HIGHWAY RESEARCH REPORT

LIME SOIL STABILIZATION STUDY
PHASE II
LABORATORY INVESTIGATION OF CALIFORNIA SOILS FOR LIME REACTIVITY

FINAL REPORT

STATE OF CALIFORNIA

BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF TRANSPORTATION

DIVISION OF HIGHWAYS

TRANSPORTATION LABORATORY

RESEARCH REPORT

CA-DOT-TL-2812-2-73-40

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration February, 1973

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Lime Soil Stabilization Study		5. REPORT DATE February 1974 6. PERFORMING ORGANIZATION CODE 19201-762503-632812
7. AUTHOR(S) Puleo, Joseph and Hannon, Joseph B.		8. PERFORMING ORGANIZATION REPORT NO. CA-DOT-TL-2812-2-73-40
9. PERFORMING ORGANIZATION NAME AND ADDRESS Transportation Laboratory 5900 Folsom Boulevard Sacramento, California 95819		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. D-2-10
12. SPONSORING AGENCY NAME AND ADDRESS Department of Transportation Division of Highways Sacramento, California 95807		13. TYPE OF REPORT & PERIOD COVERED Final Report - Phase II 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Study was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

The compressive strength due to lime-reactivity of 41 fine grained soils is reported, with the properties of the untreated soils. The variables discussed include moisture content, pH, the effects of the physical presence of lime, sulfates, mixing conditions and the electrical monitoring of the lime-soil reaction. This electrical procedure monitors an accelerated lime-soil-water (paste) reaction and provides data on conductivity and dielectric constants. This data is used to determine whether the predominate reaction is agglomeration or adsorption. Based upon the electrical data a soil can be classified as reactive or non-reactive. The electrical data can also be used to estimate the 6-month developed compression strength of a lime-soil specimen. Guidelines using electrical test data and soil properties are provided for estimating the developed strengths of soils.

17. KEY WORDS Clay (materials); conductivity; dielectric constant; electrical measurements; lime reactivity; soil-lime mixtures; soil mechanics; soil stabilization; sulfates.		18. DISTRIBUTION STATEMENT Unlimited	
19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 172	22. PRICE

HMRT 1242 (ORIG. 9/72)

STATE OF CALIFORNIA—BUSINESS AND TRANSPORTATION AGENCY

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February 1974

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State Highway Engineer

Dear Sir:

Submitted herewith is a final research report titled:

LIME SOIL STABILIZATION STUDY

PHASE II

LABORATORY INVESTIGATION

OF

CALIFORNIA SOILS

FOR

LIME REACTIVITY
(DEVELOPED STRENGTH)

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ACKNOWLEDGEMENTS

The Foundation Section of the California Transportation Laboratory conducted this study in cooperation with the Federal Highway Administration, U. S. Department of Transportation, as Item D-2-10 of Work Program HPR-PR-1(1) Phase II. The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

A review of activities conducted during Phase I of this research project was presented in the interim report titled: "Lime Soil Stabilization Study - A selected Literature Review," State of California, Division of Highways, Materials and Research Department, January 15, 1967.

The authors wish to express their gratitude to the over 40 people who have contributed to this study. The authors are especially indebted to Travis Smith, Principal Highway Engineer, the former Chief of the Foundation Section, and to Marvin L. McCauley, Senior Engineering Geologist, and to Donald L. Durr, Senior Materials and Research Engineer, for their supervision. Appreciation is extended to Grant M. Kennedy, Soil Scientist Specialist, U.S. Department of Agriculture, Soil Conservation Service, who provided soil classification details and soil data. The efforts of the soil testing personnel was appreciated in particular, James H. Gamble, Assistant Engineering Geologist, and John R. Janson, Highway Engineering Technician, who not only carried the burden of the X-ray diffraction and D.T.A. work but generously supplied helpful information on numerous occasions. We gratefully acknowledge the help of Morris Tatum who suggested captions for the photographs; Jan Shetler and Sylvester Dalske who helped with the field work; and James McFarlane who performed the strength tests for this project. The authors wish to express their thanks to John Campbell for his assistance in reviewing the manuscript. Ben Zeiler's contributions as research editor of the Foundation Section have been greatly appreciated. Special thanks are extended to Dr. Kandiah Arulanandan, Professor of Civil Engineering, University of California (Davis), for his work in supplying the electrical response data and his overall interest in this study. The chemistry advice enthusiastically given by Truman E. Burns and Carl H. Hofmann is gratefully appreciated.

The design and fabrication of the testing devices used in this project was largely the result of the expertise of the Machine Shop personnel. We wish to especially acknowledge the help of

George K. Oki and Joseph E. Wilson, Machinist and Instrument Makers, for their enthusiastic cooperation in this regard. And finally, Dr. James L. Post, of the Department of Civil Engineering, California State University, Sacramento, is acknowledged for his interest and continuing enthusiasm in this work and for his help in the analysis of a problem soil. The authors would also like to thank the Diamond Springs Lime Company for the lime which was donated for this study.

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INTRODUCTION

Man has long been aware that he can alter many of the materials in nature. Where the natural properties of a soil are not suited for a particular use, he has demonstrated resourcefulness in adjusting such properties to permit the soil to function in an acceptable manner. In recent years, economic realities have challenged the old philosophy that objectionable soils should be routinely rejected.

The current procedure used for assessing a soil's suitability for lime-soil stabilization is to fabricate a lime-soil specimen in the laboratory and test for compressive strength at 28 days. Some marginal soils may be of such a large quantity as to command a great economic impact upon a construction project. This could require a longer laboratory cure interval than 28 days to insure that a soil is not prematurely rejected as being an unsuitable construction material. Herrin and Mitchell (21) suggest that many soils require 4 to 6 months of curing to obtain a major portion of their developed strength.

The capacity to predict the strength development of a soil treated with lime and cured for 6 months in the laboratory could be invaluable as a design tool. On most projects, however, an extended curing period may not be possible as a result of construction progress. In most cases the available curing period would be dictated by the particular situation and type of application.

The ultimate goal of this research project was to formulate guidelines for estimating a soil's suitability for lime stabilization. Lime treatment has successfully been used by the California Department of Transportation for many years in the treatment of basement soils below the pavement structural section. The California Department of Transportation has also had an interest in a more extensive application of lime treatment to improve strength characteristics of embankments, and to stabilize soft foundations and landslides.

In 1966, a search of lime-soil stabilization literature disclosed many areas of disagreement in establishing the mechanism for the lime-soil reaction.

This preliminary literature search was followed by a second more extensive search (40) which, in outline form, gave immediate reference to each particular facet in the lime-soil stabilization field. Additionally, the literature search clearly indicated that one consequence of restricting the soil tested in

a lime-soil stabilization study would be to reduce the applicability of any research findings. Therefore, this research project was conducted state-wide to account for the great variety of California soil types.

Whereas most researchers in this field have limited their studies to a narrow range of soil types, Professor Marshall R. Thompson, University of Illinois, included a substantial percentage of Illinois soils in his works (51), and thus gained a better understanding of the factors which influence the lime-soil reaction.

The laboratory study described herein was patterened after the manner set forth by Professor Thompson (51). The laboratory phase is an investigation of the developed strength (lime reactivity) of 30 representative California soils from more than 900 soil units to determine the predominant factors influencing the lime-soil reaction. The results from testing 22 of these 30 soil units are reported.

Concomitant with this investigation of the lime-soil phenomena, a method was sought for a rapid test procedure to predict long-term strength gain of lime-treated soils.

Dr. Kandiah Arulanandan of the University of California, Davis, has developed a means for measuring the electrical characteristics of soils (3,4,5,6,36,44). Through his cooperation a contract was established to electrically monitor lime-soil reactions at the University laboratory. This information is presented herein and provides a procedure for determining whether lime can be beneficial or detrimental to a particular soil.

CONCLUSIONS

General

1. Soils treated with lime increase in unconfined compressive strength as a function of moisture content, density, curing period and increased lime content.

2. A maximum and minimum value for the developed unconfined compressive strength gain resulting from lime treatment can be estimated based upon the clay content. The Plasticity Index of a soil can also be used in estimating a minimum value of developed strength.

3. The unconfined compressive strength of an untreated soil increases as the clay content increases up to about 50% clay; thereafter, the strength decreases at about the same rate.

4. Decreasing soil particle size in a lime-soil system results in an increase in developed strength.

5. The pH of a natural soil is not a reliable indicator of developed strength (lime reactivity).

6. Over 90% of the "B" horizon soils tested were classified as suitable for lime treatment, based on developed strength. For the "A" and "C" horizon soils only about 60% of the soils tested are suitable for treatment.

Electrical Testing

1. The electrical response test will delineate those lime treated soils which will not achieve the minimum developed compressive strength of 100 psi after 6 months of laboratory curing.

2. The electrical response test identifies two lime-soil reactions (adsorption and agglomeration) and indicates which reaction predominates.

3. Each of the two lime-soil reactions has two subcategories: Adsorption, (montmorillonitic soil and nonmontmorillonitic soil) and agglomeration, (kaolinitic soil and nonkaolinitic soil). The dielectric constants of the soils may be useful in delineating one subcategory from another.

4. Once the lime-soil reaction subcategory is established by electrical means, the long-term (6 months) compressive strength of a lime treated soil can be estimated from the appropriate soil property.

5. In general, the exchangeable potassium ion of a soil is an indicator of which lime-soil reaction predominates. A knowledge of the predominant clay mineral present in a soil can be used to determine which lime-soil reaction subcategory phenomenon exists.

6. As an alternative to determining the clay mineral properties directly by X-ray diffraction, they may be estimated from a knowledge of the common engineering soil properties, the dielectric constant and the "Instant Test" procedure described in this report. Together, these soil properties can be used to estimate the lime-soil reaction category.

Sulfate Soils

In general, a lime treated high sulfate content soil will increse in volume upon curing. Finer grained soils will expand more than coarser grained soils.

"Instant Test"

1. A procedure defined as "Instant Test" has been developed to quickly identify a soils potential for stabilization. Soils with "Instant Test" values of developed compressive strength less than 12 psi are considered unsuitable for lime treatment.

2. The "Instant Test" can be used to differentiate the adsorptive montmorillonite subcategory from the adsorptive nonmontmorillonite subcategory. It also differentiates the adsorptive nonmontmorillonite subcategory from the agglomerative nonkaolinitic subcategory and differentiates the adsorptive nonmontmorillonite subcategory from the agglomerative kaolinitic subcategory.

Moisture Content

Lime treated montmorillonitic soils containing exchangeable calcium ions greater than 12 meg/100 grams of soil produced a significantly greater compressive strength at moisture contents in excess of optimum moisture content.

Lime treated soils with iron coating content greater than 2% and with a pH of less than 7 (for the untreated soil) produce greater compressive strength at moisture contents below optimum.

The oven moisture content of an "Instant Test" (lime-soil) specimen can be used to identify a Group 1 or a Group 4 soil.

Lime-Soil Mixing

Inadequately mixed lime-soil systems achieve about 25% of the compressive strength of a well mixed lime treated soil in the presence of a high clay content (above 70%) and about 60% of the compressive strength of a well mixed lime treated soil in the presence of a low clay content (below 12%).

Lime Reactivity (developed strength)*

1. There is some evidence to support the argument that what normally are defined as nonreactive soils can be chemically or physically highly reactive. Therefore, the term "nonreactive" when applied to lime treated soils that fail to meet the minimum developed compressive strength may not always be accurate.

*The lime treated soils were grouped according to the magnitude of developed compressive strength achieved following a 6-month cure interval. Group numbers were than assigned to each 100 psi increment. Thus, Group 1 indicates the 0-100 psi increment, Group 2 indicates the 100-200 psi increment, Group 3 indicates the 200-300 psi increment and Group 4 indicates greater than 300 psi developed compressive strength.

Although the term "lime reactivity" was initially used, a more accurate term would be "developed strength." Throughout this report, however, these two terms are used interchangeably.

2. For soils with clay content in excess of 60-70%, as much as 7% lime can be required to produce the minimum long-term developed compressive strength.

Influence of Clay Mineral Upon Developed Strength (Lime Reactivity)

The average long-term developed strength of the lime treated kaolinitic soils achieved less than half of the average developed strength of all 41 lime treated soils used in this study. They also achieved less than one-third of the average developed strength of the lime treated Hydrobiotite-Vermiculite soils.

Soils whose predominate clay mineral was Hydrobiotite-Vermiculite or Mixed Layer were all classified as suitable for lime treatment.

Nearly all of the lime treated montmorillonitic clays were either highly suitable (Group 4) or unsuitable (Group 1) whereas the kaolinitic clays were Group 3 to unsuitable (Group 1).

RECOMMENDATIONS

1. Future research is recommended to evaluate 12 additional soil horizons for which testing was only partially completed and are not reported herein. These soils are of interest because they possess soil properties not common to the initial 41 soils reported. These soils range from silts (73%) to bay soils (with oxidizable sulfur and salts).

2. There remains more than thirty soils upon which electrical characterization data were not determined. These soils should be included in any additional research into this electrical phenomenon. The advantages of using these soils are: (a) the field sampling has been completed and the natural soil properties of most of them have been determined; (b) the lime reactivities (developed strength) up to and including the 6-month cure interval are known; and (c) many extra fabricated lime-soil specimens which were reserved for the purpose of duplication (in the event the original specimens were damaged) remain unused and should be valuable for evaluation of the 2-5 year cure interval.

IMPLEMENTATION

Guideline criteria is provided in Appendix D which allows estimates of lime-soil strength development. This information is suggested as an aid to evaluate lime as a stabilizing agent for potential landslides, earth embankments, soft foundations and basement soils. A guideline test procedure will be prepared based upon the guidelines presented in Appendix D.

PRELIMINARY CONSIDERATIONS PRIOR TO LABORATORY INVESTIGATION

Soil Selection

The laboratory phase was designed to study lime reactivity (developed compressive strength) of selected California soils for the purpose of formulating guidelines to estimate the performance of lime-treated soils throughout California. A "Soil Series"* classification system established by the U.S. Department of Agriculture, Soil Conservation Service, was the system from which the aforementioned soils were selected.

Initially, three criteria controlled the selection of soils for this study: the first, to select soils exhibiting a wide range of soil properties; secondly, to choose some soils that represented large acreage of land; and finally to limit those selected to the Benchmark Soils*. The various Benchmark Soil Series were of such limited numbers that this last criterion could not always be met.

Altogether, 53 soil samples were selected which represent 30 from a total of more than 900 soil series in California (see Fig. 1). These 30 soil series were selected from 15 of a possible 58 counties. While all were gathered from the field and processed in the laboratory, only 41 of the total 53 soil samples were tested and analyzed for this report. These 41 soils represent 22 soil series from 10 counties in the state while one to three soil horizons* were sampled from each of the 22 soil series.

Therefore, the soils that are reported herein are not considered representative of the more than 900 soil series of California. These soil sites are depicted on Fig. 1 and Table 1. The basic engineering and chemical properties associated with these soils are shown on Tables 2a and 2b. Classification of these soils by the United States Department of Agriculture, Soil Conservation Service, is presented on Table 3. Photos 1 to 3 show the field location of a typical soil site.

Moisture Content and Particle Size

According to Baver (7) "dehydrated clay colloids can exert a vigorous cementation action on the soil aggregates. The reversibility of these dehydrated secondary particles may be very slow." Reconstituting a soil from its dried components may not immediately restore its original texture. Elias Zolkov (55) cautions, "In order to minimize the influence of changes in the soil due only to rewetting, it is felt that soils should be wetted well in advance of the commencement of research

*Refer to Appendix A, Glossary of Soil Science Terms.

programs." It was therefore decided not to unduly dry soils prior to mixing with lime. The soils would be moisture cured at their optimum moisture content three to six months in advance of the lime treatment procedure. The soil and water mixture was then assumed to be in equilibrium.

For the purpose of clarity the term aggregate describes a soil unit which was sieved (passing No. 8 mesh) from a soil maintained at the optimum moisture content of the soil. The soil and moisture are in equilibrium before and after the sieving operation. Furthermore, the term particle is used to describe a soil unit which was air dried or oven dried prior to the sieving operation.

LABORATORY INVESTIGATIONS

Specimen Preparation

a. Soil Processing and Specimen Fabrication

Soil samples collected from the field were packaged in canvas bags, each having two plastic bag liners to preserve field moisture. Occasionally, an excavated soil was too wet to be immediately packaged and was allowed to air dry at the field sampling site to reduce the moisture content. Photos 1 through 3 show one such soil excavated below the water table and allowed to air dry to a moist condition while the outside air temperature was nearly 110°F.

The literature search conducted prior to the actual soil sampling revealed that the soil particle sizes used by various investigators in the lime-soil stabilization field ranged from passing No. 4 to a passing No. 80 sieve size. Most of the investigators used passing No. 10 size material. A few soils were initially screened on the No. 10 size sieve. The No. 10 sieve, however, was abandoned in favor of the larger passing No. 8 size because the No. 10 sieve would clog too readily using field soil at near optimum moisture content.

The passing 3/8-inch field soil was screened in the laboratory. That portion passing the No. 8 sieve was stored at optimum moisture content for a minimum time of three months prior to fabrication in 2-inch diameter by 4-inch high cylindrical brass liners. See Photo 4.

The lime used in this study was a commercial high calcium hydrated lime donated by the Diamonds Springs Lime Company. A chemical analysis of this lime is shown in Appendix B.

A measured weight of lime and soil were mixed together using a motorized turnable and a cultivating blade. The lime was sprinkled on the rotating soil by means of a vibrating action, giving an even distribution of lime.

The mixture was then equally divided into four portions to the nearest 0.1 gram. The weight of each portion depended upon the results of the test maximum density from the California Impact Compaction Test (90% relative compaction, optimum moisture), but was usually about 100 grams. Each of the four portions was then used to fabricate a specimen lift with each lift being one inch in depth and approximately two inches in diameter. A hydraulic ram was used to compact each lift. The surface of each lift was scarified to mechanically bond the next lift to

the previous one. See Photos 5 to 10. Following fabrication, the specimen was geometrically controlled by measuring the specimen height and diameter. The specimen was then wraped with two thicknesses of "Handywrap" and sealed in wax. The sealed specimens were stored in a moisture cabinet maintained at 70°F and 100% relative humidity.

b. Laboratory Control of the Fabricated Specimens

Gravimetric control consisted of maintaining total specimen weight within ±1% of the calculated weight. The calculated weight includes the dry weight (90% relative compaction) the moisture content ("near" optimum moisture) and the lime portion (3, 5, or 7% of dry weight).

Gravimetric control is routinely desirable both for purposes of fabrication and storage and also to account for the apparent changes in moisture content; viz, moisture loss from specimen and the moisture retained by specimen.

Geometric control of the fabricated specimens were established within acceptable tolerances of diameter (±2mm) and height (±2mm). The measurements were taken after fabrication and again following the curing period but before the unconfined compressive tests were performed (see Photo 11). This procedure is useful in determining the shrink-swell potential of the natural and lime treated soils.

Moisture control proved to be the most significant of the three basic controls. The oven dry moisture content of the natural soil (near optimum) was observed to decrease with increasing lime content and increasing curing periods of the treated soils. This area of investigation requires much more analysis to understand the influence of water on lime-soil stabilization. The moisture content of all the untreated and lime treated soil specimens were initially the same (near optimum). After the specimens were tested for compressive strength the oven dry moisture content was determined. The difference in the moisture content results were then termed "Fixed Moisture" content (see Table 4).

Nomenclature

a. Lime Reactivity (Developed Strength)

A soil's interaction with lime is known to be influenced by many factors and this reactivity is considered to be a conditional property. The rate of any chemical reaction is dependent upon the natural properties of the reactants and

the environment in which they react. By changing the conditions of the reaction, the reaction velocity will probably change. This is apparent in lime-soil reactions. For example, Alexander (1) reports that quartz, which is not an active pozzolan, becomes very reactive when ground to a fine powder.

Thompson (51) defined lime reactivity (developed strength) as the "difference between the maximum compressive strength of the lime-soil mixtures (28-day cure: 3%, 5% or 7% lime treatment) and the compressive strength of the natural soil (0% lime treatment). If the compressive strength of the natural soil exceeds the strengths of the lime-soil mixtures, the lime reactivity is 0." The present study is developed along this model.

Thus,

Lime-Reactivity = Treated Strength - Untreated Strength (Eq. 1)

(NOTE: As described under the "criterion for the curing period" lime reactivity in this research project, unless otherwise noted, is based on a 6-month laboratory curing period.)

b. Percent Lime Reactivity (Percent Developed Strength)

Based upon the value of lime reactivity, the percentage increase in strength can be calculated. This term is useful when comparing reactivities of different soils.

The developed unconfined compressive strength of a lime treated soil (lime reactivity) is related to the unconfined compressive strength of the untreated soil as follows:

$$\% \text{ Lime Reactivity} = \frac{\text{Lime Reactivity (PSI)}}{\text{Untreated Strength (PSI)}} \times 100\% \qquad \text{(Eq. 2)}$$

Lime Related Research and Analyses

a. Unconfined Compressive Strength

Following a prescribed curing period, each specimen was measured for height and diameter before its unconfined compressive strength was determined. Photos 5 through 11 show the fabricating and measuring equipment used in this study. A plot of the unconfined compressive strength of the untreated soil vs. clay content is shown on Fig. 2. A general positive correlation was found between these two variables. Other relationships utilizing unconfined compressive strength are presented throughout this report.

b. Some Factors Affecting Soil Reactivity

Particle size (Fig. 3), moisture content (Fig. 4), and percent relative compaction (Fig. 5), were all found to influence the reactivity of a soil. Typically, there results a general increase in lime reactivity with reduced soil particle size (Fig. 3). Variation of moisture content from below to above optimum for the untreated specimens (Fig. 4) shows a consistent decrease in unconfined compressive strength. When lime is added to the natural soil no consistent strength pattern emerges as moisture content is increased, when all soils are considered. When clays are distinguished by mineralogy, however, various consistent patterns emerge as described later in this report. With increasing relative compaction (85-100%) there results a consistent increase in unconfined compressive strength (Fig. 5).

c. Reactivity as a Function of Clay Content

Figures 6a and 6b show lime reactivity and percent lime reactivity as a function of percent clay content. The 41 soils were treated with 5% lime and cured for six months. Data plotted on Fig. 6b is based upon Eq. 2 and calculated from data which appear on Table 10. For example, sample 10VC has an untreated strength of 6 psi and a 6-months treated strength of 301 psi with 5% lime. The percent lime reactivity is therefore

$$\frac{(301-6)}{6} \times 100\% = 4920\%.$$

Similar results are found with 3 and 7% lime content. The 5% plot (Fig. 6a) provides a tentative maximum curve for lime reactivity which is an approximate average of the three tentative maximum curves for these three lime contents.

In his lime reactivity definition, Thompson does not specify a lime content; only the range, viz 3%, 5% or 7%. The lime reactivity he used results from the maximum compressive strength of a set of untreated and lime treated soils having lime contents of 3, 5 and 7%. The listing below shows that nearly sixty percent of the Illinois soils tested attained the highest compressive strength using 5% lime content, whereas twenty-one percent of these soils exhibited the highest strength using 7% lime. Hence, the term "lime reactivity" denotes optimum lime content in Thompson's report.

Influence of Lime Content Upon Developed Compressive Strength for California and Illinois Soils Based Upon a 28-day Curing Period

State	No. of Soils	Horizons	Percentage of Soils Having Highest Compressive Strength			Average Developed Strength in psi		
			3%	5%	7% lime	3%	5%	7% lime
California	41	A, B & C	5	2	93	100	148	208
Illinois	38	A, B & C	21	59	21	68	84	64

The vast majority of California soils tested in this study resulted in higher compressive strengths using the 7% lime. This suggests that the "optimum" lime content may be 7% or greater. This conclusion is also supported by noting the average developed strength (lime reactivity) values which are listed for each lime content. The average developed strength values increase with increasing lime content for California soils; but not in the case of Illinois soils. According to Herrin and Mitchell (21) ... there may or may not be an optimum lime content, depending primarily on the length of cure.

From Figure 6a there appears an upward limit of lime reactivity for the various clay contents. In the future, other soils could be added to this curve to substantiate the possibility of a "maximum" developed compressive strength for a given clay content. If substantiated by further experimentation, this curve could be used as a guideline, e.g., soils with clay content above 65% would probably not develop more than 100 psi compressive strength from lime treatment and soils with clay content near 30% would possibly produce as much as 600 psi compressive strength given an extended curing period.

d. Criteria for the Determination of Lime Content

Stabilization can be described as any process which increases the load carrying capacity of a roadway material without deformation. The relative ease with which a soil can be deformed is called consistency. This index property is often expressed qualitatively as very soft, soft, firm, stiff and hard. This index is also convenient for describing lime altered soils.

Table 5 shows the ranges of compressive strengths which correspond to these descriptions as employed by the California Department of Transportation for estimating the unconfined compressive strength of soils. Also noted on Table 5 are the field descriptions corresponding to these ranges. Note that the consistency description "firm" is estimated to have an unconfined compressive strength range of 0.7 to 1.4 tons/sq. ft. which is equivalent to 10 to 19 psi. A value of 15 psi was selected to represent an average for this range of strength values.

While the relationship between stabilization and consistency is not perfect, a consideration of these variables can be of potential benefit in this area of research. A lime-soil mixture with a minimum lime content which results in a "firm" consistency can then be visualized as a reasonable goal in lime-soil stabilization technology. The 28-day cure lime-soil specimens with a 3% lime content (optimum moisture and 90% relative compaction) have met the criteria for firmness, although this firmness may have resulted in part from only the "drying" of the mixture by the lime. Most of the 28-day cure 3% lime treated soil specimens used in this study had a firm texture.

Thus, based on previous literature and preliminary investigation on this project, the criteria established for acceptable consistency of lime treated soils after a 28-day field curing period was established at 15 psi using 3% lime. Laboratory data suggests an increase in developed strength of about 150 percent at 28 days cure when the lime content is increased from 3% to 5%. This factor may be somewhat bias since the soils tested are not a representative sampling of all California soils. This factor does, however, provide a working relationship for strength developement with increasing lime content. A quantitative relationship using the ratio of lime contents could also provide a reasonable value in the absence of test data.

e. Criteria for the Determination of the Curing Period

The selection of a curing period should be of sufficient duration to permit long-term strength gain resulting from lime treatment. Also, the curing period should not be of such time length as to cause undue delay in data collection and analyses. In order to prevent possible construction delays, an upper limit of 28 days of field curing was considered.

Figure 7 shows the basic relationship for the average strength gains (based on all 41 samples) at three different lime contents (3%, 5% and 7%) as a function of curing period. The average of the 41 untreated specimen strengths is 38 psi.

A laboratory curing period of six months was considered since the rate of strength gain tends to diminish at the end of this period (Fig. 7). Figure 8 shows the percentage of lime-treated soils that failed to gain additional strength or actually lost strength over various curing periods up to 182 days (6 months). This plot served as additional justification for selecting a 6-month laboratory curing period for this study because this time interval was sufficient for the majority of the soils to gain the major portion of their developed strength and thus to provide a better evaluation of questionable soils. (Note: When lime content and mixing conditions are accounted for, the developed strength based upon a 6-month laboratory curing period can be estimated for the 28-day field developed strength as described in the next section).

f. Mechanics for Predicting Field Performance Based Upon Laboratory Test Data

A mean lime reactivity value for each cure interval was determined using the developed strength data from all 41 soils. A comparison of laboratory-developed strengths indicated that the 28-day mean value had achieved about one-half of the 6-month mean value. Therefore a factor of 2 was introduced to convert the 28-day strength to an approximate 6-month strength.

The relationship of the laboratory compressive strength to the field compressive strength is not known. Since the field mixing of soil with lime will not be as uniform as the laboratory-mixed controlled specimens, a tentative factor of two has been assigned to clayey soils. The basis for this factor is presented in the next section where an average mixing value for two heterogeneously lime treated soils was found to be about 2.

Using the three aforementioned factors: lime content increase, cure time change and the field mixing expression, an overall correction factor was assigned,

Strength gain factor based on lime increase from 3% to 5%	1.5
Laboratory curing time factor - 28 days to 6 months	2.0
Field to Laboratory mixing conversion factor	2.0
Multiplying these 3 factors together yields	6.0

In summation, a lime treated soil in the field containing 3% lime which is fabricated at optimum moisture content and which developes a compressive strength of 15 psi after a 28-day field cure is presumed to be comparable to a developed compressive strength of about 90 psi (15 x 6.0) following a 6-month cure interval under laboratory conditions using 5% lime. For convenience this developed strength was assumed to be 100 psi (see Fig. 9).

g. Effect of Uniformity of Mixing on Developed Strength

Some investigators (53) report on the difficulty of obtaining a uniform mixture of lime and soil when either the soil has a high clay content or is wet.

Some of the soils in this study appeared wetter than others although they were all cured at optimum moisture content. Rarely was a soil not readily miscible with lime. Higher clay content soils did not appear to be less adequately mixed. An experiment was designed to determine the effects of adequate versus inadequate mixing on strength parameters. The lime treated soil specimens fabricated in the conventional way are considered adequately mixed and are called "Regular" as shown on Table 6. The inadequately mixed lime-soil system presented a problem since there was a question as to whether two poorly mixed specimens could be compared. Since moisture samples were difficult to obtain from the untreated and treated portions when randomly mixed, the specimens were fabricated with an equal degree of disorder. The two distinct specimen constructions were of the horizontally stratified and the vertically stratified configurations (see Photo 11).

The horizontally stratified specimens (horizontal configuration Fig. 10) consisted of alternate layers (lifts) of untreated and treated soils. Overall the soil specimen contained 3% lime, but since this 3% lime was mixed with half of the soil, each treated layer contained 6% lime.

The vertically stratified specimen was constructed of four horizontally stacked layers, each layer of which consisted of a treated and untreated portion (vertical configuration Fig. 10). Refer to Photos 11 and 12 for additional details. All of the specimens were fabricated at optimum moisture content and 90% relative compaction.

The specimens after the 28-day cure interval appeared similar to the conventionally fabricated specimens except for the "lime stratification."

After determining the unconfined compression strength of the specimens the failing shear planes were observed. Both vertical and inclined shear surfaces were observed for both treated and untreated specimens with no particular trends emerging.

The resulting data is tabulated on Table 6. The values listed under the subheading of "regular" are for comparative purposes, and were obtained from the conventional 28-day sources. In the lime content column, the 5% values are an average of the 28-day cure data for the regular 5% and 7% lime treatments

The aforementioned conclusion (inadequate mixing of lime with soil results in less developed compressive strength) is supported by an experiment concerned with soil particle size. The outcome of this soil particle size experiment was that the larger aggregate sizes (analogous to the more inadequately mixed lime-soil mixtures) resulted in less developed compressive strength.

The soil 16IA, classified CH (Unified System), with a high clay content (70%) with inadequate mixing yielded only 25% of the developed strength of an adequately mixed specimen; whereas, the soil 19AB (classified SM in the Unified System) a silty sand with a clay content of 12%, and inadequately mixed gained nearly 60% of the developed strength of the adequately mixed specimen.

The oven moisture data suggests that the moisture in the untreated lifts of soil 16IA did not migrate to accommodate the lime in the treated lifts which resulted in a low percent of developed strength (25%). With the silty sand soil, 19AB, however, there is evidence that the moisture in the untreated lifts did migrate (or was forced to flow during fabrication) to the lime treated lifts to give a developed strength of nearly 60% of the level achieved by the regular specimen.

h. Lime Reactivity Groups

Based upon the foregoing, lime reactivity Group 1 is reserved for those soils that, when treated with 5% lime, $Ca(OH)_2$, and cured for 6 months, will not attain a lime reactivity value greater than 100 psi in the laboratory. Similarly, the other reactivity Groups were established using a multiple of the 100 psi increments and were classified as follows:

Lime Reactivity Group 1 - nonreactive	<100	psi	developed	strength
Lime Reactivity Group 2 - low reactive	100-200	"	"	"
Lime Reactivity Group 3 - medium reactive	200-300	"	"	"
Lime Reactivity Group 4 - highly reactive	>300	"	"	"

A tabulation of lime reactivity for each treated soil as a function of lime content and curing period is presented on Table 7. The data is further subdivided according to reactivity groups. A plot of the means of the reactivity groups for each lime content as a function of curing period is shown on Figure 11.

1. Soil properties vs. Lime Reactivity For All Groups (1, 2, 3 and 4)

Table 8 shows various natural soil properties and "Instant Test" data (as discussed in a later section) for the 41 samples tested. The data is arranged according to previously defined reactivity groups. The mean value of the various test results for each reactivity group are also listed. When the mean values of test results for the different reactivity groups are examined the only positive correlation noted is between treated "Instant Test" results and lime reactivity (based on the average "Instant Test") as a function of increasing (6-month cure) lime reactivity group number.

2. Lime Reactivity Group 1

There are only three nonreactive soil series in this study which have more than one nonreactive soil horizon. These soil series are 3S, 4T and 16I. The Sacramento soil, 3S, is nonreactive although it has many natural soil properties which are thought to be desirable for lime stabilization such as a high percent base saturation and a very large exchangeable calcium ion content. Some properties that are thought to be detrimental are: some exchangeable acid, about 1% organic carbon content, 1% iron coating and a large amount of clay. These last four properties taken together probably account for the overall nonreactivity of this soil.

The Tournquist soil, 4T, is rich in exchangeable hydrogen and iron coating with some organic carbon. These properties appear to have a great bearing upon the reactivity status of this soil and, being detrimental, the resulting reactivity is very low.

The Imperial soil series, 16I, is a calcareous soil. Calcareous soils are in general considered to be chemically reactive, but with the very large clay content (about 70%) the lime probably does not migrate sufficiently to bring about the desirable reaction. It is surmised that the natural soil property determination of the Mecca soil, 17M, is not complete and requires some special analysis before this nonreactive soil is understood. The "Instant Test" was successful in identifying the nonreactive soils about 50% of the time.

3. Lime Reactivity Groups 2, 3, and 4 (reactive)

When lime reactive Group 1 is exempted from analysis, there appears some correlation of various magnitudes between the soil reactivity groups and soil properties such as pH, CEC, percent base saturation, Ca/Mg, exchangeable H, sand and clay content, untreated strength (q_u), and the "Instant Test" results. The exchangeable Ca and Mg and the CO_3 content shows no correlation.

i. Soil Horizons of the Various Lime Reactivity Groups

In all, there are eight soil series, namely 1P, 4T, 7C, 8S, 10V, 11H, 14P and 19A, within which the 6-month cure lime reactivities (5% lime) of the individual soil horizons are in a ratio of 2 to 1 or greater (viz., 1PC., 428 psi vs. 1PB ... 210 psi). Tables 9, 10 and 11 list the treated and untreated compressive strength of the 41 natural soils treated with 3, 5 and 7% lime, respectively, and cured for various time intervals.

These soil horizons had an average of 13 soil properties which differed significantly when the soil horizons of the same soil series were compared. Of these thirteen soil properties, the exchangeable calcium, the sand/clay ratio and the sand equivalent were the most consistent, appearing as a significant property in all instances. The colloid, sand and clay properties were the next most significant while the pH, exchangeable magnesium, and the unconfined compressive strength of the untreated natural soil (q_u) were a factor about 60% of the time. Once again, referring to the 13 soil properties, only four of these were reasonably consistent 80% of the time. Those soil horizons having the largest exchangeable calcium and magnesium ion contents were also the most reactive soil horizons in terms of developed strength. The soil horizons with the largest sand equivalent value and largest sand/clay ratio were the least reactive of the paired soil horizons.

In summation, an analysis of the soil properties in lime reactivity Group 1 (nonreactive), listed near the top of Table 8, demonstrates that the natural soil properties taken together may be misleading in evaluating a soil's potential lime reactivity. The time and cost of obtaining these soil data may also be prohibitive. For the soils studied, the natural soil properties do not delineate between the reactive soils (Group 2, 3 and 4) and the nonreactive soils (Group 1). However, the natural soil properties are of value in estimating the degree of developed strength for those soils which are classified beforehand as being suitable (Group 2, 3 and 4) for lime stabilization.

j. "Instant Test" Method

Early in this laboratory phase, it was suspected that certain lime treated soils which exhibited small early strength gain had increased in strength merely because of increased specimen density and/or decreased moisture content provided by the addition of lime to the soil.

The soil that first aroused suspicion was soil 4TA. The seven-day cure treated unconfined compressive strength (gross) was 75 psi at 5% lime. The subsequent data (14-day cure to 6-month cure) varied slightly from a high of 82 psi (28-day) to a low of 61 psi for the 6-months cure interval. The resulting developed strength-time curve is flat (see Fig. 12a - 5% lime). The strength of the untreated soil averaged 41 psi. The question remained: did this "developed" strength (41 psi to about 75 psi) increase gradually, from zero days to seven days or abruptly? In an attempt to resolve this problem the cure interval was reduced to less than 30 minutes. The resulting compressive strength for the zero-day specimen at less than 30 minutes was 78 psi. The intervening cure interval strengths are assumed to vary between the zero-day and seven-day values. It appeared that, for this soil, the so-called developed strengths (lime reactivity) at the zero-day may be the result of increased specimen density and/or decreased moisture content. Other factors, such as particle grading characteristics may also significantly influence this zero-day developed strength. The decision was then made to continue to routinely determine the zero-day values for all of the soils. This zero-day test at less than 30 minutes was then designated as the "Instant Test".

The validity of the "Instant Test" procedure is supported by Figure 13 which shows an increase in lime reactivity for specimens of increasing density above 100 pcf. This plot suggests that the physical presence of lime may have produced this increased strength since the average compressive strength results for the untreated soils produced lower strength beyond 100-109 pcf density. The effects of average clay content and colloid content on strength parameters are also indicated.

Although the mechanism of the zero-day developed strength is not thoroughly understood, the data could be useful in establishing a strength threshold beyond which all higher strengths would be assigned to the chemical advantage of the lime-soil reaction.

k. Sensitivity of the Natural and Lime-Treated Soils to Changes in Moisture

1. Discussion

Many investigators have stated that the developed strength will increase when water is added beyond the optimum moisture content of the soil. Boynton (9) advises that, "because of lime's pronounced drying action, a copious amount of water is required when (lime is) used in the dry form. Use at least 5% over optimum."

Figure 4 indicates the influence of moisture content on the unconfined compressive strength of various treated and untreated soils. These lime-soil specimens were fabricated in the usual way and cured for 28 days. The moisture content level based on the natural soil as a datum was dry of optimum, optimum, and wet of optimum.

Table 12 was constructed using the compressive strength performance as a criteria for these lime-treated soils when they were fabricated drier and wetter than the optimum moisture content.

Based upon this limited testing, and using the optimum moisture content of the natural soil as the criteria, the following tentative conclusions can be helpful in predicting the performance of lime treated soils following a 28-day cure interval.

a. If a lime treated soil is fabricated with a moisture content wetter than optimum for the natural soil there will be an increase in the treated strength value when

1. the exchangeable calcium value of the natural soil is large; say about 12 meg/100 grams of soil and
2. the natural soil contains the clay mineral montmorillonite.

b. When the lime treated soil is fabricated drier than the optimum moisture level of the natural soil there will be an increase in the compressive strength when the pH of the natural soil is less than 7 and the iron coating percentage is relatively high; say about 2% and the soil contains the mineral kaolinite. Perhaps this acid condition softens the iron oxide coating and allows the lime to permeate this barrier.

c. When soils are grouped according to the scheme outlined in the section entitled "Lime Reactivity Groups," there is no apparent correlation between developed strength and moisture content for lime treated soils.

2. Implementing the Soil Moisture Sensitivity

Figure 14 is an attempt to predict developed compressive strength (lime reactivity) using the mineral content and the moisture content (near optimum) of the natural soil.

From Figure 4 and Table 13 it became apparent that some lime treated soils increased in strength when the moisture content of the natural soil was wetter than optimum. The predominate clay mineral of these soils is montmorillonite (>15%). It was thought that some combination of montmorillonite content and moisture content of the soil would in general reflect the developed strength.

Several plots were constructed in an attempt to develop this idea. The most promising (shown in Fig. 14) incorporates the three aforementioned elements: clay mineral content, moisture content and developed strength, and utilizes the ratio of the clay mineral content to the moisture content.

According to the implications of Table 12 there should be an inverse relationship between the aforementioned ratio and the developed strength. This approach is complicated by the difficulty in accurately determining the clay mineral content. A difference of ten percent in the clay mineral content can reflect a change in the ratio (clay mineral/moisture content) of 0.5. Soil 21PA, for example, containing 25% montmorillonite has a montmorillonite-moisture ratio of 1.25. This soil was independently analyzed by Dr. James L. Post, Associate Professor of Civil Engineering at California State University, Sacramento, and was reported to contain 15% montmorillonite. The ratio of montmorillonite to moisture was calculated to be 0.75 when the montmorillonite content is taken as 15% and the ratio is 1.25 when the montmorillonite content is 25%. At present the plot may be used to estimate developed strength at 6 month cure. This approach is presented in Appendix D, "Implementation Guidelines" under D-2 Rule-of-Thumb Estimation.

Attempts were also made to develop clay mineral/moisture content-developed strength relationships for kaolinitic, mixed layer and hydrobiotite-vermiculitic soils; however, data were insufficient and results proved inconclusive.

1. Moisture Content of "Instant Test" Data

The oven moisture content of a lime treated "Instant Test" specimen was observed to be less than the original moisture content. This difference in oven moisture content was termed "Fixed" moisture content because it was initially thought that the lime in the specimen mechanically held some moisture so that it remained in the specimen after the oven moisture determination procedure was complete.

It was noted that this "Fixed" moisture content of the "Instant Test" specimens varied. The largest values (>2.0%) were found to be associated with both Group 1 and Group 4 soils. This led to the contention that this large value of "Fixed" moisture content reflects high physico-chemical lime-soil activity but not necessarily high developed strength. This theory is also supported by the electrical characterization test results, viz absorptive Group 1 soils and agglomerative Group 4 soils both having a large change in conductivity when a slurry of lime and soil is allowed to react for about 50 hours.

Perhaps the high oven temperature (about 220°F) accelerates the lime-soil reaction. This could accelerate the production of various hydrates (e.g., tobermorite gel -- a calcium silicate hydrate) which ties up ("retains") some soil moisture. Not to be overlooked is the possibility that the oven moisture determination results may be different from the actual moisture content. Other methods of moisture content determination of lime treated soils may result in other "Fixed" moisture content values.

m. Sulfate Soils

1. Discussion

The insidious nature of sulfates has become well known in the technology of concrete (29, 25). Sulfates can also be detrimental to lime treated soils because they enhance swelling and may induce disintegration when the mixture is saturated (45, 16). The sulfate component may be a part of the soil or may be dissolved in the ground water.

While sulfates vary, there is a tendency to use the term "sulfate" as if it possessed consistent properties. One of the difficulties stems from the fact that the analytical chemist may hesitate to assign a cation when he reports the sulfate content of a soil. Such reluctance is understandable when there are many possible candidates for this role. Calcium, iron, sodium and lithium are some of the more common cations. Although X-ray diffraction can distinguish between some crystalline sulfates, the threshold for detection of sulfate minerals is near the 5% content level. This level is not low enough for detection of sulfates in most soils (of the 41 soils investigated in this research project the highest sulfate content was 1.03%). At present a chemical analysis is required to attain the necessary precision for detecting sulfate contents less than 5%.

There is evidence that sulfate will react with a lime-soil mixture resulting in the production of the mineral Ettringite. Some investigators report that small quantities of sulfate are beneficial in lime stabilization: (53) "$MgSO_4$ improves the strength characteristics of the stabilized soil," and (24) "calcium sulfate ... can enhance the pozzolanic activity of pulverized fuel ash." Sherwood (45), however, advises that although the sulfate ion can be beneficial in lime-stabilized soils, the possibility of deleterious effects (disintegration of the mixture when immersed in water) on the durability must not be overlooked. Sherwood suggests that the Ettringite produced occupies a greater volume than the reactants which results in an overall expansion of the mixture. According to Lea (29), Ettringite (calcium Sulphoaluminate - a two-molecule cell of $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$) yields two peaks in a Differential Thermal Analysis, the largest at 160°C and the smaller at 300°C. X-ray diffraction can also detect Ettringite according to ASTM Powder Diffraction File (1966), 9-414. It lists the main peak at 9.73 Å followed by the 80% peak at 5.61 Å while the 50% peak will be at 3.88 Å, etc.

2. Analysis

Of the 41 soils included in this report only ten have a sulfate content of 0.05% or greater. A geographical distribution of the sampled sources was presented on Figure 1.

The DTA diffractograms of the sulfate-lime-soil systems reported here did not indicate the production of the 160° and 300°C peaks. However, there was a disappearance of the familiar hemihydrate peak near 200°C (calcium sulfate) from many of the soils (namely: 16IA, 16IC and 21PC), while two other soils, 1PB and 22MC having 35 meq/100 gm and 23 meq/100 gm of exchangeable Na, respectively, are perhaps sodium sulfate soils and may have a little gypsum present. Soil 22 MC does have a small 7.56 Å on the X-ray diffraction scan which gives evidence that calcium sulfate is present.

The X-ray diffraction scans of two soils, both natural and lime treated, are reproduced in Figure 15 and suggest the presence of Ettringite in the lime treated soils, while the untreated soil scan does not give evidence of this mineral. Figure 16 shows a typical DTA of an untreated and treated soil at different curing intervals. Table 14 summarizes the mineralogy of the whole soil in percent X-ray diffraction-differential thermal analysis-microscopy.

A plot of the sulfate ion content and the percent volume increase (swell) is illustrated on Figure 17. This plot indicates that with an increase in the soil sulfate content there is a general increase in swell potential (percent volume increase). With coarser grain soils (71-94% sand content - MA) such as, 6MC, 7CA, 7CC and 19AA, the percent volume increase is less than 1% while the relatively finer grain soils (1-46% sand) 1PB, 5CB, 16IA, 16IC, 21PC and 22MC, have a volume increase greater than 1%. Perhaps the coarser grain soils can accommodate this crystal growth (Ettringite) with less outward disruption because they have larger voids than the relatively finer grain soils.

The surface area of all of these soils were calculated (37) and are listed on Table 4. The coarser grain soils have an extreme range of calculated surface area of 60 to 240 cm^2/gram whereas the finer grain soils ranged from about 400 to over 600 cm^2/gram.

Those soils which have a percent volume increase greater than 1% have a sand equivalent less than 11 whereas those soils having a percent volume increase less than 1% have a sand equivalent between 22 and 38.

n. Influence of pH

Many authorities (34, 55, 31, 8) advise cautious use of a soil's pH because of the many parameters that account for this easily obtained measurement. Bear's (8) cautions to the users of pH are worth repeating here. "Evaluation of factors associated with soil pH must be based ... on full consideration of the soil constituents controlling the pH situation rather than on pH per se." Thompson (51) states that good lime reactivity is expected when the soil pH is above 7. However, if pH values for all of the natural soils involved in this study are considered (refer to Fig. 18) Thompson's statement is not substantiated here. As described later in the electrical portion, a distinction between reactive and nonreactive California soils can be accomplished by an electrical test procedure. If this test can discriminate between soils which are suitable or unsuitable for lime stabilization, as our data indicates, then a better correlation is evident between the developed strength and the pH of the natural soil. The soils symbolized by a triangle on Figure 18 are those soils classified as nonreactive, belonging to Lime Reactivity Group 1, principally by the 6-month-5% developed strength being less than 100 psi. Of the five soils classified as being nonreactive or unsuitable for stabilization by virtue of their low developed strength (<100 psi), the results of the electrical test classified all of these five soils - and only these five - from a total of 17 soils tested, as being nonreactive.

The various natural soils used in this study are listed on Table 15 both by lime reactivity Group and by pH ranges (acid or base). This table illustrates that each of the four lime reactivity groups contains acidic and basic soils. Of the reactive soils, the higher the reactivity group number the lower the percentage of acid soils in the group. Lime reactivity Group 2 is the least reactive of the three reactive groups based on developed strength and this group contains 60% acidic soils, whereas, lime reactivity Group 3 has 25% acidic soils and lime reactivity Group 4, the most reactive, has about 12% acidic soils. Table 16 presents data on developed strength values for the different clay mineral soils under investigation.

From Table 15 a pH of 7 or greater was found in 77% of the cases (23 out of 30). This result is not significant since 73% (30 out of 41) of the soils used in this study are suitable for lime treatment. A pH on the acid side (<7) indicates a nonreactive soil in only 35% of the cases which is again not encouraging since 27% of the soils are nonreactive or unsuitable for lime treatement.

If the nonreactive soils are initially identified (i.e., by the electrical characterization test), then the 6-month cure (5% lime content) minimum and maximum developed strengths can be estimated for lime treated soils whose natural soil pH (1:1) ranges from 7 to nearly 8.5 (Fig. 18). Nearly 60% of the soils used in this study have a pH value in this range. The soils with pH values less than 7 represent 27% of the total soils used while the remaining soils, 13%, have a pH above 8.5.

In conclusion, the pH alone of a natural soil is not a reliable indicator of the potential minimum developed strength of a large variety of soils (as exists in California). However, once a soil has been established as reactive or suitable for lime stabilization (e.g., by electrical testing) there tends to be a general trend between increasing pH and developed strength.

o. Base Saturation

Figure 19 is a plot of the influence of base saturation on pH of all the natural soils used in this project. Note that when the pH is 7 or above, the minimum base saturation is about 80%. Also, when the pH of the soil is in the acid zone (<7) there appears to be a linear relationship between the base saturation and the pH. According to Thompson (49), "In general, soil pH is a reliable indicator of percent base saturation."

The following listing compares percent base saturation with soil pH (1:1):

Soil pH	Percent Base Saturation from Thompson (49)	Percent Base Saturation of the California Soils Used in This Study
Less than 5	Soil is strongly acid and is likely to be low in exchangeable bases such as Ca, Mg and K.	
5 - 5.5		0-45
6+	70-80	50-70
7±	90-100	80-100
8±	Usually contains free basic salts, primarily $CaCO_3$, and, less frequently, salts of Mg and Na.	80-100

There is a good positive correlation between percent base saturation and pH for those soils which were assumed (by virtue of the electrical response test) to be predominately "adsorptive" in their reaction with lime. The percent base saturation also correlates reasonably well with the colloid content of the natural soil.

p. Soil Plasticity vs. Developed Strength

Much has been written about the importance of the plasticity factor on the developed strength of a soil. Herrin and Mitchell (21) state that highly plastic soils are likely to be more reactive with lime whereas low plastic soils exhibit little lime reactivity. They qualify this latter observation by noting that a non-plastic pit-run gravel was treated with 10% lime and resulted in a "sizeable" increase in strength. In contrast, Thompson (51) states that the Plasticity Index as well as other engineering properties do not significantly influence lime reactivity.

On Figures 20, 21, and 22 the developed strengths are plotted against the Plasticity Index as a function of 3%, 5% and 7% lime content, respectively. (The normally anticipated positive correlation between percent clay size and PI is shown on Fig. 23.) An interesting characteristic of these plots, also noted in Thompson's plot (51), is the absence of data in the lower portion of each plot bounded by the two solid lines and the abscissa. The absence of Plasticity Indices occurs in the 0-28 portion on the 7-day, 28-day and 6-month plots. A similar absence of data area is found on Fig. 24.

1. Estimating the Compressive Strength Using P.I. of the Natural Soil

The vertices of the aforementioned triangular areas shown on Figures 21 and 22 were found to increase with curing time and lime content. These plots are useful in establishing a simplified procedure for estimating the minimum developed strength achieved knowing the value of the Plasticity Index between the limits of 0 and 28. Table 16 developed from Figures 20, 21 and 22 shows the numerical values of the minimum developed strength achieved for a soil with a given Plasticity Index. For example, a lime-soil mixture having 3% lime content is expected to achieve the 6-month minimum lime reactivity of about 100 psi for those soils with a P.I. in the range of 15-20. When 5% lime content and a 6-month cure is used, the lime-soil mixture achieves the minimum developed strength when the natural soil P.I. is between 7 and 20. The early (7-day) 100 psi developed strength for the 5% and 7% lime content mixes can also be estimated from this table.

If the soil in question is first established as a kaolinitic soil, the developed strength can be estimated from Figure 25 using the P.I. of the untreated soil.

2. Economical Use of Lime and Utilization of Soils Thought to be Unsuitable for Lime Stabilization

The purpose here is to reduce the lime content for suitable soils and to increase the utilization of nonreactive or unsuitable soils. The Plasticity Index range of the natural soil can be used to estimate an economical lime content. Figure 26 was constructed for this purpose. The soils were grouped into four Plastic Index ranges. These P.I. ranges are non-plastic, 1 to 9, 10 to 19, and 20 or greater. Mean values of developed compressive strength were then calculated for the 7-day, 28-day and 6-month cure interval for all soils treated with 5% lime. These mean strength values for the three cure intervals were then plotted as shown on Figure 26. (The supporting statistical data for this presentation is shown on Table 17). A separate solid line connects the mean developed strength values for each Plastic Index range. Note that the soils with P.I.'s in the 10-19 range have the highest developed strength, while the soils in the non-plastic and highly plastic range have the lowest. The mean developed compressive strength (lime reactivity) for the lime treated soils in the P.I. range (10-19) is about 425 psi (Figure 26). In the interest of economy the lime content of these soils can be reduced. A 3% lime content is recommended for the soils in this P.I. range. The mean 6-month cure value of developed strength for these soils, using 3% lime content, is about 280 psi as shown by the highest dashed line on

Figure 26. (These dash lines represent an attempt to normalize the developed strength curve over the entire range of P.I.'s investigated by using a variable lime content (3%, 5% or 7%) for a specific P.I. range). The soils with P.I.'s in the 1-9 range have a mean developed compressive strength (6-month cure - 5% lime content) of 300 psi. Twenty percent of these soils have a developed strength value less than 100 psi. In spite of these low values, a lime content of 5% is recommended for the soils in this P.I. range.

The soils in the extreme P.I. ranges, non-plastic and over 20, have a mean developed compressive strength (6-month cure - 5% lime content) of 190 and 200 respectively (Fig. 26). It is of interest to note that nearly 90% of the Group 1 soils are in these extreme P.I. ranges. Also, nearly half of all the soils in this study are in these extreme ranges. Thus, 41% of the non-plastic soils are classified as Group 1 (less than 100 psi developed strength - 6-month cure - 5% lime content) while 67% of the highly plastic soils (P.I.>20) are Group 1 soils. A general recommendation for these soils is to use 7% lime content. By increasing the lime content in these soils the mean developed compressive strength increased about 30%.

For a particular soil an estimate can be made as to whether the soil is below or above "average." Soils which are classified as being below average may have black color (high organic carbon) or be red or brown (high iron coating). They may also have high mica content or contain considerable sulfates. If the soil is estimated to be below "average", about 6 to 7% lime content can be used depending upon how far below "average" the questionable soil remains. If the soil in question is "average" or above, use 5% lime content or less.

Table 18 provides a listing of estimated lime requirements based upon one soil property. These lime contents could provide a starting point for estimating the required lime content to provide a minimum developed strength of 100 psi at a designated curing period of 6 months or at some shorter interval.

q. Clay Content vs. Developed Strength

Another approach in estimating a minimum developed strength of lime treated soils is by the clay content of the natural soil. Most investigators are vague about the influence of the clay content upon the developed strength. Generally they indicate that some clay is needed for a lime treated soil to increase in compressive strength.

Figure 23 suggests a good correlation exists between the clay content of a natural soil and its P.I. It would be expected that clay content could also be related to developed strength. A relationship was found to exist between clay content and developed strength which is similar to that presented on Figs. 20, 21 and 22 for developed strength vs. P.I. The triangular area previously mentioned with absence of data reaches its apex at about 40% clay content. Therefore, it is possible to predict developed strength using natural soil clay content.

If the soil in question is established as a kaolinitic soil, the developed strength can be estimated from Figure 27.

The kaolinitic soils (2AA, 2AB, $2AB_2$, 4TA, 4TB and 4TC) containing large amounts of iron coating (>2.5%) have the lowest developed strength of all the soils in the 15% to 43% clay content range. The soils with clay content <12% have low developed strength and can be identified by a very low unconfined compression strength for the untreated soil of less than 5 psi (easily crushed with fingers - 90% relative compaction - optimum moisture) or a "Fixed" moisture in the 1.3% - 1.6% range or the >2.0% range.

The lime reactivities of the predominate clay mineral soils tested during this study are presented in Table 19.

r. An Alternative to Using the Natural Soil Properties to Estimate Developed Strength

An alternative to the laborious and expensive task of determining the natural soil properties for estimating developed strength would be to empirically ascertain the predominating phenomenon of agglomeration or adsorption. This can be acomplished electrically in a day or so, at relatively low cost. The electrical response test as described in the following section can be used to achieve this goal. At present, the prime value of the electrical response test is that it permits the determination of a soils potential reactivity. Secondly, it is useful in estimating the developed long-term (6 months) compressive strength of a lime treated soil.

ELECTRICAL TESTING TO PREDICT DEVELOPED STRENGTH (LIME REACTIVITY)

Introduction

A search of the literature was undertaken to determine if any test method existed for indicating the presence of the lime-soil reaction for the purpose of predicting long term strength development. This search disclosed that Arulanandan and Mitchell (5) correlated a natural soil's electrical properties with its compressive strength, (Fig. 28). It was reasoned that a lime-soil reaction could be monitored electrically and thus offer insight as to the rate and extent of the resulting physico-chemical reaction. These nondestructive electrical response measurements could than be related to the actual unconfined compressive strength of lime-soil systems cured for various time intervals.

In this study electrical characterization results of the initial set of six lime-treated soils are shown on Figures 29 and 30. Initially, it was thought that the change in electrical conductivity with time was the sole indication of the lime-soil-water reaction. This view is supported in part by Figure 31.

When more electrical data became available (see Figs. 32a through 33c for additional lime-treated soils) it became apparent that the change in conductivity ($\Delta\sigma$)* was found to reflect the magnitude of the lime-soil reaction but not the quality of the reaction since the nonreactive soils (3SA, 3SC, 4TA, 14PA and 16IA) have a similar range for $\Delta\sigma$ as the reactive soils. These values of $\Delta\sigma$

*Diamond and Kinter (14) report that when lime (4% or less by weight of clay) was added to a suspension of a Wyoming Bentonite, which was made homionic to calcium (saturated), the electrical conductivity of the suspension decreased ... "to very low values in less than 24 hours." They regarded this action as an indication that the lime was being rapidly adsorbed by the soil from the pore solution.

Fischer (18) writes, "Of the several properties connected with flocculation, that of electrical conductivity is of some direct significance. The experiments of McDowell and Usher showed that a deflocculation suspension of carbon black in solvents (bromoform and tetrachloroethane) exhibited no measureable conductivity, but that flocculated suspensions when undisturbed allowed appreciable currents to flow. The conductivity of flocculated suspensions was attributed to direct contact between carbon-black particles and to a continuous network of the floccules. Tapping and shaking destroyed the structure and greatly reduced the conductance. The values for the measurement were not reproducible, a result attributed to the diversity in structure, which re-formed when the suspension was at rest."

(from 2 to 50 hours) for the nonreactive soils range from .000248 to .002410 mhos/cm while the value of $\Delta\sigma$ (2 to 50 hours) for the reactive soils range from .000166 to .002786 mhos/cm as indicated on Table 20. This concept was later modified to reflect the quality of the lime-soil reaction; namely, by multiplying $\Delta\sigma$ by the change in dielectric constant ($\Delta\varepsilon^1$).

At present the proposed electrical response test can be completed in about fifty hours but could easily be reduced to less than 24 hours. The use of the electrical response characteristics measurements to monitor the continuous structural change in a lime-soil mixture would enable the examination of the two lime-soil reactions; namely, agglomeration* and adsorption, and it could then be determined whether lime would provide a beneficial reaction with a particular soil. Agglomeration would account for the cementation aspect of the lime-soil reaction while adsorption would reflect the noncementious lime-soil reaction.

*Agglomeration is defined as a group of particles that are strongly adherent and can be broken by the application of relatively strong mechanical forces and is frequently used with the same meaning as aggregate. This term differs from flocculation by the nature of the forces holding the particles together. An aggregate once dispersed cannot be reformed with the same properties. This is similar to the chemical reaction of lime with soil (18). Aggregate formation requires a cementation or binding together of flocculated particles (48).

Adsorption is defined as the condensation of gases, liquid or dissolved substances on the surface of solids (10). "Adsorption reactions may be classified, generally, into two types: chemical adsorption and physical adsorption" (8).

Method

Arulanandan and Mitchell (1968) (5, 6 and 36) found that clay mineralogy, particle size, type and amount of electrolyte and the orientation of particles of a clay-water-electrolyte system can be characterized in terms of electrical dispersion (variation of conductivity and dielectric constant as a function of the frequency of an applied alternating current)*. The use of these nondestructive electrical response measurements to monitor the continuous structural change in a lime-soil mixture enables the examination of the various lime-soil reactions. Furthermore, this procedure could provide qualitative guidelines for establishing potential developed strength (lime reactivities) of fine-grained soils.

Soils Tested

A total of 18 soils representing 14 soil series were studied. These soils were indigenous to nine California counties. The 6-month developed strengths (lime reactivities) of these soils ranged from 20-770 psi at optimum moisture content and 5% lime content. The clay content of these soils varied from 11% to 70%, while the pH ranged from 5.2 to 9.3. The cation exchange capacity and percent base saturation of these soils ranged from 7-50 meq/100 gm and 7-100%, respectively. The highest recorded liquid limit was 66 while the greatest carbonate content was 9%. The mineralogy was variable - one soil (3SC) contained 37% montmorillonite while another soil ($2AB_2$) contained 47% kaolinite. Other soils contained mixed layer clay (1PB, 52%), hydro-vermiculite (13BB, 17%) and feldspar (22MC, 42%).

Procedure

Acceleration of the lime-soil reaction is desirable during electrical monitoring to reduce the overall time required to obtain the response characteristics. This is accomplished by fabricating a paste of the lime-soil-water system and thereby greatly facilitating ion migration, vastly increasing miscibility, and introducing an excess of water to the system which results in an increase in the lime-soil reaction velocity. Further, these measurements are more uniform and easier to obtain from saturated samples.

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*Although direct current measurements for obtaining resistance or conductivity would be simpler, there is a probability that an electrokinetic coupling phenomena such as electroosmosis, would with prolonged DC emf, produce a destructive effect on the system.

Laboratory results have confirmed that as long as the paste remains saturated and well mixed, the water content of the paste has very little influence on the dielectric dispersion characteristics of the soil. This can be illustrated by the results shown on Figure 34 where 3SA (natural soil) was mixed to water contents of 77% and 122%. The resulting dielectric dispersion curves from both specimens were similar. The conductivities of the natural soil were chosen at a frequency of 50 Hz and were 9.41×10^{-4} mhos/cm and 8.96×10^{-4} mhos/cm, respectively. The liquid limit of 3SA soil is 59%.

A limited number of tests were performed on fabricated specimens. Figures 30 and 35 show the electrical response characteristics of soil 2AA in fabricated specimens and paste form specimens, respectively. The pattern of variations of dielectric constants throughout the range of frequencies applied are similar for both types of samples*.

Two sets of paste specimens were prepared for each soil. One set was untreated and the other was treated. The paste form specimens were prepared at the Soil Mechanics Laboratory, University of California, Davis (see Photos 14 and 15). Electrical response characteristics obtained from the untreated set were used as the basis for comparison (referred to as "base curve"). The other set was made by adding 5% lime (dry wt. basis) to the soil-water mixture forming a lime-soil-water paste. There are two specimens in each set - one 2.5 inches high and the other 3.5 inches high (refer to Appendix A).

The amount of distilled water in the paste form samples varies with soil type. The paste was formed by mixing soil to a water content above the liquid limit of the soil. The quantity of water added was the minimum required to form a paste of flowing consistency. The soil and water were mixed thoroughly in a mixer for 30 minutes. Commercial hydrated lime was then added to the soil-water mixture and was again mixed for 15 minutes. Normally, an additional amount of distilled water was needed to bring the final mixture to the right consistency, increasing the water content of the mixture by less than 1% to 10%, depending upon soil type. The final mixture was then used to fill two measuring tubes. A sketch of the electrical response measuring apparatus is shown on Figure 36. About one and one-half inches of distilled water was added to the top of each sample thus preventing the samples from being dried out during the test period.

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*Diamond and Kinter (14) carried out a series of investigations concerning the mechanism responsible for the rapid amelioration of the properties of plastic soils by lime and concluded that, "These data indicated that the response to lime in clay-water systems of restricted water content was similar to that occurring in dilute suspension."

Analysis Based Upon Test Data and Literature Search

Though there remain many other ways to define lime-soil stabilization, the one chosen as the criterion for this report is developed strength, Thompson's lime reactivity.

According to Marks and Haliburton (30) "First, lime-clay reactions occur in two distinct stages, as modification and stabilization. During lime modification calcium ions are adsorbed by clay in cation exchange reactions. This process tends to modify the soil without producing new minerals from pozzolanic reaction. Lime stabilization occurs from lime contents above those required to modify the soil."

Although not universally agreed upon, many investigators (11, 15, 20, 26, 35, 38, 50) report the presence of an agglomeration (flocculation) phenomenon when a lime treated soil is stabilized. Furthermore, there appears to be another reaction, sometimes stated as being cation exchange (9, 15, 20, 34, 38, 50, 56) the "calcium crowding hypothesis" (34), physical adsorption (14), or more readily understood, "robbers-of-lime" (the lime depletion phenomenon) (54).

Both Phenomena - agglomeration and lime depletion - are illustrated by Shen and Arulanandan (44) on Fig. 37 and Fig. 38, respectively.

Fig. 37 shows what happens to a kaolinite (Hydrite UF), with a relatively small order of magnitude of grain size distribution (Fig. 39) and a dielectric constant (ε^1) of 9,000+(10^3Hz). When it is "hypothetically enlarged" or "agglomerized" into a kaolinite (Hydrite MP) of a coarser grain size distribution, it then exhibits an "increase" in dielectric constant to 17,000+ (at 10^3 Hz frequency). The inference is that as agglomeration takes place, and is the predominating reaction, the resulting dielectric constant is increased beyond that of the untreated (finer grain) soil. The particles have clustered together giving rise to larger (and fewer) particles with a larger value for the dielectric constant. This change in dielectric constant ($\Delta\varepsilon^1$) is shown in Column 4 (top portion) of Table 20 and is taken as an indicator of this agglomeration tendency. This observation led to the following postulate:

> When the dielectric constant of a lime treated soil is larger than the dielectric constant of the natural soil the predominating reaction is that of agglomeration. An indication of the degree of agglomeration is signified by the change in the dielectric constant from the threshold value, untreated soil state, to the treated state. The $\Delta\varepsilon^1$ indicator is shown in Column 4 (top portion) of Table 20 for those soils which behave predominately in this way. It is noteworthy to mention that the soil horizon designation may be a useful indicator of a soil's potential to be agglomerized by lime treatment.

The contention that the dielectric constant of a calcium saturated soil is less than the dielectric constant of the natural soil is supported by Fig. 38. Using this figure, the natural soil, a sodium kaolinite, is "hypothetically changed" into a calcium kaolinite. Concomitant with this change is a decrease of the dielectric constant of 8,000 to 4,000+ for calcium kaolinite, all measured at 10^3 Hz frequency. This observation led to the following postulate:

> When the dielectric constant of a lime treated soil is less than the dielectric constant of the natural soil the predominating reaction is that of calcium adsorption. An indication of the degree of calcium saturation is signified by the change in the dielectric constant from the threshold value (untreated soil state) to the calcium saturated value. This $\Delta\varepsilon^1$ indicator is shown in Column 4 (bottom portion) of Table 20 for those soils which behave predominately in this way. It is noteworthy to mention that the cation exchange capacity may be a useful indicator of a soil's potential to be calcium-saturated.

For a measured dielectric constant above the threshold value (untreated soil state) the "agglomeration effect"* predominates while below the threshold value the "adsorption effect" (lime robbing) predominates, as a quantitative indicator of $\Delta\varepsilon^1$. However, the $\Delta\varepsilon^1$ value does not entirely reflect the magnitude of the reaction. The change in conductivity is a likely indication that something (e.g., agglomeration, adsorption or a combination of the two) is happening; therefore, the change in conductivity could help to quantify these reactions. Thus, it appears that if the prevailing reaction is predominately agglomeration, then a large $\Delta\sigma$ (e.g., 22MC) may indicate that an extensive reaction of this type has taken place. Whereas, if the reaction is predominately adsorption, then a lime treated soil with a large adsorptive capacity, perhaps reflected by the soil CEC, would indicate this quantitatively by a large $\Delta\sigma$. To take advantage of the change in dielectric constant and the change in conductivity as being quantifier indicators only, they are multiplied together.

When the value of $(\Delta\sigma \times \Delta\varepsilon^1)X10^3$ is low for lime treated soils which agglomerate, say below 1,000, little beneficial reaction or developed strength is indicated. Fig. 40a is a plot of $(\Delta\sigma \times \Delta\varepsilon^1)$ vs. the corresponding 6-month developed strength (5% lime). While it appears that a positive trend could be developing for the agglomeration reaction, more work is required to account for the two soils (8SC and 13BB) which have a low $\Delta\sigma \times \Delta\varepsilon^1$ value while exhibiting a relatively high developed strength.

*(18) "Flocculation results in the formation of chains of particles and consequently should be associated with an increase in dielectric constant."

The soils with an adsorption reaction (Fig. 40b) are tabulated at the bottom portion of Table 20. When the values of $(\Delta\sigma \times \Delta\varepsilon^1)X10^3$ are large (say greater than 40,000) it indicates that the lime is being depleted and there should be a rather small strength gain. Fig. 40b illustrates the relationship between developed strength of a lime treated soil and the quantity $\Delta\sigma \times \Delta\varepsilon^1$. Note that the montmorillonitic soils show a trend but the nonmontmorillonite soils do not. Also noteworthy is that "adsorptive reaction" soils (3SA, 3SC and 161A) which are unsuitable for lime stabilization (developed strength less than 100 psi) have "Instant Test" (Table 7) values less than 12 psi.

Figure 41 shows the influence of the surface area upon the cation exchange capacity for both reaction zones. The lower plot, Fig. 41b, Adsorption Reaction, is interesting because there is visualized a curvilineal relationship between the cation exchange capacity and the soils surface area.

Fig. 42 compares the proportion of adsorptive lime-soil reactions to the agglomerative lime-soil reactions for each soil horizon. Note that the "A" horizon has the largest percentage (62%) of adsorptive lime-soil reactions (of the soils tested) while the "B" horizon soils have the largest percentage (60%) of agglomerative lime-soil reactions.

Table 21 lists all of the soils used in the electrical characterization test program. These soils are grouped according to the predominating reaction of the soil with lime in paste form. The reaction is classified as "Adsorptive" when the dielectric constant (ε^1) of the lime treated soils is less than the dielectric constant (ε^1) of the natural soil and "Aggomerative" when the dielectric constant (ε^1) of the lime treated soil is larger than the dielectric constant (ε^1) of the natural soil.

The first five "adsorptive" soils 3SA to 21PC, are montmorillonitic (by X-ray diffraction) while the remaining "adsorptive" soils 9LA to 15RB have no montmorillonite or kaolinite. This latter group of soils have been labeled as "nonmontmorillonite." The "agglomerative" soils which are kaolinitic (by X-ray diffraction) include soils 2AA, $2AB_2$ and 4TA. The remaining "agglomerative" soils are neither montmorillonitic nor kaolinitic. These soils range from 1PB to 22MC and for convenience are labeled as "nonkaolinite" (less than 15% kaolinite).

The hypothesis that there are two lime-soil reaction categories (adsorption and agglomeration) could be supported if the soil properties of the two categories with their respective subcategories are mutually exclusive. The subcategories are: montmorillonite and nonmontmorillonite (subcategories of the adsorption category;

kaolinite and nonkaolinite (subcategories of the agglomeration category). If the soil properties, other than clay mineral identification, of these categories and subcategories are mutually exclusive, it may predict not only which lime-soil reaction predominates (agglomeration or adsorption) but which subcategory (montmorillonite vs. nonmontmorillonite or kaolinite vs. nonkaolinite) prevails.

When a soil is assigned to a subcategory then a single soil property is used to determine the long-term (6-month) compressive strength of the lime treated soil. This is further elaborated in Appendix D, "Implementation Guidelines" under "Rule-of-Thumb".

Mutual Exclusiveness of the Categories and Subcategories

Four soil subcategories are inferred from Table 21. The two subcategories under the heading of "Adsorption" are montmorillonitic soils and nonmontmorillonitic soils. The other two subcategories (kaolinitic soils and nonkaolinitic soils) are listed under the heading of "Agglomeration."

The sequence of the following discussion, with appropriate charts, is outlined below. These charts provide a simplified method for rapidly classifying a questionable soil by subcategory in accordance with the various soil property criteria. The chart format enables classification of the somewhat complex data interrelationships more readily than in a written exposition.

1. Testing for Mutual Exclusivity.

Adsorption		Agglomeration	Discussion Page No.	Chart Table No.
adsorption	vs	agglomeration	38	21
montmoril. vs nonmontmoril.		-	38	22
-		kaolinite vs nonkaolinite	38	23
nonmontmorillonite	vs	nonkaolinite	39	24
montmorillonite	vs	kaolinite	39	25
montmorillonite	vs	nonkaolinite	41	26
nonmontmorillonite	vs	kaolinite	41	27

Table 28 summarizes the information given in Tables 21 to 27.

The soil specifications given in Tables 21 to 27 were determined empirically.

2. Adsorption vs. Agglomeration. Refer to Table 21.

The exchangeable K ion content presented on Table 21 distinguishes the "adsorptive" soils, 3SA to 15RB, from the "agglomerative" soils, 2AA to 22MC, reasonably well. Values of exchangeable K ion above 0.7 meq/100 gms would indicate a lime-soil reaction which is "adsorptive." Of the nine "adsorptive" soils only two had an exchangeable K ion value less than 0.7 meq/100 gm. These two exceptions are soils 3SC and 15RB. Conversely, when the value of exchangeable K ion is less than 0.7 meq/100 gm the lime-soil reaction end product would agglomerate. The only exception was soil 4TA. Soil 4TA has the highest iron coating content, 4.8%. However, the soils with the next two highest iron coating contents also agglomerate when lime treated. These are soils 2AA and $2AB_2$ with iron coating contents of 3.3% and 2.7%, respectively. Soil 4TA also has the greatest organic carbon content, 1.6%.

Montmorillonitic soils (>15% montmoril. content) are adsorptive while kaolinitic soils (>15% kaolinite content) are agglomerative.

3. Adsorptive Category, Montmorillonite vs. Nonmontmorillonite. Refer to Table 22.

The montmorillonitic soils are: 3SA, 3SC, 6MA, 16IA and 21PC. The "adsorptive" soils which are nonmontmorillonite; 9LA, 9LB, 11HA and 15RB, have a few soil properties which are different from the "adsorptive" soils which are montmorillonitic. The nonmontmorillonitic soils have a PI less than 10, a clay content less than 30, a value of more than 6 for the "Instant Test" compressive strength/pH ratio, a compressive strength (q_u) of the natural soil of less than 50 psi, a developed strength (lime reactivity, 5% lime) of more than 40 psi, and a calculated surface area of less than 500 cm^2/100 gm.

The dielectric constant (ε^1) delineates the montmorillonitic soils from the nonmontmorillonitic soils. The higher values (>20) of the dielectric constant are associated with the montmorillonitic soils.

4. Agglomeration Category, Kaolinite vs. Nonkaolinite. Refer to Table 23.

The "agglomerative" soils, which are kaolinitic, are few in number and may not be representative of the kaolinitic soil group. Inasmuch as they were a part of the group of soils which were electrically tested, however, they are included here.

The kaolinitic soils: 2AA, $2AB_2$ and 4TA, are distinguishable from the nonkaolinitic soils, 1PB, 8SC, 13BB, 14PA and 22MC, when the maximum impact dry density is less than 107 pcf, the optimum

moisture is greater than 18%, the "Fixed" moisture content is less than 10%, the iron coating content is greater than 2%, the quartz content is less than 12%, the ignition loss is greater than 10%, the base saturation is less than 60% and finally, since the kaolinitic soils may form in an acid environment, (19), the in-situ kaolinities are acidic (pH<7).

A dielectric constant greater than 20 x 10^3 indicates a non-kaolinite with but one exception. This exception is soil 14PA which has a dielectric constant of 5 x 10^3. A value less than 20 x 10^3 indicates a kaolinite.

5. Nonmontmorillonite (Adsorp.) vs. Nonkaolinite (Agglom.). Refer to Table 24.

The soil properties which can distinguish the adsorptive non-montmorillonitic soil from the agglomerative nonkaolinitic soils are: an "Instant Test"/pH value greater than 6, an exchangeable K ion greater than 0.7, and a PI less than 10. The dielectric constant quantity, shown in the last column of Table 24 also helps to differentiate the nonmontmorillonite subcategory from the nonkaolinite subcategory.

The nonmontmorillonitic-nonkaolinite dichotomy is thought to be less apparent because they do not contain soil mineral structure identifiers.

The questionable soil 13BB is not typical of the nonkaolinite group because it has 4 soil properties greater than any other in the group (viz maximum test density of 127 pcf, "Fixed" moisture value of 14%, "Instant Test"/pH value of 11 and an "Instant Test" unconfined compressive strength of 81 psi) and one property, particle surface area of 326, was less than the other soils.

The nonmontmorillonitic soils have a dielectric constant less than 20X10^3 while the nonkaolinitic soils, with the exception of soil 14PA, have a value greater than 20X10^3 The nonmontmorillonitic soils 9LA and 9LB each contain 22% mixed layer clay while the nonkaolinitic soil 1PB contains 52% mixed layer clay. Soil 13BB, a nonkaolinite, contains 17% hydrobiotite-vermiculite clay.

6. Montmorillonite (Adsorp.) vs. Kaolinite (Agglom.). Refer to Table 25.

The majority of the soil property criteria for differentiating the adsorptive montmorillonitic soils from the agglomerative kaolinitic soils were easily predictable. For example,

montmorillonitic soils have a relatively high pH and a high P.I. Also the montmorillonitic soils have a larger surface area than the kaolinitic soils.

The quantity "Instant Test" (psi)/pH distinguishes the montmorillonitic soils from the kaolinitic soils in the majority of the cases (7 out of 8). In the only instance (soil 4TA) where it failed, the value was borderline ("Instant Test"/pH=6). Table 29 contains additional soil data for montmorillonitic and kaolinitic soils. The "Instant Test"/pH mean for the ten montmorillonitic soils listed in Table 29 is 4 while the mean value of the kaolinitic soils listed in this table is 9. Three of the montmorillonitic soils (8SA, 21PA and 22MA) fail the "Instant Test"/pH criteria of <6 while only one kaolinitic soil (4TC) fails the "Instant Test"/pH criteria of >6.

Although the "Instant Test" (developed strength) is a good indicator for differentiating the soils in the "Adsorptive" category (montmorillonitic soils vs. nonmontmorillonitic soils, Table 22), it is not very useful in distinguishing the montmorillonitic soils from the kaolinitic soils (refer to Table 29).

The kaolinitic soils have a relatively larger iron coating content than the montmorillonitic soils, but it is worth repeating that there are only two kaolinitic soil series (2A and 4T) while there are six montmorillonitic soil series (3S, 6M, 8S, 16I, 21P and 22M).

Table 29 tabulates all of the montmorillonitic and kaolinitic soils used in this study with many of their respective soil properties. The obvious weakness of this tabulation is the small representation of the kaolinitic soils. The resulting soil properties are therefore not thought to be necessarily representative. For example, all of the kaolinitic soils in California may not be acidic (pH<7). Be that as it may, there are many distinguishing properties of these two soil groupings. The criteria given in Table 29 for distinguishing the montmorillonitic soils from the kaolinitic soils are generally substantiated in Table 25. Those soil property criteria that are in agreement in the two tables are the pH, PI, Fe coating and the particle surface area. The exchangeable K limit given as 0.7 in Table 25 is closer to 1.0 in Table 29. The factor "Instant Test" developed strength/pH is more useful in Table 29 than in Table 25, but its usefulness in Table 25 can be slightly increased if the value were lowered from 6 to 5.

The soil 6MC (see Table 29) is a highly cemented material in which the clay size content does not reflect the clay mineral content. In the field it resembled a hardpan and required a

jackhammer to break it up. By X-ray analysis it contains 32% montmorillonite but the PI (nonplastic), SE (25) and mechanical analysis (6% clay size) indicate that it is a sand. The high exchangeable Ca (61) content is verified by the high ignition loss (20%) property. It also has a maximum test density and optimum moisture content which are more in agreement with the mean values ($\bar{X}$) of the kaolinitic soils than the montmorillonitic soils. The dielectric constant of the montmorillonitic soils are much greater than $20X10^3$ (actually above $40X10^3$) while the dielectric constant of the kaolinitic soils are less than $20X10^3$.

7. Montmorillonite (Adsorp.) vs. Nonkaolinite (Agglom.). Refer to Table 26.

Montmorillonitic (adsorptive) soils can be separated from non-kaolinitic (agglomerative) soils by a preponderance of soil property criteria without much difficulty. The montmorillonitic soils; 3SA, 3SC, 6MA, 16IA and 21PC, have more exchangeable K ions (>0.7 meq/100 grams of soil), a higher optimum moisture content (>18%), a higher PI (>10) and, in general, a greater particle surface area (>500 cm^2/gm) than the nonkaolinitic soils. The nonkaolinitic soils have a higher test maximum density (>107 pcf) and, in general, a higher "Instant Test" developed strength (>40 psi). The dielectric constant of the montmorillonitic soils were higher than the values for the nonkaolinitic soils.

8. Nonmontmorillonite (Adsorp.) vs. Kaolinite (Agglom.). Refer to Table 27.

For nonmontmorillonite (adsorptive) vs. Kaolinite (agglomerative) soils, an iron coating content greater than 2% and a low pH value (<7) indicates a kaolinitic soil (except soil 11HA). A "Fixed" moisture content less than 10% (except soil 9LB), an unconfined compressive strength (psi) greater than 50 psi (except soil 4TA) and an "Instant Test" developed strength value less than 40 psi (except soil 2AA) could also suggest a kaolinitic soil.

Summary

Certain electrical properties were observed to change as lime reacted with soil. These properties are conductivity (σ) and the dielectric constant (ε^1).

A study of the change in electrical properties of the lime-soil reactions indicates that there are two primary lime-soil reactions: "agglomeration" and "adsorption." It is here theorized that the dielectric constant of the natural and lime-treated soil can be used in identifying each of these

reactions. When the dielectric constant of a lime-treated soil is greater than the dielectric constant of the natural soil an "agglomerative" type of lime-soil reaction is indicated. Conversely, a lime-soil reaction which is primarily "adsorptive" will have a dielectric constant value less than that of the natural soil.

The exchangeable K ion of the natural soil further delineates the "agglomerative" lime-soil reaction from the "adsorptive" reaction.

The hypothesis, that the lime-soil reaction categories - "agglomeration" and "adsorption" - each have two subcategories is supported by the soil property data.

It was established that each of the four subcategories has a group of "exclusive" soil property criteria.

Two of the subcategories are further identified by their clay mineral content: montmorillonite and kaolinite.

The dielectric constant of the natural soil is also helpful in determining the lime-soil reaction subcategory.

Thus for the adsorptive lime-soil reaction category, montmorillonite, there are twelve soil property criteria that can be used to determine if the soil in question is montmorillonitic. Of these only seven are used to determine if the soil is montmorillonitic or one of the remaining three lime-soil reaction subcategories.

Similarly, the kaolinitic soils can be identified by a total of thirteen soil property criteria. Five to seven of these soil property criteria may be used to delineate a kaolinitic soil from any of the three other subcategories.

An example of applying this concept would be to use certain soil properties of an unclassified soil to determine if it is within the range of soil property criteria for any one of the four lime-soil reaction subcategories. The unclassified soil is compared with each subcategory. When a majority of the soil property criteria meet the specifications for the particular subcategory the unclassified soil will react with lime in accordance with the subcategories designation.

LIME-SOIL REACTION ANOMALY INVOLVING SUSPICIOUS SOILS*

The literature, relative to lime-soil stabilization, broadly reflects the opinion that failure of certain lime-treated soils (of which our Group 1 classification is similar) to develop sufficient strength can be attributed to their relative inertness; chemically and physically. However, the data developed by this study does not support that viewpoint.

This study indicates that lime may, or may not, react with soils classed as Group 1. If a considerable reaction does take place, it is visualized as detrimental to strength development. Nevertheless, Group 4 soils which may be highly reactive with lime do acquire large developed strength. Thus, some Group 1 soils and some Group 4 soils are presumed to be highly lime-reactive.

Group 1 and Group 4 Exclusive Soil Property Values.

When the soils and their properties are listed according to developed strength (see Table 30) it may be noted, that, although the mean soil property values of Group 1 and Group 4 soils are similar, they substantially differ from the mean values of Group 2 and Group 3 soils.

This table also lists, on the right side, the number of soils in each group which have certain soil property specifications; e.g., 3 Group 1 soils and 8 Group 4 soils contain CO_3 in excess of 0.4 percent.

Taken together, all the soil properties listed in Table 30 support our belief that some Group 1 soils and some Group 4 soils have something in common (e.g., high lime-soil activity) which distinguishes them from the Group 2 and Group 3 soils.

Analysis

This study disclosed certain characteristics of the lime-soil reaction supportive of the contention that the most highly active lime-soil reactions result in either very little developed compressive strength (Group 1) or the highest developed strength (Group 4) of a fabricated lime-soil mixture.

Those lime-soil reaction characteristics which supports the contention given above are listed below in order of there discussion. The dielectric constant (ε^1) data of the natural soil are also included for the convenience of the reader.

*Group 1 and Group 4 soils which have certain similar soil properties.

a. Electrical Response Test

$\Delta\sigma$ (lime-soil) change in electrical conductivity

$\Delta\varepsilon^1$ " " " " dielectric constant

ε^1 (natural soil) dielectric constant of untreated soil

b. Moisture Test

"Fixed" moisture content

Change in Electrical Conductivity of Lime Treated Soils.

It is assumed that the change in electrical conductivity ($\Delta\sigma$) of a lime-soil paste (as discussed in the Electrical Section) with time reflects a chemical and/or physical reaction of the lime with the soil.

When this change in electrical conductivity is large, this implies that there is a large change in the lime-soil system. If this change in the system is beneficial to strength development, then a Group 4 soil is indicated. However, if the change results in a detrimental configuration, a Group 1 soil is indicated.

As shown in Table 20, those lime-soil paste specimens which exhibited the largest change in electrical conductivity ($\Delta\sigma > 1.60 \times 10^{-3}$ mhos/cm) over the 48 hour test period (2-50 hours) had either the lowest developed strength (Group 1) or the highest developed strength (Group 4). These soils were 3SA, 3SC, and 6MA, 21PC, 22MC, respectively.

Change in Dielectric Constant of Lime Treated Soils.

The largest changes in the dielectric constant ($\Delta\varepsilon^1$) should also be indicators of the lowest developed strength (Group 1) and highest developed strength (Group 4) for some lime-soil systems. Since the largest $\Delta\varepsilon^1$ of a lime-soil system indicates that the largest quantity of lime is "depleted" when the predominate lime-soil reaction is in the "adsorptive" mode and conversely, the largest $\Delta\varepsilon^1$ of a lime-soil system indicates that the greatest amount of soil particles coalesce when the lime-soil reaction is predominately "agglomeration."

The data in Table 20 reveals that when the $\Delta\varepsilon^1$ is greater than -20×10^3 ("adsorption" reaction) the lime-soil system yields very little developed strength (<100 psi, Group 1): soils 3SA, 3SC and 16IA. When the $\Delta\varepsilon^1$ is greater than $+20 \times 10^3$ ("agglomeration" reaction) the lime-soil system exhibits large developed strength (>300 psi, Group 4) with soil 22MC.

Dielectric Constant of Natural Soil.

It is also noteworthy that for natural soils with a dielectric constant (ε^1) greater than $40x10^3$ a Group 1 soil (3SA, 3SC and 16IA) or a Group 4 soil (6MA, 21PC and 22MC) is present.

Moisture Retained ("Fixed") by the Lime-Soil Reaction.

A Group 1 or Group 4 soil is indicated when the "Fixed" moisture content, or moisture content retained after oven drying of the "Instant Test" specimens, exceeds 2.0 percent. Perhaps this "Fixed" moisture is used in producing hydrates in the lime-soil reaction (e.g., tobermorite gel) or in the physical/chemisorption reaction.

These lime-soil reactions were greatly accelerated* by the relatively high temperature of the oven in the moisture determination procedure (220°F+ over a 24 hour period). Therefore, some Group 1 and Group 4 lime-treated soils retain more water than the Group 2 or Group 3 lime-treated soils. The Group 2 and 3 soils are visualized as having less lime-soil activity than some Group 1 and Group 4 soils.

It was further observed that more than 85% of the lime-soil specimens had less moisture content at the end of the cure period (e.g., 7 day, 28 day and 6 month) than was originally in the mixture. Also, over 45% of the 6 month cure lime-soil specimens retained more moisture than the 7 day cure lime treated specimens. It also appears that as the developed strength increases the moisture retained by the mixture increases.

In summary, large lime-soil reactions do not always result in large developed compressive strengths. These large reactions reflect the extreme values of developed compressive strength: viz Group 1 or Group 4 soils as defined in this study.

This conclusion was anticipated from the similarity of the natural soil properties of the Group 1 and Group 4 soils and was supported by the electrical response data and the "Fixed" moisture content data.

The lime reactivity Groups, as used in this study, should be redefined as "Lime Stability" Groups 1, 2, 3 and 4. This would eliminate any confusion relating to the term, lime reactivity. "Lime Stability" Group 1 soils would be considered unsuitable for lime stabilization with developed strength less than 100 psi. Group 4 soils would be considered highly suitable for stabilization. This new definition of terms is presented in Appendix D, "Implementation Guidelines."

*(8) ... "the degree of adsorption was increased by increasing [the] temperature.

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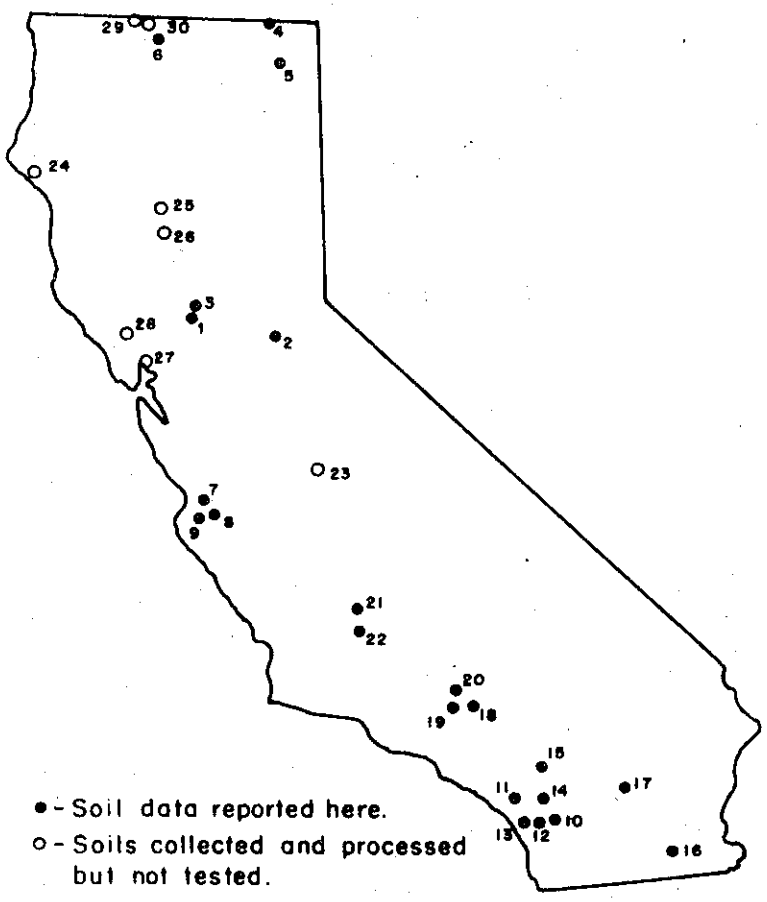


Dot No.	Soil Series	Co.
1	Pescadero	Yol
2	Aiken	Ama
3	Sacramento	Yol
4	Turnquist	Mod
5	Casuse	Mod
6	Montague	Sis
7	Chualar	Mon
8	Salinas	Mon
9	Lockwood	Mon
10	Vista	SD
11	Huerhuero	SD
12	Fallbrook	SD
13	Bonsall	SD
14	Placentia	Riv
15	Ramona	Riv
16	Imperial	Imp
17	Mecca	Riv
18	Hesperia	LA
19	Adelanto	LA
20	Oban	LA
21	Panoche	Ker
22	Merced	Ker
23	Hanford (Ripperdan)	Mad
24	Ferndale	Hum
25	Orland	Teh
26	Tehama	Gle
27	Reyes	Son
28	Wright	Son
29	Josephine	Sis
30	Hilt	Sis

Fig. 1 GEOGRAPHIC LOCATIONS OF THE SOILS USED IN THIS LIME-SOIL STABILIZATION STUDY

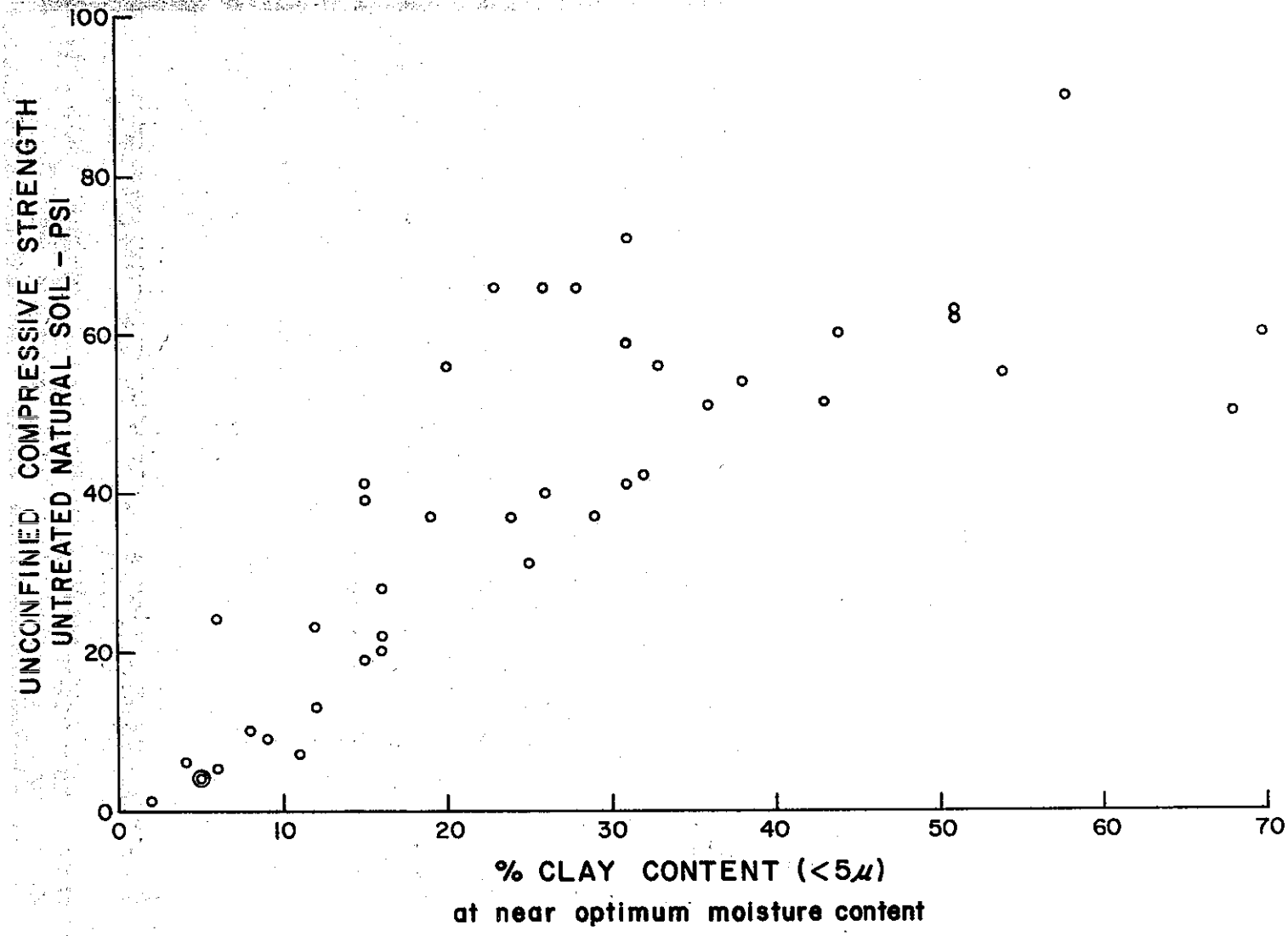


Fig. 2 STRENGTH VS CLAY CONTENT OF THE NATURAL SOILS

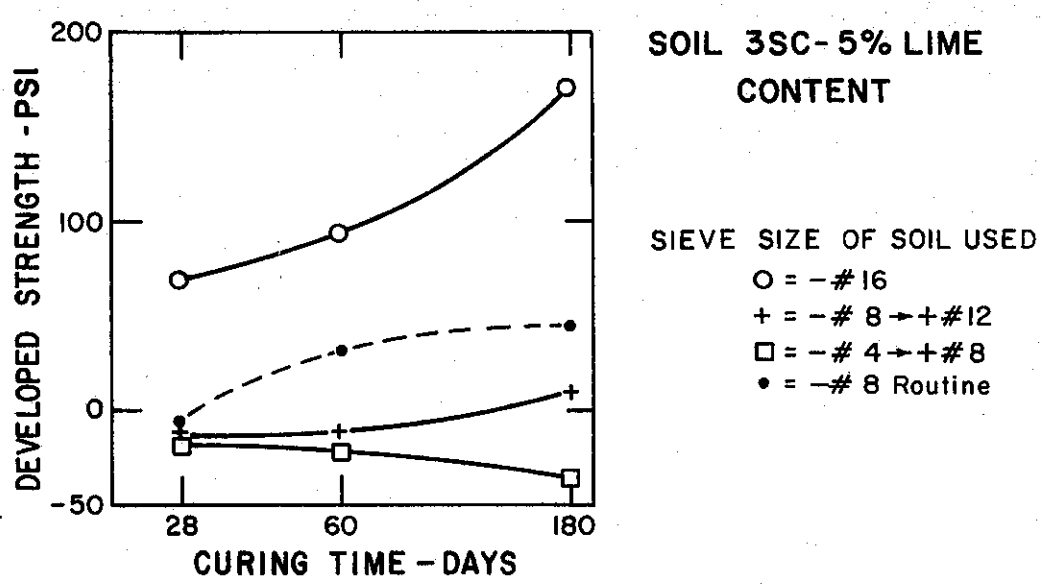


Fig.3 EFFECT OF SOIL PARTICLE SIZE ON STRENGTH FOR A TYPICAL SOIL

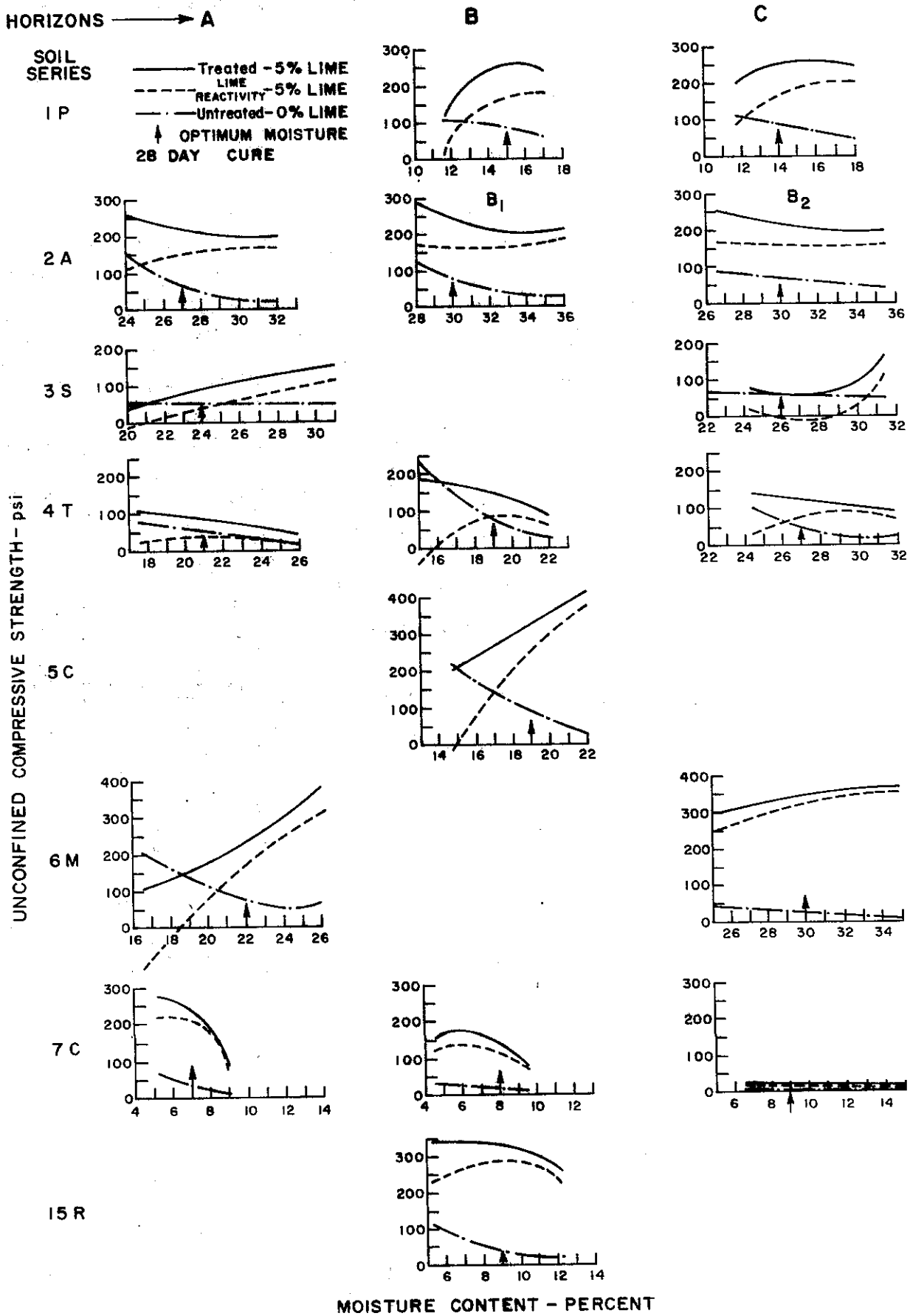
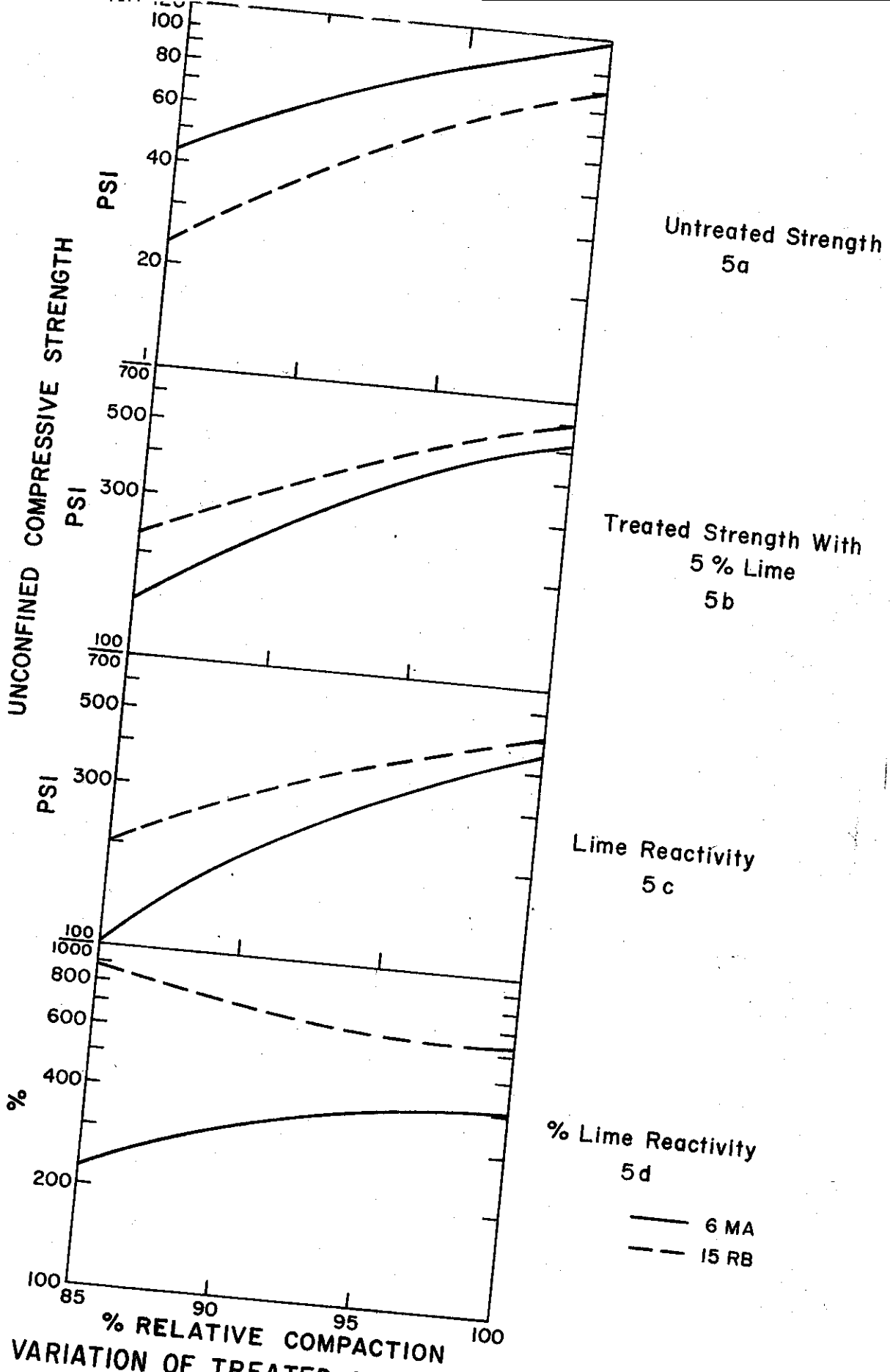


Fig. 4 SENSITIVITY OF TREATED AND UNTREATED SOILS TO VARIATIONS IN MOISTURE CONTENT



RENGTH VARIATION OF TREATED AND UNTREATED SOILS AS
...TION OF RELATIVE COMPACTION (28-DAY CURE)

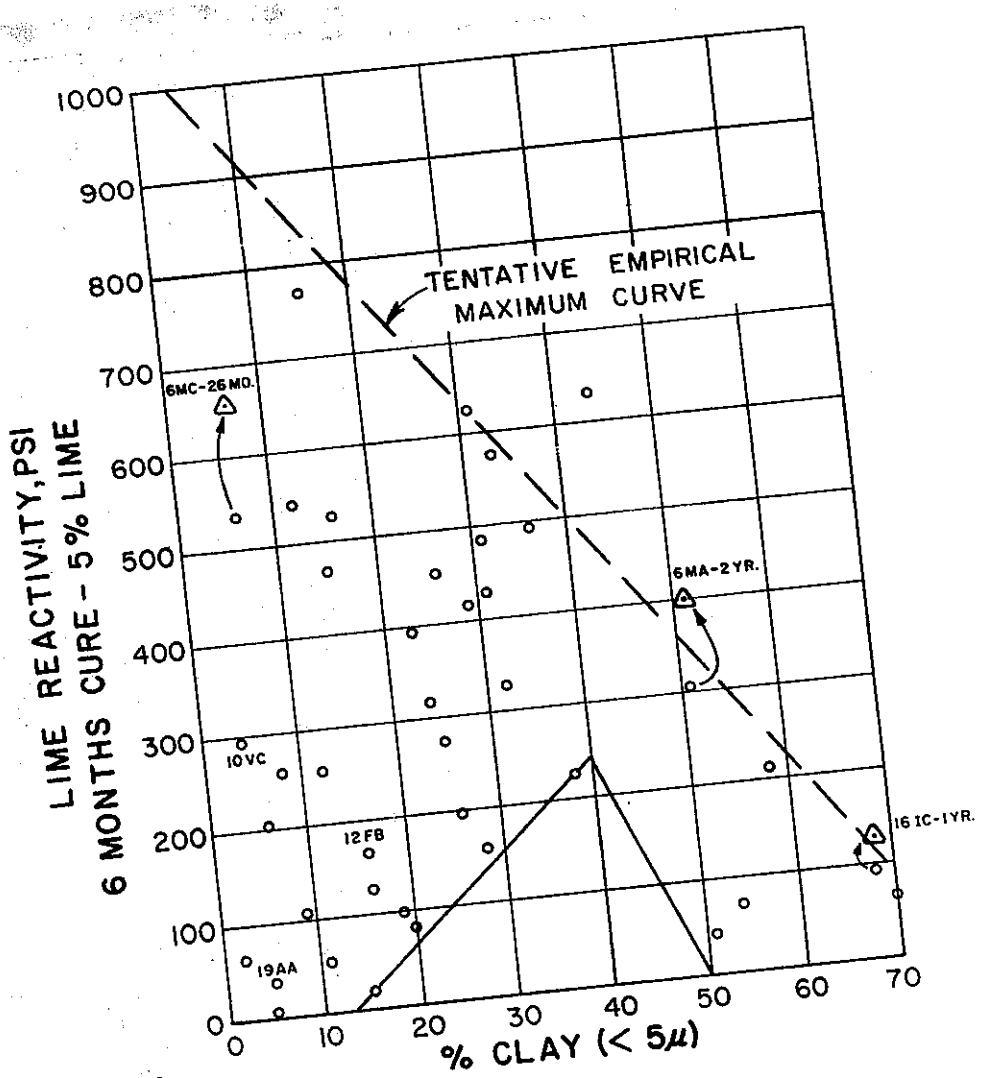


Fig.6 a

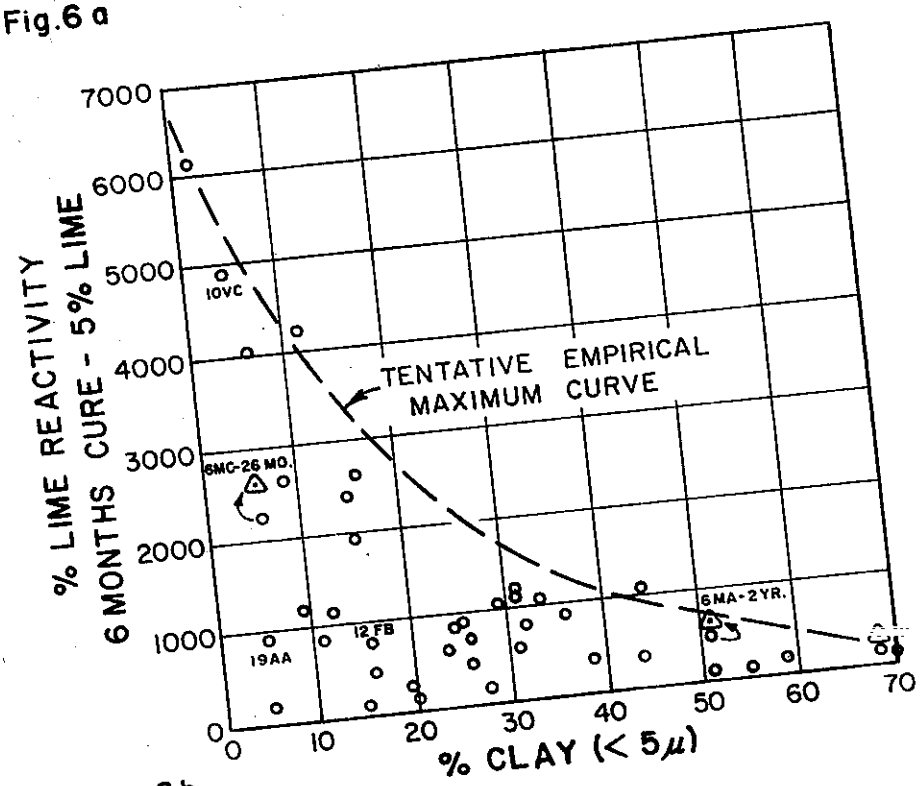


Fig.6 b

Fig. 6 INFLUENCE OF CLAY CONTENT ON ST:
OF LIME TREATED SOIL

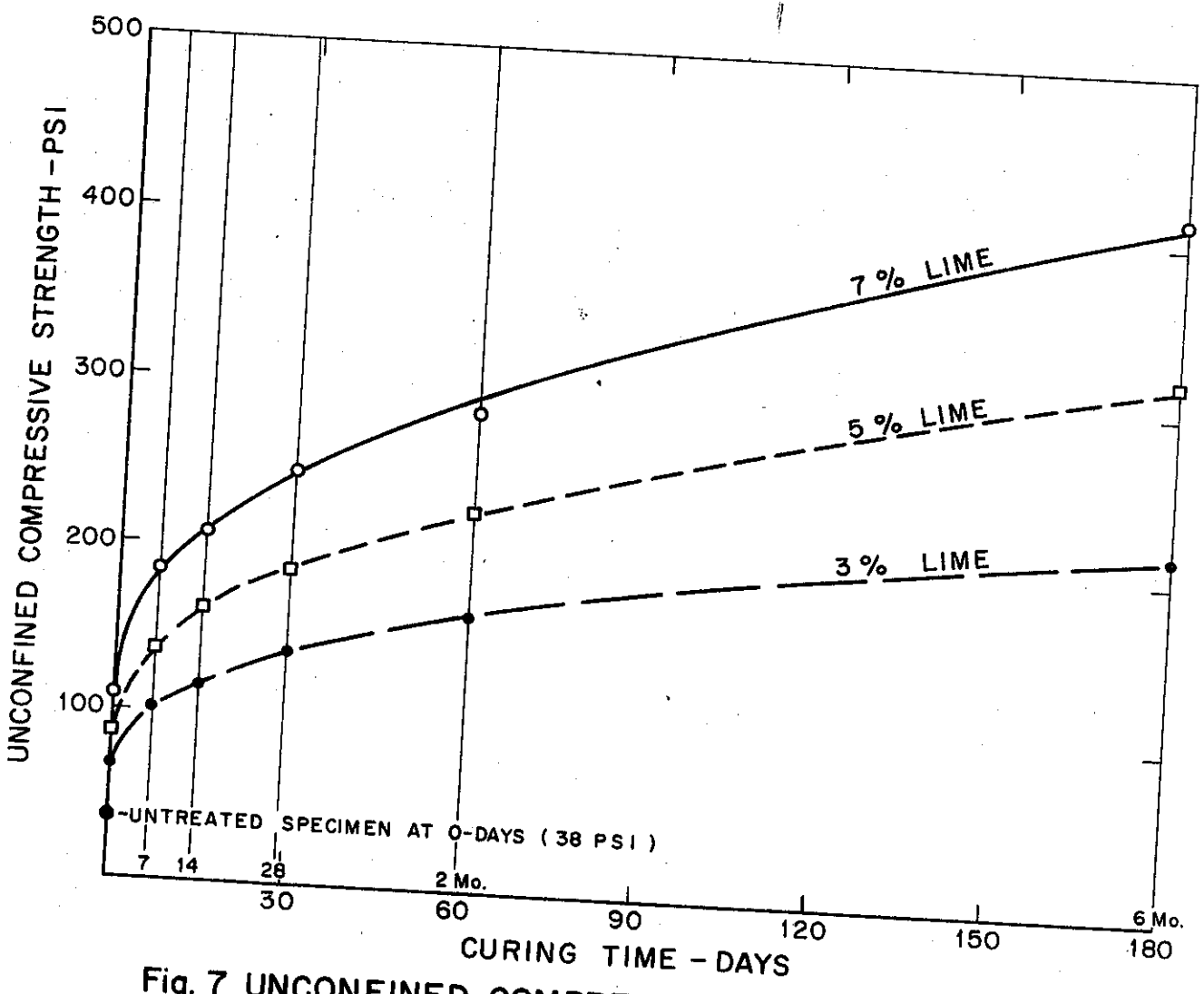


Fig. 7 UNCONFINED COMPRESSIVE STRENGTH AS A FUNCTION OF CURING TIME

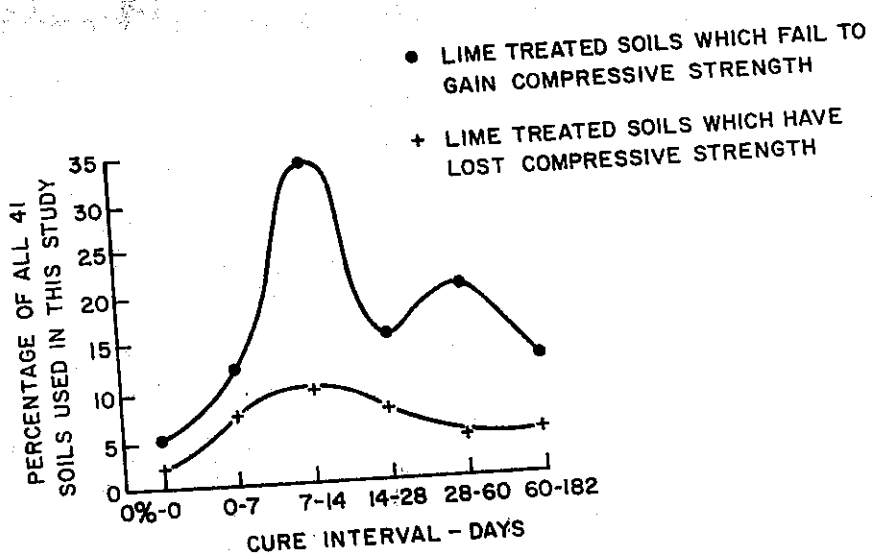


Fig.8 PERCENTAGE OF LIME TREATED SOILS WHICH FAIL TO GAIN STRENGTH OVER 5 CURE INTERVALS USING 5% LIME.

NOTE: THE UNTREATED (0%) STRENGTH VS THE "INSTANT TEST" STRENGTH AFTER (0 day) IS ALSO INCLUDED. CRITERIA: 2% OF DEVELOPED STRENGTH.

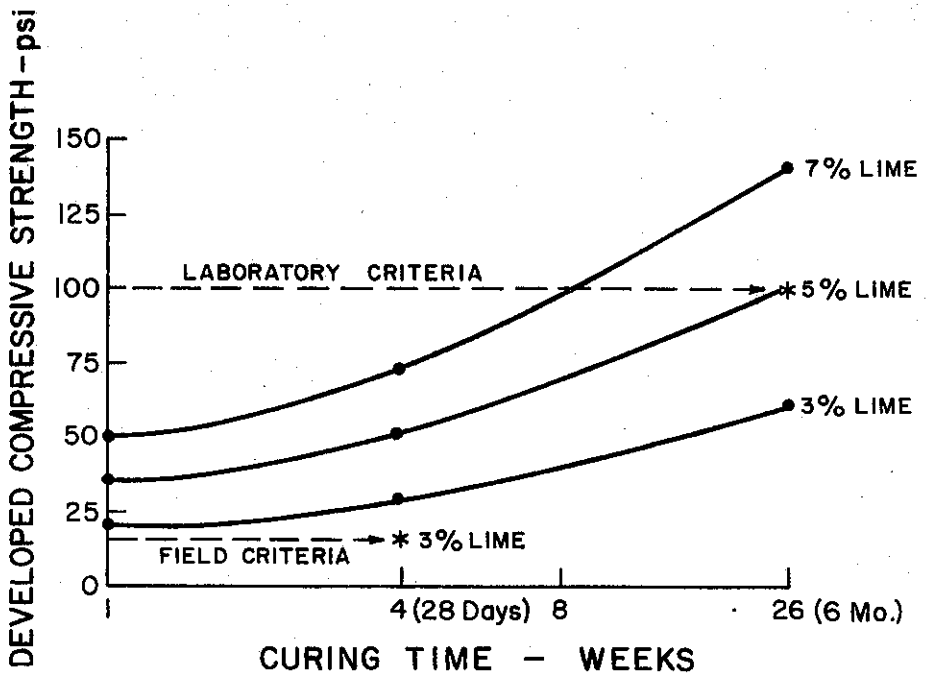


Fig. 9 RELATIONSHIP BETWEEN FIELD STRENGTH CRITERIA AND LABORATORY STRENGTH CRITERIA

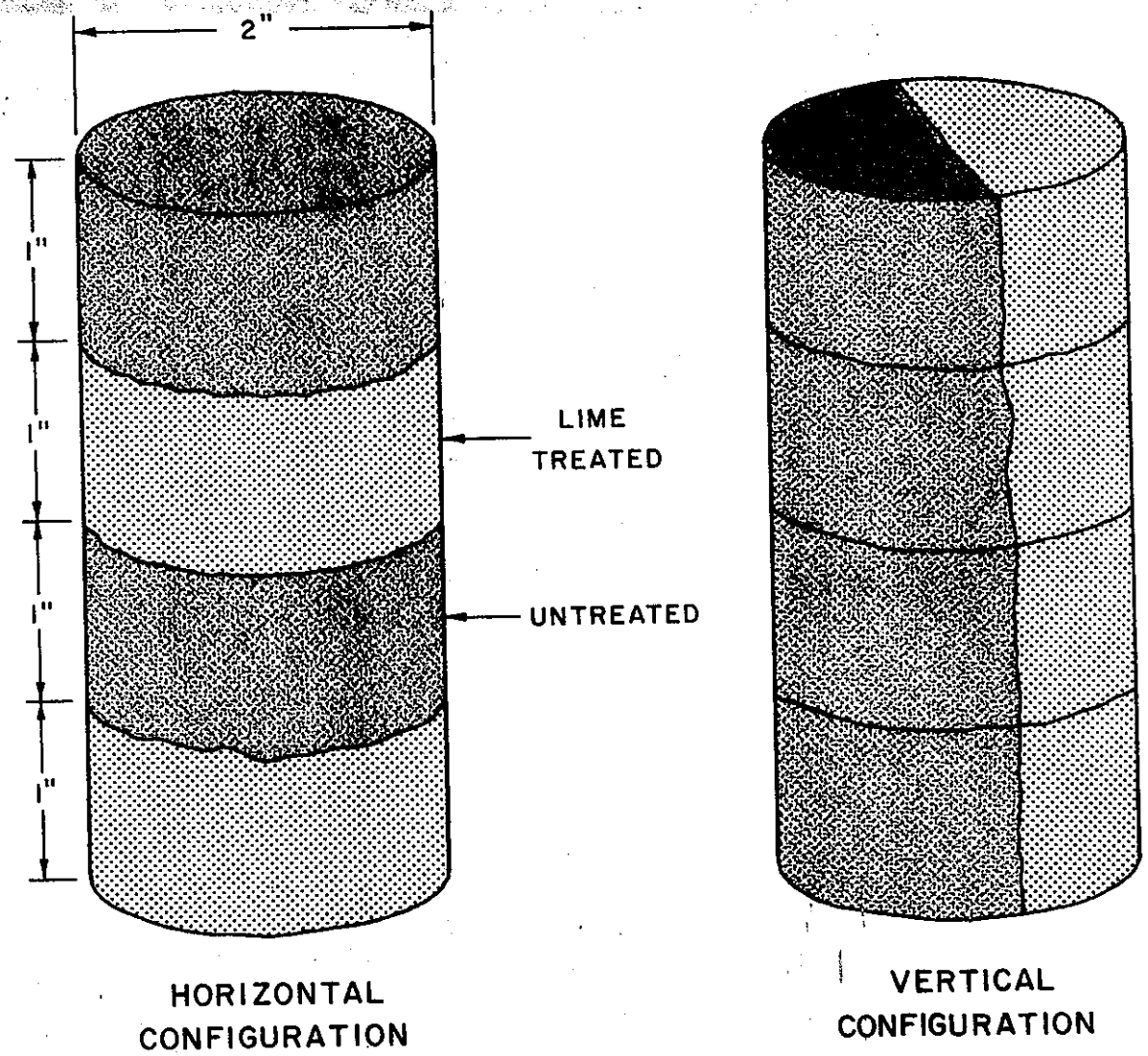


Fig. 10 Specimen preparation – "nonuniform" mixing.

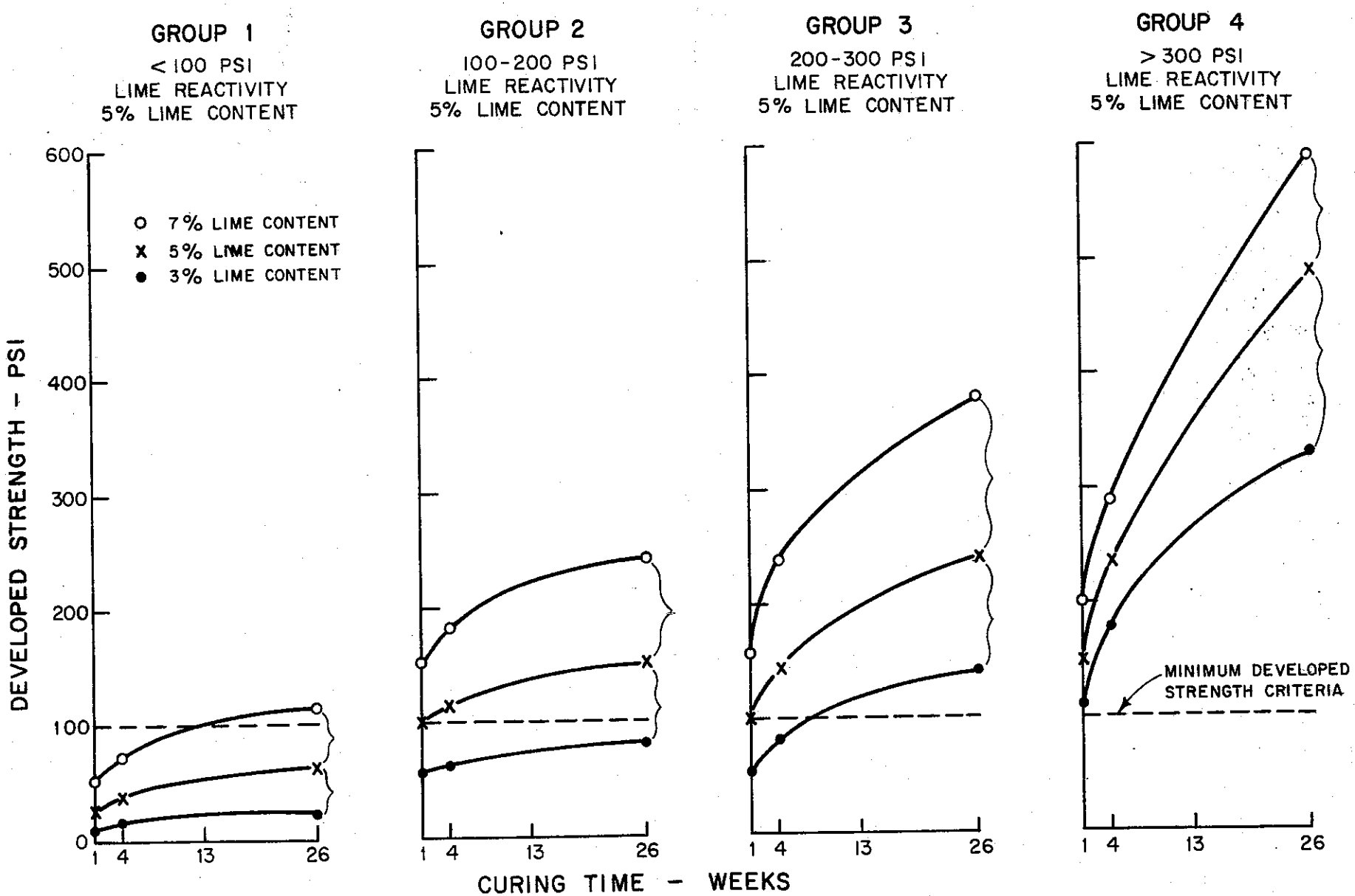


Fig. 11 AVERAGE DEVELOPED STRENGTH AS A FUNCTION OF LIME CONTENT AND CURING PERIOD FOR DIFFERENT LIME SOIL REACTIVITY GROUPS

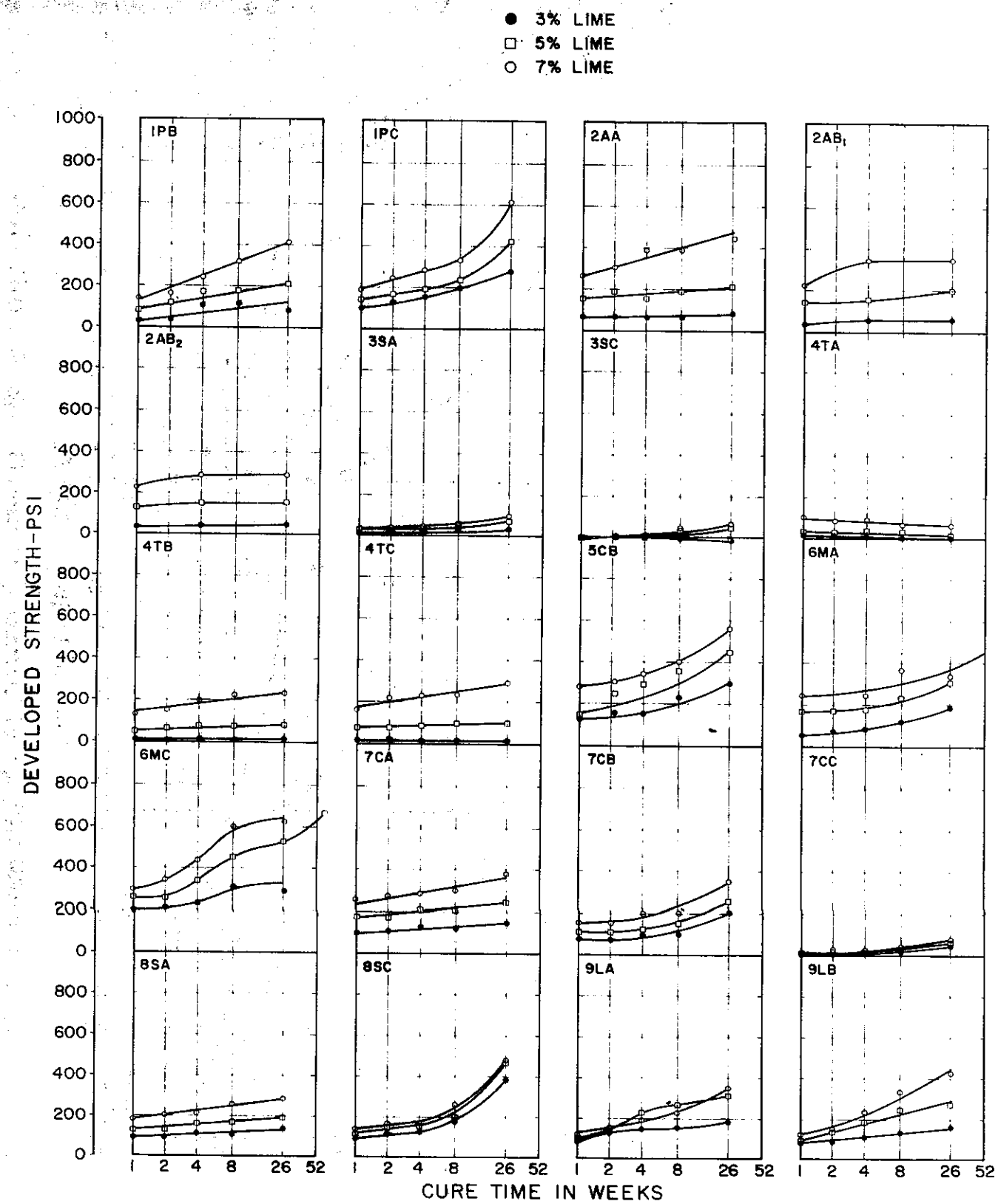


Fig. 12a CHANGE IN DEVELOPED STRENGTH WITH TIME FOR LIME TREATED SOILS

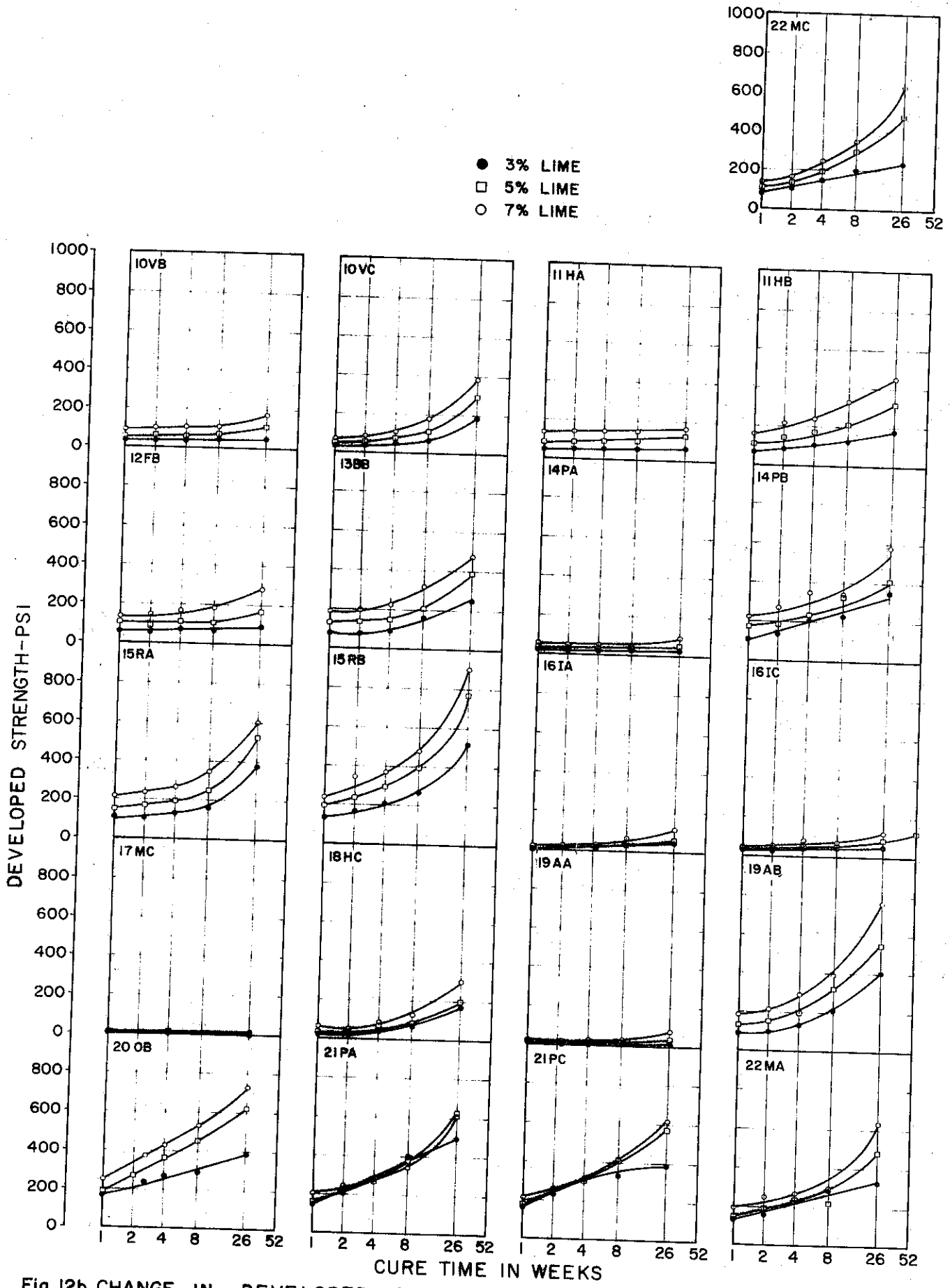


Fig. 12b CHANGE IN DEVELOPED STRENGTH WITH TIME FOR LIME TREATED SOILS

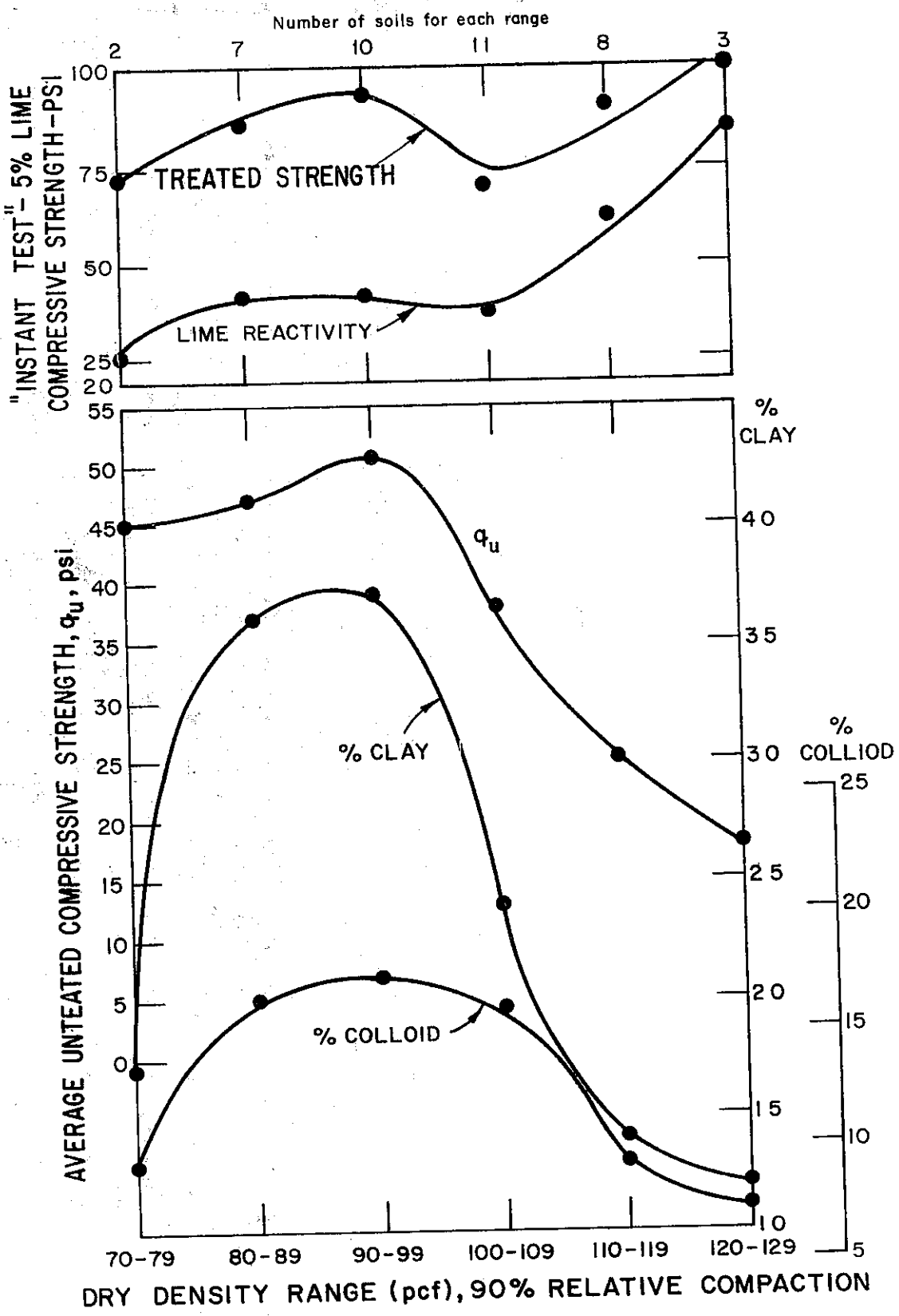


Fig. 13 INFLUENCE OF NATURAL SOIL SPECIMEN DENSITY UPON COMPRESSIVE STRENGTH OF NATURAL SOILS AND LIME TREATED SOILS ("INSTANT TEST"). CLAY AND COLLOID CONTENT ALSO INCLUDED.

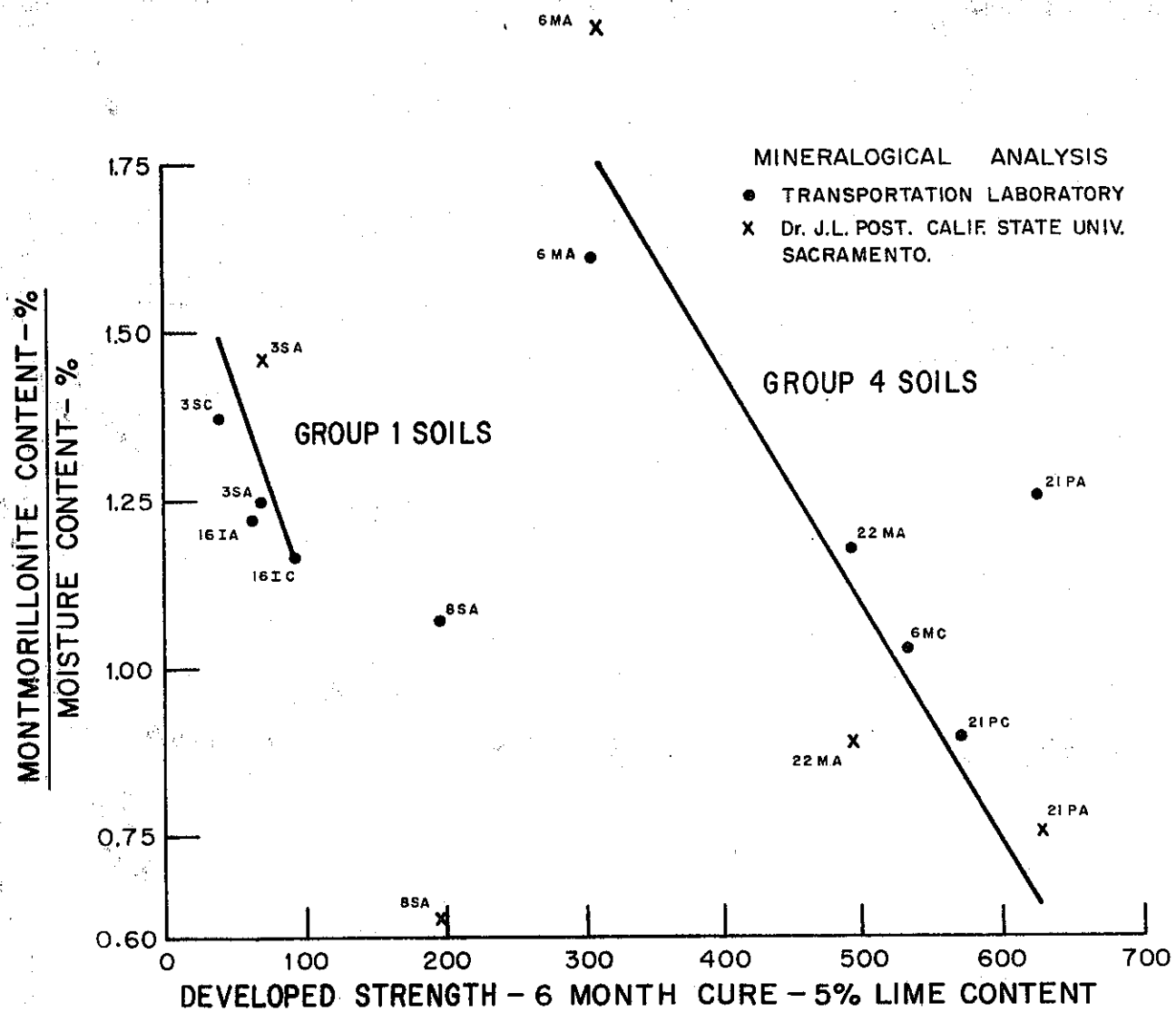
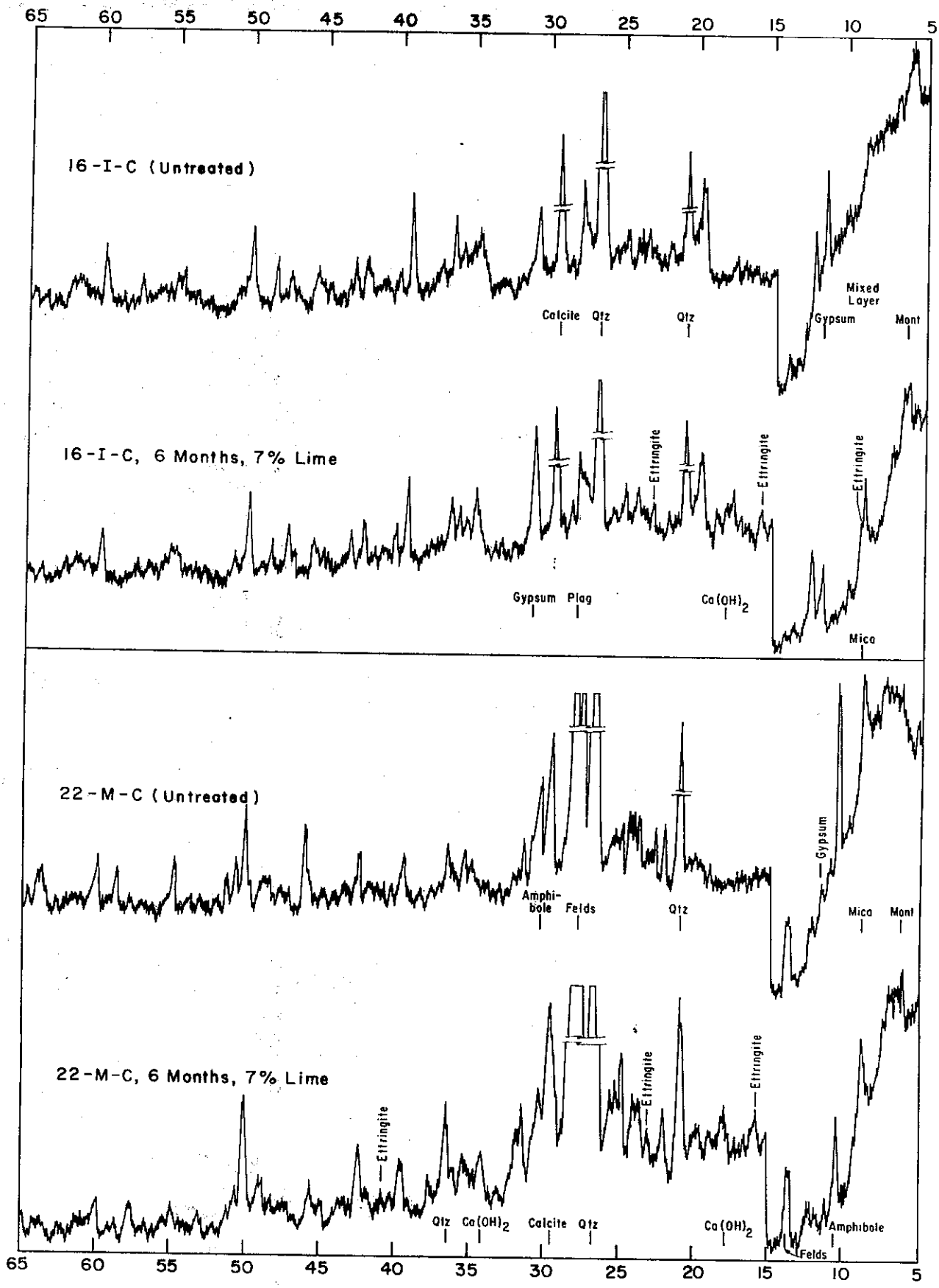


Fig. 14 ESTIMATION OF DEVELOPED COMPRESSIVE STRENGTH USING MONTMORILLONITE TO MOISTURE RATIO



GE XRD-5 Cu DS=0.2 TC=2 SR=2°/min. Filter=.00035 Ni CPS=500

Fig. 15 X-RAY DIFFRACTION SCANS OF TREATED AND UNTREATED SOILS

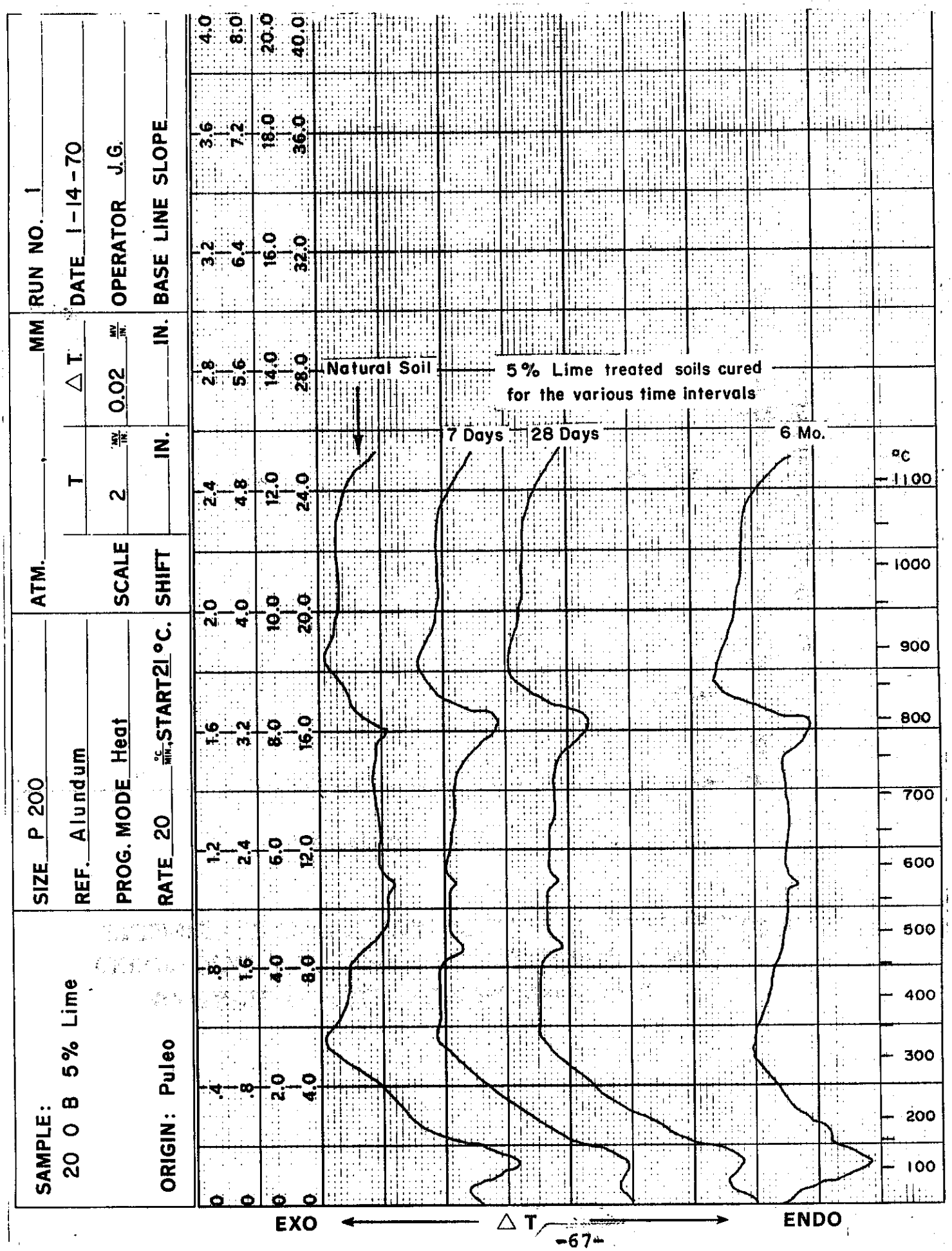


Fig. 16 D.T.A. OF AN UNTREATED AND LIME TREATED SOIL

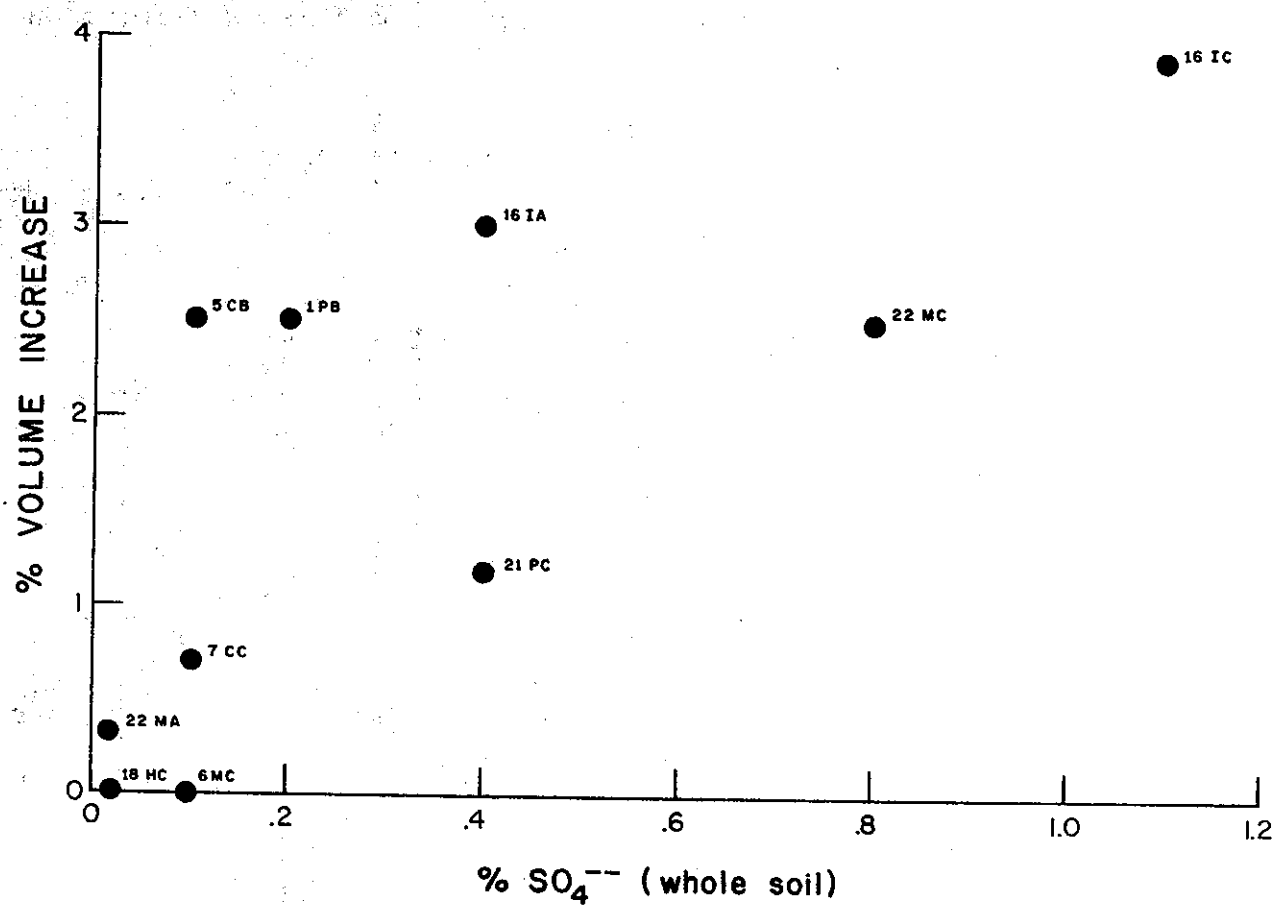


Fig.17 EFFECT OF INCREASING SULFATE CONTENT ON VOLUMETRIC CHANGES OF 6 MOS. CURED 5% LIME TREATED SOIL SPECIMENS

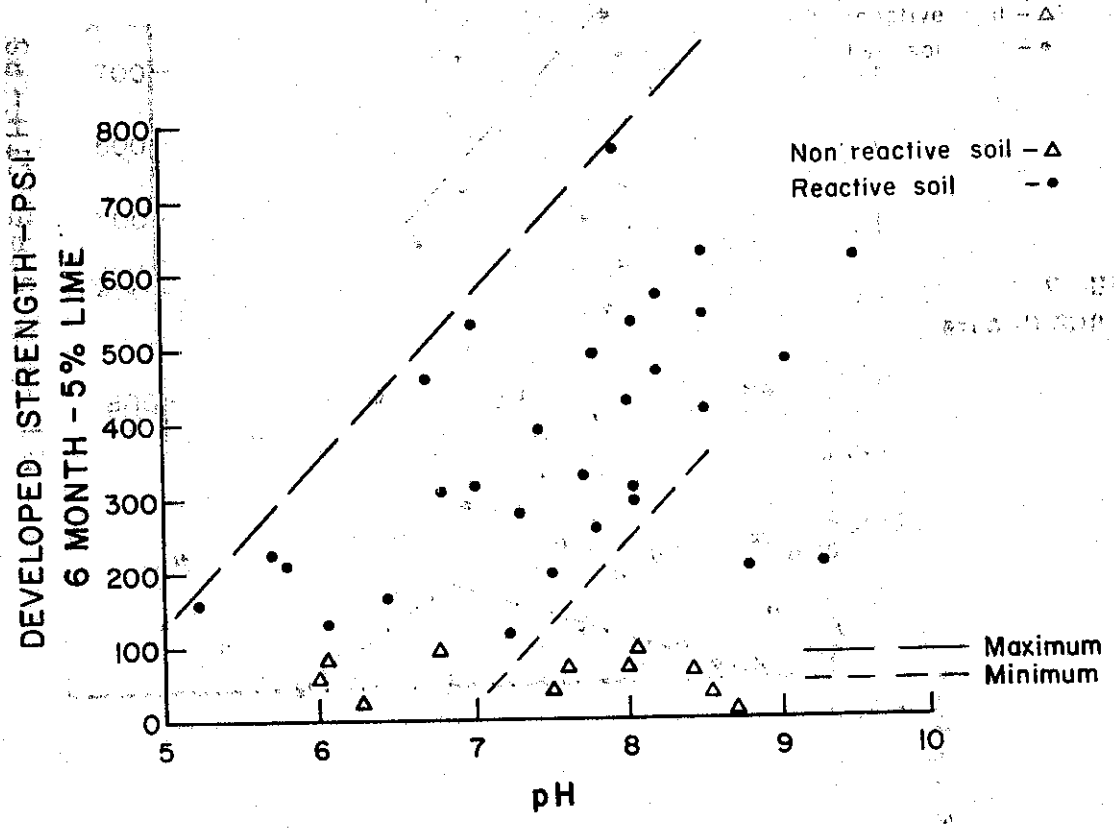


Fig.18 INFLUENCE OF pH ON DEVELOPED STRENGTH

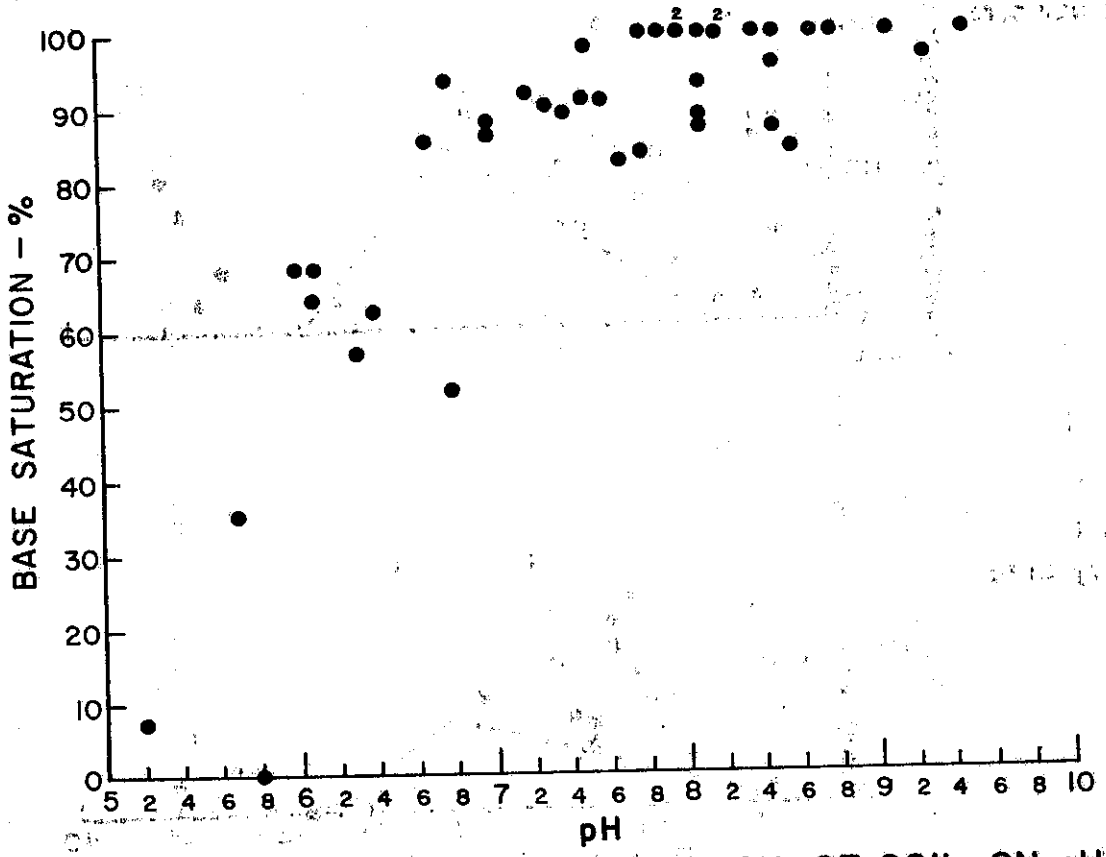


Fig.19 INFLUENCE OF BASE SATURATION OF SOIL ON pH (1:1)

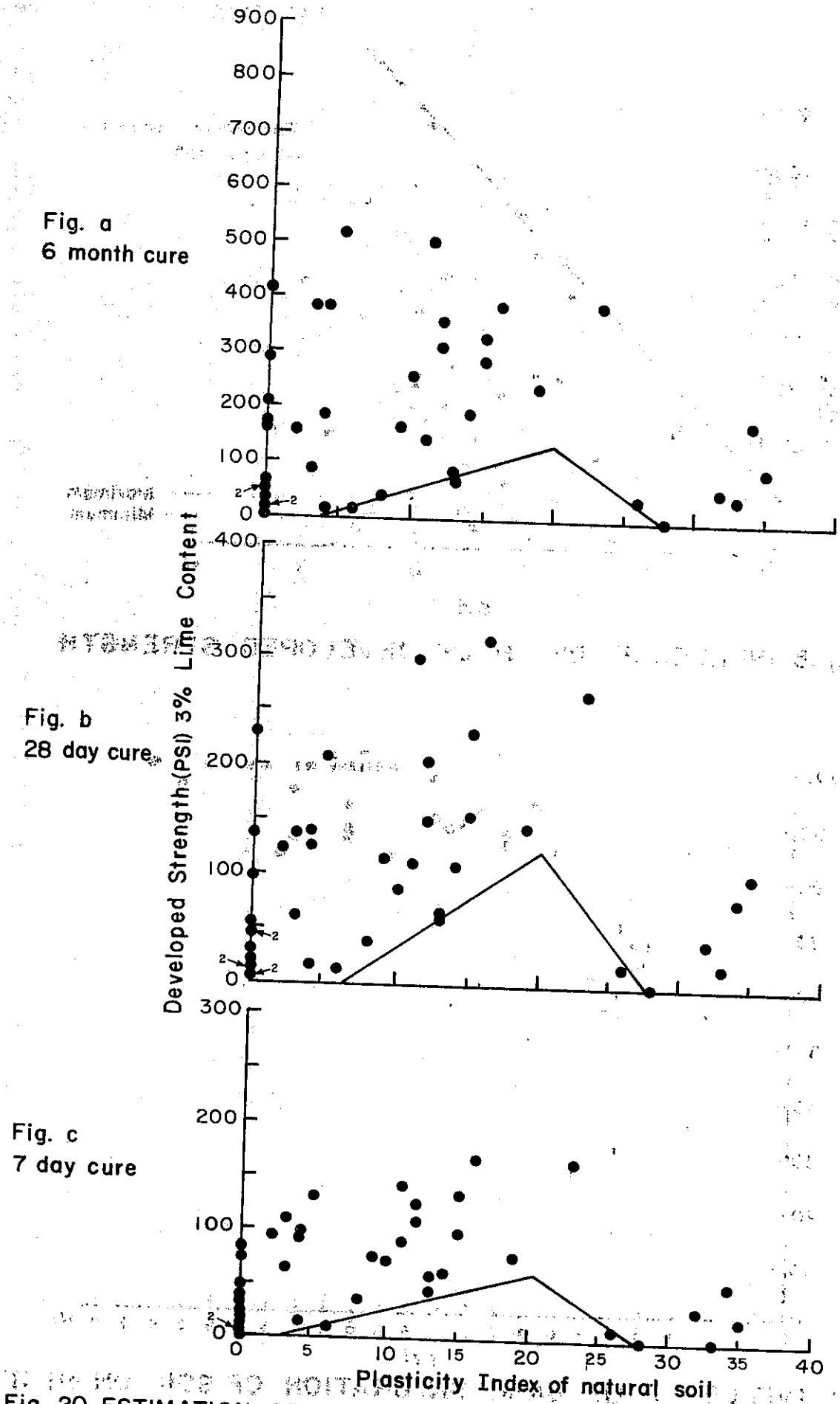


Fig. 20 ESTIMATION OF MINIMUM DEVELOPED COMPRESSIVE STRENGTH USING PLASTICITY INDEX OF SOIL (3% LIME)

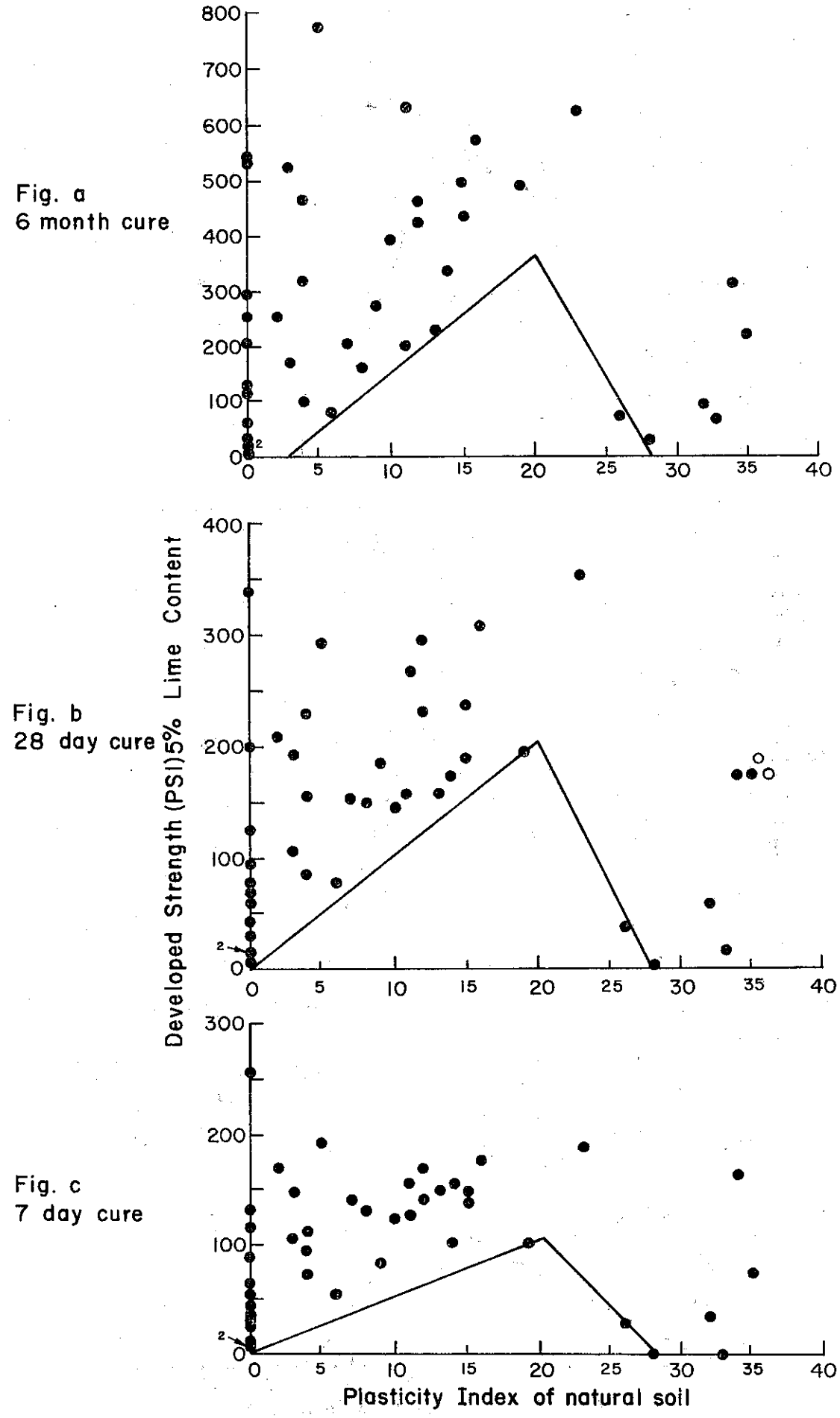


Fig. 21 ESTIMATION OF MINIMUM DEVELOPED COMPRESSIVE STRENGTH USING PLASTICITY INDEX OF SOIL (5% LIME)

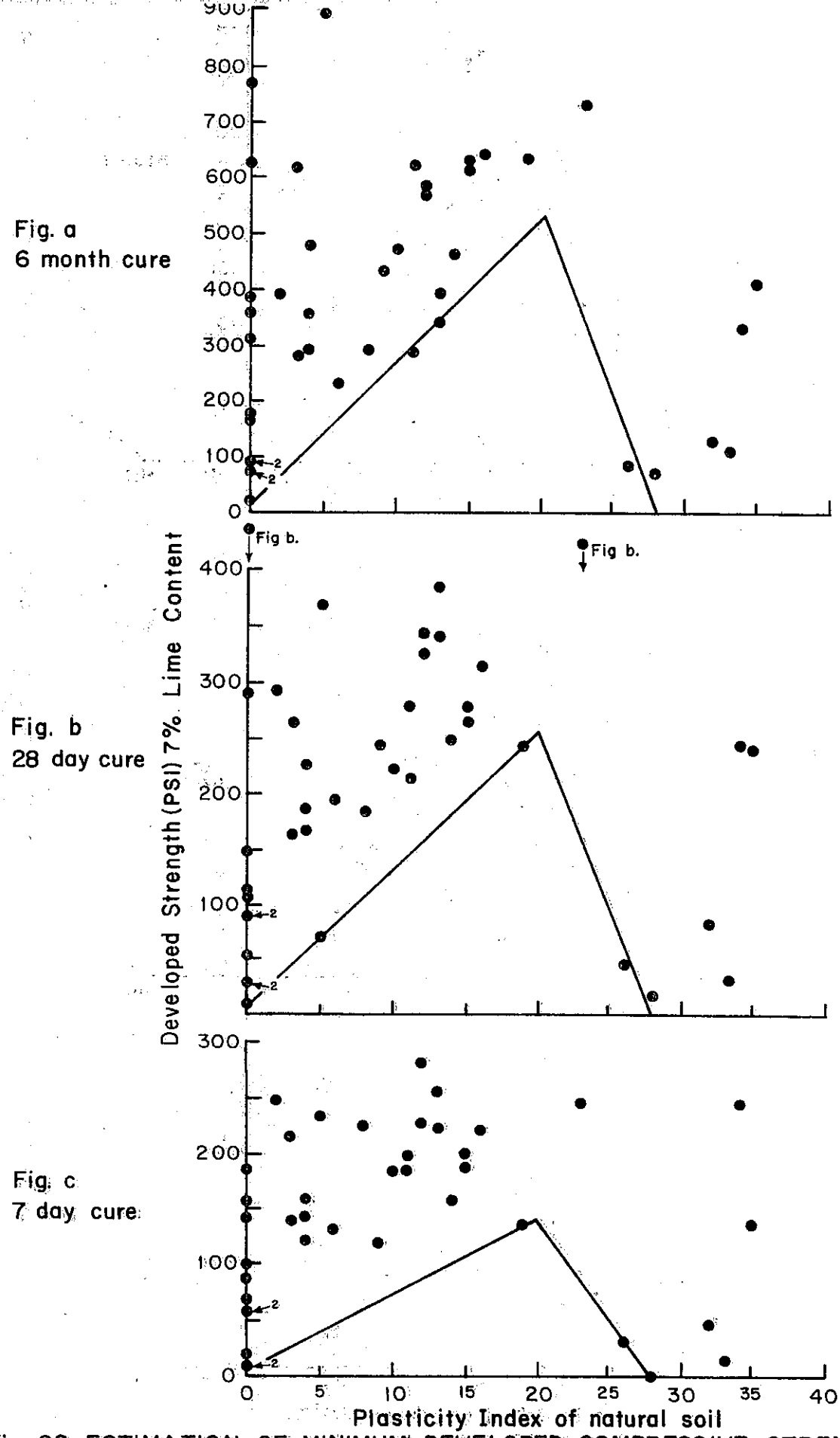


Fig. 22 ESTIMATION OF MINIMUM DEVELOPED COMPRESSIVE STRENGTH USING PLASTICITY INDEX OF SOIL (7% LIME)

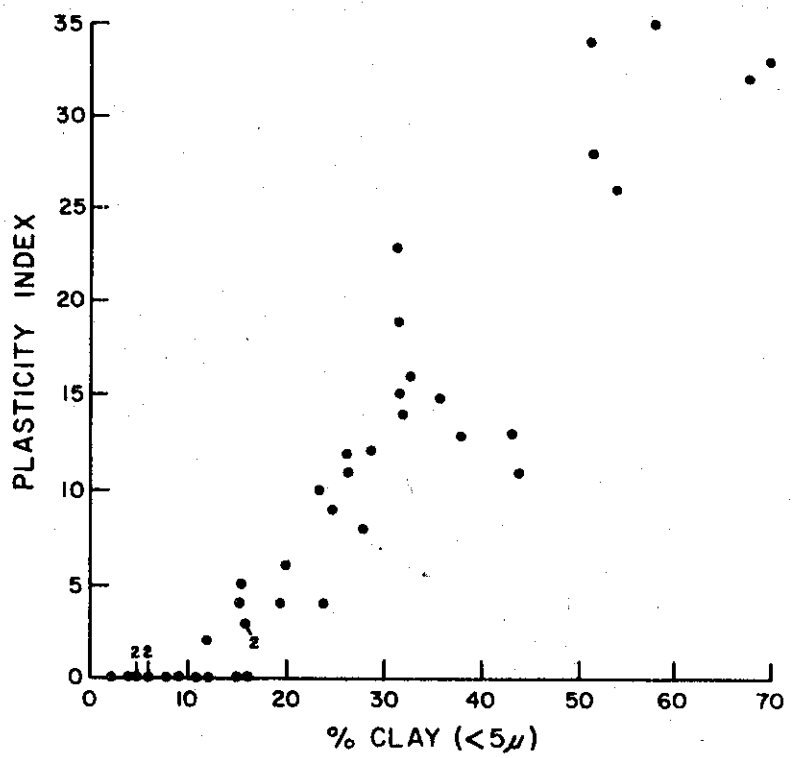


Fig. 23 RELATIONSHIP OF CLAY CONTENT TO PLASTICITY INDEX FOR NATURAL SOILS

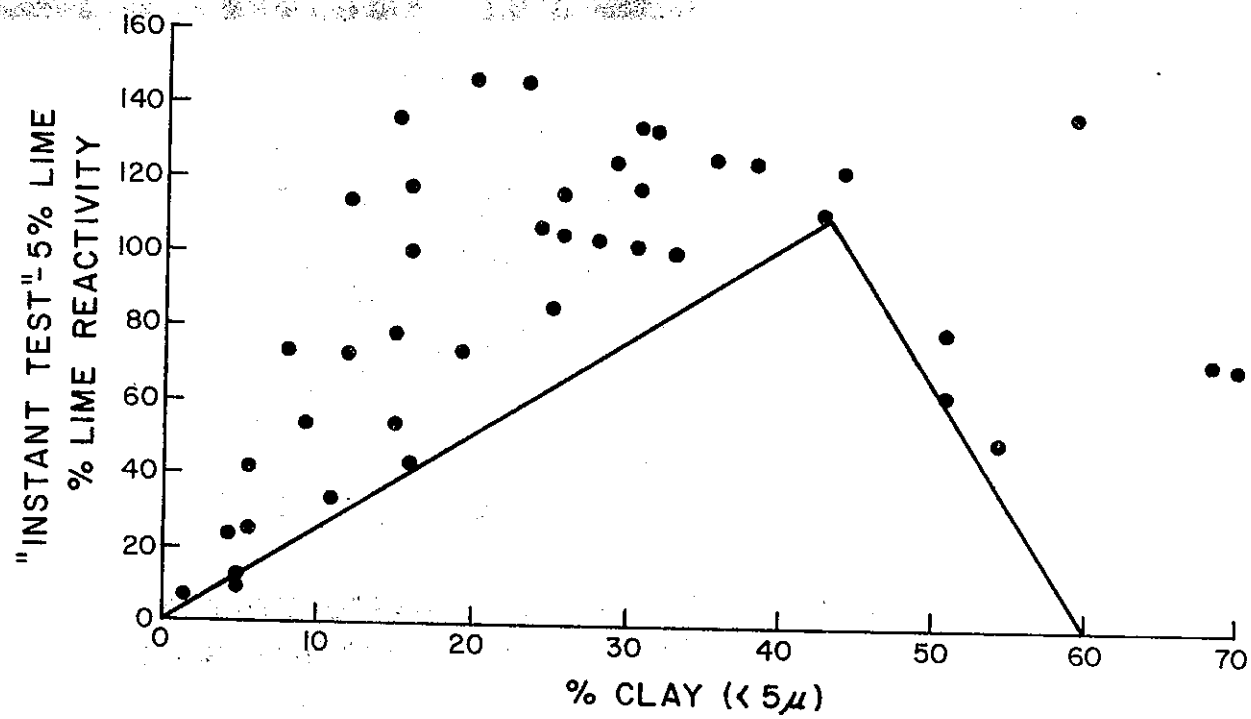


Fig. 24 PERCENT LIME REACTIVITY ("INSTANT TEST") VS CLAY CONTENT

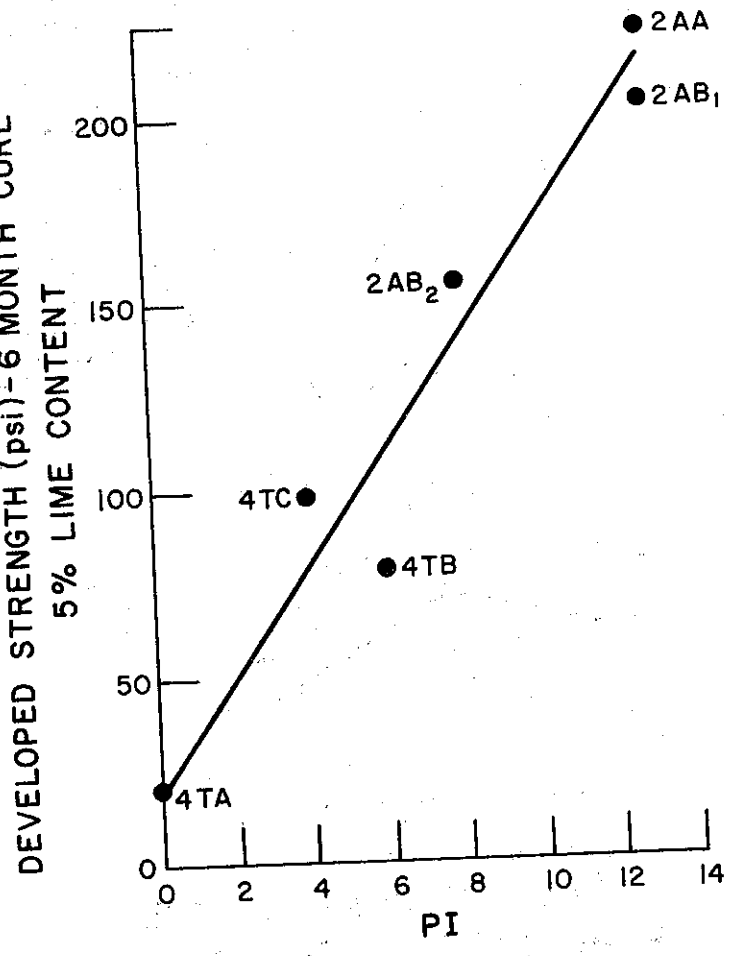


Fig.25 LONG TIME COMPRESSIVE STRENGTH DEVELOPMENT FOR KAOLINITIC SOIL (>15% KAOLINITE) VS PI OF THE UNTREATED SOIL

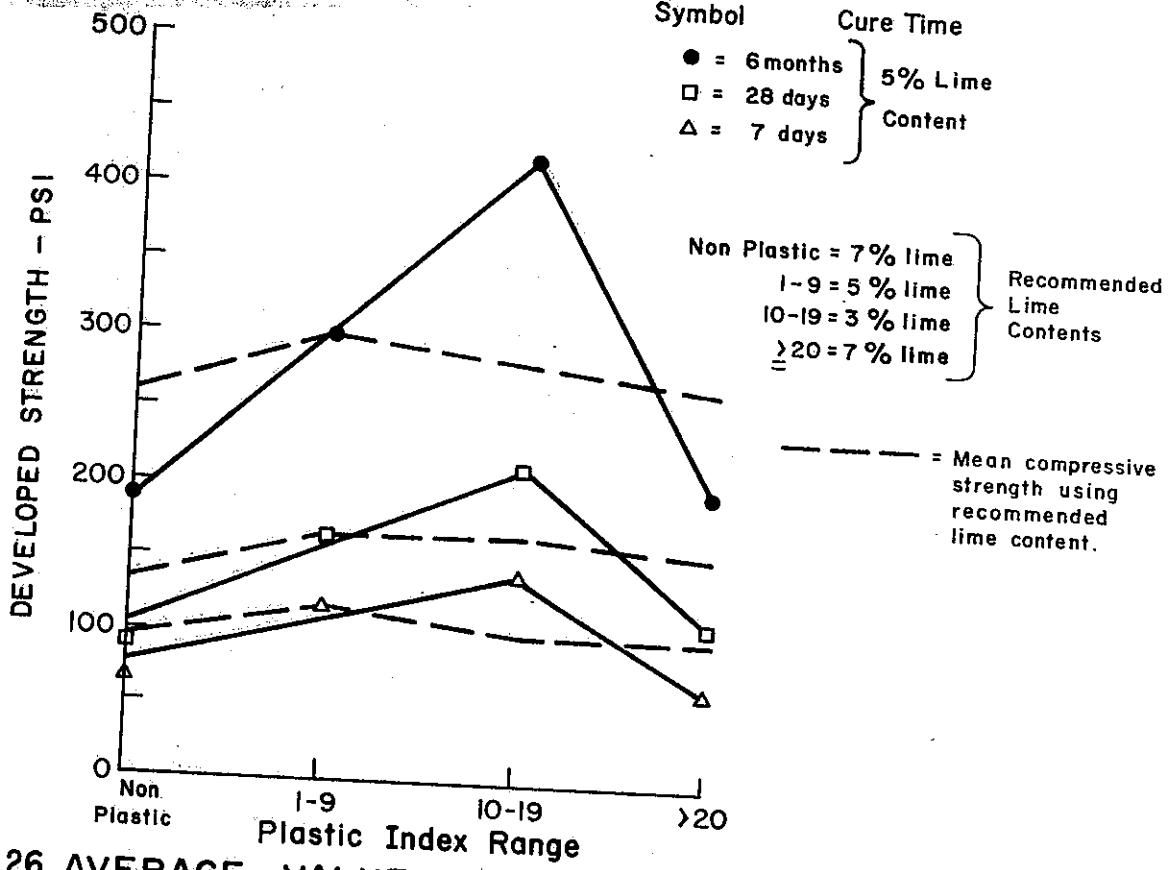


Fig. 26 AVERAGE VALUES OF COMPRESSIVE STRENGTH FOR VARIOUS P.I. INTERVALS

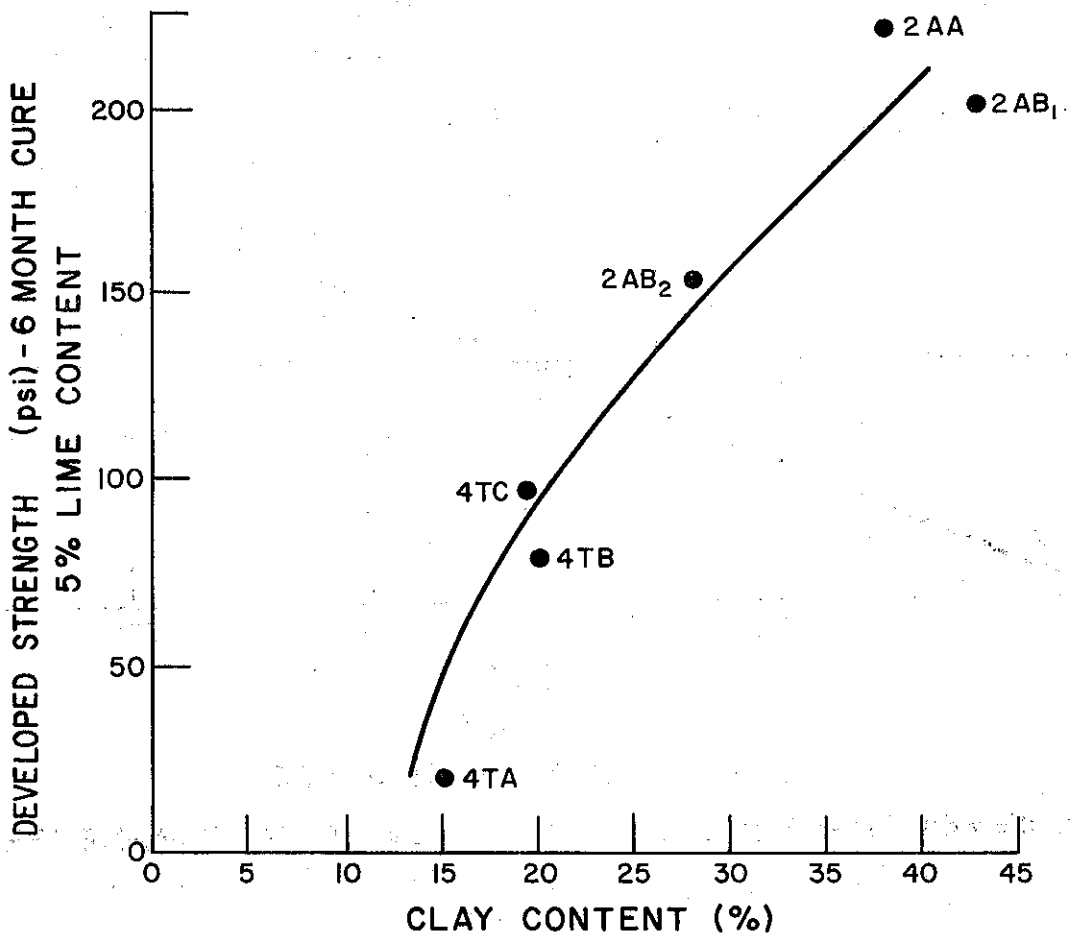
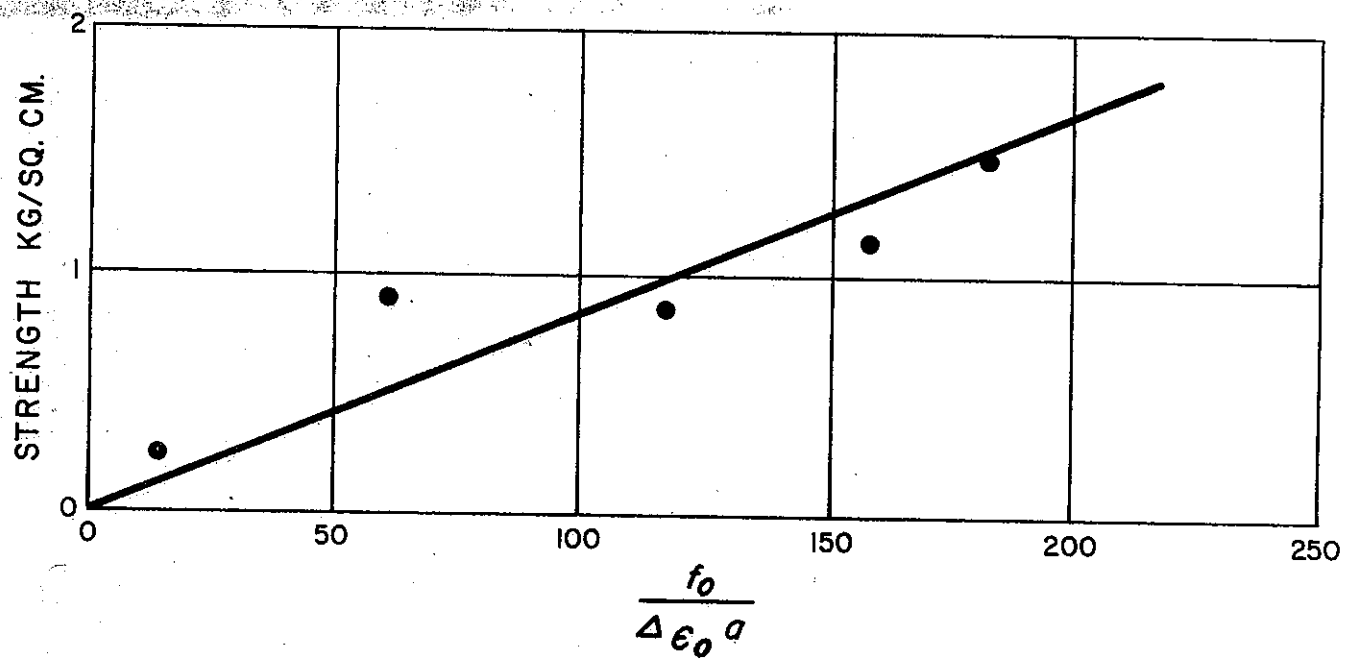


Fig. 27 LONG TIME COMPRESSIVE STRENGTH DEVELOPMENT FOR KAOLINITIC SOIL (>15% KAOLINITE) VS CLAY CONTENT



ELECTRICAL PROPERTIES

Fig. 28 UNCONFINED UNTREATED STRENGTH VS ELECTRICAL PARAMETERS OF KAOLINITE AND ILLITE (SATURATED CLAYS)

FROM: ARULANANDAN & MITCHELL (5)

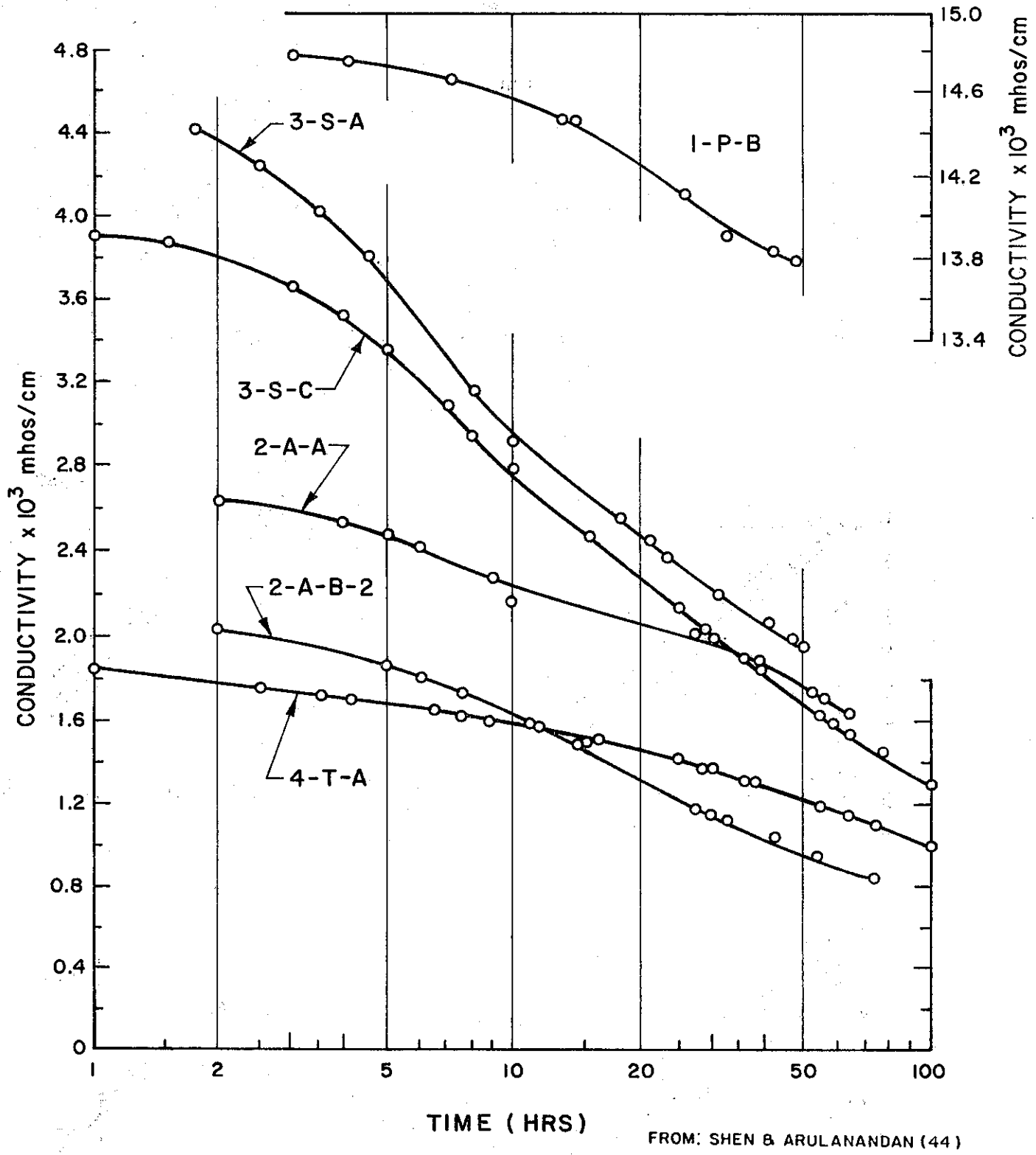
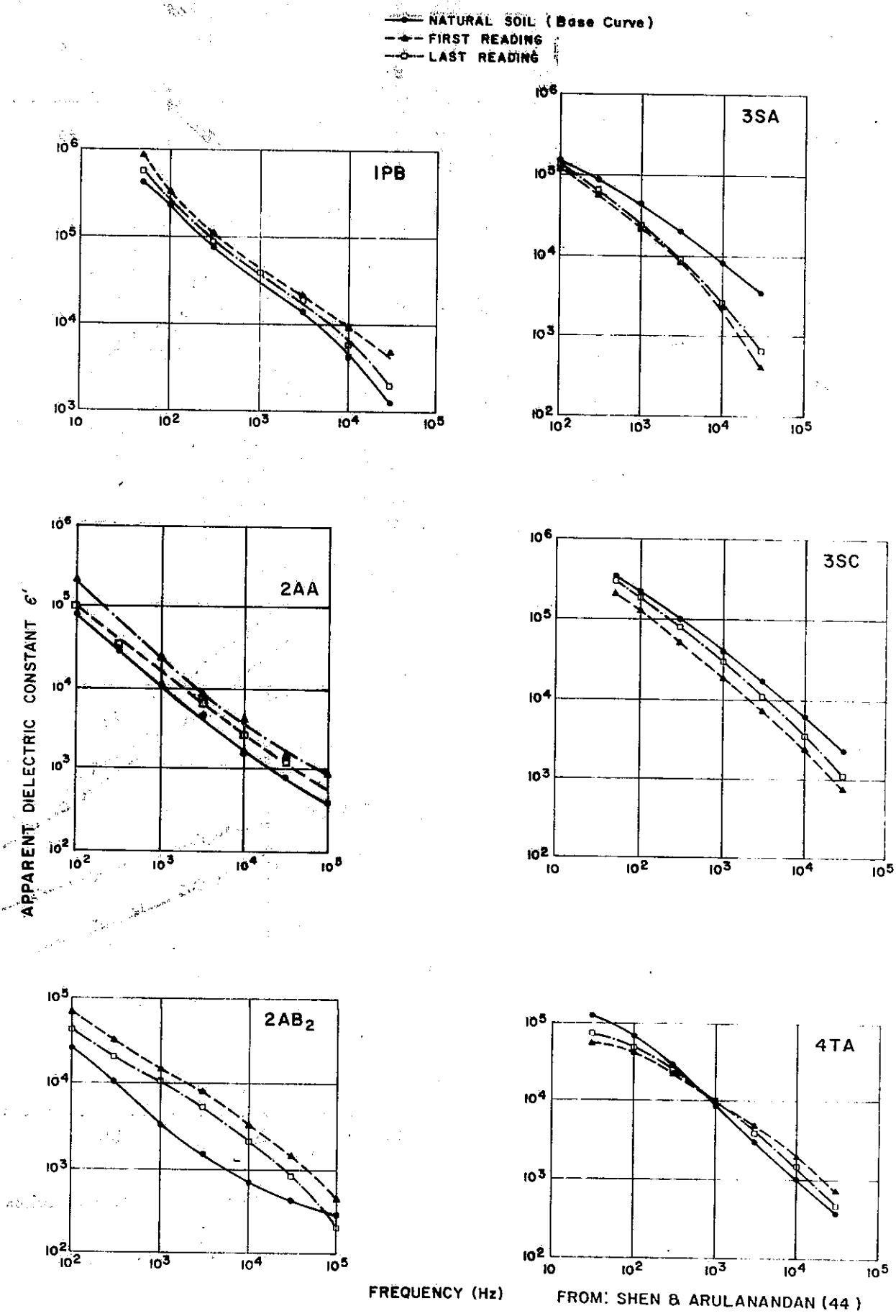


Fig.29 Conductivity Dispersion of Lime-Soil-Water Paste.



FROM: SHEN & ARULANANDAN (44)

Fig. 30 DIELECTRIC DISPERSION CHARACTERISTICS OF THE NATURAL SOILS IN PASTE FORM AND THE LIME TREATED SOILS AS A FUNCTION OF FREQUENCY

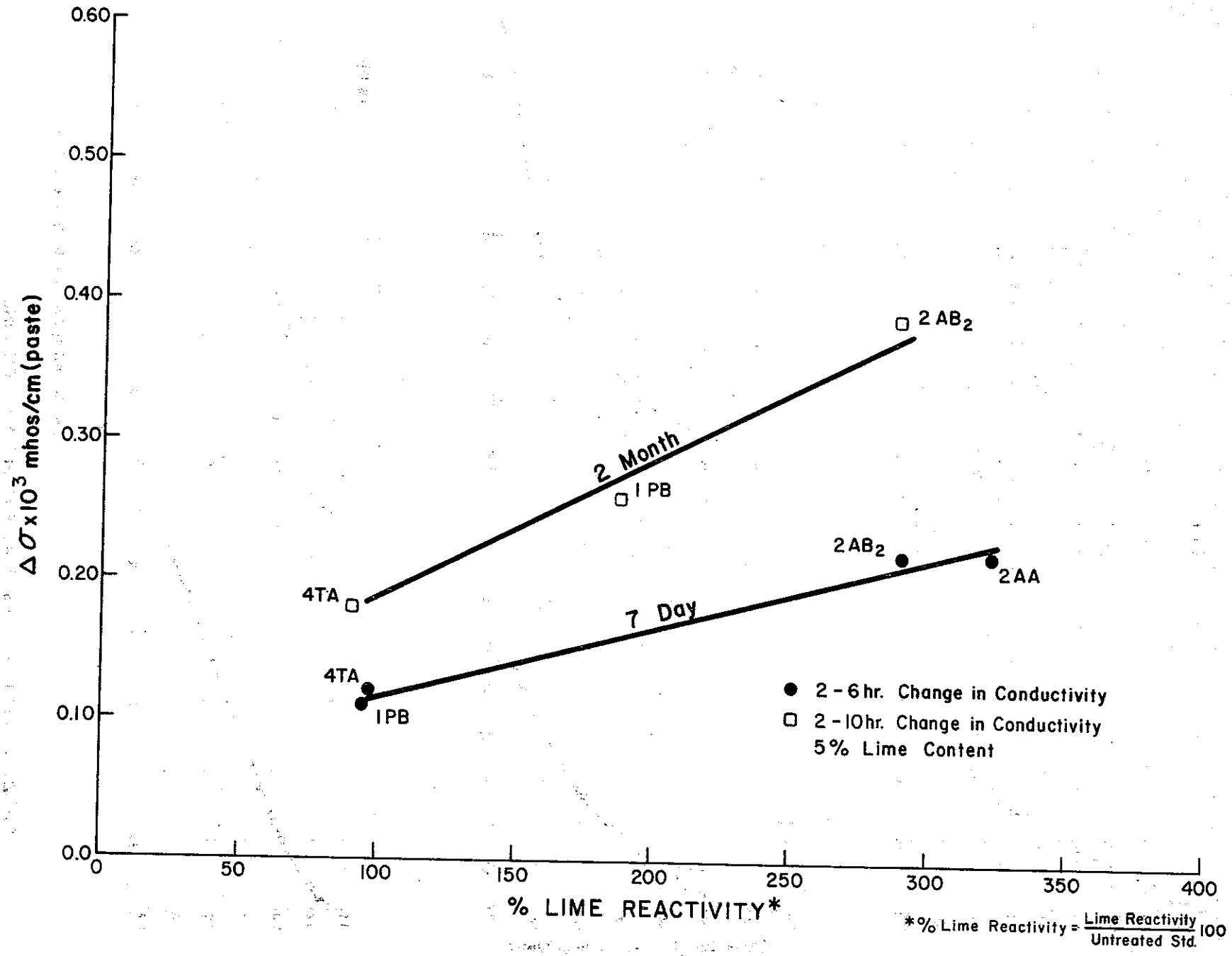
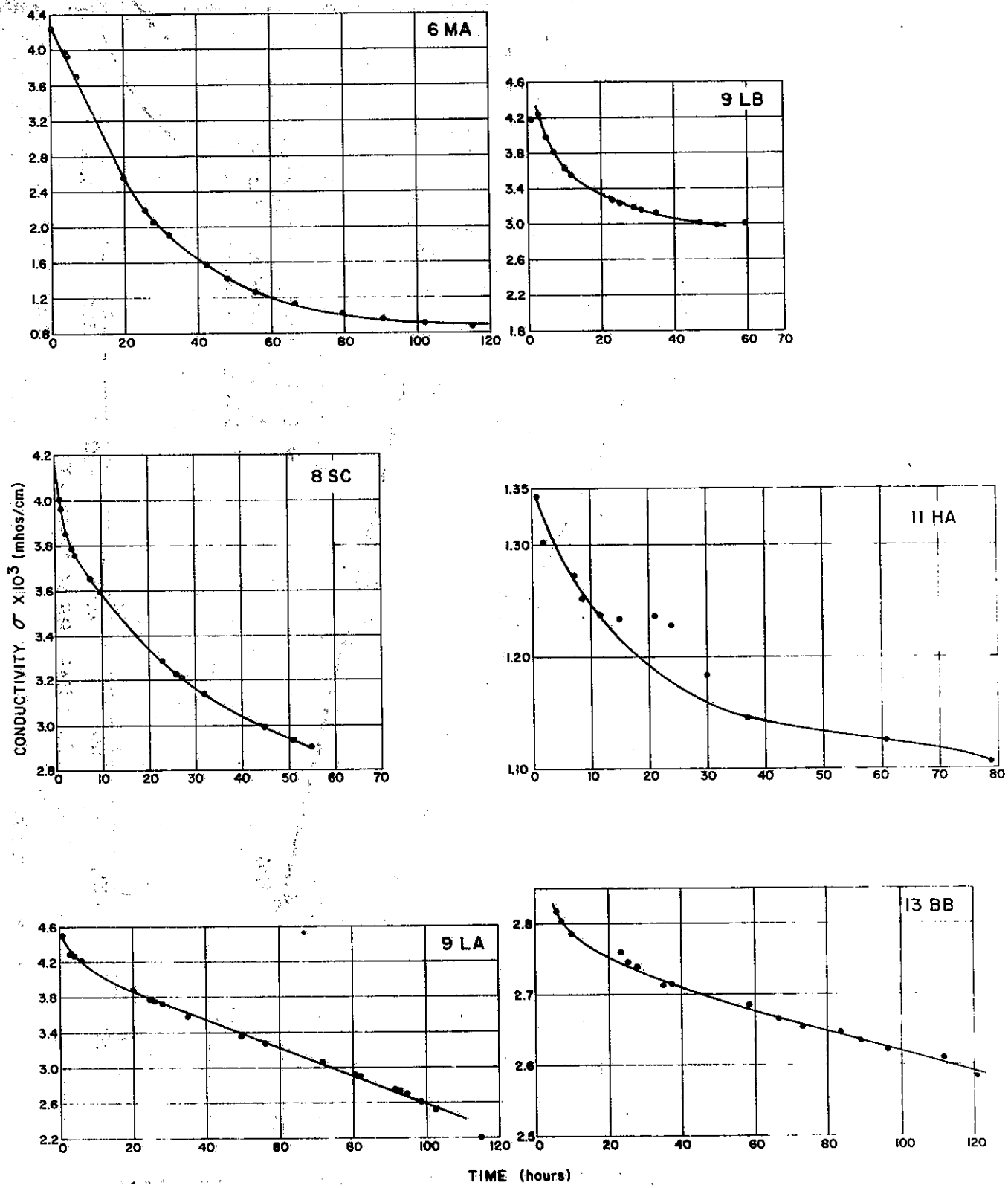
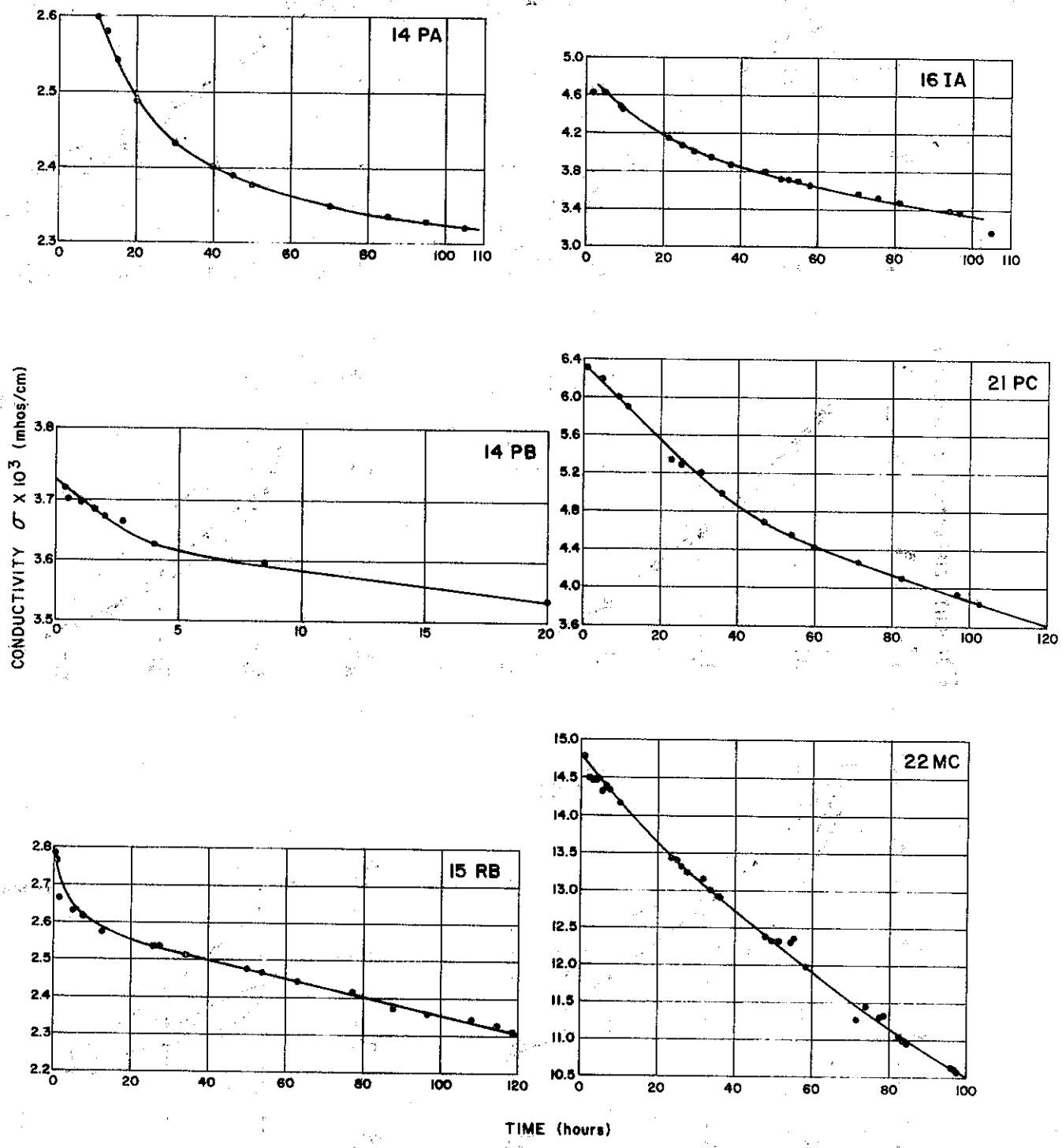


Fig. 31 % LIME REACTIVITY VS CHANGE IN CONDUCTIVITY



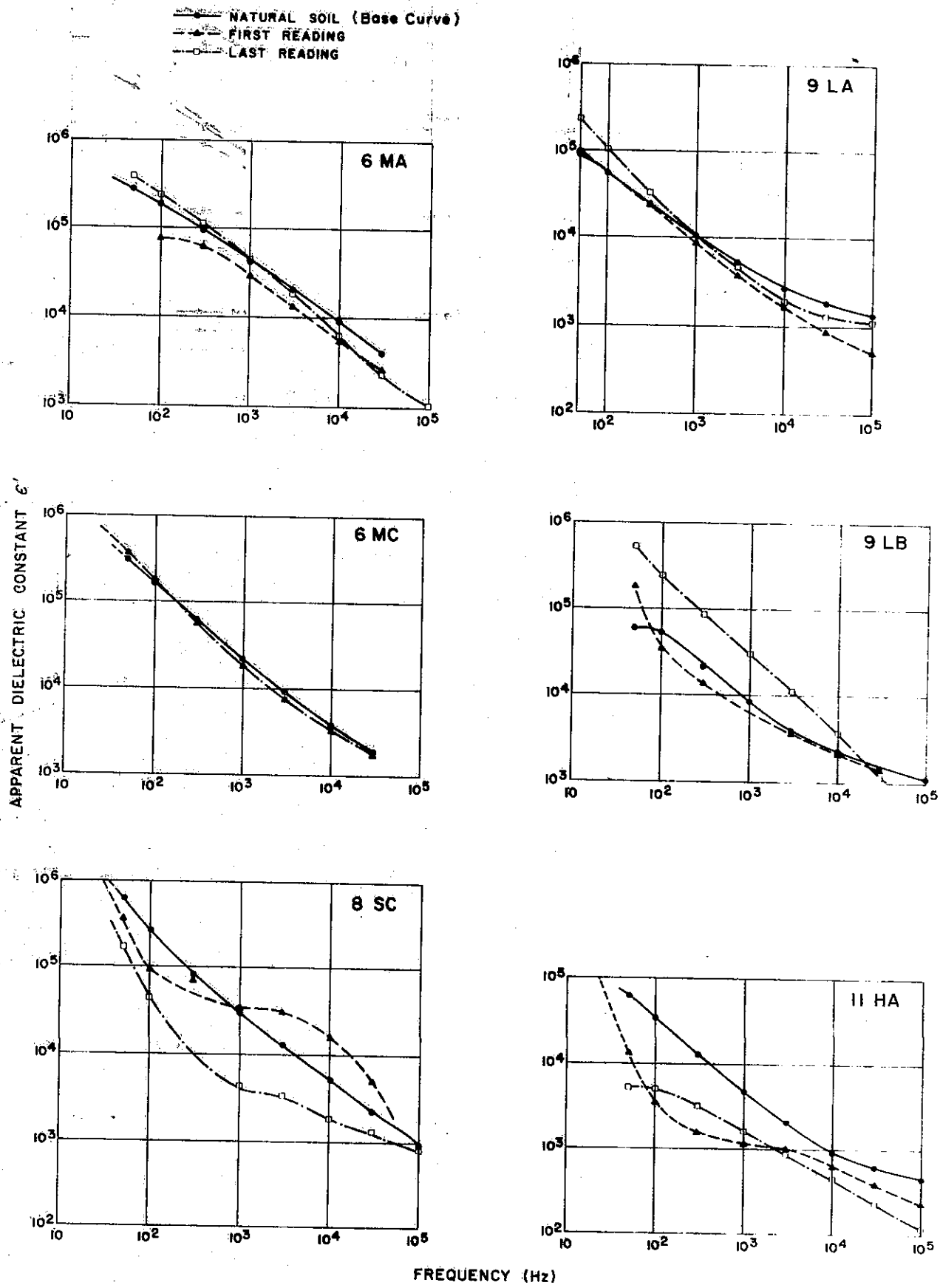
FROM: ARULANANDAN & SHEN (4)

Fig. 32a: CONDUCTIVITY VS TIME FOR SOIL WITH 5% LIME IN PASTE FORM



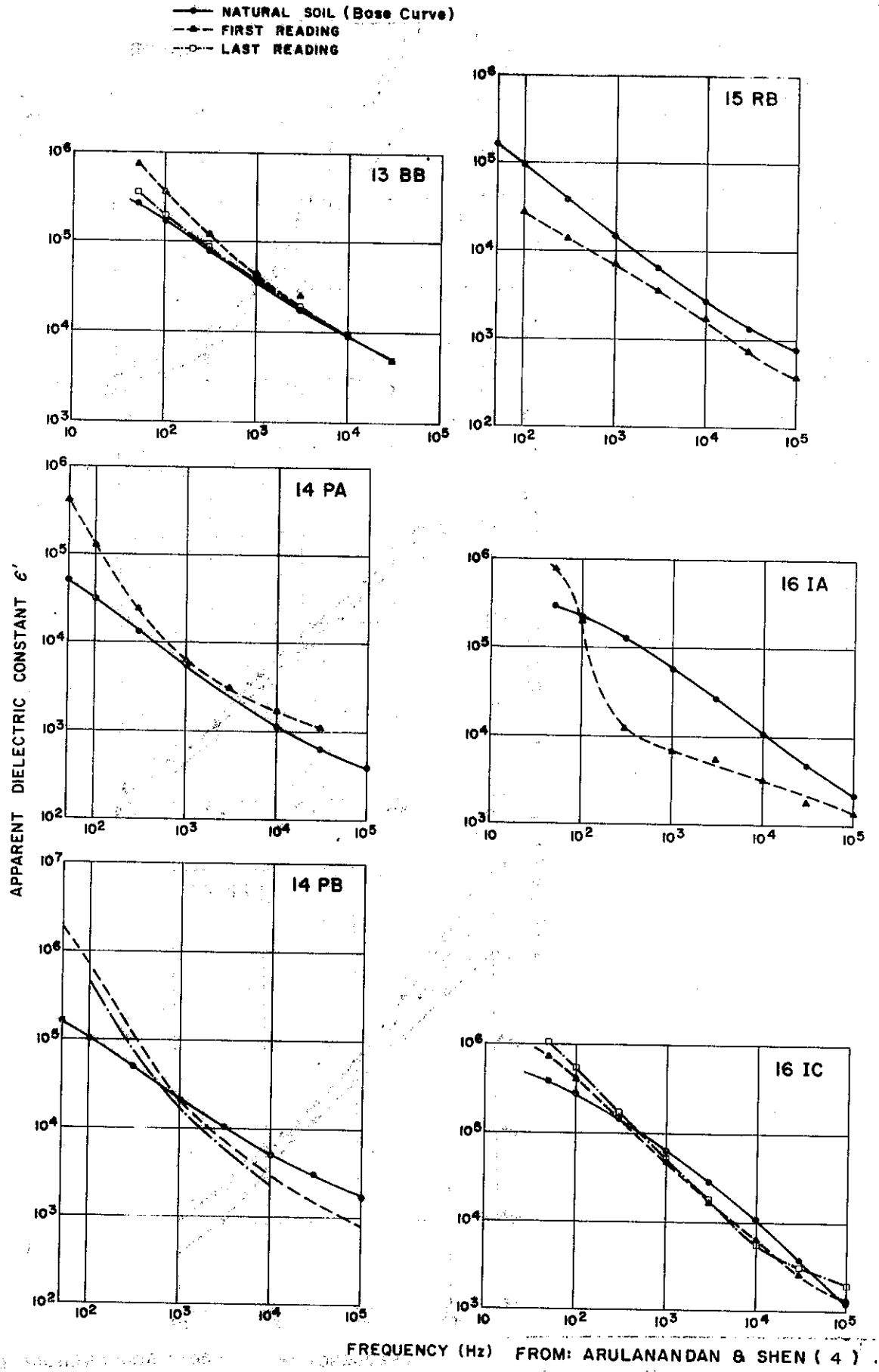
FROM: ARULANANDAN & SHEN (4)

Fig. 32b CONDUCTIVITY VS TIME FOR SOIL WITH 5% LIME IN PASTE FORM



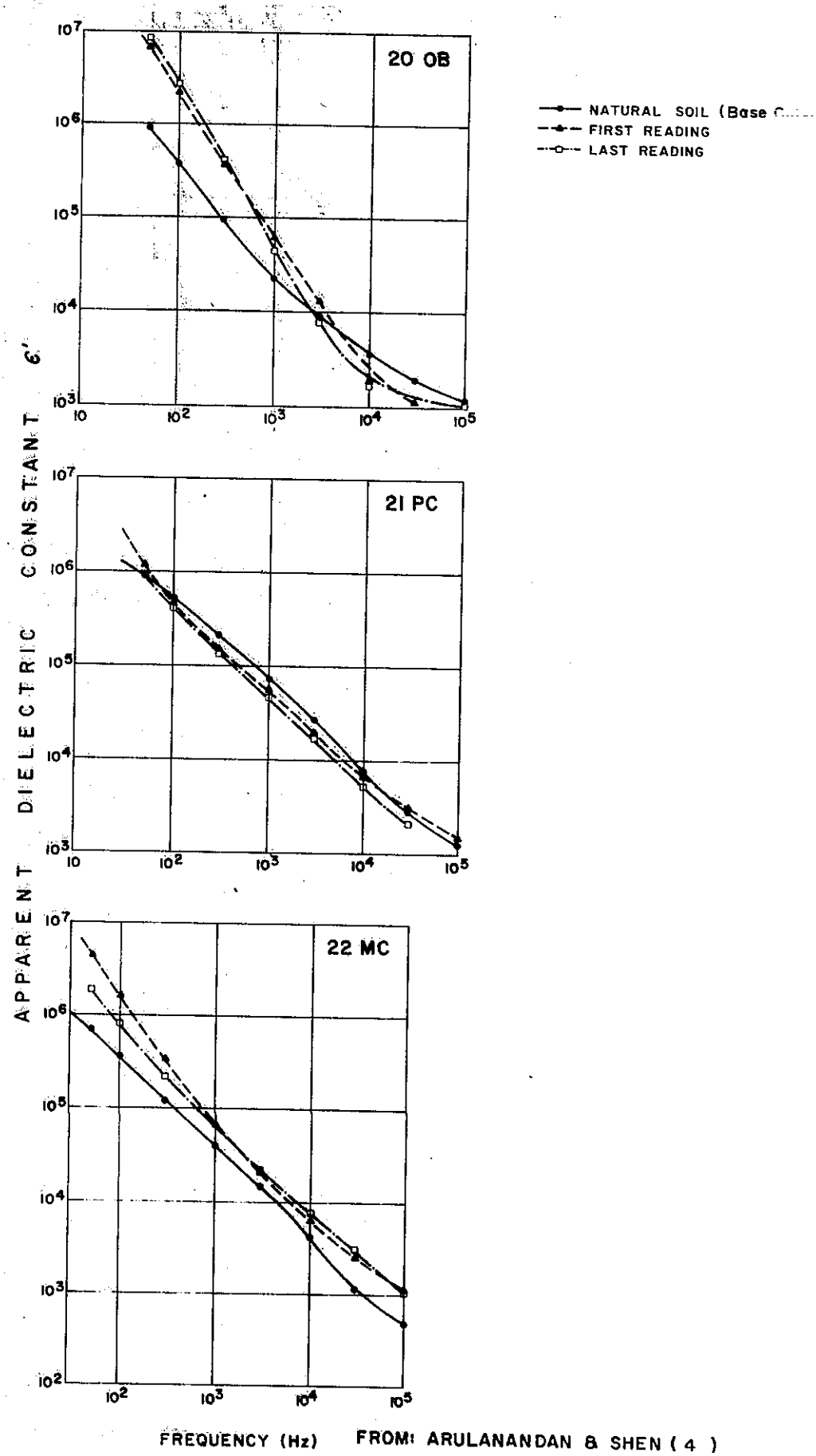
FROM: ARULANANDAN & SHEN (4)

Fig.33a DIELECTRIC DISPERSION CHARACTERISTICS OF THE NATURAL SOILS AND THE LIME TREATED SOILS AS A FUNCTION OF FREQUENCY IN PASTE FORM



FROM: ARULANANDAN & SHEN (4)

Fig. 33b DIELECTRIC DISPERSION CHARACTERISTICS OF THE NATURAL SOILS AND THE LIME TREATED SOILS AS A FUNCTION OF FREQUENCY IN PASTE FORM



FROM: ARULANANDAN & SHEN (4)

Fig. 33c DIELECTRIC DISPERSION CHARACTERISTICS OF THE NATURAL SOILS AND THE LIME TREATED SOILS AS A FUNCTION OF FREQUENCY IN PASTE FORM

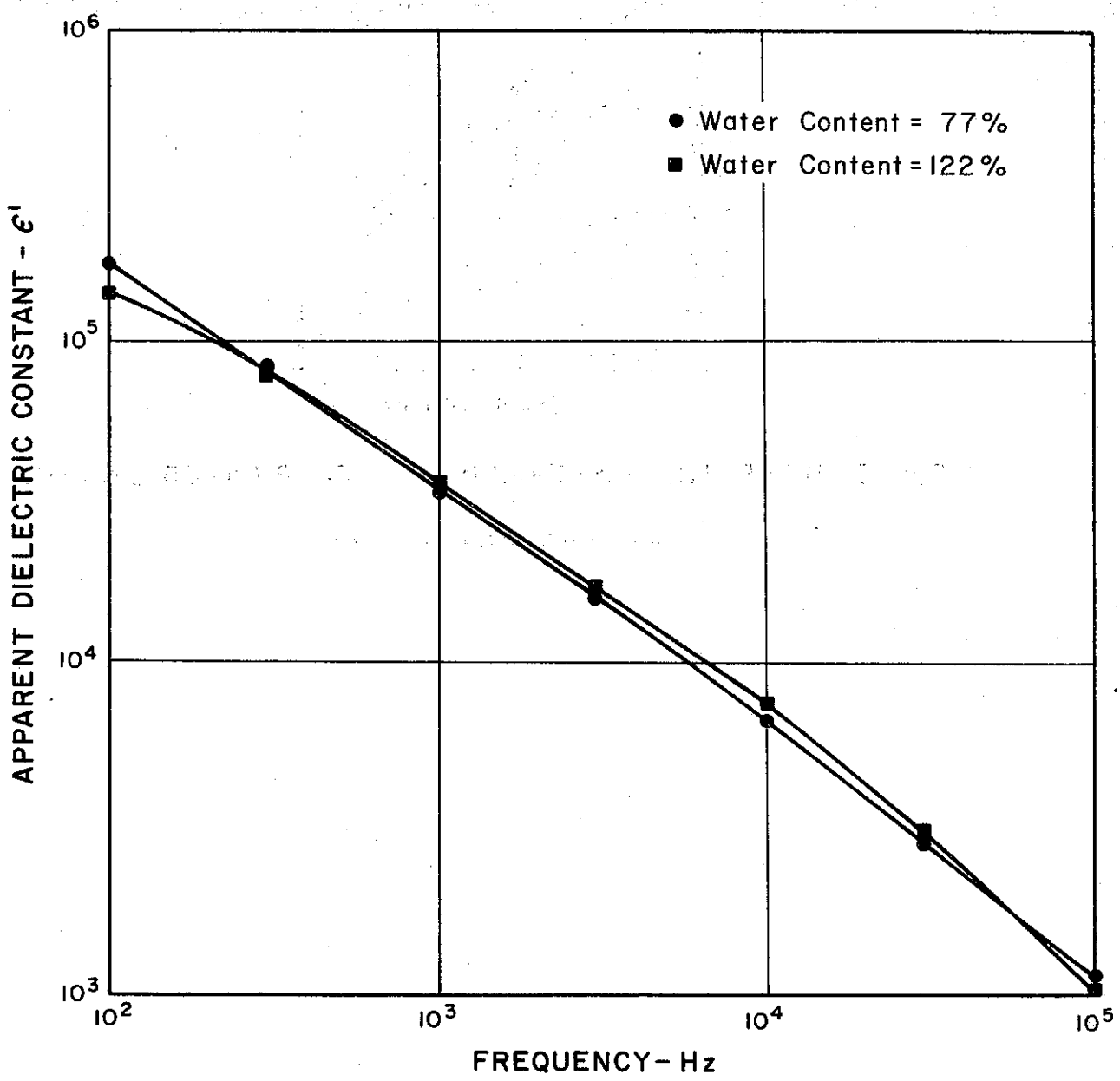


Fig. 34 Dielectric Dispersion of 3-S-A Natural Soil

FROM: SHEN & ARULANANDAN (44)

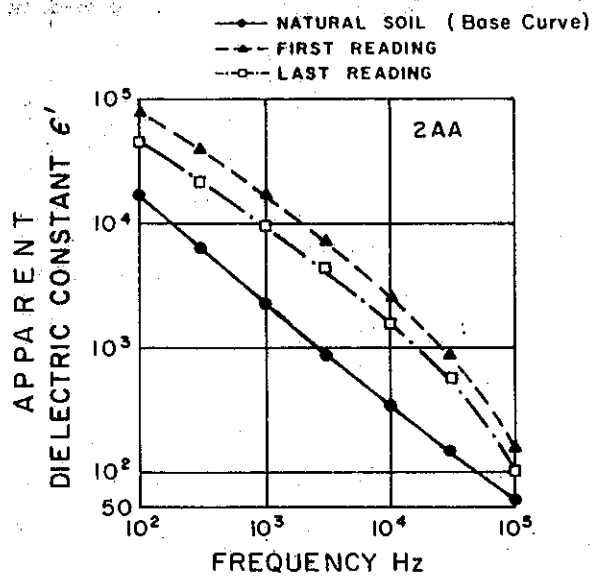


Fig. 35 DIELECTRIC DISPERSION OF A FABRICATED SPECIMEN

FROM: SHEN & ARULANANDAN (44)

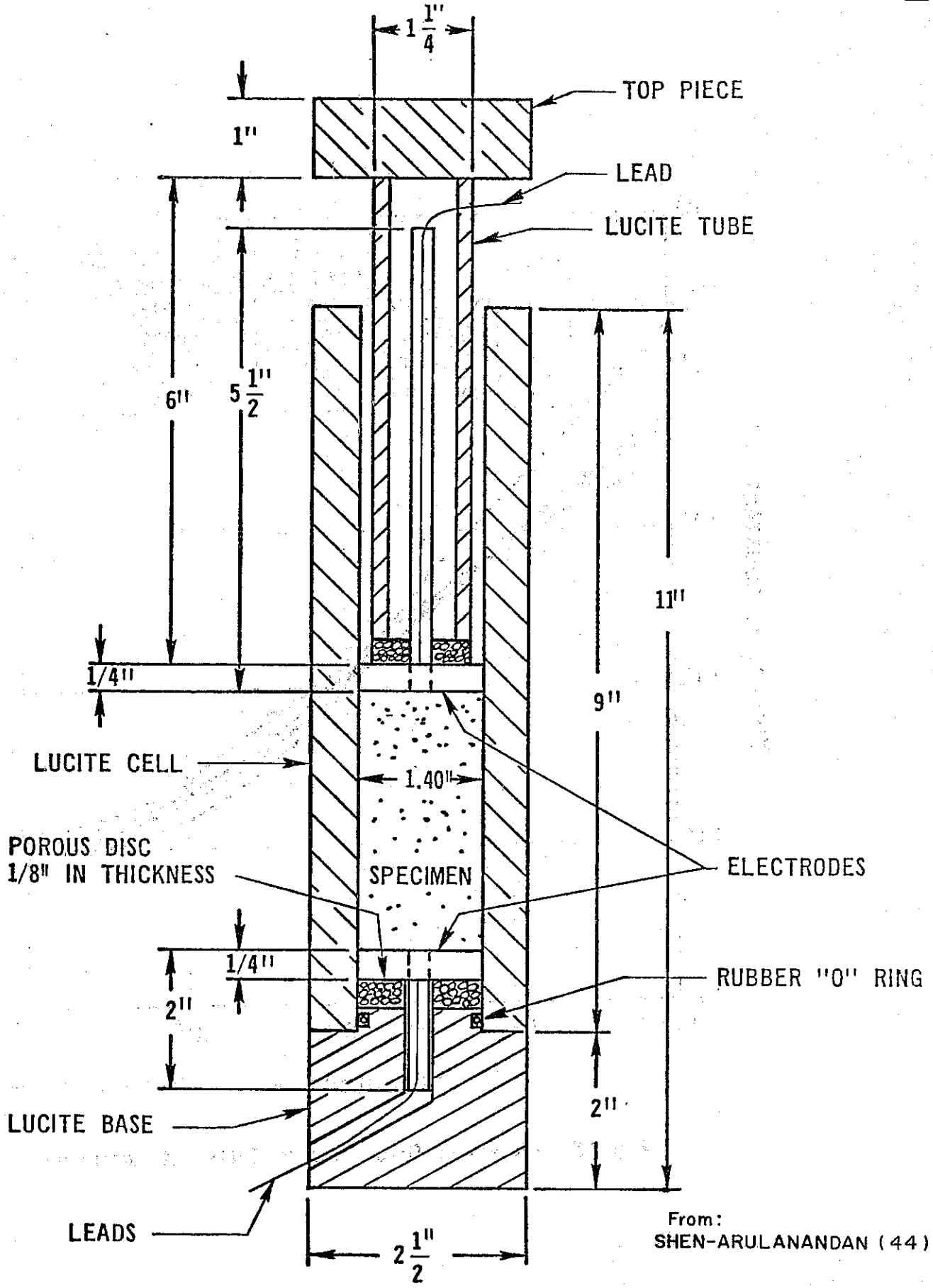
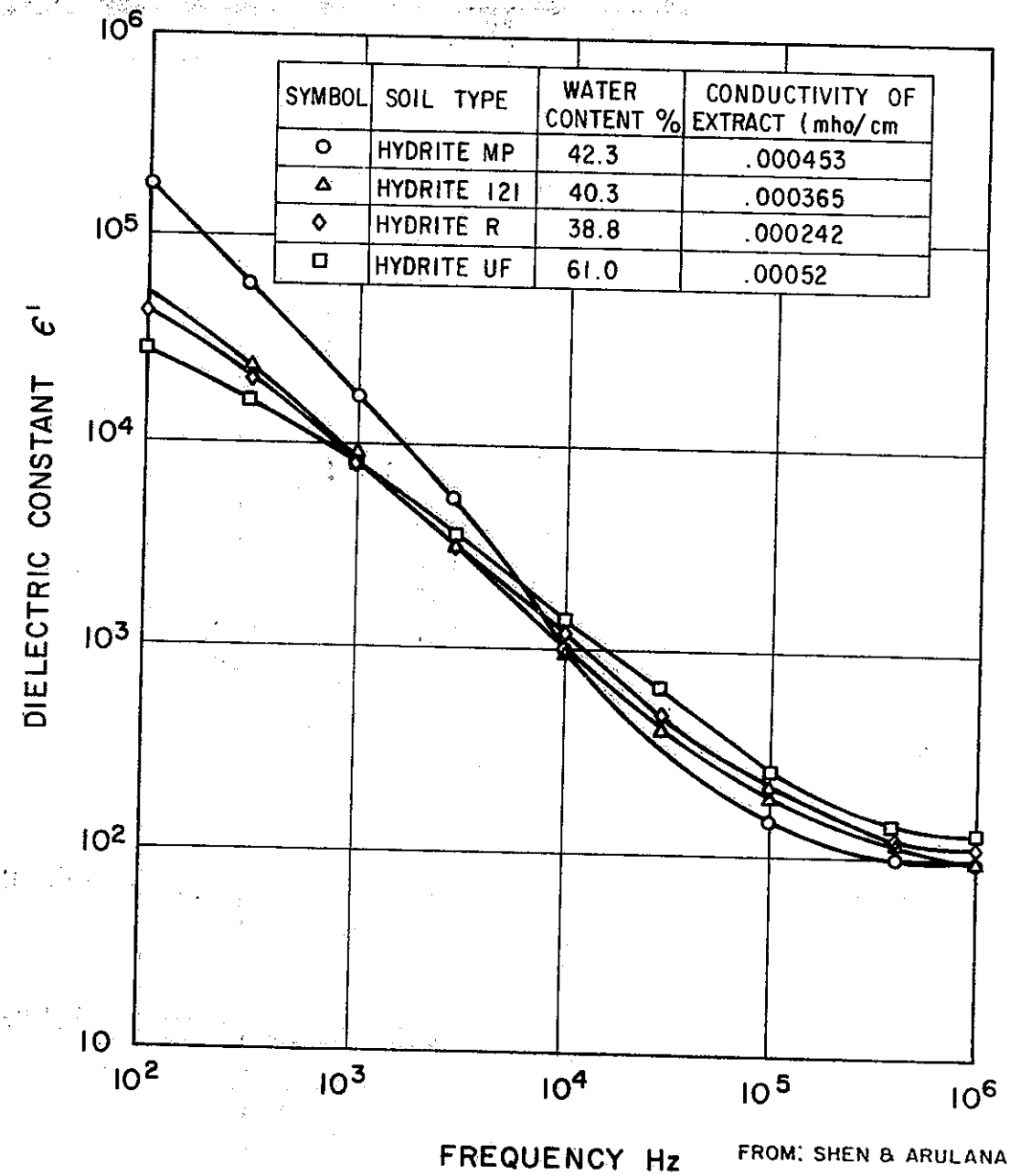


Fig. 36 ELECTRICAL RESPONSE MEASURING APPARATUS FOR PASTE FORM SPECIMENS



FROM: SHEN & ARULANANDAN (44)

Fig. 37 Dielectric Dispersion of Different Kaolinites

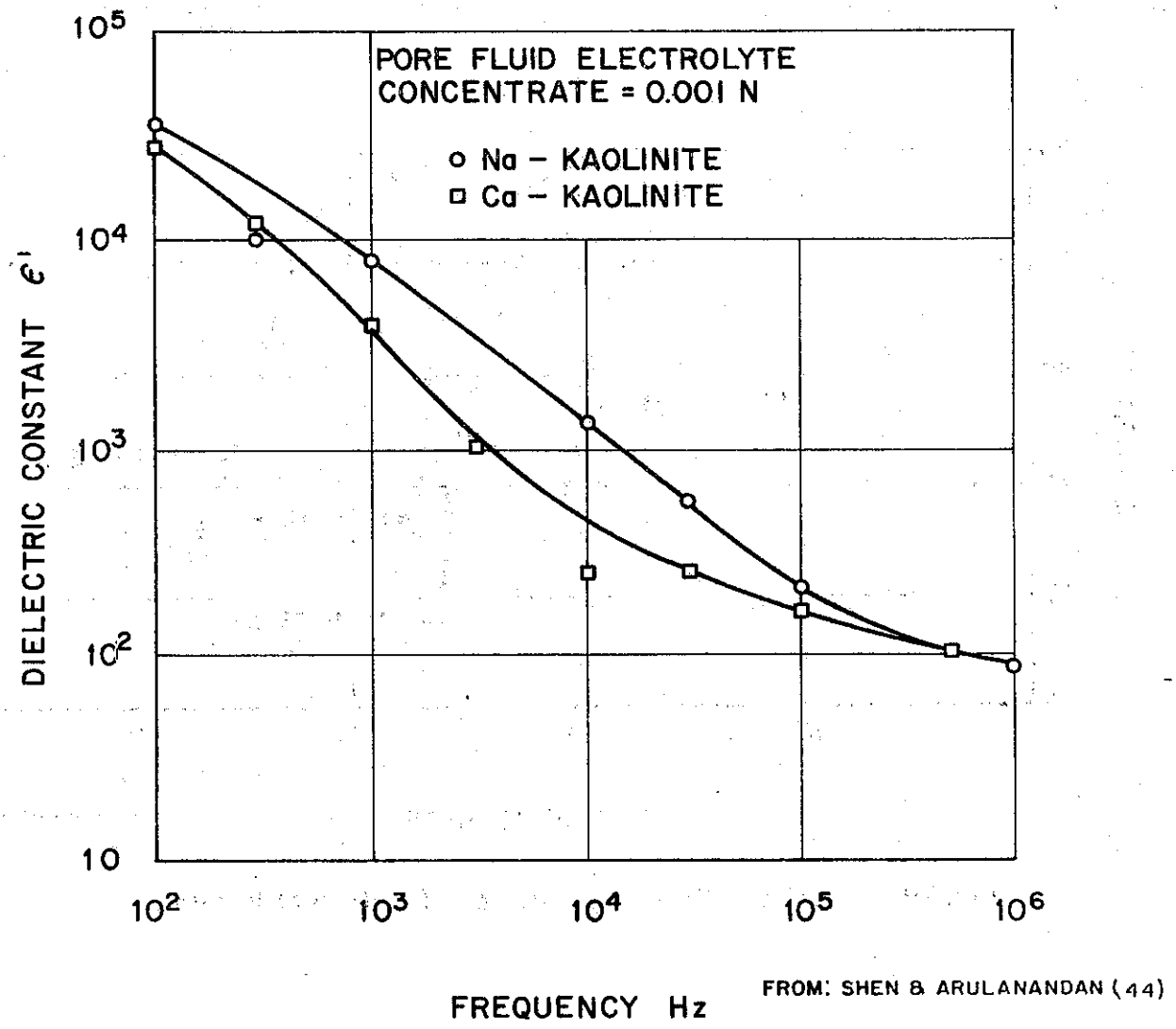
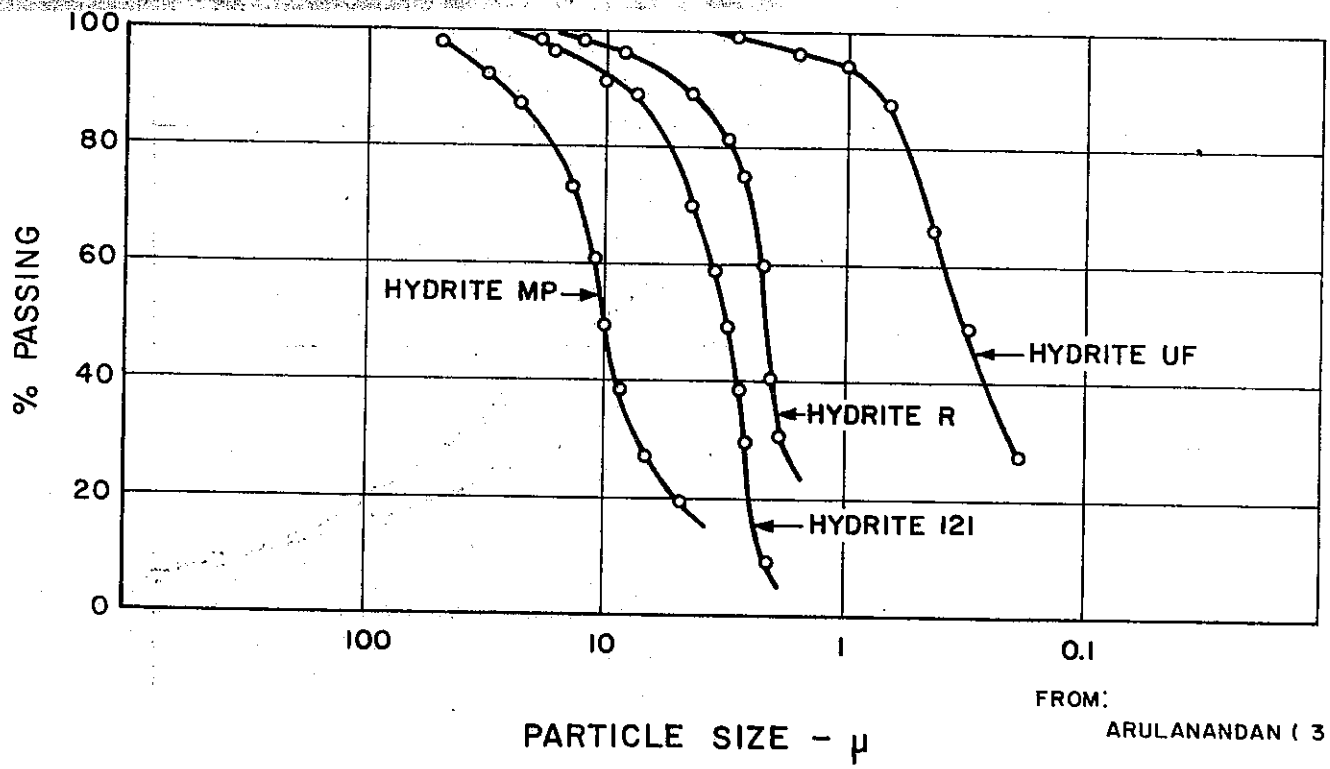


Fig. 38 Dielectric Dispersion of Ca and Na Kaolinites



FROM:
ARULANANDAN (3)

Fig. 39 Particle Size Distribution of Different Kaolinites

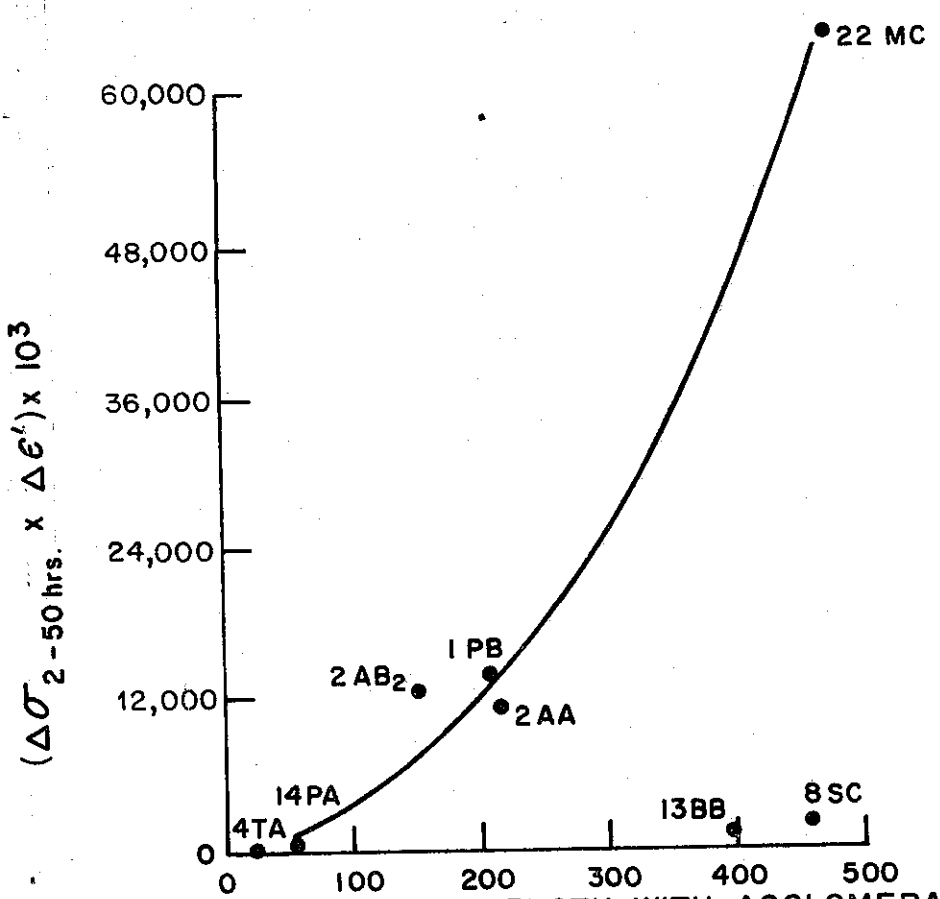


Fig. 40a DEVELOPED STRENGTH WITH AGGLOMERATION REACTION
6 MONTH CURE - 5% LIME - PSI

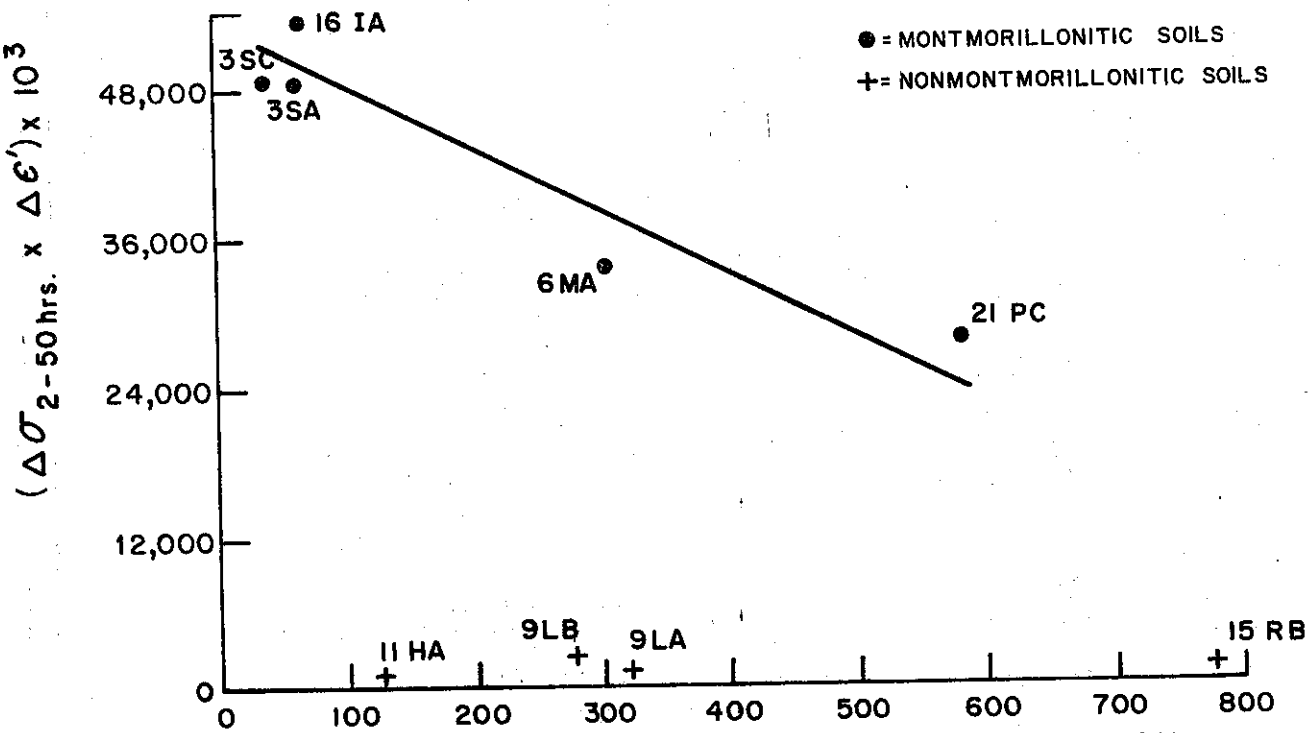


Fig. 40b DEVELOPED STRENGTH WITH ADSORPTION REACTION
6 MONTH CURE - 5% LIME - PSI

Fig. 40 Electrical Response Characteristics vs Developed Compressive Strength.

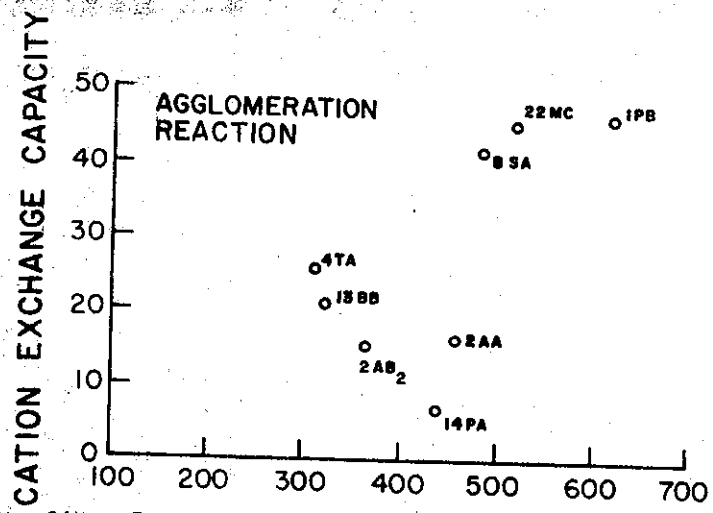


Fig.41a CALCULATED SURFACE AREA sq. cm per gram

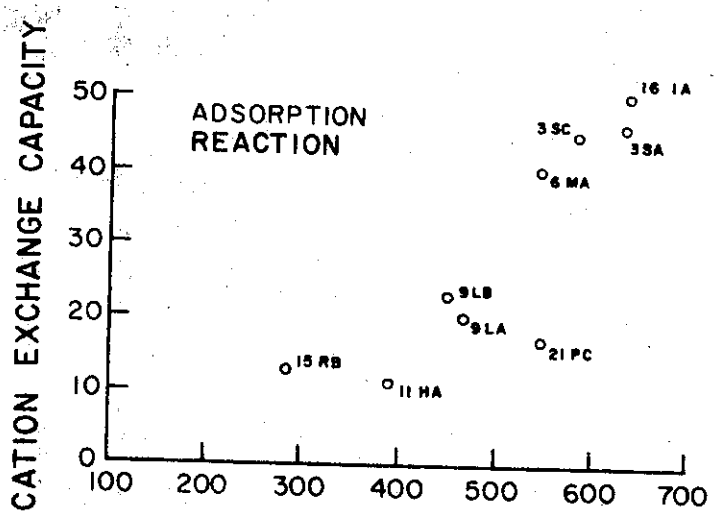


Fig.41b CALCULATED SURFACE AREA sq. cm per gram

Fig. 41 CATION EXCHANGE CAPACITY AS A FUNCTION OF SURFACE AREA

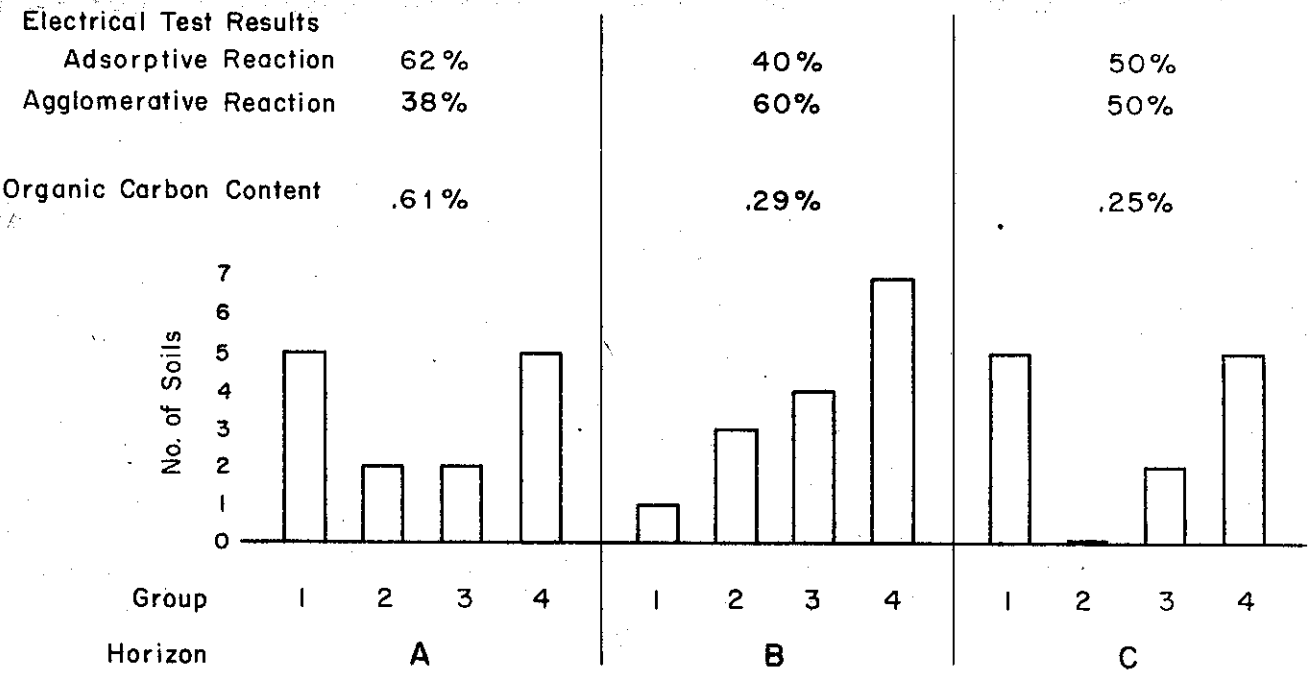


Fig. 42 SOIL HORIZONS SHOWING THE LIME-SOIL REACTIVITY GROUPS WITH THE MEAN VALVES OF THE ORGANIC CARBON CONTENT. (NOTE THAT THE "A" HORIZON SOILS REACTION WITH LIME IS LARGELY "ADSORPTIVE" WHILE THE "B" HORIZON SOILS ARE LARGELY "AGGLOMERATIVE".)

TABLE 1 SOIL SITE LOCATIONS

Soil Series	General Location	Particular Locations
1 Pescadero	SE of Woodland near Co. Road 102. Yolo Co.	0.3 mi. S of Co. Road 24 intersection thence 0.2± mile E in pasture of J. P. Brauner Ranch
2 Akin	Approx. 10 mi. E of Fiddletown. Amador Co.	0.2 mi. W of jct. State Rte. 88 and Fiddletown - Silver Lake Rd. 0.12 mi. NE of Center Sec 34, T8N, R13E, MDM on the Rd. ROW next to the Allen Ranch
3 Sacramento	About 2.5 miles NW of Knights Landing. Yolo Co.	150± N of the intersection of State Rte. 45 and Co. Rd. 112
4 Tournquist	NW of Alturas. Modoc Co.	NW 1/4 of NW 1/2 Sec 33, T4N, R11E, MDM and 402' E of line tag between Sec 32 and 33
5 Casuse	1-3/4 mi. SW of Alturas. Modoc Co.	1130' E of west side Rd. 190' W of E boundary fence line, 630' N of S boundary fence line
6 Montague	Easterly of Yreka. Siskiyou Co.	1660' N of where Montague Ditch crosses County Airport Rd., on the Lipert Ranch
7 Chualar	S of Salinas and E of Chualar. Monterey Co.	0.45 mi. on Chualar Rd. from Old Stage Rd. to pumphouse on N side of Rd., 830' NW on dirt Rd., thence 20' NE into field
8 Salinas	5.5 N of King City on Metz Rd. Monterey Co.	On Nello Salaris Ranch, W of Stockyard approx. 50'
9 Lockwood	NW of King City. Monterey Co.	7 mi. NW of King City on Central Ave., 100' SE and 50' NW from the intersection of Teague and Central Ave.
10 Vista	Approx. 2-1/2 mi. SE of Fallbrook. San Diego Co.	0.4 E of S Main St. in Fallbrook, along Winterhaven Rd., thence N 430± along an oiled road which forms the boundary between Fallbrook Hi School Compus and Dr. Edward Ames Orchard, thence E 35' into Dr. Ames Orchard

TABLE 1 (continued)

11 Huerhuero	Camp Pendleton. San Diego Co.	In Camp Pendleton, 800' E of 15, 1200' N of Stuart Mesa O.C. 100' W of Mesa Rd (near Phillips St.)
12 Fallbrook	Near Fallbrook High School near the town of Fallbrook. San Diego Co.	Located on Dr. Ames Orchard, about 350' from Winterhaven Rd. and approx. 33' from a side orchard rd.
13 Bonsall	Near Fallbrook High School near the town of Fallbrook. San Diego Co.	0.4 mi. E of S Main St. in Fallbrook, along Winterhaven Rd., near Fallbrook High School
14 Placentia	At Temecular on St Rte 7.. Riverside Co.	Near intersection of US 395 and State Rte 71, 60'± W of US 395 Sta 197+50
15 Ramona	NE of Riverside.	From Riverside proceed E on State Rt 60 to intersection with Hendrix Rd. thence N along Hendrix Rd to Ironwood St, thence .25 mi beyond Ironwood St. on E side of Hendrix Rd.
16 Imperial	3.5 mi. E of Brawley. Imperial Co.	From E Main St. (Brawley) 3.5 mi N along Best Canal, W 0.2 mi on Best Lateral #1 to gate 116-AA
17 Mecca	4 mi. S of Indio. Riverside Co.	1320' N, 20' W of SE Cor Sec 14, T6S, R7E, SBM, about 4 mi. S of Indio
18 Hesperia	E. of Lancaster. Los Angeles Co.	NE 1/4 of the SE 1/4, Sec 8, T5N, R10W, SBM
19 Adelanto	W. of Lancaster. Los Angeles Co.	NE 1/4 of the SE 1/4 Sec 6, T6N, R12W, MDB at the intersection of Ave. M8 & 37 St. W.
20 Oban	N of Lancaster. Los Angeles Co.	72' W of 22nd St W & 0.2 mi S of Ave D. NE 1/4, NE 1/4, Sec 20, R12W, T8N, SBM
21 Panoche	NW of Bakersfield. Kern Co.	About 2 mi. E of Blackwell Corner (NE 1/4 of the NE 1/4 of Sec 3, T27S, R19E, MDM)
22 Merced	West of Bakersfield and 8 mi. SW of Lost Hills. Kern Co.	Along the side of a silo pit of Blue Moon Ranch located in the NE 1/4 of the NE 1/4 of the SE 1/4 of Sec 10, MDM

TABLE NO. 2a Engineering Properties of the soils used in this study

Soil Symbol[1]	Depth in inches (Sampled)	Sand %	Silt %	Clay %	Colloid %	Soil Classification California Dept. of Transportation Grain Size*	Field Log[4]	Unified System	SE**	Atterberg Limits LL	PL	PI	Impact Compaction Test #/cf Max. Density	% Opt. Moisture****	q_u *** psi	R-Value	Drainage[3]
1PB	10-65	9	33	58	39	Cl	sSiCl	CH	nil	54	19	35	115	15	15	90	5	6
1PC	70-90	19	50	31	19	SiCl	ClSi	CL	3	33	18	15	118	14	15	72	16	
2AA	4-20	33	29	38	27	Cl	SdCl	ML	9	39	26	13	96	27	28	54	45	3
$2AB_1$	24-59	25	32	43	32	"	sSdCl	"	9	45	32	13	92	30	32	51		
$2AB_2$	59-75	45	27	28	17	SdCl	"	"	15	43	35	8	88	30	31	66	(72)	
3SA	7-48	9	37	54	22	Cl	sSiCl	MH	7	59	33	26	97	26		55	10	5
3SC	53-77	11	38	51	20	"	Cl	"	9	66	38	28	92	26	27	63	15	
4TA	4-14	60	25	15	3	SiSd	sClSd	SM	16			NP	103	21	22	41	55	3
4TB	14-34	50	30	20	9	ClSiSd	ClSd	CL-ML	13	28	22	6	107	19	20	56	16	
4TC	34-45	44	37	19	6	"	SdCl	ML	12	32	28	4	99	27	28	37	33	
5CB	3-10	46	28	26	15	SdCl	sSdCl	CL	11	34	22	12	106	19	20	66	6	3
6MA	6-24	19	30	51	26	"	sSiCl	CH	2	60	26	34	102	22	23	62	11	3
6MC	24-36	74	20	6	1	SiSd	Sd	SM	25			NP	87	30	31	24	77	6
7CA	7-21	71	17	12	6	"	"	"	22	17	15	2	135	7	8	23	58	3
7CB	21-59	78	14	8	6	"	"	"	25			NP	135	8	8	10	81	
7CC	59-80	94	4	2	1	Sd	"	SP	38			NP	115	9	10	1	76	
8SA	5-23	29	45	26	16	SiCl	ClSi	CL	4	32	21	11	113	15	16	40	19	4
8SC	23-82	46	39	15	8	ClSiSd	sClSi	ML	7	29	25	4	111	16	17	19	65	
9LA	8-30	31	45	24	13	ClSi & Sd	ClSd	"	9	32	28	4	94	25	25	37	55	3
9LB	40-82	32	43	25	17	"	"	"	9	35	26	9	94	26	27	31	29	
10VB	10-34	78	13	9	4	SiSd	Sd	SM	22			NP	132	10	11	9	68	2
10VC	34-55	84	12	4	2	"	"	"	38			NP	124	11	12	6	75	
11HA	0-10	46	38	16	5	ClSiSd	SdCl	ML	12			NP	126	9	10	28	74	4
11HB	12-36	37	31	32	23	SdCl	"	CL	9	28	14	14	122	13	14	42	11	
12FB	18-30	67	17	16	10	ClSd	sClSd	SM	20	24	21	3	130	10	11	22	26	3
13BB	10-30	57	20	23	15	"	"	SC	14	26	16	10	127	9	9	66	12	4
14PA	3-12	43	46	11	5	Si & Sd	"	ML	10			NP	120	12	12	7	80	3
14PB	20-30	32	39	29	22	SiCl	sSiCl	CL	5	28	16	12	122	13	14	37	15	
15RA	3-12	62	22	16	11	ClSd	sClSd	SM	15	20	17	3	135	9	9	20	37	3
15RB	24-48	64	21	15	8	"	ClSd	SC-SM	15	25	20	5	132	9	9	39	25	
16IA	4-10	2	28	70	58	Cl	Cl	CH	1	57	24	33	110	18	18	60	12	3
16IC	18-40	1	31	68	f	"	"	"	1	56	24	32	108	19	19	50	10	
17MC	12-33	68	27	5	3	SiSd	Si	SM	21			NP	103	17	17	4	63	3
18HC	12-60	83	11	6	4	"	Sd	"	29			NP	128	10	10	5	80	3
19AA	6-24	84	11	5	f	"	"	"	34			NP	119	10	11	4	81	3
19AB	33-62	74	14	12	8	"	SdCl	"	16			NP	130	10	11	13	71	
200B	18-28	55	14	31	22	SiCl	ClSd	SC	6	39	16	23	122	12	13	59	4	6
21PA	6-20	18	38	44	21	Cl	SiCl	ML	3	34	23	11	106	18	20	60	10	(2)
21PC	20-44	18	49	33	f	SiCl	sSiCl	"	3	38	22	16	106	18	19	60	18	
22MA	4-17	27	37	36	21	"	SiCl	"	5	36	21	15	110	16	17	51	11	(6)
22MC	22-48	34	35	31	21	"	"	"	2	37	18	19	117	14	15	41	15	

[1]See Table No. 3
[2]$B_1 + B_2$ Horizon
[3]Drainage 1 = Excessively drained.....7 = Very poorly drained. See Glossary.
[4]Determined by manual manipulation of the soil. s=slightly

*Sand 53-2380μ, Silt 5-53μ, Clay <5μ, Colloid <1μ. f=floc
**SE = Sand Equivalent. An indicator of the detrimental effect of clay-like materials.
***Unconfined Compression Test 90% Rel. Compaction at Optimum Moisture.

****Moisture content of fabricated specimens.

TABLE NO. 2b CHEMICAL PROPERTIES OF THE SOILS USED IN THIS STUDY

Soil	** pH	CEC	% Base Saturation	** Ca/Mg	Exchangeable Ions Milliequivalents Per 100 Grams Ca	Mg	Na	K	H	% Iron as Fe Total	Coating *	% Magnetic Mat'l.	% Organic Carbon	% $SO_4^{=}$	% $CO_3^{=}$	% Cl
1PB	9.3	47.4	97	.91	5.0	5.5	35.2	.4	1.3	5.0	1.1	0	.4	.16	0	0
1PC	8.0	26.4	100	.69	10.0	14.4	1.6	.4	0	5.0	.8	.4	.1	0	1.5	.1
2AA	5.7	15.5	35	3.9	3.9	1.0	0	.6	10.0	8.8	3.3	0	.8	0	0	0
$2AB_1$	5.8	10.4	0	n	0	0	0	0	10.4	9.1	3.3	10.1	.2	.02	0	.2
$2AB_2$	5.2	14.7	7	.8	.4	.5	0	.2	13.6	8.7	2.7	0	.3	0	0	0
3SA	7.6	46.5	91	2.55	27.8	10.9	2.9	.8	4.1	6.1	1.3	0	.8	0	0	0
3SC	7.5	44.6	91	.98	18.9	19.3	1.9	.4	4.1	5.0	1.4	0	.7	0	.1	.1
4TA	6.3	26	57	2.74	9.6	3.5	.3	1.3	11.3	8.5	4.8	2.4	1.6	0	.1	.1
4TB	6.1	31.6	68	.63	7.8	12.4	.3	1.1	10.0	9.0	5.2	3.2	1.0	0	.1	.1
4TC	6.8	26	52	1.42	7.1	5.0	0	2.1	12.4	11.5	5.8	2.1	.3	.04	0	.2
5CB	6.7	32	86	2.86	14.3	5.0	0	2.1	4.5	6.3	.8	4.6	.8	.06	0	.1
6MA	6.8	39.6	94	.85	16.0	18.8	1.0	1.3	2.5	3.5	.4	1.0	.5	0	0	0
6MC	8.1	24	87	4.07	60.6	14.9	0	0	3.2	2.9	.1	.7	.4	.15	15.1	.1
7CA	7.8	9	84	c	7.1	0	0	0	1.4	2.3	.3	.2	.5	.05	.1	0
7CB	8.1	4.1	88	c	3.6	0	0	0	.5	1.9	.3	.1	.1	.04	0	0
7CC	8.4	4.6	100	2.1	2.1	1.0	1.3	.2	0	1.7	.2	0	0	.12	0	0
8SA	7.5	23.6	98	2.56	12.8	5.0	3.2	2.1	.5	2.9	.6	.3	1.1	0	.1	.1
8SC	8.2	41.6	100	2.88	28.5	9.9	3.2	0	0	3.4	.5	.3	.3	0	1.1	.1
9LA	7.0	19.9	86	2.02	10.1	5.0	0	2.1	2.7	1.7	.4	.1	1.0	0	.1	.1
9LB	7.3	22.7	90	2.02	10.1	5.0	3.2	2.1	2.3	3.1	.5	.2	.3	.02	.1	0
10VB	7.2	11	92	c	10.1	0	0	0	.9	4.7	.4	1.1	.3	0	.1	0
10VC	8.1	12.3	93	1.42	5.7	4.0	1.6	.2	.8	6.2	.4	.4	0	.02	.1	0
11HA	6.1	11.4	64	3.6	3.6	1.0	.6	2.1	4.1	4.1	1.4	.4	.5	.03	.1	0
11HB	7.7	21	83	1.42	7.1	5.0	3.2	2.1	3.6	4.8	1.6	.2	.3	.02	.1	0
12FB	6.4	11	63	1.77	5.3	3.0	.6	.2	4.1	5.3	.5	.5	0	.02	.3	0
13BB	7.4	21.0	89	2.02	10.1	5.0	3.2	.4	2.3	4.6	.3	.5	.3	0	0	0
14PA	6.0	7.1	68	3.6	3.6	1.0	.6	.4	2.3	3.1	.2	0	.4	.03	.1	0
14PB	8.5	14	96	2.86	14.3	5.0	3.2	.4	.5	2.5	.2	0	.2	.01	.3	0
15RA	7.0	7	87	7.1	7.1	1.0	.6	2.1	.9	3.8	.2	.3	.1	0	.3	0
15RB	7.9	13.1	100	1.42	7.1	5.0	.6	.4	0	5.1	.2	.2	0	.02	0	0
16IA	8.0	50.6	100	3.24	32.1	9.9	6.5	2.1	0	3.1	.3	0	.5	.31	9.0	.1
16IC	8.1	50.2	100	2.88	28.5	9.9	9.7	2.1	0	3.8	.2	0	.3	1.03	8.0	.1
17MC	8.7	22.5	100	7.12	17.8	2.5	1.6	.6	0	4.6	.1	.2	.2	.02	.5	0
18HC	8.8	6.7	100	4.3	4.3	1.0	1.0	.4	0	4.9	.3	.4	0	.02	.1	0
19AA	8.6	7.3	84	3.9	3.9	1.0	.6	.6	1.2	3.1	.3	.3	.1	.05	0	0
19AB	8.5	9.1	87	3.8	5.7	1.5	.3	.4	1.2	4.1	.5	.3	0	.01	0	0
20OB	9.5	72.7	100	.72	21.4	29.8	19.4	2.1	0	1.7	.1	.2	.2	.02	4.1	.1
21PA	8.5	41.3	100	4.95	31.7	6.4	1.9	1.3	0	5.7	.8	0	.5	.04	1.4	0
21PC	8.2	17.2	100	.72	3.6	5.0	6.5	2.1	0	5.1	.8	.1	.4	.39	1.9	.1
22MA	7.8	30.7	100	2.09	19.6	9.4	.6	1.1	0	4.8	.3	0	.6	.02	.9	.1
22MC	9.1	45.8	100	3.56	17.8	5.0	22.6	.4	0	1.7	.1	0	.3	.82	7.0	.1

*By Dithionite-citrate method
**Poorly drained soils have generally high Ca/Mg, and high pH
n = no calcium or magnesium present
c = calcium present but no magnesium

TABLE NO, 3 U.S. Dept. of Agriculture Soil Conservation Service Classification of Soils Used in This Study

Soil Symbol	Soil Series	Horizons	Parent Material*	Family**	Subgroup	Order	County
1P	Pescadero	B,C	alluvium (sed)	fine, montmorillonitic, thermic	Aquic Natrixoralfs	Alfisol	Yolo
2A	Aiken[1]	A,B_1,B_2	andesitic cong	clayey, Kaolinitic, mesic	Xeric Palehumults	Ultisol	Amador
3S	Sacramento	A,C	alluvium (mixed fine)	" " "	Vertic Haplaquolls	Mollisols	Yolo
4T	Tourniquist[1]	A,B,C	reddish mudflow	" loamy, mixed, frigid	Typic Eutrandepts	Alfisol-Mollisol	Modoc
5C	Casuse	B	pumice tuff	loamy, mixed, mesic	Aridic Argixerolls	Mollisol	"
6M	Montague[1]	A,C	alluvium (basic igne)	fine, montmorillonitic, mesic	Typic Chromoxerts	Vertisol	Siskiyou
7C	Chualar[1]	A,B,C	" (granitic)	" loamy, mixed, thermic	" Argixerolls	Alfisol-Mollisol	Monterey
8S	Salinas[1]	A,C	" (sed)	" " " "	Pachic Haploxerolls	Mollisol	"
9L	Lockwood[1]	A,B	" (diat. shale)	" " " "	Typic Argixerolls	"	"
10V	Vista[1]	B,C	granodiorite	coarse loamy, mixed, thermic	" Xerochrepts	Alfisol	San Diego
11H	Huerhuero	A,B	sandy marine sed.	fine, montmorillonitic, thermic	" Natrixeralfs	"	"
12F	Fallbrook[1]	B	granodiorite	" loamy, mixed, thermic	" Haploxeralfs	"	"
13B	Bonsall	B	grano/quartz diorite)	" montmorillonitic, thermic	Natric Palexeralfs	"	"
14P	Placentia	A,B	alluvium (granitic)	" " "	Typic Natrixeralfs	"	Riverside
15R	Ramona[1]	A,B	" (acid igne)	" loamy, mixed, thermic	" Haploxeralfs	"	"
16I	Imperial[1]	A,C	lacustrine sed.	" montmorillonitic, hyperthermic	Vertic Torriorthents	Entisol	Imperial
17M	Mecca	C	alluvium (granitic)	coarse-loamy, mixed, hyperthermic	Typic "	"	Riverside
18H	Hesperia[1]	C	" (gran/acid)	" " " thermic	" "	"	Los Angeles
19A	Adelanto[1]	A,B	" "	" " " "	" Haplargids	Aridisol	"
20O	Oban	B	" "	fine, montmorillonitic, thermic	" Natrargids	"	"
21P	Panoche[1]	A,C	alluvium (sed)	" loamy, mixed, thermic	" Torriorthents	Entisol	Kern
22M	Merced[1]	A,C	" (gran/acid)	" montmorillonitic, thermic	Pachic Haploxerolls	Mollisol	"

[1]Benchmark soil. A soil, because of its great extent or key position in the soil classification system, or both, is important in determining and understanding the variety of soil conditions in a State or other area. As a group these soils (approximately 115 Statewide vs. over 900 soil series) should embrace the extreme ranges in soil characteristics. Refer to U. S. Department of Agriculture - Soil Conservation Service for further information.

* Abbreviations. cong = conglomerate, diat = diatomaceous, gran/acid = granitic and other acid igneous rocks, igne = igneous, sed = sedimentary.

** Mean Annual Soil Temperature taken 20 inches below the surface of the soil.

frigid	less than 47°F
mesic	47° to 59°F
thermic	59° to 72°F
hyperthermic	above 72°F

TABLE NO. 4 . MISCELLANEOUS DATA

Soil	Calc. Surface Area cm^2/gram x 10^2 corrected*		Ignition Loss ***	**** "Instant Test" Fixed Moisture	
	No	Yes	%	% Remaining	% of Original
1PB		616	6.1	1.1	7.3
1PC	506		5.5	1.1	7.3
2AA		460	13.6	1.8	6.4
$2AB_1$	478		17.4	1.9	5.9
$2AB_2$		368	12.4	1.1	3.6
3SA		581	7.8	-	-
3SC		580	8.4	3.3	12.2
4TA		323	11.9	1.3	5.9
4TB	369		11.1	3.0	15.0
4TC	396		16.7	1.7	6.1
5CB		386	9.1	1.6	8.0
6MA		537	5.0	0.4	1.7
6MC	209**		19.5	2.7	8.7
7CA	224		2.6	0.6	8.0
7CB	181		1.7	1.2	15.0
7CC	73		1.1	1.3	13.7
8SA	508		7.3	1.0	6.2
8SC		484	6.3	1.5	9.0
9LA		459	9.6	2.9	11.6
9LB		449	10.7	1.7	6.4
10VB	192		3.9	0.8	7.5
10VC	147		3.0	0.6	5.1
11HA		386	4.3	1.1	11.1
1HB	420		7.0	2.3	16.8
12FB	271		3.7	1.0	9.5
13BB		326	5.3	1.2	13.6
14PA		445	3.1	1.3	10.7
14PB		502	6.0	1.7	12.5
15RA	287		3.4	1.0	11.0
15RB		287	4.1	1.0	11.0
16IA		635	15.8	0.7	3.8
16IC	611		15.4	1.3	6.7
17MC	379		2.6	2.1	12.4
18HC	197		3.2	1.8	17.8
19AA	210		1.8	0.7	6.7
19AB	263		2.5	1.1	10.5
200B	320		7.7	1.0	7.9
21PA	529		7.2	1.3	6.6
21PC		547	10.2	0.8	4.2
22MA	504		5.9	1.3	7.8
22MC		518	9.2	1.5	9.9

*for Specific Gravity, see reference #37 for method.
**grading is off due to cemented particles.
***sample initially dried at 110°C.
****moisture remaining in "Instant Test" specimen (5% lime content).
% remaining = original specimen moist. -- oven-dry specimen moist.
example 1PB opt. moist = 15.0%. Oven-dry moisture (lime treated)=13.9%
percent remaining = 15.0 - 13.9 = 1.1%
% of original = 100 (percent remaining)/original specimen moisture
example 1PB = 100 (1.1)/15.0 = 7.3%

TABLE 5 CALIFORNIA METHOD FOR ESTIMATING UNCONFINED COMPRESSIVE STRENGTH OF SOILS

Field Description	Consistency	Unconfined Compressive Strength at 28 days	
		Tons/sq.ft.	psi
Exudes between fingers when squeezed	Very soft	<0.3	
Easily molded in fingers	Soft	0.3-0.7	
Can be molded by strong pressure in fingers	Firm	0.7-1.4	10-19
Cannot be molded in fingers	Stiff	1.4-2.8	
Brittle or very tough	Hard	>2.8	

CRITERION FOR ACCEPTABLE CONSISTENCY OF FIELD SOILS 3% LIME TREATED SOILS CURED FOR 28 DAYS, OPTIMUM MOISTURE AND 90% RELATIVE COMPACTION	15 psi

Table No. 6 Effect of soil mixing on developed strength (5% lime content, near optimum moisture, 90% relative compaction and 28-day cure)

Soil	Fabrication Configuration	Lime Content	Moisture Content After UC Test	Developed Strength psi	Dev. Strength (Avg. for Horiz. & Vert. Specimens)	Remarks
16IA Clay	Horiz. Lift*	0%	18.5			
	" "	6%	16.7	6		
		Avg.	17.6		5	$\frac{5}{20}(100) = 25\%$
	Vert. Lift	0%	18.3			
	" "	6%	16.5	4		Therefore, the inadequately mixed Horiz. and Vert. specimens achieved about 25% of the regular specimens developed strength.
		Avg.	17.4			
	Regular	0%	18.2			
	"	3%	17.4	20	20	
	"**	6%	17.0	25		
19AB Silty Sand	Horiz. Lift	0%	8.7			
	" "	6%	9.1	58		
		Avg.	8.9		77	$\frac{77}{135}(100) = 57\%$
	Vert. Lift	0%	8.9			
	" "	6%	9.3	96		Therefore, the inadequately mixed Horiz. and Vert. specimens achieved about 60% of the regular specimens developed strength.
		Avg.	9.1			
	Regular	0%	10.2			
	"	3%	9.8	135	135	
	"**	6%	9.5	244		

16IA Optimum Moisture = 18.2%. Clay Content = 70%

19AB " " = 10.2%. Clay Content = 12%

*The various lifts, e.g., Horizontal 0% and Horizontal 6% are given here separately to show the resulting oven moisture content for the 28-day cured specimen.

**Values averaged from the regular 5% and 7% lime treatments given here for comparison purposes with the Horizontal and Vertical 6% lime treated lifts.

Table No. 7 Tabulation of developed strengths of soils treated with 3%, 5% and 7% lime and cured for various periods.

	3% Lime Content			5% Lime Content			7% Lime Content		
Group 1 <100 psi	7d	28d	6m	7d	28d	6m*	7d	28d	6m
17MC	3	3	4	6	6	6	9	7	10
4TA	10	10	2	34	41	20	99	88	73
19AA	2	7	14	10	14	37	16	26	74
3SC	-16	-14	-20	-8	-9	41	-7	13	72
14PA	15	16	28	33	30	52	58	51	90
7CC	1	5	43	8	15	61	10	27	79
16IA	-2	20	49	-3	17	62	16	32	116
3SA	7	18	36	25	36	70	26	44	92
4TB	7	13	10	52	77	79	126	193	229
16IC	26	39	51	34	53	93	41	83	126
4TC	13	15	19	74	85	97	159	225	292
Ave.**	8	13	23	25	34	56	51	72	114
Group 2 100-200 psi									
10VB	34	33	47	54	58	109	87	103	175
11HA	45	53	62	87	96	126	138	145	163
$2AB_2$	34	39	42	128	150	154	224	284	290
12FB	63	64	90	103	105	164	137	162	277
8SA	87	110	145	126	160	198	178	211	293
Ave.	53	60	77	100	114	150	153	181	240
Group 3 200-300 psi									
18HC	24	40	171	26	70	201	63	88	306
$2AB_1$	39	57	60	142	153	202	223	344	347
1PB	18	101	81	74	172	210	133	239	414
2AA	61	63	76	149	154	222	255	387	392
7CA	96	124	153	172	207	251	248	290	391
7CB	74	95	203	116	125	258	153	202	356
9LB	75	115	163	80	186	273	119	243	428
10VC	30	47	183	45	76	295	69	109	383
Ave.	52	80	136	101	143	239	158	238	377
Group 4 >300 psi									
6MA	50	80	187	165	171	305	243	241	334
9LA	88	138	184	93	226	314	122	188	353
11HB	60	106	192	102	172	328	153	247	462
13BB	72	87	251	124	147	392	178	224	480
14PB	109	203	355	170	231	419	225	350	582
1PC	95	152	279	137	188	428	183	276	616
5CB	124	149	304	144	292	453	280	341	565
8SC	95	124	383	114	157	467	140	168	477
22MC	75	144	241	100	194	485	132	241	633
22MA	128	227	337	146	234	492	195	265	637
15RA	108	133	383	148	195	527	214	265	607
6MC	192	229	287	255	335	534	285	438	625
19AB	84	135	407	132	198	542	181	288	762
21PC	164	316	385	175	308	572	216	315	618
20OB	162	266	388	186	356	623	244	424	731
21PA	141	298	500	153	270	630	196	277	611
15RB	127	207	518	193	296	770	228	367	896
Ave.	110	176	328	149	234	490	201	289	588

* The soils were assigned to the various groups according to the developed strength criteria of the 6 month - 5% lime content soils.

** The average values for each lime reactivity group, lime content and cure time are plotted in Figure .

Table No. 8 Soils assembled into lime reactivity groups with natural soil properties and "Instant Test" included for comparative purposes.

	Soil	2 Dev. Strgth.	1 pH	3 CEC	% BS	Ca/Mg	3 Exchange Capacity Ca	Mg	Na	K	H	% Iron Total	Coat	% Organic Carbon	% CO_3	MA % Sd	Si	Cl	SE	Test Density	Opt. Moist.	Nat. Soil q_u	5% Lime "Instant Test" Gross q_u	Developed Strgth.
Group 1 <100 psi	17MC	6	8.7	22	100	7.1	18	2	2	1	0	5	0	0.2	0.5	68	27	5	21	103	17**	4	9	5
	4TA	20	6.3	26	57	2.7	10	4	0	1	11	8	5	1.6	0.1	60	25	15	16	103	21*	41	78	37
	19AA	37	8.6	7	84	3.9	4	1	1	1	1	3	0	0.1	0	84	11	5	34	119	10	4	11	7
	3SC	41	7.5	45	91	1.0	19	19	2	0	4	5	1	0.7	0.1	11	38	51	9	92	26**	63	62	-1
	14PA	52	6.0	7	68	3.6	4	1	1	0	2	3	0	0.4	0.1	43	46	11	10	120	12*	7	32	25
	7CC	61	8.4	5	100	2.1	2	1	1	0	0	2	0	0	0	94	4	2	38	115	9*	1	7	6
	16IA	62	8.0	51	100	3.2	32	10	6	2	0	3	0	0.5	9.0	2	28	70	1	110	18	60	71	11
	3SA	70	7.6	46	91	2.6	28	11	3	1	4	6	1	0.8	0	9	37	54	7	97	26	55	50	-5
	4TB	79	6.1	32	68	0.6	8	12	0	1	10	9	5	1.0	0.1	50	30	20	13	107	19**	56	147	91
	16IC	93	8.1	50	100	2.9	28	10	10	2	0	4	0	0.3	8.0	1	31	68	1	108	19*	50	72	22
	4TC	97	6.8	26	52	1.4	7	5	0	2	12	12	6	0.3	0	44	37	19	12	99	27	37	74	37
	mean		7.5	29	83	2.8	14	7	2	1	4	5	2	0.5	1.6	42	29	29	15	107	19	34	54	21
Group 2 100-200 psi	10VB	109	7.2	11	92	-	10	0	0	0	1	5	0	0.3	0.1	78	13	9	22	132	10	9	52	43
	11HA	126	6.1	11	64	3.6	4	1	1	2	4	4	1	0.5	0.1	46	38	16	12	126	9	28	100	72
	$2AB_2$	154	5.2	15	7	0.8	0	1	0	0	14	9	3	0.3	0	45	27	28	15	88	30	66	103	37
	12FB	164	6.4	11	63	1.8	5	3	1	0	4	5	1	0	0.3	67	17	16	20	130	10	22	43	21
	8SA	198	7.5	24	98	2.6	13	5	3	2	1	3	1	1.1	0.1	29	45	26	4	113	15	40	105	65
	mean		6.5	14	65	2.2	6	2	1	1	5	5	1	0.4	0.1	53	28	19	15	118	15	33	81	48
Group 3 200-300 psi	18HC	201	8.8	7	100	4.3	4	1	1	0	0	5	0	0	0.1	83	11	6	29	128	10	5	25	20
	$2AB_1$	202	5.8	10	0	-	0	0	0	0	10	9	3	0.2	0	25	32	43	9	92	30	51	111	60
	1PB	210	9.3	47	97	0.9	5	6	35	0	1	5	1	0.4	0	9	33	58	0	115	15	90	139	49
	2AA	222	5.7	16	35	3.9	4	1	0	1	10	9	3	0.8	0	33	29	38	9	96	27	54	125	71
	7CA	251	7.8	9	84	-	7	0	0	0	1	2	0	0.5	0.1	71	17	12	22	135	7	23	113	90
	7CB	258	8.1	4	88	-	4	0	0	0	1	2	0	0.1	0	78	14	8	25	135	8	10	72	62
	9LB	273	7.3	23	90	2.0	10	5	3	2	2	3	1	0.3	0.1	32	43	25	9	94	26	31	85	54
	10VC	295	8.1	12	93	1.4	6	4	2	0	8	6	0	0	0.1	84	12	4	38	124	11	6	23	17
	mean		7.6	16	73	2.5	5	2	5	0	3	5	1	0.3	0.1	52	24	24	18	115	17	34	87	53
Group 4 >300 psi	6MA	305	6.8	40	94	0.8	16	19	1	1	2	4	0	0.5	0	19	30	51	2	102	22	62	80	18
	9LA	314	7.0	20	86	2.0	10	5	0	2	3	2	0	1.0	0.1	31	45	24	9	94	25**	37	106	69
	11HB	328	7.7	21	83	1.4	7	5	3	2	4	5	2	0.3	0.1	37	31	32	9	122	13**	42	134	92
	13BB	392	7.4	21	89	2.0	10	5	3	0	2	5	0	0.3	0	57	20	23	14	127	9	66	147	81
	14PB	419	8.5	14	96	2.9	14	5	3	0	1	2	0	0.2	0.3	32	39	29	5	122	13	37	125	88
	1PC	428	8.0	26	100	0.7	10	14	2	0	0	5	1	0.1	1.5	19	50	31	3	118	14	72	118	46
	5CB	453	6.7	32	86	2.9	14	5	0	2	4	6	1	0.8	0	46	28	26	11	106	19*	66	116	50
	8SC	467	8.2	42	100	2.9	28	10	3	0	0	3	1	0.3	1.1	46	39	15	7	111	16*	19	54	35
	22MC	485	9.1	46	100	3.6	18	5	23	0	0	2	0	0.3	7.0	34	35	31	2	117	14*	41	101	60
	22MA	492	7.8	31	100	2.1	20	9	1	1	0	5	0	0.6	0.9	27	37	36	5	110	16*	51	127	76
	15RA	527	7.0	7	87	7.1	7	1	1	2	1	4	0	0.1	0.3	62	22	16	15	135	9	20	118	98
	6MC	534	8.1	27	87	4.1	61	15	0	0	3	3	0	0.4	15.1	74	20	6	25	87	30**	24	41	17
	19AB	542	8.5	9	87	3.8	6	2	0	0	1	4	1	0	0	74	14	12	16	130	10	13	72	59
	21PC	572	8.2	17	100	0.7	4	5	6	2	0	5	1	0.4	1.9	18	49	33	3	106	18*	56	100	44
	20OB	623	9.5	73	100	0.7	21	30	19	2	0	2	0	0.2	4.1	55	14	31	6	122	12	59	135	76
	21PA	630	8.5	41	100	5.0	32	6	2	1	0	6	1	0.5	1.4	18	38	44	3	106	18	60	122	62
	15RB	770	7.9	13	100	1.4	7	5	1	0	0	5	0	0	0	64	21	15	15	132	9	39	135	96
	mean		7.9	28	94	2.6	17	9	4	1	1	4	1	0.4	2.0	42	31	27	9	115	16	45	108	63

1 pH averaged for comparative purposes only.
2 6 month cure and 5% lime.
3 Meq/100g

*"Instant Test" Fixed Moisture 1.3% to 1.6% remaining
** " " " " >2.0% remaining

TABLE NO. 9 GROSS UNCONFINED COMPRESSIVE STRENGTH IN PSI

3% Lime Content

	Natural Soil	Cure Time*** 0d *	7d	14d	28d	2m	6m
1PB	90	116	108	130	191	213	171
1PC	72	99	167	191	224	262	351
2AA	54	90	115	119	117	125	130
$2AB_1$	51	85	90	(102)	108	(111)	111
$2AB_2$	66	86	100	(103)	105	(106)	108
3SA	55	47	62	64	73	75	91
3SC	63	60	47	49	49	56	43
4TA	41	63	51	49	51	46	43
4TB	56	110	63	64	69	68	66
4TC	37	57	50	52	52	57	56
5CB	66	100	190	218	215	295	370
6MA	62	72	112	132	142	183	249
6MC	24	34	216	229	253	325	311
7CA	23	75	119	132	147	140	176
7CB	10	47	84	83	105	108	213
7CC	1	5	2	5	6	20	44
8SA	40	75	127	133	150	146	185
8SC	19	38	114	137	143	185	402
9LA	37	75	125	162	175	197	221
9LB	31	61	106	117	146	170	194
10VB	9	33	43	42	42	49	56
10VC	6	15	36	41	53	67	189
11HA	28	70	73	72	81	84	90
11HB	42	95	102	125	148	166	234
12FB	22	33	85	74	86	85	112
13BB	66	111	138	141	153	226	317
14PA	7	20	22	23	23	27	35
14PB	37	88	146	166	240	269	392
15RA	20	87	128	126	153	182	403
15RB	39	95	166	205	246	305	557
16IA	60	68**	58	67	80	86	109
16IC	50	63	76	69	89	107	101
17MC	4	7	7	(7)	7	(8)	8
18HC	5	17	29	26	45	78	176
19AA	4	8	6	8	11	12	18
19AB	13	47	97	110	148	227	420
20OB	59	103	221	292	325	359	447
21PA	60	93	201	268	358	460	560
21PC	56	85	220	275	372	390	441
22MA	51	94	179	212	278	340	388
22MC	41	76	116	140	185	243	282
Ave.	38	28 DS	64 DS	78 DS	100 DS	124 DS	178 DS

Values in parenthesis are interpolations

* interpolations ("Instant Test")

** true value

*** d = day, m = months

DS = Developed Strength

TABLE NO. 10 GROSS UNCONFINED COMPRESSIVE STRENGTH IN PSI

5% Lime Content

	Natural Soil	Cure Time** 0d*	7d	14d	28d	2m	6m
1PB	90	139	164	209	262	276	300
1PC	72	118	209	229	260	306	500
2AA	54	125	203	246	208	249	276
2AB1	51	111	193	(196)	204	(217)	253
2AB2	66	103	194	(206)	216	(218)	220
3SA	55	50	80	81	91	100	125
3SC	63	62	55	53	54	95	104
4TA	41	78	75	72	82	76	61
4TB	56	147	108	120	133	137	135
4TC	37	74	111	111	122	137	134
5CB	66	116	210	307	358	426	519
6MA	62	80	227	230	233	295	367
6MC	24	41	279	343	359	480	558
7CA	23	113	195	200	230	227	274
7CB	10	72	126	123	135	166	268
7CC	1	7	9	21	16	31	62
8SA	40	105	166	168	200	204	238
8SC	19	54	133	162	176	211	486
9LA	37	106	130	175	263	306	351
9LB	31	85	111	151	217	281	304
10VB	9	52	63	70	67	82	118
10VC	6	23	51	65	82	123	301
11HA	28	100	115	115	124	130	154
11HB	42	134	144	185	214	260	370
12FB	22	43	125	111	127	128	186
13BB	66	147	190	200	213	273	458
14PA	7	32	40	30	37	42	59
14PB	37	125	207	221	268	367	456
15RA	20	118	168	187	215	274	547
15RB	39	135	232	278	335	433	809
16IA	60	71	57	68	77	86	122
16IC	50	72	84	80	103	106	143
17MC	4	9	10	8	10	8	10
18HC	5	25	31	41	75	91	206
19AA	4	11	14	15	18	21	41
19AB	13	72	145	170	212	333	555
200B	59	135	245	332	415	515	682
21PA	60	122	213	285	330	437	690
21PC	56	100	231	296	364	466	628
22MA	51	127	197	248	285	273	543
22MC	41	101	141	173	235	342	526
Ave.	38	48 DS	100 DS	123 DS	148 DS	187 DS	282 DS

Values in parenthesis are interpolations

* True values ("Instant Test")

** d = day, m = months

DS = Developed Strength

TABLE NO. 11 GROSS UNCONFINED COMPRESSIVE STRENGTH IN PSI

	Natural Soil	7% Lime Content					
		Cure Time***					
		0d *	7d	14d	28d	2m	6m
1PB	90	162	223	254	329	423	504
1PC	72	140	255	308	348	402	688
2AA	54	157	309	359	441	443	446
2AB1	51	138	274	(351)	395	(397)	398
2AB2	66	116	290	(331)	350	(354)	356
3SA	55	71	81	87	99	109	147
3SC	63	64	56	67	76	102	135
4TA	41	96	140	126	129	110	114
4TB	56	190	182	205	249	277	285
4TC	37	89	196	252	262	270	329
5CB	66	135	346	365	407	468	631
6MA	62	88	305	237	303	427	396
6MC	24	50	309	368	462	618	649
7CA	23	152	271	292	313	316	414
7CB	10	97	163	166	212	215	366
7CC	1	9	11	33	28	41	80
8SA	40	135	218	239	251	293	333
8SC	19	68	159	188	187	277	496
9LA	37	137	159	188	225	288	390
9LB	31	114	150	171	274	369	459
10VB	9	71	96	110	112	116	184
10VC	6	31	75	92	115	185	389
11HA	28	127	166	166	173	179	191
11HB	42	177	195	254	289	375	504
12FB	22	51	159	165	184	204	299
13BB	66	182	244	260	290	383	546
14PA	7	42	65	57	58	69	97
14PB	37	163	262	302	387	385	619
15RA	20	179	234	258	285	368	627
15RB	39	180	267	385	406	531	935
16IA	60	110 **	76	84	92	122	176
16IC	50	83	91	102	133	128	176
17MC	4	11	13	(12)	11	(12)	14
18HC	5	34	68	61	93	138	311
19AA	4	14	20	23	30	35	78
19AB	13	98	194	228	301	407	775
200B	59	166	303	338	483	595	790
21PA	60	149	256	302	337	401	671
21PC	56	120	272	308	371	469	674
22MA	51	159	246	302	316	356	688
22MC	41	131	173	201	282	390	674
Ave.	38	71 DS	146 DS	171 DS	208 DS	247 DS	377 DS

Values in parenthesis are interpolations

* interpolations ("Instant Test")

** true value

*** d = day, m = months

DS = Developed Strength

Table No.12 Some natural soil properties of the soils used in the moisture "Sensitivity" tests. (Specimens fabricated at 90% R.C., with 5% lime content and cured for 28 days)

MOISTURE CONTENT WETTER THAN OPTIMUM

Treated soils which increased in gross compressive strength.

% Moisture Content				pH	exchangeable ions-meq/100g					% Iron		% Montmor-illonite	% Kaolin-ite
Dry	Opt.	Wet		(1:1)	Ca	Mg	Na	K	H	Total	Coating		
20	24	31	3SA	7.6	28	11	3	1	4	6	1	27	0
24	26	31	3SC	7.5	19	19	2	0	4	5	1	37	0
15	19	22	5CB	6.7	14	5	0	2	4	6	1	7	0
15	22	28	6MA	6.8	16	19	1	1	2	4	0	37	0
25	30	35	6MC	8.1	61	15	0	0	3	3	0	32	0

Treated soils which decrease in gross compressive strength.

12	15	17	1PB	9.3	5	6	35	0	1	5	1	0	5
24	27	32	2AA	5.7	4	1	0	1	10	9	3	0	37
28	30	36	$2AB_1$	5.8	0	0	0	0	10	9	3	0	47
27	30	35	$2AB_2$	5.2	0	1	0	0	14	9	3	0	47
17	21	26	4TA	6.3	10	4	0	1	11	9	5	0	40
15	19	22	4TB	6.1	8	12	0	1	10	9	5	0	42
24	27	32	4TC	6.8	7	5	0	2	12	12	6	0	47
5	7	9	7CA	7.8	7	0	0	0	1	2	0	0	0
4	8	10	7CB	8.1	4	0	0	0	1	2	0	0	0
7	10	15	7CC	8.4	2	1	1	0	0	2	0	0	0
5	9	12	15RB	7.9	7	5	1	0	0	5	0	0	0

MOISTURE CONTENT DRIER THAN OPTIMUM

Treated soils which increased in gross compressive strength.

			2AA	5.7	4	1	0	1	10	9	3	0	37
			$2AB_1$	5.8	0	0	0	0	10	9	3	0	47
			$2AB_2$	5.2	0	1	0	0	14	9	3	0	47
			3SC	7.5	19	19	2	0	4	5	1	37	0
			4TA	6.3	10	4	0	1	11	9	5	0	40
			4TB	6.1	8	12	0	1	10	9	5	0	42
			4TC	6.8	7	5	0	2	12	12	6	0	47
			7CA	7.8	7	0	0	0	1	2	0	0	0
			7CB	8.1	4	0	0	0	1	2	0	0	0
			7CC	8.4	2	1	1	0	0	2	0	0	0
			15RB	7.9	7	5	1	0	0	5	0	0	0

Treated soils which decreased in gross compressive strength.

			1PB	9.3	5	6	35	0	1	5	1	0	5
12	14	18	1PC	8.0	10	14	2	0	0	5	1	0	0
			3SA	7.6	28	11	3	1	4	6	1	27	0
			5CB	6.7	14	5	0	2	4	6	1	7	0
			6MA	6.8	16	19	1	1	2	4	0	37	0
			6MC	8.1	61	15	0	0	3	3	0	32	0

Table 13 Influence of moisture content on compressive strength of montmorillonitic and kaolinitic soils. (Conditions: 5% lime content, 90% relative compaction and 28 day cure.)

Note: Values were extrapolated when necessary.

Soil	% Montmorillonite	% Kaolinite	Gross Compressive Strength: Optimum Moisture	Gross Compressive Strength: 5% Wetter than OM	Gross Compressive Strength: 4% Drier than OM	% Change in Strength from Strength at OM: Wetter than OM	% Change in Strength from Strength at OM: Drier than OM
3SA	27	0	91	130	30	+43	-65
3SC	37	0	54	165	72	+206	+33
5CB	7	0	358	475	210	+33	-41
6MA	37	0	233	430	130	+85	-44
6MC	32	0	359	375	300	+4	-16
2AA	0	37	208	200	275	-4	+32
$2AB_1$	0	47	204	220	360	+8	+76
$2AB_2$	0	47	216	200	260	-7	+20
4TA	0	40	82	40	110	-51	+34
4TB	0	42	133	25	185	-81	+39
4TC	0	47	122	90	150	-26	+23

Table No. 14 Estimate of Soil Mineralogy of the Whole Soil in Percent by X-ray Diffraction-Differential Thermal Analysis-Microscopy

Soil Symbol	Montmorillonite	Mixed Layer	Illite	Vermiculite	Hydro-Verm*	Kaolinite	Halloysite	Chlorite	Mica	Biotite	Feldspar	Plagioclase	Microcline	Goethite	Magnetite	Calcite	Gypsum	Amphibole	Quartz	Remarks
1PB		52				5		5	5	5	10	10		5		5			20	
1PC		32						7	5		17	17				5			22	
2AA						37	37	t	7					5				t	5	7Cristobolite,5Gibbsite,7Tridymite
$2AB_1$						47	47				7			5					5	12 " 7 "
$2AB_2$				5		47	47		5		7				5				5	7 " 12 "
3SA	27	7						10	5		15	15				5			12	5 Amorphous
3SC	37	5						12	7		12	12							15	
4TA		5				40	17		5		22	15	7		5			7	7	5 Pyrite, 5
4TB						42			5		7				5	5		5	15	5 Serpentine
4TC		5	7			47					12								7	
5CB	7										57	57			5	5		5		15 Amorphous
6MA	37										17	12	5					5	22	5 Dolomite
6MC	32							5	5		7	7				30			17	
7CA									5		72	55	17					5	22	
7CB									7		42	22	20					7	35	
7CC		7							5		52	40	12					7	32	
8SA	17							5	12	12	27	17	10		1	1			27	
8SC	12	5						5	5		32	27	5				5	5	27	
9LA		22							7		15	10	5					5	25	10 Cristobolite
9LB		22		5					5		27	22	5						25	10 Tridymite
10VB					37				5		20	20						12	15	
10VC					20	7	7				27	22	5					12	17	5 Leonhardite
11HA		10							5		22	12	10					5	42	5 Amorphous
11HB		5						5	5		25	15	10					7	32	5 "
12FB		5			15	7	7				25	20	5		5			15	22	5 Pyrolusite
13BB		5			17	5	5		5	5	32	27	5					5	22	
14PA					10	5	5		5	5	25	15	10				5	12	32	
14PB					15	5	5		5		30	25	5				5	12	25	
15RA		5							7	7	30	25	5					10	35	
15RB					12				12	12	30	25	5	5				10	25	
16IA	22	7				5			5		5	5		5		12	5		20	
16IC	22	5				7			5		5	5		5		10	5		25	
17MC		5						7	25	20	27	17	10			5		12	17	5 Muscovite
18HC		10						5	20	20	25	20	5		1			7	22	
19AA								5	7		40	20	20					7	35	
19AB		10						5	5		32	20	12					7	30	5 Amorphous
20OB		12						5	5		27	15	12			5		5	27	
21PA	25							5	5		15	15				5		t	25	
21PC	17							5	5		15	10	5	5		5		5	35	5 Dolomite
22MA	20	5						5	5	5	30	25	5			5		5	20	
22MC	5	10							5		42	20	22			5	5	7	17	

% were originally given in ranges but recorded here as mid range values (10-15 as 12)

* Hydrobiotite-Vermiculite

Bar under figure signifies "less than".

t = trace

TABLE NO.15 LISTING OF THE ACIDIC AND BASIC NATURAL SOILS BY LIME REACTIVITY GROUPS

	pH <7 ACIDIC	pH 7+ BASIC
unsuitable soils		
Group 1		
	4TA	3SA, 3SC
	14PA	7CC, 16IA
	4TB	16IC, 17MC
	4TC	19AA
suitable soils		
Group 2	$2AB_2$	8SA
	11HA	10VB
	12FB	
Group 3	2AA	1PB, 7CA, 7CB
	$2AB_1$	9LB, 10VC, 18HC
Group 4	5CB	1PC, 6MC, 8SC
	6MA	9LA, 11HB, 13BB
		14PB, 15RA, 15RB
		19AB,200B, 21PA
		21PC, 22MA, 22MC

Table No. 16 Estimated Minimum Developed Strength for Values of Plasticity Index (P.I.) Up to 20 for 3%, 5% and 7% Lime Content.

Cure Interval	Plasticity Index	Lime Content * 3%	** 5%	*** 7%
		Minimum Developed Strength (psi)		
7 Day	0	0	0	0
	5	0	25	40
	10	25	50	75
	15	40	80	105
	20	60	100	140
28 Day	0	0	0	0
	5	0	50	70
	10	35	100	130
	15	80	150	190
	20	120	200	250
6 Month	0	0	0	0
	5	10	50	140
	10	50	160	270
	15	90	270	400
	20	130	380	530

Note all values rounded off to the nearest 5 psi.

*From Figure 20
**From Figure 21
***From Figure 22

Table No. 17 Average Values of Compressive Strength (Developed Strength, psi) for the Various P.I. Ranges. With a Measure of the Variation.

Lime Content	Cure Interval	Non-Plastic	Plasticity Index Range			$\bar{x}$ psi	Range psi	V	S psi
			1-9	10-19	>20				
Variable	7 Day	97*	118**	101***	100*	104	21	10	10
	28 Day	131*	167**	169***	154*	155	38	11	17
	6 Month	258*	300**	279***	269*	276	42	7	18
Specific									
3%	6 Month	121	182	279	113	174	166	44	77
5%	6 Month	187	300	420	200	277	233	39	108
7%	6 Month	258	417	535	269	370	277	36	132

* = 7% Lime Content
** = 5% Lime Content
*** = 3% Lime Content

S = Standard Deviation
V = Coefficient of Variation = $100S/\bar{x}$

TABLE NO. 18 ESTIMATION OF LIME CONTENT USING A SINGLE SOIL PROPERTY. (BASED UPON AVERAGE DEVELOPED STRENGTHS OF LIME TREATED SOILS USED IN THIS STUDY).

Property	Lime Content-% 7 Day High Early Strength	6 Month Cure
Lime Reactivity Group		
1	-	7
2	5	5
3	5	4
4	3	3
PI of Natural Soil		
NP	-	7
1-9	5	5
10-19	5	3
≧20	-	7
Soil Horizon		
A	7	5
B	5	3
C	7	5
Soil Dry Density pcf		
<100	-	6
100-121	-	5
>121	-	3

TABLE NO. 19 DEVELOPED STRENGTH FOR VARIOUS SOILS ARRANGED ACCORDING TO PREDOMINATE CLAY MINERAL

Predominate Clay Mineral	Number of Soils	Soil Series*	Developed Strength 6-mo. Cure-5% Lime (psi)			% of Soils Unsuitable (<100 psi)
			** Avg.	Low	High	
Kaolinite	6	2A and 4T	129	20	222	50
Mixed Layer	10	1P, 9L, 11H, 18HC, 19AB, 200B and 22MC	356	126	623	0
Montmorillonite	11	3S, 6M, 8S, 16I, 21P and 22MA	300	41	630	40
Hydrobiotite-Vermiculite	5	10V, 13BB, 14PB and 15RB	397	109	770	0

*Soil series symbols see Table 2 for further description.
**Average developed strength for all soils in this clay mineral group.

Note: Average developed strength (6 months cure-5% lime) for all 41 soils used in this study is 283 psi.

Table 20 Electrical Characterization Test Values with Calculations for Indicating a Soils Suitability for Lime Stabilization

AGGLOMERATION

When ε' Of Lime Treated Soil Is Larger Then ε' Of The Natural Soil

	dielectric constant					conductivity		
	1 CEC[1]	2 Natural Soil $x10^{-3}$	3 Treated[2] Soil $x10^{-3}$	4 $\Delta\varepsilon'$ $x10^{-3}$ (Col.3-Col.2)	5 * Time Hrs.	6 $\Delta\sigma$ mhos/cm ($x\ 10^3$)	7 $\Delta\sigma \times \Delta\varepsilon'$ ($x\ 10^3$) Col. 4 x Col.6	Developed Strength 6 month 5% Lime psi
22MC	46	41	70	29	4	2.225	64,500	485
8SC	42	30	33	3	1	.969	2,900	467
13BB	21	37	45	8	1	.166	1,300	392
2AA	16	10	23	13	1	.850	11,000	222
1PB	47	31	45	14	6	1.040	14,600	210
2AB	15	3.3	15	11.7	5	1.060	12,400	154
4TA[2]	26	9	10	1	3	.560	600**	20****
14PA	7	5.4	6.2	0.8	1	.248	200**	52****

ADSORPTION

When ε' Of The Lime Treated Soil Is Smaller Than ε' Of The Natural Soil.

	dielectric constant					conductivity		
	1 CEC[1]	2 Natural Soil $x10^{-3}$	3 Treated[2] Soil $x10^{-3}$	4 $\Delta\varepsilon'$ $x10^{-3}$ (Col.3-Col.2)	5 Time Hrs.	6 $\Delta\sigma$ mhos/cm ($x\ 10^3$)	7 $\Delta\sigma \times \Delta\varepsilon'$ ($x\ 10^3$) Col. 4 x Col. 6	Developed Strength 6 month 5% Lime psi
15RB	13	15	7.2	7.8	2	.199	1,600	770
21PC	17	73	56	17	1	1.661	28,200	572
9LA	20	10.3	8.7	1.6	6	.988	1,600	314
6MA	40	42	30	12	6	2.786	33,400	305
9LB	23	8.5	6.5	2	1	1.264	2,500	273
11HA	11	4.9	1.2	3.7	1	.173	600	126
3SA	46	43	21	22	8	2.410	53,000***	70****
16IA	50	59	7	52	2	.925	48,100***	62****
3SC	45	42	19	23	3	2.120	48,800***	41****

*Time lapse between addition of lime to soil-water slurry and initial electrical measurement (ε').

**Soils with values of $\Delta\sigma x \Delta\varepsilon'$ ($x\ 10^3$) less than 1000 are not desirable for lime stabilization.

***Soils with values of $\Delta\sigma x \Delta\varepsilon'$ ($x\ 10^3$) larger than 40,000 are not desirable for lime stabilization.

[1]CEC by NH_4OAc method (meq/100g). The 5% like added would be nearly equivalent to 130 meq/100g of soil.

[2]Soil treated with 5% lime.

****Undesirable for lime soil stabilization based upon the 100 psi developed strength (Lime Reactivity - 6 month cure - 5% Lime Content) criteria.

Table 21 Soils Arranged According to the Quality* of the Lime-Soil Reaction

	% Montmor-illonite	% Mixed Layer	% Kaolinite	% Quartz	Exch K ion **	pH	% Clay	Max. Den. pcf	% Opt. Moist.	PI	%Fixed Moist. ***	% Fe Coat.	"Inst. Test" pH	% Ignition Loss	% Base Sat.	Compressive Strength qu psi	5% Lime "Inst. Test" Gross psi	Developed Strength psi	Organic Carbon %	Surface Area 1	CEC	Electrical Properties: Natural Soil ε 2	Treated Soil σ 3
Soil Adsorption																							
3SA	27	7	0	12	.8	7.6	54	97	26	26	-	1.3	0	8	91	55	50	0	.8	581	46	43	(4.6)
3SC	37	5	"	15	.4	7.5	51	92	"	28	12	1.4	0	"	"	63	62	"	.7	580	45	42	(4.0)
6MA	"	0	"	22	1.3	6.8	"	102	22	34	2	0.4	3	5	94	62	80	18	.5	537	40	"	4.3
16IA	22	7	5	20	2.1	8.0	70	110	18	33	4	0.3	1	16	100	60	71	11	"	635	51	59	4.7
21PC	17	0	0	35	"	8.2	33	106	"	16	"	0.8	5	10	"	56	100	44	.4	547	17	73	6.3
9LA	0	22	"	25	"	7.0	24	94	25	4	12	0.4	10	10	86	37	106	69	1.0	459	20	10	4.6
9LB	"	"	"	"	"	7.3	25	"	26	9	6	0.5	7	11	90	31	85	54	.3	449	23	8	4.4
11HA	"	10	"	42	"	6.1	16	126	9	0	11	1.4	12	4	64	28	100	72	.5	386	11	5	1.4
15RB	"	0	"	25	.4	7.9	15	132	"	5	"	0.2	"	"	100	39	135	96	0	287	13	15	2.8
glomeration																							
2AA	"	"	37	5	.6	5.7	38	96	27	13	6	3.3	12	14	35	54	125	71	.8	460	16	10	(2.7)
2AB	"	"	47	5	.2	5.2	28	88	30	8	1	2.7	7	12	7	66	103	37	.3	368	15	3	(2.2)
4TA	"	5	40	7	1.3	6.3	15	103	21	0	6	4.8	6	"	57	41	78	"	1.6	323	26	9	(2.0)
1PB	"	52	5	20	.4	9.3	58	115	15	35	7	1.1	5	6	97	90	139	49	.4	616	47	31	(14.9)
8SC	"	5	0	27	0	8.2	15	111	16	4	9	0.5	4	"	100	19	54	35	.3	484	42	30	4.2
13BB	"	"	5	22	.4	7.4	23	127	9	10	14	0.3	11	5	89	66	147	81	"	326	21	37	2.9
14PA	"	0	"	32	"	6.0	11	120	12	0	11	0.2	4	3	68	7	32	25	.4	445	7	5	2.7
22MC	"	10	0	17	"	9.1	31	117	14	19	10	0.1	7	9	100	41	101	60	.3	518	46	41	14.9

* As signified by the electrical test
** meq/100 gm.
*** Moisture remaining in "Instant Test" specimen after oven-drying test, i.e., 100 (Orig.-Oven)/Orig.

1 Calculated. cm^2/gram.

2 dielectric constant $x10^3$
3 conductivity x 10^3 mhos/cm. Values in parenthesis are estimation of the zero hour reading which was not otherwise available.

Table 22 Tentative Guidelines for resolving the Montmorillonitic Soils (Adsorptive Lime-Soil Reaction) vs. the Nonmontmorillonitic Soils (Adsorptive Lime-Soil Reaction) by the preponderance of the various soil property criteria. Montmorillonitic soils 3SA-21PC. Nonmontmorillonitic soils 9LA-15RB.

Symbol	*** Adsorption Reaction	Soil	Clay	P.I.	Compressive Strength, q_u	* "Instant Test" Inst/pH	* "Instant Test" Developed Strength	Surface Area	Dielectric Constant x 10^{-3} ****
			%		psi		psi	**	ε^1
3SA		Montmorillonite ✓	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite	<30	<10	<50	>6	>40	<500	<20
3SC		Montmorillonite ✓	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite	<30	<10	<50	>6	>40	<500	<20
6MA		Montmorillonite ✓	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite	<30	<10	<50	>6	>40	<500	<20
16IA		Montmorillonite ✓	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite	<30	<10	<50	>6	>40	<500	<20
21PC		Montmorillonite ✓	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite	<30	<10	<50	>6	>40	<500	<20
9LA		Montmorillonite	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite ✓	<30	<10	<50	>6	>40	<500	<20
9LB		Montmorillonite	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite ✓	<30	<10	<50	>6	>40	<500	<20
11HA		Montmorillonite	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite ✓	<30	<10	<50	>6	>40	<500	<20
15RB		Montmorillonite	>30	>10	>50	<6	<40	>500	>20
		Nonmontmorillonite ✓	<30	<10	<50	>6	>40	<500	<20

Note: Enclosed (>10) spec. indicates level of soil property.
✓ The preponderance (4 or more) of these various properties indicates this soil.
* Instant Test (less than 30 minutes total life of treated specimen). 5% lime content. Developed Strength =(Treated strength)lime-soil / (Untreated strength) natural soil.
** Calculated using Mechanical Analysis. $cm^2/gram \times 10^2$
*** So classified by virtue of the electrical characteristic test.
**** Natural Soil

Table 23 Tentative Guidelines for Resolving the Kaolinitic Soils (Agglomerative Lime-Soil Reaction) vs. the Nonkaolinitic Soils (Agglomerative Lime-Soil Reaction) by the preponderance of the various soil property criteria. Kaolinitic soils 2AA-4TA. Nonkaolinitic soils 1PB-22MC.

Symbol	*** Agglomeration Reaction Soil	Quartz %	pH	Test Maximum Density pcf	Optimum Moisture %	Fixed* Moisture %	Iron** Coating %	Ignition Loss %	Base Saturation %	Dielectric Constant x 10^{-3} **** ε^1
2AA	Kaolinitic √	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic	>12	>7	>107	<18	>10	<2	<10	>60	>20
$2AB_2$	Kaolinitic √	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic	>12	>7	>107	<18	>10	<2	<10	>60	>20
4TA	Kaolinitic √	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic	>12	>7	>107	<18	>10	<2	<10	>60	>20
1PB	Kaolinitic	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic√	>12	>7	>107	<18	>10	<2	<10	>60	>20
8SC	Kaolinitic	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic√	>12	>7	>107	<18	>10	<2	<10	>60	>20
13BB	Kaolinitic	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic√	>12	>7	>107	<18	>10	<2	<10	>60	>20
14PA	Kaolinitic	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic√	>12	>7	>107	<18	>10	<2	<10	>60	>20
22MC	Kaolinitic	<12	<7	<107	>18	<10	>2	>10	<60	<20
	Nonkaolinitic√	>12	>7	>107	<18	>10	<2	<10	>60	>20

Note: Enclosed (>10) Spec. indicates level of soil property.
√ The preponderance (5 or more) of the various properties indicates this soil.
* Moisture remaining in "Instant Test" specimen after oven-drying test, i.e., 100 (Orig.-Oven)/Orig.
"Instant Test" - The time from soil fabrication to unconfined compression test is less than 30 minutes.
** By the dithionite-citrate method.
*** So classified by virtue of the electrical characteristic test.
**** Natural Soil

Table 24 Tentative Guidelines for Resolving the Nonmontmorillonitic Soils (Adsorptive Lime-Soil Reaction) vs. the Nonkaolinitic Soils (Agglomerative Lime-Soil Reaction) by the preponderance of the various soil property criteria. Nonmontmorillinitic soils 9LA-15RB. Nonkaolinitic soils 1PB-22MC.

Soil	CLASSIFICATION: Lime-Soil Reaction * Electrical (ε')	Soil Clay Mineral Characteristic	Inst/pH	*** Exchg. K	PI	Dielectric Constant 10^{-3} **** ε^1	
9LA	Adsorption	Nonmontmoril. ✓	>6	>0.7	<10	<20	
		Nonkaolinite	<6	<0.7	>10	>20	
9LB	"	Nonmontmoril. ✓	>6	>0.7	<10	<20	
		Nonkaolinite	<6	<0.7	>10	>20	
11HA	"	Nonmontmoril. ✓	>6	>0.7	<10	<20	
		Nonkaolinite	<6	<0.7	>10	>20	
15RB	"	Nonmontmoril. ✓	>6	>0.7	<10	<20	
		Nonkaolinite	<6	<0.7	>10	>20	
1PB	Agglomeration	Nonmontmoril.	>6	>0.7	<10	<20	
		Nonkaolinite ✓	<6	<0.7	>10	>20	
8SC	"	Nonmontmoril.	>6	>0.7	<10	<20	
		Nonkaolinite ✓	<6	<0.7	>10	>20	
13BB **	"	Nonmontmoril. ?	>6	>0.7	<10	<20	(Inconclusive)
		Nonkaolinite ?	<6	<0.7	>10	>20	
14PA	"	Nonmontmoril.	>6	>0.7	<10	<20	
		Nonkaolinite ✓	<6	<0.7	>10	>20	
22MC	"	Nonmontmoril.	>6	>0.7	<10	<20	
		Nonkaolinite ✓	<6	<0.7	>10	>20	

Note: Enclosed (>10) specification indicates level of soil property.
*These soils were classified as "Adsorptive" or "Agglomerative" by virtue of the electrical characterization test.

**The lime-soil reaction classification , by the "electrical test" and by the "perponderance of soil properties", is not conclusive
***Exchangeable K ion, meq/100 gm.
✓The preponderance (2 or more) of the various properties indicates this lime-soil reaction. The dielectric constant is not to be counted.
**** Natural soil

Table 25 Tentative Guidelines for resolving the Montmorillonitic Soils (adsorptive Lime-Soil Reaction) vs. the Kaolinitic Soils (agglomerative Lime-Soil Reaction) by the preponderance of the Various soil property criteria. Montmorillonitic soils 3SA-21PC. Kaolinitic soils 2AA-4TA.

Soil	CLASSIFICATION: Lime-Soil Reaction * Electrical (ε')	Soil Clay Mineral Characteristic	Montmoril., %	Kaolinite, %	Quartz, %	Exch. K **	pH	PI	Fe Coat, % ***	"Instant" Test **** Inst/pH	Developed Strength	Surface Area *****	Dielectric Constant x 10^{-3} ε' ******
3SA	Adsorption	Montmoril. ✓	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
3SC	"	Montmoril. ✓	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
6MA	"	Montmoril. ✓	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
16IA	"	Montmoril. ✓	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
21PC	"	Montmoril. ✓	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
2AA	Agglomeration	Montmoril.	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite ✓	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
$2AB_2$	"	Montmoril.	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite ✓	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20
4TA	"	Montmoril.	>15	<15	>12	>0.7	>7	>10	<2	<6	<40	>500	>20
		Kaolinite ✓	<15	>15	<12	<0.7	<7	<10	>2	>6	>40	<500	<20

Note: Enclosed (>10) specification indicates level of soil property.

✓ The preponderance (6 or more) of these various properties indicates this lime-soil reaction.

* These soils were classified as "Adsorptive" or "Agglomerative" by virtue of the electrical characterization test.

** Exchangeable K ion. Meq/100 gm.

*** By the Dithionite-Citrate method.

**** "Instant Test" - The time from soil fabrication to unconfined compression test is less than 30 minutes. Lime reactivity = $\frac{\text{(treated strength)}_{\text{lime soil}}}{\text{(Untreated Strength)}_{\text{natural soil}}}$.

***** Calculated using Mechanical Analysis. $Cm^2/gram \times 10^2$

****** Natural Soil

Table 26 Tentative Guidelines for Resolving the Montmorillonitic Soils (Adsorptive Lime-Soil Reaction) vs. the Nonkaolinitic Soils (Agglomerative Lime-Soil Reaction) by the preponderance of the various soil property criteria. Montmorillonitic soils 3SA-21PC. Nonkaolinitic soils 1PB-22MC.

Soil	CLASSIFICATION: Lime-Soil Reaction * Electrical (ε')	Soil Clay Mineral Characteristic	Montmorillonite, %	Exch. K ion **	Test Maximum Density, pcf	Optimum Moisture, %	PI	"Inst. Test" Developed Strength psi	Surface Area ***	**** ε^1
3SA	Adsorption	Montmoril. ✓	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite	<15	<.7	>107	<18	<10	> 40	<500	<41
3SC	"	Montmoril. ✓	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite	<15	<.7	>107	<18	<10	> 40	<500	<41
6MA	"	Montmoril. ✓	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite	<15	<.7	>107	<18	<10	> 40	<500	<41
16IA	"	Montmoril. ✓	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite	<15	<.7	>107	<18	<10	> 40	<500	<41
21PC	"	Montmoril. ✓	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite	<15	<.7	>107	<18	<10	> 40	<500	<41
1PB	Agglomeration	Montmoril.	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite ✓	<15	<.7	>107	<18	<10	> 40	<500	<41
8SC	"	Montmoril.	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite ✓	<15	<.7	>107	<18	<10	> 40	<500	<41
13BB	"	Montmoril.	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite ✓	<15	<.7	>107	<18	<10	> 40	<500	<41
14PA	"	Montmoril.	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite ✓	<15	<.7	>107	<18	<10	> 40	<500	<41
22MC	"	Montmoril.	>15	>.7	<107	>18	>10	< 40	>500	>41
		Nonkaolinite ✓	<15	<.7	>107	<18	<10	> 40	<500	<41

Note: Enclosed (>10) specification indicates level of soil property.

✓ The preponderance (4 or more) of these various properties indicates this lime-soil reaction.

* These soils were classified as "Adsorptive" or "Agglomerative" by virtue of the electrical characterization test.

** Exchangeable K ion. meq/100 gm.

*** Calculated using Mechanical Analysis. $cm^2/gram \times 10^2$

**** Dielectric constant $\times 10^{-3}$ of the natural soil.

Table 27 Tentative Guidelines for resolving the Nonmontmorillonitic Soils (Adsorptive Lime-Soil Reaction) vs. the Kaolinitic Soils (Agglomerative Lime-Soil Reaction) by the preponderance of the various property criteria. Nonmontmorillonitic soils 9LA-15RB. Kaolinitic soils 2AA-4TA.

Soil	CLASSIFICATION: Lime-Soil Reaction / * Electrical (ε')	Soil Clay Mineral Charactistic	Kaolinite, %	pH	% Fixed Moist.**	% Iron Coating ***	Compressive Strength, psi	"Inst. Test" Developed Strength psi
9LA	Adsorption	Nonmontmoril.✓	<15	>7	>10	<2	<50	>40
		Kaolinite	>15	<7	<10	>2	>50	<40
9LB	"	Nonmontmoril.✓	<15	>7	>10	<2	<50	>40
		Kaolinite	>15	<7	<10	>2	>50	<40
11HA	"	Nonmontmoril.✓	<15	>7	>10	<2	<50	>40
		Kaolinite	>15	<7	<10	>2	>50	<40
15RB	"	Nonmontmoril.✓	<15	>7	>10	<2	<50	>40
		Kaolinite	>15	<7	<10	>2	>50	<40
2AA	Agglomeration	Nonmontmoril.	<15	>7	>10	<2	<50	>40
		Kaolinite ✓	>15	<7	<10	>2	>50	<40
$2AB_2$	"	Nonmontmoril.	<15	>7	>10	<2	<50	>40
		Kaolinite ✓	>15	<7	<10	>2	>50	<40
4TA	"	Nonmontmoril.	<15	>7	>10	<2	<50	>40
		Kaolinite ✓	>15	<7	<10	>2	>50	<40

Note: Enclosed (>10) spec. indicates level of soil property.

✓ The preponderance (4 or more) of these various properties indicates this lime-soil reaction.

* These soils were classified as "Adsorptive" or "Agglomerative" by virtue of the electrical characterization test.

** Moisture remaining in "Instant Test" specimen after oven-drying test, i.e., 100 (Orig.-Oven)/Orig.

*** By the Dithionite-Citrate method.

Table 28 Tentative Guidelines based upon soil property criteria for resolving the lime-soil reaction categories (adsorption and agglomeration), and subcategories.

Table Reference	CLASSIFICATION: Lime-Soil Reaction * Electrical (ε')	No. of Soils	Soil Clay Mineral Characteristic	% Montmorillonite	% Kaolinite	Exch K ion [1]	pH (1:1)	% Clay	Test Maximum Density, pcf.	% Opt. Moisture	PI	% Fixed Moisture **	% Fe Coat. [2]	Compressive Strength, psi: Inst. Test"/pH ***	Compressive Strength, psi: Inst. Test" 5% Lime ***	Compressive Strength, psi: Natural Soil, q_u	% Ignition Loss	Surface Area [3]	Natural Soil Dielectric Constant x 10^{-3} ε
21	Adsorption	9		>15	<15	>0.7													
	vs			ψ		82%													
	Agglomeration	8		<15	>15	<0.7													
22	Adsorption	5	Montmorillonite	>15	<15			>30			>10			<6	<40	>50		>500	>20
			vs	ψ				ψ			ψ			ψ	91%	ψ		ψ	ψ
	"	4	Nonmontmoril.	<15	<15			<30			<10			>6	>40	<50		<500	<20
23	Agglomeration	3	Kaolinite	<15	>15		<7		<107	>18		<10	>2				>10		<20
			vs	ψ			88%		ψ	ψ		72%	ψ				ψ		88%
	"	5	Nonkaolinite	<15	<15		>7		>107	<18		>10	<2				<10		>20
24	Adsorption	4	Nonmontmoril.	<15	<15	>0.7					<10			>6					<20
			vs			91%					78%			82%					89%
	Agglomeration	5	Nonkaolinite	<15	<15	<0.7					>10			<6					>20
25	Adsorption	5	Montmorillonite	>15	<15	>0.7	>7				>10		<2	<6				>500	>20
			vs	ψ		75%	88%				88%		ψ	88%				ψ	ψ
	Agglomeration	3	Kaolinite	<15	>15	<0.7	<7				<10		>2	>6				<500	<20
26	Adsorption	5	Montmorillonite	>15	<15	>0.7			<107	>18	>10				<40			>500	>41
			vs	ψ		ψ			ψ	ψ	78%				70%			80%	ψ
	Agglomeration	5	Nonkaolinite	<15	<15	<0.7			>107	<18	<10				>40			<500	<41
27	Adsorption	4	Nonmontmoril.	<15	<15		>7					>10	<2		>40	<50			
			vs	ψ			79%					86%	ψ		86%	86%			
	Agglomeration	3	Kaolinite	<15	>15		<7					<10	>2		<40	>50			

* These soils were classified as "Adsorptive" or "Agglomerative" by virtue of the electrical characterization test.

** Moisture remaining in "Instant Test" specimen after oven-drying test, i.e., 100 (Orig.-Oven)/Orig.

*** "Instant Test". The time between soil fabrication and the unconfined compression test is less than 30 minutes. Value of "Instant Test" in Psi, developed strength (Compressive Strength) treated soil ——— (Compressive Strength natural soil)

1 Exchangeable K ion meq/100 gm.

2 By the Dithionite-Citrate method.

3 Calculated using Mechanical Analysis. $cm^2/gram \times 10^2$

ψ 100% successful delineation (no exception). Lesser values as shown.

Table 29 Some Soil Properties of Montmorillonitic and Kaolinitic Soils.

Soil	Montmon. %	Kaolin. %	pH	Fe Coat. %	Ca/Mg	Exchangeable ion Ca	Mg	Na	K	H	PI	SE	Max. Density pcf	Opt. Moist. %	"Instant Test" Fixed Moist. % ***	Gross qu psi	Developed Strength psi.	Inst. pH	Ignition Loss %	Base Sat. %	Calc. Surface Area $Cm^2/gm \times 10^2$
Montmorillonitic Soils																					
3SA	27	0	7.6	1	3	28	11	3	.8	4	26	7	97	26	-	50	0	0	8	91	581
3SC	37	0	7.5	1	1	19	19	2	.4	4	28	9	92	26	1	62	0	0	8	91	580
6MA	37	0	6.8	0	1	16	19	1	1.3	2	34	2	102	22	9	80	18	3	5	94	537
6MC	32	0	8.1	0	4	61	15	0	0	3	0	25	87	30	9	41	17	2	20	87	209**
8SA	17	0	7.5	1	3	13	5	3	2.1	1	11	4	113	15	6	105	65	9	7	98	508**
16IA	22	5	8.0	0	3	32	10	6	2.1	0	33	1	110	18	4	71	11	1	16	100	635
16IC	22	7	8.1	0	3	28	10	10	2.1	0	32	1	108	19	7	72	22	3	15	100	611**
21PA	25	0	8.5	1	5	32	6	2	1.3	0	11	3	106	18	6	122	62	7	7	100	529**
21PC	17	0	8.2	1	1	4	5	6	2.1	0	16	3	106	18	4	100	44	5	10	100	547
22MA	20	0	7.8	0	2	20	9	1	1.1	0	15	5	110	16	8	127	76	10	6	100	504**
$\overline{X}$				1	3	25	11	3	1.3	1	21	6	103	21	6	83	32	4	10	96	524
S				2	4	15	5	3	.8	2	12	7	9	5	3	29	28	4	5	5	119
Kaolinitic Soils																					
2AA	0	37	5.7	3	4	4	1	0	.6	10	13	9	96	27	6	125	71	12	14	35	460
$2AB_1$	0	47	5.8	3	0	0	0	0	0	10	13	9	92	30	3	111	60	10	17	17	478**
$2AB_2$	0	47	5.2	3	1	0	1	0	.2	14	8	15	88	30	3	103	37	7	12	7	368
4TA	0	40	6.3	5	3	10	4	0	1.3	11	0	16	103	21	6	78	37	6	12	57	323
4TB	0	42	6.1	5	1	8	12	0	1.1	10	6	13	107	19	15	147	91	15	11	68	369**
4TC	0	47	6.8	6	1	7	5	0	2.1	12	4	12	99	27	6	74	37	5	17	52	396**
$\overline{X}$				4	1	5	4	0	.9	11	7	12	98	26	6	106	56	9	14	39	399
S				1	1	4	4	-	.6	2	5	3	7	5	4	28	23	3	3	24	59

* Unconfine Compression Test. Maximum time between lime-soil fabrication (initial mixing) to compression test 30 minutes. 5% lime content.

** Calculated Soil Particle Surface Area - Not corrected for specific gravity. 209 highly cemented soil 6MC. 35% Montmorillonite, 6% Clay size (MA).

*** Moisture remaining in "Instant Test" specimen after oven-drying procedure,

$\overline{X}$ = mean

S = estimation of the standard deviation

Table 30 Similarity of Soil Properties of Group 1 and Group 4 Soils

Reactivity Group	Developed Strength Criteria	No. of Soils	Mean Values * CEC	% BS	Ca/Mg	* Ca	* Mg	% CO_3	% Sd	% Si	% Cl	Sd/Si	Sd/Cl	Exclusive Properties for Group 1 and 4 — Values indicate number of soils: % Fixed Moisture 1.3 to 1.6	% Fixed Moisture >2.0	% CO_3 >0.4%	% SO_4 >0.20	Misc. % Montmorillonite >15%
1	fails	11	29	83	2.8	14	7	1.6	42	29	29	1.4	1.4	4	3	3	2	4
4	high	17	28	94	2.6	17	9	1.0**	42	31	27	1.4	1.6	5	3	8	2	5
mean			28	88	2.7	16	8	1.3	42	30	28	1.4	1.5					
2	low	5	14	65	2.2	6	2	.1	53	28	19	1.9	2.8	0	0	0	0	1
3	medium	8	10	73	2.5	5	2	.1	52	24	24	2.2	2.2	0	0	0	0	0
mean			12	69	2.4	6	2	.1	52	26	22	2.0	2.5					

* Meq/100 gm

** Soil 6 MC with 15.1% CO_3 was not included because it tends to distort the other values.

Sacramento Soil Series

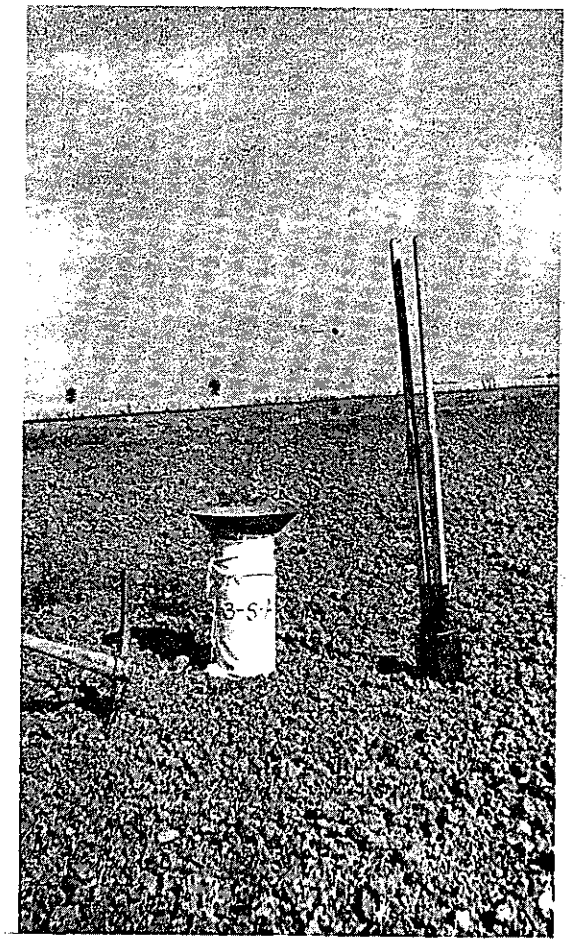


Photo 1 Field location of Sacramento soil series.

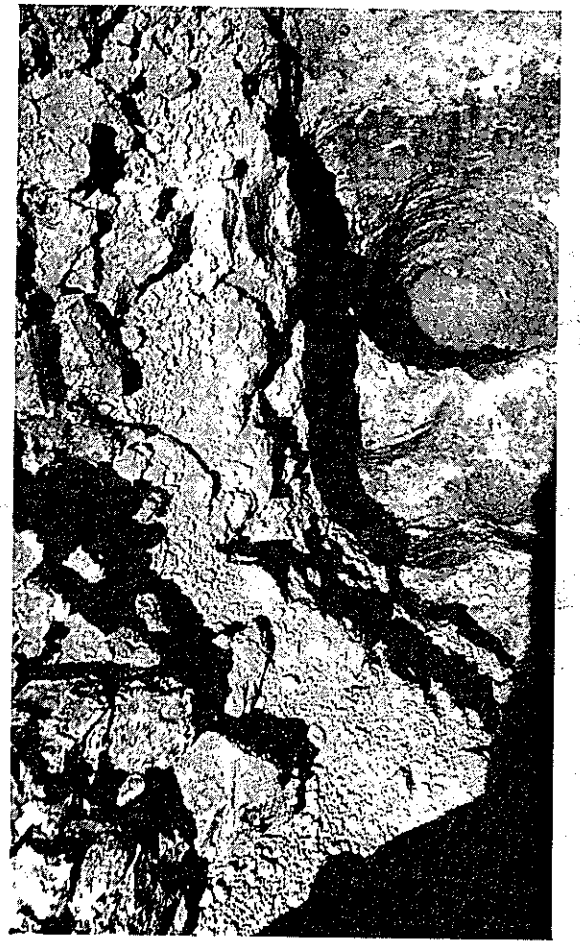


Photo 2 View showing excavation. Note: Water table.

Photo 3 Wet soil ("C" horizon) being air dried.

Photo 4 Soil being processed before fabrication.

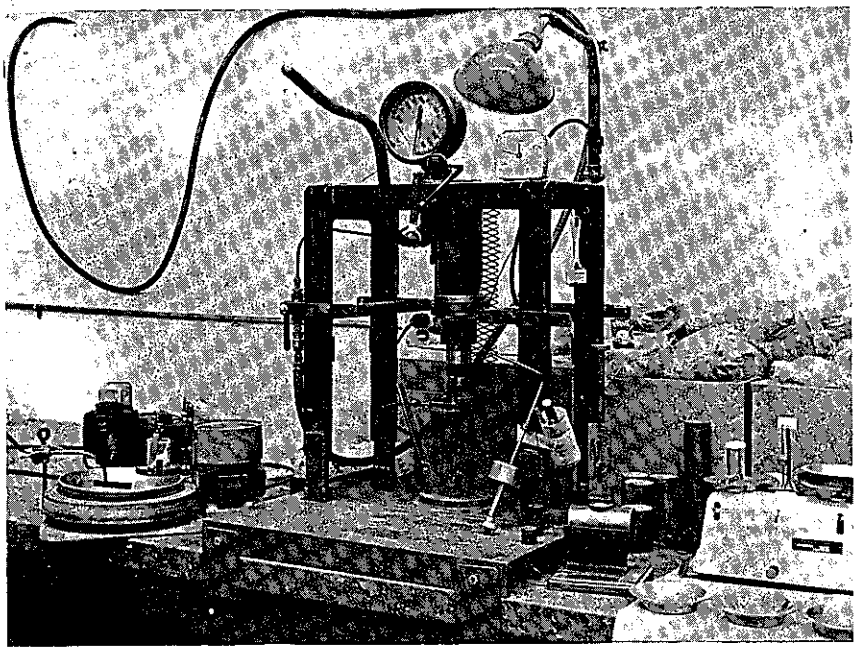


Photo 5 Main elements of the specimen fabrication equipment. Left to right: Balance, soil specimen caliper, compactor and mixing equipment.

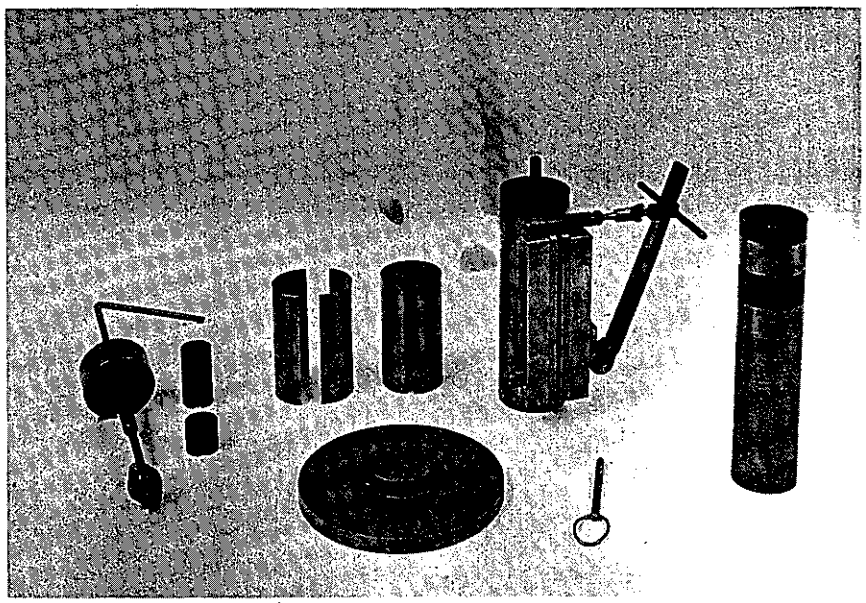


Photo 6 Quick release mold showing uniform depth scarifier and double split specimen retainer

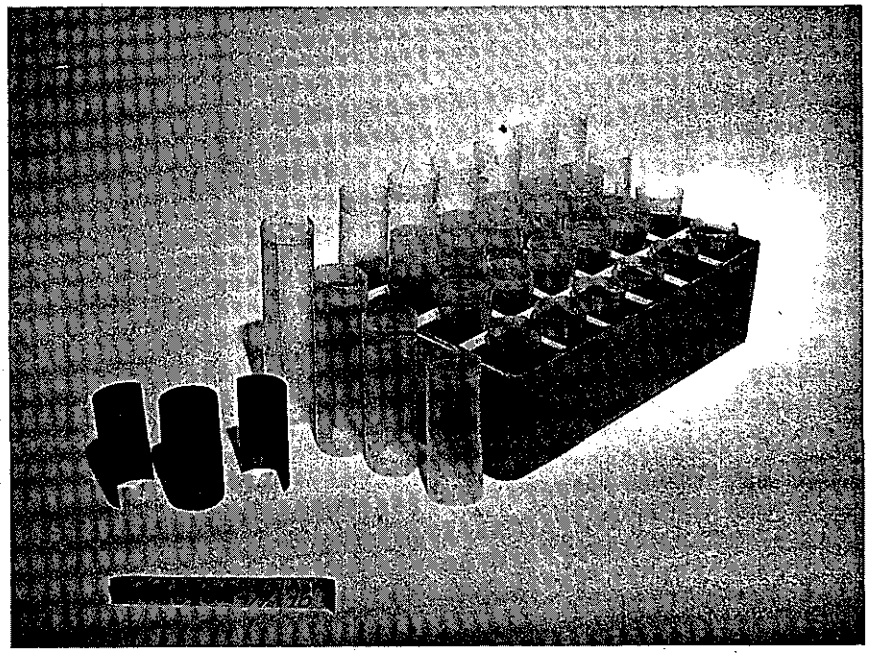


Photo 7 Waxed paper liner ready to be placed in a mold for fabricating sticky soils and sandy soils.

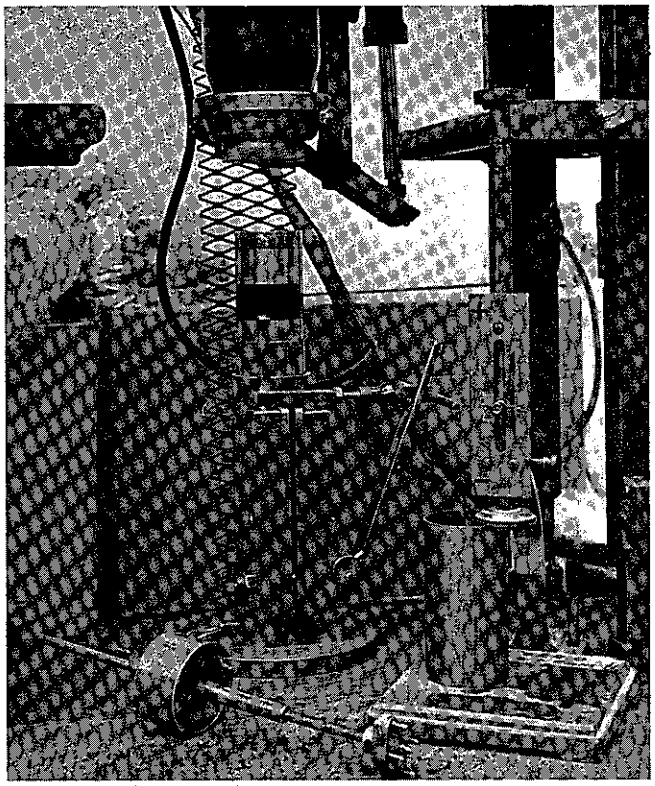


Photo 8 Close-up view of the "quick" release fabrication mold with piston in place. Also showing uniform depth scarifier (lower left) and device for obtaining geometric properties after fabrication.

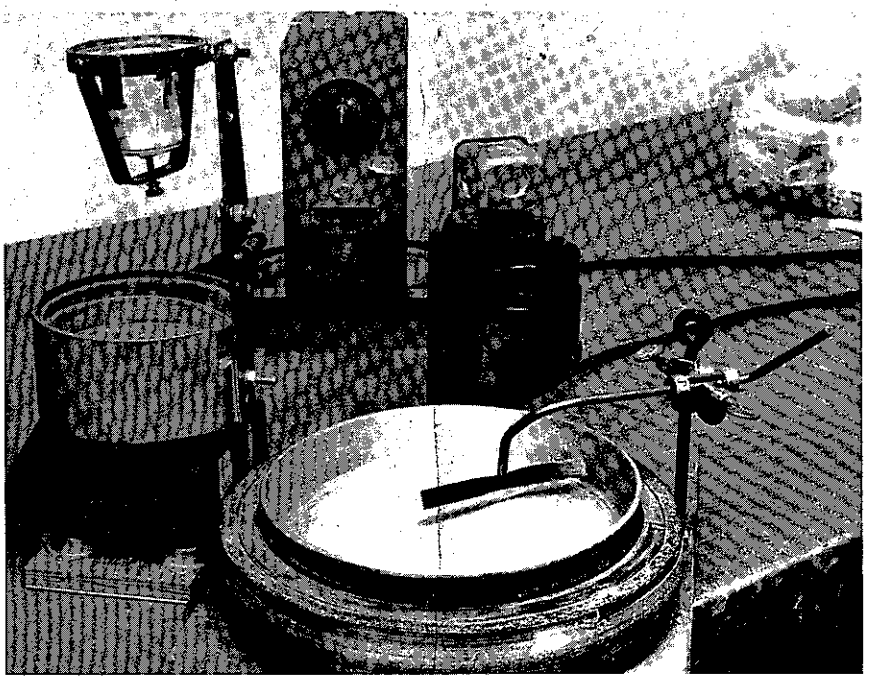


Photo 9 Lime-soil mixing equipment showing motorized turntable and lime vibrator in loading position.

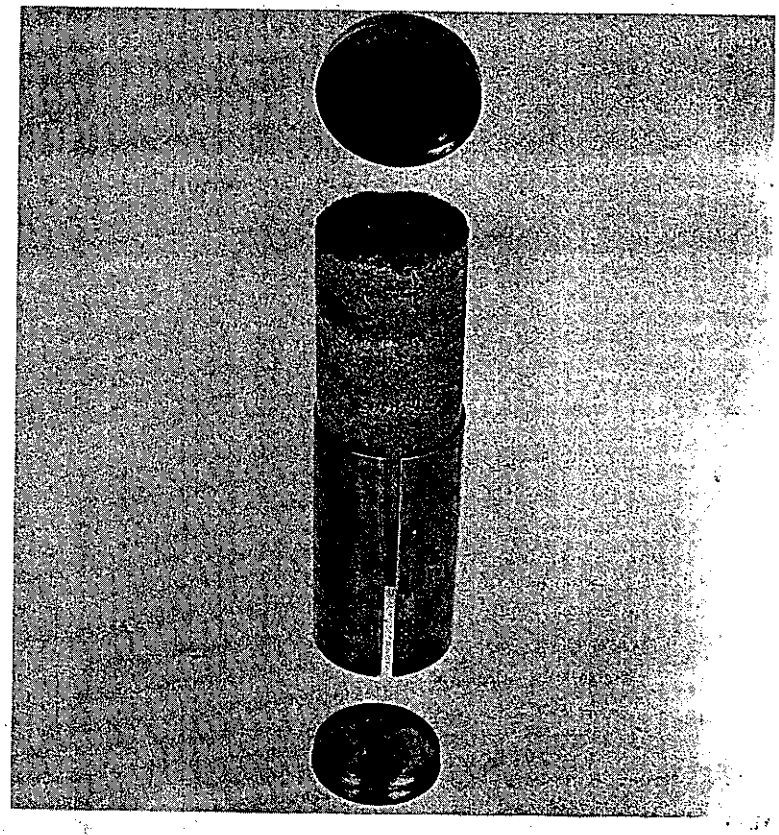


Photo 10 Lime treated specimen in "split" California sample retainer.

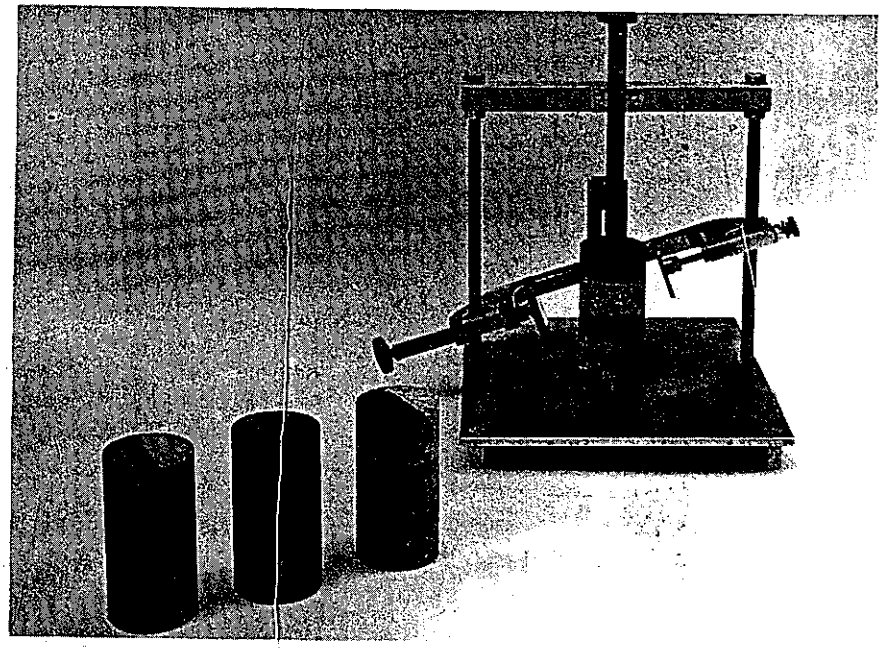


Photo 11 Device for determining geometric properties of specimens after curing. Note: Treated (light) and untreated (dark) portions. See Mixing in text.

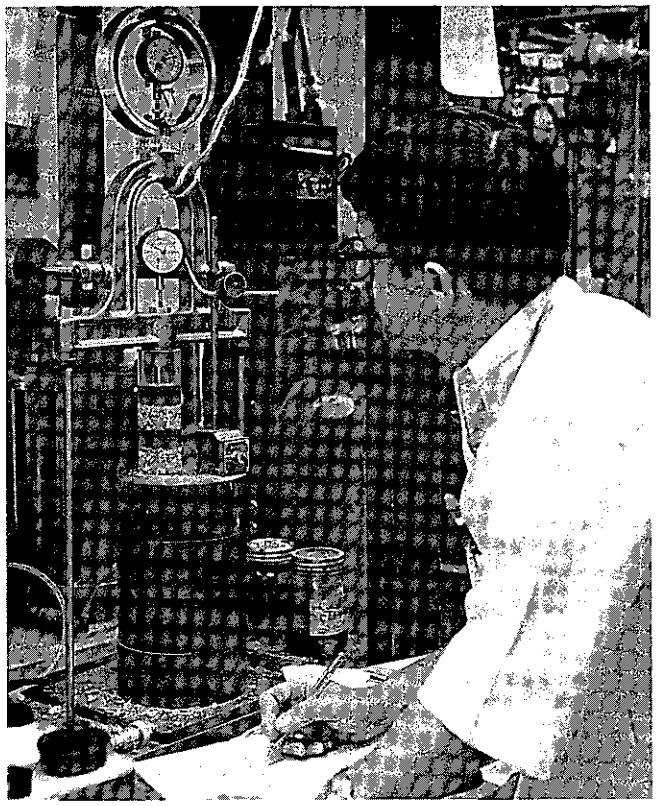


Photo 12 View showing triaxial equipment being used to determine unconfined compressive strength values.

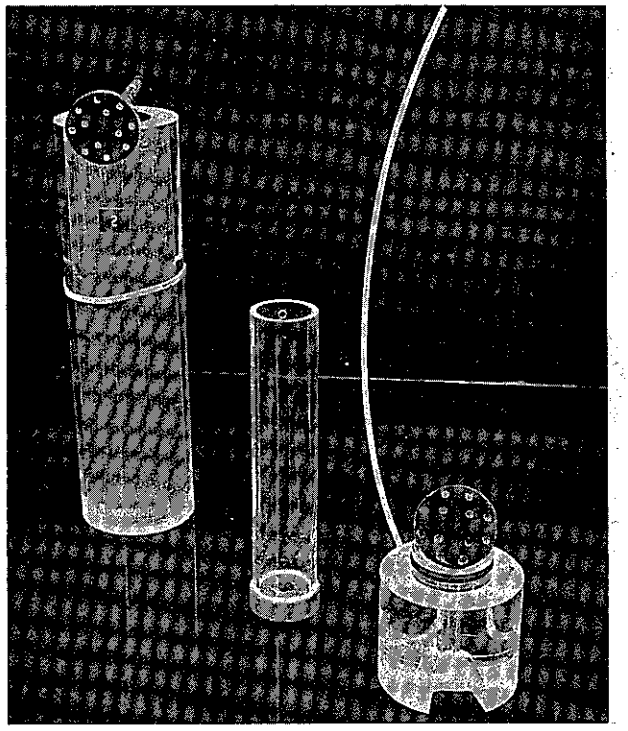


Photo 13 A view of the specimen cell showing platinum coated electrodes. Used when electrically monitoring the lime-soil reaction.

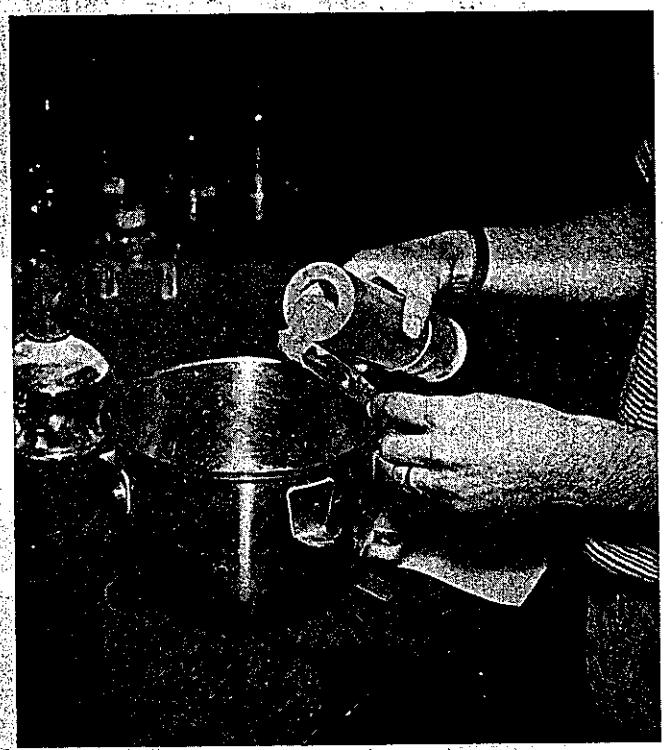


Photo 14 Specimen cell being filled with lime-soil water paste.

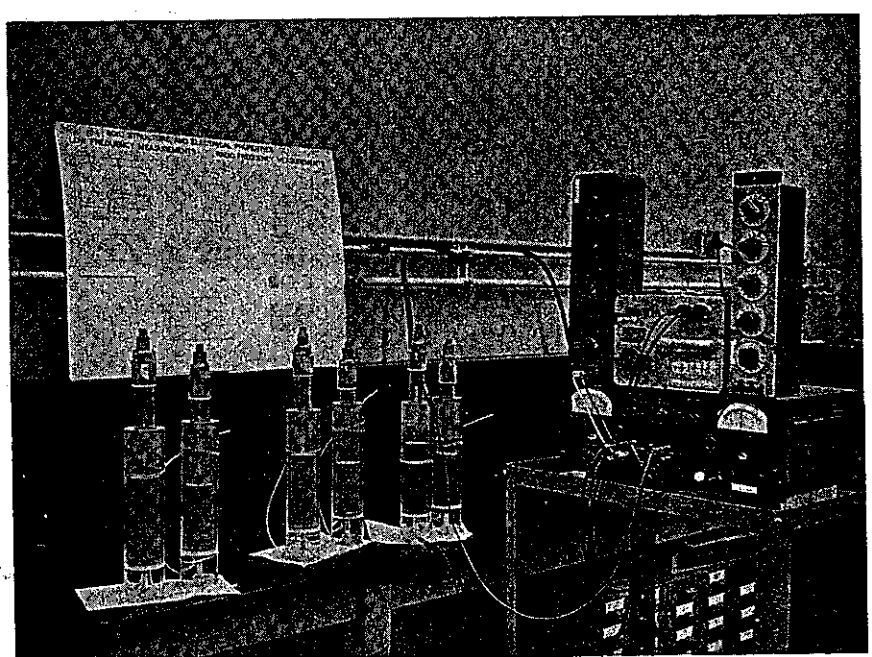


Photo 15 View showing 3 sets of lime-soil slurry specimen cells. One cell is temporarily attached to the electrical response detecting equipment. Note: the two different specimen heights (4" and 2½").

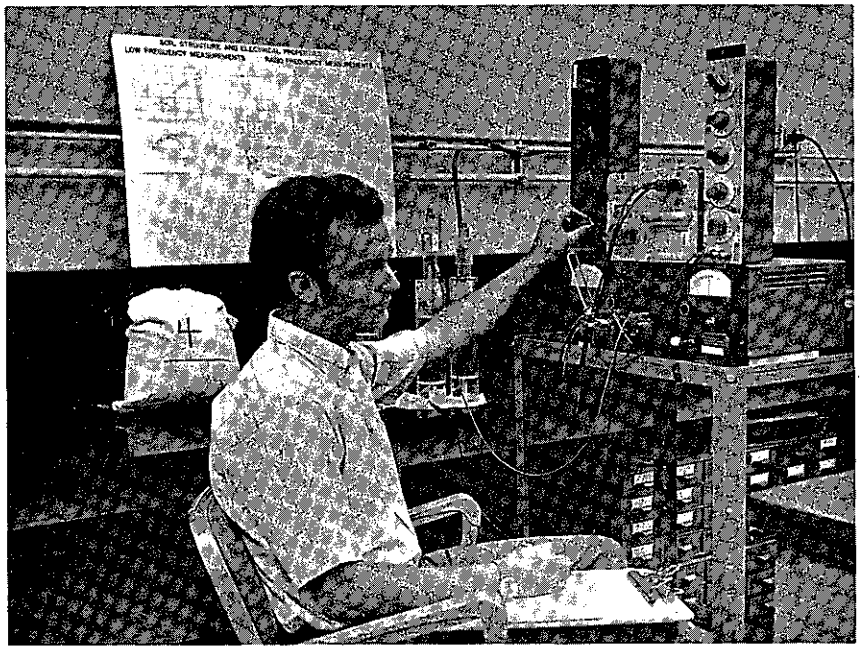


Photo 16 Operator making final adjustments prior to taking electrical data which will be used in calculating the resistance and capacitance of the paste specimens. Equipment top left to right: decade capacitor, precision capacitor 1 - 100 pf and decade resistor. Bottom impedence comparator.

GLOSSARY A

SOIL SCIENCE TERMS
(references 13, 46, 47)

BASE-SATURATION PERCENTAGE - - The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen. It is expressed as a percentage of the total cation-exchange capacity.

BENCHMARK SOILS - - A soil classification system, compiled by the United States Department of Agriculture, Soil Conservation Service, will be used for the selection of soil samples. This classification system defines Land Resource Regions which in turn are divided into Major Land Resource Areas.

The Land Resource Areas contain various benchmark soils. Benchmark soils are soils selected from a soil classification chart for the State, and, taken together, will represent extreme ranges in soil properties. These soils usually represent major great soil groups that occur in the State. They were selected because they represent a large area or a key position in the soil classification system or both. Their selection may also depend upon certain critical soil properties such as permeability, texture and pH. These benchmark soils taken together, say in a given county, represent a range of soil conditions existing within the county.

To date, there are approximately 116 soil units selected as benchmark soils in California by the U. S. Department of Agriculture, Soil Conservation Service.

CATION-EXCHANGE CAPACITY - - The sum total of exchangeable cations that a soil can adsorb. Sometimes called "total-exchange capacity," "base-exchange capacity," or "Cation-adsorption capacity." Expressed in milliequivalents per 100 grams of soil (or of other adsorbing material such as clay).

CLASSIFICATION, SOIL - - The systematic arrangement of soils into groups or categories on the basis of their characteristics. Broad groupings are made on the basis of general characteristics and subdivisions on the basis of more detailed differences in specific properties. In the United States the following system has been used for a number of years (from Soil Survey Staff, SCS, USDA. 1960. Soil Classification: A comprehensive system -- 7th approximation. p. 9. U. S. Government Printing Office, Washington). See order, soil association, soil horizon and soil series.

DRAINAGE, NATURAL - - Refers to moisture conditions that existed during the development of the soil, as opposed to altered drainage, which is commonly the result of artificial drainage or irrigation but may be caused by the sudden deepening of channels or the blocking of drainage outlets. Seven different classes of natural drainage are recognized.

1. Excessively drained soils are commonly very porous and very rapidly permeable and have a low water-holding capacity.

2. Somewhat excessively drained soils are rapidly permeable and are free from mottling throughout their profile.

3. Well-drained soils are typically free from mottling, moderately permeable, and commonly of medium texture.

4. Moderately well drained soils commonly have a slowly permeable layer in or immediately beneath the lower subsoil. They have uniform color in the surface soil and in the upper subsoil and have mottling in the lower subsoil and in the substratum.

5. Imperfectly or somewhat poorly drained soils are wet for significant periods but not all the time, and many soils commonly have mottlings below 6 to 16 inches in the lower surface soil and in the upper subsoil.

6. Poorly drained soils are wet for long periods and are light gray and generally mottled from the surface downward, although mottling may be absent or nearly so in some soils.

7. Very poorly drained soils are wet nearly all the time. They have a dark-gray or black surface layer and are gray or light gray, with or without mottling, in the deeper parts of the profile.

Source: U. S. Dept. of Agriculture Soil Conservation Service

ORDER - - The following scheme has been proposed for adoption as the official system in the United States (from Soil Survey Staff, SCS, USDA, 1960. Soil classification: A comprehensive system--7th approximation. p. 13. U. S. Government Printing Office, Washington)

Present order	Approximate equivalents
1. Entisols	Azonal soils, and some Low-Humic Gley soils
2. Vertisols	Grumusols

3.	Inceptisols	Ando, Sol Brun Acide, some Brown Forest, Low-Humic Gley, and Humic Gley soils
4.	Aridisols	Desert, Reddish Desert, Sierozem, Solonchak, some Brown and Reddish Brown soils, and associated Solonetz
5.	Mollisols	Chestnut, Chernozem, Brunizem (Prairie), Rendzina, some Brown, Brown Forest, and associated Solonetz and Humic Gley soils
6.	Spodosol	Podzols, Brown Podzolic soils, and Ground-Water Podzols
7.	Alfisols	Gray-Brown Podzolic, Gray Wooded soils, Non-calcic Brown soils, Degraded Chernozem, and associated Planosols and some Half-Bog soils
8.	Ultisols	Red-Yellow Podzolic soils, Reddish-Brown Lateritic soils of the USA, and associated Planosols and half-Bog soils
9.	Oxisols	Laterite soils, Latosols
10.	Histosols	Bog soils

PARENT MATERIAL - - The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum of soils is developed by pedogenic processes.

PED - - A unit of soil structure such as an aggregate, crumb, prism, block, or granule, formed by natural processes (in contrast with a clod, which is formed artificially)

SOIL ASSOCIATION - - (i) A group of defined and named taxonomic soil units occurring together in an individual and characteristic pattern over a geographic region, comparable to plant associations in many ways. (Sometimes called "natural land type.") (ii) A mapping unit used on general soil maps, in which two or more defined taxonomic units occurring together in a characteristic pattern are combined because the scale of the map or the purpose for which it is being made does not require delineation of the individual soils. Four soils used in this study are associated in this way. They are: the Bonsall, Placentia, Vista and Fallbrook soil series.

SOIL HORIZON - - A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, strucutre, texture, consistency, kinds and numbers of organisms present, degree of acidity or alkalinity, etc. The following table lists the designations and properties of the major soil horizons. Very few if any soils have all of these horizons well developed but every soil has some of them.

A. Mineral horizons consisting of: (i) horizons of organic-matter accumulation formed or forming at or adjacent to the surface; (ii) horizons that have lost clay, iron, or aluminum with resultant concentration of quartz or other resistant minerals of sand or silt size; or (iii) horizons dominated by (i) or (ii) above but transitional to an underlying B or C.

B. Horizons in which the dominant feature or features is one or more of the following: (i) an illuvial concentration of silicate clay, iron, aluminum, or humus, alone or in combination; (ii) a residual concentration of sesquioxides or silicate clays, alone or mixed, that has formed by means other than solution and removal of carbonates or more soluble salts; (iii) coatings of sesquioxides adequate to give conspicuously darker, stronger, or redder colors than overlying and underlying horizons in the same sequum but without apparent illuviation of iron and not genetically related to B Horizons that meet requirements of (i) or (ii) in the same sequum; or (iv) an alteration of material from its original condition in sequums lacking conditions defined in (i), (ii), and (iii) that obliterates original rock structure, that forms silicate clays, liberates oxides, or both, and forms granular, blocky, or prismatic structure if textures are such that volume changes accompany changes in moisture.

C. A mineral horizon or layer, excluding bedrock, that is either like or unlike the material from which the solum is presumed to have formed, relatively little affected by pedogenic processes, and lacking properties diagnostic of A or B but including materials modified by: (i) weathering outside the zone of major biological activity; (ii) reversible cementation, development of brittleness, development of high bulk density, and other properties characteristic of fragipans; (iii) gleying; (iv) accumulation of calcium or magnesium carbonate or more soluble salts; or (vi) cementation by alkali-soluble siliceous material or by iron and silica.

SOIL SERIES - - The basic unit of soil classification being a subdivision of a family and consisting of soils which are essentially alike in all major profile characteristics except the texture of the A horizon.

TAXONOMIC UNIT - - A taxonomic unit is a creation in the mind of man to facilitate his thought about objects in numbers so great that he cannot comprehend them individually. At a single site, the soil is examined vertically and horizontally in one place. The observer digs deeply enough to examine each horizon, including the parent material and any underlying strata that influence the genesis and behavior of the soil. The soil examination extends horizontally, in the third dimension, far enough for sampling. In relation to the whole three-dimension soil area, the places examined are little more than points.

GLOSSARY B

ELECTRICAL TERMS AND CHARACTERISTICS

(From 5, 36, Handbk. of Chem. & Physics, The Chem. Rubber Pub. Co. and 43rd Ed. Electronics and Nucleonics Dictionary. McGraw-Hill 1960 by Nelson M. Cooke and John Markus)

CONDUCTANCE - - The reciprocal of resistance, is measured by the ratio of the current flowing through a conductor to the difference of the potential between its ends.

CONDUCTIVITY - - is measured by the quantity of electricity transferred across a unit area, per unit potential gradient per unit time, reciprocal of resistivity.

COMPARATOR - - An electronic instrument that measures a quantity and compares it with a precision standard.

DIELECTRIC - - A material that can serve as an insulator because it has poor electric conductivity.

DIELECTRIC CONSTANT (ALSO CALLED PERMITTIVITY) - - The property of a material that determines how much electrostatic energy can be stored per unit volume when unit voltage is applied.

If for a sinsoidal current a phase difference exists between current and field then one obtains a complex dielectric constant ε^*, which can be separated into real and imaginary parts as

$$\varepsilon^* = \varepsilon^1 - j\varepsilon^{11}$$

The imaginary part of the complex dielectric constant ε^{11} is related to the conductivity, σ, $\sigma=\omega\varepsilon^{11}\varepsilon_r$. If a conductivity due to ionic origin, σ_o, exists at DC level when $\sigma-\sigma_o=\omega\varepsilon^{11}\varepsilon_r$; therefore, $\varepsilon^{11}=(\sigma-\sigma_o)/\omega\varepsilon_r$, in which ε_r = the dielectric constant of vacuum = 8.85×10^{-14} farads per cm.

The term j is a complex operator that is mathematically equivalent to the square root of -1. ε^1 of pure water is 78.5

DISPERSION CHARACTERISTICS - - The magnitude and nature of the variation of conductivity (σ) and dielectric constant (ε) with frequency ($\sim$).

DIELECTRIC DISPERSION AND CONDUCTIVITY VS. SOIL VARIABLES

Electrolyte concentration

Dielectric disperson, σ_{DC}/σ_{AC} et. al., increased with an increase in the electrolyte concentration

Electrolyte type

The larger the hydration radius of an ion (e.g., Li 9.8Å, N_a 6.7Å and K 4.5Å), the larger is the dielectric dispersion and the smaller is the value of σ_{DC}/σ_{AC}

ELECTRICAL CHARGES IN FINE-GRAIN MATERIAL

AC dielectric constant (ε^1) and conductivity (σ)

The impressed AC field produces a response which can be measured in terms of resistance (R), and capacitance C.

Where:

$$\varepsilon^1 = \frac{Cd}{A}\,\frac{1}{\varepsilon_r} \text{ and } \sigma = \frac{d}{RA}$$

Then d = length of specimen
A = cross sectional area
ε_r = dielectric constant of vacuum (8.85×10^{-14} farads per cm)

When C and R are independent of voltage then the electrical response characteristics depend only on the structure and composition of the material.

Amplitude (the value of a varying quantity at a specified instant) will vary with

1. Type of charge
2. Degree of association of charge with particle surfaces
3. Particle orientation
4. Temperature
5. Strength of electrical field
6. Frequency of " "

Dielectric constant at low frequency

A measure of the amount of polarization that can develop when a relatively long time is available.

Nature of surface

Since the relative bonding intensities in clays are $Li^+ < Na^+ < K^+$ etc., the relative ease of displacement of the different ions would be expected to be Li>Na>K and thus the dielectric disperson change for a Li clay would be greater than a Na clay which would be greater than a K clay.

Particle orientation

When the current is parallel to the long axes (or oriented particles) the dielectric disperson is 2-3 fold greater (charges easier displaced) than when the current is perpendicular to the long axes, whereas the σ_{DC}/σ_{AC} changes are similar whether the current is parallel or perpendicular to the long axes (perhaps the free charges are involved rather than the bond charges).

Particle size

For a given system, with an increase in particle size, there is an increase in dielectric dispersion and σ_{AC} decreases more rapidly than σ_{DC} with an increase in particle size.

Some types of charges

1. Ions in solution

   Free to drift through the system and discharge at the electrodes producing a DC conductivity.

2. Bound charges

   Not free to drift from one electrode to the other. Oscillates under the action of an AC field which produces a polarization and can be measured as a polarization current.
   The amount and strength of these charges are influenced by

   1. Particle surface structure
   2. Number of unsatisfied surface bonding sites
   3. Net electrical charge of the particle itself

Temperature

With an increase in temperature the dielectric dispersion increases (the charges are made more mobile by a decrease in the binding tendency to the surface) whereas the σ_{DC}/σ_{AC} remains constant (probably due to the relative mobilities of the dissociated + and - charges remaining constant).

Water content

When the water content is decreased there is an increase in the dielectric dispersion (due to the increased amount of surface charge relative to the free charges in the pore water) but there is a decrease in the σ_{DC}/σ_{AC}. (This may reflect the coupling effects between the current flow and water flow and the increase in surface conductance with decrease in water content).

Polarization

A separation between centers of + and - charge at any instant.

Polarization current

A measure of oscillation of charges.

Polarizability of a medium

Number of charges per unit volume times the average displacement. The magnitude is determined by the composition and structure of the material. The magnitude is also reflected by the dielectric constant, ε.

The precise relationship between dielectric constant and polarizability is dependent on the model chosen to describe polarization. At a given void ratio, the dielectric dispersion is directly related to the polarizability.

Resistivity (Resistance, specific)

A proportionality factor characteristic of different substances equal to the resistance that a centimeter cube of the substance offers to the passage of electricity, the current being perpendicular to two parallel faces. Reciprocal of conductivity.

$R = p \frac{l}{A}$

R = resistance
l = length
A = cross-sectional area
p = resistivity

Zeta potential

A measure of the effective negative charge at the surface of the clay. Holds bound water film to the clay particle. Decreased by Ca^{++} replacing H^{+}, K^{+} and Na^{+}.

APPENDIX A

ELECTRICAL RESPONSE MEASURING TECHNIQUE

The following information is taken from K. Arulanandan and J. K. Mitchell (6, 36, et.al.,).

Electrode polarization developed into a major problem but was solved by the Schwan "electrode variation" technique*. This adverse polarization came about when the measurements were made using a two electrode system. The sought for data was the impedence of the highly conductive soil systems. By measuring the impedence of a soil specimen of length d_1 and then determining the impedence of a specimen of length d_2 the difference in the impedence values reflects the impedence of a phantom specimen of length equal to d_1-d_2 without the adverse polarization impedence.

Since the change of conductivity with frequency is usually small, minor temperature drifts can be important. Compensation for temperature drift is made by returning after each reading to a standard frequency (say 1 Kc). Plots of 1 Kc values versus time usually yield smooth curves which permit the application of an interpolated temperature correction to conductivity values at other frequencies. The validity of this technique was based on the experimentally verified assumption that the temperature drift equally affects values at all frequencies.

Measurements were made in the frequency range of $30-10^5$ Hz at such low intensities of applied voltage that Ohm's Law was fulfilled.

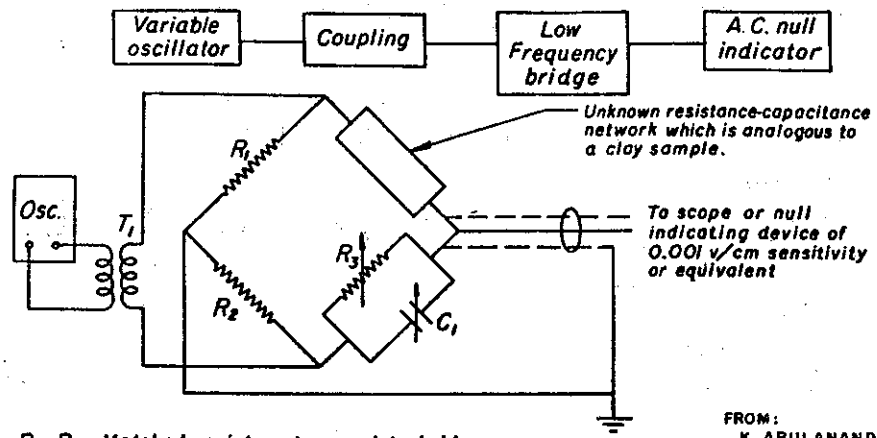
It has been shown that linearity between voltages and current exists when current densities less than 10^{-3} amps/cm^2 were used. In all measurements a current density less than 10^{-3} amps/cm^2 was used and found to be satisfactory.

INSTRUMENTATION

Impedances were measured with a "Comparator", Type 1605 AM (General Radio Corporation). This instrument is essentially a wheatstone bridge with a sensitive visual null indicator. Series of measurements of the impedances of clay-water-electrolyte systems were carried out within the frequency range 100-100,000 Hz using the comparator. Since the comparator only enables deter-

*Schwan, H. P., "Determination of Biological Impedence", Physical Techniques in Biological Research, Vol. VI, Academic Press, New York and London (1963).

mination of capacitance and resistance at frequencies of 100 Hz, 1,000 Hz, 10,000 Hz, and 100,000 Hz, a special low frequency bridge was developed for measurements at 30 and 300 Hz. The schematic diagram of this low frequency bridge is shown below.



FROM: K. ARULANANDAN AND J. K. MITCHELL (6)

R_1-R_2 Matched resistors to complete bridge
R_3 Resistance decade box
C_1 Capacitance
T_1 Transformer to isolate bridge network from oscillator ground. Frequency response flat from 20 to 3000 cps

Schematic diagram of low frequency bridge.

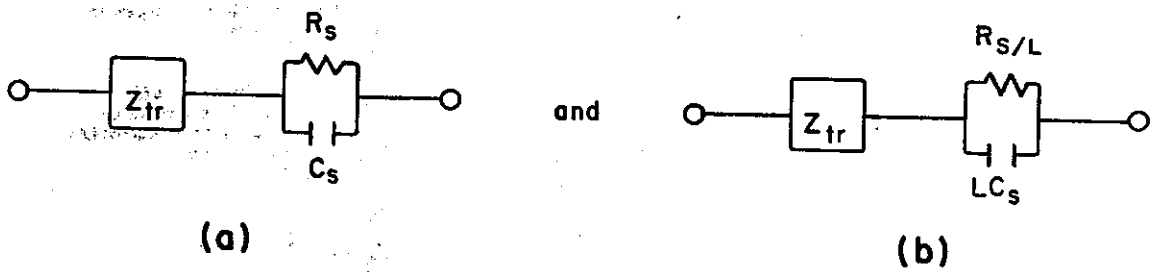
At each frequency the bridge was balanced with a standard capacitance and resistance. The value of standard resistance chosen was nearly equal to that of the soil sample. Standard capacitances of 0.01μ and 150μμf were used at 100 Hz and at 1,000, 10,000, 100,000 Hz, respectively. The standard resistance was then removed and the cell with the soil sample connected in parallel with the standard capacitance and the bridge balanced again. The values of capacitance and resistance of an equivalent parallel circuit of these two components were read directly on the instrument. The instrument readings gave the resistance of the sample, the capacitance of the sample, the capacitance due to electrode polarization and the standard capacitance. The standard capacitance was subtracted from the instrument raading to obtain the sample capacitance and the effects due to electrode polarization.

The design of the sample cell and the connections to the bridge terminals enabled measurements of soil columns of different lengths and thus elimination by computation of the appreciable influence of electrode polarization, especially at the very low

frequencies. The cylindrical sample was held between two flat circular platinum electrodes which were platinum black coated. The distance between these electrodes could be changed and thus samples of different lengths could be tested.

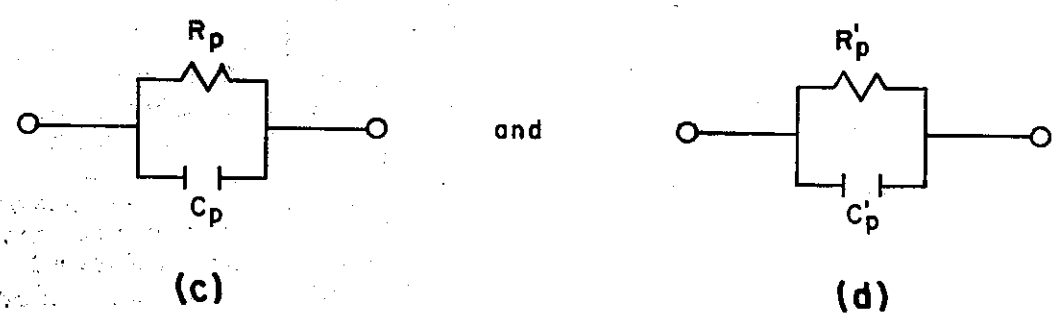
ANALYSIS OF DATA

The measured impedances were interpreted in terms of the following circuits:



These networks consist simply of two impedances in series. One of these series impedances, Z_{tr}, represents the electrode polarization impedance, the other composed of a resistance and a capacitance in parallel (R_s, C_s and $R_{s/L}$, C_sL as depicted in the above graphical illustrations for samples whose lengths are in the ratio L, respectively) represents the sample.

Equating the expressions for the impedances of circuits (a) and (b) obtained from elementary network analysis, to those of (c) and (d),



respectively, one obtains two equations of complex variables from which the electrode polarization impedance, Z_{tr}, can be eliminated. The real and imaginary parts of the resulting single equation then lead to Eqs. (1) and (2) for the true resistance (ohms) and capacitance (μμf) of the sample, respectively, at frequency, f(sec^{-1}).

Equations (1) and (2) below contain R_p, C_p, R_p^1, and C_p^1 which are read directly from the comparator and the low frequency bridge at the frequency, ω. By performing these measurement at different frequencies, the source data were obtained:

$$R_s = \frac{\left[\frac{R_p^2 C_p}{1+\omega^2 R_p^2 C_p^2} - \frac{R_p'^2 C_p'}{1+\omega^2 R_p'^2 C_p'^2}\right]^2 (1+R_p^2\omega^2 C_p^2)(1+R_p'^2\omega^2 C_p'^2)\, l\omega^2}{[R_p(1+R_p'^2\omega^2 C_p'^2) - R_p'(1+R_p^2\omega^2 C_p^2)]\,(l-1)} + \frac{[R_p(1+R_p'^2\omega^2 C_p'^2) - R_p'(1+R_p^2\omega^2 C_p^2)]\, l}{(1+R_p^2\omega^2 C_p^2)(1+R_p'^2\omega^2 C_p'^2)\,(l-1)} \quad (1)$$

$$C_s = \left[\frac{(1+R_p\,\omega^2 C_p^2)(1+R_p'^2 C_p'^2\omega^2)(l-1)}{R_s\omega^2 R_p(1+R_p'^2 C_p'^2\omega^2) - R_p(1+R_p^2\omega^2 C_p^2)\, l} - \frac{1}{R_s^2\omega^2}\right]^{1/2} \quad (2)$$

Conductivity (σ) mhos/cm: the dielectric constant (ε^1): and dielectric loss, $\varepsilon^{11} = (\sigma - \sigma_0/\omega\varepsilon_r)$, where σ_0 is the D.C. conductivity: $\omega = 2\pi f$; and $\varepsilon_r = 8.85 \times 10^{-14}$ F*/cm, the dielectric constant in vacuum, were obtained by use of the expressions:

$$\sigma = \frac{d}{R_s A}$$

$$\varepsilon^1 \varepsilon_r = \frac{C_s d}{A}$$

Where d is the length and A the cross-section area of the sample.

These values of σ, ε^1 and ε^{11} depend only on the structure and composition of the material, provided the values of R_s and C_s are independent of voltage. The measurements of R_s and C_s were made at such low intensities of applied voltage that Ohm's Law was fulfilled, thus insuring the required voltage independence. In all measurements, a current density less than 10^{-3} amps/cm^2 was used and found to be satisfactory.

*F = Farads

APPENDIX B

CHEMICAL ANALYSIS OF LIME

A commerical grade of lime was generously donated by Diamond Springs Lime Company, Diamond Springs, Calif.

Hi Calcium Lime

CaO	68.8%
MgO	0.59%
K_2O	0.04%
Na_2O	0.04%
CO_3	3.37%
SiO_2	0.8%
Sieve Size	100% passing 100 mesh
	93.8% " 200 "

The lime was packaged in a heavy fiber bag wrapped in plastic and then stored in an air tight steel drum. A chemical analysis was determined from time to time and the results were consistent.

APPENDIX C

TEST METHODS USED TO DETERMINE NATURAL SOIL PROPERTIES

Soil Properties	Test Method
Engineering Properties	
Mechanical Analysis	Test Method No. Calif. 203*
Liquid Limit	" " " " 204
Plastic Limit	" " " " "
Sand Equivalent	" " " " 217
Impact Compaction Test	" " " " 216
R-value Test	" " " " 301
Unconfined Compression Test	" " " " 221
Surface Area	" " " " 340
Moisture Content	" " " " 216
Mineralogical Properties	
Qualitative Analysis	X-ray diffraction
" "	Differential Thermal Analysis
" "	Microscope (as required)
Chemical Properties	
SO_3	Routine analysis
CO_3	" "
Chloride	Test Method No. Calif. 404
Fe	
Total	Routine
Coating	Dithionite extraction - 6C2**
Magnetic Material	Routine
pH (1·1)	Routine
Extractable bases	5A3a**
" acidity	6H1a**
Cation-exchange capacity	5A2a**
Organic carbon	6A1**
Electrical Properties	Dr. Kandiah Arulanandan's Method (see Electrical Section of this report)

*Test Method in use by the California Department of Transportation
**U. S. Dept. of Agriculture (SCS) "Soil Survey Laboratory Methods and Procedure for Collecting Soil Samples" 1967

APPENDIX D

IMPLEMENTATION GUIDELINES

Introduction

As indicated in this report under "Lime-Soil Reaction Anomaly Involving Suspicious Soils," large lime-soil reactions do not always result in developed compressive strengths. There is evidence to support the theory that what normally are defined as nonreactive soils are chemically or physically highly reactive. Therefore, the term "nonreactive" when applied to lime treated soils that fail to meet the minimum developed compressive strength is not accurate.

For implementation purposes the Lime Reactivity Groups have been renamed as "Lime Stability" Group 1, 2, 3 and 4. Stability Group 1 (nonreactive) is considered unsuitable for lime stabilization based on low developed strength. On the other end of the scale, Group 4 soils are highly suitable for stabilization.

The variability in the magnitude and rate of gain of compressive strength of lime treated California soils has been substantiated in this study. This can be illustrated by the fact that the average developed strength of the highly reactive lime treated (Group 4) soils which were cured for less than 30 minutes ("Instant Test") was greater (63 psi) than the average developed strength of the nonreactive or unsuitable lime treated (Group 1) soils which were cured for 6 months (56 psi).

Montmorillonitic soils were found to increase in developed compressive strength when the lime treated soil is wetter than optimum moisture content while kaolinitic soils increase in developed compressive strength when the lime treated soil is drier than optimum.

Thus, the variability in the rate of gain in compressive strength of the lime treated soils used in this study was much in evidence. This rate of gain in compressive strength and the net amount of developed strength are the crux of the lime-soil stabilization problem. It has been often stated in the lime-soil statilization field that no variable (e.g., a natural soil property) can be considered as a separate isolated entity in the prediction of the compressive strength gained by a soil when it is treated with lime. Although in a negative sense, a single variable (e.g., a large quantity of organic matter) can be so overwhelmingly detrimental to the lime-soil stabilization mechanism that the

soil is immediately rejected from further consideration as a candidate for stabilization with lime. This rate of gain in compressive strength is then the central issue in lime-soil stabilization, and a method for predicting this phenomena is necessary. Furthermore, since the size of a lime-soil stabilization job can vary considerably and testing facilities are so diverse, one set of guidelines would be too cumbersome for field engineers or not detailed enough for a laboratory approach. This was resolved by using two approaches in presenting the implementation of the findings of this study. The "Generalized" method for the laboratory evaluation and the "rule-of-thumb" approach for estimation of developed compressive strength.

D-1 Generalized Laboratory Approach for Predicting Developed Strength

The first method encompasses the "Generalized" approach toward the implementation of the results from this study and may be used in its entirety or not, depending upon the comprehensive nature of the project. The developed compressive strength results generated from the use of this approach are expressed as psi and/or lime stability groups.

This method consists of three major divisions, which are: classification, identification and observation.

The classification portion (I), listed on Table D-1, includes the normal methods of classifying soils for engineering work. These methods are, "the Unified Soil Classification System," the USSCS soil series classification system with its soil horizon designation feature (see Glossary) and the two California Department of Transportation soil classification systems (see Table 2a, Classification).

The identification portion (II) includes those soil properties which may have a bearing on the overall stabilization results. These properties are categorized as engineering, mineralogical, chemical and electrical. These properties are not mutually exclusive however, because some of them (e.g., organic matter and carbonate) occur in more than one of the categories.

In the last portion (III), observation, of this "Generalized" approach, the behavior of the lime-soil mixture is noted. At present it consists of three subcategories: the electrical characterization of the lime-soil reaction (adsorption reaction and agglomeration reaction), the "Instant Test" compressive strength, and finally the "Fixed" moisture determination of the "Instant Test" specimen.

This "Generalized" method is summarized on Table D-1. A model procedure would be to first classify the questionable soil according to one or more of the tabulated classification systems. The United States Department of Agriculture - Soil Conservation Service publishes "Soil Survey Reports" which list the soil series classification and the soil horizon designation of the land surveyed. It also classifies soils for in situ drainage characteristics. These reports often contain voluminous amounts of useful soil property data.

The California Department of Transportation soils classification has two aspects. One is the field log soil description while the other is based upon the grain size analysis of the soil.

The field log soil description is obtained by manipulation of a small quantity of soil with the fingers. Water may be added to facilitate the test. The plastic behavior of the soil is noted as well as its "gritty" aspect. These and other observations (e.g., odor and color) are then combined to describe the soils texture.

The grain size description utilizes the mechanical analysis of the soil and subsequently the grain size triangular chart is used to determine the soil texture.

The classification of a soil can provide a preliminary indication of its potential developed strength. For example, if a questionable soil is classified as SC according to the Unified Soil Classification System it is a highly reactive soil and a 3% lime content could tentatively be selected. However, compressive strength tests would be required to confirm the final design.

Following the classification of the questionable soil the natural soil properties are estimated or determined. They may be estimated from the aforementioned U.S.D.A. - SCS Soil Survey Report. This can be accomplished by comparing the questionable soil with local soil samples or by determining the soil series name of the questionable soil and then searching through the various soil survey reports for a description and soil analysis of the same soil series.

The natural soil properties may be valuable in estimating the degree of developed strength of a soil. These soil properties are identified as engineering, mineralogical, chemical or electrical. The individual utilization of soil property data is given in the third column, labeled "Use" (Table D-1). Although one soil property such as clay content may provide an estimate of the minimum developed strength, an additional soil property such as percent iron coating, if negligible for instance, can be useful in justifying a tentative lower lime content, say 3% instead of 5% lime content.

When the questionable soil is lime treated, at least three basic observations can be made. These three observations result from knowing the nature of the lime soil reaction by the electrical characterization test, testing the strength of a fabricated lime-soil mixture ("Instant Test") and finally an indication of the degree of the physical/chemical reaction by the "Fixed" moisture determined from an "Instant Test" specimen.

Not all of the items listed in column 1 of Table D-1 need be determined. Familiarity of the use of this chart will result in estimating a soil's developed strength using a minimum of test data. Some questionable soils require more than one estimator for developed strength in order to increase the degree of confidence in the overall estimation.

Presented below is an example showing the use of the "generalized" approach for estimating lime reactivity using Table D-1:

Assume the questionable soil is 13BB.

The following soil properties have been determined: (See Table 2a)

	Atterberg Limits
Sand 57%	LL = 26
Silt 20%	PL = 16
Clay 23%	PI = 10
Colloids 15%	

Max. Impact Dry Density (natural soil) = 127 pcf

Optimum Moisture Content of Natural Soil = 9%

Untreated, unconfined compressive strength = 66 psi

5% LC " " " 7-day cure = 124 psi (Table 10) Developed Strg

" " " " " 28-day cure = 147 psi Developed Strg

Instant test (<30 min.) developed strength (5% lime) = 81 psi (Table 8)

Instant test "fixed" moisture

Remaining = 1.2% (Table 4)

Original = 13.6%

Ingnition Loss = 5.3%

Iron coating = 0.3% Fe

Sulfate (SO_4) = 0%

Carbonate (CO_3) = 0%

Organic Carbon = 0.3%

Chloride = 0%

% Base Saturation = 89

Exchangeable Ca = 10.1 (Table 26)

Mg = 5.0

Nz = 3.2

K = 0.4

H = 2.3

pH (1:1) = 7.4

Soil Mineralogy (Table 14)

Mixed layer <5%, Hydrobiotite-Vermiculite 17%, Kaolinite 5% (Halloysite) Mica <5% (biotite), Feldspar 32% (Plagioclase 27%, Microcline 5%), Amphibole 5% and Quartz 22%.

Electrical Test Measurements (Table 20)

Dielectric constant, $\varepsilon^1 = 37 \times 10^3$ Native soil

$= 45 \times 10^3$ Treated soil

$\Delta\varepsilon^1 = 8 \times 10^3$ " "

Conductivity, $\Delta\sigma = 0.166 \times 10^{-3}$ mhos/cm

The first step in the "generalized" procedure is to classify the soil.

From Item I, this soil is a Bonsall B horizon; a clayey sand. It is an SC according to the Unified Classification System and as such is considered a Group 4 soil. From Item ID1 this clayey sand soil may be a Group 2, 3 or 4 soil.

There are no obvious detrimental natural soil properties such as sulfates.

The soils large (127 pcf) Impact Dry Density signifies a Group 2, 3 or 4 soil but from the MA (57% sand, 23% clay and 20% silt) it is a Group 1 soil with a minimum 6-month cure (5% lime content) developed strength of 90 psi (Fig. 6a). With a PI of 10 the soil is a Group 2, 3 or 4 according to IIA3a.

Next note the electrical characterization of the lime-soil reaction (IIIA2). This data (ε^1 of treated $>\varepsilon^1$ of natural and $\Delta\sigma \times \Delta\varepsilon^1 \times 10^3 > 1000$) indicates an agglomerative type reaction takes place. The x-ray diffraction scan estimates that this soil is not kaolinitic. Taken together, this indicates a Group 2, 3 or 4 soil (if the x-ray diffraction data is not available, use Table D-3 to estimate whether the soil is montmorillonitic, kaolinitic or none of these).

The value of the "Instant Test" is 81 psi. This developed strength indicates, according to IIIB, a Group 2, 3 and 4 soil but more probable a Group 4 soil.

The observed "Fixed" moisture content indicates that this lime treated soil does not behave as a lime treated montmorillonite nor a lime treated kaolinite.

Utilizing the "Tentative" guidelines (Tables 22 to 27) it is determined that this would be an agglomerative nonkaolinitic reaction.

In combining the results using the electrical characterization test (IIIA2), the "Fixed" moisture content (IIIC) and the "Tentative" guidelines (Tables 22 to 27) there is an overwhelming conclusion that the lime soil reaction is agglomerative non-kaolinitic.

That being the case, from IIIA2b, the 6-month developed unconfined compressive strength will be about 400 psi, using the dielectric constant of the natural soil of 37×10^3.

This long-term strength potential is supported by Items IA and IIIB and is further supported that this lime-soil reaction will be beneficial for strength development from Items IC, IIA1a, IIA3a, IIIA2 and IIIB. Only Item IIA2 detracts from this conclusion. An indication of the economical lime content can be obtained from Items IIA3c and e suggesting 3% and 3-1/2% lime contents respectively. Using the mechanical analysis, IIA2, for indicating economical lime content (which utilizes the clay content) a 5% lime content is suggested. However, the 7-day cure (5% LC) developed strength was 124 psi which is a very large developed strength and the soils which border the minimum developed strength curve (Fig. 6, soils 2AA, $2AB_2$, 4TA, 4TB and 4TC) were found to be acid soils (pH 5.2 to 6.8). These soils also have a high iron coating content (2.7% to 5.8%). The soil in question, 13BB, does not have these detrimental properties. Therefore soil 13BB can be thought of as an average soil with a 23% clay content for the purpose of using Fig. 6a.

D-2 Rule-of-Thumb Estimation of Developed Strength Based on Soil Properties

The following is a simplified procedure, or "Rule-of-Thumb" method, for predicting whether treatment of a particular soil with lime will produce a beneficial or detrimental result.

If the result is estimated to be beneficial, it would then be desirable to know what would be the minimum curing time required to achieve the minimum developed compressive strength. Values developed for lime stability Groups 2, 3 and 4 are tabulated near the bottom of Table D-1. For example, a soil classified as a Group 4 soil with high developed strength when treated with 5% lime will probably achieve the minimum developed strength of 100 psi in about 7 days.

The initial step then is to determine if a soil is suitable for lime stabilization. To do this begin with Step 1 on Table D-2. If the soil in question meets the criteria for any one of the soil properties in this category it may be assumed that the soil

will be unsuitable for lime treatment (from a developed strength point of view). One need go no further. Not all of the soil properties in Step 1 are relevant, however. As an example, if the only soil property known is its California Soil Classification, a judgment is made solely upon this property. However, more soil properties should be used, if known. Thus, a soil classified as a "sand" according to the California soil Classification and as "SP" according to the Unified Soil Classification is considered unsuitable for lime stabilization.

If the soil in question does not meet the criteria for any one of the known soil properties listed in Step 1 (unsuitable soils) proceed to Step 2 (mostly unsuitable Group 1, 2, 3 and 4 soils). If a lime treated (5%) soil is fabricated (90% relative compaction, optimum moisture, surface sealed, 70°F and 100% relative humidity) for 7 days and its compressive strength is determined to be greater than 160% lime reactivity then proceed to Step 3 to determine if the soil in question belongs in Group 1 or Group 4.

The soils qualifying in Step 3 are to be regarded with suspicion. They are either unsuitable or highly suitable. For instance, if the optimum moisture content of a soil is between 15% and 26% then the soil in question is a Group 1 or Group 4 soil. If the moisture content is, say 15% or less or greater than 26% the soil in question is not exclusively in Group 1 or 4.

If the soil qualifies in Step 3 (Group 1 or Group 4) then proceed to Step 7 (Group 4) to determine if the soil in question is highly suitable. Since not all highly suitable soils (Group 4) are covered in Step 7 it may be necessary to proceed to Step 4. Some of the soil properties listed in the various steps have an indication of the favorability of certain groups. Thus, in Step 5 when the P.I. of the soil is known and the value is greater than 10 and the soil is classified as a "B" horizon soil (see Glossary A) then from Table D-2 (Step 5) we find that it is likely that the soil is highly suitable (Group 4).

Therefore, since the soil in question qualifies in Step 3 and Step 5 (P.I. 10, "B" horizon soil), it can be classified as a Group 4 soil and suitable for lime stabilization. To increase the probability of correctly assigning the soil in question to its proper group use another soil property (e.g., Unified Soil Classification in Step 5 or Step 7). If the soil, however, does not qualify in Step 3 then proceed to Step 4 then Step 5 and finally Step 6.

After a soil is assigned to a lime stability group (1, 2, 3 or 4) it is then desirable to determine an economic lime content to use. Step 8 utilizes the Plasticity Index of the natural soil for this purpose. A Group 1 soil (unsuitable) requires 7%

lime. Caution: the use of 7% lime content with Group 1 soils is no guarantee of success, however. In Table 10 it can be seen that soil 17MC, when treated with 7% lime and cured for a 6-month interval, had a developed strength of only 10 psi (treated compressive strength of 14 psi).

Step 9 was added as a reminder that some lime treated soils (kaolinites) achieve greater strength when they are on the dry side of optimum moisture while others (montmorillonites) achieve greater strength when they are wetter than optimum.

The following is an example showing the use of the "Rule of Thumb" Method (Table D-2):

Assume the questionable soil is 13BB as before in the previous example (D-1). Note: The SCS (Soil Conservation Service) Soil Classification criteria considers only those soils with two or more soil horizons.

Step 1 indicates that the soil in question may not be unsuitable for stabilization with lime.

Proceed to Step 2

$$\% \text{ Developed compressive strength} = \frac{190-66}{66}(100) =$$

188%, >160% at 7 days

Therefore this lime treated soil is probably not mostly unsuitable.

Proceed to Step 3 to determine if soil belongs in Group 1 or 4, even though the Group 1 possibility has been largely discounted, only one soil property in this step suggests that the soil under consideration could be classified as being "suspicious." This soil property is the "Fixed" moisture content criteria; 12%-14%. Keep this item of verification in mind but do not allow it to attribute much weight to the final analysis.

From Step 4, the fact that this particular soil is suitable for lime stabilization is becoming more convincing. That the soils' maximum test density does not qualify for being "most suitable", is of minor concern, notwithstanding the fact that there were 27 soils (the largest number of soils in any one subcategory except Step 8 subcategories where it was intended to include all soils) that gave rise to this subcategory. But note that 41% of the 27 soils are classified as unsuitable (Group 1). Of the remaining subcategories, "Instant Test" (developed strength and % developed strength) and soil horizon designation taken together adds more credence that the soil in question is suitable for lime stabilization. Note that the "Instant Test" value of 188% developed strength is near the 200% specification.

Next compare this soil with the soil properties characterizing specifically suitable soils (Step 5).

Step 5. The soil, according to the criteria for this subcategory, meets nearly half (meets 5 criterion and fails 6 criterion) of the specifications for this subcategory.

Step 6. Since this soil is not Kaolinitic it may be in the "Not Highly Suitable" category. The "Highly Suitable" category is not strongly justified. Proceed to Step 7 for this consideration.

Step 7. According to the Unified Soil Classification this soil is "Highly Suitable" for stabilization with lime. Since this criteria is scantily based, viz only two soils (Remarks Col. Table D-2) support this criteria and one of them is the soil in question, leaves very little in the way of discovery that can be found here. As to the other two criteria, the SCS (Soil Classification System) is not to be considered, as noted immediately prior to Step 1, and, the carbonate specification is application to the "C" horizon soils only.

In summary, there is a stronger indication that this soil, 13BB, is not "unsuitable" for lime stabilization then there is for it being "suitable". But taken together the soil is estimated to be "suitable".

Since the soil is estimated to be "suitable" for stabilization, there remains the problem of estimating an economical lime content to use.

The Plasticity Index of the soil is utilized for this purpose according to Step 8. Since the plasticity of soil 13BB is within the 10-19 PI range 3% lime content is indicated. An estimate of the minimum developed strength from the clay content using 3% lime is 10 psi for the 7-day cure and 20 psi for the six-month cure (refer to figure at bottom of Table D-2). This is not too encouraging but the average developed strength using 3% lime is, according to Fig. 26, 100 psi for the 7-day cure and more than 250 psi for the 6-month cure. This soil, not having obvious detrimental natural soil properties, and no particular strong mineralogy may be considered to be an "average" soil.

<u>Estimation of a Soils Montmorillonitic or Kaolinitic Property by Soil Properties Alone (Not Using X-ray Diffraction or D.T.A.)</u>

It is desirable to know if a soil is montmorillonitic or kaolinitic in order to estimate the developed compressive strength when the soil is treated with lime. If a soil is montmorillonitic the 6 month developed compressive strength can be estimated by calculating

the montmorillonite content/moisture content ratio and then using the curve in Figure 14. The increase in strength may also be estimated if the electrical response test results are known. Figures 40a and 40b give a relationship between the electrical response ($\Delta\varepsilon^1 x \Delta\sigma$) and the developed strength after 6 months curing. Figure D-1 utilizes the dielectric constant for a similar purpose. It is also important to know if the soil in question is montmorillonitic because montmorillonitic soils increase more in strength when the moisture content of the lime treated soil is wetter than optimum. From Table 13 it is seen that the increase in strength can exceed 200%.

Similarly, if the soil is kaolinitic, the 6-month developed compressive strength can be estimated by knowing the clay content (Fig. 27) or the Plasticity Index of the natural soil (Fig. 25). When Kaolinitic soils are drier than optimum moisture the compressive strength increases. Table 13 shows that this increase is as much as 76%, while a wetter than optimum moisture lime-soil mixture can produce a strength loss up to 81%.

The knowledge that both montmorillonite and kaolinite are absent may also be valuable. For instance the 6 month developed strength of a lime treated nonmontmorillonitic soil (adsorptive lime-soil reaction) may be estimated when the pH of the natural soil is known (Fig. D-2) and Figure D-3 can be utilized for a nonkaolinitic soil (agglomerative lime-soil reaction) using the dielectric constant of the natural soil. Table D-3 was constructed to facilitate the estimation of a soils clay property. The four "clay properties" considered are those stated in the electrical portion of this report namely:

1. Montmorillonitic soils (adsorptive lime-soil reaction)

2. Nonmontmorillonitic soils (adsorptive lime-soil reaction)

3. Kaolinitic soils (agglomerative lime-soil reaction)

4. Nonkaolinitic soils (agglomerative lime-soil reaction)

The basic idea is to determine which one of the four "clay properties" listed above most nearly matches the soil (fine grain) in question. It is not sufficient to conclude that a given set of soil properties is indicative of a certain soil matrix (i.e. montmorillonitic soil). It is necessary, in the overall estimation, to be confident that the soil in question is NOT any one of the other three alternatives.

An example of this procedure is to consider the possibility that the soil in question is a montmorillonite. To test the validity of the assumption (using Table D-3) begin the comparisons with Part A, Step 1. In this step there are three common soil property criteria; surface area, clay content and PI, and four other soil property criteria; unconfined compressive strength, "Instant Test" (developed strength), "Instant Test"/pH, and dielectric constant. If a soil property value meets or exceeds the listed criteria, e.g., calculated surface area >500 cm^2/gm, then the questionable soil meets one of the conditions favoring the montmorillonitic subcategory selection. When a majority of the soil property criteria are met in Step 1, this indicates that the questionable soil should not be classified in the nonmontmorillonitic soil subcategory (adsorption category). However, the questionable soil is classified as a "possible" montmorillonitic soil but it does not necessarily follow that the questionable soil is classified in the montmorillonitic subcategory. Proceed to Step 2, and in a similiar manner, ascertain whether the questionable soil is a kaolinite (agglomeration) or if a montmorillonitic property criteria is met, then proceed to Step 3. If a majority of the questionable soil properties meet or exceed the criteria in this step, the questionable soil is not classified in the nonkaolinitic soil subcategory but is classified as belonging to the montmorillonitic soil subcategory. If the majority of the soil property criteria is not met in any one of the steps the questionable soil should not be classified in the montmorillonitic soil subcategory. The soil in question could be any one of the remaining three subcategories. Use Part B, Steps 1, 2 and 3 of the same table to ascertain whether the soil in question is in the kaolinitic soil subcategory.

The absence of some soil property criteria indicates that these soil properties are not considered significant for the particular comparisons. Thus, a soils calculated surface area may be significant when the montmorillonitic soil subcategory is being considered (viz Part A Step 1, 2 and 3; Part B Step 2) but is not significant when a questionable kaolinitic soil subcategory is being compared with a nonmontmorillonitic soil subcategory or a nonkaolinitic soil subcategory.

In summary, to estimate if a soil is predominately montmorillonitic or kaolinitic test each hypothesis to determine that the soil in question is <u>NOT</u> one of the other three alternatives. If the soil is not any one of the three other alternatives, then the hypothesis is presumed to be valid.

TABLE D-1 A "generalized" approach for estimating the lime reactivity of lime treated soils. Lime content is 5% and optimum moisture prevails unless otherwise noted. Results expressed in Developed Strength, psi, or Lime Stability Groups (see footnote).

Note: Abbreviations are given the footnote.

Item	Quantity	Use	Remarks	Reference
I. Soil Classification				
A. Unified soil classification	Group symbols SP,SM,SC, ML,CL,MH & CH.	SP, MH and CL-ML are Group 1 soils. CL is a group 2, 3 or 4 soil. SC is a Group 4 soil.	Boundary classification are also used.	
B. Soil series classification	Over 900 soil series thus far in California.	Imperial, Sacramento and Tournquist soil series are Group 1 soils. Aiken, Huerhuero, Lockwood, Merced, Montague, Panoche, Pescadero, Ramona, Salinas and Vista soil series are Group 2, 3 or 4 soils.	16I, 3S and 4T. Two or more soil horizons.	USDA-Soil Conservation Service Refer to Table 3
C. Soil horizon designation	A, B and C	Categorizing soil strata which differ in soil properties.	See IIA3b,c; IIC4 and IIIB	USDA-SCS Refer to Table 3.
D. Calif. Div. of Hwys. soil class				
1. Grain size	Sd, Si & Cl plus modifiers.	Sd or Si & Sd are Group 1 soils. SdCl, SiCl or ClSd are Group 2, 3 or 4 soils.	Use M.A. and grain size chart.	
2. Field log	Sd, Si & Cl plus modifiers.	Cl or Si are Group 1 soils. ClSi Group 2, 3 or 4	Manual manipulation and wetting of soil.	Table 5
II. Identification - natural soil properties				
A. Engineering				
1. Impact compaction test				
a. dry density	pcf	Value > 121 pcf all soils are reactive Groups 2, 3 or 4.	14 soils	
		Value > 96 and < 112 pcf (dry wt) Group 1 or Group 4 soil.	7 Group 1 and 6 Group 4.	
b. optimum moisture	% of dry soil weight.	Value > 15 and < 26% (dry wt) Group 1 or Group 4 soil.	6 Group 1 and 7 Group 4.	
2. Mechanical analysis	Clay content	% Clay vs DS		Fig. 6
		% Clay vs DS	Kaolinitic soils only.	Fig. 27
		% Clay vs DS	Minimum DS for 3, 5 & 7% LC and 7d, 28d & 6m cure.	Table D-2 footnote
3. Atterberg limits	Plasticity Index	PI vs DS 6 month cure	Kaolinitic soils only	Fig. 25
		PI (range) vs DS	Var. LC & var. cure time	Fig. 26
		PI vs DS	Min. DS var LC & var cure time.	Fig. 20-22
a. all soil horizons		Nat. soil PI range 10-19	8% Group 2, 92% Group 3 or 4	
b. " " "		Nat. soil PI range 12-23	Min. 100 psi DS, 7 day cure - 5% LC.	
c. " " "	Economical lime content	Nat. soil PI NP & > 20 use 7%	Min. Strg. Values	Table No. 16 & Fig. 20-22
		LC. PI 1-9 use 5% LC and PI 10-19 use 3% LC.	Ave. Strg. Values	Table No. 17 & Fig. 26
d. "A" soil horizons		Nat. soil PI range 1-19.	Group 2, 3 or 4 early strg. 5% LC, long term strg. 3½% LC	
e. "B" soil horizons		Nat. soil PI > 10. PI range 10-19	Group 2, 3 or 4 Early strg. 5% LC, long term strg. 3½% LC	
4. Unconfined compression test	qu	To determine unconfined comp. strg. for natural and LT soils. See II C, II D and III A.		
B. Mineralogical determination				
1. Montmorillonite	X-ray diff. and D.T.A.	See III A1a		
2. Mixed layer	" " " "			
3. Kaolinite	" " " "	See III A2a		
4. Mica	" " " "	> 20% mica and < 108 pcf Test Density	Unsuitable (Group 1 soil)	
5. Calcite	" " " "	See II C4		
6. Sulfates	" " " "	See II C7		
7. Organic matter	D.T.A.	See II C5		
C. Chemistry				
1. Exchangeable calcium	meq/100 gm soil	Value > 13.5 Group 1 or Group 4	Suspicious soils (Group 1 or Group 4) seek other data***	
		5 Group 1 & 9 Group 4 soils.		
2. Exchangeable magnesium	" " " "	Value > 6.0 Group 1 or Group 4	Suspicious soils seek other data***	
		5 Group 1 & 7 Group 4 soils.		
3. pH (1:1)	Nearest 0.1	Nonmont. soils (adsor. LS reaction) vs. 6m DS	Results from III Alb (this chart).	Fig. D-2
4. Carbonate	% CO_3	Value > 1.0% and "C" horizon Group 4 soil.	See IC	
		Value > .4 Group 1 or Group 4 soil (natural soil pH >7.8) gross 7d cure comp. strg. DS (5% LC) <75 psi for Group 1 and > 75 for Group 4.	3 Group 1 & 8 Group 4 soils, suspicious soils***.	

TABLE D-1 (Continued)

5. Organic carbon	% organic carbon	Values > 1.5 use caution. 2% or larger Group 1 soil	Estimated mainly from other investigators.	
6. Iron coating	% Fe	Value > 4.0% the Group 1 soils. Value 0.2% or less Grp 1 or Grp 4 soils. 4 Grp 1 & 6 Grp 4 soils.	Suspicious soils, seek other data***	
7. Sulfate	% SO_4, whole soil	Class. as a Cl having % of sulfate > .2 Grp 1 soil.	CA Div. of Hwys.-ID.	Fig. 17
		Class. as a SiCl having % of sulfate > .2 Grp 4 soil.	CA Div. of Hwys.-ID.	Fig. 17
D. Electrical				
1. Dielectric constant	ε^1 soil water slurry	Values >20x10³ montm. or nonk. soils. >41x10³ montm.**	See III A1a and III A2a.	Table 21
		Values <20x10³ nonm. or kaolinitic soils. <41x10³ nonk.**	See III A1b	Table 21
2. Conductivity	σ soil-water slurry	Montm. vs. 6m DS		Fig. D-1
		Higher values indicate larger percentage of salt.		
III. Observation of the lime-soil reaction				
A. Electrical characterization				
1. Adsorption reaction	$\Delta\sigma, \Delta\varepsilon^1$ LT and nat.	$\Delta\sigma x \Delta\varepsilon^1$ x10³ > 40,000 are Grp 1 soils.	5% LC	Fig. 42, Table 20
		$\Delta\sigma x \Delta\varepsilon^1$ x10³ < 40,000 are Grp 2,3 or 4.	5% LC	
a. montmorillonitic soils	> 15% montmorillonite	6mDS (5% LC) vs. montm/moist ratio	Group 4 soils.	Fig. 14
		" " " " ε^1		Fig. D-1
		" " " " $\Delta\varepsilon^1 x \Delta\sigma$		Fig. 40b
		" " " " pH of nat soil		Fig. D-2
b. nonmontmorillonitic soils				
2. Agglomeration reaction	$\Delta\sigma, \Delta\varepsilon^1$ LT and N soils	$\Delta\sigma x \Delta\varepsilon^1$ x10³ <1000 are Grp 1 soils	5% LC	Fig. 40a, 42, Table 20
		$\Delta\sigma x \Delta\varepsilon^1$ x10³ >1000 are Grp 2,3, or 4	5% LC	Table 20, Fig. 40a
a. Kaolinitic soils	>15% Kaolinite	6mDS (5% LC) vs. clay content		Fig. 27
		6mDS (5% LC) vs. PI		Fig. 25
		No Group 4 Kaolinitic soils		
b. Nonkaolinitic soils		6mDS (5% LC) vs. ε^1 of nat. soil		Fig. D-3
B. "Instant Test" - 5% lime Content	q_u	Values <12 psi DS Grp 1 soil Values >45 psi DS 5% of soils in Group 1, 60% in Group 4.		
		"A" horizon "Instant Test" (5% LC) <80 psi Gross Group 1 soil.		
		"A" horizon "Instant Test" (5% LC) 80 psi or > Gross Group 2, 3 or 4 soil.		
C. "Fixed" Moisture Determination				
a. % remaining	Im-Fm	Value 1.3 to 1.6% or> 2.0% Group 1 or 4 soils.	of "Instant Test" specimen Suspicious soils, seek other data***	
b. % of original	100 (Im-Fm)/Im	Value 0.8 to 1.2% Group 2, 3 or 4 soils.		
		<10% indicates a nonkaolinite (agg) or a nonmontmorillonite (adsorp).		
		<10% indicates a kaolinite.		
		Value 12% to 14% Group 1 or 4 soils.	Suspicious soils, seek other data	
		Value >7 and <10% Group 2, 3 or 4 soils.		

LIME STABILITY GROUPS

Group	Earliest min. Developed Strg. of 100 psi	6-month Developed Strg.-5% lime	Lime treatment
1	more than 6 months	less than 100 psi	not suitable
2	about 28 days	100-200 psi	satisfactory
3	" 14 "	200-300 "	good
4	" 7 "	greater than 300 psi	excellent

*Abbreviations used here.
- adsor = adsorption LS reaction
- agg = agglomeration LS reaction
- class = classification
- comp = compression(ive)
- DS = developed strength
- D.T.A. = Differential Thermal Analysis
- Fm = Final moisture content of specimen in %
- Gp = Stability Group
- Im = Initial moisture content of soil in %
- LC = lime content
- LS = lime-soil
- LT = lime treated
- m = month
- montm = montmorillonite(ic)
- nat = natural soil (untreated)
- nonk = nonkaolinite (agg)
- nonm = nonmontmorillonite (adsor)
- SCS = Soil Conservation Service
- strg = strength
- q_u = unconfined compressive strength
- var = various
- ε^1 = dielectric constant of nat. soil or lime-soil.
- σ = conductivity of nat. soil or lime-soil.

*** Seek other data to distinguish between Group 1 and Group 4 soil.

Average or limited values of soil properties

	Group 1	Group 4
Impact Density, pcf	107	115
"Instant Test", psi	<30 DS	>30 DS
Nat. Soil Strg., psi	34	45
7d cure-5% LC, psi	<100	>100
exchangeable Na, meq/100g	2	4
" H, " "	>7	
Iron coating, % Fe	>4	
Hydrobiotite-Vermiculite	None	

for other distinguishing features refer to Table D-2 Step 1.

**When montmorillonite and nonkaolinite are compared with one another.

Table D-2 Rule-of-thumb method for progressive estimation of the developed strength of a lime treated soil. Based upon the data from this study.

Step	Item	Soil Property	Qualifications	Remarks	No. of Soils
1	Unsuitable Soils	"Instant Test"	less than 15psi developed strg.		6
		Calif. Soil Class.			
		grain size	soils class. as Sd or Si & Sd	7CC & 14PA	2
		field log	" " " Cl " Si	3SC, 16IA & 16IC are clays, 17 MC is a silt	4
		Unified Soil Class.	" " " SP, MH or CL-ML	SP=7CC, MH=3SA & 3SC, CL-ML=4TB	4
		SCS* Soil Class.	Imperial, Sacramento, and Tourniquist Soil Series	16I, 3S & 4T	6
		28 day cure**	less than 160% developed strg.	3SA, 3SC, 4TA, 4TB, 16IA, 16IC & 17MC. 5% lime cont.	7
		Carbonaceous soil	greater than 1.3% organic carbon	4TA	1
		Micaceous soil	" " 20% mica	17MC, natural soil compressive strg. = 4 psi	1
		Soil Horizon "A"	less than 80 psi "Inst.Test" gross	3SA, 4TA, 14PA, 16IA & 19AA	5
2	Mostly Unsuitable Group 1,2,3 & 4	7-day cure**	less than 160% developed strg.	88% are Group 1 soils, Group 3 soil 1PB. 5% lime cont.	8
3	Suspicious Soils***** Group 1 or Group 4	Optimum Moisture	greater than 15% & less than 26%	Detrimental or highly beneficial to strg. develop.	12
		"Fixed" " ***			
		% remaining	1.3 to 1.6% or greater than 2.0%	" " " " " " "	15
		% of original	12 to 14%	" " " " " " "	5
		Max. Test Density	greater than 96 & less than 112 pcf	" " " " " " "	13
		Carbonate	" " .4% CO_3	27% are Group 1, 73% are Group 4. Group 1 soils "Inst. Test" less than 30 psi (except highly cemented soil)	11
4	Mostly Suitable Group 1,2,3 & 4	Max. Test Density	less than 121 pcf dry unit wt.	41% of soils are unsuitable (Group 1)	27
		"Instant Test"	greater than 45 psi develop. strg.	5% " " " " " 60% are Gp 4	22
		" "	" " 200% " "	15% " " " " "	13
		Soil Horizon "B"	"B" Horizon	7% " " " " "	15
5	Suitable Soils Group 2,3 & 4	Optimum Moisture	13 to 16%	75% are Group 4 soils	8
		P.I. of nat. soil	soils in the 10-19 P.I. range	92% " " 3 or Group 4 soils	12
		" " " "	" " " 1-19 P.I. range "A" Horizon soils only	86% " " " " " " "	7
		" " " "	greater than 10 P.I. "B" Horiz. soils only.	29% " " " & 71% are Group 4 soils	7
		Max. Test Density	greater than 121 pcf dry unit wt.	50% " " 4 soils	14
		Calif. Soil Class.			
		grain size	soils class. as SdCl, SiCl or ClSd	73% " " " "	15
		field log	" " " ClSi		3
		"Fixed" Moisture***			
		% remaining	.8 to 1.2%		14
		% of original	greater than 7 & less than 10%	64% are Group 4 soils	11
		Unified Soil Class.	soils classified as CL	80% " " " "	5
		SCS* Soil Class.	Aiken, Huerhuero, Lockwood, Merced, Montague, Panoche, Pescadero, Ramona, Salinas, & Vista Soil Series	Soil symbol: 1P,2A,6M,8S,9L,10V,11H,15R,21P & 22M	21
		Clay content	greater than 20% & less than 45%	88% are Group 3 or Group 4 soils	16
		Sand "	" " 15% " " " 40%	69% " " 4 soils	13
6	Not Highly Suitable Group 1,2 & 3	Kaolinitic soils	greater than 15% kaolinite		6
7	Highly Suitable Group 4	Unified Soil Class.	soils classified as SC	13BB & 20OB	2
		SCS* Soil Class.	Montague, Ramona, Panoche & Merced Soil Series	6M, 15R, 21P & 22M	8
		Carbonate	all "C" Horizon soils in Group 4 have more than 1.0% CO_3	1PC, 6MC, 8SC, 21PC & 22MC	5
8	Lime Content Economy	P.I. of nat. soil	soils in the NP, 1-9, 10-19 & greater than 20 P.I. ranges	NP soils use 7% lime, 1-9 PI soils use 5% lime, 10-19 PI soils use 3% lime & soils with PI greater than 20 use 7% lime	41
		Clay content******	use compressive strg. vs clay content curves	curves will give minimum developed strength for 3, 5 & 7% lime contents & the desired cure period	41
9	To Increase Strength	Kaolinite	greater than 15% kaolinite****	decrease moisture content 4% below optimum	6
		Montmorillonite	" " " montmorillonite****	increase " " 5% above "	5

LIME STABILITY GROUPS

Group	Earliest min. Developed Strg. of 100 psi	6-month Developed Strg.-5% lime	Lime treatment
1	more than 6 months	less than 100 psi	not suitable
2	about 28 days	100-200 psi	satisfactory
3	" 14 "	200-300 "	good
4	" 7 "	greater than 300 psi	excellent

* U.S. Dept. of Agriculture, Soil Conservation Service.

** Fabricated specimen 2" dia. by 4" high, optimum moisture, 90% rel. comp., passing 1/8" size and 4 one inch lifts.

*** Moisture retained in "Instant Test" specimen. Im = % initial moisture content. Fm = % final moisture content.
% remaining = Im - Fm
% of original = 100(Im - Fm)/Im

**** For an estimation of whether a soil is montmorillonitic or kaolinitic refer to appropriate section of this report.

***** Seek other data to distinguish between Gp 1 & Gp 4 average or limiting values of soil properties

	Group 1	Group 4
Impact Density, pcf	107	115
"Instant Test", psi	<30 DS	>30 DS
Natural Soil Strg., psi	34	45
7d cure-5% LC, psi	<100	>100
exchangeable Na, meq/100g	2	4
" H, " " "	>7	
Iron coating, % Fe	>4	
Hydrobiotite-Vermiculite	None	

for other distinguishing features refer to Step 1 and Step 7 above.

****** Estimation of minimum Developed Strength from Clay Content
upper curve = 6-month cure
dashed " = 28-day "
lower " = 7-day "

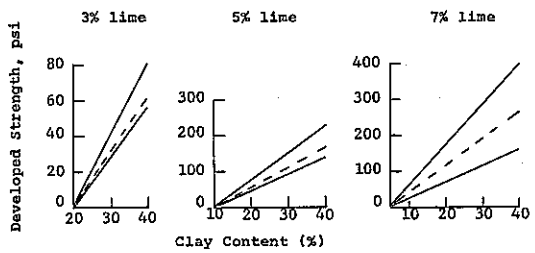


Table D-3 Guidelines to estimate whether a soil is montmorillonitic or kaolinitic.

Part A- To distinguish Montmorillonitic soils from other soils by soil properties other than X-ray diffraction/D.T.A.

Step	Refer Table	Soil Designation	Test Max. Density pcf	Optimum Moisture %	Calculated Surface Area $cm^2/gm.$	Clay %	PI	pH	Natural Soil (q_u) psi	Instant Test (Developed strength) psi	Inst. Test pH	Exchangeable K ion(meq/100 gm)	Fe Coating %	(10^3) ε'
1	22	Ads. nonmont.			>500*	>30	>10		>50	<40	< 6			>20
2	25	Agg. kaolinite			"		"	>7			< 6	<.7	> 2	
3	26	Agg. nonkaol.	<107	>18	"		"			<40		<.7		> 41

* The soil properties listed describe montmorillonitic soils

Part B - To distinguish Kaolinitic soils from other soils by soil properties other than X-ray diffraction/D.T.A.

Step	Refer Table	Soil Designation	Test Max. Density pcf	Optimum Moisture %	Fixed Moist %	Ign. Loss %	Calc. Surface Area cm^2/gm	PI	pH	Natural Soil(q_u) psi	Instant Test (Developed Str.) psi	Inst. Test pH	Exchangeable K ion(meq/100g)	Fe Coating %	(10^3) ε'
1	23	Agg. nonkaol	<107*	>18	<10	>10			<7				> 2		<20
2	25	Ads. montm.					<500	<10	"			>6	<.7	"	<20
3	27	Ads. nonmont			<10				"	>50	<40			"	

* The soil properties listed describe kaolinitic soils.

Note: The underlined properties were 100% successful in delineating the subcategories.

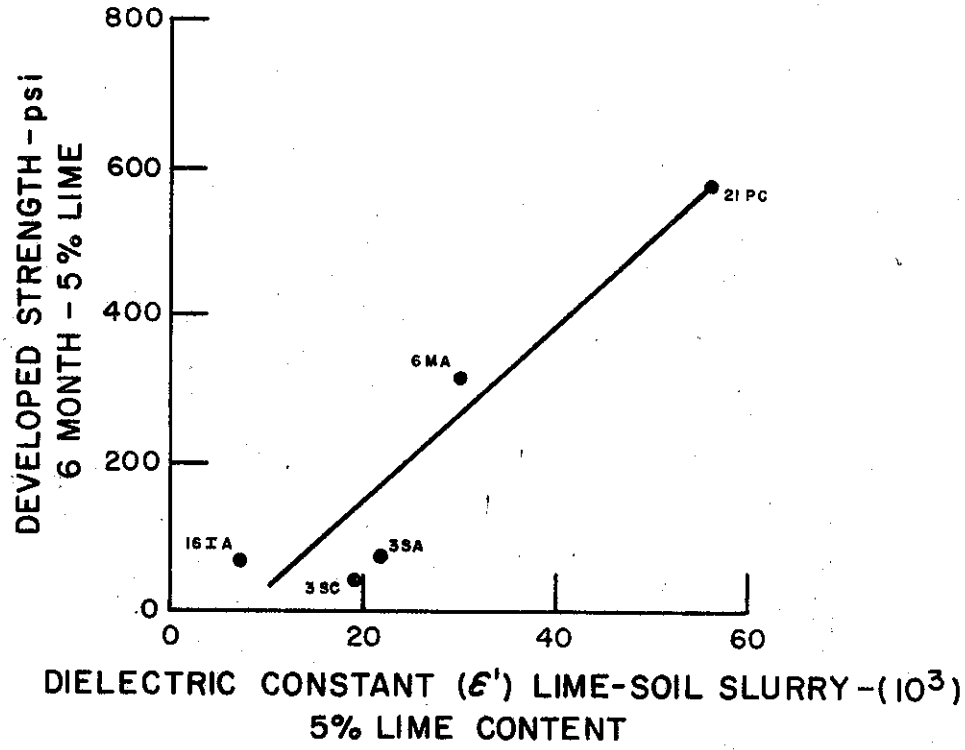


Fig.D-1 ESTIMATING THE LONG TIME DEVELOPED STRENGTH OF ADSORPTIVE MONTMORILLONITIC SOILS

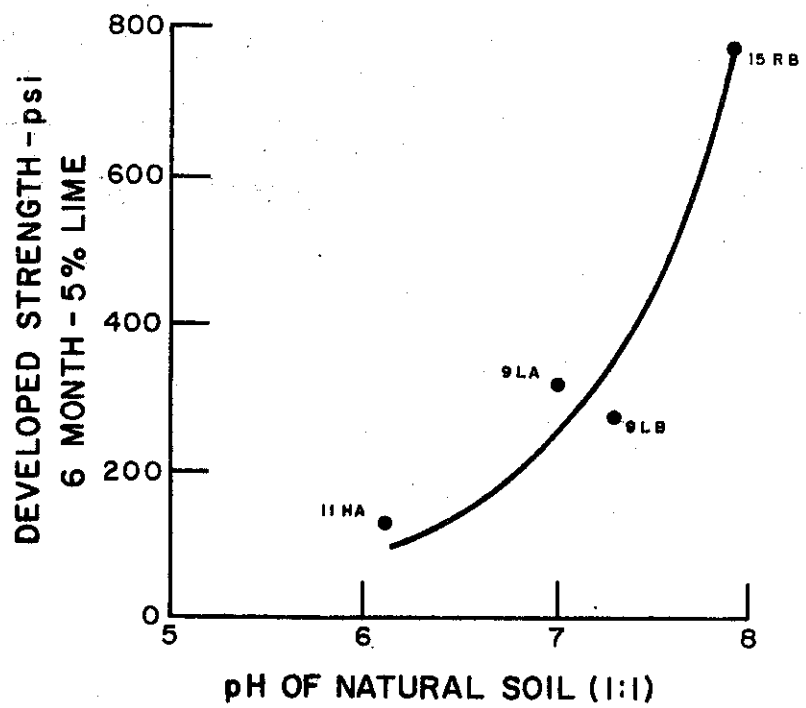


Fig.D-2 ESTIMATING THE LONG TIME DEVELOPED STRENGTH OF ADSORPTIVE NONMONTMORILLONITIC SOILS

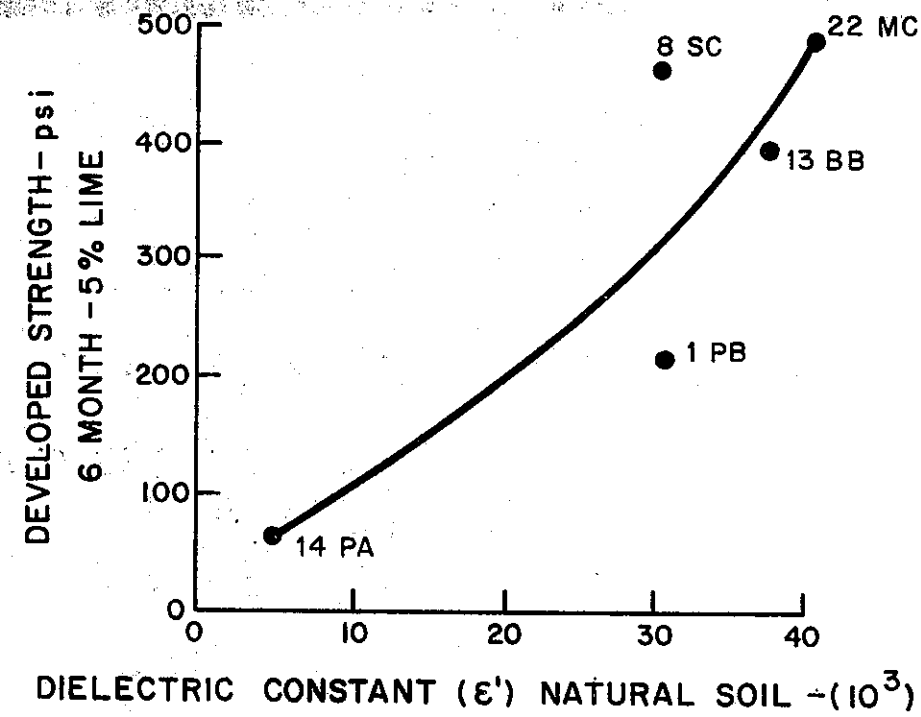


Fig. D-3 ESTIMATING THE LONG TIME DEVELOPED STRENGTH OF AGGLOMERATIVE NONKAOLINITIC SOILS