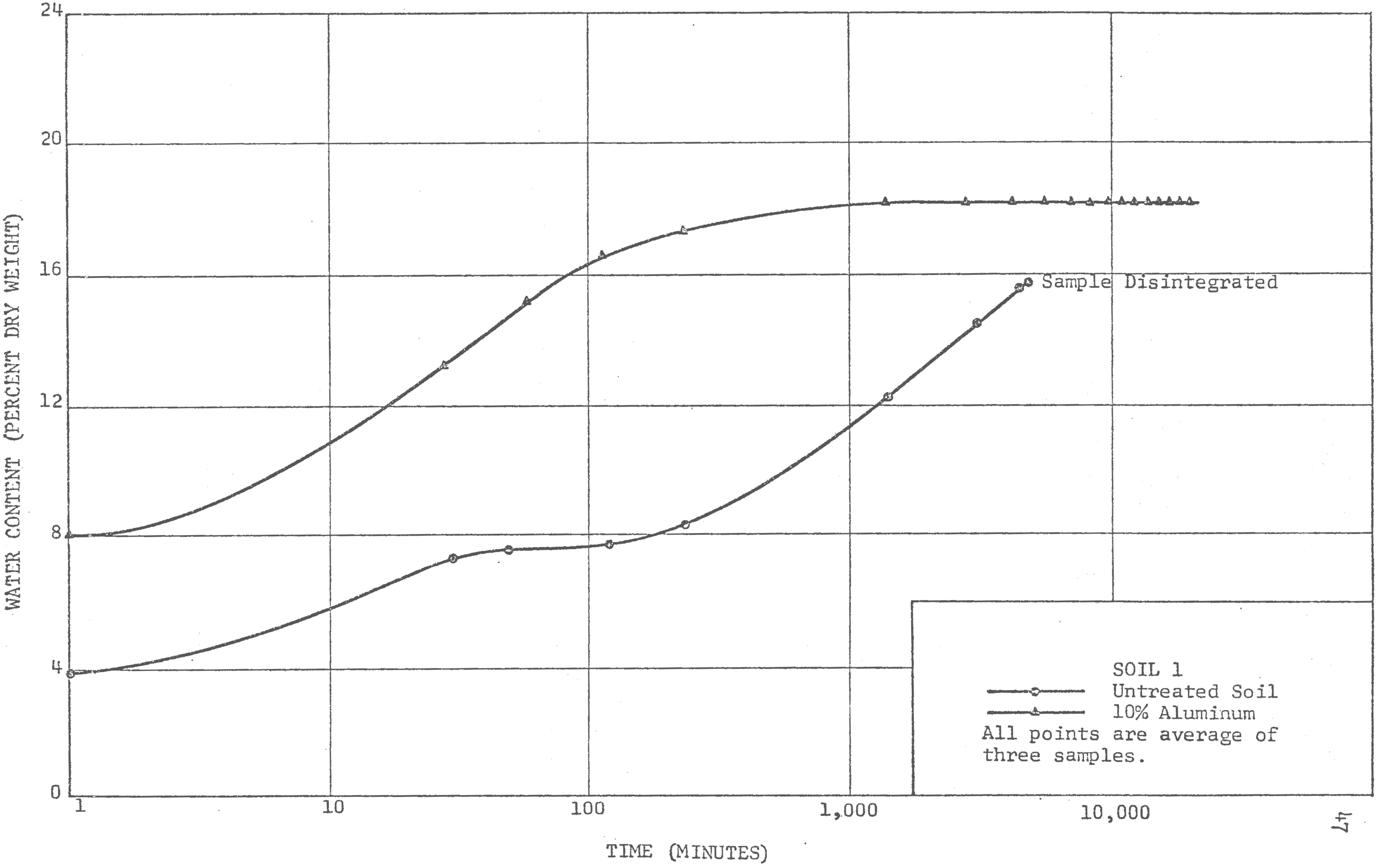
Absorption tests were performed using Soil 1 with no treatment and specimens treated with 10 percent of the aluminum by-product. The results showed that the untreated soil, cured for 7 days at 90 percent humidity, gained from an initial water content of about 4 percent to a water content of 16 percent in approximately 4 days, and disintegrated while still increasing in water content. The specimens prepared using 10 percent aluminum by-product increased from the initial water content of 8 percent to a water content of 18 percent in less than 10 hours. However, these specimens did not disintegrate or gain additional water for 14 days. A curve showing log time versus percent water content for treated and untreated specimens is shown in Figure 14.

5.2 Aluminum By-Product and Cement

To study the effectiveness of the aluminum by-product and cement, Soil 1 was mixed with 0, 2, 4, 6 and 8 percent cement, and to each of these mixtures were added 5 and 10 percent of the aluminum by-product. The results of these laboratory tests may be analyzed by comparing the

FIGURE 14

TYPICAL ABSORPTION CURVES FOR SOIL 1



stability of the untreated soil, the cement-treated soil and the cement-aluminum by-product treated soil.

Under the initial cure condition, Condition 1, little variation in strengths was observed, since time is required for the cement to take its initial set. These results are shown in Figure 15.

After 7 days humid cure, Condition 2, the strengths increased with the higher percentage of cement. The addition of 5 percent aluminum by-product resulted in slightly higher strengths, lower density and higher water contents. The addition of 10 percent aluminum by-product did not result in a marked change. These results are shown in Figure 16.

After 7 days humid cure and 6 days complete submerging, Condition 3, the strengths of the specimens treated with 6 to 8 percent cement and 5 or 10 percent aluminum by-product were 20 to 35 percent higher than specimens treated with cement only. These results also show that the density of the aluminum by-product treated specimens were lower and the water contents were higher than the cement treated specimens. These results are illustrated in Figure 17.

The results of absorption tests show that for a given percent cement the water content at the end of 7 and 14 days humid cure increases with increasing amounts of aluminum by-products added to the soil. These results are illustrated for 2, 4, 6 and 8 percent cement and for the same percentages of cement with 5 and 10 percent aluminum additive in Figures 18, 19 and 20.

FIGURE 15

EFFECT OF CEMENT AND ALUMINUM ADDITIVES ON THE COMPRESSIVE STRENGTH OF SOIL 1 PRIOR TO CURING

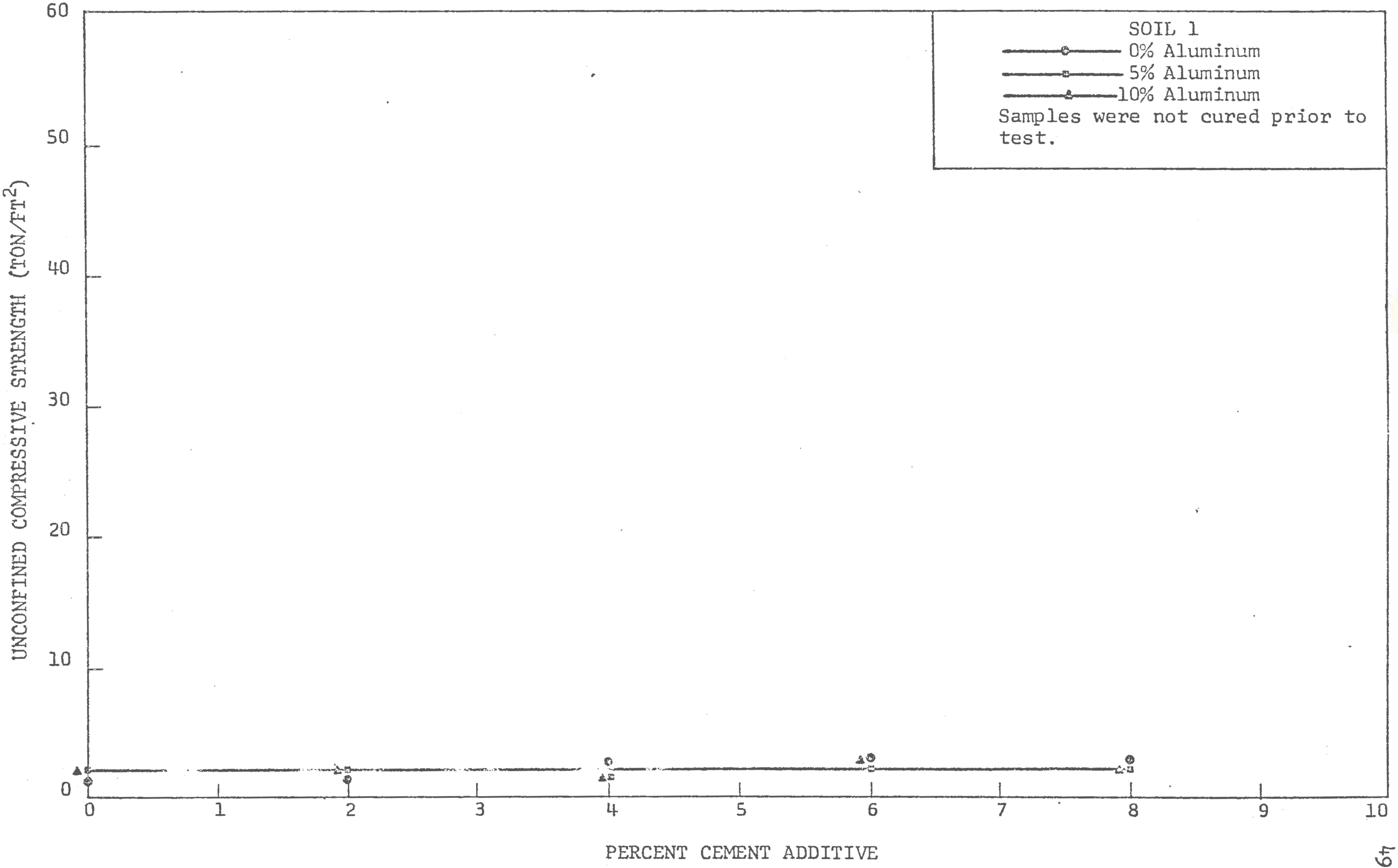


FIGURE 16

EFFECT OF CEMENT AND ALUMINUM ADDITIVES ON THE COMPRESSIVE STRENGTH OF SOIL 1 AFTER SEVEN DAYS HUMID CURE

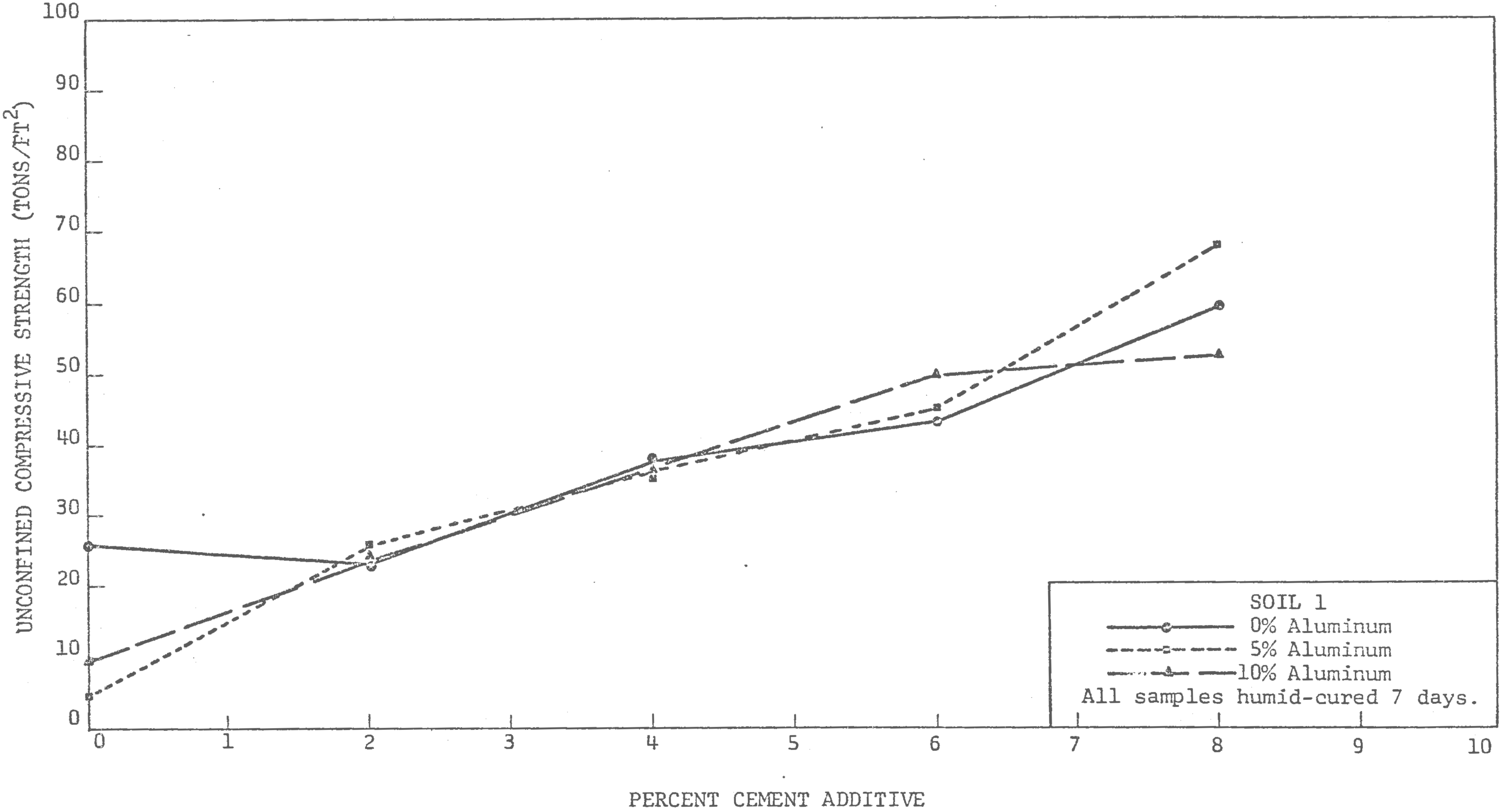
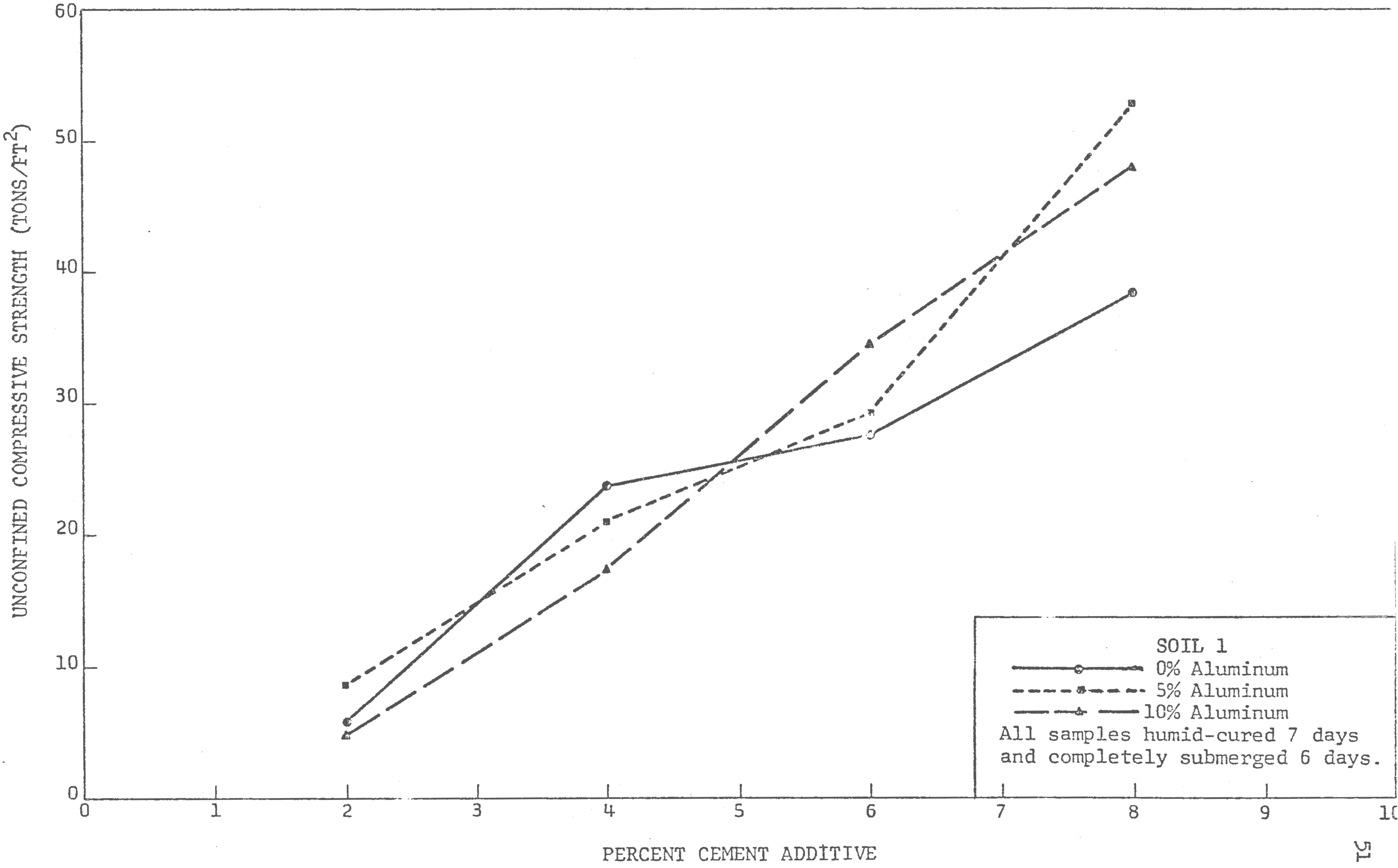


FIGURE 17

EFFECT OF CEMENT AND ALUMINUM ADDITIVES ON THE COMPRESSIVE STRENGTH OF SOIL 1



All samples humid-cured 7 days and completely submerged 6 days.

FIGURE 18

RESULTS OF ABSORPTION TESTS ON SOIL STABILIZED BY THE ADDITION OF VARYING PERCENTAGES OF CEMENT

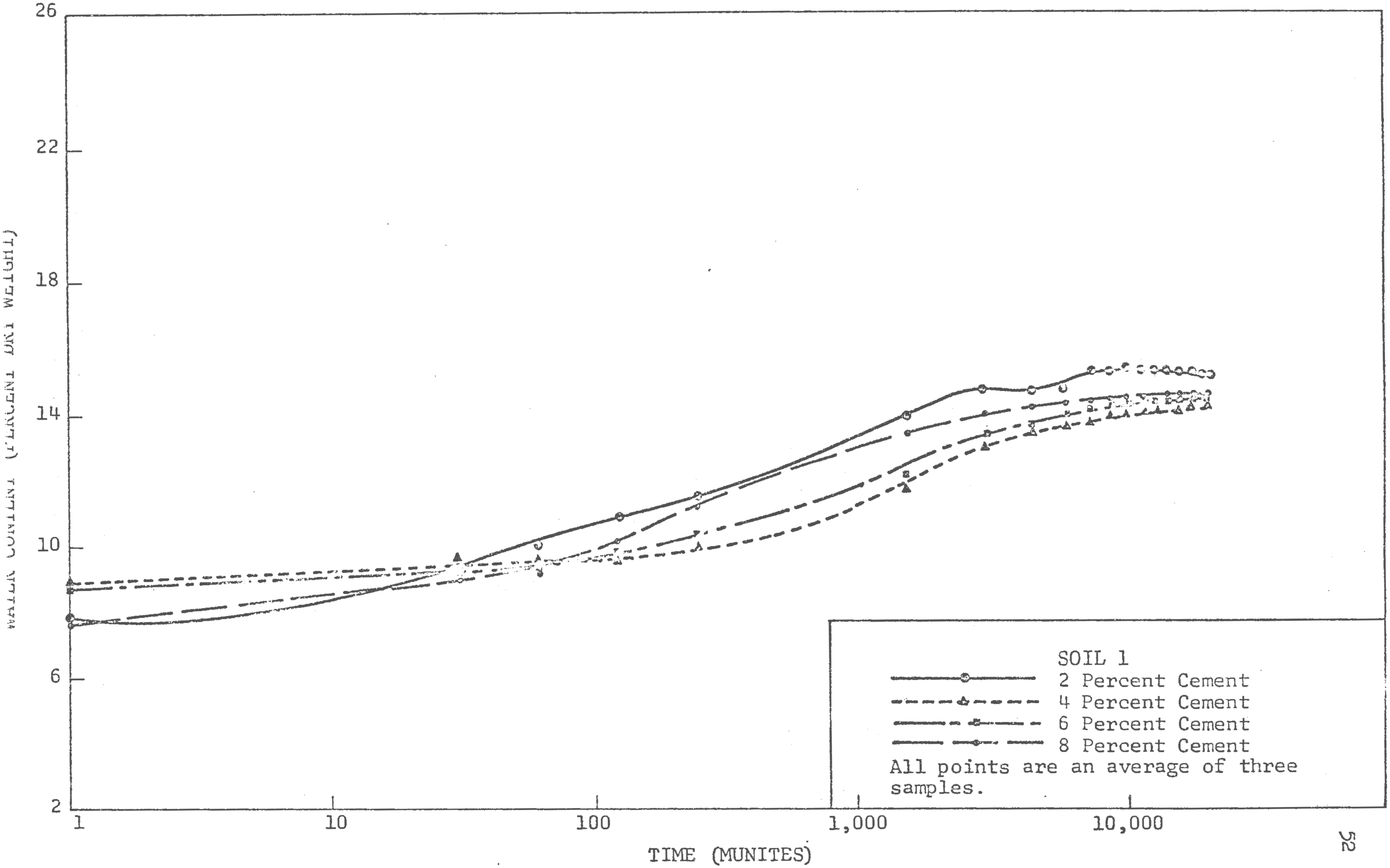
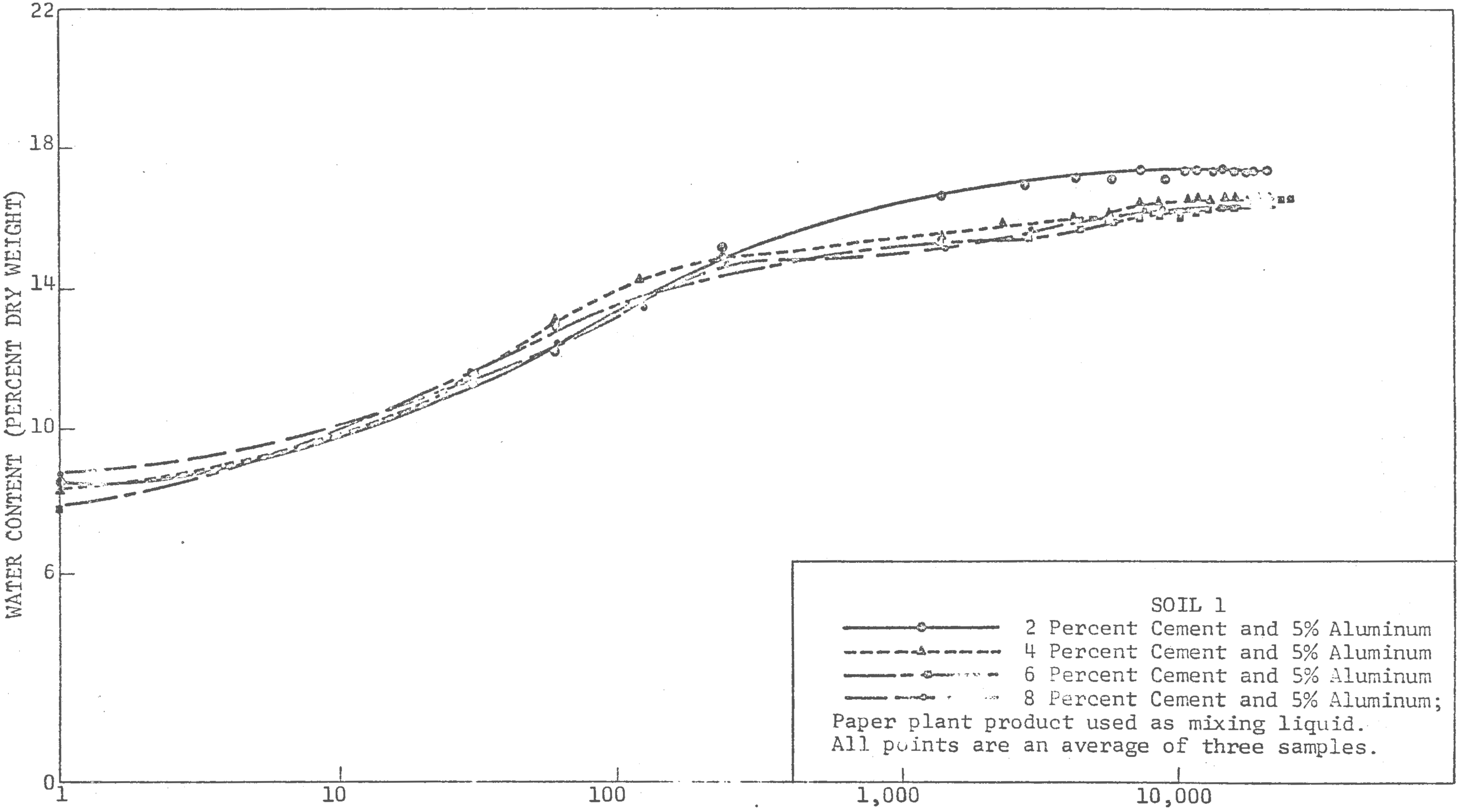


FIGURE 19

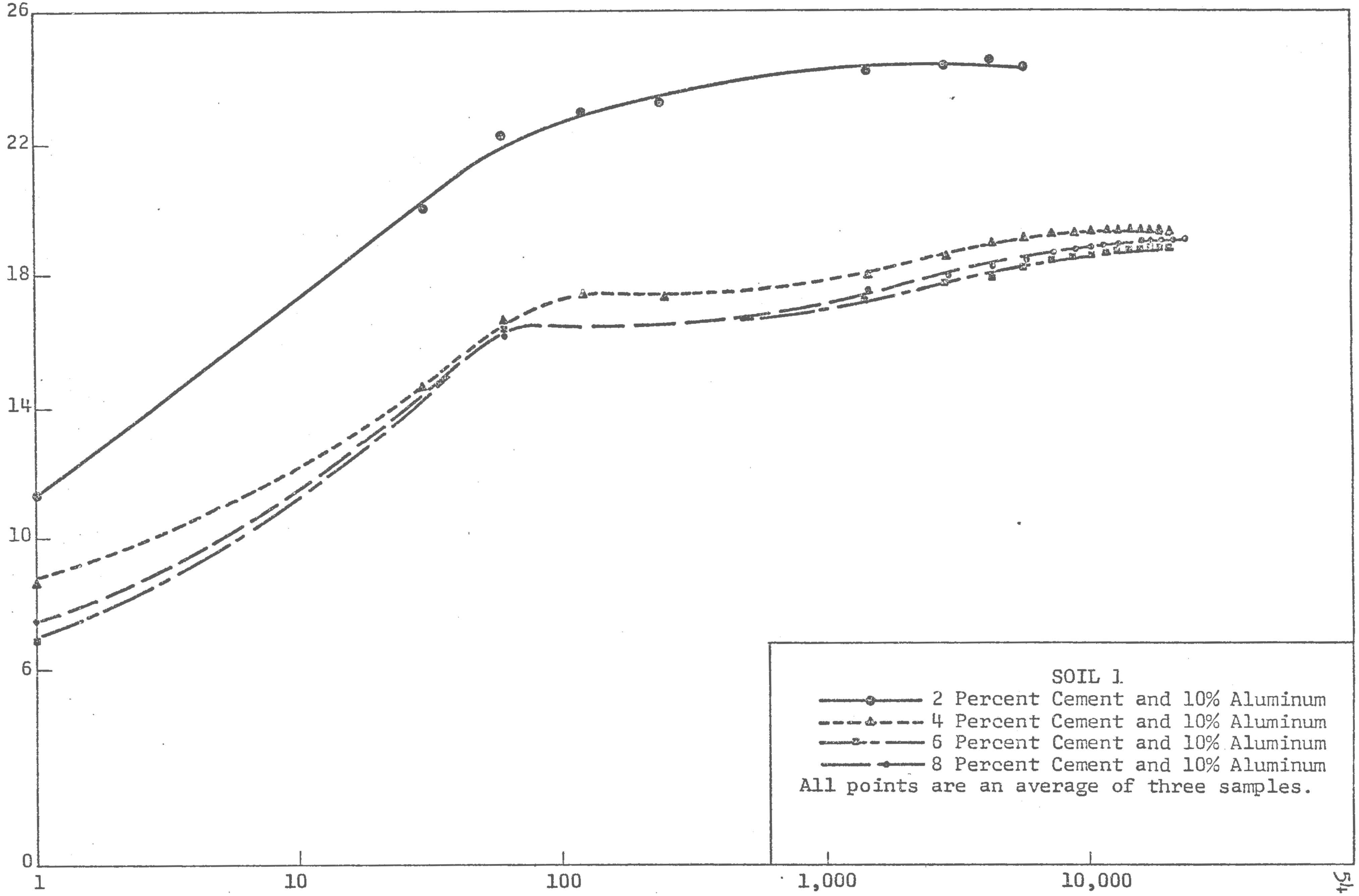
RESULTS OF ABSORPTION TESTS ON SOIL STABILIZED BY THE ADDITION OF VARYING PERCENTAGES OF CEMENT AND 5% ALUMINUM



Paper plant product used as mixing liquid.
All points are an average of three samples.

FIGURE 20

RESULTS OF ABSORPTION TESTS ON SOIL STABILIZED BY THE ADDITION OF VARYING PERCENTAGES OF CEMENT AND 10% ALUMINUM



5.3 Aluminum By-Product and Lime

To study the effectiveness of mixtures of aluminum by-product and lime, Soil 2 was treated with 0, 2 and 4 percent lime. To these mixtures 5 and 10 percent aluminum by-product was added. The results of strength tests show that although a lower density was attained at constant compaction energy using the aluminum by-product, the strengths of specimens were practically independent of the amount of the aluminum additive present. The results of the aluminum by-product and the lime mixtures for the initial cure condition, Condition 1, and the 7-day humid cure condition, Condition 2, are shown in Figure 21.

Absorption tests performed using Soil 2 and lime-aluminum by-product mixtures show that the aluminum by-product was in general detrimental to the behavior of the test specimens. Most aluminum-treated specimens disintegrated by the end of one day of the test. The lime-treated specimens with or without the aluminum admixture stood to the end of the 14-day test cycle. An example of the absorption test results is shown in Figure 22 for the untreated soil and for 4 percent lime alone and with 5 and 10 percent aluminum by-product treatment.

5.4 Paper Plant By-Product

For the liquid paper plant by-product to be effective as a stabilizer it must demonstrate either the ability to water-proof the soil or provide for a cation exchange reaction. The effect of the paper plant by-product on the Atterberg limits was studied using Soil 3. Table 8 shows the results of these tests. As can

FIGURE 21

EFFECT OF VARYING AMOUNTS OF LIME AND ALUMINUM
ON THE COMPRESSIVE STRENGTH OF SOIL 2

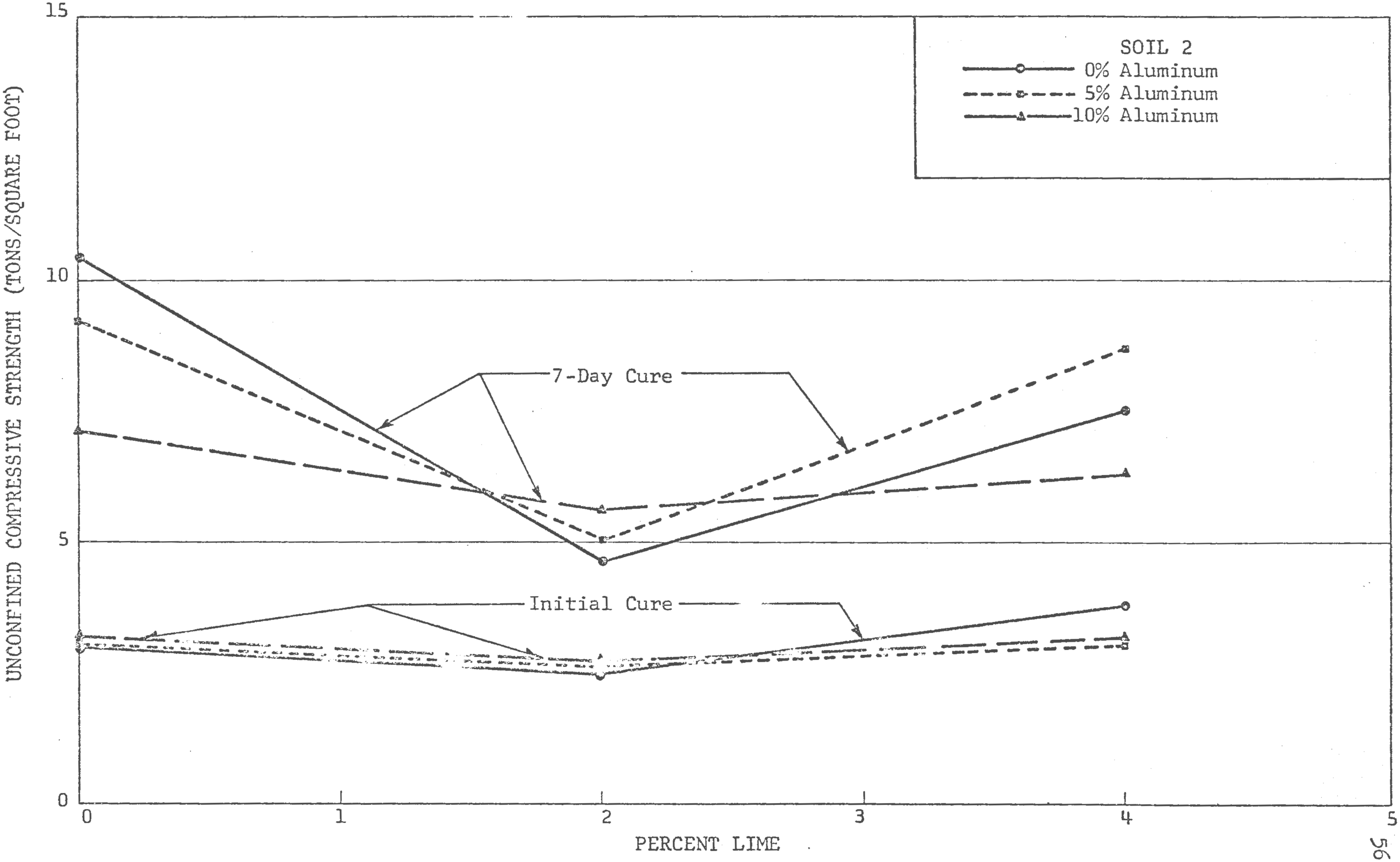


FIGURE 22

RESULTS OF ABSORPTION TESTS FOR THE EFFECT OF LIME AND ALUMINUM ON SOIL 2

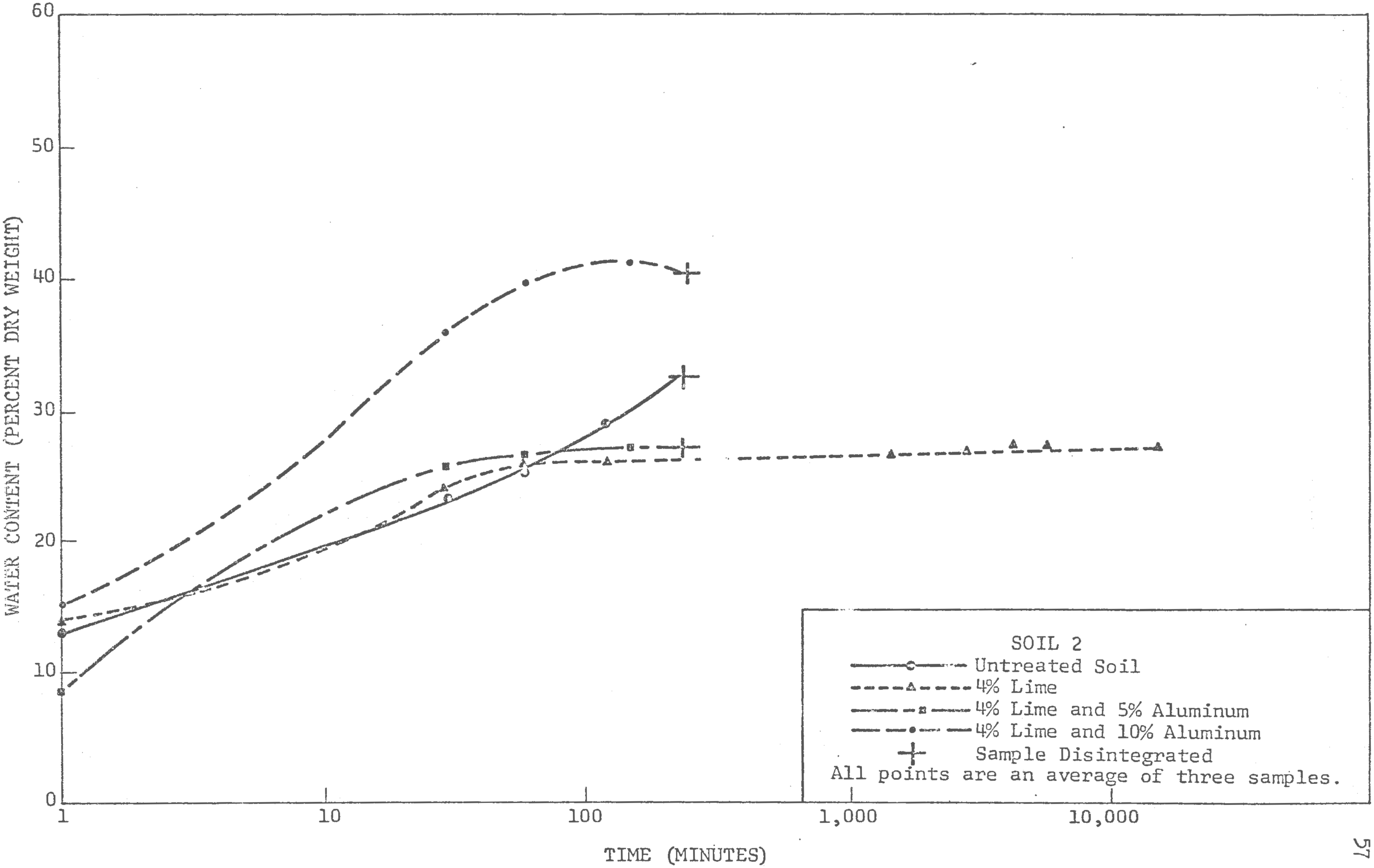


TABLE 8

EFFECT OF PAPER PLANT BY-PRODUCT ON THE ATTERBERG LIMITS OF SOIL 3

Condition	Liquid Limit	Plastic Limit	Plasticity Index
Test Performed using water	82	37	45
Test performed using paper plant by-product on air-dried soil	66	38	28
Soil wet with paper plant by-product then dried and tested using water	73	39	34
Soil wet with paper plant by-product then dried and tested using paper plant product	69	40	29

be seen from these results, the paper plant by-product does reduce the plasticity index, however the conditions for which the reduction was observed are considered impractical.

The ability of the paper by-product as a water-proofing agent was tested by using Soil 2 stabilized with 4 percent lime and 5 percent aluminum by-product and the paper plant material. Tests using Soil 2 illustrated that the paper plant liquid was not effective as a stabilizer, as shown in Figure 23.

5.5 Lime

The Atterberg limits for Soils 2 and 3 were determined using various percentages of lime. The results of these studies are shown in Figures 24 and 25 for Soils 2 and 3, respectively. As can be seen, the higher the percent of lime used, the smaller the plasticity index becomes. Simple laboratory determinations of this kind may be used successfully in selecting the lime content required for a plastic clay. For Soil 2 the optimum lime content is approximately 4 percent, while for Soil 3 the optimum lime content is approximately 8 percent.

5.6 Sarabond

The effectiveness of Sarabond as a possible stabilizer was investigated using Soil 4. Five series of unconfined compression tests were performed using a slightly different procedure than previously outlined. In every instance use of soil, cement and

FIGURE 23

WATER-PROOFING CHARACTERISTICS OF PAPER PLANT BY-PRODUCT

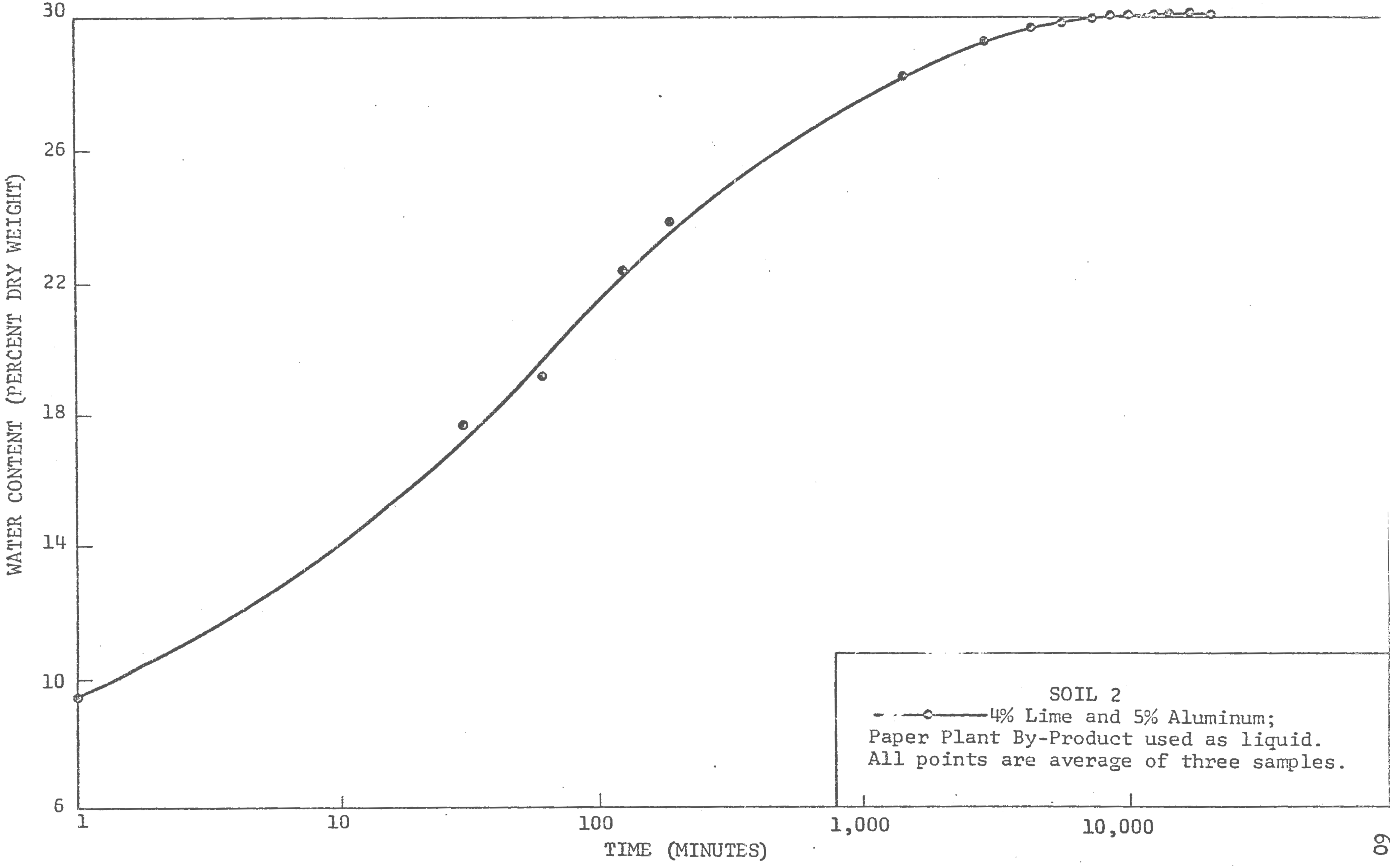


FIGURE 24

EFFECT OF VARIOUS PERCENTAGES OF LIME ON THE ATTERBERG LIMITS OF SOIL 2

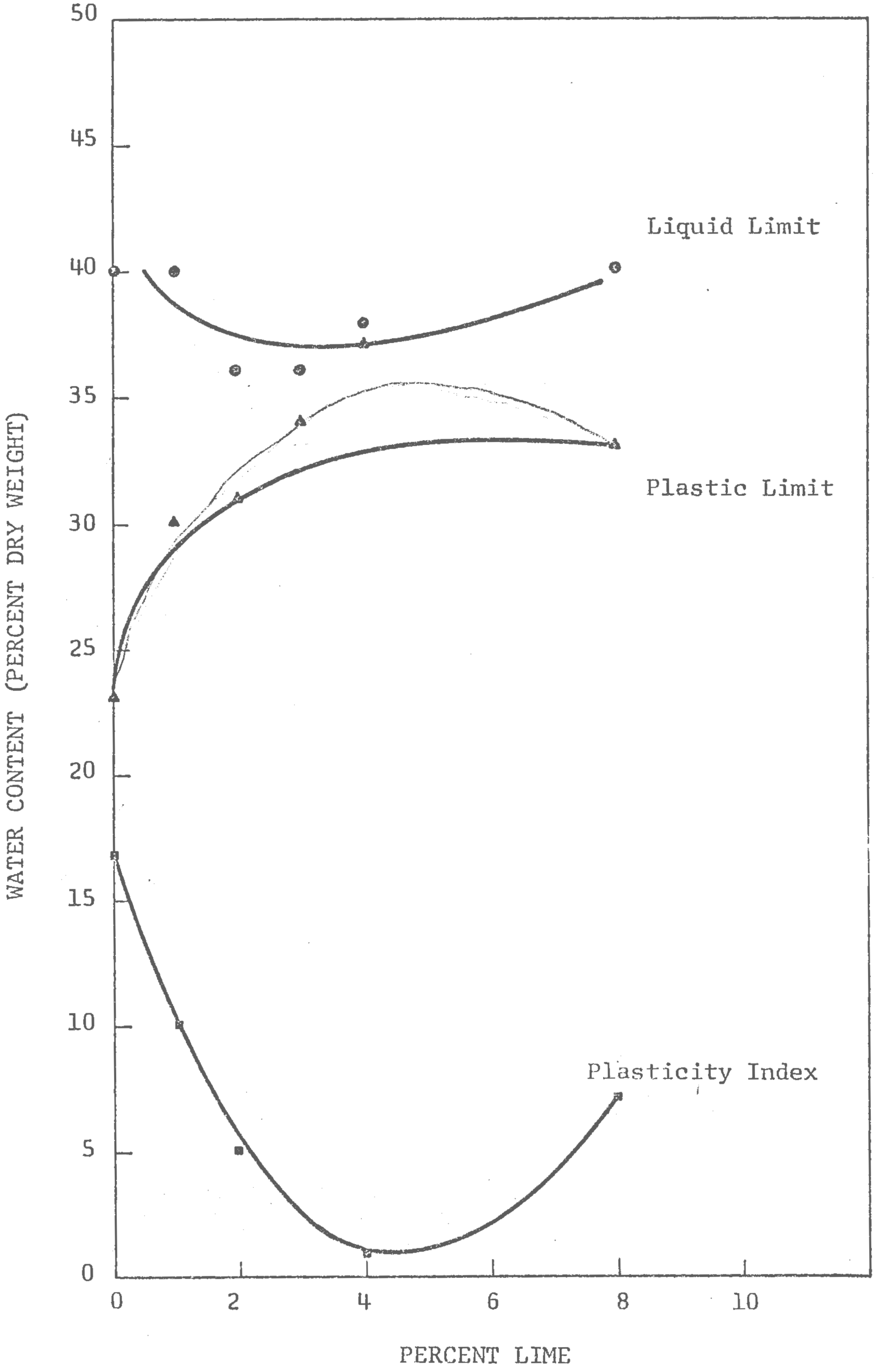
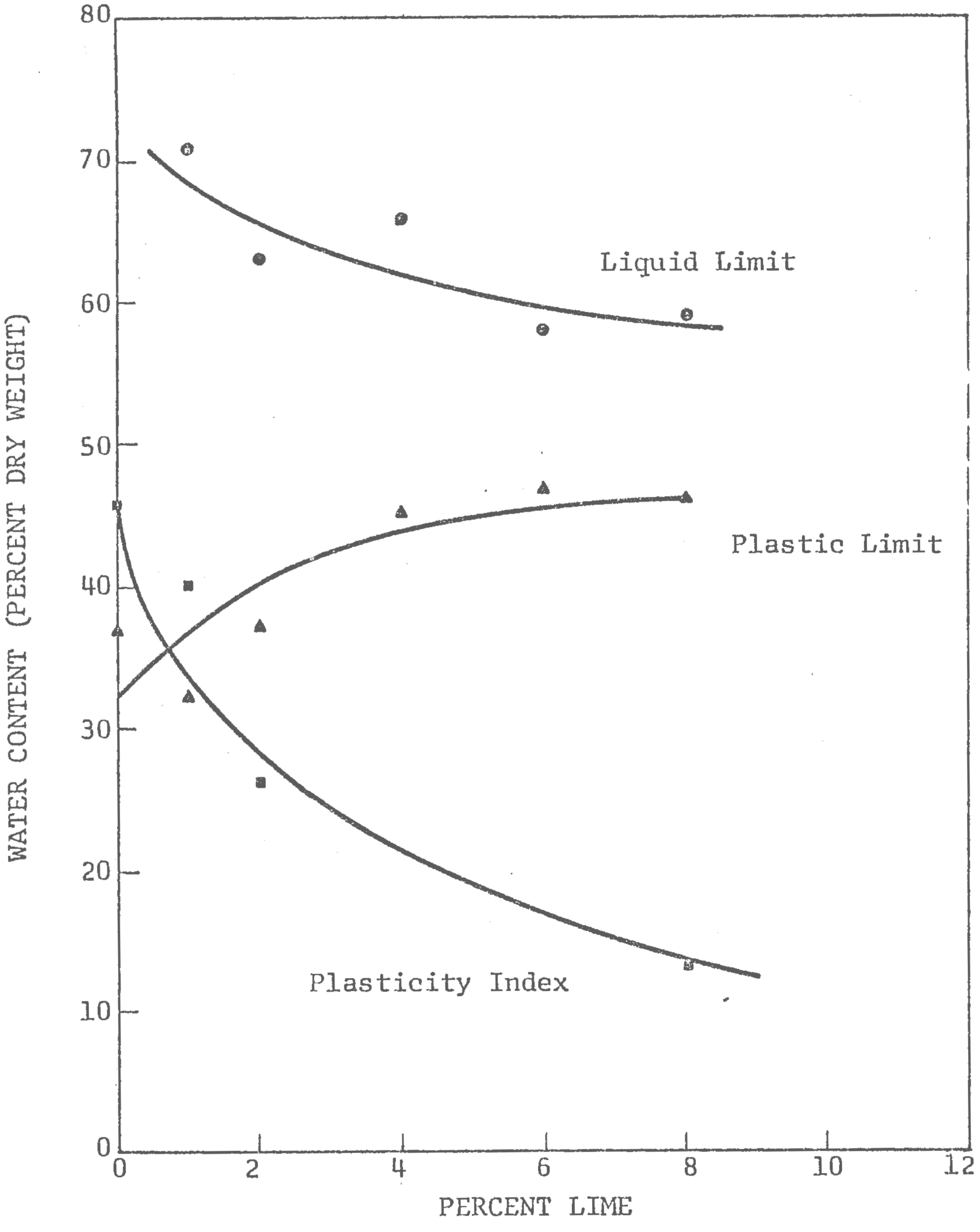


FIGURE 25

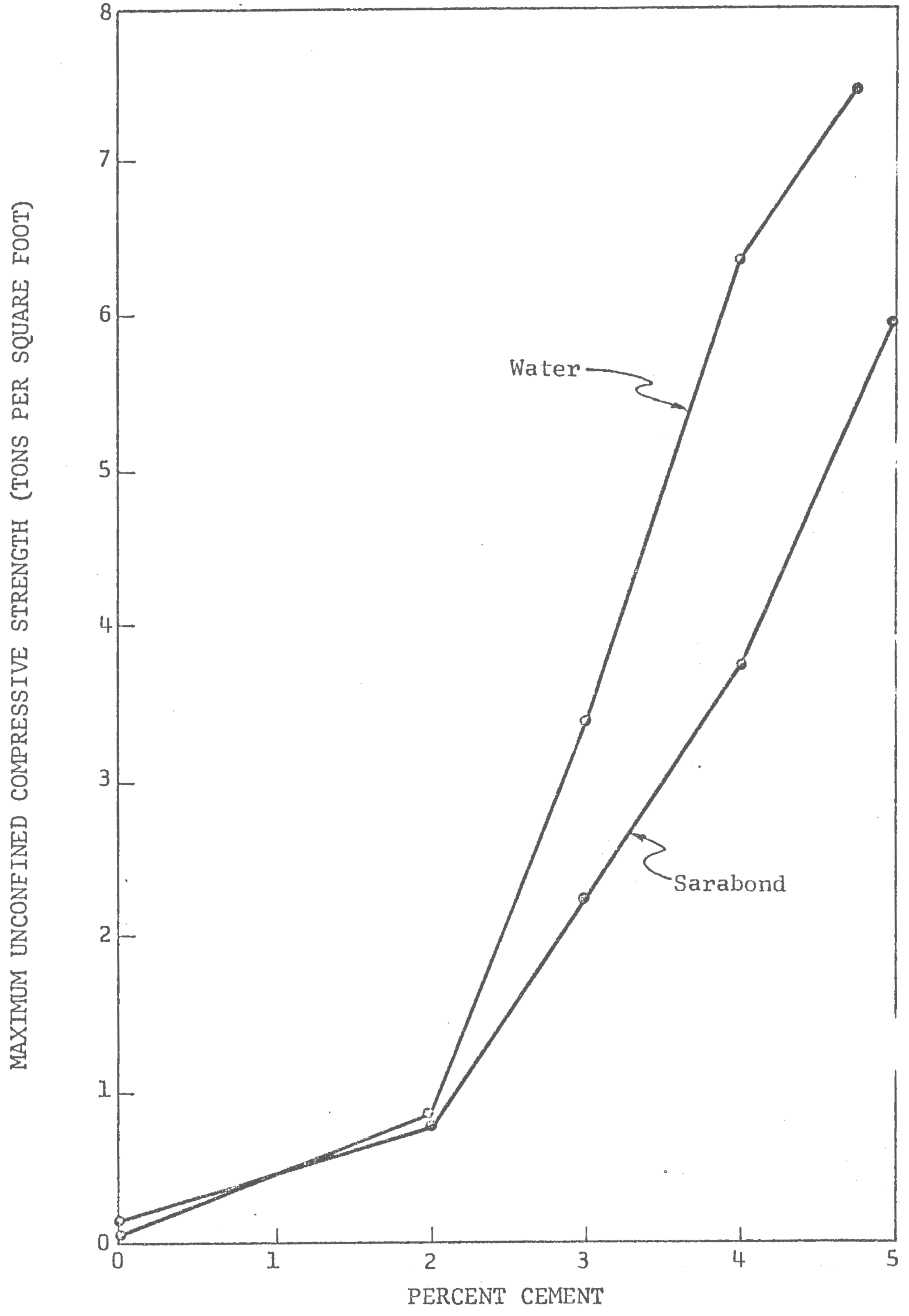
EFFECT OF VARIOUS PERCENTAGES OF LIME ON THE ATTERBERG LIMITS OF SOIL 3



Sarabond resulted in lower strengths than those obtained using soil, cement and water. These results have been presented by E. R. Beckel (2) in an unpublished Master of Science Thesis at the University of Arkansas in 1964. Figure 26 is typical of his results. On the basis of his results Sarabond was eliminated from the possible list of stabilizers investigated.

FIGURE 26

RESULTS OF UNCONFINED COMPRESSIVE TEST ON SOIL 4 - SARABOND - CEMENT MIXTURE AND SOIL 4 - WATER - CEMENT MIXTURE AFTER ONE DAY AIR DRY AND THREE DAY IMMERSION IN WATER



CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The following may be concluded from the results of the laboratory investigation and literature study:

1. The aluminum by-product used as a soil additive in concentrations up to 10 percent by weight was ineffective as a stabilizing agent. In general the treated soil did not dry as rapidly and adsorbed greater amounts of water than untreated specimens.

2. Admixtures of aluminum by-product with cement generally showed a slight tendency to increase strengths. However, these increases are minor and economically infeasible. In general water absorption characteristics were enhanced by the addition of the aluminum by-product.

3. The aluminum by-product mixed with lime treated soils was in general detrimental to the behavior of test specimens especially in absorptions studies. Results of the strength tests showed that the strengths of specimens were practically independent of the amount of aluminum by-product added.

4. The liquid paper plant by-product was shown to be only slightly effective as to its ability to reduce the plasticity of highly plastic clays. The conditions of most effective usage as described in article 5.4 are not practical for field use. This treatment also demonstrated a lack of effectiveness as a waterproofing agent.

5. The use of lime has long been a well established treatment for clay of medium to high plasticity. Although it was not the purpose of this report to evaluate lime as a soil additive, basic comparative tests were performed which indicated its effectiveness. It may be concluded from this study and the current literature that lime is generally most effective as a stabilizer when used with soils having a liquid limit of 40 or above. The approximate optimum lime content can be established for each soil by performing

series of Atterberg Limit Tests in which the lime content is varied. For very highly plastic soils it is often advantageous to add lime to the soil to improve its workability and then add portland cement to increase the strength characteristics.

6. The use of Sarabond with portland cement as a soil stabilizer resulted in reduced soil strengths.

It is recommended that additional studies on the effects of lime and portland cement be conducted in connection with Highway Research Project Number 20. These studies should include the effects of lime, portland cement and combinations of the two stabilizers on the Group Index, R-value and Soil Support Values currently being investigated. It is the intention of the project personnel to conduct such studies.

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