THE EFFECTS OF GYPSUM ON THE STRENGTH OF CLAY

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CHAPTER I

INTRODUCTION

General

The last thirty years have seen a revolution in the transportation industry in the United States. The motor vehicle has become the principal carrier of people and goods, and vast numbers of automobiles and trucks have flooded the nation's highways. The increasing volume of vehicles has been accompanied by an increase in the size and weight of trucks. In addition to being clogged, many highways are breaking up under the heavy traffic load. Fortunately, the present inadequate highway system is rapidly being replaced by a network of freeways designed to handle the large volume of high speed traffic that has developed in recent years. In addition to improved geometrics, improved structural sections are being built to handle the expanding number of heavy trucks.

The structural section of a highway consists of the pavement; one or more layers of graded, compacted aggregate; and, sometimes, a layer of selected soil of good bearing capacity. In many areas of the country, building a strong structural section is only a small problem. Local soils are of good quality and nearby streambeds and quarries yield strong aggregates suitable for base and subbase material. In other sections of the nation, however, supplies of suitable material are limited or nonexistent, and the cost of bringing good material into the area is often prohibitively high. It is then necessary to find some way of strengthening locally available materials so that they can be used to provide the high strength needed in the structural section of a highway.

Origin of Project

The process of strengthening soils and increasing their bearing capacity, by the addition of chemicals or by other means, is known as soil stabilization. Materials such as portland cement, asphalt, and lime have proved to be successful and economical soil stabilizers. Some other chemicals find only limited use because of their high cost. The search for new and better materials goes on as the highway program continues to expand.

Gypsum, which contains the same calcium cation found in lime, attracted the attention of the Oklahoma Highway Department because of the vast quantities of the mineral found in Oklahoma. Gypsum is used chiefly for the manufacture of cement plasters for the building industry. It is also used as a fertilizer and its chemical effects on soil have been carefully investigated. However, almost no investigation of the effect of gypsum on the physical properties of soil has been undertaken.

Miller (1) found that gypsum-treated soils resisted frost heave. Davidson and Mateos (2) subjected some gypsum-treated soils to freeze-thaw tests, but the specimens were destroyed and could not be tested for strength. The United States Gypsum Company has made some use of the mineral as a soil stabilizer for the internal road system of its plant at Southard, Oklahoma. Although satisfactory results were obtained, the tests were not conducted as part of an organized program, and no quantitative results are available. (3). Matalucci conducted the first organized research at Oklahoma State University in 1961. (4). This investigation indicated that gypsum increases the strength of Permian red clay and might prove to be a good soil stabilizer.

Encouraged by the results of these preliminary experiments, the Oklahoma Highway Department and the United States Bureau of Public Roads financed a more extensive study, at Oklahoma State University, into the use of gypsum and its products as soil stabilizers.

Scope of Investigation

This investigation deals with a limited portion of the research on gypsum stabilization. Only the effects of gypsum on the strength and plastic properties of clay are discussed. The investigation was so organized that the strength and plastic properties of the specimens could be compared to their gypsum content, water content, and curing time.

Primary importance was placed on the effects of gypsum on the strength of clay. The unconfined compression test was selected for measuring the strength of the stabilized specimens. It is simple and easy to perform and does not require elaborate preparations. Plastic limit and liquid limit tests were performed by the standard laboratory methods. In order to have some standard of comparison, a limited number of specimens were stabilized with lime and subjected to the unconfined compression test.

While gypsum was found to provide some increase in the strength of the clays tested, its effects are minor when compared to those of lime. It is doubtful that the small increase in strength would justify the use of gypsum as a stabilizer for clay if, indeed, strength is to be used as the criterion for stability. Gypsum has a marked effect on the plasticity of the soil, however. The liquid limit dropped sharply as the gypsum content of the soil specimens increased. The soil became much easier to work and handle and did not stick to the compaction equipment. It would seem that instead of a soil stabilizer, gypsum should probably be classed as a soil modifier.

CHAPTER II

SOIL STABILIZATION

General

Soil stabilization is any process which increases the bearing capacity of a soil or imparts other desirable volumetric stability. Soils can be stabilized by physical methods, chemical methods, or a combination of the two. Most physical stabilization is done by remolding and compacting the soil to increase its density. This is the method employed in the construction of earth dams and highway embankments. Coarse-grained soils used for highway base courses are usually screened and blended to produce a specified gradation before compaction. Soils can also be stabilized in situ by physical methods. Cohesionless soils are often vibrated to increase their density and bearing capacity before a structure is erected on them.

Chemical stabilization is accomplished by mixing the soil with some chemical additive. In grouting a soil, for example, some type of cementing material is injected into the soil to fill the voids and bind the soil grains together. This is chemical soil stabilization in the strictest sense. The soil mass is treated in place, with as little disturbance of the soil grains as possible. Often, soils used in highway base courses are mixed with chemical additives before they are placed on the roadbed and compacted. Although this process is referred to as chemical soil stabilization, it is actually a combination of both chemical and physical soil stabilization methods. It is this particular type of soil stabilization with which this investigation is concerned.

Soil Stabilization Materials

In the past few years, lime has become an important stabilizer for fine-grained cohesive soils. It has been subjected to a great amount of research and study in both the laboratory and the field. As a result, lime has been shown to be an efficient soil stabilizer that produces strong, durable highway base material. Because of the large amount of detailed information available on lime stabilization, it was selected as the standard of comparison for this investigation.

Dolomitic and calcitic hydrated limes are commonly used in highway work. Both types of lime are manufactured in the same way. Either limestone or dolomite is heated in the presence of oxygen to form calcium oxide or quick lime. Water is added to the corrosive quick lime to form hydrated lime, calcium hydroxide, which can be handled safely. The particular rock used in the manufacture of the lime will impart certain impurities and properties to the material. Although these differences must be considered in the design of a stabilized soil base course, they do not affect the basic properties of the lime.

Lime acts in three ways to strengthen cohesive soils, (5). First, calcium cations liberated from the lime enter into cation exchange reactions with the clay minerals. The cation exchange changes the electrical charge density on the clay particles, causing them to attract each other and flocculate. These floccules act like cohesionless silt particles and reduce the plasticity of the soil. A second reaction is the carbonation of the lime by the carbon dioxide in the atmosphere to form a weak calcium carbonate cement. The most important action of the lime, however, is the pozzolanic reaction between the lime and the clay minerals. This slow, long-term reaction forms strong calcium-alumino-silicate compounds that bind the soil particles together. It is this action that provides lime stabilized soils with most of their strength. Much of the research on lime stabilization has been directed toward the improvement of the pozzolanic reaction. Fly ash and other chemicals are often added to the soil to increase the amount of aluminum and silica available for reaction with the lime.

Historically, asphalt was one of the first materials to be used for soil stabilization. It was not until the development of the modern highway system, however, that asphalt stabilization received any scientific study. Unlike lime, asphalt may be used to stabilize both cohesive and cohesionless soils. The coarse-grained cohesionless soils are stabilized by the cementing action of asphalt. The individual grains are coated with asphalt and cemented together at the points of contact. Only a small amount of asphalt is used and the voids remain unfilled. The action of asphalt on cohesive soils is somewhat different. The grains are too small and too numerous to be individually coated with asphalt.

Instead, small clods of the soil are coated and waterproofed by the asphalt to preserve the natural cohesion and stability. (6).

Cutback asphalts and asphalt emulsions are used for soil stabilization. Because of the difficulties encountered when using asphalt emulsions, cutback asphalts find wider use as soil stabilizers. Emulsions are composed of asphalt particles suspended in water. The fines in the soil often cause the emulsion to "break" before construction can be completed. Cutbacks are asphalt cements dissolved in some petroleum solvent such as naphtha or kerosene. Over a period of time, the solvent evaporates from the soil mixture leaving the asphalt cement to stabilize the soil. A number of cutback asphalts are available and one can usually be found that will fit the needs of the particular soil to be stabilized.

Portland cement is one of the most widely used soil stabilizers employed in highway construction. Soil-cement has been carefully studied since its inception, and a complete technology has been developed. First used in England in 1916, cement-stabilized soils went unnoticed until several highway departments in the United States began investigating the material in the early 1930's. (7). In 1935, the first "engineered" soil-cement road was build near Johnsonville, South Carolina. Since then, soil-cement has been developed into a highly-specialized and widely-used construction material.

The action of portland cement depends on the type of soil being stabilized. (8). When mixed with fine-grained cohesive soils, the cement develops a strong matrix that encases the soil particles. The matrix fixes the soil particles so that they can no longer slide on each other. As is the case with lime, cation exchange plays an important part in the stabilization of cohesive soils. Calcium cations, released from the portland cement, enter into cation exchange with the clay particles. As a result, the electrical charge density of the clay particles is changed, causing them to attract each other and flocculate. The floccules behave as silt particles and cause a reduction in the plasticity of the soil. Cohesionless coarse-grained soils act somewhat like concrete when stabilized with portland cement. The aggregate particles are cemented together at their points of contact but the voids remain largely unfilled because of the small amount of cement used in the mixture.

While asphalt, lime, and portland cement are the most widely used soil stabilizers, other chemicals are employed on a limited scale. Many chemicals have been investigated and reported but few have found their way into the field. Economics and a lack of detailed design information limit practical soil stabilizers to a very few. Two chemicals that find some use are calcium chloride and sulfate lignin. Calcium chloride has long been used as a dust palliative and now finds limited use as a soil stabilizer. (9). Sulfate lignin is a waste product of the paper industry. Although good results have been obtained with lignin, transportation difficulties limit its use. (10).

Construction Methods

All stabilized soils must be individually designed. There is no way to predict, without laboratory testing, how a particular soil will react with a particular stabilizer. The type of soil, its mineralogical composition, the type of chemical stabilizer, the construction methods, and the climatic conditions all influence the properties of the finished material. Design methods vary from agency to agency, but all are aimed at finding the combination of stabilizer and soil that will produce the strongest base material.

Two basic methods are employed in the construction of stabilized soil base materials. Most common is the road mixing method. Road mixing is done with a traveling pug mill which picks up the soil from the roadbed, mixes it with the chemical additive, and redeposits it on the roadbed ready for compaction and trimming. Although road mixing is a simple operation, requiring a minimum of men and equipment, several passes of the pug mill may be required to completely mix the soil with the chemical additive. It is also difficult to obtain a mixture that is consistently uniform. Plant mixing is done with a stationary pug mill, usually an asphalt plant, and the soil mixture is trucked to the roadbed for spreading and compacting. While plant mixing is more expensive than road mixing, it produces a better quality material and provides better control of the operation.

Once the soil-chemical mixture has been deposited on the roadbed, it is compacted and the upper surface trimmed to the proper shape. Compaction is done with sheepsfoot rollers, pneumatic rollers, or steel-wheel rollers, and trimming is usually done with a motor grader. The exact methods of mixing and compacting are varied to suit the requirements of the soils and chemicals involved. The end result is a hard, strong, stabilized soil capable of supporting heavy traffic loads.

CHAPTER III

MATERIALS USED IN THE INVESTIGATION

Gypsum

Gypsum is a soft, white sedimentary rock that occurs in large deposits throughout the world. In the United States, extensive deposits are found in California, Nevada, and Utah, and in an area extending from New York through Michigan to Iowa and southward to the Pecos River in Texas. The majority of the deposits are in the form of rock gypsum, but beds of alabaster, selenite, satin spar, and gypsite are found in some areas. (11). All of these minerals are forms of the dihydrate of calcium sulfate, $CaSO_4 \cdot 2H_2O$.

Rock gypsum, usually referred to simply as gypsum, is the most common and most valuable of the various forms. It is made up of minute tubular crystals in the monoclinic system. (12). Pure gypsum is white in color and contains 32.5% calcium oxide, 42.6% sulfur trioxide, and 20.9% water. Pure gypsum is rare, the deposits usually being contaminated with other minerals such as iron, aluminum, or magnesium oxides which impart a red, pink, or blue tint to the gypsum. (11). Gypsum is a soft, water soluble material having a hardness of second degree on Moh's scale. Its specific gravity varies from 2.3 to 2.4 . (11).

Gypsum is believed to have been formed during the evaporation of the inland seas that once covered parts of the world' s land masses. The exact mechanics of the formation are open to question, however. In many cases deposits of both the dihydrate and the anhydrite of calcium sulfate occur side by side. One theory suggests that anhydrite was precipitated and later hydrated to gypsum. (11). Laboratory evidence indicates gypsum can be precipitated directly from solution if conditions are correct. Neither of these theories offers a satisfactory answer to all questions.

Gypsum has one important property not found in any other material. It can be calcined to drive off part of the water of crystallization. Mixed with water it will then recrystallize to form gypsum. No other mineral, once separated from its combined water, can be returned to its original form by so simple a procedure. Calcining is done at a temperature of 125° C and creates the hydrate of calcium sulfate, $CaSO_4 \cdot \frac{1}{2} H_2O$, commonly known as plaster of Paris. Plaster of Paris, mixed with fiber for reinforcement, is used in the building industry for wall plasters and wall board. (11).

Plaster of Paris is not the only product of gypsum, however. By heating gypsum to 595° C, the anhydrite, $CaSO_4$, can be produced. This product, known as Keen's cement, can be used as a high strength cement when combined with other chemicals. (3). It is also used as an inert filter in products such as baking powder and toothpaste. Special purpose cements are also manufactured from gypsum by the addition of chemicals and by varying the temperature during the calcining process. Most of these processes are trade secrets of the manufacturer.

Raw gypsum has several important uses. It is sometimes used as an inert filler material and finds wide use as the retarding agent in portland cement. Gypsum, or land plaster, is also used as fertilizer. When applied to the top soil, it reacts with the volatile ammonium carbonates to form the more stable compound, ammonium sulfate. (13). The manufacture of plaster of Paris, however, is the most important use of gypsum.

The other forms of gypsum are much rarer than rock gypsum and are of little commercial value. Alabaster is a very fine-grained form of gypsum used chiefly for sculpture. Selenite, on the other hand, is very coarse grained, having crystals visible to the eye. Satin spar has very long, needle like, parallel crystals. Its name is derived from the satin-like appearance of the surface. Gypsite is gypsum mixed with sand, clay or other impurities. (11).

A mineral closely associated with gypsum is anhydrite, $CaSO_4$. Similar in appearance to gypsum, it has a density of 2.9 and a hardness of 3 on Moh's scale. Anhydrite is being used, on a limited scale, as a retarder for portland cement. In general, however, it has little commercial value and is considered a waste material.

The gypsum used for the test discussed in this paper was rock gypsum obtained from the United States Gypsum Company plant at Southard, Oklahoma. The deposits worked by the plant are associated with the Permian Redbeds and, consequently, most of the gypsum was contaminated and had a slight reddish color. No attempt was made to remove the impurities from the gypsum. For most of the test, the gypsum was screened to pass the No. 10 sieve. In some tests, gypsum passing the No. 100 sieve was used. A sieve analysis of the gypsum is shown in Fig. 1. Except for the crushing and screening, the gypsum was not treated or altered in any way.

Clay

The word clay implies a fine-grained, natural, earthy, plastic material. There is, however, no precise definition of the material. Clays are often defined by particle size, but no agreement exists as to the exact size of a clay particle. Geologists usually describe a clay particle as being smaller than four microns. In soil mechanics, however, two microns is the accepted maximum size of a clay particle. Grim (14) points out that clay mineral particles are concentrated in a size of less than two microns, but nonclay minerals generally are found as particles not smaller than one or two microns. There is, therefore, a sound reason for selecting two microns as the upper limit for clay size particles.

Clays cannot be described by size alone. Rock flours fall into the clay size range and sometimes are classified as clays. However,

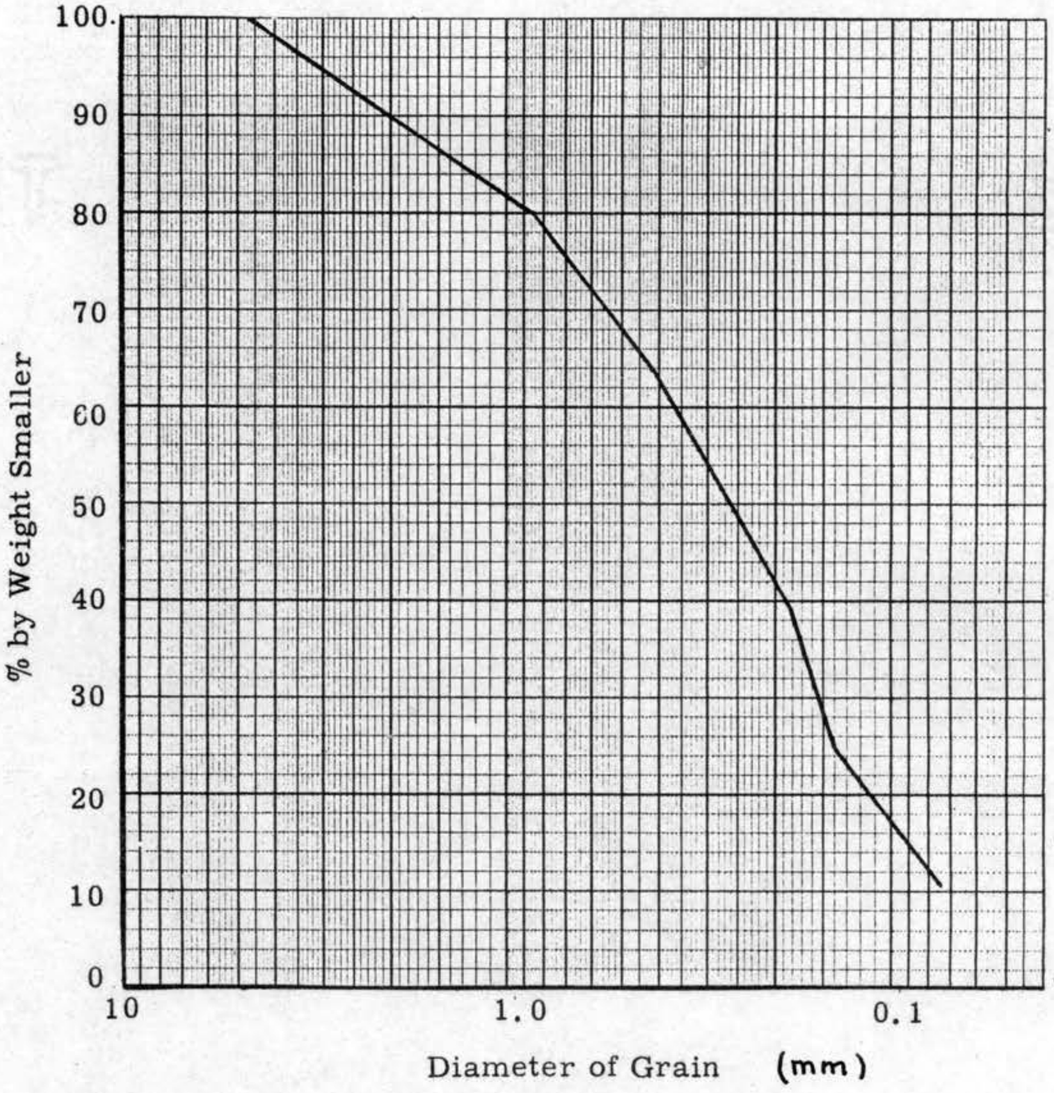


FIGURE 1

SIEVE ANALYSIS OF GYPSUM

rock flours exhibit no true plasticity when mixed with water. There are other soils that consist primarily of clay and exhibit plasticity but contain large amounts of nonclay material such as sand or silt. These soils are usually described as silty clay or sandy clay.

It has long been theorized that clay minerals are made up of very small particles of a limited number of crystalline minerals. Only with the development of the electron microscope and X-ray diffraction analysis has it been possible to prove the theory. It is now known that two atomic structural units make up the atomic lattices of most clay minerals. (14). One unit consists of octahedrons with a hydroxyl ion at each apex and a magnesium, aluminum, or iron atom imbedded in the center. The octahedrons are packed together so as to form a sheet with a layer of hydroxyls on the top and bottom and a layer of iron, magnesium, or aluminum atoms situated between them. The other basic structural unit is built up of tetrahedrons with an oxygen ion at each point and a silica atom suspended in the center. Six of these tetrahedrons are joined together in a hexagon with their tips pointing in one direction and their bases in a common plane. The hexagons are joined together to form a continuous sheet. In a few clay minerals, the hexagons form a chain, but these clays are rare.

The tetrahedral and octahedral units are the basic atomic structures of most clay minerals. The different clay minerals are formed by the pattern in which the sheets are arranged and by the metallic ion present in the octahedral units. Kaolinite has the simplest structure of all the clay minerals. It is composed of one sheet of silica tetrahedrons and one sheet of alumina octahedrons. Montmorillonite, another common clay mineral, is composed of two tetrahedral sheets with an octahedral sheet between them. Either aluminum, iron, or magnesium can be found in the octahedral sheet. Other minerals are formed by more complex arrangements of the sheets and variations of the metallic ion.

Ion exchange is an important phenomenon associated with clay minerals. Clays are capable of sorbing certain anions and cations and holding them in an exchangeable state. A good example is the zeolite water softener. In this process, sodium cations held by the zeolite are exchanged for calcium cations in the water. The sorbed cations, held by a clay mineral, influence the physical properties of the clay. Bentonite, for example, is well known for its thixotropic action. However, unless sodium cations are present, bentonite does not exhibit thixotropic action. (14). The plastic properties of clay can be altered by saturating the clay with the proper cation. Clays used for ceramics can be altered in this manner for easier handling and processing.

Adsorbed cations are thought to be held on the surfaces of the clay particles. Clay particles are flakes arranged in a sheet-like lattice structure. Any interruption of a lattice structure, such as along the edges of the clay particles or the cleavage planes that form their surfaces, creates an electrical unbalance. On the large surfaces of the clay flakes, the negatively charged oxygens and hydroxyls are exposed. These attract the positively charged cations to the surfaces of the clay particles where they are firmly held until displaced by some other cation. (14).

The amount of ions that a clay mineral can adsorb and exchange is called its ion exchange capacity. Different soils have different exchange capacities depending on the amount of clay in the soil, the types of clay minerals present, and the size of the clay particles. In general, montmorillonites have the highest exchange capacities while kaolinites have the lowest capacities. Most clays are mixtures of the various clay minerals and their cation exchange capacities fall somewhere between the two extremes.

Three clays were selected for use in this investigation. They were Permian red clay, bentonite, and kaolinite. The bulk of the investigation centered around the Permian clay. It was chosen for the study because of its widespread occurrence in central Oklahoma and because it is practically worthless as a highway building material. Permian red clay is a reddish prairie soil derived from the Permian Red Beds. These soils contain about 40% montmorillonite, 30% to 35% illite, and 25% to 30% unidentified materials. The unidentified material is believed to be quartz with traces of kaolinite, chlorite, and iron oxide. (15).

The particular Permian soil used in this investigation was obtained from several sources in Stillwater, Oklahoma. Part of the soil was already on hand in the Soil Mechanics Laboratory. The rest was dug from under the Life Sciences Building on the Oklahoma State University campus. All of the material was air dried to a moisture content of two percent, crushed, and screened through a No. 10 sieve. The crushed soils were mixed and blended until a homogenous mixture was obtained. About 250 pounds of Permian clay was obtained in this manner. This insured enough uniform soil to carry out all tests without having to change soils and soil properties in the middle of the investigation. All of the Permian clay was obtained from six or more feet below the ground surface and contains no organic material. Figure 2 shows a hydrometer analysis of the soil. Some of the properties of the clay are listed in Table I.

Because cation exchange was expected to play an important part in the investigation, two pure clay minerals, bentonite and kaolinite, were selected for testing. These clays were produced for industrial use and were not pure in an analytical sense. The amount of impurities in the clays was minor and probably had no effect on the test results. Bentonite was selected because of its high cation exchange capacity and expansive properties. Conversely, kaolinite was chosen because of its low cation exchange capacity. Some of the properties of bentonite and kaolinite are listed in Table I.

TABLE I

PROPERTIES OF CLAY

Property	Kaolinite	Bentonite	Permian Clay
Plastic Limit	32.4	42.4	15.0
Liquid Limit	60.8	603.5	40.5
Plastic Index	28.4	561.1	25.5
Compacted Density	75 lb/cf	64 lb/cf	110 lb/cf
Optimum Moisture Content	37.0%	53.0%	17.0%
Specific Gravity	----	----	2.72
Percent Clay Size	100	100	30

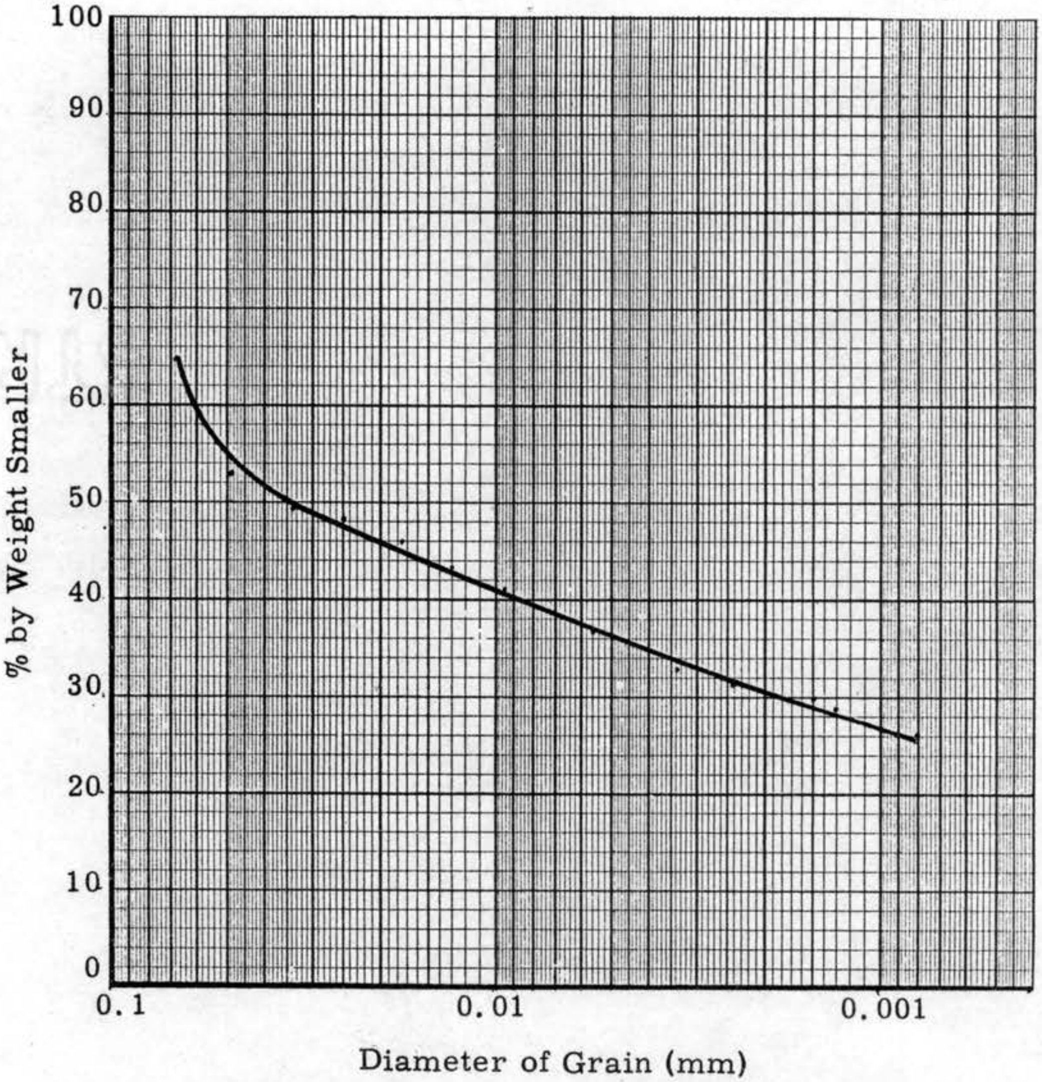


FIGURE 2

GRAIN SIZE DISTRIBUTION OF PERMIAN CLAY

CHAPTER IV

TEST METHODS

Types of Tests Performed

It was apparent at the outset of this investigation that the large scope of the over-all program made it imperative that the bulk of the experiments be simple and easy to perform. Simple testing procedures reduce the amount of error, both human and experimental, to a minimum. While they do not yield a large variety of detailed data, they eliminate many of the variables found in more sophisticated experiments. If the data collected in this investigation was to be readily compared to information available on other stabilizing agents, standard test methods had to be used.

As previously stated, this paper is limited to a small portion of the research being conducted on stabilizing soils with gypsum. Only the effects of gypsum on the strength and plasticity of soil are discussed. For the tests on the strength characteristics of gypsum-stabilized soils, it was obvious that the unconfined compression test must supply the data. Several factors dictated the use of this test. It is a standard test used for all load-bearing materials. The test can be performed and the results computed in a few minutes. Because of this, a large number of tests can be completed in a short time. The unconfined compression test has several disadvantages. Soils, in place, are always subjected to some confinement. Therefore, the results of an unconfined compression test are relative and can be compared to the results of another unconfined compression test, but they do not necessarily represent the true strength of the material. No information about the cohesion or the angle of internal friction can be obtained from these tests.

All of the specimens used in the unconfined compression tests were prepared with the Harvard Miniature Compaction Apparatus. This device, developed by S. D. Wilson at Harvard University, is commonly used in research but is not used for field work. It produces specimens 1.3 in. in diameter and 2.8 in. high. They are easy to handle and store, do not require a large amount of material, and can be molded rapidly. In addition, the testing equipment already available in the laboratory was designed to handle samples of the size produced by the Harvard Apparatus.

One of the important aspects of this investigation was the effects of gypsum on the plasticity of clay. To measure this property, liquid limits and plastic limits were determined for various mixtures of clay and gypsum. The standard laboratory procedures were used to perform these tests.

Specimens Tested

A large number of factors, ranging from the percentage of stabilizer to the testing conditions, influence the properties of a stabilized soil. It was impossible to investigate all of the factors, so four variables, considered to be of prime importance and interest, were introduced into the investigation. These were gypsum content, gradation of gypsum, water content, and curing time. Other factors, such as testing conditions, curing conditions, and gradation of soil were held constant. Specimens were prepared so that various combinations of the four variables could be investigated.

The plastic properties of gypsum-treated soils were investigated first. Permian red clay was mixed with gypsum graded to pass the No. 10 sieve and distilled water, and the liquid and plastic limits were immediately determined. At the same time, part of the mixture was set aside to cure for twenty-eight days before the limits were determined. Originally, the limits were to be determined for mixtures varying from zero to ninety percent gypsum in increments of ten percent. However, when a mixture of forty percent Permian red clay and sixty percent gypsum was tested, it was found to behave as a cohesionless soil, and the test series was ended. About the same time, it was discovered that the gypsum contents used in the limit test were in error. The percentage of gypsum in each specimen had to be determined mathematically. Although the pattern of the test series was radically changed, the results were unaffected and still usable.

Another series of limit investigations was performed using gypsum graded to pass the No. 100 sieve. Permian red clay samples, with gypsum contents varying from zero to forty percent in increments of ten percent, were tested immediately after preparation. No provision was made for curing any of the samples. All four variables - gradation of gypsum, gypsum content, water content, and curing time - were introduced into the unconfined compression test series on Permian red clay. Specimens were compacted with gypsum contents varying from zero to sixty percent in increments of ten percent. The gypsum was graded to pass the No. 10 sieve. At each gypsum content, specimens were prepared using three water contents. The water contents were optimum, two percent above optimum, and two percent below optimum. Eight specimens were prepared at each of these moisture contents so that each could be cured for one day, seven days, twenty-eight days, and six months.

A second, more limited, series of specimens was prepared later. These specimens used gypsum passing the No. 100 sieve. Gypsum contents of six, ten, fourteen, twenty, thirty, and forty percent were used in the specimens. All specimens were compacted at optimum moisture content. Six specimens were prepared at each gypsum content so that two each could be cured for one, seven, and twenty-eight days.

Two series of specimens composed of pure clay minerals and gypsum passing the No. 10 sieve were also prepared for unconfined compression testing. The first series was composed of bentonite with gypsum contents of zero, five, ten, twenty-five, and fifty percent. All compaction was done at optimum moisture content with six specimens prepared at each gypsum content so that two each could be cured for one, seven, and twenty-eight days. The second series was composed of kaolinite and gypsum passing the No. 10 sieve. The gypsum contents and curing times used for bentonite were also used for the kaolinite specimens. All compaction was done at optimum moisture content.

The final series of specimens prepared for unconfined compression testing was the control group using hydrated lime and Permian red clay. Specimens using lime contents of two, four, six, nine, and twelve percent were compacted at optimum moisture content. Six specimens were prepared at each lime content so that two each could be cured for one, seven, and twenty-eight days.

Preparation and Testing of Specimens

The plasticity of the gypsum-Permian red clay mixtures was measured by the plastic and liquid limits of the materials. The gypsum was screened on the proper sieve and blended, in the desired proportions, with the dry soil. Enough of the mixture was prepared so that two tests could be performed immediately and two more after twenty-eight days curing time. When the dry ingredients were thoroughly mixed, enough distilled water was added to make the mixture plastic. The portion of the mixture designated for curing was sealed in a Mason jar and stored in a humid room.

The limits were determined by the standard laboratory methods. Briefly, the plastic limit is the moisture content at which the soil will crumble when rolled into a thread three millimeters in diameter. The liquid limit was determined using the mechanical liquid limit device. The exact procedures for performing these tests can be found in any text on elementary soil mechanics.

Specimens for unconfined compression testing were prepared with the Harvard Miniature Compaction Apparatus. Specimens for triaxial compression tests, as well as several other tests not covered in this investigation, were compacted at the same time the unconfined compression specimens were prepared. The stabilizer and soil were blended in the proper proportion and stored in cans until needed. The proper amount of distilled water needed to produce the desired moisture content was slowly added to the dry mixture as it was stirred in a large dough mixer. When thoroughly mixed, the soil was covered to reduce evaporation losses and compaction began immediately.

The Harvard Apparatus consists, basically, of a cylindrical mold 2.8 in. high and 1.3 in. in diameter and a spring loaded tamper. The size and length of the tamper spring can be regulated so that a deflection of the spring causes the tamper to impart a specified pressure to the soil. Most of the specimens were compacted using three layers of soil with twenty-five blows of twenty pounds each on each layer. Several of the specimens could not be compacted by this method because of their high moisture contents. The soil was displaced by the tamper instead of being compacted, and the compaction procedure had to be modified. These specimens were compacted in six layers with twenty-five blows of ten pounds each on each layer of soil. The densities produced by this modification were commensurate with the densities obtained using the standard method.

After compaction, the specimens were carefully trimmed, weighed to determine their density, and extruded from the mold with a hand operated ram. To insure that the moisture content of the specimens would not change during the curing period, they were immediately wrapped in aluminum foil and coated with wax. The sealed specimens were stored in a humid room until tested. This procedure was altered when it was discovered that the lime specimens were reacting with the aluminum foil. A sheet of polyethylene was placed between the foil and the specimens containing lime to correct the problem.

A motor-driven compression testing machine with a capacity of five-hundred pounds was used for all unconfined compression tests. The electric motor, used to drive the machine, was equipped with a Variac so that the rate of loading applied to a specimen could be controlled. Deformation of the specimen was measured with a dial gage in contact with the traveling head of the machine. Loads were determined from the deflection of a proving ring mounted in the machine and attached to the fixed head. These deflections were measured with a dial gage mounted in the proving ring.

Because the soils dealt with in this investigation were plastic materials, lateral deformation of a specimen causes a large and continuing increase in its cross-sectional area. Therefore, the maximum load supported by a specimen did not necessarily correspond with the maximum stress. In order to determine the maximum stress carried by a specimen, it was necessary to record the load and deformation periodically throughout each test, compute the stress for each of these points, and select the maximum stress by inspection of the results. To standardize the procedure and simplify the computations, it was decided to record the deformation of the proving ring at each 0.05 in. of specimen deformation.

After a specimen had cured for the desired length of time, it was removed from the humid room and the wax and aluminum wrapping was carefully stripped. The specimen was centered on the heads of the testing machine, and a small load was applied. The dial gage measuring deformation of the specimen was set at zero, and the specimen was deformed at the rate of 0.089 in. per min. This insured that no specimen would be exposed to the atmosphere for more than ten minutes and minimized moisture changes. As loading continued, the deflection of the proving ring was recorded at each 0.05 in. of specimen deformation until the deflection of the proving ring began to decrease. This indicated that the maximum load, as well as the maximum stress the specimen could support, had been exceeded and the test was terminated. The specimen was removed from the machine, examined to determine the type of failure, and weighed and dried to determine its true moisture content. The latter step was useful in discovering undesirable moisture changes that might have occurred during compaction or curing of the specimen.

Problems Encountered

Problems involving moisture contents plagued this investigation from the start. Standard laboratory practice requires soil specimens to be dried at 105°C and this procedure was followed at the start of the investigation. During the early stages of the investigation, a sample of air-dried gypsum was dried at 105°C to determine its water content. This test indicated an air-dried moisture content of twenty-one percent. Visual inspection of the gypsum indicated this figure was erroneous and an investigation of the properties of gypsum was undertaken. It was soon discovered that a temperature of 105°C is high enough to calcine gypsum and drive off part of the water of crystallization. It was this water, rather than free moisture, that gave the gypsum its apparent high water content. A sample of gypsum was subjected to increasingly higher drying temperatures to determine its apparent water content at various temperatures. The results of that study are shown in Fig. 3. Based on this investigation and information supplied by the U. S. Gypsum Company (3), a temperature of 65°C was selected as the proper drying temperature for specimens containing gypsum. This temperature removes all free moisture from the specimens but is below the calcining temperature of gypsum.

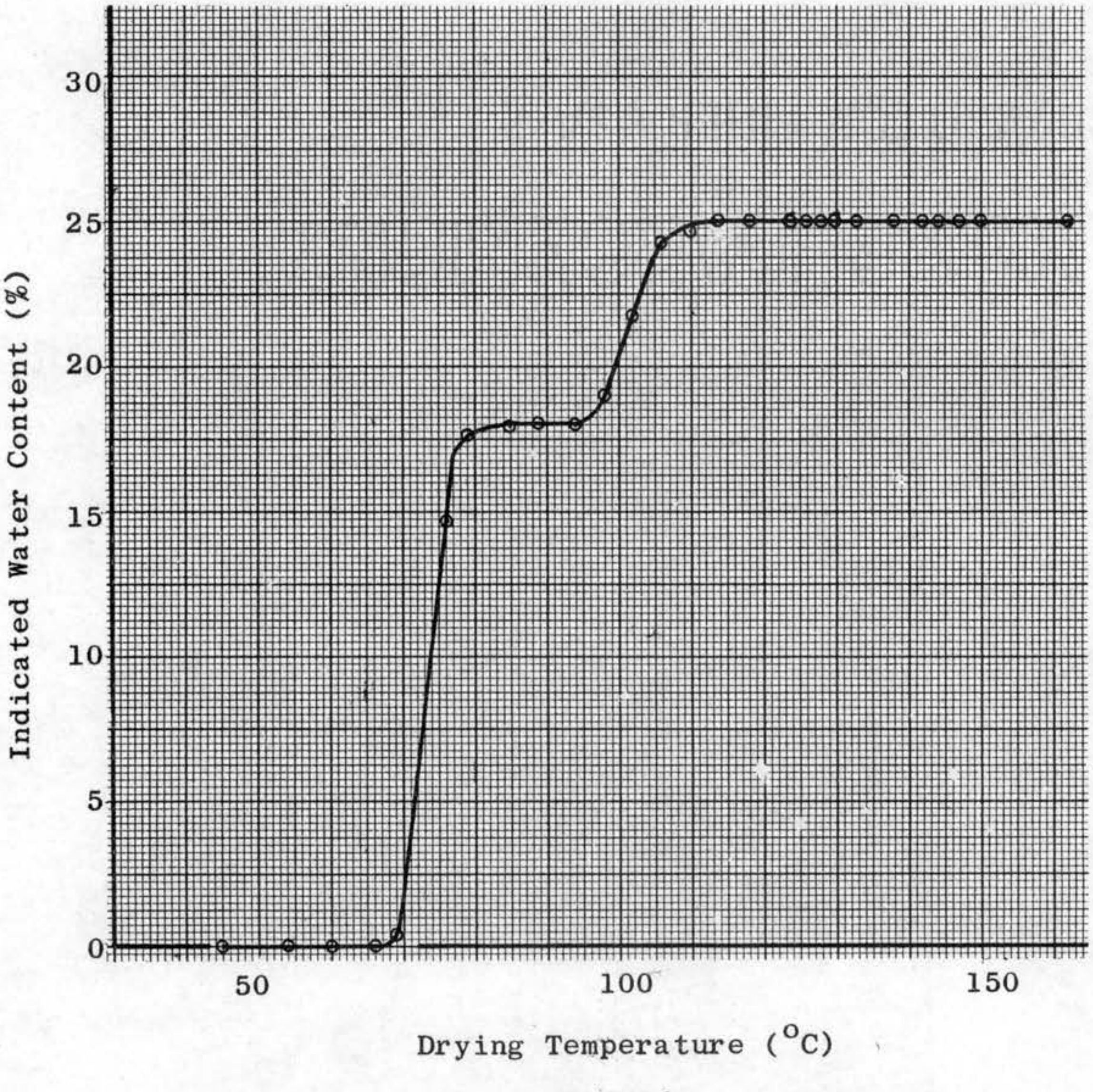


FIGURE 3

RELATIONSHIP BETWEEN INDICATED MOISTURE AND DRYING TEMPERATURE FOR GYPSUM - $CaSO_4 \cdot 2H_2O$

Most of the limits tests had been completed when the relationship between water content and temperature was discovered. The specimens used for the liquid and plastic limits had been dried at 105°C, and the true limits were lower than those indicated by the tests. It was possible, however, to make a mathematical correction and calculate the true limits. The amount of water of crystallization removed from the gypsum by a drying temperature of 105°C, expressed as percent by weight, was determined from Fig. 3. The amount of water of crystallization removed from the gypsum in a given specimen was calculated and expressed as a percentage of the dry weight of the mixture. This was subtracted from the indicated limit to obtain the true limit of the mixture. These calculated limits were found to agree very closely with limits determined by another series of tests dried at 65°C.

Difficulties with water content were also encountered in the unconfined compression tests. These specimens were compacted at optimum moisture content as well as two percent above and below optimum. A previous investigation indicated that the gypsum content of the specimens would have little effect on the optimum moisture content. (4). That is, the optimum moisture content of a specimen containing thirty percent gypsum would be about the same as the optimum moisture content of a specimen containing no gypsum. However, when the specimens containing thirty percent gypsum were compacted, it became apparent that their water contents were greater than optimum.

The mixtures were excessively soft and had very low shear strengths. As a result, the optimum moisture content for each combination of clay and gypsum was determined from a series of tests, and the compaction moisture contents were selected in reference to these optimums.

The results of the earlier tests were retained, however, because of the large number of specimens involved. In some cases, the specimens believed to have been compacted at two percent below optimum moisture content were found actually to be at optimum. The results of all tests can be evaluated by the exercise of considerable judgment. It is believed that these tests have been interpreted and integrated into the test data in a reasonable manner.

After the problem with optimum moisture contents was detected, subsequent series of specimens were compacted at their individual optimum moisture contents. However, controlling the moisture content continued to be a problem, and variations between the predicted and the actual water contents proved to be the rule rather than the exception. These variations apparently were caused by evaporation losses during mixing and compaction of the specimens.

Operation of the Harvard Miniature Compaction Apparatus presented some problems. Difficulty was experienced in controlling the deflection of the spring in the tamper. This meant that the same pressure was not applied to the soil with each blow, and the density of the soil varied from specimen to specimen. As the operators gained more experience with the apparatus, however, this problem disappeared and uniform specimens were produced without difficulty.

CHAPTER V

TEST RESULTS

Effects of Gypsum on Plasticity

Gypsum has a great influence on the plastic properties of Permian clay. Figure 4 shows the average results of plastic limit and liquid limit tests performed on mixtures of gypsum and Permian clay. The gradation of the gypsum had no effect on the plasticity of the mixtures. Mixtures using gypsum passing the No. 10 sieve and mixtures using gypsum passing the No. 100 sieve had the same plastic and liquid limits.

The liquid limit decreases from 41.0 for a specimen containing no gypsum to 21.0 for a specimen containing sixty percent gypsum. This decrease is practically uniform across the range of mixtures investigated. The plastic limit, however, is hardly affected by the addition of gypsum to the soil. Because of the constant plastic limit, the curve representing the plastic index closely parallels that for the liquid limit. It declines from 25.5 for a specimen containing no gypsum to 7.0 for a specimen containing sixty percent gypsum.

Curing had a minor effect on the plastic properties of the soil. After curing twenty-eight days, the limits declined slightly. This decrease was uniform over the entire range of gypsum contents.

During the investigation it was noticed that gypsum improved the workability of Permian clay. The untreated clay was difficult to work with, sticking to tools and mixing equipment, and forming into small balls that made uniform mixing difficult. When compacted into unconfined compression specimens, it tended to form honeycomb layers in the cylinders. The addition of gypsum to the soil eliminated these problems. The clay became much easier to mix with water, it did not stick to the mixing equipment, and the honeycombs disappeared from the cylinders. More than ten percent gypsum passing the No. 10 sieve was required to accomplish this change. Essentially the same results were achieved with six percent gypsum passing the No. 100 sieve, however.

Effects of Gypsum on Strength

In order to interpret the results of the unconfined compression tests, it was necessary to make some adjustment of the test results to compensate for the erratic moisture contents of the specimens. These moisture content variations had a greater effect on the strength than the gypsum did in some cases. Using Fig. 5 as an example, it can be seen that, for a given gypsum content, specimens compacted at a moisture content two percent below the optimum moisture content (L line) have a greater strength than specimens compacted at either optimum moisture content (M line) or two percent above the optimum moisture content (H line). In other words, the dryer a specimen is, the stronger it is, all other factors remaining constant. Conversely, as the moisture content increases, the strength of the specimen decreases.

On each figure showing the relationship between gypsum content and strength, two sets of data were plotted. The actual strengths of the specimens were plotted on the upper part of the figure, and the corresponding moisture contents were plotted on the lower half. Lines representing the optimum moisture content and moisture contents two percent above and below optimum were drawn on the lower portion of the figure. By comparing the actual moisture content of a specimen to the desired moisture content, an estimate of the effect of the moisture content on the strength of the specimen could be made.

Figure 5, which shows the average strengths and moisture contents of mixtures of Permian clay and gypsum passing the No. 10 sieve, serves as a good example of the procedure. Specimens containing twenty percent gypsum and compacted at a moisture content 2% below optimum had an average strength of 1.35 T/sq. ft. and a moisture content of 14.8%. As indicated on Fig. 5, this moisture content is higher than the desired moisture content of 13.4%. Had the specimens been compacted at the proper moisture content, their average strengths would have been higher than 1.35 T/sq. ft.

The average strength of specimens containing ten percent gypsum and compacted at two percent below optimum is 1.75 T/sq. ft.

Their average moisture contents were 14.2%. The desired moisture content of these specimens was also 14.2%. It can be assumed that it is unnecessary to apply any correction to the measured strengths of these specimens.

This type of analysis was carried out on each point to determine how moisture content had influenced the strength of each specimen. The curve representing the relationship between strength and gypsum content was drawn to pass through the points unaffected by moisture, above those weakened by excessive moisture, and below those strengthened by a lack of moisture. The resulting curves are thought to represent accurately the general effects of gypsum on Permain clay.

Gypsum Passing the No. 10 Sieve - Permian Red Clay

It can be seen from Figs. 5 through 8 that gypsum passing the No. 10 sieve had very little effect on the strength of Permian clay. In fact, a slight decrease in strength is noted in most cases. The specimens exhibiting the highest strengths are those compacted below the optimum moisture content. The specimens compacted at water contents above optimum had the lowest strengths. A comparison of Figs. 5 through 8, and an examination of Fig. 9, shows that curing time does not affect the specimens with low gypsum contents and low water contents. The specimens containing fifty percent gypsum and compacted at and above optimum moisture content exhibit an increase in strength with curing. The increase is not large, however.

Gypsum Passing the No. 100 Sieve - Permian Red Clay

Figure 10 shows that gypsum passing the No. 100 sieve has a more positive effect on the strength of Permian clay than does the coarser material. The increase is minor for specimens containing small amounts of gypsum, but the addition of forty percent gypsum to the soil doubles its strength.

Both Fig. 10 and Fig. 11 indicate the large impact of curing on the strength of the specimens. Specimens containing large quantities of gypsum are more affected by curing than are the specimens with lesser amounts of the material. It appears that there is no optimum gypsum content within the range of gypsum contents investigated. The strength of specimens containing gypsum passing the No. 10 sieve reaches a peak at about fifty percent gypsum. This does not seem to be the case with the finer material. There is some indication of a leveling off of the strength after the gypsum content passes forty percent, but there is no evidence that this is the optimum mixture of soil and gypsum.

Lime - Permian Red Clay

As expected, lime produced very strong specimens of stabilized soil (Fig. 12). A strength of more than 18 T/sq. ft. was achieved, more than six times as strong as the strongest gypsum-treated specimens (Fig. 13). This high strength was reached at a lime content of nine percent as compared to the fifty percent of gypsum needed to produce the strongest gypsum-treated specimens.

The lime stabilized soils responded favorably to curing (Fig. 12). The specimens cured twenty-eight days were four and one-half times stronger than specimens cured only one day - an increase much greater than any achieved by the gypsum-treated specimens.

Gypsum Passing the No. 10 Sieve - Kaolinite

Kaolinite was one of the two pure clay minerals used in this investigation. It is a relatively inactive clay mineral with low cation exchange capacity. Figure 14 shows that adding less than ten percent gypsum to the material does not increase the strength but causes a decrease in strength in specimens cured only a short time. Larger quantities of gypsum cause a marked increase in strength, however. The mixtures of gypsum and kaolinite respond well to curing when large quantities of gypsum are present in the mixture. Figure 14 shows the increases in strength achieved with curing.

Gypsum Passing the No. 10 Sieve - Bentonite

Bentonite was the other pure clay mineral used in this investigation. This active mineral, with its high cation exchange capacity, is noted for its swelling characteristics and its thixotropic properties. Gypsum has little over-all effect on the strength of bentonite (Fig. 15). There is an initial increase in the strength of the material, reaching a peak at a gypsum content of ten percent. The strength declines after the gypsum content passes ten percent, finally leveling off to form a flat curve. Curing does not greatly increase the strength of gypsum-bentonite mixtures.

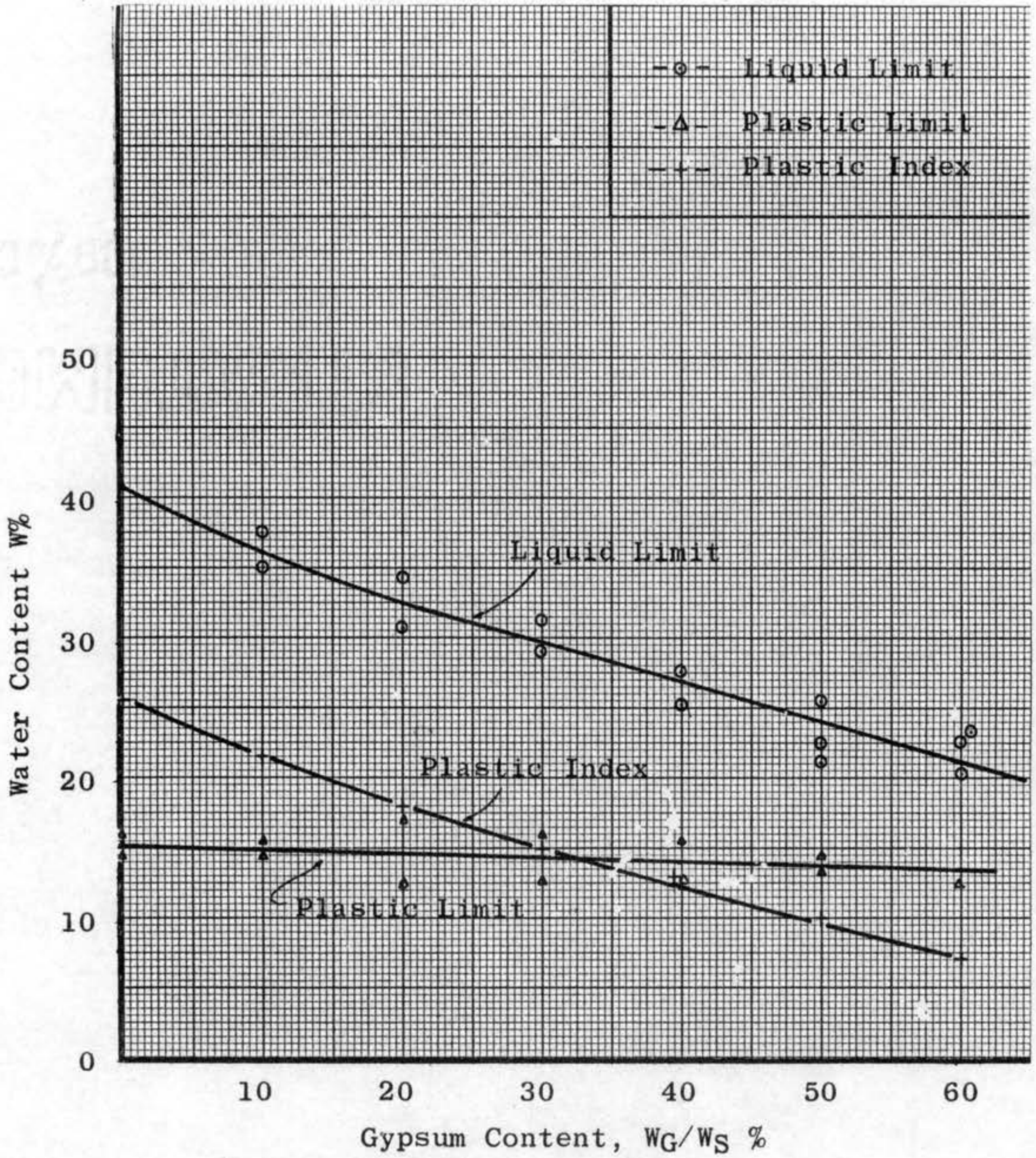


FIGURE 4

EFFECT OF GYPSUM
ON
PLASTICITY OF PERMIAN CLAY

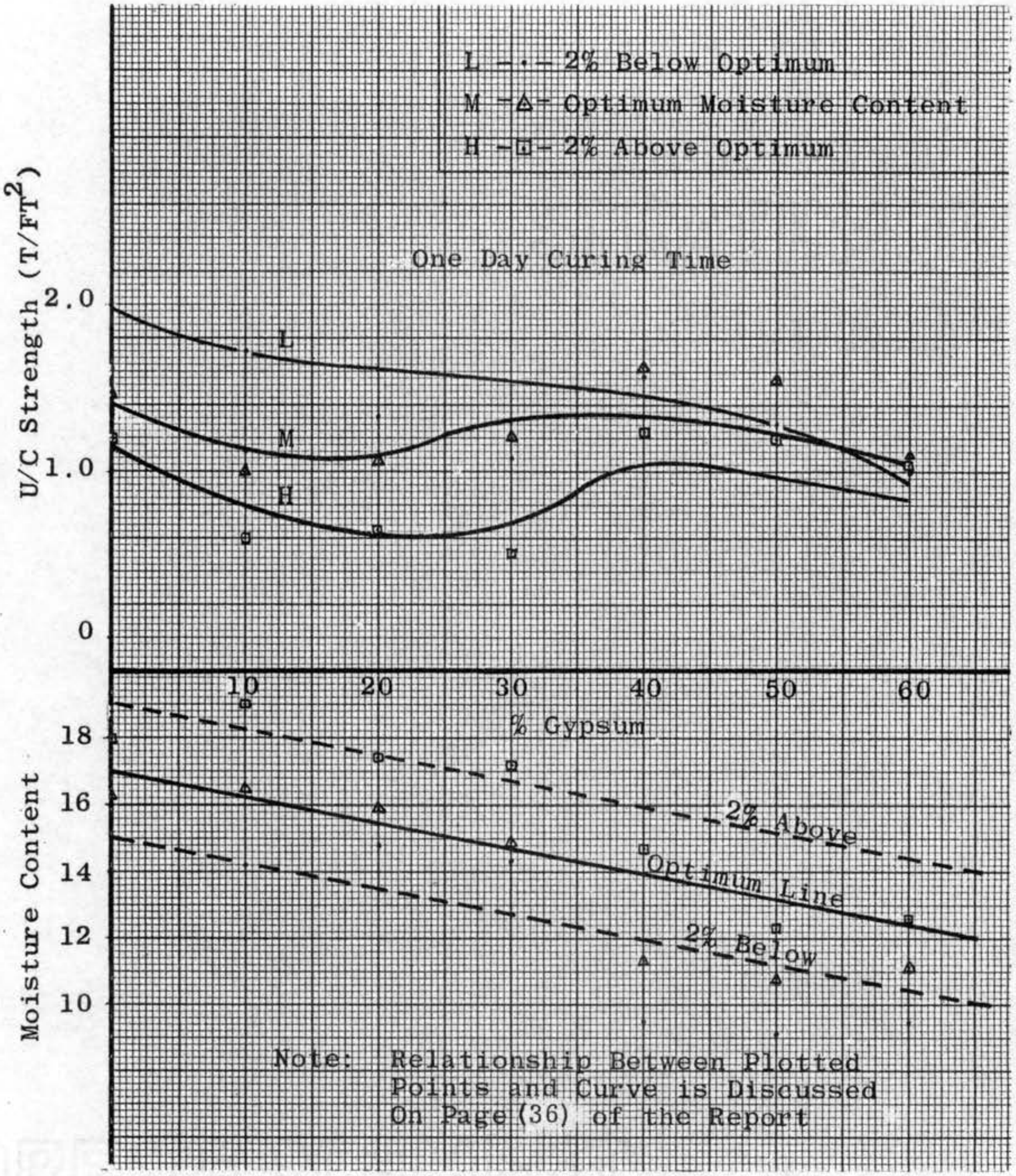


FIGURE 5

EFFECT OF GYPSUM CONTENT
ON THE
STRENGTH OF PERMIAN CLAY

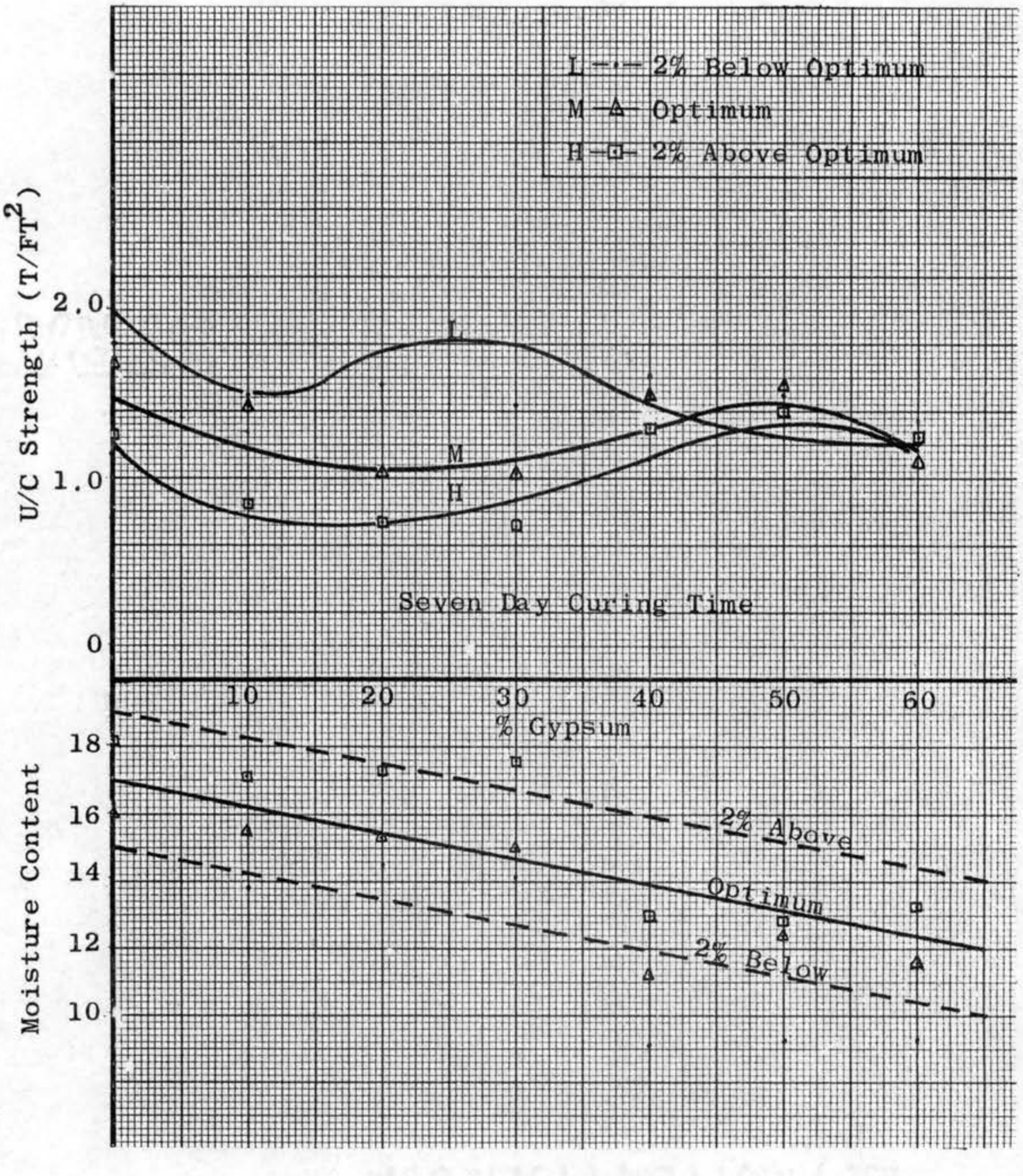


FIGURE 6

EFFECT OF GYPSUM CONTENT
ON THE
STRENGTH OF PERMIAN CLAY

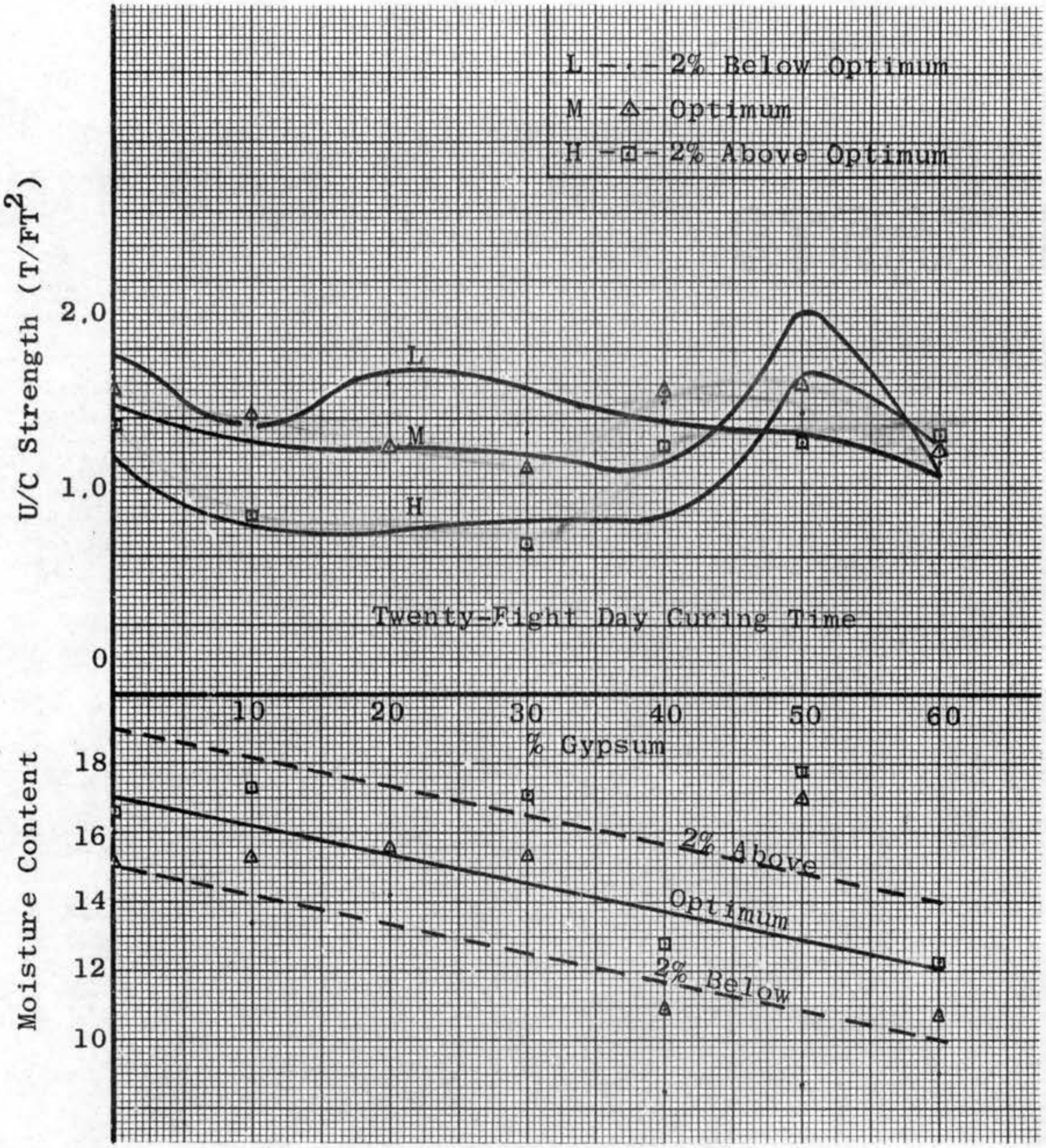


FIGURE 7

EFFECT OF GYPSUM CONTENT
ON THE
STRENGTH OF PERMIAN CLAY

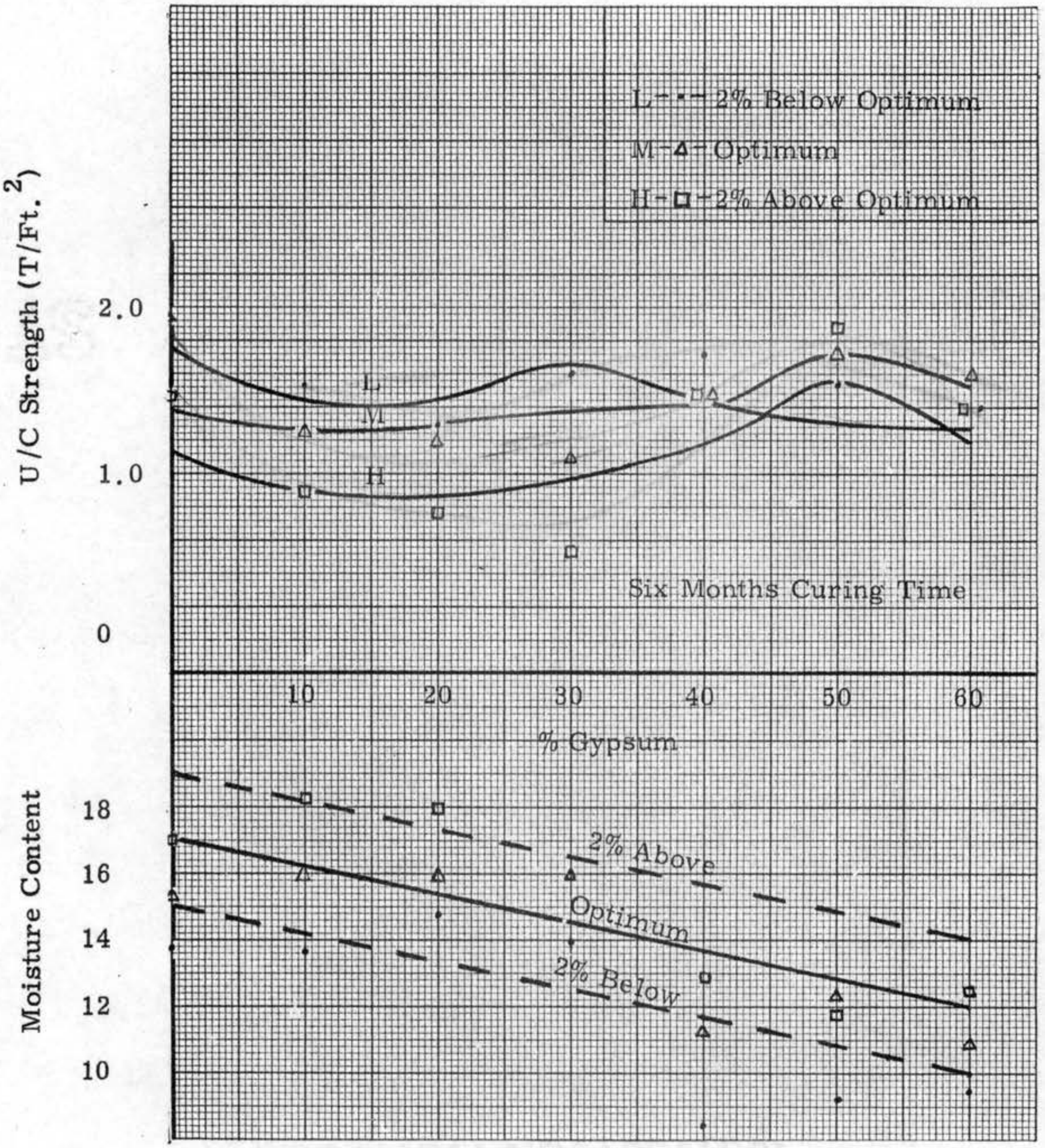


FIGURE 8

EFFECT OF GYPSUM CONTENT
ON THE STRENGTH OF CLAY

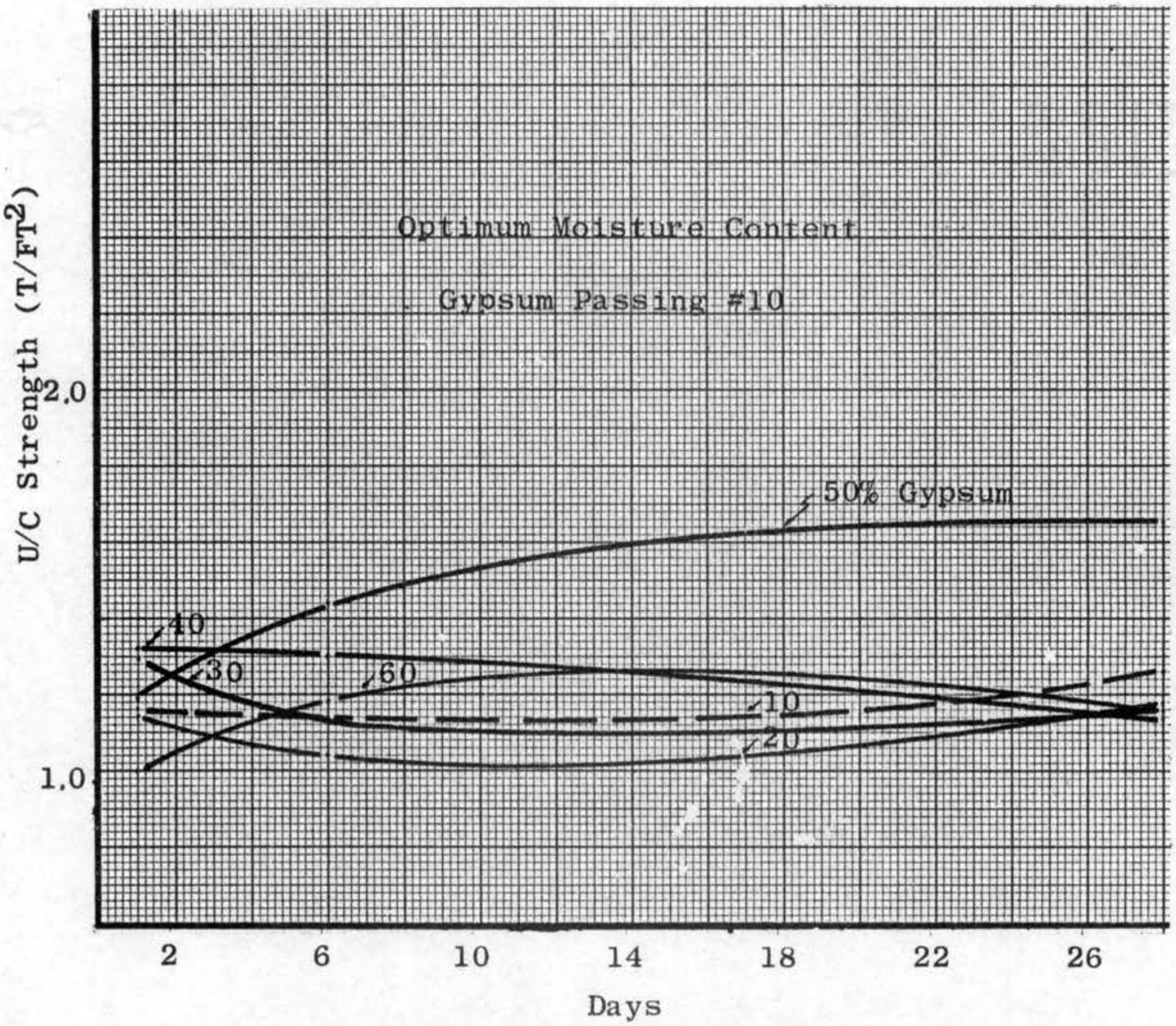


FIGURE 9

EFFECT OF CURING TIME
ON THE
STRENGTH OF PERMIAN CLAY AND GYPSUM

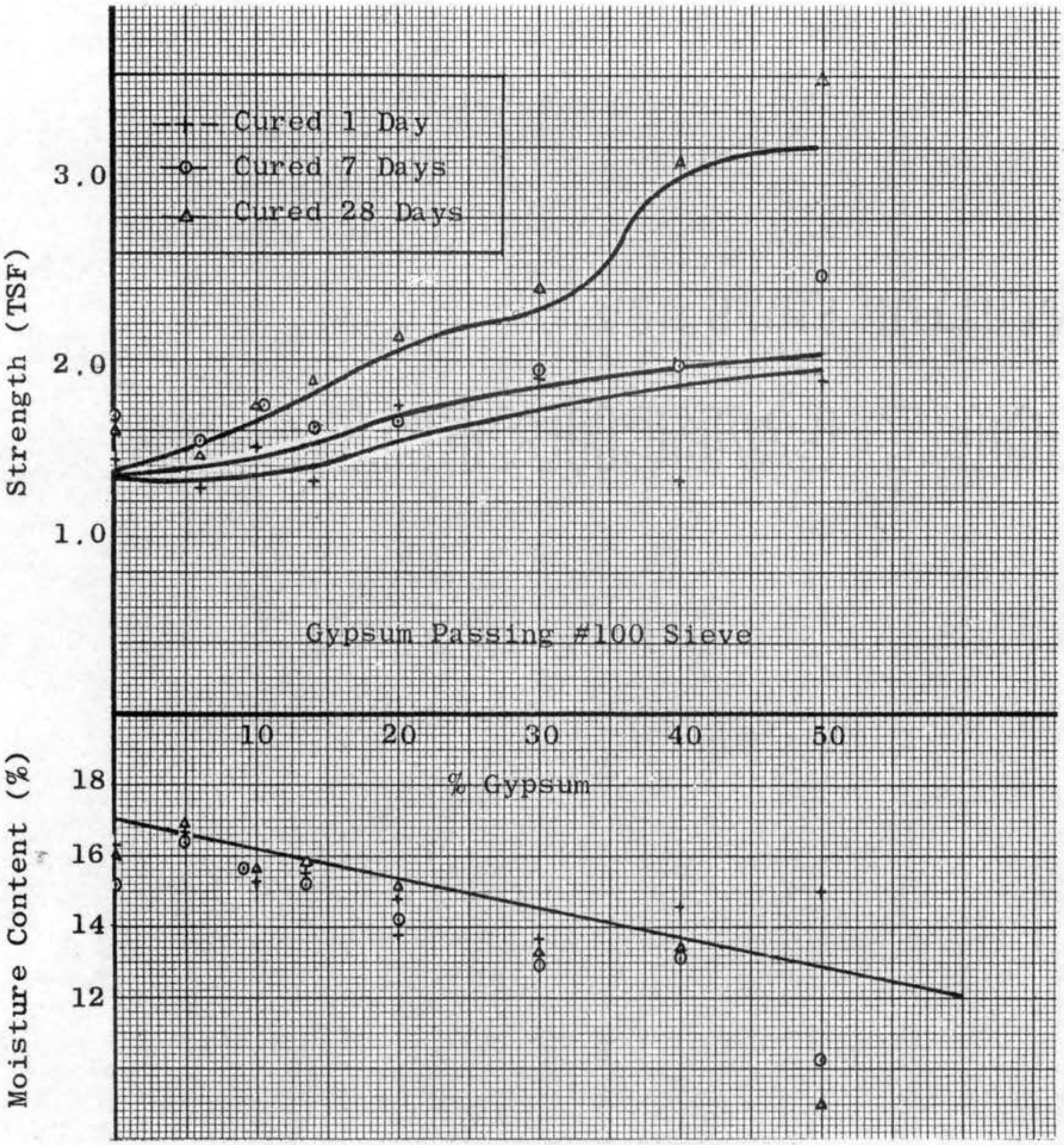


FIGURE 10

EFFECT OF GYPSUM CONTENT
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF PERMIAN CLAY

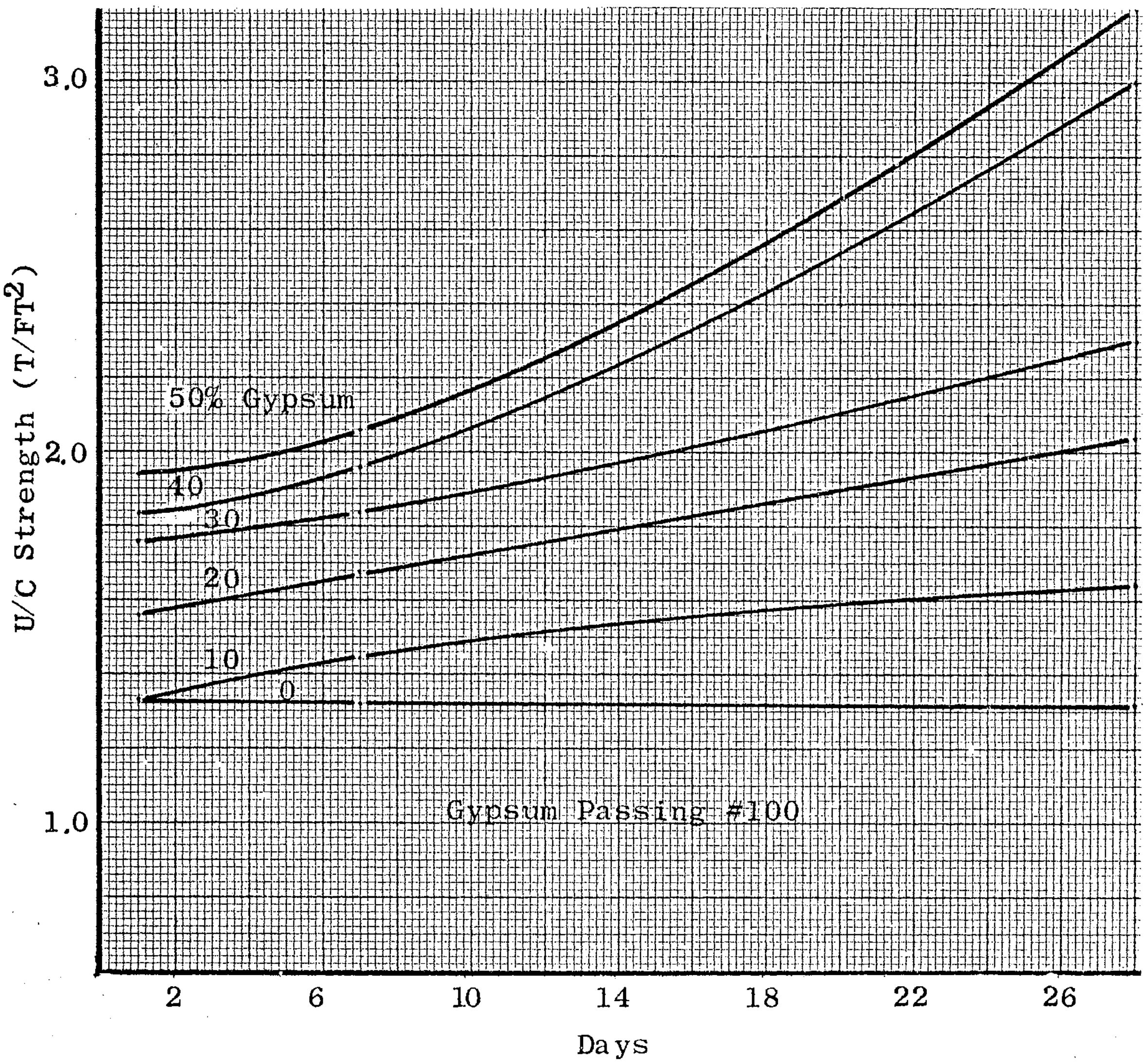
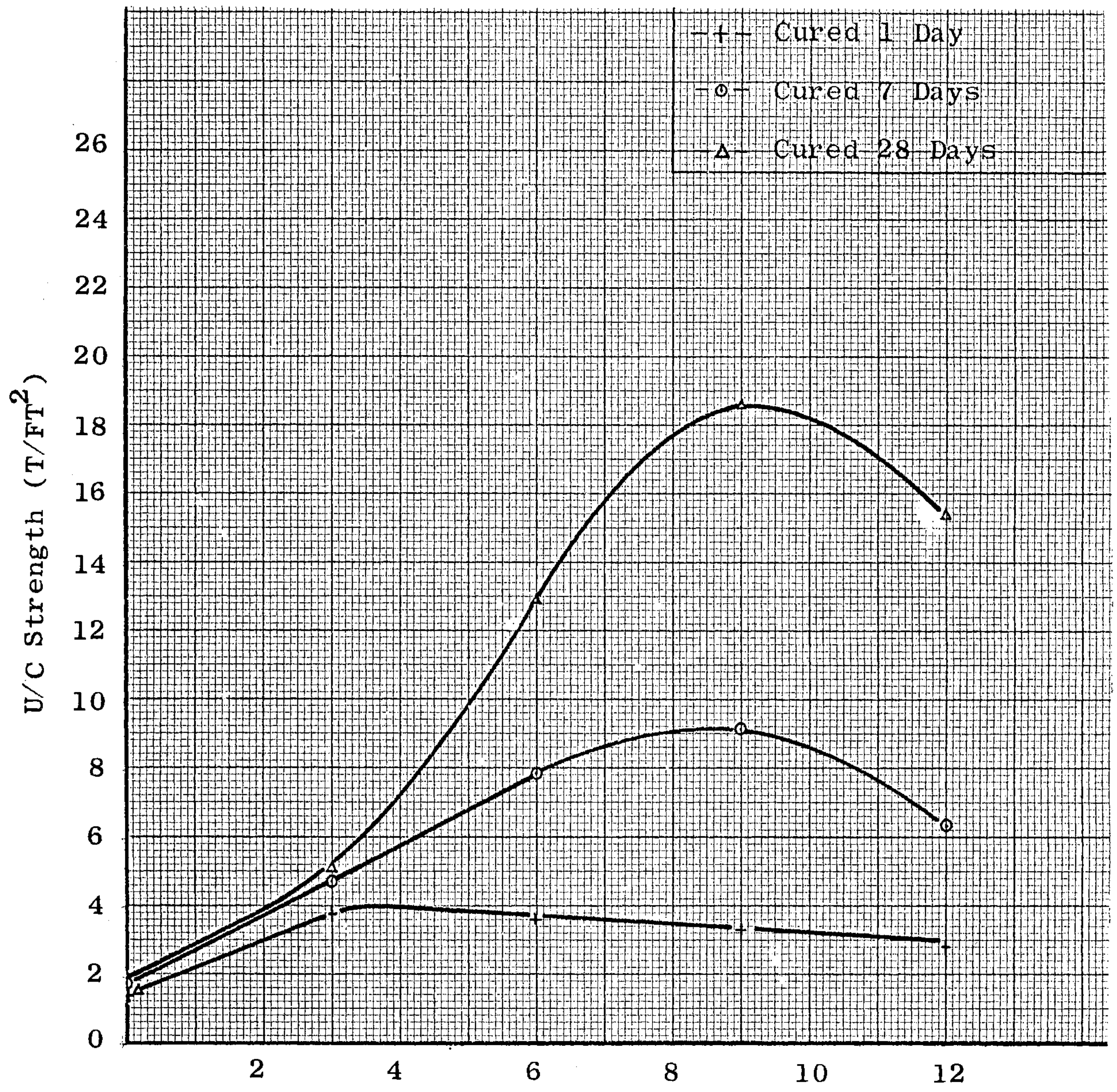


FIGURE 11

EFFECT OF CURING TIME
ON THE
STRENGTH OF PERMIAN CLAY AND GYPSUM



% Lime

FIGURE 12

EFFECT OF LIME
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF PERMIAN CLAYS

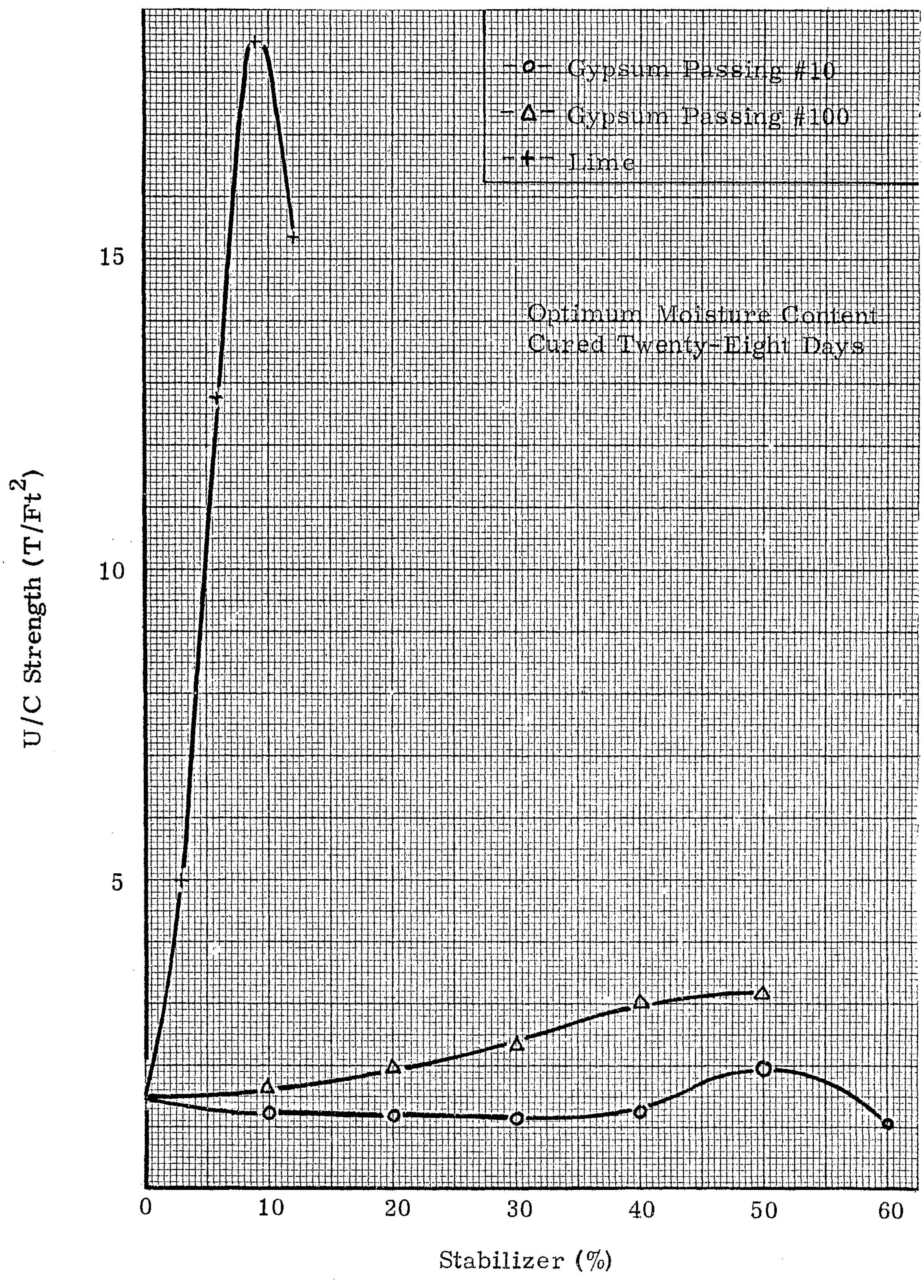


FIGURE 13

STRENGTH OF STABILIZED PERMIAN CLAY

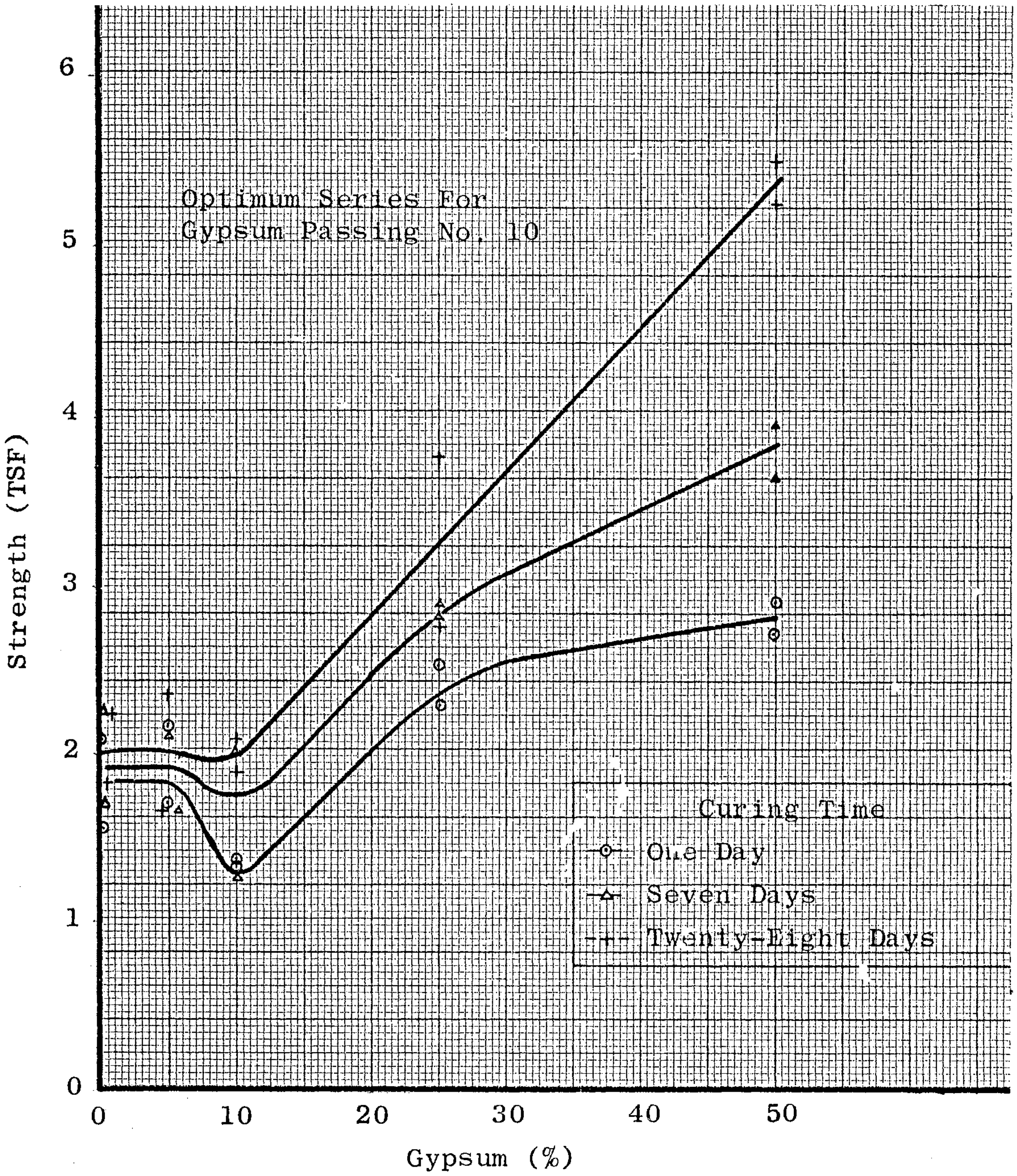


FIGURE 14

EFFECT OF GYPSUM
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF KAOLINITE

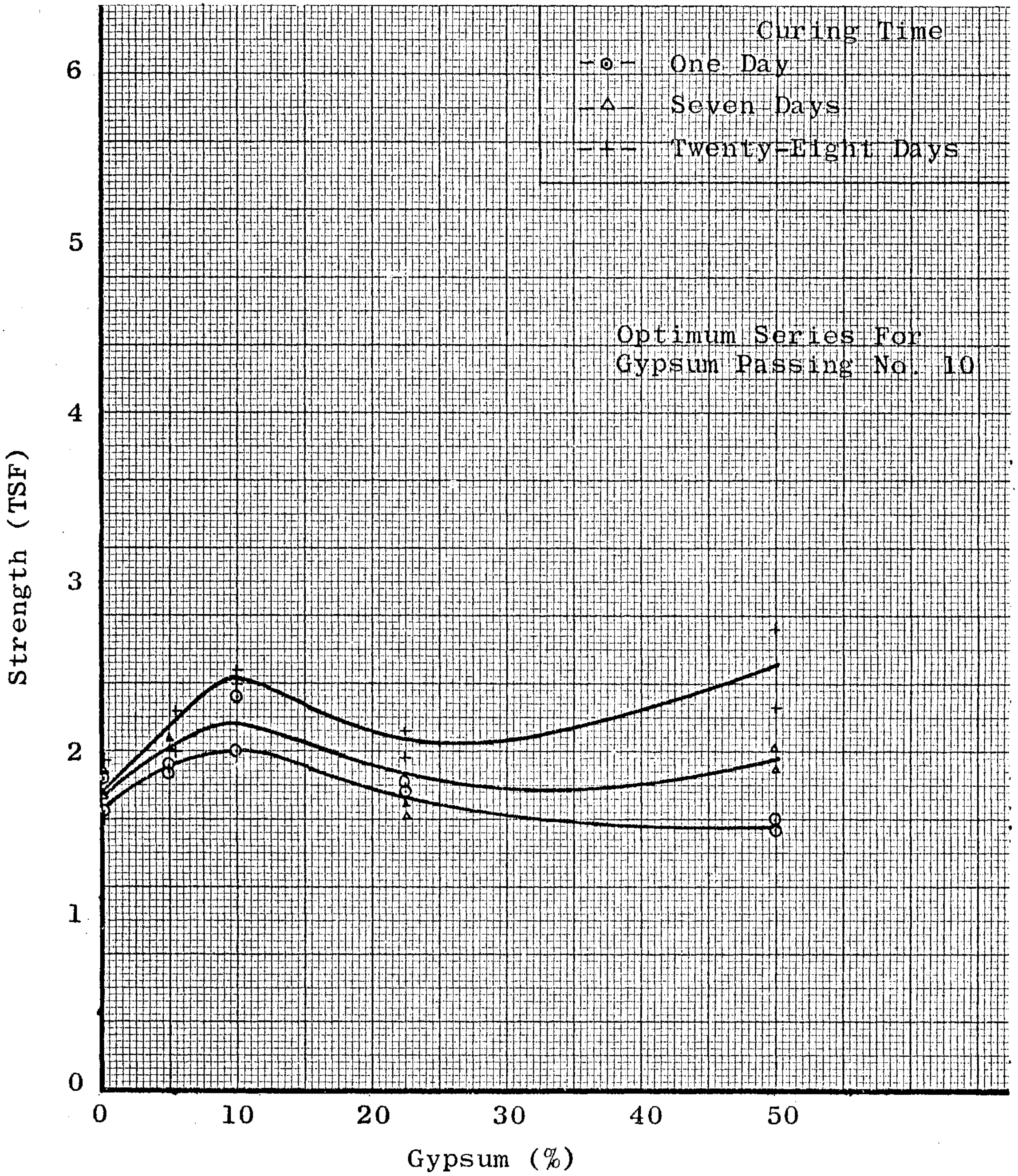


FIGURE 15

EFFECT OF GYPSUM
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF BENTONITE

CHAPTER VI

CONCLUSIONS

It must be concluded that gypsum cannot be used as a soil stabilizer in the sense that lime or portland cement are used. The strength of the strongest gypsum-treated specimens did not approach the strengths achieved by lime-stabilized specimens. Furthermore, gypsum contents in the neighborhood of forty and fifty percent are required to produce an appreciable increase in strength. Indeed, such large quantities of gypsum were required that a question arises as to whether soil or gypsum is being stabilized. By way of contrast, only nine percent lime is required to produce strong specimens of the Permian clay.

Although the investigation failed to prove gypsum as a soil stabilizer equal to lime or portland cement, it did reveal several factors worthy of comment and further study.

Gypsum's effects on the plasticity and workability of Permian soil were quite remarkable. Part of the reduction in plasticity was probably due to the cohesionless nature of the gypsum. An inert sand, added to the soil, would have probably reduced the liquid limit too. It is probable that cation exchange plays a part in the reduction of plasticity also. This is known to be the case with lime-stabilized soils where the calcium cation liberated from the lime causes the clay particles to flocculate and behave as silt grains. This same calcium cation is present in gypsum, and there is no reason to believe that the same action does not take place.

The gains in strength experienced by the gypsum-treated specimens may be explained, in part, by the cohesionless nature of the gypsum. Inert sand, added to the soil, would have caused some increase in the strength. It should be noted, however, that the greatest gains in the strength of the Permian clay were achieved with the fine gypsum rather than the coarse material passing the No. 10 sieve.

It is doubtful that the cation exchange associated with the change in plasticity had any influence on the strength of the soil. Only small quantities of gypsum are required to saturate the soil with calcium cations, yet none of the clays investigated displayed much change in strength at low gypsum contents. Bentonite, one of the most active clay minerals in terms of cation exchange capacity, displayed little change in strength at any gypsum content (Fig. 15). Kaolinite, one of the least active clay minerals, shows large increases in strength (Fig. 14).

The strength of lime is derived from a chemical reaction between the lime and the soil particles. There is evidence to show that such a chemical reaction takes place between the gypsum and the soil particles, though to a lesser degree. The increases in strength brought about by curing of the specimens points to a slow chemical reaction. The thixotropic properties, which all clays possess to some degree, can be ruled out as a cause of the increases in strength. Figures 9, 10, and 11 show that the Permian clay specimens containing no gypsum did not improve in strength during the curing period. Figures 14 and 15 show that thixotropic action affected the specimens of kaolinite and bentonite containing no gypsum only to a minor extent. These figures show, rather, that the more gypsum a specimen contains the greater the improvement in strength with curing.

An increase in strength was produced by gypsum passing the No. 100 sieve while gypsum passing the No. 10 sieve had no effect on the strength of Permian clay. The fine gypsum provides a greater surface area per unit volume than does the coarse gypsum, and it is more susceptible to chemical reactions because of this. Given enough time, the Permian clay containing the coarser gypsum might also exhibit a comparable increase in strength.

In connection with this project, a number of X-ray diffraction studies were made on samples of gypsum and clay that had been cured for various periods of time. The X-ray photographs indicate chemical compounds present in the mixtures that are not present in either the gypsum or the Permian clay. Unfortunately, the equipment needed to fully analyze these X-ray patterns was not available and the exact nature of the suspected reaction could not be discovered.

There are, therefore, several factors that point to a chemical reaction between the soil and the gypsum. It is believed that further research should be conducted to determine the exact nature of this reaction and to discover ways of exploiting it to produce a good soil stabilizer. It is possible that the addition of some admixture could make gypsum as effective a soil stabilizer as lime or portland cement.

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