

LABORATORY EXPERIMENTS IN THE STABILIZATION  
OF CLAY WITH GYPSUM

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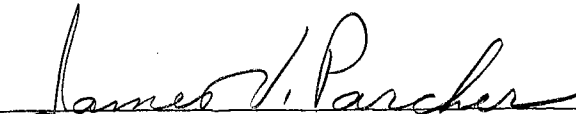
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## CHAPTER I

### INTRODUCTION

#### Problem

Enormous increases in volume and weight of traffic on U. S. Highways have increased the importance of a sound base and subbase in modern highway construction. In fact, it is essential to have stable, durable road bases for large volumes of heavy traffic. Such bases represent no particular problem in those locations where satisfactory base course materials are abundantly available. The dearth of good road material, however, in many areas of the United States is becoming continually more serious; many states possessing adequate materials are facing a constant depletion problem due to the heavy consumption of aggregate in the recent construction boom. As a result, with the exception of only a few states, an economical supply of satisfactory base material is a common problem.

To solve this problem and still produce satisfactory bases, highway and airfield engineers have been forced to employ questionable base course material modified or improved with chemical admixtures. It has been shown that ultimately it usually costs far less to use materials of inferior quality improved with additives than to transport materials of superior quality from distant locations to the construction site. Consequently, there has been extensive research done investigating the effects that various additives have on the load bearing capacities of particular

types of soil.

### Objective

It is the general objective of the research described herein to gain an understanding of the primary effects of gypsum on the properties of a clay soil. Specifically, this research is limited to an investigation of the influence of gypsum on the plasticity, compaction, and strength characteristics of a clay soil. The material set forth in this report is fundamental in serving as a foundation for subsequent research in this field.

### Need For Research

Recent years have shown considerable progress in the development of techniques for controlling soil properties. In many soil problems, only a small improvement in soil properties is necessary; however, a low cost treatment is essential. There is, therefore, a great need for inexpensive treatments of soil.

The State of Oklahoma is fortunate in having within its limits an abundant supply of relatively pure gypsum. Most of the deposits of gypsum are located in the western part of the state, but nevertheless, in a relatively accessible geographic location. Most of the natural material is presently processed for building construction and farming purposes. The use of gypsum as a pavement base stabilizer has been discussed and its future use in this field anticipated, but no research was ever initiated to investigate the effects of gypsum on the stability of Oklahoma Permian Red Clay.

State Highway Department engineers, as well as other engineers within the state, are vitally concerned with stabilizing materials to improve the poor quality of local base materials. Since gypsum is rather



plentiful and available in Oklahoma, and since gypsum has the same calcium cation which has so successfully been provided before by lime for stabilization of clay, Professor J. V. Parcher of the Civil Engineering School at Oklahoma State University inspired the writer to investigate the potentials of gypsum for this new use. A study of gypsum-stabilization was, therefore, initiated.

### Delimitations

It is realized that in order to test the effectiveness of prospective gypsum stabilization, a wide range of clay materials should be tested. This study concerns itself, however, with the effects of gypsum on one clay sample.

Only those properties of clay minerals that are related to Soil Mechanics are considered herein. No attempt is made to discuss the procedures for determining the clay minerals in the sample.

The triaxial test is performed with one constant chamber pressure. From the plot of only one Mohr's circle, neither the angle of internal friction nor the cohesion constant can be determined.

In studying the results, it should be realized that the gypsum used was not developed commercially for soil stabilization. The gypsum used for testing was that which is bagged and sold commercially for agricultural purposes.

## CHAPTER II

### DEFINITIONS AND CONCEPTS

#### Clay

Clay cannot be very easily defined in precise terms. The word has a popular and also a series of technical meanings. The Foundation Engineer's concept of clay may be rejected by a potter, a brick manufacturer, an agronomist, or a farmer. Nevertheless, in the popular sense, clay is a finely-grained material which becomes sticky when wet. In a more technical sense, all clay minerals can be considered very fine soil particles having a pronounced basal cleavage. As a consequence, individual clay particles are flat and flake-shaped.

In general, the term "clay" implies a natural, earthy, fine-grained material which when mixed with a limited amount of water develops plastic properties. Plasticity, as related to Soil Mechanics, is that property which allows a material to undergo rapid deformation without rupture, volume change, or elastic rebound. Chemical analyses of clays show them to have essentially silica, alumina, iron, alkalies, and alkaline earths. The term "clay" is sometimes used to signify a material that is the product of weathering, that formed by hydrothermal action, or that deposited as a sediment. As a particle-size term, soil investigators tend to consider two microns as the upper limit of the clay particle size.

A large number of mineralogical studies by Grim (7) has shown that almost all clays and soils are composed of particles of one or more

of the following three groups. Other clay minerals are of such minor importance to this discussion that they may be neglected here.

- (1) Montmorillonite group - The theoretical composition of montmorillonite is  $(\text{OH})_4\text{Al}_4\text{Si}_8\text{O}_{20}$ , but the aluminum is usually partially replaced by iron or magnesium.
- (2) Kaolinite group - The mineral, kaolinite, has a chemical composition of  $(\text{OH})_8\text{Al}_4\text{Si}_4\text{O}_{10}$ .
- (3) Illite group - This name has been applied to the widespread and abundant clay minerals that resemble muscovite mica in their composition and structure. The composition of minerals belonging to this group varies somewhat, but the general formula  $(\text{OH})_4\text{K}_x(\text{Al}_4 \cdot \text{Fe}_4 \cdot \text{Mg}_4 \cdot \text{Mg}_6)$   $(\text{Si}_{8-x} \cdot \text{Al}_x)\text{O}_{20}$  may be written.

According to Grim<sup>(8)</sup>, the modern concept of the term "clay" carries three implications: (1) a natural material possessing plastic properties, (2) a composition of particles of very fine size grains, and (3) a composition of crystalline minerals consisting of essentially hydrous aluminum silicates. This modern concept of clay concerns itself with the properties, texture, and composition of clay without regard to its origin. Due to the definite crystalline composition, R. E. Grim<sup>(8)</sup> introduces the term "clay mineral" when discussing clays.

### Structure of Clay Minerals

The atomic structure of common clay has been determined in considerable detail by Dr. Grim<sup>(6)</sup> and by many investigators. In the discussion of the atomic lattices of clays, two structural units are considered. One consists of two sheets of closely packed oxygens or hydroxyls in which aluminum, iron, or magnesium atoms are connected

in octahedral coordination. (Fig. 1) The second unit is built of silica tetrahedrons. In each tetrahedron, a silicon atom is equidistant from four oxygens or hydroxyls arranged in a form of a tetrahedron with a silicon atom at the center. (Fig. 2)

Diagrammatic sketch  
showing structure of  
octahedron unit

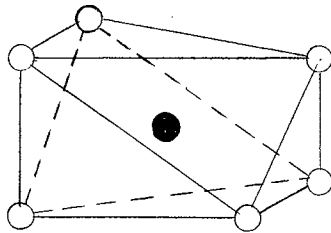


Figure 1

○ - hydroxyls  
● - aluminums,  
magnesiums, etc.

Diagrammatic sketch  
showing structure of  
tetrahedron unit

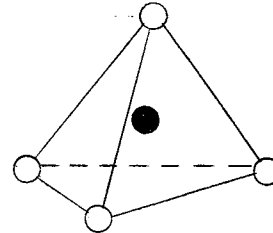


Figure 2

○ - oxygens  
● - silicons

Montmorillonite is composed of units made up of two silica tetrahedral sheets with a central alumina octahedral sheet.

The Kaolinite structure is composed of a single silica tetrahedral sheet and a single alumina octahedral sheet combined in units. The tips of the silica tetrahedrons and one of the layers of the octahedral sheet form a common layer.

The Illite mineral unit is the same as the montmorillonite except that some of the silicons are always replaced by aluminums and the resultant charge deficiency is balanced by potassium ions.

### Soil Stabilization

Stabilization is a term being discussed with increasing frequency at every gathering of highway or paving engineers. According to the

Universal Dictionary of the English Language, stability means, "The quality or state of being stable or firm, strength to stand and to resist being moved . . . fixedness as opposed to fluidity; not subject to change or destruction; not easily moved from a state of equilibrium." Stabilization would therefore mean the imparting of these properties to a material.

According to Hogentogler,<sup>(12)</sup> soil stabilization is the process of giving natural soils enough abrasive resistance and shear strength to accomodate traffic or loads under prevailing weather conditions, without detrimental deformations.

Soil stabilization may be defined as a modification of an existing soil so as to improve its bearing or load absorbing characteristics. Such an effect may be accomplished by mechanical consolidation (compaction) or by the incorporation within the soil of certain additives which would provide the desired qualities of permanent stability.

Ever since the beginning of road building, it has been recognized that some soils were extremely unstable, particularly in the presence of moisture, and that other soils were stable and would support traffic with less deformation. An attempt was made to define the properties which rendered a soil "weak, unstable, yielding, unreliable." Much progress was made and "soil constants" were defined by which good or poor soils could be evaluated and from which the performance could be predicted.

In general, soil stabilization is divided roughly into two parts; one a physico-chemical process where the character of the soil is altered, and the other, the preservation of the soil's characteristics of maximum density by an addition of some material. Ultimately, it is

known that instability of soils is related directly to their water susceptibility.

In the first part, a physico-chemical process imparted by an addition of chemicals such as lime, cement, calcium chloride, flyash, and other additives improves the load carrying capacity of the soil. In the latter, a water proofing or water retention process imparted by the addition of asphalts and other bituminous materials, preserves the characteristics of that soil at its optimum conditions.

The term "soil stabilization" has been used to describe many construction procedures involving soil. In order to avoid confusion, it is advantageous to distinguish between the procedures and materials involved so as to clarify some of the terminology applicable to this field:

1. Compaction stabilization - densifying a material mechanically without admixture
2. Waterproofing stabilization - the addition of water-insoluble binders to a soil to reduce a change in water content
3. Dilution stabilization - addition of other suitable soils for the attainment of a specified gradation
4. Cementation stabilization - the addition of a hydrating material capable of developing setting properties
5. Chemical stabilization - treatment of a soil with water soluble salts to induce a chemical reaction.

The problem of deciding which one of the above methods of stabilization applies for a project is left to the judgement of the engineer. The primary consideration is that of economics. All other considerations are studied subsequently, and a selection is made of the type of stabilization most suitable for the prevailing conditions.

## Gypsum

Hertslet<sup>(11)</sup> investigated the gypsum industry in Oklahoma. The material in the following section was obtained from his report.

Gypsum is a mineral which has properties that have long been familiar to man. The property of gypsum rock which enables it, after losing its water of crystallization through heating, to recombine with water to set into its original hard, rock-like state has increased its usefulness. Its widespread occurrence in nature has directed much attention towards its use for many industries.

Historically, gypsum was first applied in ancient Ethiopia as a preserving material for the dead. Ancient Egyptians utilized gypsum in the construction of their pyramids. Later years saw France, Portugal, Greece, and Spain use gypsum to treat wine which made it ripen earlier. And so the use of gypsum in the early days became well known.

Today, gypsum is quarried and produced commercially in many countries. In gypsum production, Oklahoma ranks among the top seven states in the United States, producing approximately 5%, with New York and Michigan supplying 18% and 15% respectively. The deposits in Oklahoma are located primarily in the western area of the state.

Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), a hydrate of calcium, is sedimentary in nature. It may be formed by the action of sulfuric acid or soluble sulfates on limestone, by the evaporation of sea water of which 3.6% of the total mineral content is  $\text{CaSO}_4$ , or by the crystallization of anhydrite.

The anhydrite is a distinct mineral and cannot be considered as a form of gypsum. Anhydrite is  $\text{CaSO}_4$  without the water of crystallization. One molecule of gypsum has two molecules of water of crystalli-

zation while anhydrite has none. The anhydrite is much harder and more weather resistant than gypsum. Anhydrite has been used as a road base material in place of gravel. It has primarily a mechanical effect on stability because of its rock-like properties.

Gypsum owes its economic importance as a mineral to its property, after being calcined or heated, of uniting with water and setting to a hard material. By controlling the amount of heat and the time in the calcining of gypsum, it is possible to produce a plaster of almost any specification. When calcined at a low temperature, plaster of paris can be produced that will set in six to ten minutes. When calcined at higher temperatures, it is possible to produce a plaster which when set will have a higher compressive strength.

Gypsum is presently used extensively in the construction field. It is used as a plaster material, in wallboard, pottery, casting, sculptures, fertilizers, and if uncalcined as a retarder in cement. The variety of gypsum known as alabaster has long been used for sculpturing and for making vases, statues, and other ornamental objects. Gypsum's principle use today is in the cement industry.



## CHAPTER III

### OTHER MATERIALS USED FOR SOIL STABILIZATION

Much has been written and otherwise reported on materials used for stabilization of soils. Portland cement, water-soluble salts, lime, various types of bituminous compounds, and various combinations of the above have been used with very successful results. Each has its particular influence on the properties of different soils, all tending to improve the load carrying qualities of the relatively inferior materials available.

Many soil stabilization laboratories have for years conducted research on improving the properties of soils by using additives. Massachusetts Institute of Technology, Purdue University, Texas A&M College, and the Federal and State Highway Departments are a few among the many that directed research in this field. It has been learned through their experiments that certain general correlations exist between soil composition and soil response to various types of additives.

#### Bituminous-Soil Stabilization

It has been shown that instability of soils is directly related to their water-wetting propensities. According to B. H. Dent<sup>(5)</sup>, in stabilization with emulsified asphalts, each separate particle is coated with a thin film of asphalt and made water repellent. It is, therefore,

apparent that asphalt primarily stabilizes by water-proofing each particle.

C. F. McKesson <sup>(18)</sup> found that all types of soil can be stabilized with emulsified asphalt except those containing considerable amounts of mineral salts, providing a sufficient amount of clay is present in each soil to act as a binding medium. However, McKesson further states that the quantity of emulsified asphalt stabilizer required increases as particle sizes decrease. It can be concluded from this that materials having large amounts of fine particles cannot be very economically stabilized with asphalt. Nevertheless, if the proper amount of clay is present, the addition of asphalt is capable of inducing great cohesive strength to the material. The strength may be as much as nineteen times as great (in compression) as the strength obtained by adding an equal proportion of Portland cement binder to the same material.

In addition, asphalt tremendously reduces capillarity as well as increasing resistance to displacement. It has been found by Roediger and Klinger <sup>(22)</sup> that capillarity absorption is reduced 90%, and after a month of continuous exposure to free water at the under side, the soil treated will usually contain only ten to twenty percent of the moisture found in the same soil untreated.

The entire subject of bituminous stabilization can probably be summarized by a few principles formulated from the laboratory analyses and field experiences of Muir, Hughes, and Browning <sup>(20)</sup>:

- (1) The primary object of bituminous stabilization is waterproofing to prevent capillary action.
- (2) The secondary object is increased stability of the soil

through the inherent cohesive qualities of the bitumen.

- (3) For emulsions, water content should be about that required for the plastic limit.
- (4) Soap must be used in sufficient quantities.
- (5) Practically all bituminous materials can be used successfully under proper conditions.

There have been additional investigations, e. g., by Benson and Becker<sup>(1)</sup>, of bituminous stabilization of soil using supplementary additives such as cement, lime, and aqueous solutions of certain heavy metal salts. Tests have indicated that with further addition of another material, stabilization consists of two separate functions; one an alteration of the soil character, and the other a cementation of the altered particles into a water-tight cohesive mass.

#### Lime-Soil Stabilization

Lime as an admixture has been used rather extensively in agriculture for its plant sustaining qualities and improvement of soil workability. It was not until Texas highway engineers conceived the idea of employing hydrated lime for highway soil stabilization that a full scale research was initiated. The results of the Texas Engineering Experiment Station and those of Purdue University, showed lime stabilization of soils to be feasible.

The results of a study by Clare and Cruchley<sup>(3)</sup> showed that, almost without exception, two to five percent of hydrated lime (by weight) added to the soil increases the strength of the soil specimens. A very marked decrease in the plasticity index of very highly plastic, fine-grained and coarse-grained soils also results. Hardly any change in the P.I. of non-plastic (sandy) soils and silts and loams of low

plasticity is produced.

Lime was found most effective with clay-gravel mixes. According to the investigations by Johnson <sup>(14)</sup> and McDowell <sup>(17)</sup>, a substantial reduction in plasticity was achieved along with a great increase in compressive strength with lime admixture. The reason for this is that a pozzolanic reaction occurs between the lime and the available silica and probably some alumina in the clay, forming in effect a natural cement. The experiments of Johnson and McDowell have shown that only two to four percent (by weight) of lime is needed to obtain marked results.

A lime-fly ash combination has been reported as having very successful effects in stabilizing soils. The American Society for Testing Materials defines the process involved in lime-fly ash as pozzolanic. A pozzolan is defined as: "A siliceous or aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds possessing cementitious properties".

Fly ash is a waste material from burned coal which has abundant quantities of silica and alumina. Lime added to a soil which is later furnished additional compounds to intensify a pozzolanic reaction results in an extremely well cemented mass. J. Eldridge Wood <sup>(27)</sup>, Materials Engineer of the Maryland State Roads Commission, presents valuable information on lime-fly ash soil stabilization in his paper to the American Road Builders' Association.

Lime-Portland cement and lime-bituminous mixtures have also effected great improvements in soil characteristics.

In conclusion, lime stabilization has been found to be chemical in nature. It was learned that the chemical reaction caused by the lime is not restricted to a specific group of the clay family. Any material which can undergo a base exchange or a replacement of the weaker cation by a stronger calcium cation of the lime can experience a significant improvement in its plasticity characteristics.

#### Calcium-Chloride Stabilization

Calcium chloride is a salt which has been used in increasing quantities in conjunction with construction and maintenance of road bases. This relatively inexpensive chemical is not a cureall, but its ability to attract moisture from the atmosphere and its ability to hold moisture by reducing the rate of evaporation make its use desirable. H. F. Clemmer <sup>(4)</sup>, in his report to the American Road Builders' Association, presents the effectiveness of calcium chloride as an agent for stabilizing soils.

#### Soil-Cement Stabilization

Portland cement has been one of the most common and successful stabilizers for soils. Excellent results with cement have been obtained and its use has become increasingly popular for stabilizing pavement bases and subgrades. With very few exceptions, most soils have been found to respond favorably to cement treatment. One disadvantage in employing cement in plastic soils is that a high cement addition is necessary to improve the soil qualities. However, the M. I. T. Soil Stabilization Laboratory, under the direction of Lambe and Moh <sup>(15)</sup>, has for several years studied the effects of secondary salt additives

recognizing the importance and potential of soil-cement. Based on their tests, it was reasoned that the effectiveness of Portland Cement as a soil stabilizer could be enhanced with secondary chemical additives.

### Secondary Chemical Additives

In recent papers presented by the M. I. T. Soil Stabilization Laboratory before the Highway Research Board, a review of the improvements of soil-cement with additives was discussed. (15, 19) The papers indicated that very large improvements were obtainable if some secondary chemical additives were used.

The research considered the effects of many chemicals on the strength of soils of different composition stabilized with a constant quantity of cement. Dispersants, synthetic resins, bonding and water proofing agents, alkalies, and other salts were investigated for their effects on soil-cement mixtures.

Test results showed that none of the trace additives studied had any large effect on the compaction characteristics of the soil. Most chemicals caused a modest increase in maximum compacted density (1 to 7 pounds per cu. ft.) and a slight decrease in optimum moisture. Several chemicals increased the strength of the soils, but the strength improvements were not found to be primarily due to the increase of compacted density.

From all the tests performed by Moh, Lambe, and Michaels, (19) behavior was established. The general findings, based on the soils studied, were:

- (1) Sodium hydroxide is effective in improving strength of all soils with low to moderate amounts of organic matter.

- (2) Sodium salts of weak acids are not effective in heavy clays.
- (3) Sodium sulfate is uniquely effective on sandy soil containing organic matter.
- (4) The effectiveness of sodium compounds decreases with increasing plasticity and/or organic matter content of the soil.

The research summarized included the following:

- (1) An examination of the effects of sulfates on the stability of cement stabilized soils.
- (2) An examination of the effects of soda-to-silica ratio in sodium silicate as a secondary additive.

These and many other considerations point to the increased cementing action caused by some chemical reactions between the components of soils and the additive. Now in progress are numerous investigations directed towards determining what reactions occur and what effects result from these chemicals. Needless to say, an enormous amount of research is being conducted throughout the country to further evaluate the effects of all types of materials on improving the quality of a soil in the most economical manner.

## CHAPTER IV

### BASIC CONSIDERATIONS

#### Surface Phenomena and Base Exchange

An understanding of some of the effects of chemical admixtures with clay soils is obtained by reviewing the basic properties of clay minerals. The properties are primarily influenced by the presence of complex compounds of silicas, magnesium, sodium, aluminum, oxygen, potassium, and calcium which vary because of a difference in surface activity. This variation in surface activity can be due to the type of exchange ions present, the crystalline structure of the mineral, or the electrical charges carried by the particles and moisture film.

Clay particles when suspended in water are surrounded by a water film within which are ions of different charges. Around the particle is a layer of negatively charged ions which are balanced by cations which are diffused throughout the water film. The strength of the bond between the particle and cation depends on the atoms of the clay particle and their arrangement. The negatively charged clay particle and positively charged cation result in an electromotive force generated by the oppositely charged particles. The characteristics of this surface phenomenon depend on the cation present and its relative position on the replacibility scale. The process by which the cation present in the water layer is replaced by another cation is known as Base Exchange. This process is similar to the phenomenon illustrated by the zeolite



water softeners where the calcium ion in the hard water is exchanged for the sodium in the zeolite.

Clay materials carry cations which may be exchanged for others by treatment with water solutions containing the second cation. In this process, the structure of the clay soil is not changed. The binding force between particles is only altered. The property of clay materials to carry exchangeable cations is designated as "base-exchange capacity" and is measured in terms of milliequivalents per 100 grams.

The research by R. E. Grim <sup>(6)</sup> shows the Base Exchange capacities of the three basic members of the clay family. These are shown in Table 1.

TABLE 1

Base Exchange Capacity	
(In milliequivalents per 100 grams)	
Montmorillonite . . . . .	60 to 120
Illite . . . . .	20 to 40
Kaolinite . . . . .	3 to 15

Table 1 can be taken as an indication that the Base Exchange capacity of a clay soil may be an index of a reaction with chemical admixtures.

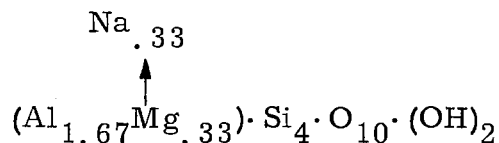
A satisfactory method for determining base exchange capacity of clay materials is the Ammonium Acetate Method. Extensive research was conducted in determining base exchange capacities by Schollenberger and Simon. <sup>(24)</sup> Peech <sup>(21)</sup> also performed tests to determine exchangeable cation and exchange capacities of soils.

## Crystalline Structure and Base Exchange

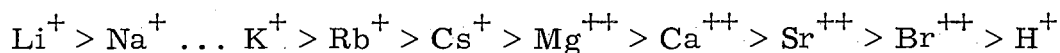
The crystalline structure of almost all clays is the layer-lattice type. Any substitution of cations occurs within the crystal lattice.

Data from investigations of the relation of exchangeable bases to plastic properties indicate that in some way the character of the absorbed cation affects the thickness of the water film. When the water film is large, the particles are at the maximum separation, and free viscous flow is possible. Cohesion results when the separating water film is reduced. At low water contents, the individual particles touch and plasticity is destroyed. Plasticity, which is a function of water content, can be correlated with the influence cations have on the water film. That is to say, since the character of the absorbed cation affects the thickness of the water film, that same cation can act as a bridge to bind the clay mineral sheets together and, therefore, influence the plasticity and stability of the mass.

The extensive research by Ross and Hendricks <sup>(23)</sup> is instructive in showing how the replacement of ions may occur. A somewhat complicated composition of montmorillonite was selected for the explanation because the sodium cation on the surface of the clay particle is replaceable. Its composition may be noted from the following chemical formula:



The relative order of cation replacement, as reported by Grim <sup>(8)</sup> is as follows:



The order of sequence is that of generally increasing difficulty of replacement. In other words,  $\text{Li}^+$  can be replaced by all the ions shown, while  $\text{H}^+$  cannot be replaced by any of the ions shown.

The relative replaceability of the ions shown indicates the important role cations high on the scale have in the stabilization of clay. The scale shows that an acid abundant in  $\text{H}^+$  would have the greatest influence on stability. Calcium which is relatively abundant in nature ranks relatively high in replaceability. From the scale and from the chemical formula above, it is apparent that the  $\text{Na}^+$  from montmorillonite clays can be very easily replaced by all the ions shown except  $\text{Li}^+$ .  $\text{Ca}^{++}$ , which is the cation in lime and gypsum, for example, can very easily replace the  $\text{Na}^+$  and render the clay mass more stable.

It has been shown that the stability of clay is a function of the relative thickness of the water film and the electromotive force with which the particles are bound together. A summary of the findings of modern clay researchers shows that (1) the crystal structure of their surfaces determines their affinity for water, with the type and amount of exchangeable cation playing an exceedingly important role in this connection; (2) as a consequence, the water affinity and stability may be radically altered by introduction of different exchange ions.

## CHAPTER V

### TESTING PROCEDURE

#### Plasticity

It was decided to examine the effect of gypsum on the plastic properties of a clay soil. The plasticity tests required relatively small quantities of soil and experimental effort, and it was hoped that the soils would show a pronounced change in plastic properties following the addition of gypsum.

A representative, uniform clay sample was obtained from the surface layer of the earth, approximately two to three feet below ground surface in a construction area in Stillwater, Oklahoma. Very little, if any, organic material was present at this depth. It was felt that the clay at this depth would represent most closely the clay material which would be used for pavement base construction in the vicinity.

The sample was air-dried, pulverized and passed through a #10 sieve. A sieve analysis was made of the pulverized clay and is shown in Figure 11. A grain size distribution by the hydrometer method was performed on the clay and the curve is also shown in Figure 11.

Mixtures of clay and gypsum were prepared with gypsum contents of 0, 3, 6, 9 and 12% by weight of the air-dry clay. Since the moisture content of both gypsum and clay in the air-dry condition was the same, a quantity of clay was weighed, and the amount of gypsum desired to be added was determined directly from the weight of the clay.

Batches of mixture were prepared at each gypsum content which enabled tests to be performed immediately after mixing and also after periods of storage. These periods of storage ranged from one to seven days. The appropriate weights of clay and gypsum were mixed dry, and water was added until the moisture content of the mixture appeared to approach the plastic limit. Portions were placed in jars and sealed to prevent subsequent change in moisture content. After different lengths of storage time, the liquid limits and plastic limits were determined using standard procedures.

The plasticity tests in this report are limited to the clay/gypsum mixture stored with water content near plastic limit for periods of time which did not exceed seven days. The values obtained for each percentage of added gypsum are averages for the seven-day period.

### Compaction

For the compaction test, the same representative, uniform clay sample from Stillwater, Oklahoma, was used. 0, 3, 6, 9, and 12% of gypsum was added, as in the plasticity tests, and portions of each gypsum/clay mixture were stored containing incremental differences of water contents. Within periods of one to seven days, compaction tests were performed on each mixture using the Harvard Miniature compaction apparatus. All the values of dry density and corresponding moisture content for each percentage of gypsum added were plotted. The optimum moisture content and the maximum dry density for each mixture were determined. The results are shown on Figure 3.

## Strength

### Unconfined Compression

The same Stillwater, Oklahoma, clay was used for this test. 0, 3, 6, 9, and 12% gypsum was added to the air-dried clay and hand mixed. Enough water was added to each mixture to bring the sample to its optimum moisture content. The results of strength tests depend upon the moisture content of the stabilized soil. In order that the moisture content might approximate that in practice under a pavement, the optimum moisture content was used in all tests.

Specimens were then molded in a Harvard Miniature compaction apparatus at optimum moisture content. At this water content, the specimens were at their maximum densities.

All specimens were then wrapped in aluminum foil, sealed in wax and allowed to cure without subsequent change in moisture content.

Each compacted mixture was allowed to cure for 1, 4, 7 and 28 days while sealed. Immediately after curing, the specimens were broken in compression, at a uniform rate of loading, by a manually operated unconfined compression machine. This apparatus, used for determining compression strength, was a proving-ring machine with deflection dials. The maximum pressure causing failure of the specimen was taken as the compressive strength.

During loading, extreme care was taken to assure that little water would be lost from the specimen. A damp cloth was placed around the sample in a curtain affair to retard evaporation. After failure, the specimen was immediately weighed and placed in a drying oven so that the actual water content could be determined. Tests with water contents which varied more than  $\pm 1\%$  from optimum were disre-

garded.

A calibration curve for the compression apparatus was used to determine the applied loads from the dial readings. Stress-strain curves were plotted and strength and strain at failure were determined from the curve. Figure 4 shows a plot of stress versus percent strain for a typical specimen.

### Triaxial

The same representative clay material from Stillwater, Oklahoma, was selected for examination using gypsum contents of 0, 3, 6, 9 and 12% to cover a practical range.

Clay/gypsum batches were hand mixed in the air-dry condition. Water was then added until optimum moisture content was reached. Specimens were molded from the batches at optimum moisture content using the Harvard Miniature compaction apparatus. Specimens were wrapped in aluminum foil and sealed in wax to be allowed to cure for fifteen days without subsequent moisture change.

After the fifteen day curing period, specimens were removed from the seal and placed in a triaxial testing apparatus. Silicone rubber and latex membranes, and filter strips to facilitate water drainage, were used. Distilled water was used for the chamber liquid subjected to a pressure of  $1 \text{ kg/cm}^2$ .

After complete consolidation was permitted, samples were loaded to failure. From the deviator stress and chamber pressure ( $\sigma_3$ ), a Mohr's circle was constructed to determine the shear strength. (The major principle stress ( $\sigma_1$ ) is equal to the deviator stress plus the chamber pressure ( $\sigma_3$ )). Two tests for each mixture were performed using a chamber pressure of  $1 \text{ kg/cm}^2$  for both specimens. A Mohr's

circle was constructed from the test data and the average shear strength was taken from the two circles.

Figure 9 shows a typical plot of deviator stress and strain to establish a Mohr's circle. From the Mohr's circle as shown, the maximum shear stress was determined.



## CHAPTER VI

### RESULTS AND DISCUSSION

One of the outstanding recent developments in the study of clay minerals has been the discovery that exchangeable bases exert an important effect on physical properties. Two soils with the same composition of mineral and organic material may have different reactions to gypsum if one has sodium as its exchangeable base and the other has magnesium. It follows, therefore, that clays containing primarily montmorillonite, because of its high base exchange capacity, will have their properties most greatly influenced by a calcium cation added.

It is a common chemical phenomenon that gypsum, in solution, liberates calcium ions which in turn replace those cations in the material which are lower in the replaceability scale discussed previously. The results of the tests performed will support the view that immediate effects are due to flocculation of the clay particles, as the result of the replacement of the sodium, potassium or magnesium ions by the calcium ion of the gypsum. This is followed, during curing, by bonding of the particles by calcium silicates and/or aluminates formed by a chemical reaction between gypsum and clay.

In this research, the mineral composition of the clay was not determined. However, previous analysis of the soil shows the local material has to be montmorillonitic.

### Influence of Gypsum on Plasticity Characteristics

The effects of gypsum on the Atterberg Limits of the clay soil sample tested after a storage period of from one to seven days are shown in Table 2. The values shown are average limits determined after different periods of storage. In general, gypsum produced no effect on the liquid and plastic limits. The very slight variation seems to be due to human error in performing the tests.

Although gypsum had no apparent effect on plasticity, it is felt that insufficient tests were performed to allow any general conclusions regarding the effects of gypsum on the plasticity of clays. First, only one particular type of clay was selected for the investigation, and secondly, storage periods not exceeding seven days may not have been adequate for gypsum to react completely. In addition, 12% gypsum was the largest quantity used for testing. Higher percentages may have greater influences on plasticity. Nevertheless, the data show that the percent of gypsum has a relatively minor effect on plasticity.

### Influence of Gypsum on the Compaction Characteristics

Table 3 presents the effects of gypsum on the compaction characteristics of the one type of clay. The data show a fairly consistent decrease in maximum dry density, and an increase in optimum water content with increasing percentages of gypsum. Figure 3 shows the plot of the compaction tests for each percentage of gypsum added and the effect is obvious although rather minor.

From other studies in chemical soil stabilization, it was found that the amount of curing allowed a sample, prior to its subjection to test, is of considerable importance. Prior to compaction, the samples

cured for periods of from one to seven days. The values used to plot Figure 3 were averages for each percentage of gypsum added.

### Influence of Gypsum on Strength Properties

#### Unconfined Compression

Figure 4 is a typical plot of values for a stress-strain graph for 12% gypsum cured for one day. Strengths and percent strains at failure for each period of curing for each quantity of gypsum added are shown in Table 4. From this table, various curves are plotted using different relationships.

Figure 5 shows the relationship of strength and curing time for the percentages of gypsum added. The curve for clay is the control which shows that the strength of clay alone, after being compacted at optimum moisture, increased with storage time. Each increment of gypsum additive induced a proportional increase in strength. The largest increase per incremental addition of gypsum is between the six and nine percent gypsum curves. This indicates that optimum gypsum content, which is considered the amount of gypsum which induces the maximum increase of strength per incremental amount of gypsum content added, is approximately nine percent.

The rate of increase of strength is most pronounced within the seven days of curing. Thereafter, the influence of curing time gradually diminishes. It appears that beyond twenty-eight days of curing, strength increase is very slight.

Figure 6 shows the relationship of percent strain at failure and curing time. Here the addition of gypsum induces a decrease in strain. The largest decrease of strain per incremental addition of gypsum lies

between the six and nine percent gypsum curves. This indicates an optimum gypsum content of approximately nine percent, also.

The rate of decrease of percent strain is most pronounced within seven days of curing. Thereafter, curing time has a diminishing effect on strain. Therefore, for strain as well as for strength, discussed above, curing beyond twenty-eight days appears to have little effect on the load bearing properties of a clay-gypsum mixture.

Figure 7 presents the relationship of percent gypsum to strain and Figure 8, the relationship of percent gypsum to strength, both with respect to curing time. As is evident in both figures, gypsum has a favorable influence on both strength and strain. The pattern with respect to curing time does not show any consistent trend. However, from these figures it is most apparent that the addition of gypsum increases strength and decreases strain at failure of a clay sample. Both figures might lead one to assume that the addition of gypsum increases strength and decreases strain at failure indefinitely. However, no tests were performed at high percentages of gypsum to support any general conclusions. A zone of influence is shown from the points plotted.

Chemically speaking, those data support the theories of many investigators that a high order replacing cation stabilizes clay materials. The calcium ion of the gypsum replaces the weaker cations of the clay and induces a stronger bond between clay particles. This increased bonding force tends to increase the strength of a clay material until all the replaceable cations, sodium, potassium, magnesium and others have been exchanged. The time necessary for this exchange to occur completely is not known. However, knowing the base exchange capacity of the clay material and performing additional tests with this infor-

mation, a direct correlation between quantity of gypsum added and reaction time necessary may be determined.

### Triaxial Compression

Figure 9 is a typical plot from a triaxial test on two specimens holding the percentage of gypsum additive and the chamber pressure constant for each of two specimens. The maximum shear stresses obtained from the average triaxial values of the specimens for each percentage of gypsum added is shown on figure 10. As is shown, the minimum shear strength is  $0.64 \text{ kg/cm}^2$  and exists for 0% gypsum specimens while maximum shear of  $0.87 \text{ kg/cm}^2$ , for the samples tested, at 12% gypsum.

It is evident that a marked increase in shear strength is induced by increased amounts of gypsum added. The rate of increase is most substantial up to 6% gypsum. Thereafter, the rate of increase decreases. The curve of Figure 10 indicates an optimum gypsum content for maximum shear strength to lie within 6 - 9%.

The tendency of the plotted curve to flatten at higher percentages of gypsum indicates a decreasing effect beyond a certain quantity. Practically speaking, a point is reached where only a part of the additional gypsum induces any cementing action. Chemically speaking, this point is reached when base exchange terminates.

At this point it may be assumed that practically all of the available replaceable cations in the clay material, primarily sodium, magnesium, potassium, have been exchanged by the calcium cation of the gypsum which is a higher order cation. Calcium being of higher chemical potential, in turn, induces higher bonding between clay layers.

Therefore, shear strength increases with addition of gypsum until the

base exchange capacity of the clay is chemically satisfied.

Curing time for this test was held at fifteen days. In other words, the reaction time for each gypsum/clay mixture was held constant. This study does not determine the effects of reaction time on shear strength improvements.

## CHAPTER VII

### CONCLUSIONS

#### General

Clays have long been looked upon as a rather hopeless material for highway and airfield construction. This outlook led to an intensive investigation of clay minerals to establish the constituents which might render it unfit for construction material. A study of this type includes a thorough understanding of the distinct minerals that go into making up the soil, their chemical composition, their physical properties, their chemistry and limits of base exchange, and methods for identification.

This study made no attempt to investigate all aspects of clay materials. A general introduction to clay mineralogy and a particular approach to soil stabilization has been presented. Since this investigation involved the stabilization of a clay soil with gypsum, a chemical approach was used to explain the phenomenon of stability. All the tests performed were those used in very basic soil mechanics studies.

It has been demonstrated that the development of satisfactory means of stabilizing soils with gypsum is undoubtedly extremely important at present in Oklahoma. However, it must still be kept in mind that a method of stabilization which is applicable to the type of clay used in this test is not necessarily applicable to soil from a different source.

The greatest difficulty encountered during this study was testing without complete knowledge of the composition of the natural clay,

and therefore, without knowledge of its probable reactivity to gypsum. Until the clay composition can be more fully determined, further development of soil stabilization with gypsum cannot be directed with optimum efficiency.

### Specific

From the tests performed, the following specific conclusions may be drawn:

- (1) Gypsum has a relatively minor effect on plasticity.
- (2) Gypsum added to the clay material slightly decreases the maximum density and slightly increases the optimum moisture content.
- (3) Gypsum induces a very marked increase in compressive strength and marked decrease in percent strain at failure.
- (4) Gypsum added to clay appears to influence indefinitely the strength and strain; however, the optimum and most efficient gypsum content is observed to be at approximately 9% by weight.
- (5) Gypsum added to clay appears to produce the most pronounced effects on strength and strain at failure for a curing time of up to 7 days. However, some slight additional improvement results from longer curing periods.

The effect suggested as contributing to the favorable influence brought about by the addition of gypsum to clay is:

The formation of calcium silicates and/or aluminates with cementing properties brought about by a chemical reaction between gypsum and clay.



This report presents the results obtained from a laboratory investigation of the clay stabilizing properties of gypsum. Laboratory testing procedures were described which were developed for evaluating the effects of gypsum on a Permian Red Clay. As a result of this study, it has become apparent that more thorough understanding of gypsum-clay reactions is required before gypsum stabilization can be fully evaluated.

## CHAPTER VIII

### RECOMMENDATIONS FOR FURTHER RESEARCH

The following recommendations are presented by the writer for further research to investigate the effectiveness of gypsum as an agent in stabilizing soils:

- (1) Further testing for plasticity and strength changes due to higher quantities of gypsum.
- (2) Investigation to discover whether the improvement in soil properties brought about by the addition of gypsum is permanent when the material is subjected to weathering.
- (3) Chemical analysis of sample after test to determine amount of calcium in the gypsum that actually entered into the chemical combination.
- (4) Investigation of strength after subjecting specimen to long periods of immersion in distilled water. This may show the influence excess moisture has on the bonding action of the calcium ion of gypsum.
- (5) Determination of the effectiveness of anhydrite and other gypsum modifications as agents for stabilizing various soils.
- (6) Investigation to discover the effect gypsum has on the angle of internal friction and cohesion constant of a clay soil.
- (7) Economic study of feasibility of gypsum-soil stabilization.

TABLE NO. 2

PLASTICITY OF THE CLAY WITH  
ADDED PERCENTAGES OF GYPSUM

	LL	PL	PI
Clay	47.0	17.0	30.0
+ 3% Gypsum	47.0	16.5	30.5
+ 6% Gypsum	48.0	16.0	32.0
+ 9% Gypsum	47.5	15.5	32.0
+ 12% Gypsum	48.0	16.0	32.0

TABLE NO. 3

COMPACTION CHARACTERISTICS WITH  
ADDED PERCENTAGES OF GYPSUM

	Max. Dry Density lbs./ft <sup>3</sup>	Optimum Moisture Content (% Dry Weight)
Clay	102.0	21
+ 3% Gypsum	101.5	21
+ 6% Gypsum	101.5	21
+ 9% Gypsum	99.0	24
+ 12% Gypsum	98.0	25

TABLE 4  
RESULTS FROM UNCONFINED COMPRESSION TEST

	Curing Time							
	1 - Day		4 - Days		7 - Days		28 - Days	
	Strength kg/cm <sup>2</sup>	% Strain	Strength kg/cm <sup>2</sup>	% Strain	Strength kg/cm <sup>2</sup>	% Strain	Strength kg/cm <sup>2</sup>	% Strain
Clay	0.49	20.5	1.19*	16.0*	0.95	14.0	1.23	13.0
3% Gypsum	0.82	18.0	1.13*	15.0*	1.02	13.0	1.32	12.5
6% Gypsum	0.92	15.5	1.32	13.0	1.39*	14.0*	1.32	12.0
9% Gypsum	1.72	12.0	1.52	8.0	1.76	11.0	1.77	8.0
12% Gypsum	1.84	10.0	1.53*	8.0*	1.77*	11.0*	1.80	7.0

Note: % strain values obtained at failure.

\* Values which were obtained from specimens experiencing unusual modes of failure.

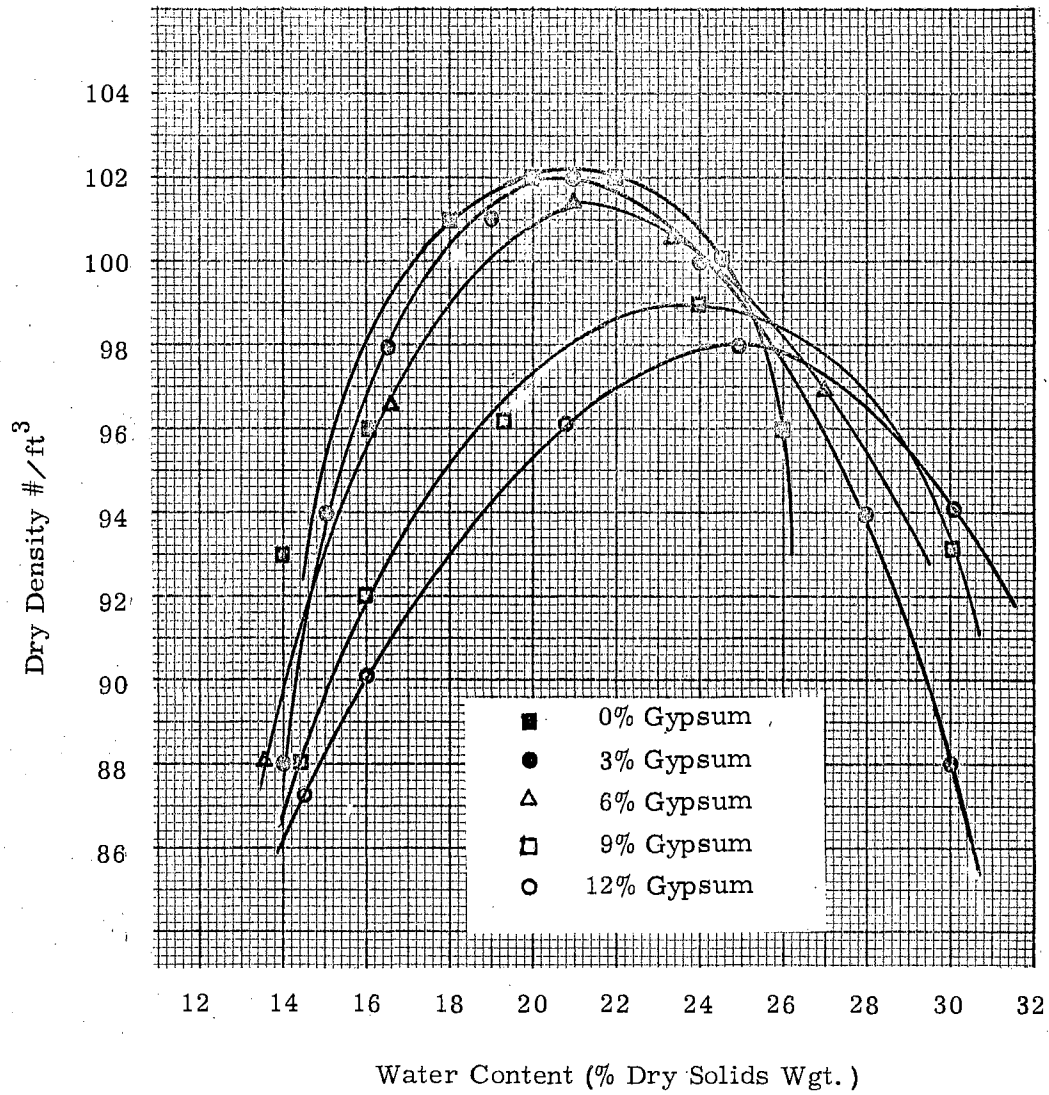


Figure 3

VARIATION IN EFFECTS OF GYPSUM ON COMPACTION

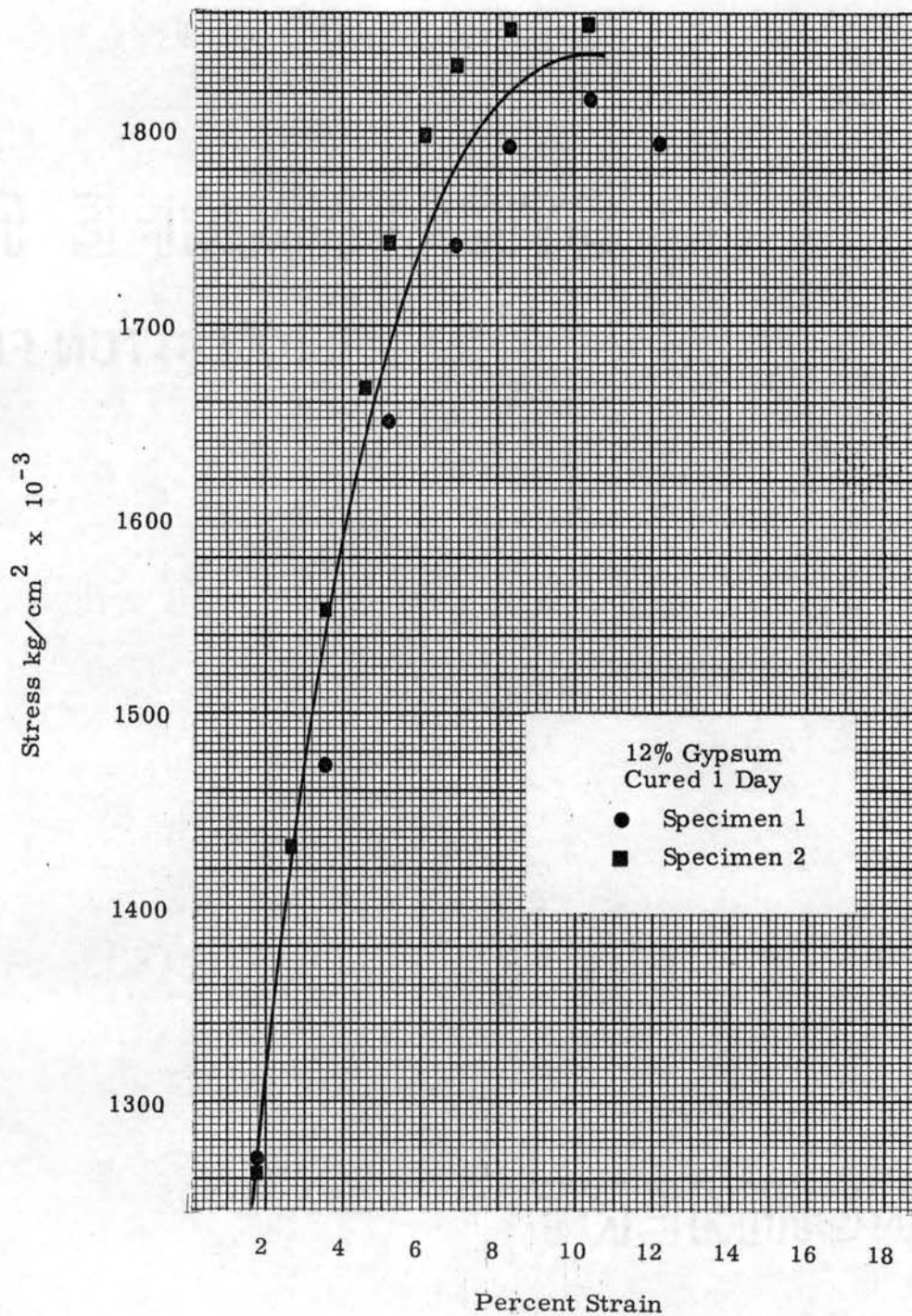


Figure 4  
TYPICAL STRESS-STRAIN CURVE FROM  
UNCONFINED COMPRESSION TEST

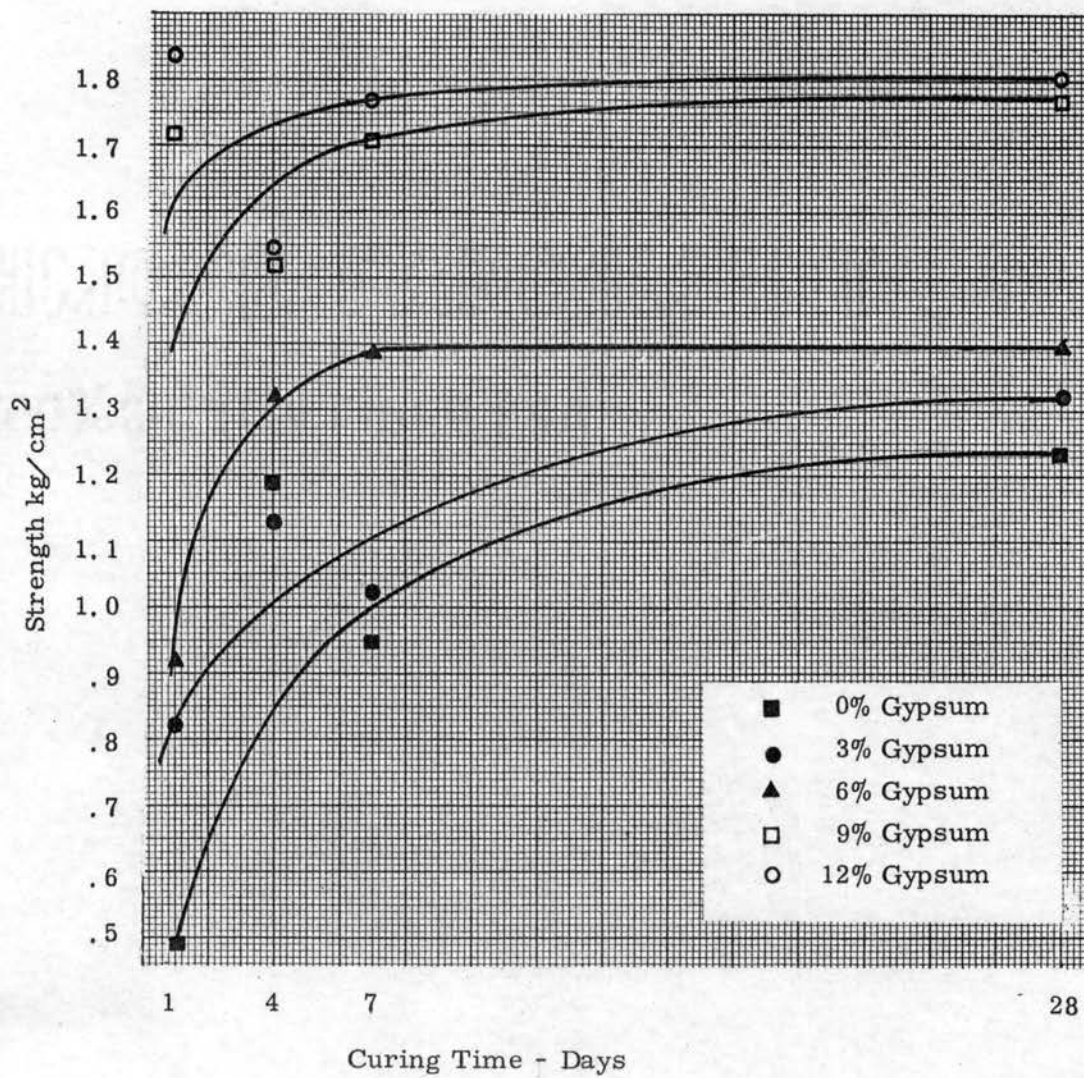


Figure 5

THE EFFECTS OF CURING TIME ON  
UNCONFINED COMPRESSION STRENGTH

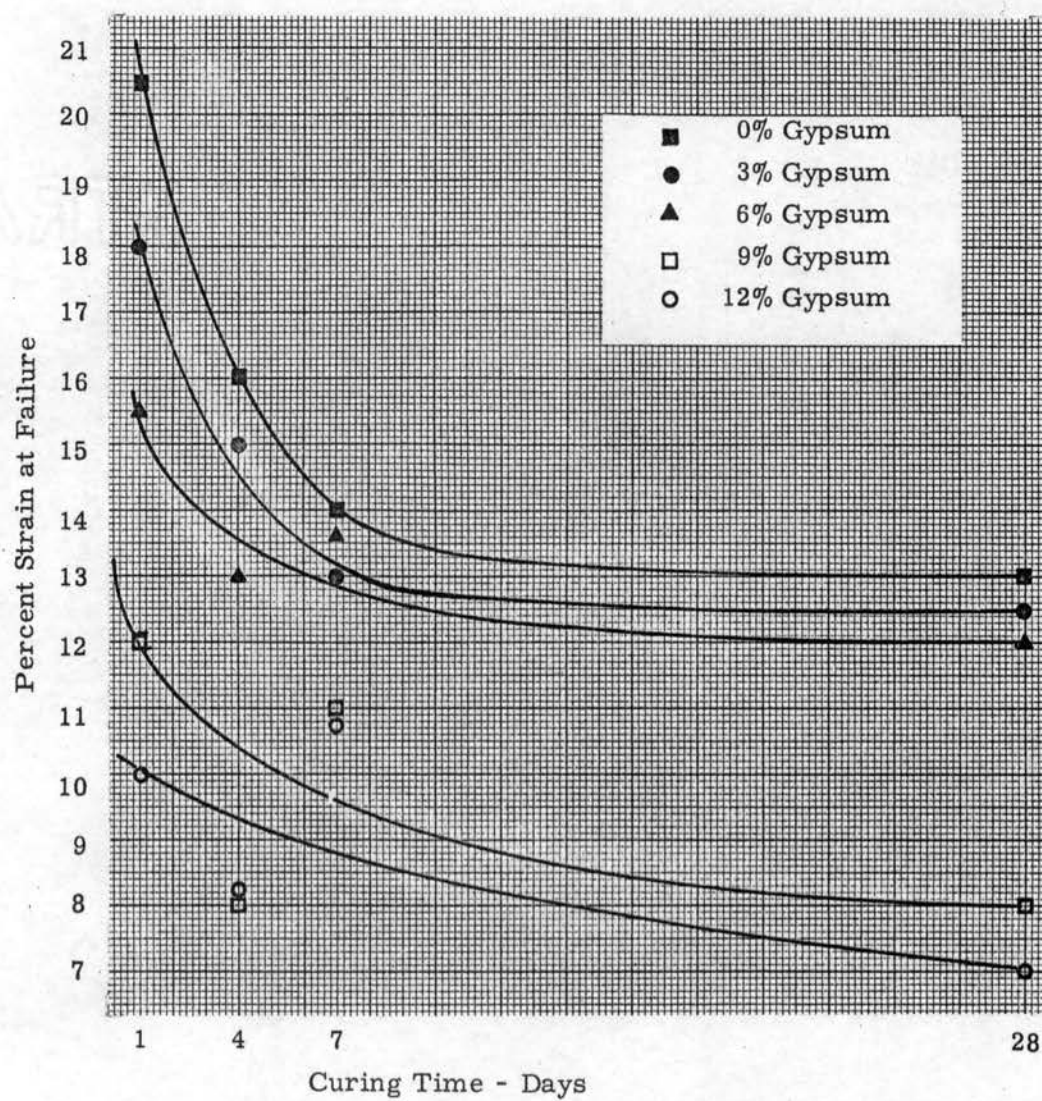


Figure 6  
THE EFFECTS OF CURING TIME ON  
STRAIN AT FAILURE FOR  
UNCONFINED COMPRESSION TEST



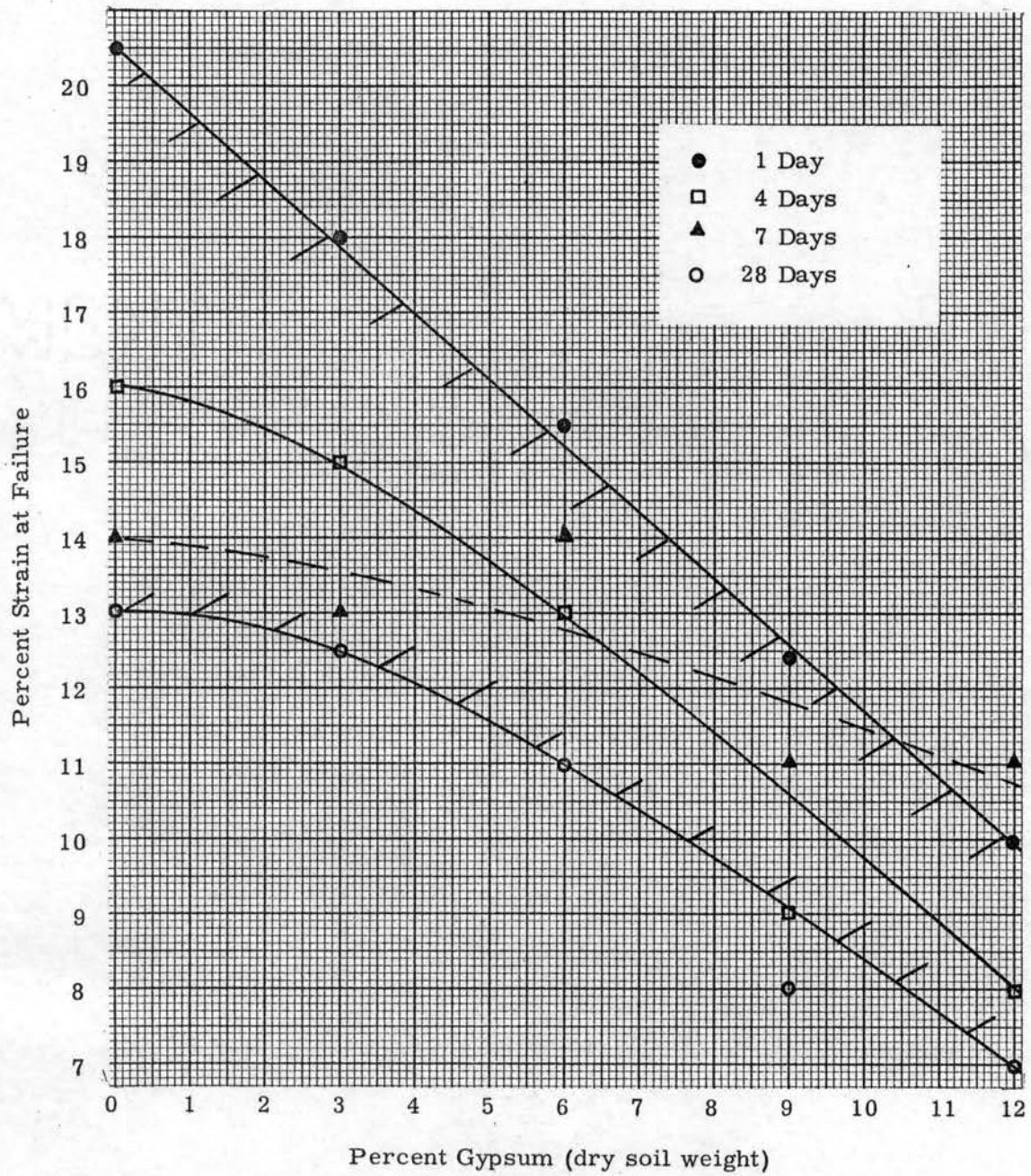


Figure 7  
 THE EFFECTS OF GYPSUM ON  
 STRAIN AT FAILURE FROM  
 UNCONFINED COMPRESSION TEST

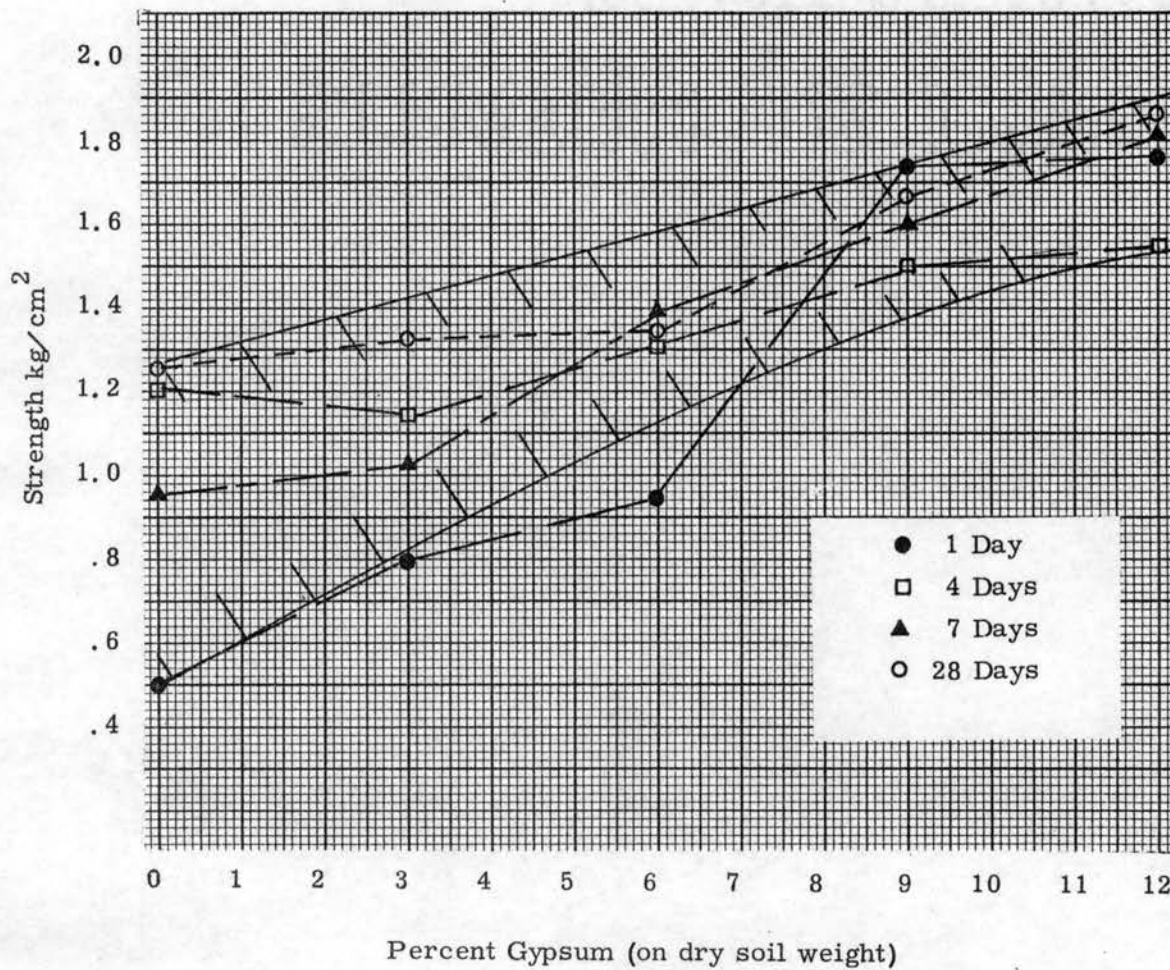


Figure 8  
 THE EFFECTS OF GYPSUM ON  
 UNCONFINED COMPRESSION STRENGTH

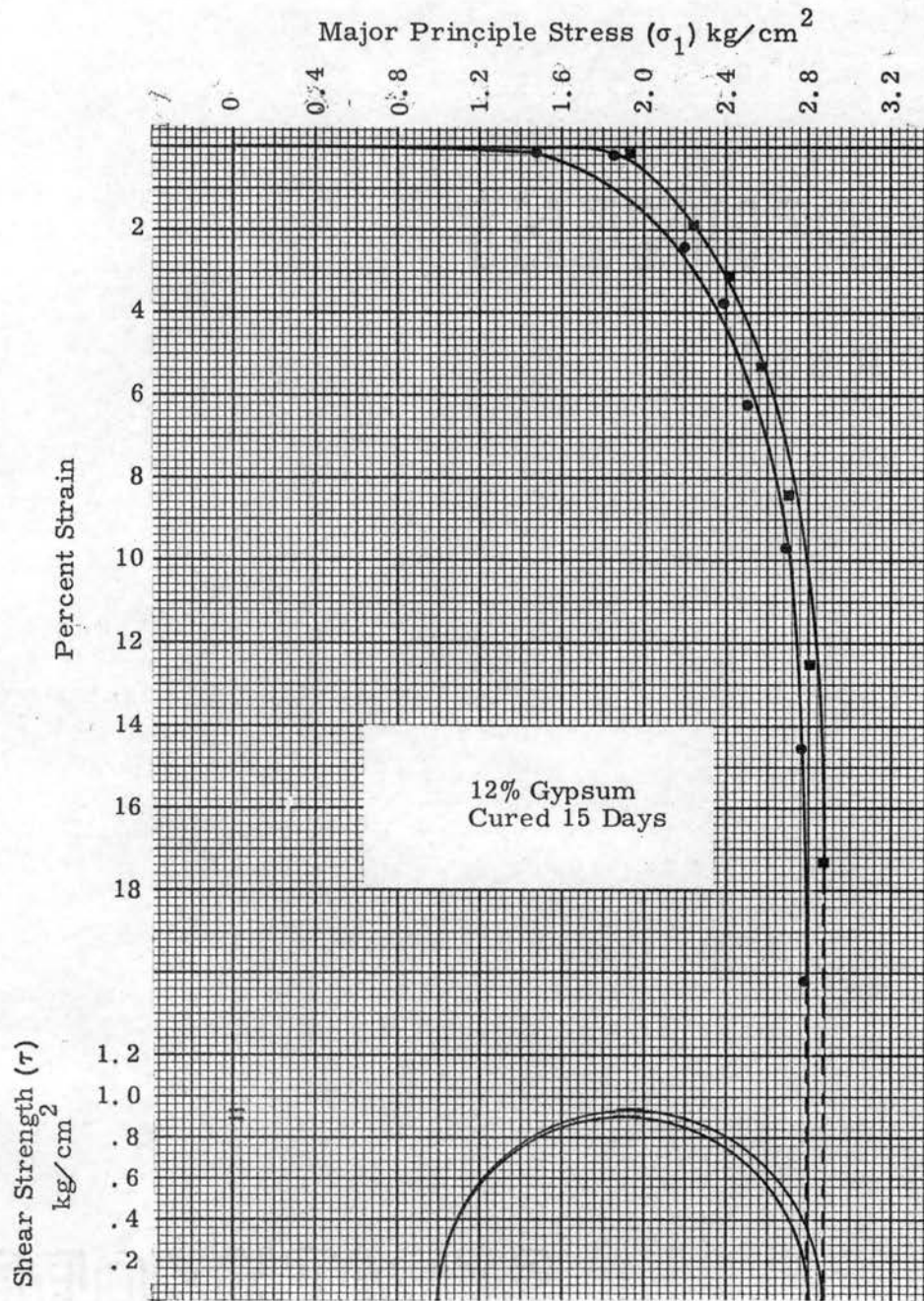


Figure 9

## TRIAXIAL TEST RESULTS

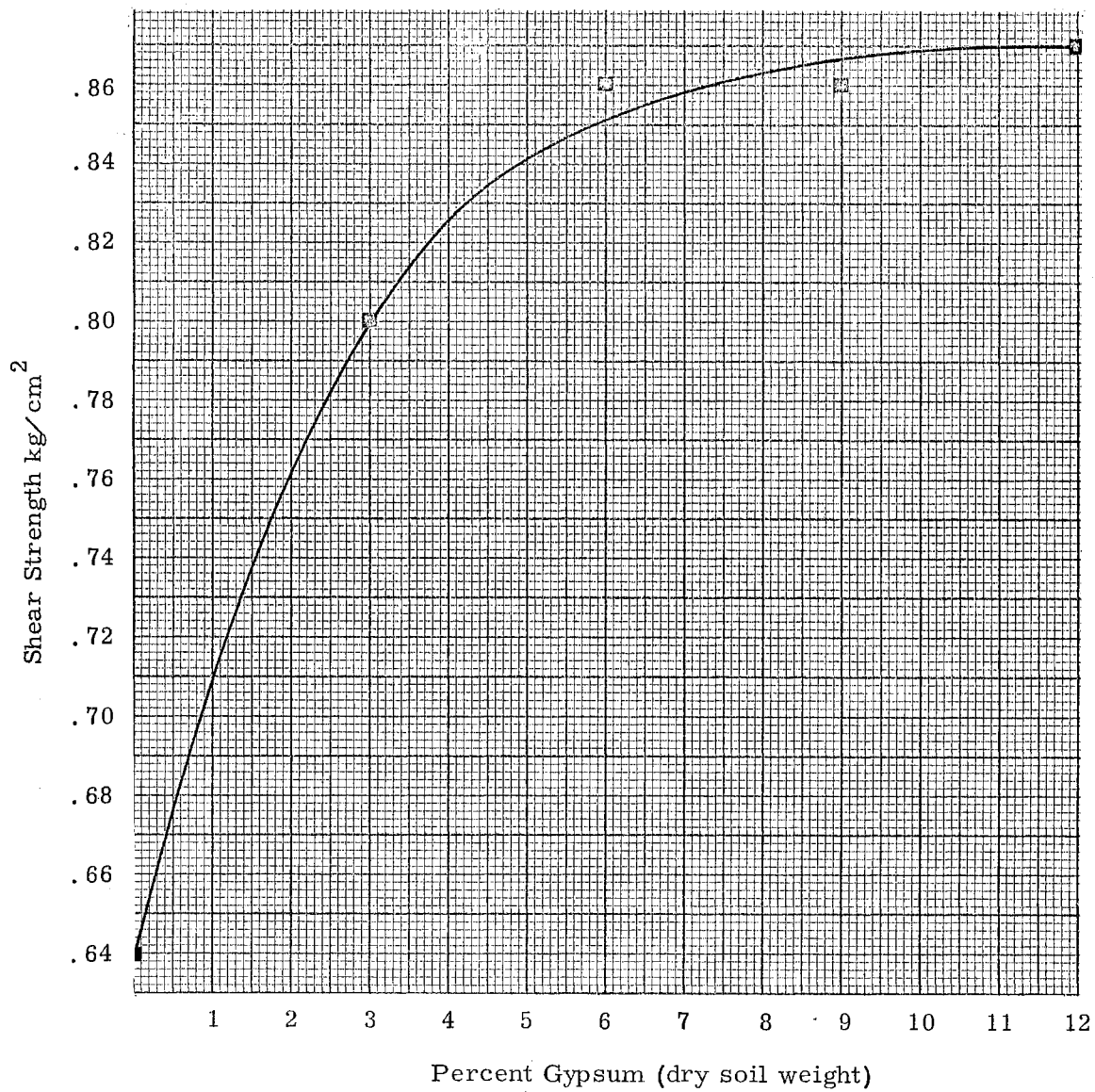


Figure 10

THE EFFECTS OF GYPSUM ON  
SHEAR STRENGTH FROM TRIAXIAL TEST

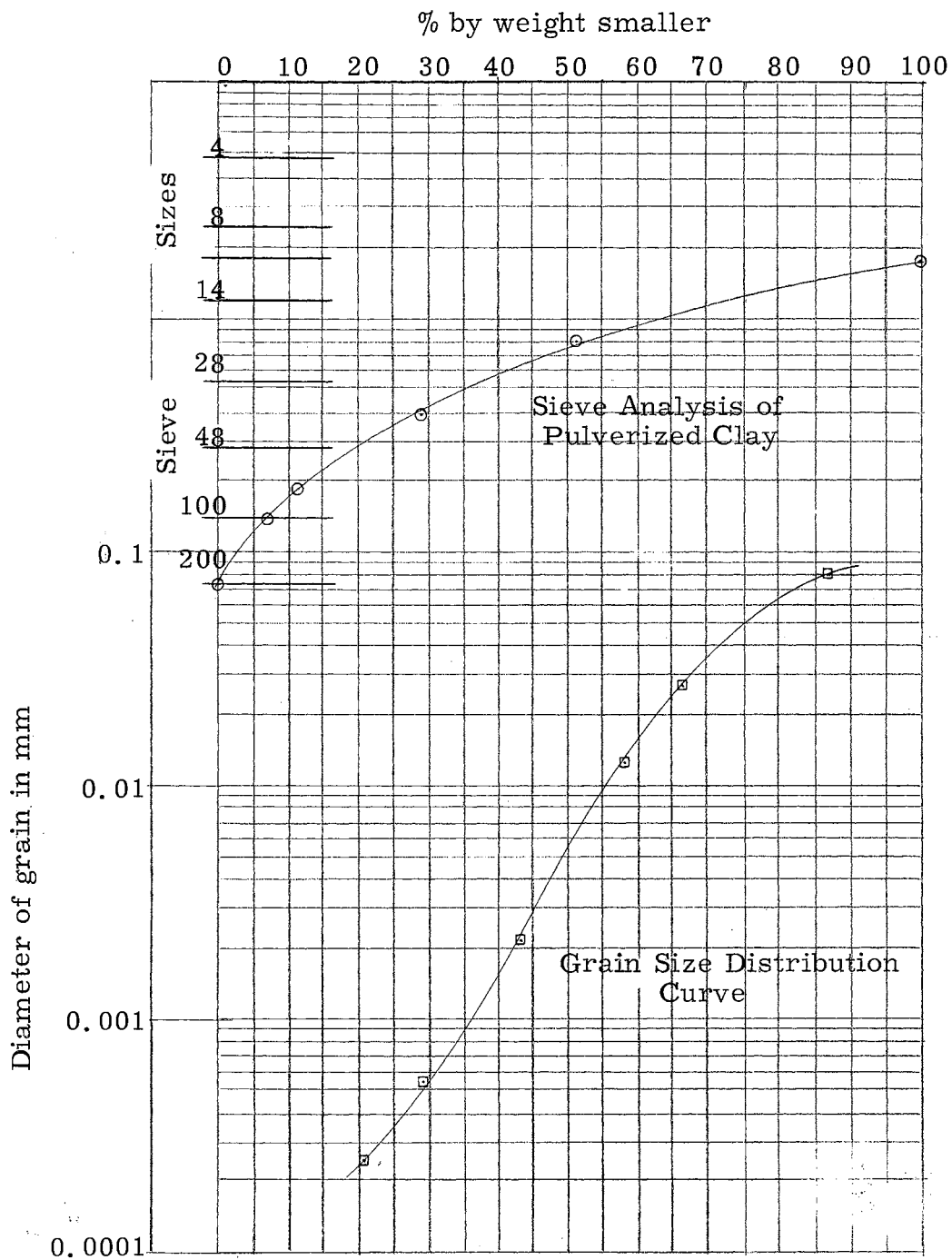


Figure 11

SIEVE ANALYSIS OF PULVERIZED CLAY  
AND GRAIN SIZE DISTRIBUTION CURVES

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