

ENGINEERING BEHAVIOR OF NATURAL
AND LIME-MODIFIED SALINE
COHESIVE SOILS

By

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AND LIME-MODIFIED SALINE
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TABLE OF CONTENTS

Chapter	Page
I. INTRODUCTION	1
Statement of the Problem	1
Scope of the Investigation	2
II. LITERATURE REVIEW	3
Origin and Physical Properties	3
Salt Treatment of Cohesive Soils	6
Summary	7
III. MATERIALS	8
Soil Location	8
Physical Properties	9
Chemical and Mineralogical Properties	10
Chemical Additives	12
IV. SOIL PREPARATION AND TESTING PROCEDURE	16
Soil Preparation	16
Testing Procedure	18
Summary	20
V. TEST RESULTS AND DISCUSSION	21
Atterberg Limits and Linear Shrinkage	21
Compaction Properties	29
Unconfined Compressive Strength	32
Summary	43
VI. CONCLUSIONS AND RECOMMENDATIONS	44
REFERENCES	46

LIST OF TABLES

Table	Page
3.1. Index Properties of Saline and Leached Soils	9
3.2. Soil Salinity Analysis of Natural and Leached Saline Soils	11
5.1. Effect of Lime and Salt Treatment on Optimum Moisture and Dry Density for Saline and Leached Saline Soils	33

LIST OF FIGURES

Figure	Page
3.1. DTA Thermograms of WSS, Leached WSS, and Illite	13
3.2. DTA Thermograms of GSS, Leached GSS, and Chlorite	14
5.1. Effect of Lime Treatment on Atterberg Limits of WSS and Leached WSS	23
5.2. Effect of Lime Treatment on Atterberg Limits of Leached GSS Plus 0.7% NaCl	25
5.3. Effect of Lime Treatment on Atterberg Limits of WSS and Leached WSS	26
5.4. Effect of Lime Treatment on Atterberg Limits of Leached WSS Plus 0.6% NaCl	28
5.5. Effect of Lime Treatment on Lineal Shrinkage for Natural, Leached, and NaCl Treated Saline Soils	30
5.6. Effect of Lime and Salt Treatment on Unconfined Compres- sive Strength for Natural and Leached WSS	36
5.7. Effect of Lime and Salt Treatment on Unconfined Compres- sive Strength for Natural and Leached GSS	37
5.8. DTA Thermograms of Leached Saline Soils Plus Salt After 7 and 28 Days of Curing.	38
5.9. DTA Thermograms of Lime Modified Natural and Leached WSS After 7 and 28 Days of Curing.	41
5.10. DTA Thermograms of Lime Modified Natural and Leached GSS After 7 and 28 Days of Curing.	42

CHAPTER I

INTRODUCTION

For several years soils engineers have sought additives to modify highly cohesive soils, thus improving their engineering properties. Some of these additives have produced desirable results; however, most are not economically feasible, or do not allow themselves to be easily used in field construction. Various additives tried include cement, calcium chloride, potash, molasses, emulsions, etc. However, probably the more commonly used chemical additive is lime, in both hydrated and oxide form. In addition, salt (NaCl) and salt-lime combinations have also been tested as possible chemical additives (Ref 1). Lime and salt are both abundant, which allow them to be used economically. Moreover, methods for mixing these additives with cohesive soils in the field have been developed and used quite successfully.

Statement of the Problem

In many areas of Oklahoma, soils containing significant quantities of natural salts can be found. These saline areas, because of their high salt content, produce few if any agricultural crops and are therefore normally not used for any purpose. Therefore because of their low economic value to agriculture, saline soils might be considered for use in highway or related construction. This consideration was based on the idea that salts contained in the saline soils may produce soils with

more desirable engineering properties than that of the surrounding non-saline soil.

It was, therefore, the purpose of this study to determine the engineering properties which might be expected of cohesive saline soils in Oklahoma and their response to lime treatment.

Scope of the Investigation

The scope of the investigation was to determine (1) the engineering properties of two Oklahoma cohesive saline soils (2) the engineering properties of the same saline soils after leaching the salts, and (3) the engineering properties of lime modified natural and leached saline soils.

CHAPTER II

LITERATURE REVIEW

Agriculturalists have long considered the problem of soil salinization, because of its destructiveness to crops. For this reason, agricultural research has produced an abundance of information concerning physical properties, improvement, and control of saline soils. However, soils engineers have done very little to determine engineering properties of cohesive saline soils, and have not seriously considered their possible use in engineering construction. For this reason, a discussion of the origin and physical properties of saline soils is presented in this Chapter, along with a discussion of the engineering properties of salt and salt-lime treated cohesive soils.

Origin and Physical Properties

The soluble salts contained in most saline soils are primarily those with cations of calcium and sodium. Lesser amounts of potassium and magnesium are sometimes found. The chief anions are chloride, sulfate, and, sometimes, nitrate. Small amounts of bicarbonate may occur, but soluble carbonates are almost never present. The prime source of all the salt constituents is from primary minerals found in soils and rocks of the earth's crust. During chemical weathering the salt constituents are gradually released from parent materials.

Although weathering of primary minerals is the indirect source of nearly all soluble salts, few instances arise where sufficient salts accumulate from this source alone to form a saline soil. These soils usually occur in areas which have become contaminated with salts transported by water from other locations. A good example of this is saline soils which at one time underlay oceans but have since been uplifted. Low-lying soils along coastal regions are sometimes contaminated with saline water through transportation of spray by winds (Ref 2). A more direct source of salts, however, is from surface and ground waters. The concentration of salts in these waters is dependent on the salt content of the soil with which the water has been in contact. A good example of such a body of saline water is the Great Salt Plains Reservoir near Jet, Oklahoma. The soil surrounding this reservoir and the soil along the river which flows from the reservoir are highly contaminated with salts.

Generally speaking, saline soils occur in regions of arid or semi-arid climate. In these regions leaching and transportation of soluble salts is usually limited by the low rainfall received. Leaching usually occurs only in localized areas and the salts are transported only short distances. This condition exists not only because of little rainfall but also because of high evaporation rates which tend to further concentrate the salts in soils and surface waters. In humid regions saline soils are practically nonexistent because of the abundance of rainfall, which carries the soluble salts downward into the groundwater, where it is ultimately transported by streams and rivers to the ocean.

Low soil permeability and the presence of a high groundwater table usually results in restricted drainage, which is a main factor contributing to salinization of soils. Low permeability impedes the downward

movement of water, thus causing poor drainage. Low permeability may be a result of a deep fine clay strata or the presence of a claypan or a caliche layer underlying a more permeable soil surface. Because of low rainfall in some regions drainage basins may be poorly developed and have no outlet to permanent streams. As a result of poor drainage, saline water from higher elevations may raise the groundwater level to the soil surface on the lower lands, may cause temporary flooding, or may form semipermanent salty pools of water. Such circumstances allow upward movement of saline groundwater or evaporation of surface water, resulting in the formation of saline soil (Ref 3). The saline areas formed in this manner usually vary in size from a few acres to hundreds of square miles. Poor drainage is probably the main cause of salinization in most of Oklahoma.

Saline soils normally exhibit certain physical properties that distinguish them from normal soils. The conductivity of saturated saline soil extract is more than 4 mmhos/cm at 25°C, the exchangeable-sodium-percentage is less than 15, and the pH is usually less than 8.5 (Ref 3). Saline soils are often characterized by the presence of white salt crusts on the surface. When adequately drained the excessive soluble salts may be removed by leaching, thereby returning the saline soils to their "original" condition. As a result of excess salts, saline soils are generally flocculant, resulting in a permeability equal to or higher than that of similar nonsaline soils.

Most saline soils seem to have similar mineralogical properties. Kanwar (Ref 4) reported that saline soils of the Punjab region were composed mainly of chloritic and illitic minerals, and leaching seemed to have no effect mineralogically on the soils. Grim (Ref 5) also

reported that Solonetz soils tested were composed primarily of illitic minerals. Neither author reported any traces of kaolinite and only small amounts of montmorillite present in the saline soils.

Salt Treatment of Cohesive Soils

Marks (~~Ref-6~~) has presented probably the most extensive experimental data and discussion of data concerning the salt treatment of cohesive soils to date. The addition of 2% sodium chloride caused a substantial increase in compacted unit dry weight and a reduction of corresponding optimum moisture content of the soils tested. This increase in dry density was attributed to flocculation caused by the addition of sodium chloride. Increases in densities of soil-aggregate mixtures with the addition of sodium chloride have also been reported by Gow, Davidson and Sheeler (~~Ref-7~~). Unconfined compressive strength of cohesive soils has also been affected by salt treatment. Marks reported an increase of nearly 100% in compressive strength with the addition of small percentages of sodium chloride. The salt-clay reactions occurred rapidly as indicated by a high rate of strength gain during early stages of curing. However, some adverse effects of sodium chloride treatment were also reported by Marks. Increased percentages of sodium chloride caused corresponding increases in liquid limits of the cohesive soils tested. Plastic limit values increased at approximately the same rate, thus the resulting plasticity indices were not changed. Sodium chloride treatment increased swelling potential of the soils with increase in salt content.

Probably the most encouraging use of salt is in combination with lime treatment of cohesive soils. Marks and Haliburton (~~Ref-1~~) reported

that the addition of sodium chloride in conjunction with lime increased compacted unit weights and reduced optimum moisture contents of the two soils tested. Salt-lime treatment produced higher strengths than lime treatment alone and increased the rate of strength gain during curing. Sodium chloride, however, as a chemical additive at modification lime contents caused negligible increases in PI.

Summary

In this Chapter a short review of the origins and physical properties of saline soils in addition to a summary of research performed on salt-treatment of cohesive soils has been presented. In the following Chapter more detailed information of the saline soils used in this study will be given.

CHAPTER III

MATERIALS

This Chapter provides descriptive information on the location and physical, chemical, and mineralogical properties of two saline soils used for these studies. Also discussed are the properties of two laboratory soils obtained by leaching soluble salts from the saline soils. The Chapter is concluded with a brief description of the chemical additives used to modify the saline and leached saline soils.

Soil Location

Saline soil samples were selected from two typical saline soil areas in north central Oklahoma. Type and concentration of salinity were prime considerations when selecting the soils. The so-named Wakita saline soil (WSS) was taken from a wheat field one mile south of Wakita in Grant County. The other saline soil was selected from an alfalfa field one-half mile east of Gibbon in Grant County. Hereafter this soil will be referred to as Gibbon saline soil (GSS). In both cases, the saline soils supported no type of vegetation. Size of the contaminated areas ranged from a few square feet to several acres.

Salinization of the soils resulted primarily from the topography and underground strata of the area. WSS was taken from an extremely flat area where runoff from the surrounding area was usually trapped, because of poor surface drainage. Underground drainage was prohibited

by an impervious red shale, located approximately five feet below the surface. Salinization of GSS occurred in a similar manner.

Physical Properties

Wakita saline soil was characterized by the presence of thin crusts of white salts on the surface. Between a depth of two and three feet, the level from which the soil sample was taken, the reddish-brown soil was heavily fissured, and the fissures encrusted with salts. Conversely, the Gibbon saline soil surface had a damp blackish appearance and white salt crusts were not noted in the area. However, between a depth of two and three feet, also the level at which the soil sample was taken, the soil fissures were filled with salts.

Index properties of the saline and leached saline soils were determined in the laboratory and are given in Table 3.1.

TABLE 3.1
INDEX PROPERTIES OF SALINE AND LEACHED SOILS

Properties	WSS	Leached WSS	GSS	Leached GSS
Specific Gravity	2.72	----	2.70	----
Liquid Limit	46.0	48.7	39.2	49.0
Plastic Limit	20.7	18.7	17.3	18.4
Plasticity Index	25.3	30.0	22.0	30.6
Flow Index	2.3	2.6	3.7	2.5
Toughness Index	8.8	7.2	4.7	7.4
Linear Shrinkage, %	20.0	19.3	15.0	14.2
% Passing No. 200 Sieve	93.0	----	95.0	----

GSS and WSS are both of medium plasticity. They would be classified as A-7-5 material by the ASSHO Soil Classification system and CL by the Unified System. After leaching, the soils become more plastic, as

indicated by an increase in their liquid limit and plasticity indices. Toughness and flow indices for the two saline soils differed somewhat, but after leaching the indices were almost identical. Linear shrinkage values for the leached saline soils were slightly less than that of the soil in their natural condition.

The saline soils were noted to be highly flocculant in their natural state. However, after leaching, the soils no longer exhibited this property. Consequently, the flocculant nature of the saline soils obviously resulted from the presence of salts in the soil.

Chemical and Mineralogical Properties

Soil salinity analyses were performed by the Soil and Water Service Laboratory, Agronomy Department, OSU Extension Division, on both natural and leached soils. Results are given in Table 3.2. Salinity analysis indicated that WSS contained high concentrations of calcium and sodium cations, combined primarily with sulfate anions. Total soluble solids were 0.8 percent. Conversely, GSS essentially contains concentrations of sodium cations combined with approximately equivalent amounts of sulfate and chloride anions, totaling 0.86 percent soluble solids.

Leaching the saline soils was quite effective in removing significant quantities of soluble salts. Parts per million of calcium and sodium cations in WSS were reduced from 990 and 1,200 to 22 and 344 respectively. Sulfate anions were reduced to 325 ppm from an initial 5,750 ppm. The same was true for GSS, where sodium cations were reduced from 2,225 to 344 ppm. Chloride and sulfate anions were reduced from 2,769 and 3,213 ppm to 290 to 312 ppm respectively. Total soluble salts for both saline soils were reduced to about 0.15 percent.

TABLE 3.2.

SOIL SALINITY ANALYSIS OF NATURAL AND LEACHED SALINE SOILS

Soil Sample	Calcium ppm	Magnesium ppm	Sodium ppm	Chloride ppm	Sulfate ppm	Carbonate ppm	Bicarbonatè ppm	Total Solids ppm	Soluble Solids Tons/Ac-ft
GSS	325	200	2225	2769	3212	0	140	8560	15.1
Leached GSS	23	20	344	290	312	0	390	1400	2.4
WSS	990	190	1200	234	5750	0	165	8000	14.0
Leached GSS	22	8	344	280	324	0	439	1600	2.8

Differential thermal analysis (DTA) of WSS, leached WSS, and nearly pure illite mineral from Union City, Oklahoma are shown in Figure 3.1. It is quite evident from the curves that WSS is composed predominately of illitic clay minerals. Both the WSS and pure illite have endothermic peaks at 100°C, 570°C, 780°C, and 1100°C. The 170°C endothermic peak of WSS results from the high concentration of sulfate anions present. This is substantiated by the fact that after leaching the 170°C peaks no longer existed. It should be also noted that leaching did not change WSS mineralogically.

Shown in Figure 3.2 are DTA curves for GSS, leached GSS and a nearly pure chlorite mineral. These curves indicate that GSS is predominately chlorite. GSS and chlorite exhibit endothermic peaks at 100°C, 570°C, and 1100°C, but do not have an endotherm at 780°C as in illite and WSS. Salts are not indicated in the DTA curves of GSS. This is probably a result of lower concentrations of any one cation or anion. Again, as with WSS, leaching of GSS did not cause any mineralogical changes in the soil.

Chemical Additives

Lime in the form of calcium oxide (quicklime) was used as a chemical additive throughout the investigation. The pelletized quicklime was stored in tightly sealed containers. Prior to use, the quicklime was passed through a U.S. No. 40 sieve to eliminate any carbonated lime which might have been present. St. Clair Lime Company, Sallisaw, Oklahoma, produced and supplied the quicklime. Pure calcium oxide content was 97.5 percent by weight.

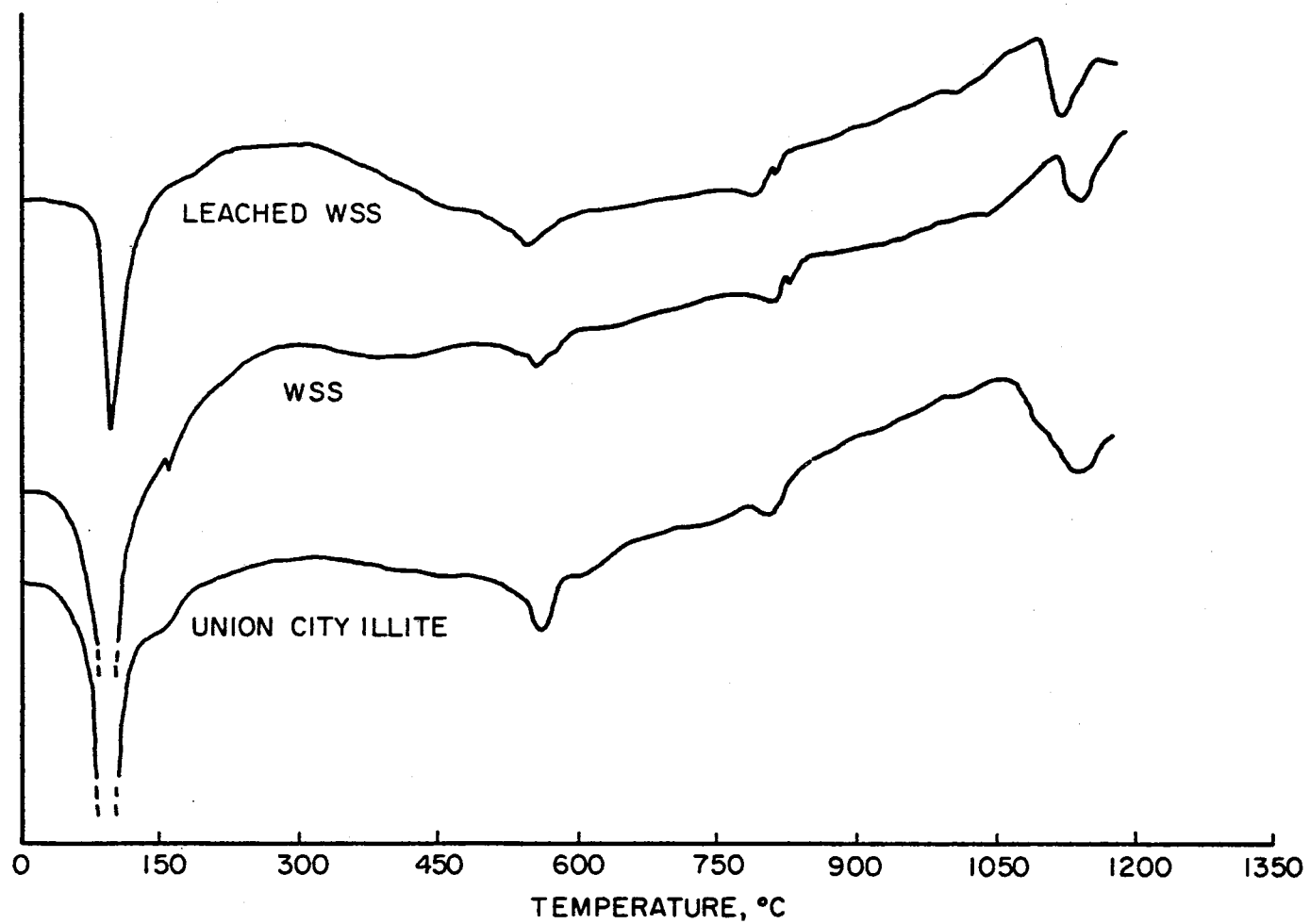


Figure 3.1. DTA Thermograms of WSS, Leached WSS, and Illite

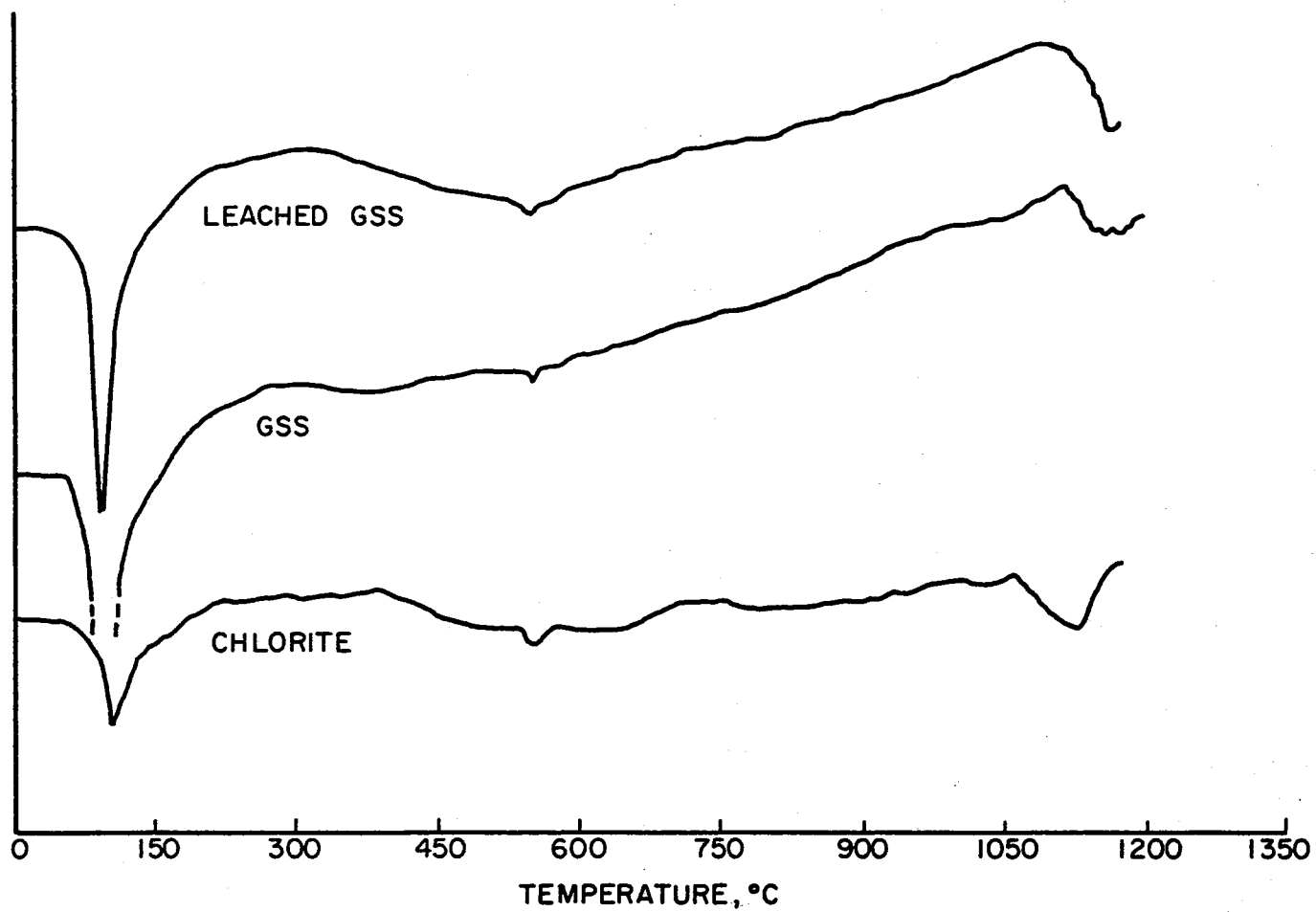


Figure 3.2. DTA Thermograms of GSS, Leached GSS, and Chlorite

Commercial grade sodium chloride was also used as a chemical additive. Ten percent of the salt passed a U.S. No. 40 sieve while 90 percent was retained on the U.S. No. 80 sieve. Pure sodium chloride content was about 99.5 percent by weight.

CHAPTER IV

SOIL PREPARATION AND TESTING PROCEDURE

This Chapter provides information concerning soil preparation for testing and the testing procedures used throughout the investigation. A consistent mixing procedure was adopted, to reduce variations in test results. Testing was conducted by standard procedures when possible. However, in some cases, modification of standard procedures was necessary and new testing procedures were devised in the laboratory.

Soil Preparation

Approximately eight hundred pounds of each saline soil were obtained and processed for testing. Processing consisted of drying, grinding, and storing the soil. The natural soil was first dried in a large gas oven at 110°C for twenty-four hours. After drying, the soil was removed and all large, hard clods were reduced in size with a polyethylene mallet. Further reduction of clods and loose soil was accomplished by grinding in a Straub Model 4E laboratory mill. The mill was set to produce soil passing a U.S. No. 40 sieve. After setting the grinder, only occasional resetting was required to maintain the soil at the desired particle size. The soil was then stored in large plastic containers.

For later comparative testing, some of the prepared saline soil was leached of its soluble salts. Leaching was accomplished by mixing three pounds of saline soil with water at a soil-water ratio of 1:5. The

soil-water solution was then mixed in a Reynolds Chef II mixer for one hour. The mixer was set on low speed with a batter beater attachment. Water was then extracted by centrifuging. The procedure was repeated until centrifuging would no longer produce a clear water supernatant, thus indicating a non-flocculant soil. Moreover, since natural salts were the prime reason for the flocculant nature of the soils, the soluble salts were considered to be removed to an acceptable extent.

After sufficient leaching, 3 washings for GSS and 5 washings for WSS, the soil was oven-dried at 110°C and again ground in the Straub Laboratory mill. The leaching and drying procedure was repeated until approximately 20 pounds of leached GSS and WSS were obtained. The leached saline soils were then stored.

After preparation and leaching of the saline soils, a procedure for mixing soil, water, and chemical additives prior to testing was adopted. Twenty-four hours prior to testing the required quantity of soil, weighed to the nearest 0.1 gram, was mixed with, if any, the desired percentages of chemical additives; based on the dry weight of soil, the materials were thoroughly mixed and leveled in a suitable container. Water (quantity approximately equal to the plastic limit) was sprinkled on the entire surface, thus allowing it to migrate evenly through the sample. The container was then sealed to prevent evaporation. If a known moisture content was desired, e.g., samples for unconfined compression testing compacted at optimum moisture and density, the equivalent quantity of water was added evenly on the surface, the gross weight recorded, and the container sealed. Immediately before testing, the container was reweighed and water was added if needed.

After the 24-hour curing period, the sample was prepared for testing, by thoroughly mixing by hand. After mixing it was resealed to prevent moisture loss during usage.

Testing Procedures

Physical properties of the soil and soil plus chemical additives were determined initially. Liquid limit tests were performed in accordance with ASTM D 423-66, whereas the plastic limit and plasticity index were conducted according to ASTM D 424-59 (65) (Ref 8). Linear shrinkage was determined following a procedure developed by the Texas Highway Department (Ref 9). Linear shrinkage was expressed as a percent of length lost during drying. Two bars were usually made and the linear shrinkages were averaged.

Moisture-density curves were determined by a modified (impact) Harvard miniature compaction test. The soil sample was compacted in a mold of 2.8125 in. length and 1.3125 in. diameter. Impact loading was applied with an 0.825 pound hammer in three lifts at 25 blows per lift. The mold and hammer are reduced proportionally from the standard Proctor mold and hammer. From the moisture-density curves the optimum moisture and density were then determined.

Unconfined compression samples were compacted at optimum moisture and density using the mold and hammer described above. All samples were then sealed with Saran wrap and coated with a thin layer of wax. This prevented any moisture from leaving or entering the sample during curing. After coating, the test samples were stored in a moist room at 80°F and 100 percent humidity. Unconfined compression testing was then performed after 7, 14, 21, and 28 days curing at a loading rate of 0.02

inches per minute, equivalent to approximately 5 percent strain in ten minutes. In all cases three specimens of each mixture were tested and the value averaged. When the unconfined compressive strength of one of the three samples was much higher or lower than the other two, this result was discarded and the remaining two results were averaged.

Differential thermal analysis of the two saline soils with and without chemical additives was conducted according to a procedure developed in the OSU Soil Mechanics Laboratory (Ref 10). Samples for DTA were taken from the unconfined compression test samples after 7 and 28 days of curing. Soil tested was air-dried and ground with mortar and pestle. After grinding, the soil was sieved and that fraction passing the U.S. No. 80 sieve and retained on the U.S. No. 200 sieve was used. The thermally inert reference material used was of the same sieve size. By having both the soil sample and reference material the same sieve size, baseline drift and baseline shift was kept to a minimum. The sieved soil fraction was then stored in a desiccator, over a saturated solution of $\text{Mg}(\text{NO}_3)_2 + 6 \text{H}_2\text{O}$, to allow even distribution of moisture in all samples. At the end of four days, 0.15 grams of the sample were removed and compacted at 530 psi in quartz crucibles. The sample was then ready for testing.

Differential thermal analysis curves were obtained from a Fisher Model 260 Differential Thermolyzer which was connected to a 1 mv Texas Instruments, Incorporated Servo/riter II strip chart recorder. Aluminum Oxide (Al_2O_3) was used as the thermally inert reference material. Platinum Differential Thermocouples were used and the heating rate was 10°C per minute. Recorder chart speed was set at 4 inches per hour.

Summary

In this Chapter, information concerning procedures for soil preparation and testing have been given. In the next Chapter, test results and discussion of test results are presented, thus showing the effects of leaching and chemical treatment on both saline soils.

CHAPTER V

TEST RESULTS AND DISCUSSION

Test results are presented and discussed in this Chapter. Test results for raw and chemically treated saline and leached saline soils were divided into three major portions: Atterberg limits and lineal shrinkage, compaction properties, and unconfined compressive strength.

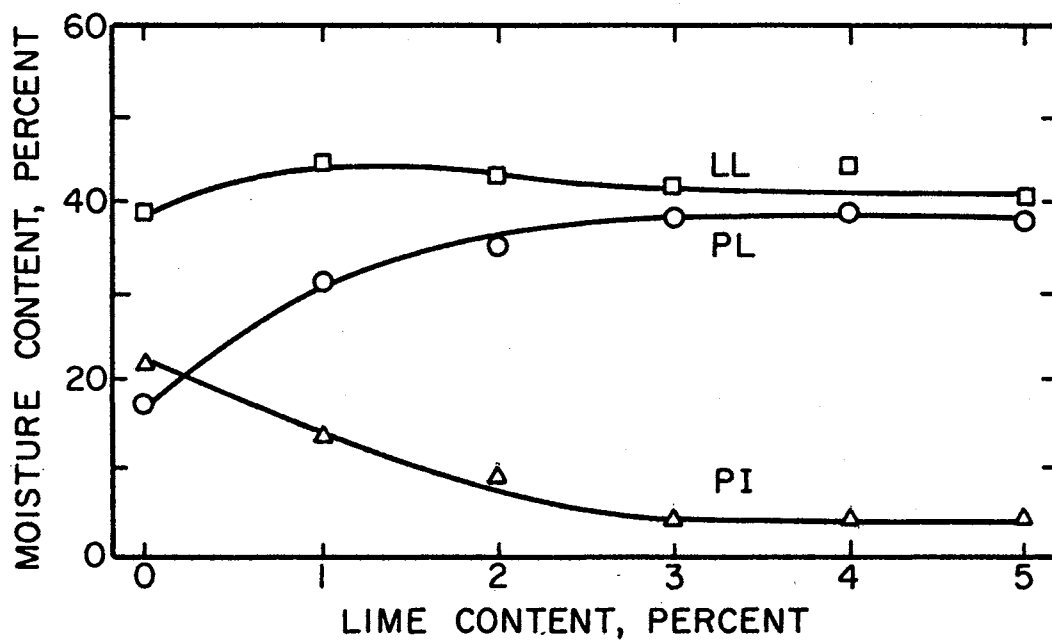
Atterberg Limits and Lineal Shrinkage

Soluble salts had a definite effect on Atterberg limits of both saline soils. After leaching, the liquid limit of GSS increased by 9.8, while the plastic limit remained relatively constant, thus an increase of 8.6 in the plasticity index resulted. The liquid limit of WSS also increased after leaching, but only by 2.7. For this soil, the plastic limit decreased somewhat, causing a 4.7 increase in plasticity index. Therefore, the presence of natural salts in the two saline soils very definitely reduced their plasticity indices, assuming that the leaching process returned the soils to their "original" condition.

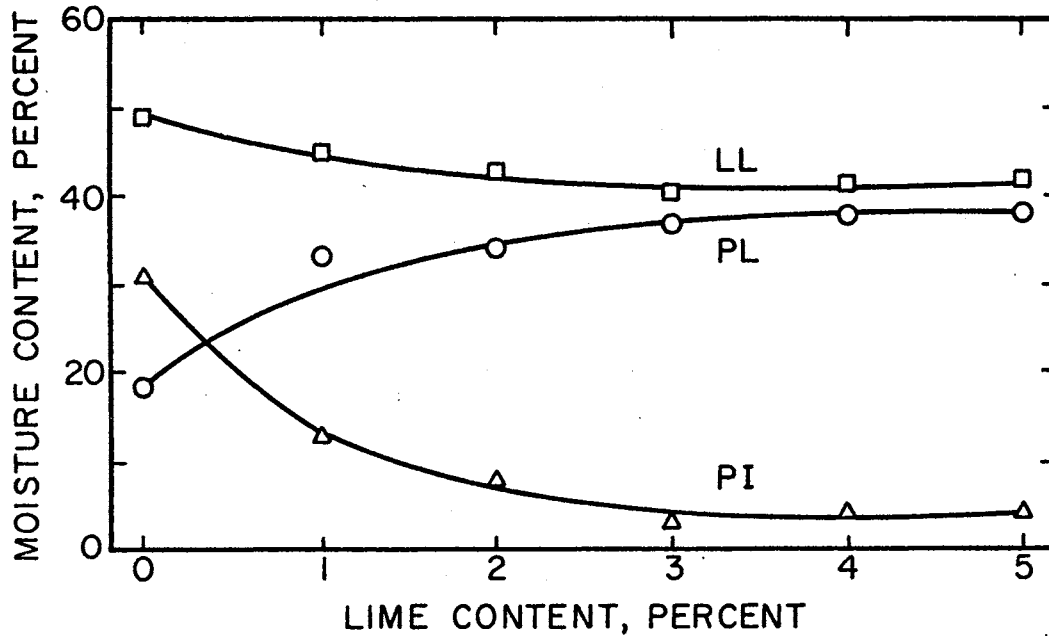
To further investigate this idea, sodium chloride was added to leached GSS and WSS in approximately the same concentration as the natural salts. The liquid limit of leached GSS plus 0.7% NaCl decreased, while the plastic limit remained relatively constant. The resulting plasticity index was 22.5, nearly the same as raw GSS (22.0), and 8.0 less than leached GSS. The liquid limit of leached WSS plus 0.6% NaCl

also decreased while the plastic limit increased slightly. The resulting plasticity index was 26.0, very nearly that of raw WSS (25.3), but 4.0 less than leached WSS. Consequently, sodium chloride reduced the plasticity index of leached GSS and WSS the same amount as did the natural salts found in the two saline soils.

Substantial changes in Atterberg limits of GSS, leached GSS, and leached GSS plus 0.7% NaCl occurred when increasing percentages of lime were added. Figure 5.1a shows the effect on Atterberg limits of adding various lime percentages to GSS. The liquid limit increased slightly with the addition of one percent lime and then declined to a constant 43.0 with increasing lime content. The plastic limit, however, increased rapidly with the addition of one and two percent lime but remained constant with the addition of higher percentages of lime. The plasticity index, consequently, declined from 22.0 to 4.0 with the addition of three percent lime. No further reduction in plasticity index was accomplished with increase in lime content. Three percent lime was thus the lime modification optimum, or the percentage of lime at which no further reduction in plasticity index was obtained. By comparison, liquid limit values for leached GSS decreased slowly with the addition of increasing lime contents. A constant value of 42.0 was obtained with the addition of three percent lime. Figure 5.1b shows the effect on Atterberg limits by adding increasing percentages of lime to leached GSS. The plastic limits of leached GSS behaved the same as for GSS; increasing rapidly before leveling off at three percent lime. Consequently, the plasticity index decreased with increasing lime content, and as for GSS, the lime modification optimum was three percent. When 0.7% NaCl and increasing percentages of lime were added to leached GSS, the liquid limit was



(a) Behavior of GSS



(b) Behavior of Leached GSS

Figure 5.1. Effect of Lime Treatment on Atterberg Limits of WSS and Leached WSS

effected in much the same way as that of lime-treated GSS. The liquid limit increased slightly with one and two percent lime before remaining constant at three and four percent lime. Figure 5.2 shows the effect on Atterberg limits of adding increasing amounts of lime to leached GSS plus 0.7% NaCl. The plastic limit was affected much the same way as the previous soils by increasing rapidly with one and two percent lime before remaining constant at three and four percent lime. The plasticity index, therefore, decreased with increasing lime content, and the lime modification optimum was again found to be three percent.

The addition of lime to WSS, leached WSS, and leached WSS plus 0.6% NaCl produced much the same effects on Atterberg limits as were observed for Gibbon saline soil mixtures. Figure 5.3a shows the effect on Atterberg limits by adding increasing percentages of lime to WSS. The liquid limit of WSS increased slightly with one percent lime, but otherwise remained constant with increasing lime content. The plastic limit, however, increased by 17.0 with the addition of two percent lime. Additional lime above two percent had little effect on the plastic limit. Consequently, the plasticity index decreased rapidly with increasing lime content before remaining constant at a plasticity index of six. Modification optimum was found to be three percent lime. Liquid limit of leached WSS decreased with increasing lime content, as was noted for leached GSS. Figure 5.3b shows the effect on Atterberg limits of adding increasing percentages of lime to leached WSS. A constant liquid limit value of 42.6 was obtained with three percent lime. The plastic limit of leached WSS increased from 19 to 37 at a lime content of three percent. No additional increase in plastic limit was obtained with four percent and five percent. As a result, the plasticity index decreased

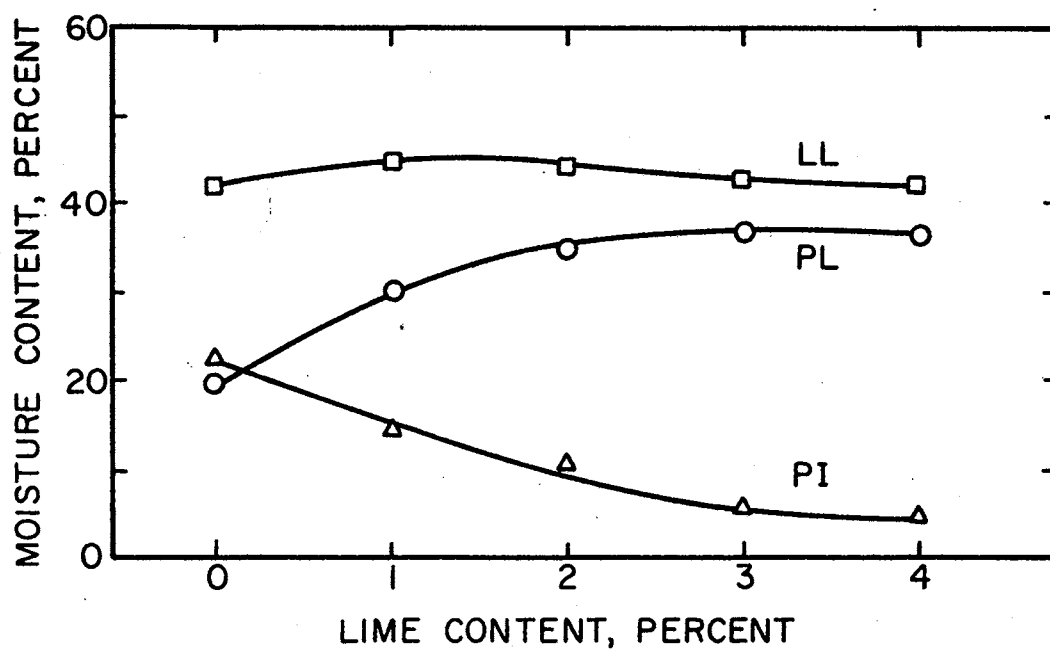
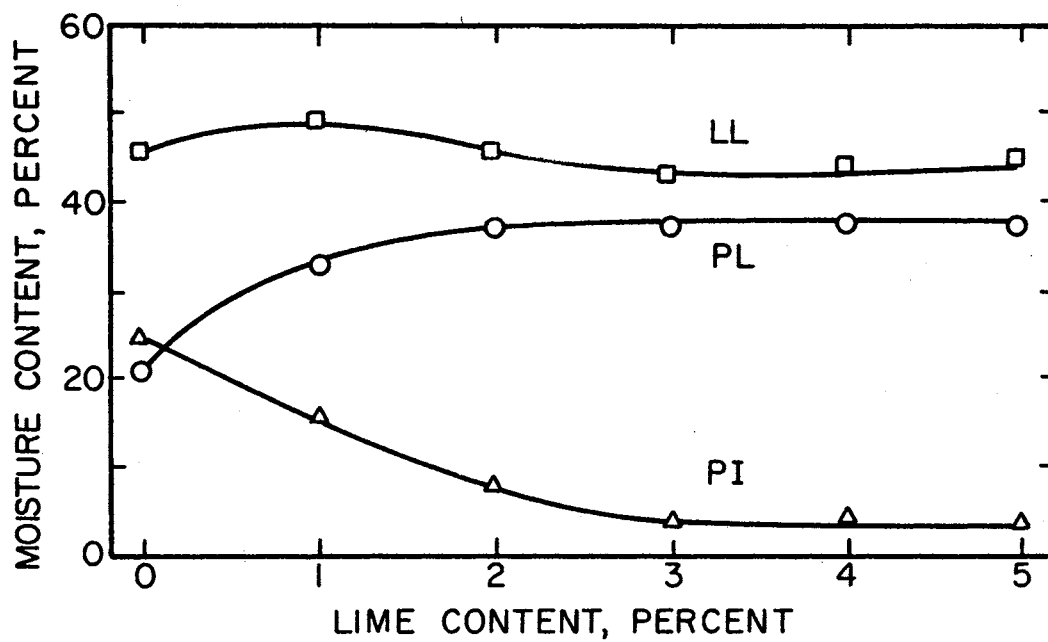
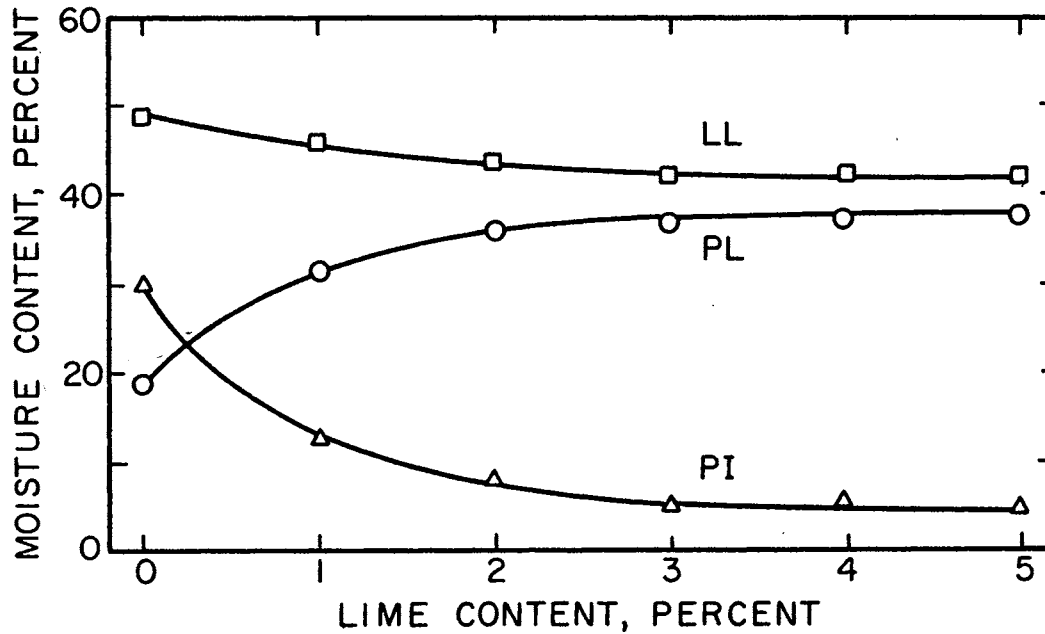


Figure 5.2. Effect of Lime Treatment on Atterberg Limits of Leached GSS Plus 0.7% NaCl



(a) Behavior of WSS



(b) Behavior of Leached WSS

Figure 5.3. Effect of Lime Treatment on Atterberg Limits of WSS and Leached WSS

from 30.0 to 6.0 with three percent lime which proved to be the modification optimum. Results identical to the Atterberg limits of lime-treated raw WSS were obtained by adding 0.6% NaCl and increasing percentages of lime to leached WSS. Figure 5.4 shows the effect on Atterberg limits for leached WSS plus 0.6% NaCl of adding various percentages of lime. The liquid limit increased slightly with one percent lime and then declined to a constant value of 45.0 with the addition of three percent lime. The plastic limit again increased rapidly from 20.0 to a constant 39.0 at three percent lime. Consequently, the plasticity index decreased steadily to a value of 6.0, where it remained constant at four and five percent lime. Modification optimum, as before, was three percent lime.

As a result of leaching and lime treating saline, leached, and sodium chloride treated soils, two conclusions were apparent. Naturally occurring salts and artificially added sodium chloride greatly affected the Atterberg limits of the soils. Salts decreased the liquid limit by five to ten percent while having little effect on the plastic limit. Consequently, a decrease in plasticity index of GSS and WSS resulted from the addition of salts. However, presence of salts in conjunction with lime treatment of the soils had little effect on the Atterberg limits. For both soils, whether raw, leached, or sodium chloride treated, modification optimum was found to be three percent lime. Thus, modification of the cohesive soils by the addition of lime was not inhibited by various naturally occurring salts or the addition of sodium chloride.

Lineal shrinkage was only slightly affected by the salinity of the soils. WSS, leached WSS and leached WSS plus 0.6% NaCl had lineal

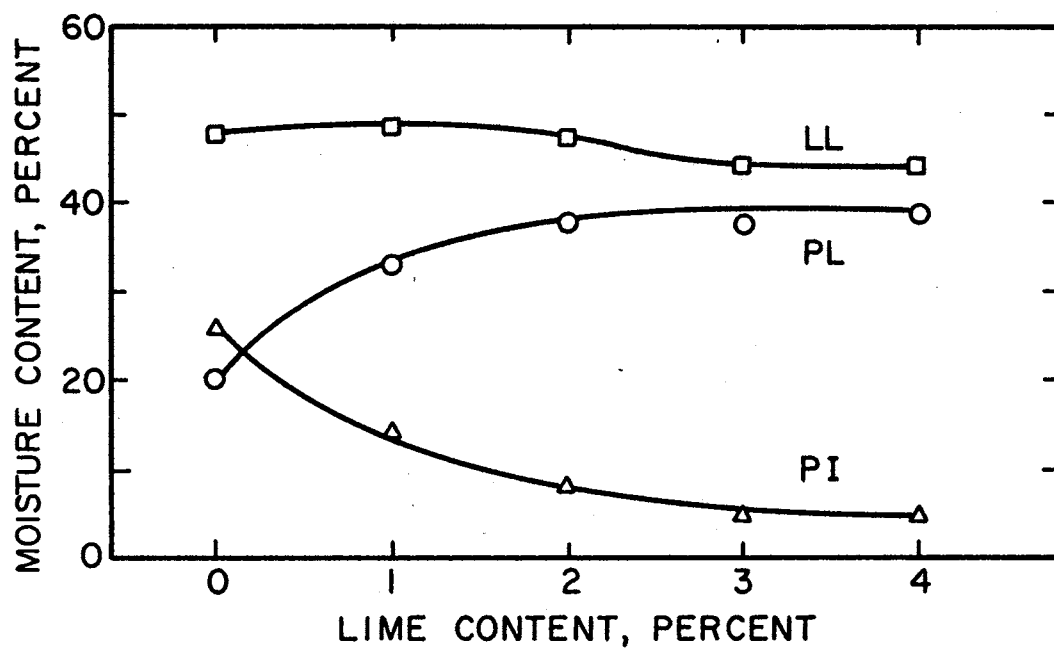


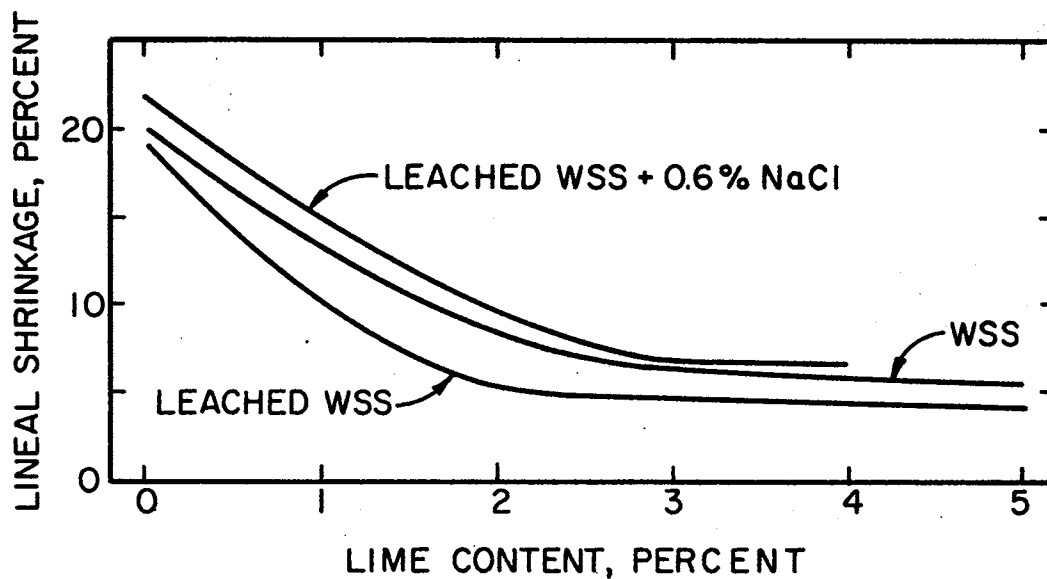
Figure 5.4. Effect of Lime Treatment on Atterberg Limits of Leached WSS Plus 0.6% NaCl

shrinkage for GSS, leached GSS, and leached GSS plus 0.7% NaCl were 15%, 14%, and 16% respectively. Thus, sodium chloride treatment slightly increased the lineal shrinkage of both soils, but differences were negligible.

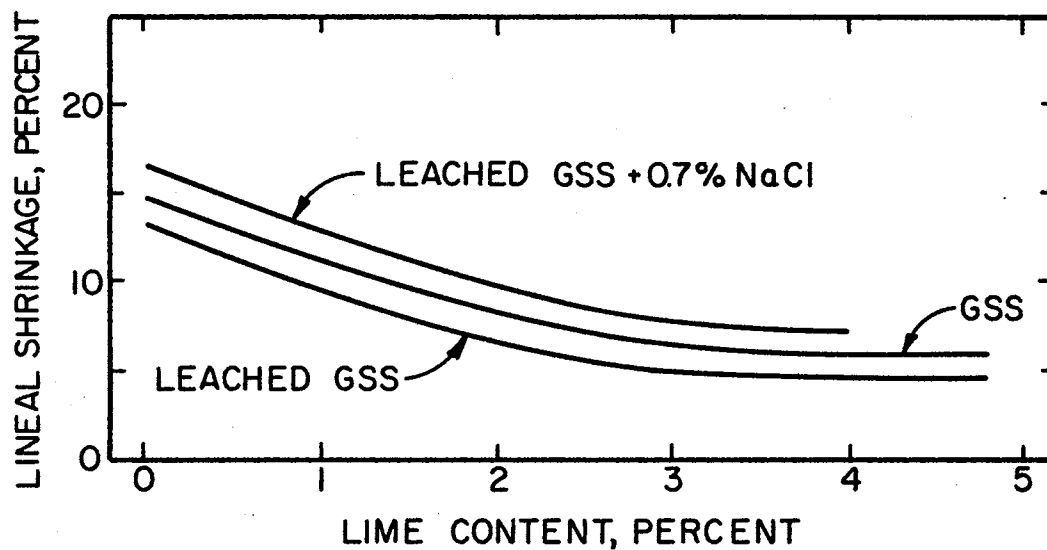
Lime treatment reduced lineal shrinkage of the soils as expected. Even though WSS had a larger initial lineal shrinkage value than GSS, the addition of one through five percent lime yielded nearly the same shrinkage values for the two soils. Figures 5.5a and 5.5b show the effect of lime treatment on lineal shrinkage for natural and leached saline soils. As indicated in the Figures, lime treatment does decrease the lineal shrinkage of the soils, but only to a constant value between five and eight percent. Lime contents greater than modification optimum fail to decrease lineal shrinkage values any further. Thus, salinity of the soils slightly increases their lineal shrinkage values but does not hinder lime reaction with the clay particles, which reduces lineal shrinkage.

Compaction Properties

Naturally occurring salts and artificially added sodium chloride had a definite effect on maximum dry density for leached WSS. Dry densities of WSS and leached WSS were 97.5 pcf and 93.5 pcf respectively, a decrease of 4.0 pcf with the natural salts leached out. Concurrently, optimum moisture increased from 21% to 25.5% as a result of the leaching. When 0.6% sodium chloride was added to leached WSS, dry density increased only slightly. However, the optimum moisture content was reduced to 22 percent. Optimum moisture contents of natural WSS and leached WSS plus 0.6% NaCl were very nearly equivalent to their respective plastic limits



(a) Behavior of WSS, Leached WSS, and Leached WSS Plus 0.6% NaCl



(b) Behavior of GSS, Leached GSS, and Leached GSS Plus 0.7% NaCl

Figure 5.5. Effect of Lime Treatment on Lineal Shrinkage for Natural, Leached, and NaCl Treated Saline Soils

(20%), whereas optimum moisture content for leached WSS was greater than its plastic limit by 5.5%. This is an important factor to consider during highway construction. It is often difficult, if not impossible, to compact soil in the field to maximum dry density when the corresponding optimum moisture content is greater than the plastic limit.

Natural salts and artificially added sodium chloride had a similar effect on maximum dry density for leached GSS. Maximum dry densities for GSS and leached GSS were 100 pcf and 94.3 pcf respectively, a decrease of 5.7 pcf as a result of the leaching. When 0.7% NaCl was added to leached GSS, the maximum dry density increased to 101 pcf; approximately equal to that of natural GSS. The optimum moisture contents for GSS and leached GSS plus 0.7% NaCl were 19% and 22% respectively, compared to 25.3% for leached GSS. As with WSS, the optimum moisture contents for GSS and leached GSS plus 0.7% NaCl were very nearly equal to their respective plastic limits. However, optimum moisture content for leached GSS was greater than its plastic limit by 7.0 percent.

As a result of natural salts or the addition of sodium chloride to the soils, maximum dry density increased while optimum moisture content decreased. The increase in maximum dry density was possibly a result of flocculation of the saline soils. Natural salts and added sodium chloride caused the soils to become more nearly flocculant which resulted in a more nearly random structure of clay particles, as opposed to a more nearly paralld orientation of clay particles after leaching. For this reason a greater dry density was achieved, thus explaining the increase in dry density as a result of natural salts and added sodium chloride. Flocculation was also the cause of a decrease in optimum moisture content with the addition of natural salts and sodium chloride.

The addition of three percent lime (modification optimum) to natural, leached, and NaCl treated saline soils changed the maximum dry density and optimum moisture content significantly. However, the resultant values were all approximately equal. As indicated in Table 5.1a, maximum dry densities, of WSS, leached WSS, and leached WSS plus 0.6% NaCl were reduced to 89 pcf, 88.5 pcf, and 88 pcf respectively with the addition of three percent lime. At the same time, however, respective optimum moisture content increased to 29%, 28%, and 29.5%. A similar effect on maximum dry density and optimum moisture content occurred when three percent lime was added to GSS, leached GSS, and leached GSS plus 0.7% NaCl. As indicated in Table 5.1b, maximum dry densities of GSS, and leached GSS, and leached GSS plus 0.7% NaCl were 90 pcf, 89.5 pcf, and 88 pcf respectively, approximately equal to values obtained for lime-treated WSS. Respective optimum moisture contents were increased to 28%, 27.5%, and 29%. One may conclude, therefore, that neither natural salts nor sodium chloride affect the reaction of the soils with lime to any great extent. The effects of lime treatment usually include a decrease of maximum dry density and an increase in optimum moisture content of the treated soils.

Unconfined Compressive Strength

In this study, emphasis was placed on determining the engineering properties which could be expected from saline and lime-modified saline soils. For this reason, unconfined compressive strength tests were conducted on saline soils and soil admixtures compacted at maximum dry density and optimum moisture content, as opposed to testing samples compacted at equivalent dry densities and moisture contents. This point

Material	Optimum Moisture, %	Maximum Dry Density, lb/ft ³
WSS	21.0	97.5
Leached WSS + 0.6% NaCl	22.0	94.0
Leached WSS	25.5	93.5
WSS + 3% CaO	29.0	89.0
Leached WSS + 3% CaO + 0.6% NaCl	29.5	88.0
Leached WSS + 3% CaO	28.0	88.5

(a) Behavior of Raw and Chemically Treated WSS and Leached WSS

Material	Optimum Moisture, %	Maximum Dry Density, lb/ft ³
GSS	19.0	100.0
Leached GSS + 0.7% NaCl	22.0	101.0
Leached GSS	25.3	94.3
GSS + 3% CaO	28.0	90.0
Leached GSS + 3% CaO + 0.7% NaCl	29.0	88.0
Leached GSS + 3% CaO	27.5	89.5

(b) Behavior of Raw and Chemically Treated GSS and Leached GSS

TABLE 5.1. Effect of Lime and Salt Treatment on Optimum Moisture and Density for Saline and Leached Saline Soils

is stressed because compressive strength normally increases with increasing dry density or decreasing moisture content. Because maximum dry densities and optimum moisture contents vary among saline and leached soils, not all variations in strength are a result of natural salts or sodium chloride treatment. However, this is not the case for lime-modified saline and leached saline soils, in which all compacted dry densities and moisture contents were approximately the same.

Natural saline soils had a greater unconfined compressive strength than leached saline soils. After 7 days of curing leached WSS had a compressive strength of 11 psi, whereas WSS obtained a strength of 20 psi; nearly twice as great. As curing time increased to 28 days little change in compressive strength occurred for natural or leached WSS. GSS obtained a strength of 28 psi at the end of 7 days curing. For the same curing period leached GSS developed a strength of 12 psi; less than one-half that of natural GSS. Neither GSS nor leached GSS developed any appreciable strength increase with increasing curing time. The lack of increase of compressive strength with increasing curing period was to be expected. Because of the long period of natural salinization, any or all chemical changes affecting soil strength had already occurred and 28 days further curing would have no effect on the compressive strength of natural and leached saline soils may partially have been a result of increased unit dry weight, some increase was probably caused by the natural salts contained in both soils. These salts could have allowed some type of salt-clay reaction to occur with a resultant increase in strength. During the leaching process to remove the salts, the salt-clay reaction products may have possibly been dissolved or broken up by the added water and agitation, resulting in a decrease in strength.

The addition of sodium chloride caused different compressive strength behavior for the two leached soils. Leached WSS plus 0.6% NaCl maintained a strength of 27 psi after 7, 12, 21, and 28 days of curing; greater by 16 psi than leached WSS and 7 psi greater than that of natural WSS. However, leached GSS plus 0.7% NaCl developed a strength of 15 psi for all curing periods; only 3 psi greater than leached GSS and 13 psi less than natural GSS. Consequently, the strength of leached WSS was greatly increased with the addition of sodium chloride, whereas the strength of leached GSS was hardly affected. Characteristics of natural, leached, and sodium chloride treated WSS and GSS are shown in Figs 5.6 and 5.7 respectively by curves representing unconfined compressive strength as a function of curing time.

Aside from the increases in strength resulting from variations in dry densities and moisture contents, some increase in compressive strength was caused by the sodium chloride. Differential thermograms, given in Fig 5.8 for both sodium chloride treated leached soils, may possibly explain the reason why sodium chloride treated WSS increased in strength while the strength of salt-treated leached GSS was unchanged. The exothermic peak occurring at 860°C for natural and leached WSS was eliminated with the addition of sodium chloride, indicating some type of salt-clay reaction. Also, the 570°C exothermic peak appears to be slightly altered which may possibly indicate a reaction of sodium chloride with the silica and alumina of the clay. No such alteration in thermograms occurred when sodium chloride was added to leached GSS, possibly indicative of little or no salt-clay reaction. However, this may be a result of using a salt content much lower or higher than the optimum for strength purposes. For example, the addition of 0.5% or one

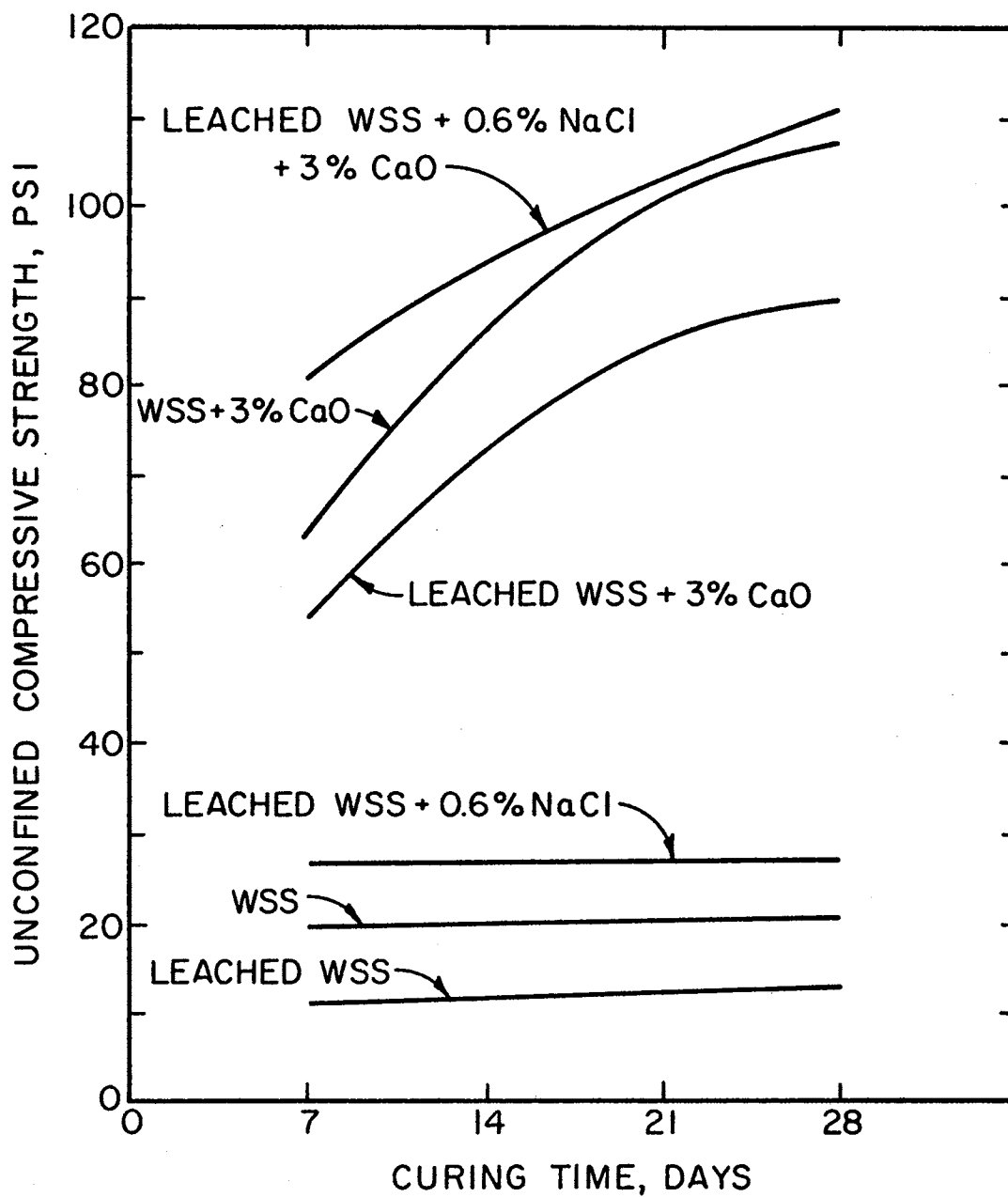


Figure 5.6. Effect of Lime and Salt Treatment on Unconfined Compressive Strength for Natural and Leached WSS

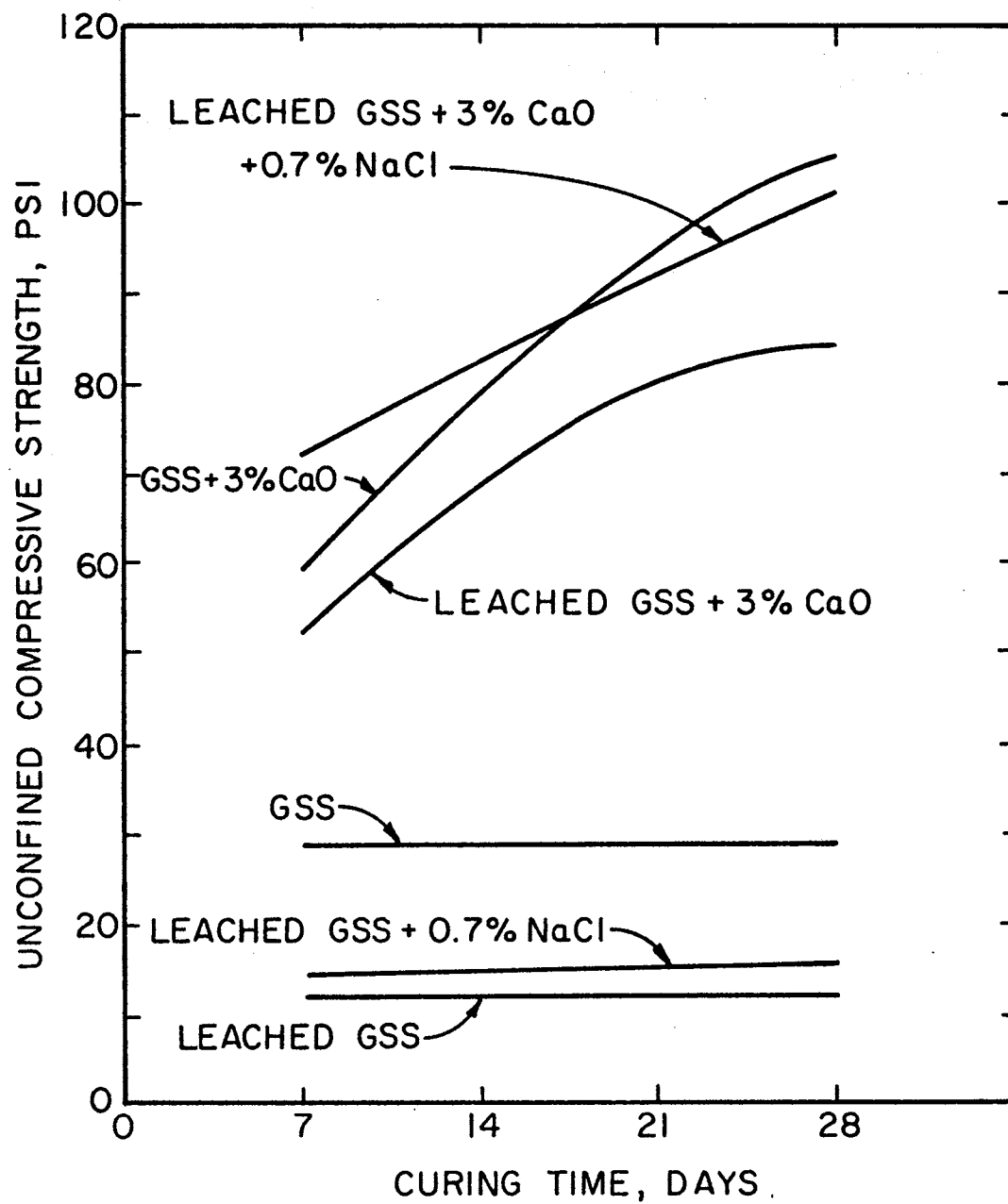


Figure 5.7. Effect of Lime and Salt Treatment on Unconfined Compressive Strength for Natural and Leached GSS

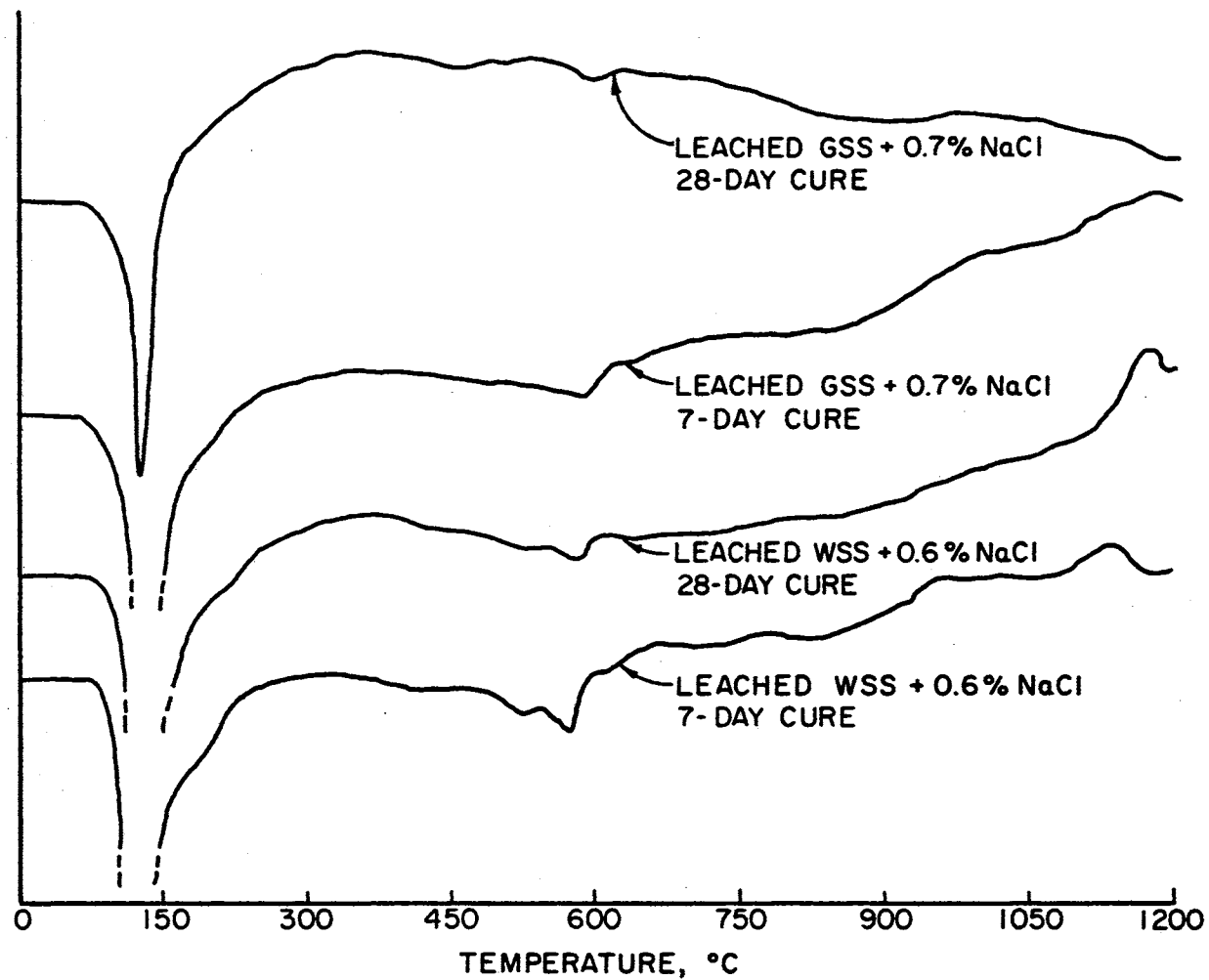


Figure 5.8. DTA Thermograms of Leached Saline Soils Plus Salt After 7 and 28 Days of Curing

percent sodium chloride to leached GSS may have created a salt-clay reaction that would have produced a strength equal to or higher than that of natural GSS.

Although strength gain is normally not of prime interest during lime modification, considerable gain in compressive strength was obtained for both saline and leached soils with the addition of small lime percentages. The addition of three percent lime to leached WSS increased the compressive strength to 54 psi after 7 days of curing and the strength increased steadily to 87 psi after 28 days. Natural WSS plus three percent lime had a 7-day strength of 63 psi increasing to 107 psi after 28 days. Despite a nearly equivalent 7-day strength, 28-day compressive strength for lime treated WSS was about 23% higher than lime-treated WSS. Lime modified leached GSS had a 7-day strength of 54 psi increasing to 84 psi after 28 days. GSS developed a strength of 60 psi at the end of 7 days but increased rapidly to 107 psi at the end of 28 days of curing. In Figs 5.6 and 5.7 curves representing unconfined compressive strength as a function of curing period for lime modified natural and leached WSS and GSS are presented.

For both soils natural salts in combination with lime produced some increase in early strengths and a much greater increase of 28 day strengths. These strength gains were probably a result of granulation of clay particles or the formation of cementitious gels which may occur during lime modification in the presence of salt. Differential thermograms of lime modified leached WSS indicated that little or no chemical changes had occurred after 7 or 28 days of curing. The same was true for leached GSS. However, differential thermograms did reveal chemical changes in lime modified natural WSS. These were indicated by the newly

formed exothermic peaks at 200°C and alterations in the 570°C peak. Differential thermograms of lime-modified natural and leached WSS and GSS after 7 and 28 days curing are given in Figs 5.9 and 5.10 respectively.

The addition of sodium chloride to both lime-modified leached saline soils resulted in greatly increased strength. Leached WSS + 3% CaO + 0.6% NaCl had a compressive strength of 81 psi at the end of 7 days. This was a strength increase of 50% over that of leached WSS + 3% CaO and a 29% increase over that of WSS + 3% CaO. Sodium chloride had a similar effect on GSS. Leached GSS + 3% CaO + 0.7% NaCl developed a compressive strength of 74 psi after 7 days. This was an increase in strength of 37% over that of leached GSS + 3% CaO and a 26% increase over that of GSS + 3% CaO. Sodium chloride, either added or naturally occurring, greatly increased the early strength of lime modified soils. Also, in the absence of other inhibiting anions and cations, i.e. naturally occurring sulfate, magnesium, etc., the gain in early strength was greater. Another interesting type of strength behavior occurred after 28 days of curing. The 28-day strength of the lime modified natural and sodium chloride treated saline soils were nearly equivalent. Figures 5.6 and 5.7 show the unconfined compressive strength after various curing periods for lime-salt treated leached saline soils. Therefore, presence of sodium chloride in conjunction with lime treatment of the soils created greater compressive strengths after all curing periods than lime treatment without sodium chloride. Furthermore, the greatest strength increase was during early curing periods.

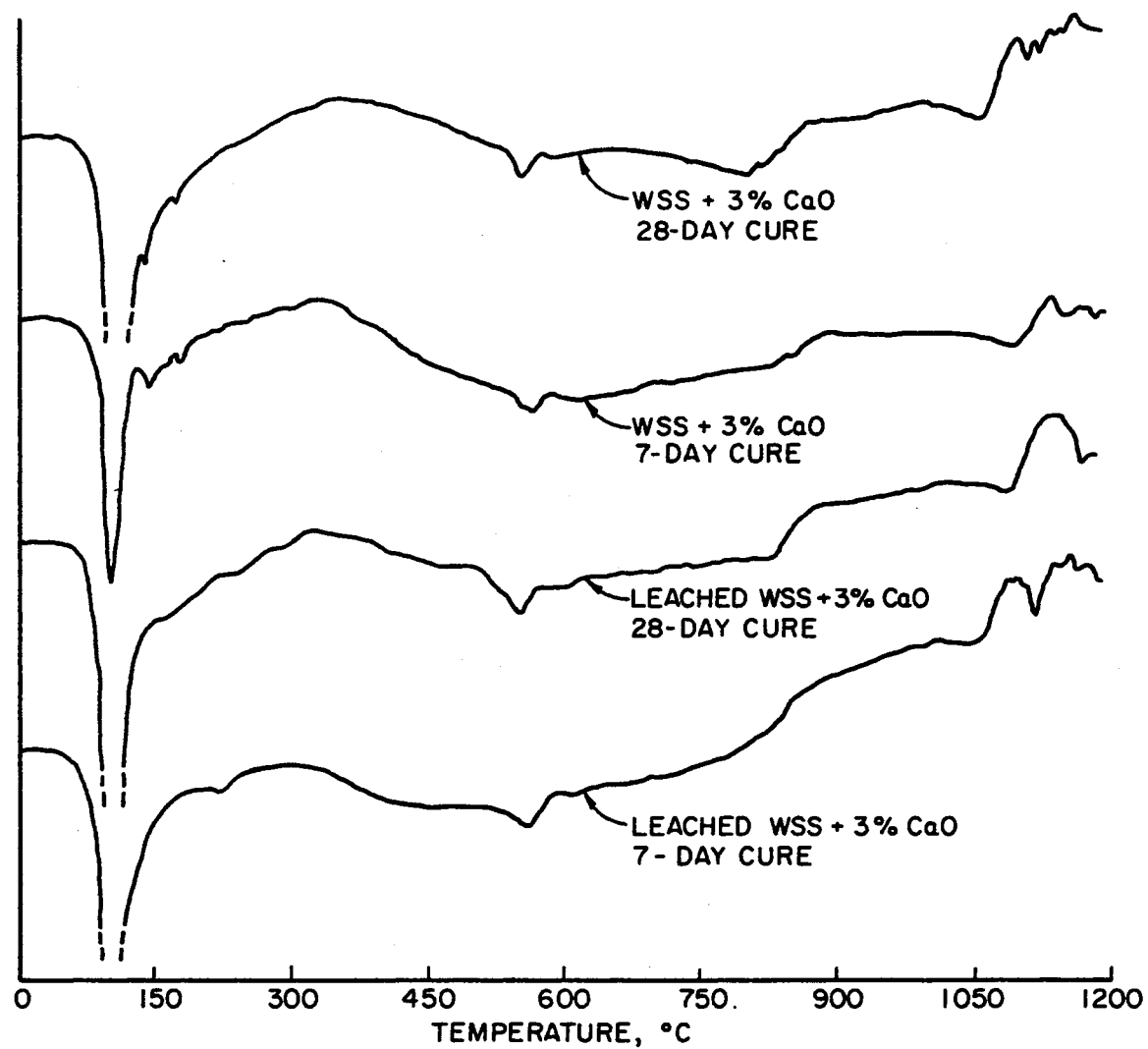


Figure 5.9. DTA Thermograms of Lime Modified Natural and Leached WSS After 7 and 28 Days of Curing

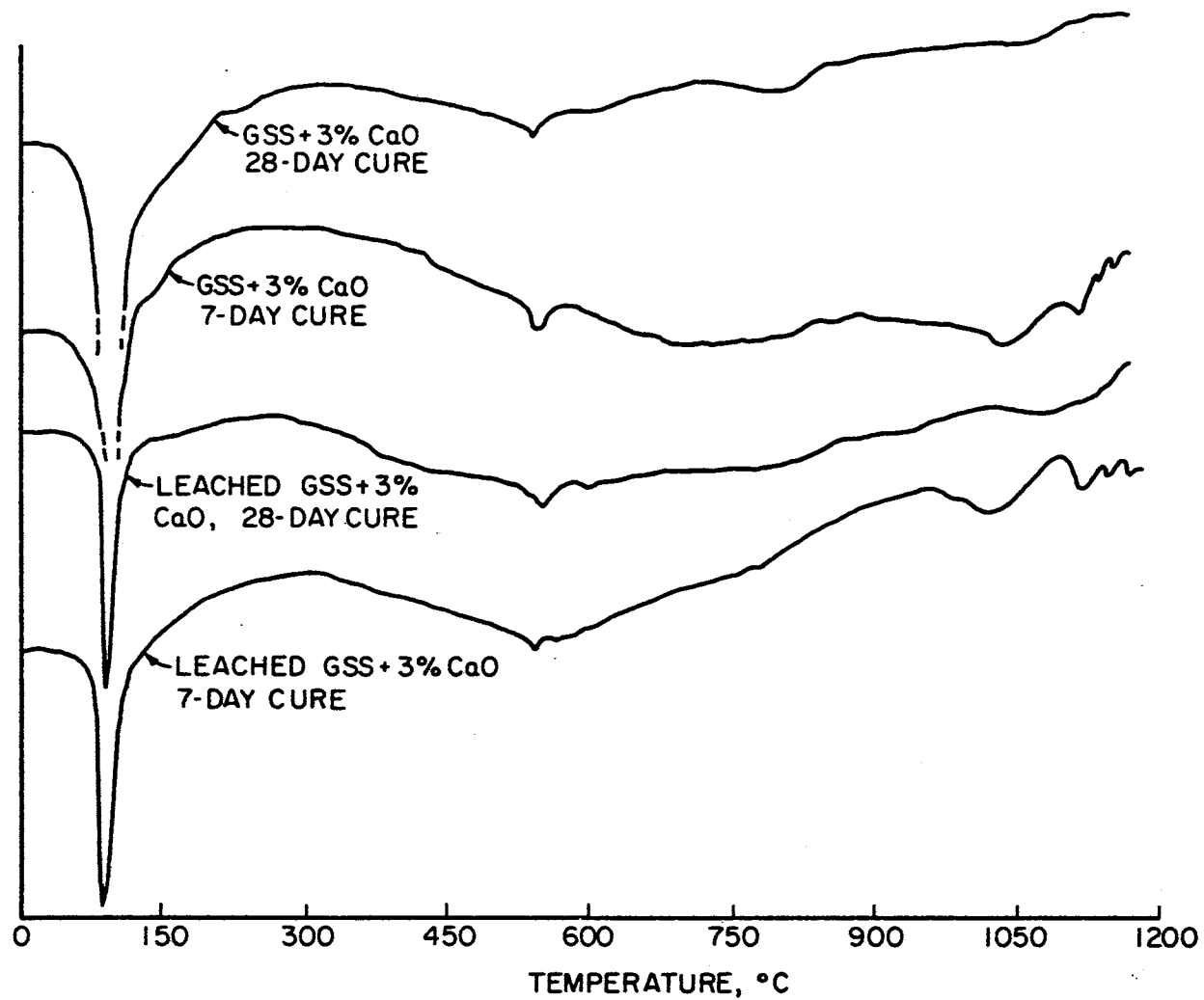


Figure 5.10. DTA Thermograms of Lime Modified Natural and Leached GSS After 7 and 28 Days of Curing

Summary

In this Chapter test results and discussion of test results for the saline and lime modified saline soils have been presented. This Chapter has presented information which should provide a better understanding of saline soil engineering properties. In Chapter VI conclusions and recommendations for future research will be given.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

In the preceding Chapter tests results were presented and discussed. Evaluation of these test results produced the following conclusions:

1. GSS is composed predominantly of chloritic clay minerals; whereas WSS is composed mainly of illitic clay minerals. Both soils contain 0.6% to 0.8% soluble salts, which are composed primarily of calcium and sodium in combination with chloride and sulfate.
2. The natural salts contained in both soils aided in the reduction of their respective plasticity indices by reducing the liquid limit. Sodium chloride, when added to the leached saline soils, had a similar effect on Atterberg limits.
3. Atterberg limits of the saline soils were altered considerably by the addition of lime. The presence of added sodium chloride did not inhibit the lime-clay reaction, as noted by its effect on Atterberg limits.
4. Lineal shrinkage was unaffected by the natural salts but was reduced 50% at the lime modification optimum.
5. Natural salts caused an increase in the maximum compacted dry density while reducing optimum moisture content of both soils. Sodium chloride treatment had a similar effect.
6. Lime modification at the optimum lime content of the soils reduced the maximum dry density while increasing the optimum moisture con-

tent. However, neither sodium chloride nor natural salts affected the compaction properties of the lime-treated soils.

7. Unconfined compressive strength of the natural saline and sodium chloride treated soils was greater than that of leached saline soil.
8. Lime modification increased the compressive strength of natural, leached, and sodium chloride-treated saline soils.
9. Natural salts and sodium chloride in combination with lime treatment produced greater strengths than lime treatment alone. Salts were especially effective in creating greater early strengths of lime treated soils.
10. Use of saline soils should be given considerable consideration because of their lower PI, greater maximum dry density, higher unconfined compressive strength, and accelerated reaction with lime than may be expected from nonsaline soils of similar properties.

For future study of engineering behavior of saline cohesive soils, the following is recommended:
 1. The effects of lime stabilization, i.e. lime contents greater than 3%, may show more clearly the role natural salts play to increase compressive strength of lime treated saline soils.
 2. Differential thermal analysis of lime stabilized natural and leached saline soils would provide information concerning mineral growth that may be causing strength increases during salt-lime treatment.
 3. Investigation of the effects of using saline water to provide compaction moisture for nonsaline cohesive soils may provide information ultimately leading to saline water use in highway construction, helping to reduce salt-water pollution and disposal problems.

REFERENCES

1. Marks, B. D. and T. Allan Haliburton, "Effects of Sodium Chloride and Sodium Chloride-Lime Admixtures on Cohesive Oklahoma Soils," Highway Research Board Record Number 315, 1970, pp. 102-111.
2. Teakle, L. J. H., "The Salt (Sodium Chloride) Content of Rainwater," West. Austral. Dept. Agr. Jour., Ser. 2, 14:115-123, illus., 1937.
3. United States Salinity Laboratory Staff, Diagnosis and Improvements of Saline and Alkali Soils, Agriculture Handbook No. 60, United States Department of Agriculture, 1954.
4. Kanwar, J. S., "Clay Minerals in Saline Alkali Soils of the Punjab," Journal of the Indian Society of Soil Science, Volume 9, 1961, pp. 35-40.
5. Grim, R. E., Clay Mineralogy, McGraw-Hill Book Company, Inc., New York, 1953.
6. Marks, B. D., "Sodium Chloride and Sodium Chloride-Lime Treatment of Cohesive Oklahoma Soils," Submitted to the faculty of the Graduate College of Oklahoma State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Stillwater, Oklahoma, July, 1970.
7. Gow, A. J., D. T. Davidson, and J. B. Sheeler, "Relative Effects of Chlorides, Lignosulfonates and Molasses on Properties of a Soil-Aggregate Mix," Highway Research Board Bulletin 287, 1967, pp. 66-83.
8. _____, ASTM Standards, Part II, Bituminous Materials; Soils; Skid Resistance, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1969, pp. 311-316.
9. _____, Test Method Tex-107-E, Determination of Shrinkage Factors of Soil, Materials and Tests Division, Texas Highway Department, Austin, Texas, June, 1962.
10. Calsing, R. L., "Operating Manual for Fisher Model 260 Differential Thermalizer," Soil Mechanics Laboratory, School of Civil Engineering, Oklahoma State University, First Edition, November, 1970.

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