# SODIUM CHLORIDE AND SODIUM CHLORIDE-LIME TREATMENT OF COHESIVE OKLAHOMA SOILS

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Submitted to the Faculty of the Graduate College
of Oklahoma State University
in partial fulfillment of requirements
for the Degree of
DOCTOR OF PHILOSOPHY
July, 1970

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To my wife, Jane, for her continued encouragement, understanding, and patience throughout this study.

# ACKNOWLEDGEMENTS

The author wishes to express gratitude and sincere appreciation to the following individuals:

To his major adviser, Professor T. Allan Haliburton, for his consultation, guidance, and support in pursuit of the degree associatied with this study.

To his committee members, Professor James V. Parcher, Professor M. Abdel-Hady, and Professor Lester Reed, for their interest and encouragement throughout this study.

To his parents, B. D. and Jimmie J. Marks, Jr., for inspiration and guidance during earlier years.

To fellow graduate students, Frank C. Townsend and Michael L. Hughes, for their suggestions, assistance, and fellowship.

To Cecil Sharp, Civil Engineering Shop Technician, for his assistance in construction of special laboratory equipment and fellowship.

To Mr. Bill Bellis and Mrs. Linda Hare, School of Geology Laboratory at the University of Oklahoma, for assistance in scanning electron microscopy used in this study.

To Mrs. Linda Schroeder for typing of this manuscript.

To Mr. Eldon Hardy for assistance in preparation of graphical portions of this manuscript.

To the National Defense Education Act Fellowship Program for support during this study.

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# CHAPTER I

# INTRODUCTION

Improvement of existing cohesive subgrade soils by chemical treatment has received much attention from highway engineers in recent years. Concentration of interest is a result of several factors which include: availability of material, higher quality specifications, and economics of construction. In certain areas of the United States and parts of the world of concern to the United States, materials adequate for even low quality road construction are not available. In these areas some process must be used to upgrade existing soils regardless of cost. Chemical treatment has been found to fulfill requirements. Subgrade soils which have been used for years as highway foundations are now also being chemically treated to produce higher quality material, because of more exacting highway specifications necessary to provide for more and heavier wheel loads. Increasing requirements is particularly true for interstate highway specifications as compared to long existing federal aid highway specifications. Economics is usually of major concern in procurement and placement of select materials. It has been found that, in many instances, existing cohesive soils can be upgraded by chemical treatment more economically than high quality materials can be located and brought to the construction site.

Lime, in both hydrated and oxide form, has become one of the most widely used chemical additives for treatment of highly plastic cohesive soils. Two types of lime treatment, often confused or used in the wrong context, are lime modification and lime stabilization. Lime modification is treatment of cohesive soil with relatively low percentages of lime to reduce plasticity and volume change potential and increase workability. Lime stabilization is treatment of cohesive soil with sufficient lime to produce chemical reactions which form cementitious bonds, contributing to significant strength increases. Stabilization normally requires greater percentages of lime than does modification.

Although lime treatment produces very desirable results, some undesirable effects also occur. These effects are more pronounced in lime modification than in stabilization. Undesirable properties associated with lime treatment include reduced compacted unit dry weight, increased optimum moisture content, little change in workability during mixing operations, and relatively slow gain of high strength during stabilization.

## Statement of the Problem

Addition of other chemical additives in conjunction with lime might be an effective way to minimize these undesirable effects. Many chemical additives have been found to be beneficial; however, most of these chemical additives have been impracticable for field use because of their expense.

Sodium chloride has been used as a stabilizing agent for select gravel base course materials containing clay binder; however, very little work has been done on the use of salt for treatment of cohesive soils or as a chemical additive in conjunction with lime.

The immediate concern of this study was to determine the feasibility of sodium chloride and sodium chloride-lime treatment of cohesive Oklahoma soils.

## Scope of the Investigation

The scope of this investigation was in actuality twofold: 1) investigation of effects of soidum chloride admixtures on cohesive soils, and 2) investigation of effects of sodium chloride-lime admixtures on cohesive soils. However, it was also necessary to investigate behavior of the two selected cohesive Oklahoma soils during both lime modification and lime stabilization to gain a better understanding of reactions occurring during salt-lime treatments.

# CHAPTER II

# A LITERATURE CRITIQUE OF SOIL CHEMISTRY AND CHEMICAL TREATMENT OF SOIL

## Introduction

Treatment of highly plastic cohesive soils with chemical additives to produce more desirable construction material has been in the development stage for some years. Present knowledge in the area indicates cohesive soils may be chemically treated to produce desired results; however, much remains to be learned about mechanisms which control reactions between clays and chemical additives. Only through understanding and application of fundamental concepts in soil chemistry may these reactions be explained. Thus, future developments in chemical treatment of cohesive soils hinge on the application of soil chemistry by soils and foundation engineers.

The purpose of this chapter is to provide a working knowledge of basic concepts and theories in soil chemistry which may affect chemical treatment of cohesive soils. Present theories and hypotheses concerning treatment of clays with various additives are also presented.

## Soil Chemistry

Throughout the following section, clay fractions of soil will be defined as in soil science. Clay particles are considered to be that fraction of the soil having an equivalent Stokes diameter of less than two microns.

Clay soils are composed of extremely small crystalline particles, of one or more basic clay minerals. These minerals are essentially hydrous aluminum silicates with magnesium and iron substituting wholly or in part for aluminum in their lattice structure (Ref 1).

Clay minerals may be formed in nature by alteration of rock minerals or from other clay minerals, either directly or through a solution phase. This type of mineral formation is termed diagenesis. Clay minerals may also be formed by genesis, which involves synthesis of clay minerals in nature directly from solution (Ref 2).

Two other types of particles found in clay fractions of soil should be mentioned. The first of these includes extremely small fragments of pure rock minerals such as quartz, feldspar, calcite, pyrite, etc. Very little of the chemical behavior of clays is dependent upon these particles. Other particles ("gunk") found in the clay fraction have no crystalline structure. This amorphous material has been named allophane. Allophane has been found to be predominant in some clay minerals, and its presence greatly affects chemical behavior of these clays.

When subjected to an electrical field, charged particles in suspension migrate toward one of the electrodes. In the case of most clays, movement is toward the positive pole; however, other particles such as oxides of iron and aluminum, often termed sesquioxides, migrate toward the anode. This migration is called electrophoresis, which replaces a formerly used, more restrictive term, cataphoresis. Importance of these charged particles on the chemical behavior of soil colloidals was noted very early by Robinson and Holmes (Ref 3). In continued study, Mattson (Ref 4) found that soils may be divided into two distinct groups according to their electrical behavior. The first group consists of clay soils containing high silica and low sesquioxide contents. None of these soils are characterized by dominant reddish and yellowish oxide colors. These clays are nonreactive to acid solutions. The second group of soils, reddish or yellowish in color as a result of high sesquioxide content, react very rapidly to acid solutions and become electropositive. This is not difficult to understand upon examination of pure sesquioxide behavior. These oxides are electrical ampholytes. Their isoelectric point is very near the true neutral point; consequently, above pH 7.0 they are electronegative, and below pH 7.0 they are electropositive. Thus passing from pure quartz, which is strongly electronegative and not an electrical ampholyte, through soils of varying silica-sesquioxide ratio to lateritic soils which have very high sesquioxide contents and on to the pure oxides themselves, a uniform gradation of electrical behavior exists which is evidently linked to chemical composition of clay minerals.

Clay particles obtain an initial charge by at least three recognizable phenomena which include: broken bonds, isomorphic substitution or inner-lattice imperfection, and hydrogen bonding.

Broken bonds around the edges of silica-alumina units create unsatisfied charges which must be balanced by counter-ions adsorbed on or attracted near the clay particle surface. In some clays, such as kaolinite and halloysite, broken bonds constitute the major cause of electrical charge; whereas in minerals such as illite, chloride, montmorillonite, and others, the major portion of surface charge is created by other factors.

Unbalanced charges caused by isomorphic substitution are incurred as a result of lower valence ions, particularly magnesium, substituting for trivalent aluminum and/or quardrivalent silicon in tetrahedral sheets of clay minerals. Imperfections in the pure crystalline structure of the clay minerals are often the cause of isomorphic substitution.

Hydrogen ions of exposed hydroxyl groups, which are an integral part of the structure rather than broken bonds, may be replaced by other exchangeable cations. This type of change is often referred to as "specific" or "preferred" adsorption of ions.

Both hydrogen and aluminum bonding have been used to explain soil acidity. Jenny (Ref 5) has presented an excellent account of different views on soil acidity throughout the past; however, Jackson (Ref 6) indicates that aluminum bonding may be used as a unifying explanation of soil colloidal behavior.

Clay suspensions, as ionic solutions, cannot exist with a net electrical charge; therefore, charged particles must be balanced by counter-ions or adsorbed ions. Counter-ions associated with clay particles may be replaced or exchanged by other ions in solution. Thus, charges on clay particles may be measured by the number of exchangeable cations associated with the clay. This ion replacement phenomenon is referred to as cation exchange capacity (CEC) of clay. Cation exchange capacities of various clay minerals are quite different; however, the CEC of any particular clay may vary as a result of several factors. Some of these factors controlling CEC are: particle size, temperature, exchangeable cations present, concentration of exchanging ion, and pH.

Cation exchange capacity of clay fractions usually increases rapidly with decrease in particle size. Ormsby et al (Ref 7) found that surface area of clay fractions was more critical in affecting CEC than crystallinity perfection of clay minerals comprising the clay particles.

Temperature has been found to have varied effects on CEC of clay minerals. Effects depend upon clay minerals and exchanging ions used during a particular experiment. Generally, however, temperature has been found to have very little effect on CEC.

Research in the area of cation exchange of clays provided evidence that no single, universal, replaceable ion series exists. A series of ions which will replace other ions most easily varies, depending upon experimental conditions, cations involved in exchange, and clay minerals used in the experiment (Ref 8). Jenny and Ayers (Ref 9) produced conclusive results which indicate the replacability of an ion depends not only upon the nature of the ion itself but also on the nature of complementary ions filling other exchange positions and the degree to which the exchange ion saturated available exchange positions.

Concentration of exchangeable ions in solution is constantly found to reappear as a major factor controlling ion adsorption and exchange equilibria in clays (Refs 10, 11, and 12). In general, increased concentration of replacing cation causes greater exchange by that ion. This is to be expected since CEC is a stoichiometric reaction which requires that laws of mass action be upheld.

Effects of pH on CEC of clays were studied in detail by Lunin and Batchelder (Ref 13). Their results indicate that $Na^+$-$Ca^{++}$ adsorption ratios increase with a decrease in pH of soils. It has been shown that soils with pH 5 and above have very little acidity exchangeable with neutral salts. That is, soils of pH 5 and above are essentially saturated with cations: $Ca^{++}$, $Mg^{++}$, $Na^+$, and $K^+$. However, increase in adsorption of these ions as a result of increase in CEC occurs with an increase in pH of the system (Ref 14). Pratt et al (Ref 15) found that experimentally determined adsorption ratios compared very closely with theoretically obtained values, provided surface charge correction factors were used for various soils. However, they found that correction factors used for particular clays remained constant for all pH conditions.

The ionic atmosphere or diffused double layer, which is composed of counter-ions balancing particle charges, is greatly influential in physico-chemical behavior of clay soils. Without demanding acceptance of either the Gouy Theory or Stern-Gouy Theory of the diffuse double layer, the basic concepts of behavior are discussed below.

Ions of both positive and negative charge exist in the double layer. Counter-ions are usually considered to be adsorbed to particles. Ions of the same charge as the clay particle are said to be negatively adsorbed to the clay. The double layer exists as a result of a force equilibrium system. Counter-ions are attracted to particles by electrostatic forces, and they are held away by osmotic forces of dispersion. Negatively adsorbed ions are repelled by particle charges, but held by Van der Waal forces. Thus, concentration of counter-ions decreases as distance from the particle is increased; whereas, negatively adsorbed ions increase in concentration as distance from the particle is increased.

Among the most important phenomena in soil colloidal chemistry are flocculation and deflocculation or dispersion. Since each is the reverse of the other, mechanisms which control are equally applicable to either phenomenon. Thus, only flocculation will be discussed here. In a stable condition, particles in suspension are in constant motion as a result of Brownian movement. Colliding particles are quickly repelled by electrical repulsion forces which greatly overpower very weak Van der Waal forces of attraction. Upon addition of an electrolyte to the solution, particles begin remaining together after collision. As more particles agglomerate and the force of gravity overcomes Brownian motion, flocculation occurs. Rate of flocculation is obviously dependent upon electrolyte concentration. Thus electrolytes must affect the double layers of clay particles; and in fact, double layers are compressed upon addition of an electrolyte to the suspension. Compression of particle double layers is dependent upon the surface charge and surface potential of the clay particles.

Effects of an electrolyte on surface potential and surface charge of clay particles depend on the type of existing double layer. If surface potential is derived from potential-determined ions or specific adsorption, surface potential is not affected by the electrolyte; however, surface charge increases, thus causing compression of the double layer. Particles which have surface charge as a result of interior lattice imperfections or isomorphic substitution undergo no change in surface charge with addition of an electrolyte; however surface potential decreases, causing a compression of the double layer.

Whitney and Peech (Ref 16) found that ion activity does not cease with cation saturation. Contrary to expectation, both activity of dissociated $Na^+$ and apparent degree of dissociation of Na-Clay increase with increasing NaCl concentration. Since no additional $Na^+$ is taken up by the clay upon addition of NaCl, increases in activity of dissociated $Na^+$ must result from a decrease in ionic atmosphere thickness around clay particles.

Mattson (Ref 17) explained variation in thickness of double layers of clay very well by comparing the micelle (clay particle and double layer) to a living organism. Because the micelle strives to maintain a definite osmotic pressure within the double layer, micelles swell in dilute solutions and shrink in concentrated solutions. This phenomenon is the same as that found for proteins and spores. Thus, flocculation and deflocculation depend upon osmotic pressures of dispersion which are controlled or influenced by electrolyte concentration of the solution.

With a basic knowledge of mechanisms controlling soil colloidal behavior and some insight as to how chemicals and ions affect clay behavior, chemical treatment of cohesive soils will be thoroughly discussed in following sections of this chapter.

## Lime Treatment

Treatment of cohesive soils with lime, either in oxide or hydrated form, has become one of the most widely used and accepted forms of chemical treatment. Although this treatment is very popular, lime-soil reactions are probably among the least understood phenomena in modern soils engineering and research.

Discussions concerning lime treatment should be divided into two distinct divisions, depending upon quantity of lime additive being used with soil. The two subdivisions of lime treatment are lime modification and lime stabilization.

Modification of cohesive soils by addition of lime usually requires small percentages. Physical properties or consistency limits of clays are affected by modification with very little strength gain attributable to addition of the lime.

Lime stabilization is the addition of lime to clay soils to obtain substantial strength gains. Thus, stabilization of cohesive soils requires greater percentages of lime than does modification.

Lime treatment is usually discussed in literature as lime stabilization alone with no distinction between the two phases of modification and stabilization. It should be obvious that mechanisms which control modification are not necessarily, and most probably are not, those which control stabilization. However, at least four mechanisms are usually found in literature which are used to explain lime treatment as one phenomenon rather than two distinct reactions. These four mechanisms are: cation exchange, flocculation, carbonation, and pozzolanic reaction. Diamond and Kinter (Ref 18) attempted to show that the first three of these mechanisms offer inadequate explanations for reactions occurring during lime treatment. This is true if lime treatment effects are not considered as two distinct phenomena. However, arguments offered to disclaim these three phenomena are contested here on the basis that phenomena controlling modification may or may not control stabilization reactions.

Cation exchange as a possible mechanism for lime-soil reactions was discounted on the basis of misunderstanding a previously discussed concept in soil chemistry. Many $Ca^{++}$ saturated clays have been found to be very reactive to lime treatment; however, it has been shown that ion activity does not cease with saturation since CEC increases with concentration and with increase in pH of the system. Since lime treatment does increase $Ca^{++}$ concentration and pH of the system, it is obvious that cation exchange must take place and cannot be discounted as a mechanism controlling lime treatment.

Flocculation was discredited by a similar hypothesis. It is well known that high sesquioxide, reddish and yellowish soils of the southern United States exist in a flocculated state in nature. It is also known that these soils are susceptible to lime treatment. Although it must be agreed that flocculation is certainly not solely responsible for lime-soil reactions; presence of a more nearly compressed ionic atmosphere around clay particles, which may be obtained even in flocculated suspensions, in conjunction with other reaction mechanisms could certainly be influential in lime treatment, especially lime modification (Ref 19).

Reaction of lime with carbon dioxide from the atmosphere to form calcium carbonate, a cementitious compound, does occur during lime treatment of soils in the field (Ref 20). However, it is very doubtful that strength gains obtained during lime stabilization could be derived from carbonation alone. Laboratory research has shown that lime-treated soil samples obtained high strengths during stabilization even when completely sealed to prevent carbonation (Refs 21, 22). Thus, although carbonation does occur, it is unlikely that this factor contributes much to stabilization of clays with lime admixtures.

The final mechanism to be discussed is one which seems to be most favorably accounted for in current literature. This mechanism involves pozzolanic reactions between the clay particles and lime. It is well known that materials low in natural pozzolan content react poorly to lime stabilization; however, addition of Fly Ash, a natural pozzolan, greatly enhances lime stabilization of these materials (Refs 23, 24, 25). Although this fact is recognized, it appears strange that the same pozzolanic reactions which contribute to high strength gains during stabilization affect only the physical properties or consistency limits of the soil to any appreciable amount during modification.

In order to support the lime modification-stabilization idea, the following discussion is concerned with phenomena which occur as lime content is increased in a cohesive soil. The lime will be considered to be mixed with the soil in the presence of moisture required to obtain desired densities during compaction of soil-lime mixtures.

As small percentages of lime are added to plastic soils, the material becomes friable and attains a silty texture upon curing. These phenomena occur rapidly and may be attributed to one of two phenomena or a combination of both. The first involves the cation exchange reactions which occur as $Ca^{++}$ replaces exchangeable ions such as $Na^+$, $H^+$, and $K^+$ which exist on clay particle surfaces. The second phenomenon involves compression of double layers of clay particles or "ion crowding" as it is sometimes called. This reaction occurs as a result of increased pH of the system and an increased concentration of $Ca^{++}$ made possible by addition of lime (Ref 26).

The result of these two phenomena is a reduction in plasticity of the treated cohesive soil. Although plasticity is usually indicated by the plasticity index (PI), a reduction in this value may not always be indicative of behavior. For instance, the liquid limit may be substantially increased by addition of lime, but a simultaneous increase in the plastic limit will be sufficient to cause a reduction in PI. On the other hand, lime treatment may cause a reduction of the liquid limit with very little effect on the plastic limit, thus reducing the PI. Some conflicting opinions exist regarding effects of lime treatment on the liquid limit of clays. This is to be expected since it has been found that the liquid limit of the soil is more sensitive to cations present in clay than the plastic limit (Grim, 1963).

As lime content is gradually increased, plasticity of the clay is sharply reduced, and pH of the soil-lime mixture increases rapidly. The lime content at which the plasticity becomes zero and the pH approaches 12.4 has been termed the "lime fixation point" by some authors (Ref 27). At this lime percentage, maximum compression of the ionic atmosphere and all cation-exchange reactions have occurred since there is no further change in pH of the system and the soil has become supersaturated with $Ca^{++}$. Since this point or lime percentage represents maximum modification conditions, the term "modification optimum" will be used to refer to this lime percentage throughout the remainder of this publication. Although small strength gains are obtained with lime contents below and at modification optimum, these gains are most probably related to aggregation of clay particles and increased angle of internal friction of the cohesive soil rather than formation of new minerals by pozzolanic reactions.

Addition of lime percentages in excess of modification optimum provides free calcium ions, which are available for reaction with amorphous silica and alumina to form new minerals. Presence of amorphous materials, often termed "gunk", has been found to be necessary for good lime reactivity. Reactivity of cohesive soils to lime stabilization varies directly with abundance of gunk in the clay fraction (Ref 28). Calcium combines with the aluminum hydroxyl groups to form tetracalcium aluminate hydrates which produce quick, low strength, cementing bonds within the treated soil. These compounds are considered to be gelatinous and poorly structurally ordered, thus they can contribute little to strength gains. Higher, long-term strength gains are obtained by formation of tobermonite minerals. These minerals are strongly bonded hydrates of calcium and silica. Their formation is thought to be through a gradual crystallization of new minerals species from gelatinous reaction products (Ref 29). Formation of these tobermonites such as calcium silicate hydrate by pozzolanic reaction has been found to be greatly enhanced by high pH conditions. This is a direct result of the effect of pH on solubility of amorphous silica required for formation of tobermonites. A pH in excess of ten increases the solubility of quartz, thus acting as a catalyst for new mineral formation by pozzolanic reactions (Eades, et al, 1962).

Many factors exist which affect behavior of lime-treated cohesive soils. The presence of particular cations in soil has been shown to be influential during lime modification; however, since stabilization depends upon formation of new minerals from hydrates of silica and alumina, it seems reasonable to suspect that the silica-sesquioxide ratio of treated soils may be very important in lime stabilization. Influence of this ratio on chemical behavior of cohesive soils has been discussed previously. The susceptibility of clays to lime stabilization may be dependent upon the silica-sesquioxide ratio. This is evidenced by the fact that most lateritic soils, having low silica-sesquioxide ratios, react very poorly to lime stabilization.

In an attempt to obtain more desirable results from lime treatment, many additives have been used in conjunction with lime. Sodium additives constitute a major portion of these chemical compounds. Prior to discussing use of sodium chloride as a chemical additive in conjunction with lime treatment, a brief discussion of the stabilizing effects of sodium chloride alone is offered. Through discussions of both lime treatment and sodium chloride treatment, considering basic knowledge of important soil chemistry concepts, some prediction of phenomena which will occur upon addition of sodium chloride-lime admixtures to cohesive soils may be made.

## Sodium Chloride Treatment

Use of sodium chloride in stabilization of road aggregate mixtures is certainly not a new technique in highway soils engineering. It has been reported by some historians that sodium chloride was used in construction of Macadam-type Roman roads after accidental discovery of stabilization effects. Sodium chloride found extensive use as a stabilizer in road building in the United States shortly after 1900.

Although sodium chloride has been used extensively throughout the United States in construction of secondary roads, it has always been used in stabilization of soil-aggregate mixtures, i.e., select gravel base materials with good clay binder. Sheeler (Ref 30), in reporting on use of salt for stabilization of soil-aggregate mixture roads throughout Iowa, indicates that roads constructed by salt stabilization wear longer without deterioration, have smoother riding surfaces, and are freer from dust than roads built of comparable untreated mixtures.

Sodium chloride has been used in primary road systems for stabilization of base course aggregates. Moinfort (Ref 31) reported results of salt stabilization in Michigan highway test sections. Soil-aggregate mixtures used varied in clay fraction content from slight up to 12 percent. Data obtained indicated that optimum moisture contents were reduced with accompanying increases in densities in treated sections, particularly in sections containing mixtures with high fine-soil-fraction contents. Subgrade moisture variations remained relatively constant in treated sections after an initial moisture loss which occurred during the first year. Salt contents of the stabilized base course material were found to decrease appreciably in low clay content sections. However, in sections containing relatively high percentages of clay in the treated mixture, salt contents were found to level off at contents of from two to five percent by dry weight.

Crystallization has been offered as an explanation for behavior of sodium chloride stabilized soil-aggregate mixtures. It is claimed that recrystallization of salt from solution after mixing plugs the voids of the mixture, thus retarding evaporation of pore water and preventing shrinkage. Recrystallization of salt has also been said to act as a cementing bond within the treated mixture and provide a hard traffic surface as the result of formation of a crust on stabilized material (Ref 32). Although it may be possible for recrystallization to occur in some of the larger voids in open graded soil-aggregate mixtures, it seems improbable that this process occurs in clay fractions. It has been shown that clay content definitely affects stabilization results, thus salt-clay reactions must occur during treatment of soil-aggregate mixtures.

Importance of salt-clay reactions has long been realized in soil sciences associated with agriculture. A great deal of work has been done in this area of adsorption of salt ions by clay particles (Refs 33, 34, 35).

Effects of sodium chloride treatment on consistency limits of clay size fractions of soil-aggregate mixtures were reported by Makley and Sheeler (Ref 36). Their data indicates that salt contents of 0.5 percent to 3.0 percent by total weight cause reduction of PI as a result of both a reduction of liquid limit and an increase in plastic limit of binder clay. Although only 0.5 percent sodium chloride, by dry weight of the total mix, was used in treatment, this represented a salt content of 2.9 percent by dry weight of the minus 40, silt-clay fraction of the mixture. Therefore, the small percentage added to the soil-aggregate mixture must have affected the consistency limits and physical properties of the clay binder material.

Importance of sodium chloride effects on clay fractions of soil-aggregate mixtures was emphasized in an excellent recent review of literature on salt stabilization. Thornburn and Mura (Ref 37) state that there is a general agreement on effects of salt stabilization; however, there seems to be very little agreement on mechanisms producing these effects. Since it is very doubtful that sodium chloride reacts with or affects the properties of rock aggregates in soil-aggregate mixture, both physical and chemical phenomena which occur during salt stabilization must be results of salt-clay reactions. Thus, a thorough understanding of salt-clay reactions must be attained before salt treatment can be employed most effectively.

Flocculation has often been used to explain phenomena which occur upon treatment of soils with sodium chloride. Although it has been shown that flocculation and deflocculation may change soil properties very rapidly, even after construction of earth structures (Ref 38), it is doubtful, as in lime treatment, that double layer compression occurring during flocculation is the only mechanism controlling clay-sodium chloride reactions.

Sodium chloride has been reported to affect the liquid limit of highly plastic smectitic clay (Ref 39). The liquid limit, which is sensitive to cation exchange, was found to be reduced by addition of salt. Although the liquid limit was reduced, the plastic limit was affected so minutely that the soil was not reduced in plasticity (PI) sufficiently to change its Unified Classification from that of a CH material. The shrinkage limit was found to increase initially upon addition of salt, but to decrease at higher salt percentages.

Sodium chloride treatment of soil-aggregate mixtures and clay soils should not be viewed in any light that is not cast upon other forms of chemical treatment. Physico-chemical reactions controlling salt treatment, as lime treatment, must involve those particles capable of reacting chemically. These particles include clay fractions of all soil materials.

Lime treatment and sodium chloride stabilization of cohesive soils and soil-aggregate mixtures have been reviewed in previous sections in order to provide a basis for a more hypothetical and less researched area of chemical treatment of soils. The following section is devoted to treatment of soils with sodium chloride-lime admixtures.

## Sodium Chloride-Lime Treatment

Lime treatment of cohesive soils produces relatively low early strength gains even though long-term strength gains may be quite high. This phenomenon presents the problem of finding an economical procedure by which soil-lime pozzolanic reactions governing strength gains during stabilization may be accelerated to produce more desirable early strength gains.

Effects of chemical additives such as sodium chloride on soil-lime reactions may be grouped into one or more of the following catagories: acceleration of pozzolanic reactions, production of new cementitous minerals, or combination with pozzolanic cementitious products.

The first category is of a catalytic nature and would be the reaction most expected to occur between sodium chloride, lime and clay. Since it has been found that solubility of quartz or silica is greatly increased in the presence of very low normality solutions of sodium chloride (Ref 40), it would be expected that more readily available silica would greatly accelerate pozzolanic reactions.

The second phenomenon would require that sodium chloride react chemically with natural pozzolans in soils or with lime to form new minerals which would provide a cementing bond of the clay matrix. At the present no evidence exists that these reactions occur; however, there is no chemical reason that necessary reactions between salt and clay or salt and lime-clay particles could not occur.

Modification of existing minerals formed pozzolanically by presence of sodium chloride may very well be the mechanism which occurs during treatment of cohesive soils with salt-lime admixtures. In this case normally formed tobermonites would be altered by incorporation of ions of sodium chloride. These minerals may grow more rapidly and produce greater cementing bonds to clay particles.

Research conducted by Mateos and Davidson (Ref 41) indicates that addition of sodium chloride to lime-fly ash soil mixtures did increase immersed compression strength of the treated soil. They also found that best results were obtained from sandy clay soils, with benefits of sodium chloride addition decreasing with increased clay content of treated soils.

Moh (Ref 42) found through his research that regardless of anions associated with added sodium compounds, effects on treated samples were: an increase in pH, a reduction in calcium ion concentration, and an increase in the sodium-calcium ratio in solution. Results of these effects were: an increased rate and extent of solubility of soil silica, retardation of calcium silicate gel precipitation, and formation of highly hydrated silicate gels containing sodium in substantial quantities. These pehnomena provided an increased volume and wider distribution of cementitious gels which definitely improved the stabilization effect of the soil treatment.

Although research in this area of chemical treatment has been relatively inactive, it appears that addition of sodium chloride would provide an economical means of accelerating and improving the stabilization effects of lime treatment on cohesive soils.

# CHAPTER III

# MATERIALS AND SAMPLE PREPARATION

## Introduction

This chapter provides background information concerning cohesive soils selected and sample preparation procedures employed throughout the associated research. Physical characteristics and geological origins of soils selected will receive detailed discussion, since some of these factors may be vital in understanding reactivity of the soils to chemical treatment. Preparation procedures used for both raw soils and chemically treated soil mixtures definitely affected results obtained from tests conducted.

Standardized procedures were established for use throughout the study in order to produce samples as nearly uniform as possible. Thus, variation in tests results from nonuniformity of prepared soil mixtures was minimized. Establishment of sample preparation procedures also allowed more nearly efficient material usage and test scheduling.

## Materials

For preliminary testing and establishment of research procedures, a cohesive soil which was abundant and readily accessible was used. This soil is a material of medium plasticity, obtained from the Permian deposits of Oklahoma. These marine deposits are the dominant geological formation of central Oklahoma. The formation has a distinctive red color from its high iron oxide content, and is commonly termed the Permian Red Beds. The red beds are composed partially of Permian Red Clay (PRC) which overlies soft, variable red clay shale. This heavily overconsolidated, dessicated clay outcrops in and around Stillwater, Oklahoma, and has a relatively gentle dip to the southwest. Both the clay and clay shale have moderately high volume change characteristics, associated with variations in moisture content. PRC used throughout the study was obtained from the excavation for a new fine arts building being constructed on the campus of Oklahoma State University at Stillwater. The clay was obtained from a depth of approximately ten feet below the existing surface in the southeast corner of the main excavation.

The second cohesive soil was selected after procedures and preliminary testing had been well established and advanced with PRC. The material was selected because of its difference in physical characteristics and geographical origin from that of the previously selected PRC. The second material was a highly plastic clay obtained from Roger Mills County, in western Oklahoma. The clay has a distinctive steel gray color, resulting from absence of high percentages of iron oxides, thus the material was named Roger Mills Gray Clay (RMGC). RMGC used throughout the study was obtained from a depth of approximately three feet below the surface on private land located seven miles west of Rollo, Oklahoma.

Index properties of both PRC and RMGC are presented in Table 3.1. As may be seen the two materials have quite different physical characteristics. Texture of the two cohesive soils also varies quite noticeably, although the same processing procedure was used for both soils. PRC contains much lower percentages of the coarse clay fraction than does RMGC; conversely, RMGC contains much lower percentages of the fine clay fraction. Grain size distribution curves for both PRC and RMGC are shown in Fig 3.1 for comparative purposes.

| Properties | PRC | RMGC |
|---|---|---|
| Specific Gravity | 2.72 | 2.73 |
| Liquid Limit | 38.6 | 60.5 |
| Plastic Limit | 17.6 | 29.8 |
| Plasticity Index | 21.0 | 30.7 |
| Flow Index | 3.0 | 7.7 |
| Toughness Index | 7.0 | 4.0 |
| Liquidity Index | --- | 0.33 |
| Lineal Shrinkage | 12.0% | 17.8% |

Table 3.1. Index Properties of PRC and RMGC

Quicklime or calcium oxide was used for lime treatment of the cohesive soils throughout the study. The lime was produced and supplied by St. Clair Lime Company Sallisaw, Oklahoma. The chemical composition of the pelletized quicklime is given in Table 3.2. Limestone found in this area of Oklahoma is of such quality that pelletized quicklime may be easily produced, thus calcium oxide receives much use for lime treatment throughout Oklahoma. Quicklime used was of very fine texture. Before mixing with soil the calcium oxide was passed through a U.S. No. 40 sieve to insure that no large carbonated fractions were added to the soil mixture. Carbonation of the quicklime as a result of contact with carbon dioxide in the atmosphere was never found to produce serious problems, since the calcium oxide was kept in tightly sealed containers until used.

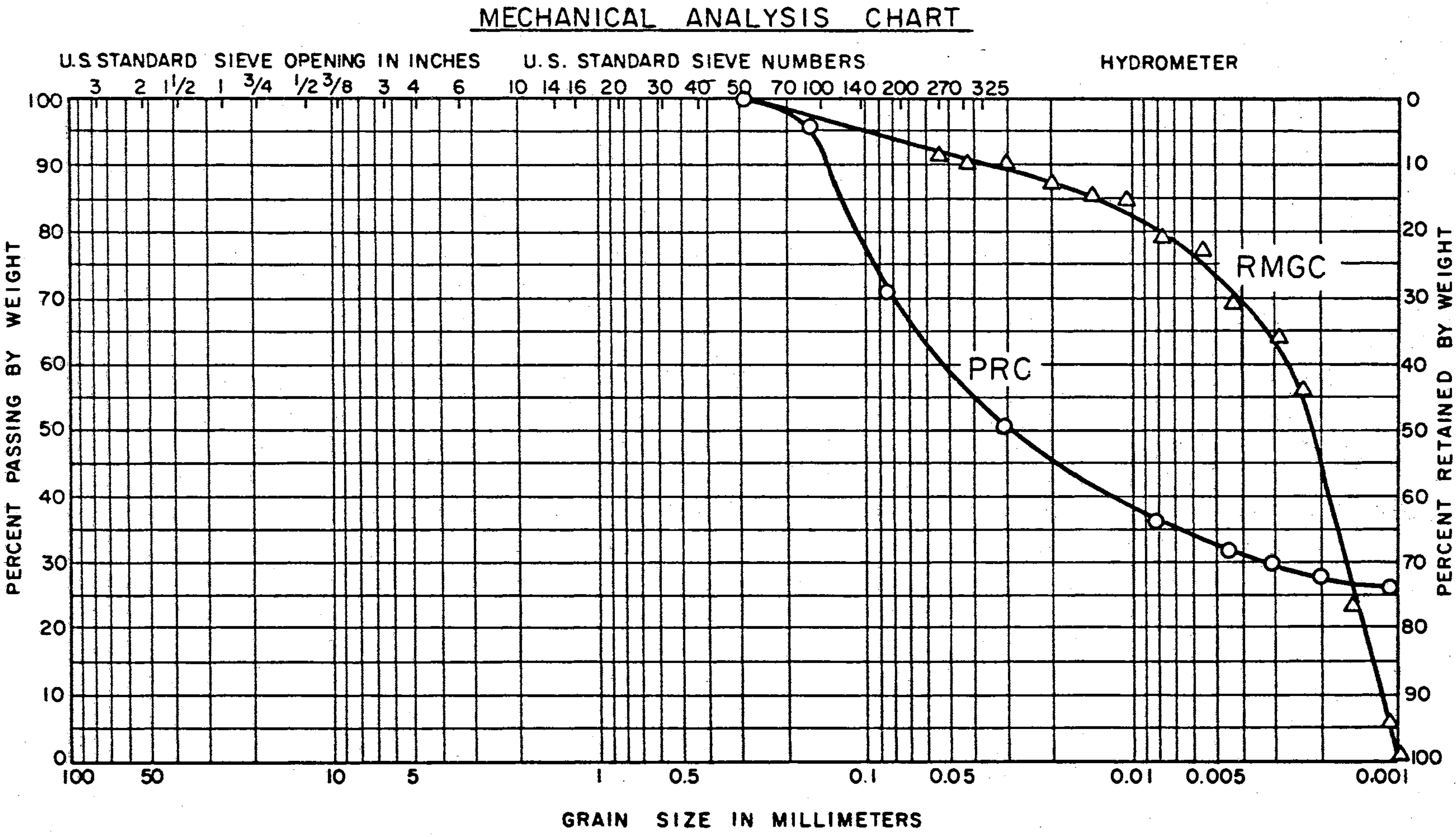


Figure 3.1. Grain Size Distribution Curves for PRC and RMGC

| Constituents | Percent by Weight |
|---|---|
| Calcium Oxide | 97.50 |
| Magnesium Oxide | 0.50 |
| Aluminum Oxide | 0.15 |
| Silica Dioxide | 0.20 |
| Iron | 0.30 |
| Sulfur | 0.01 - 0.008 |
| Arsenic | Trace |
| Phosphorous | Trace |

Table 3.2. Chemical Composition of Quicklime Used for Lime Treatment

Sodium chloride used as a chemical additive throughout the study was non-iodized commercial grade rather than reagent grade. Since field application of any results obtained from the research would most probably involve the use of rock salt, it was felt that commercial grade salt would more nearly represent results obtainable from the use of rock salt than would reagent grade sodium chloride. Sodium chloride used was of medium texture and very poorly graded. Ten percent was retained on the U.S. No. 40 sieve with ninety percent retained on the U.S. No. 80 sieve. The salt contained at least 99.5 percent sodium chloride.

## Sample Preparation

Between fifteen hundred and two thousand pounds of each of the two soils were obtained at their respective natural moisture contents. The raw soil had to be processed before it could be used in the study. Processing of raw soils included drying, grinding, sieving, and storing. Upon delivery of the two clays in their natural condition, processing was begun by drying the materials. A large aggregate oven was used to dry the soils at 100° centigrade for twenty-four hours. Large clods of dry clay had to be reduced in size before the grinding stage of soil processing could begin. Dried material was placed in the Los Angeles Abrasion Apparatus for reduction of large, hard clods. Small fragments of the clods and all loose soil were removed from the tumbler ready for grinding. Continued processing required that all dry material be passed through a Model 4E Straub laboratory mill. The grinder was adjusted to produce soil particles passing the U.S. No. 40 sieve. As material came through the grinder it was checked frequently by sieving small samples of the soil. Upon completion of the grinding phase it was estimated that not less than 98 percent of the processed soil would pass the U.S. No. 40 sieve. Processed soils, totalling approximately one thousand to fifteen hundred pounds for each type, were stored in thirty gallon galvanized steel trash cans.

In the preparation of all soil mixtures for testing and in the production of samples, a standard mixing and curing procedure was adopted. The procedure was found to produce mixtures with more nearly constant moisture contents and better workability than any other procedure tried. In order to produce a desired soil mixture, dry soil of sufficient quantity was necessary for tests or sample production was weighed into shallow, large-area mixing pans to the nearest 0.1 gram. Chemical additives required to produce desired soil mixtures were expressed as percentages of dry soil weight. Chemical additives were weighed to the nearest 0.1 gram and added to the soil in dry form. Soil and additives were thoroughly mixed in the dry state for several minutes to produce a well blended mixture. Soil mixtures were leveled off in the shallow pans after blending, ready for addition of required moisture. Desired moisture contents were obtained by sprinkling the entire sample surface evenly with water. In tests where predetermined moisture contents were unknown or sought as test results, sufficient water was added to soil mixtures to produce a moisture content near the plastic limit of the mixtures. Mixtures were not blended immediately after addition of water but were sealed and allowed to cure for eight to twelve hours at room temperature. The curing period allowed moisture to migrate evenly and naturally through the soil mixture, as well as allowing ample time for reactions between soil and chemical additives to occur, before testing began. At the end of the curing period desired moisture contents were checked by total sample weight. If additional moisture was required, water was added prior to thorough mixing of soil mixtures in the moist condition. Blending in the moist condition was done by hand as quickly as possible to prevent moisture loss. Mechanical mixing of moist samples was found to result in severe moisture loss. After blending, moist mixtures were again sealed to prevent moisture loss during testing or manipulation.

# CHAPTER IV

# EFFECTS OF CHEMICAL TREATMENT ON SOIL PHYSICAL PROPERTIES

## Introduction

The purpose of this chapter is to present data and associated discussions concerning effects of various chemical additives on physical properties of selected soils. Properties include consistency limits, linear shrinkage, and moisture retention characteristics.

Atterberg limits are used as index properties for classification of soils. Certain behavioral characteristics have been associated with soils having Atterberg limits that fall within certain ranges. However, only general indications should be drawn from these limits, since consistency limits of clays are greatly affected by their composition and chemical environment. Atterberg limits which receive most usage in engineering include the liquid limit, plastic limit, and shrinkage limit. These limits are expressed as percentage of moisture by dry weight of soil, commonly referred to as engineering moisture content.

Linear shrinkage is the amount of shrinkage which actually occurs as soil is air-dried from a moisture content above the liquid limit to a moisture content equal to or less than the shrinkage limit. Linear shrinkage is usually represented as a percentage of the original wet sample length.

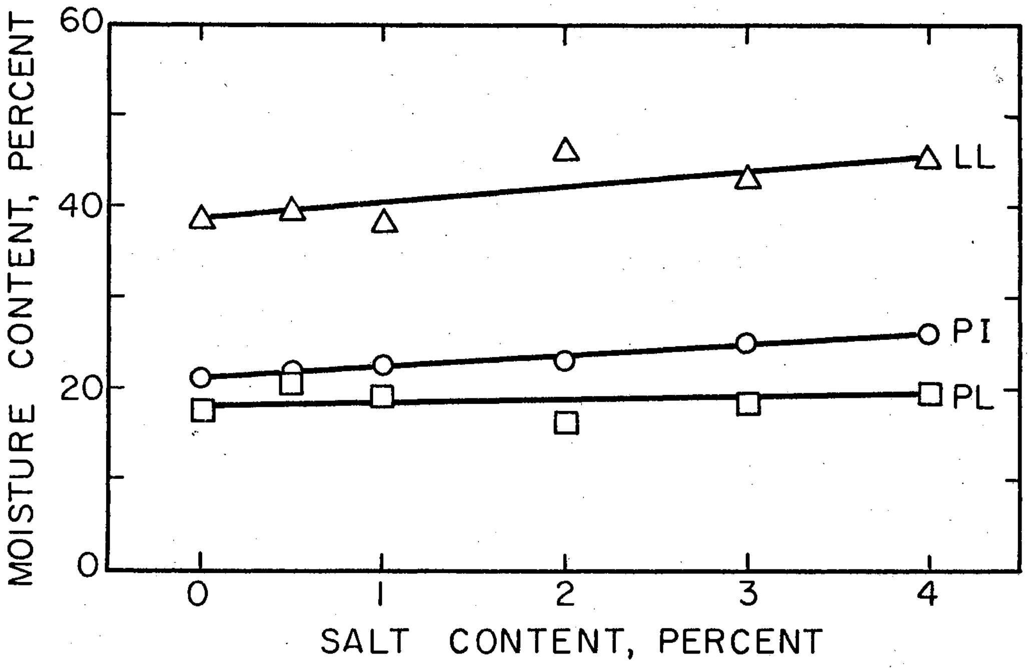
Soil moisture content control is an important factor both during and after construction. Since many engineering properties of soil are also moisture dependent, proper moisture control affects performance of engineering works. Moisture loss during manipulation of fill materials prior to compaction may produce characteristics completely different from those desired or expected. Post-construction moisture changes or variations are the direct cause of failure in many types of foundations, particularly highway subgrades.

## Atterberg Limits

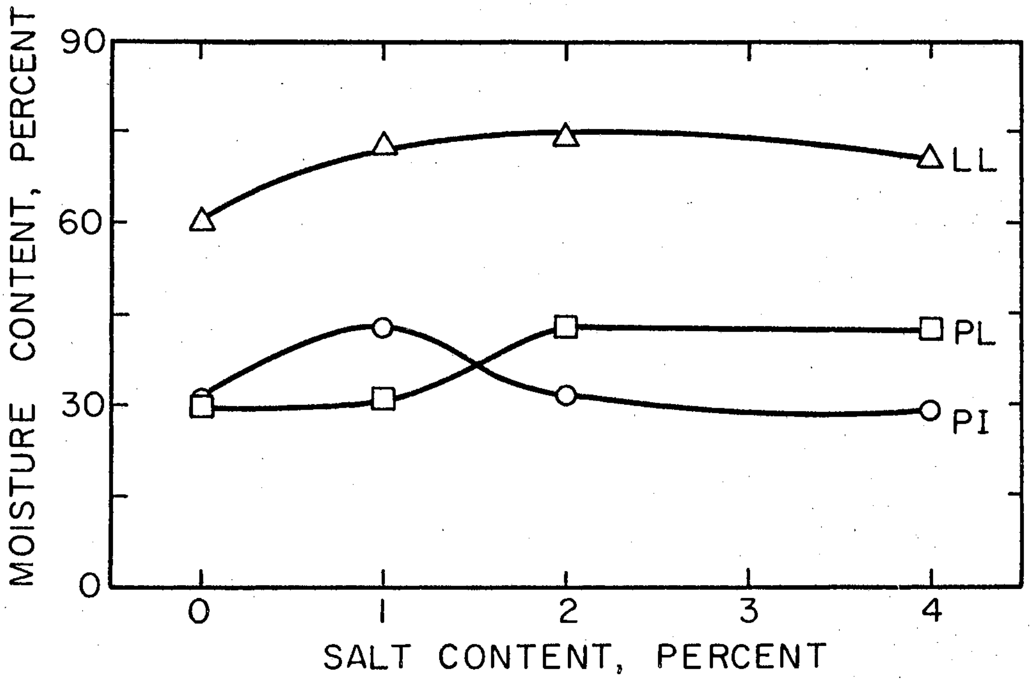
Soil mixtures to be used for determination of liquid and plastic limits were prepared by the adopted standard procedure. This fact is emphasized since curing time after addition of chemical additives to soils has a distinct effect on consistency limit values obtained, particularly within the first few hours of curing. Thus, data presented throughout this section represent those obtained after the specified curing time adopted in the standard mixture preparation technique.

Liquid limit tests were conducted according to ASTM D 423-66, whereas plastic limit tests and plasticity index determinations complied with ASTM D 424-59(65) (Ref 45).

Effect of sodium chloride treatment on Atterberg limits of both soils was generally the same; however, response was more pronounced for RMGC than for PRC. Increased percentages of salt produced corresponding increases in liquid limits of both soils. Liquid limit values of PRC were found to increase gradually and constantly with increasing salt content. However, RMGC liquid limits increased abruptly with addition of very low salt percentages, and little change occurred with increasing sodium chloride percentages. Plastic limits were affected in much the same manner as were liquid limits upon addition of increasing percentages of salt. Although a slight increase in PRC plastic limits was observed, salt was found to produce more noticeable effects on RMGC plastic limits. RMGC plastic limit values approached a maximum value with the addition of one percent sodium chloride. Increasing salt contents reduced plastic limit values of salt treated RMGC to that obtained from raw RMGC. Once this reduction occurred, no other changes were obtained in plastic limit values by adding higher percentages of salt. Simultaneous increases in both liquid and plastic limits of both soils were such that resulting plasticity indices (PI) were found to be generally increased. As a result of slight and gradually increasing Atterberg limits, the PI of PRC was found to increase only slightly with increasing salt content. PRC had a maximum PI increase of 4.0 at a salt content of four percent, compared to a PI increase of 14.0 for RMGC at the same salt content. Although the increase in PI for RMGC was significantly large at four percent salt content, it was found that RMGC PI values at low salt contents were only slightly changed, as was also found for PRC. From these data it would appear that salt contents below two percent affect the PI of these soils very little, even though the Atterberg limits of RMGC undergo considerable change at low salt contents. Effects of sodium chloride treatment on Atterberg limits and plasticity indices of PRC and RMGC are illustrated in Figs 4.1a and 4.1b respectively, by curves which express moisture content as a function of salt content. From observed differences in behavior of these two soils to sodium chloride treatment, it appears that chemical composition and associated chemistry have a



(a) Behavior of PRC Mixtures

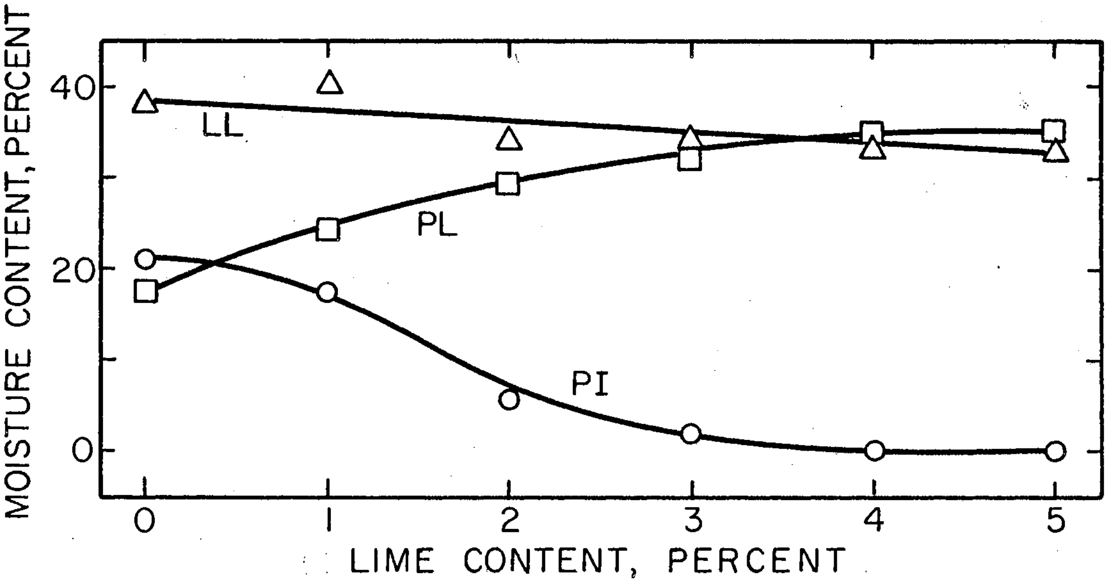


(b) Behavior of RMGC Mixtures

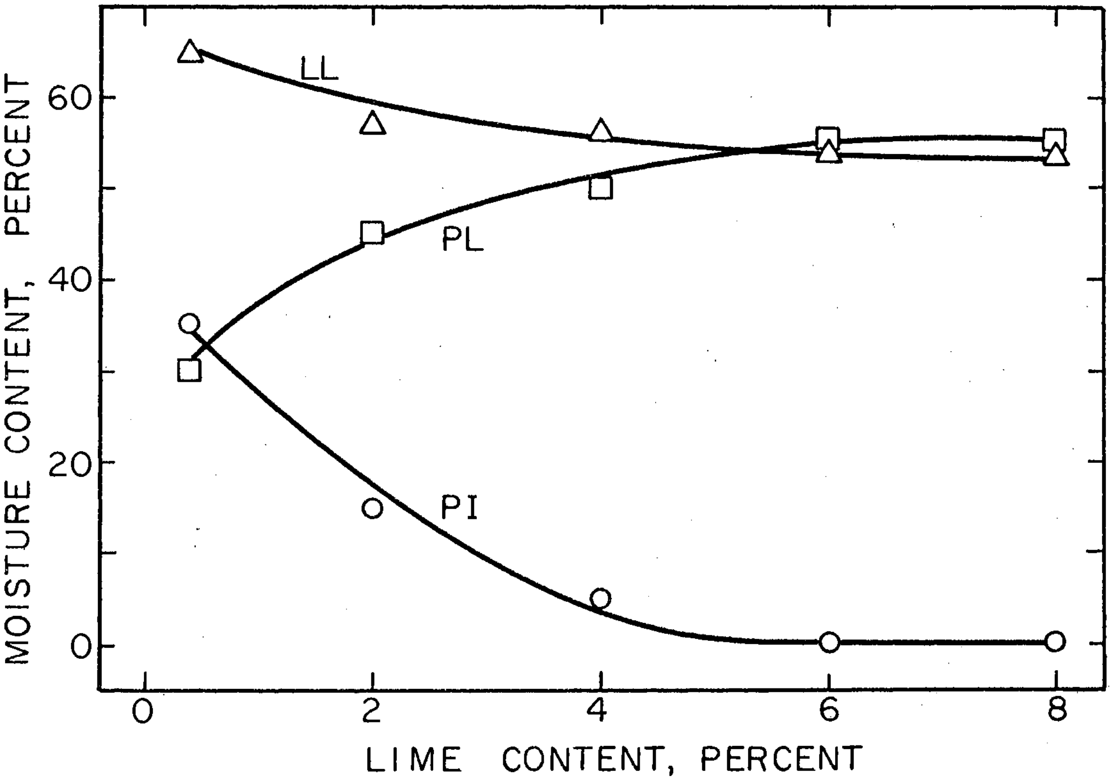
Figure 4.1. Effect of Salt Treatment on Atterberg Limits

definite effect on consistency of chemically treated soils. PRC, high in sesquioxide content, shows little response to salt treatment while RMGC, which has a much lower sesquioxide content, is more reactive to sodium chloride treatment. This phenomenon is reasonable, since the addition of a neutral salt would have little effect on high valence ions associated with high sesquioxide clay, whereas monovalent sodium ions may be readily adsorbed or replace ions associated with low sesquioxide content RMGC. Also of particular interest is the fact that responses of RMGC Atterberg limits were abrupt and occurred at low salt contents, while increasing percentages of sodium chloride produced only minor changes. This behavior would indicate that sodium ions were immediately adsorbed by RMGC, filling exchange positions or compressing double layers. Once all the exchange positions were filled and double water layers compressed, addition of more salt had very little influence on clay behavior.

Addition of calcium oxide to both soils had the same general effects on their Atterberg limits and plasticity indices. Liquid limits of PRC and RMGC were found to be reduced with addition of increasing lime percentages. Thus the effect of calcium oxide on liquid limit values of both soils is opposite to that obtained by addition of sodium chloride. This phenomenon is in agreement with the fact that liquid limits of soils are affected by cations associated with clay particles (Ref 23). In the case of salt treatment and lime treatment both soils reacted in similar manner; however, alteration of the chemical additive produced opposing effects on liquid limits values of both materials. Reduction of liquid limits obtained by addition of lime was similar for both materials. PRC liquid limit values were reduced by 6.0% while RMGC had a liquid limit reduction of 10.0%. Reductions were obtained at relatively constant rates for both materials, up to a lime content of 4.0% for PRC and 6.0% for RMGC. Above these lime contents very little additional change in the liquid limits of either soil was obtained by increasing lime content. Plastic limits of PRC and RMGC increased sharply with increasing lime percentages. Increase in plastic limits and reduction in liquid limits for both soils were found to be relatively the same. As found for liquid limit changes, maximum plastic limit values obtained required the addition of more lime for RMGC than for PRC. At a lime content of 4.0% PRC obtained a maximum plastic limit increase of 17.0%, whereas at 6.0% lime RMGC obtained a maximum gain of 25.0%. Plasticity indices of both soils were found to decrease rapidly by addition of increasing lime contents. Reduction in PI was very abrupt, as a result of decreasing liquid limits and increasing plastic limits. PRC was found to have a PI of zero at 4.0% calcium oxide whereas RMGC required 6.0% to reduce its plasticity to zero. Thus, as previously defined, modification optimum for PRC is 4.0% calcium oxide and for RMGC 6.0%. Lime modification effects on Atterberg limits and plasticity indices for both soils are presented in Figs 4.2a and 4.2b. Contrary to behavior of these soils when treated with sodium chloride, PRC appears to be more reactive or responsive to addition of small percentages of calcium oxide than does RMGC. This fact implies that less cation exchange or ion adsorption is necessary to produce modifying conditions in PRC than in RMGC, which agrees with the fact that PRC is a lower plasticity soil than RMGC and has a thinner or less developed double water layer than RMGC. Double layers of RMGC require more calcium ions to compress



(a) Behavior of PRC Mixtures

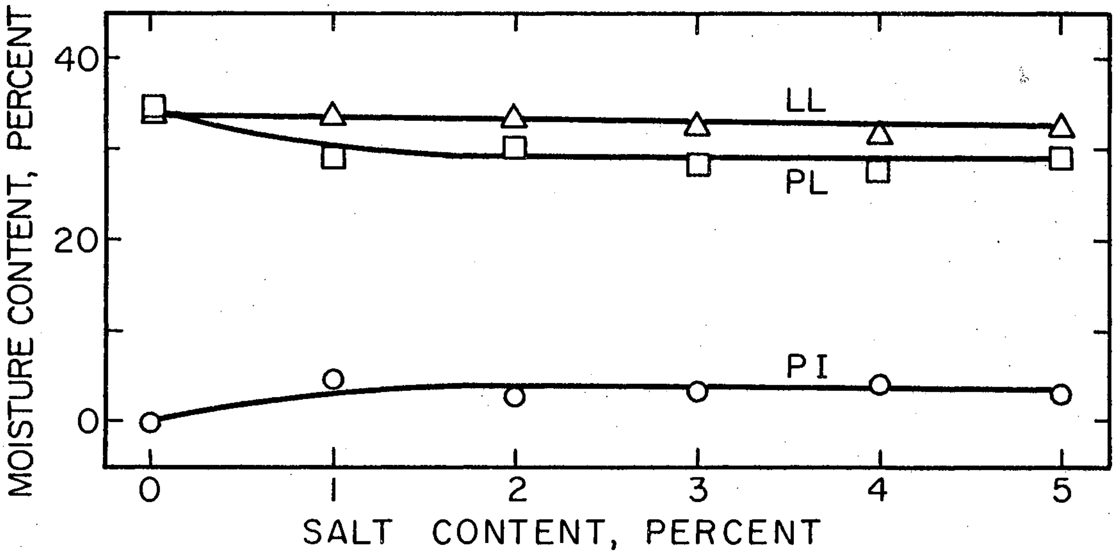


(b) Behavior of RMGC Mixtures

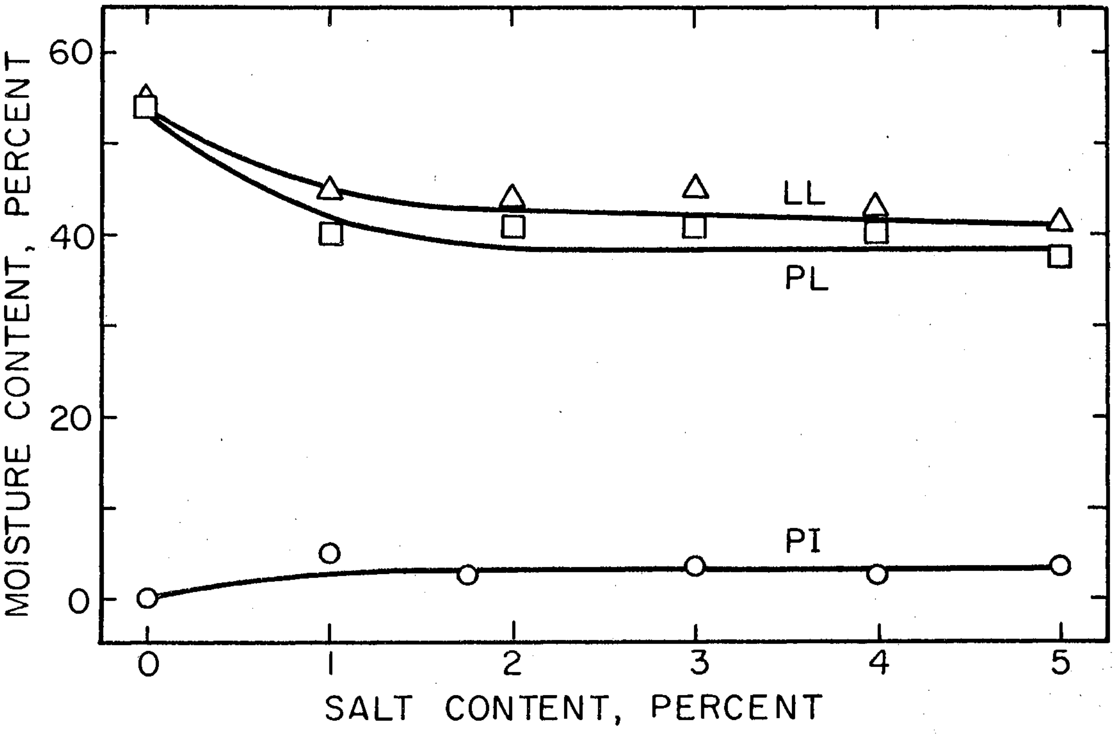
Figure 4.2. Effect of Lime Treatment on Atterberg Limits

the layers; consequently, higher lime contents are required to produce modification.

Addition of sodium chloride at modification optimum lime contents of both soils caused little change in Atterberg limits and plasticity indices obtained with lime treatment alone. PRC was found to increase in PI from zero to 4.0 with addition of one percent salt; however, addition of increasing percentages of sodium chloride produce no further change. PI increase of PRC resulted from a decrease in the plastic limit, since the liquid limit was not affected by addition of salt in conjunction with lime. As with PRC, one percent sodium chloride in addition to six percent lime caused an increase in RMGC PI of 4.0. Addition of greater percentages of salt with six percent lime produced no additional PI change. Unlike PRC, RMGC underwent reduction in both liquid and plastic limits. As the PI indicated, no change in Atterberg limits occurred with percentages greater than one percent. Effects of sodium chloride addition to soil-lime mixtures, at lime contents equivalent to modification optimum, on Atterberg limits are presented for PRC and RMGC in Figs 4.3a and 4.3b, respectively. From collected data it appears that monovalent sodium ions do not inhibit reactions of calcium ions with clay particles, which produce modification of cohesive soils. Thus, if addition of sodium chloride is found to produce more desirable engineering characteristics when used at modification lime contents, specifications for maximum plasticity allowable should not prohibit its use, as PI is practically unaffected.



(a) Behavior of PRC Mixtures



(b) Behavior of RMGC Mixtures

Figure 4.3. Effect of Salt-Lime Treatment on Atterberg Limits of PRC and RMGC

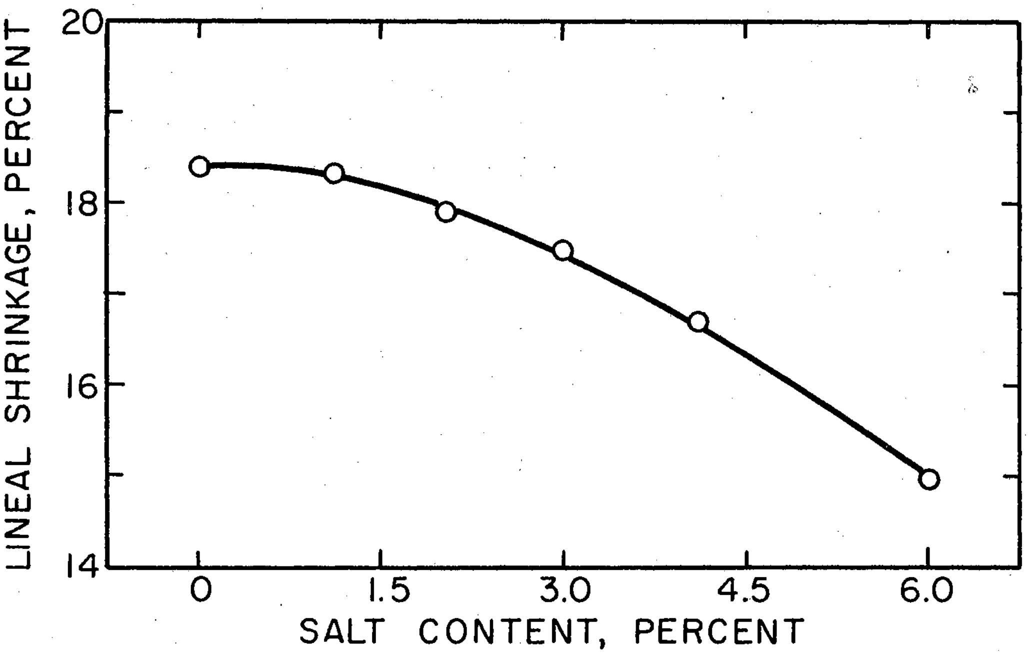
## Linear Shrinkage

Linear shrinkage tests were conducted in accordance with a procedure developed by the Texas Highway Department (Ref 44). This procedure involves mixing soil with sufficient water to produce a viscous suspension slightly more fluid than the liquid limit. The resulting slurry is placed in greased bar molds. Shrinkage samples are air-dried until a color change in the soil occurs, at which time they may be oven dried at 110°C. for 24 hours. Dried soil bars are carefully removed from molds and measured. Linear shrinkage is calculated as a percentage of the original wet sample length. Two samples are usually prepared simultaneously and linear shrinkages of the two are averaged.

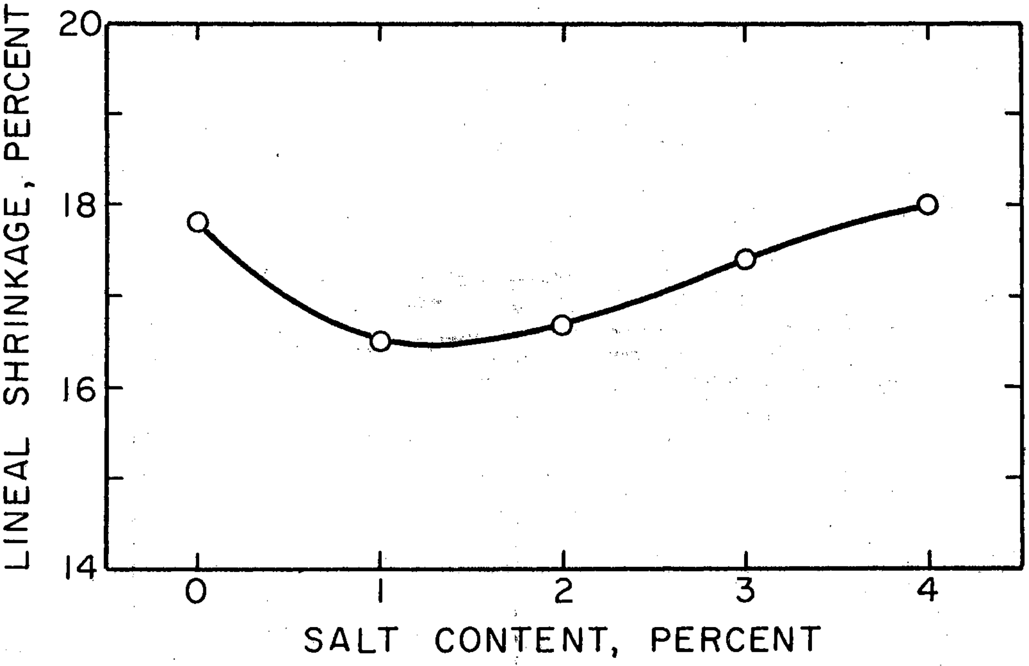
Sodium chloride treatment produced decreases in the linear shrinkage of both soils; however, the reductions were relatively small. PRC underwent a gradual reduction in linear shrinkage up to 6.0% sodium chloride, the maximum amount used. A maximum reduction of 3.4% was obtained at maximum salt content. Although RMGC linear shrinkage values were reduced by addition of salt, a maximum reduction of only 1.3% was found to occur with addition of one percent sodium chloride. Increasing salt percentages caused linear shrinkage values to increase back to the shrinkage value obtained for raw RMGC. Although addition of salt caused reduction of linear shrinkage values for both soils, reductions were of such magnitude that, for all practical purposes, shrinkage characteristics of both PRC and RMGC were not affected by sodium chloride treatment, particularly at small salt percentages. Effects of sodium chloride treatment on linear shrinkage characteristics of PRC and RMGC are illustrated in

Figs 4.4a and 4.4b by curves showing linear shrinkage of these soils as a function of salt content.

Lime modification of the two cohesive soils caused a reduction in linear shrinkage values of both soils as was expected; however, contrary to expectations linear shrinkage of neither soil was reduced to zero but rather to some constant value. Both materials were found to undergo gradual reductions in shrinkage as lime contents increased to modification optimum. Addition of lime percentages above modification optimum caused no additional reduction in linear shrinkage. Minimum linear shrinkage values obtained for both PRC and RMGC were nearly the same. PRC obtained a minimum linear shrinkage of 8.4% while RMGC linear shrinkage was reduced to 9.5%, reductions in linear shrinkage from raw soil values were 10.0% for PRC and 8.3% for RMGC. Curves representing linear shrinkage as a function of lime content for both soils are shown in Figs 4.5a and 4.5b. After considerable deliberation, only one explanation could be offered to observed behavior. Since both soils (which are widely different in physical properties) were reduced in linear shrinkage to approximately the same value, it would appear that shrinkage which occurs at or above modification optimum of these materials is similar to that which would occur in the drying of a very fine-grained sand. As evaporation of water in the voids of these materials occurs, relatively high tensile forces are developed by surface tension of the retracting water-air interface. These forces cause soil grains or particles to be pulled together. Thus, it appears that approximately 9.0 percent linear shrinkage, the average of the two minimum values obtained for PRC and RMGC, is

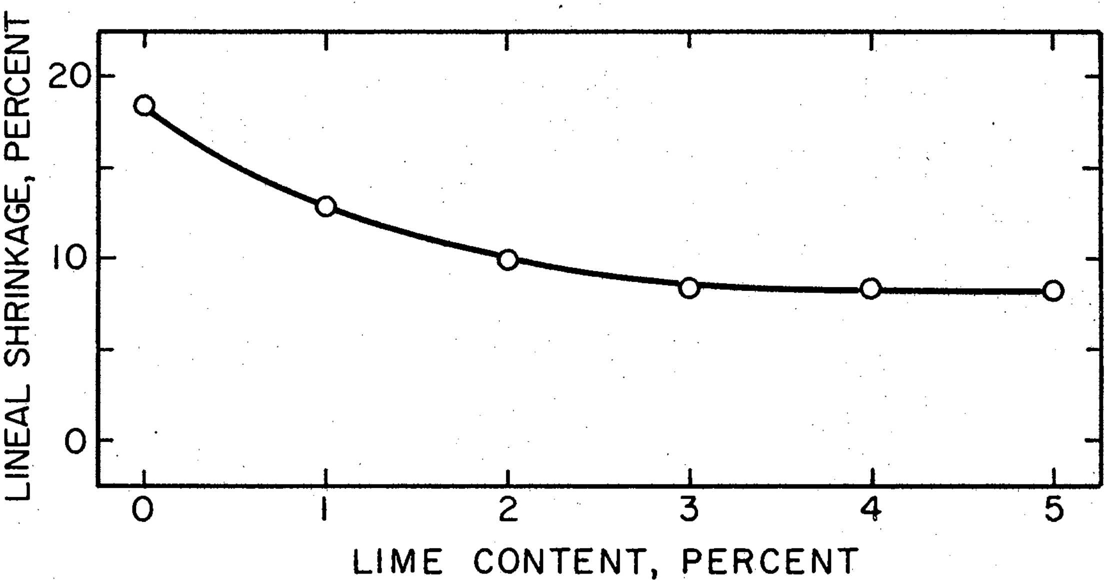


(a) Behavior of PRC Mixtures

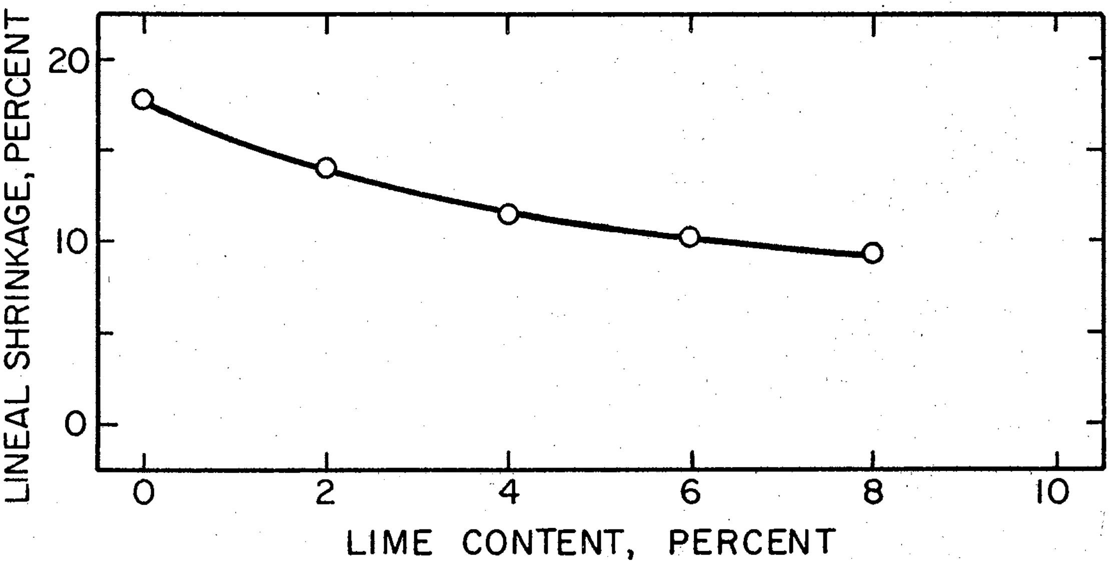


(b) Behavior of RMGC Mixtures

Figure 4.4. Effect of Salt Treatment on Linear Shrinkage



(a) Behavior of PRC Mixtures



(b) Behavior of RMGC Mixtures

Figure 4.5. Effect of Lime Treatment on Linear Shrinkage

the amount of dessication shrinkage which will occur in fine-grained soils, regardless of lime content.

Linear shrinkage characteristics of sodium chloride-lime soil mixtures were identical to those for the same soils treated only with lime. Varying percentages of salt added to both soils at respective modification optima did not affect linear shrinkage values obtained at these lime contents. Thus, from analysis of linear shrinkage data presented and discussed herein, sodium chloride has very little effect on linear shrinkage of either PRC or RMGC whether used as a sole chemical additive or used in conjunction with lime treatment.

## Moisture Retention

Soil mixtures to be used in moisture retention studies were blended at moisture contents near their respective optimum moisture contents, by means of the established sample preparation technique. Moist mixtures were divided into twelve fractions weighing approximately twenty-five grams each. Samples were placed in individual tare cans and sealed immediately to prevent moisture loss during weighing operations.

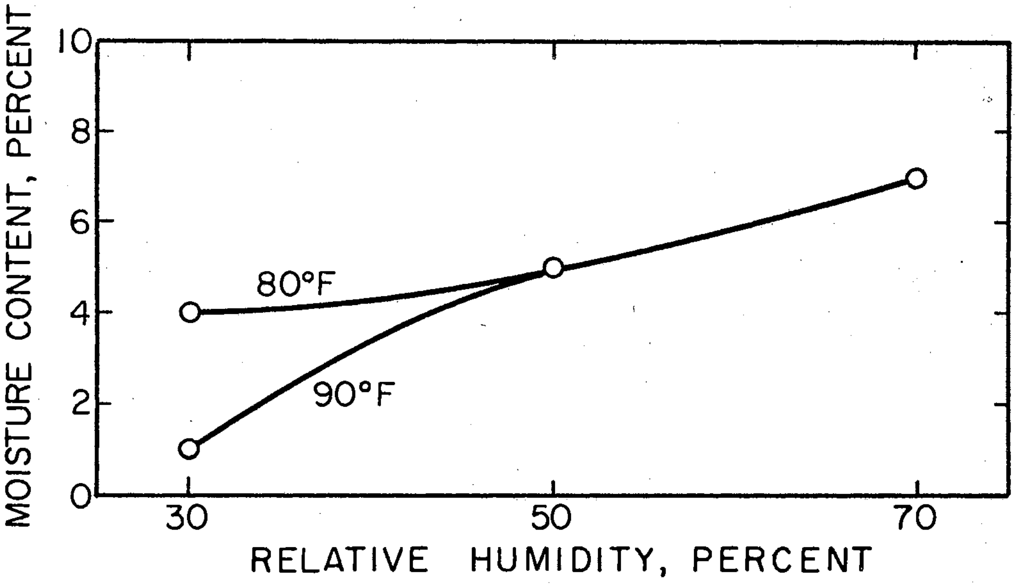
Since methods of lime treatment employed most often in Oklahoma are classified as lime modification, only four soil mixtures for each soil were tested under selected climatic conditions. These mixtures included raw soil, sodium chloride treated soil, lime modified soil, and salt-lime treated soil. Sodium chloride percentages used were those found to be most influential on engineering characteristics of PRC and RMGC, to be discussed in the following chapter. These percentages were found to be one percent for PRC and two percent for

RMGC. Modification optimum lime contents were used for both lime treated and salt-lime treated mixtures of PRC and RMGC.

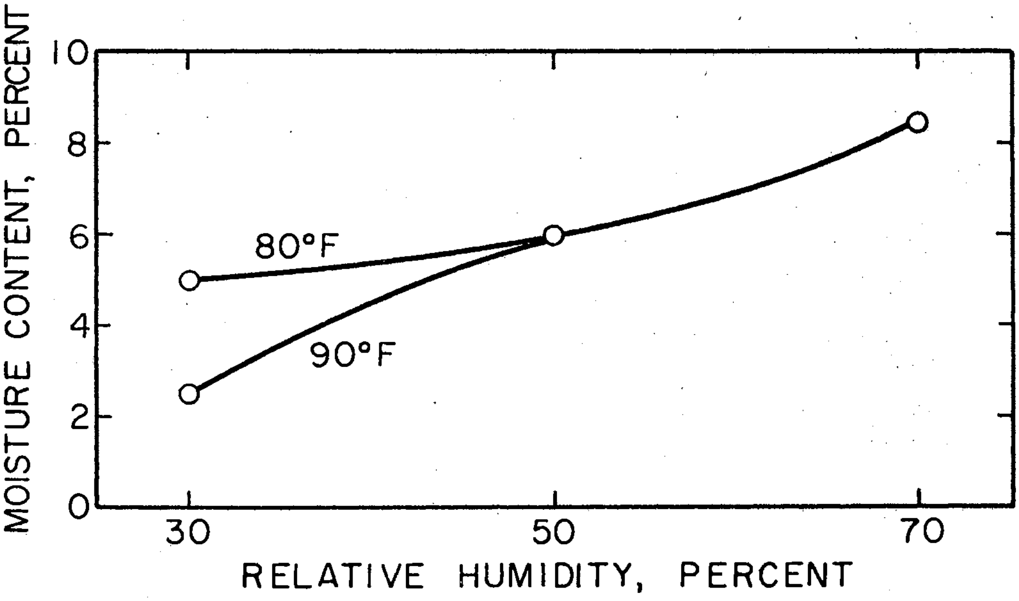
Constant temperatures and relative humidities were maintained throughout seventy-two hour test periods by means of a controlled temperature humidity chamber. A Blue M Vapor-Temp humidity chamber, which automatically controls and records both wet and dry bulb temperature, was used to obtain desired conditions. The apparatus is also equipped with a circulation fan, by which air flow through the chamber may be controlled. Full circulation was used during testing of all mixtures, to simulate high wind conditions often prevalent in Oklahoma. Employment of this technique provided uniform temperatures throughout the entire chamber, even when completely filled with samples. Typical climatic conditions which might occur during an Oklahoma construction season were used in selecting temperatures and relative humidities for the moisture retention studies. Since it would be impossible to duplicate all conditions which might prevail, three relative humidities and two temperatures were selected. Relative humidities used were 30, 50, and 70 percent. At each relative humidity, temperatures of 80° Farenheit and 90° Farenheit were used, thus six climatic conditions were applied to the four soil mixtures of both PRC and RMGC.

Salt treatment was found to increase the moisture retention characteristics of PRC. Variations in relative humidity affected moisture retention to a greater extent than did variation in dry bulb temperatures associated with the relative humidities, except at the lowest relative humidity, thirty percent. This behavior was found for all soil mixtures tested. Effects of relative humidity and dry bulb temperature on PRC and salt treated PRC moisture contents at the end of seventy-two hours of exposure to indicated climatic conditions are presented in Figs 4.6a and 4.6b. Although it is seen that sodium chloride increases the moisture retention capacity of PRC, the most pronounced differences in moisture retention occurred before twenty-four hours of exposure. For construction purposes, this time duration is the most critical since compaction of fill material usually follows watering and mixing within twenty-four hours. Curves representing moisture loss as a function of exposure time are presented in Appendix A to show more clearly moisture retention characteristics of PRC and salt treated PRC.

Moisture retention characteristics of lime modified PRC mixtures were similar to those of the raw soil, based on seventy-two hour moisture contents. Although final moisture contents at all climatic conditions were essentially the same for PRC and lime modified PRC, lime-soil mixtures were found to lose moisture more rapidly than raw PRC in early stages of testing. Addition of sodium chloride in conjunction with lime modification of PRC produced virtually no change in moisture retention characteristics from those of lime modified PRC mixtures. In fact, moisture contents for both lime treated and salt-lime treated PRC obtained at both temperatures with a relative humidity of thirty percent could be represented as one curve throughout the entire test period. Responses of lime treated and salt-lime treated PRC moisture retention characteristics to various climatic conditions are represented in Figs 4.7a and 4.7b, based on the final seventy-two hour moisture contents of the mixtures. As was found in the case of sodium chloride treatment, the most beneficial effects of salt addition

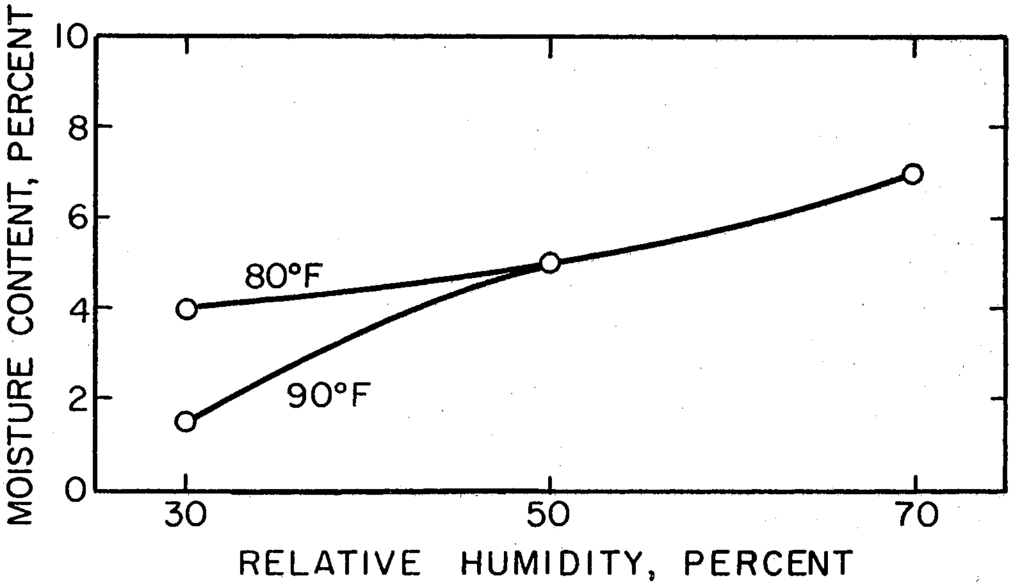


(a) Behavior of PRC

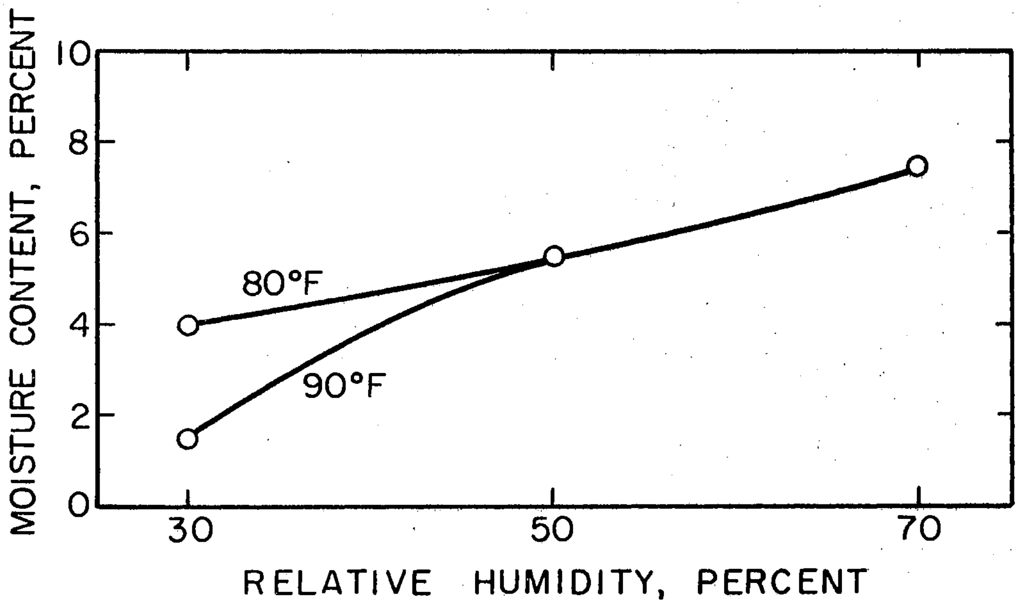


(b) Behavior of PRC-Salt Mixtures

Figure 4.6. Effect of Climatic Conditions on 72-Hour Moisture Contents



(a) Behavior of PRC-Lime Mixtures



(b) Behavior of PRC-Salt-Lime Mixtures

Figure 4.7. Effect of Climatic Conditions on 72-Hour Moisture Contents of Lime and Salt-Lime Treated PRC

at modification lime contents were found to occur in early stages of exposure to various climatic conditions as exemplified by Fig 4.8.

RMGC mixtures were found to have moisture retention characteristics very similar to those of PRC with respect to climatic conditions. Variation in temperature at all relative humidities was found to affect 72-hour moisture contents of RMGC even less than found for PRC. Addition of salt to RMGC and RMGC-lime mixtures improved the moisture retention as in the case of PRC mixtures. However, salt was found to have very little effect on 72-hour moisture contents of RMGC mixtures at the lowest relative humidity. Figs 4.9a and 4.9b illustrate the effects of climatic conditions on moisture retention of RMGC and salt treated RMGC.

Lime modification of RMGC caused more moisture loss during exposure to selected climatic conditions than untreated RMGC. Addition of two percent sodium chloride in conjunction with lime not only improved moisture retention but increased moisture retention potential to a level above that of RMGC. Effects of various climatic conditions on lime and salt-lime modified RMGC are shown in Figs 4.10a and 4.10b. Moisture retention curves representing moisture content as a function of exposure time used to obtain these curves are presented in Appendix A. These curves illustrate the advantageous effects of sodium chloride additives during the first 25 hours of exposure as was found in the case of PRC.

Moisture control in lime modification of cohesive subgrades is usually more critical than for untreated soil. Since lime modification requires the addition of moisture to obtain desired soil-lime reactions, it would be extremely economical if moisture contents could be

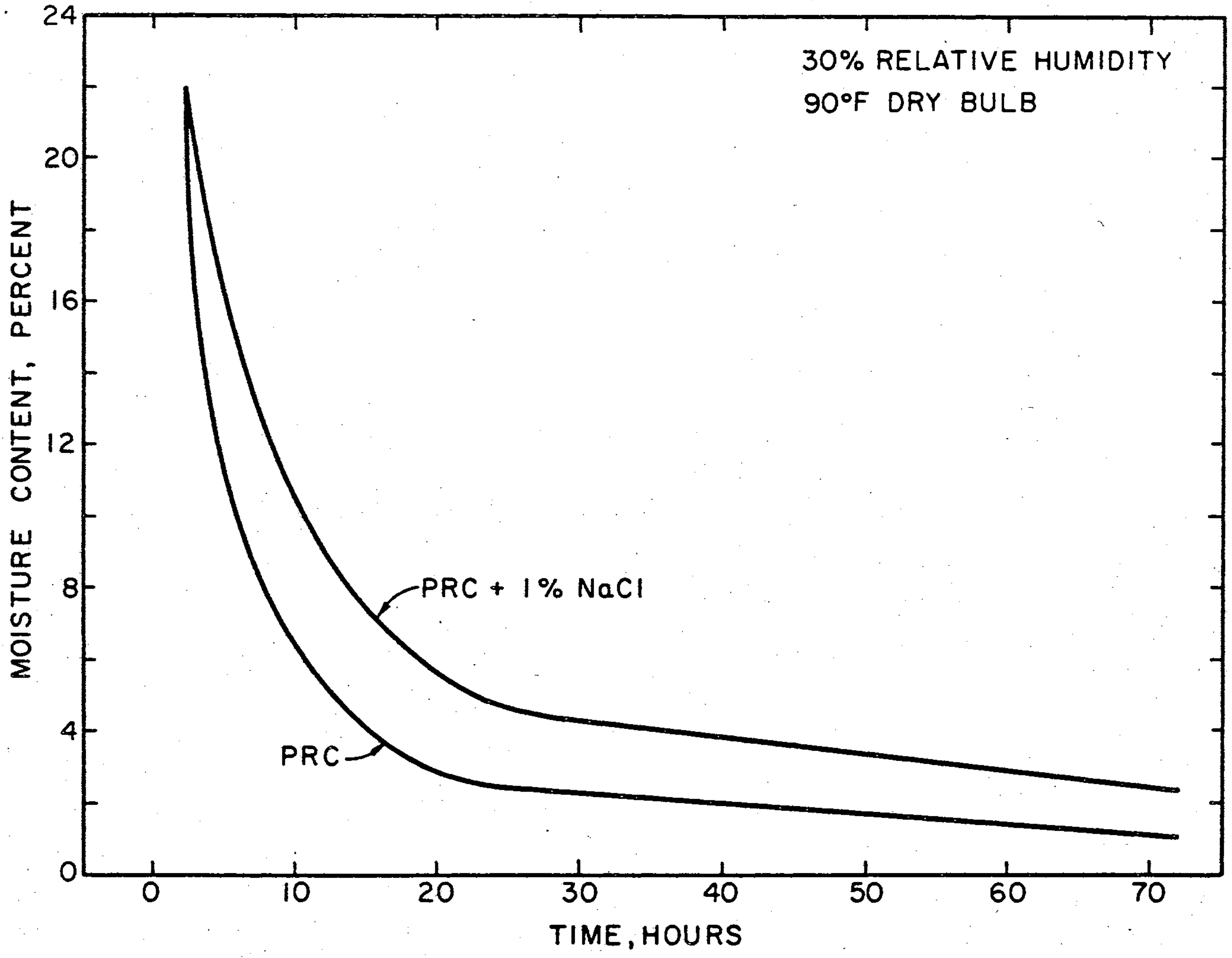
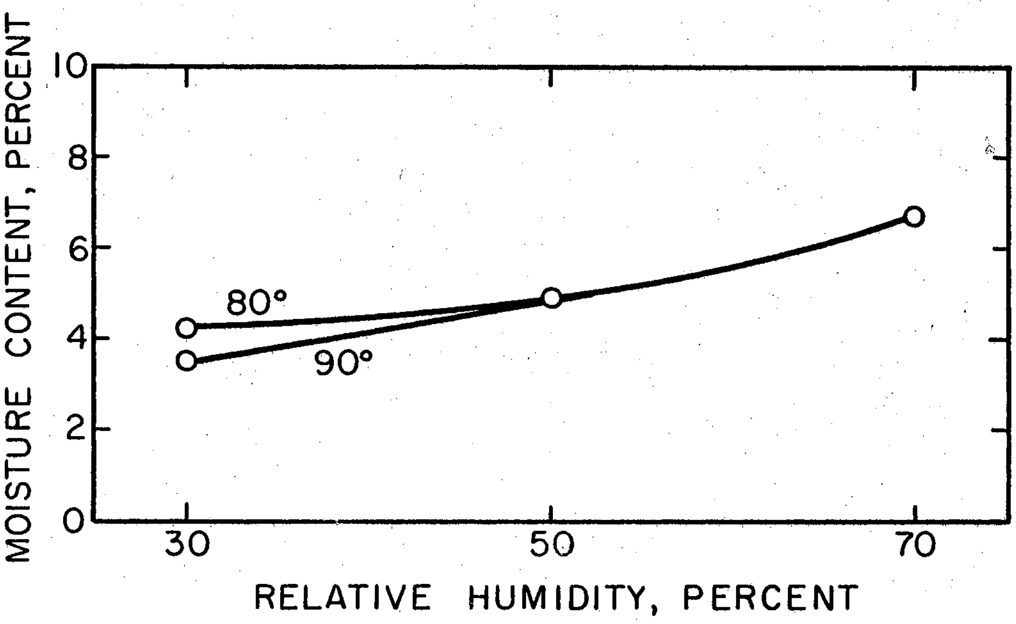
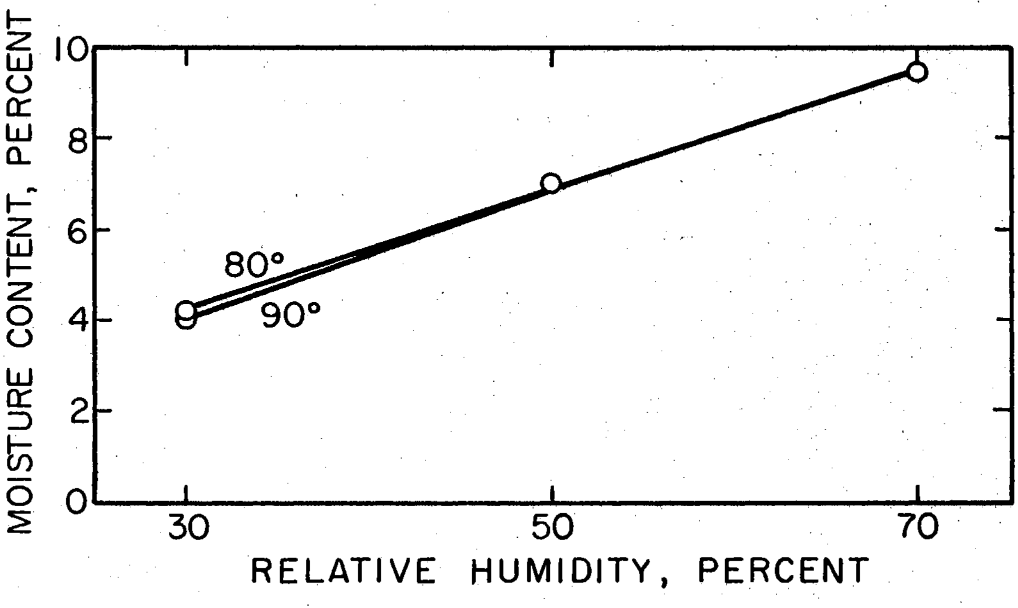


Figure 4.8. Moisture Retention Characteristics of PRC and PRC-Salt Mixtures

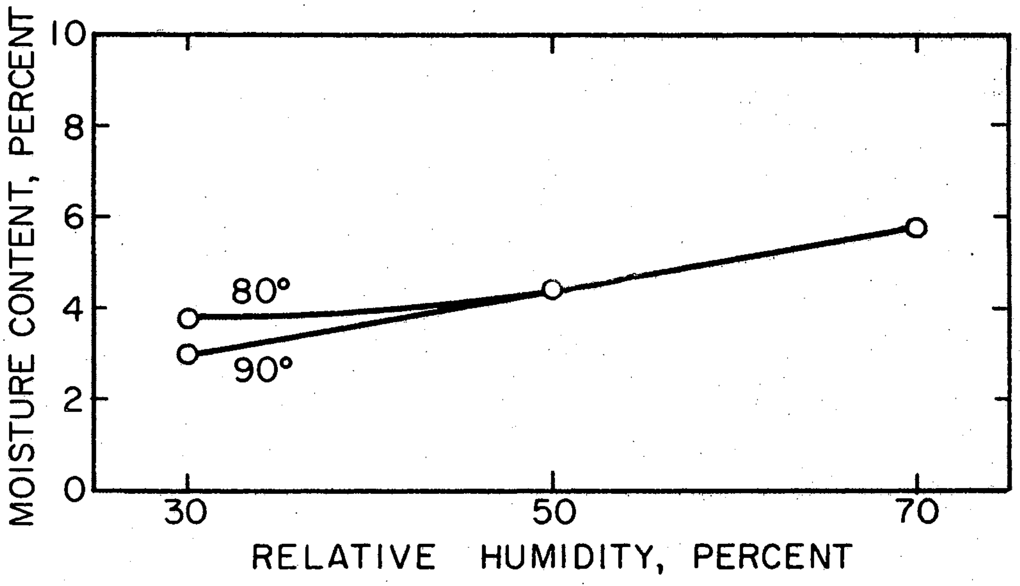


(a) Behavior of RMGC

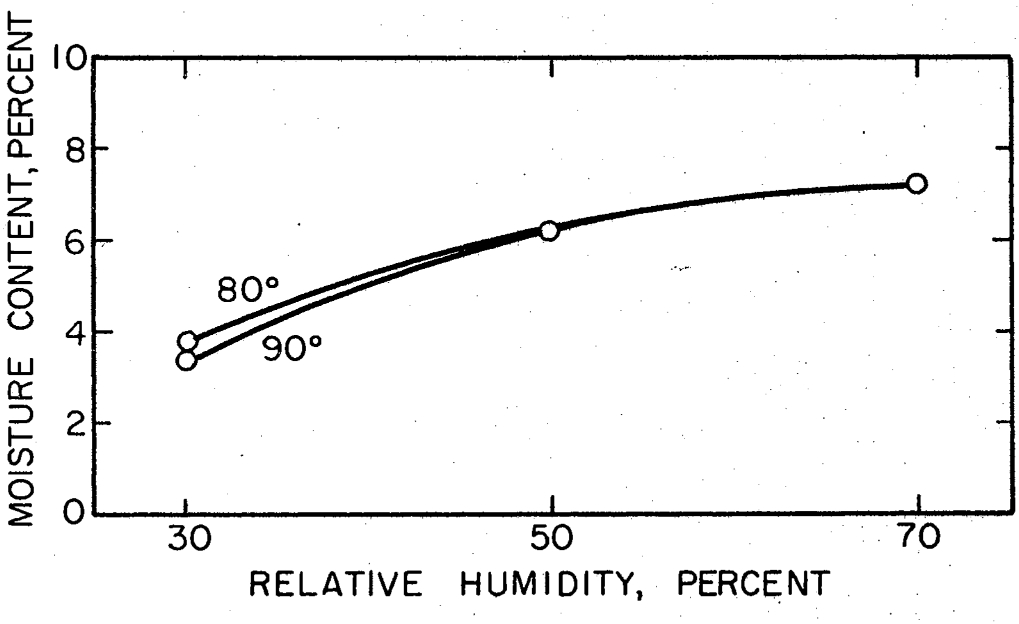


(b) Behavior of RMGC-Salt Mixtures

Figure 4.9. Effects of Climatic Conditions on 72-Hour Moisture Contents of RMGC Mixtures



(a) Behavior of RMGC-Lime Mixtures



(b) Behavior of RMGC Salt-Lime Mixtures

Figure 4.10. Effects of Climatic Conditions on 72-Hour Moisture Contents of Lime and Salt-Lime Treated RMGC

maintained for longer periods of time to allow reactions. Thus, addition of small percentages of sodium chloride would be advantageous in that moisture losses would be retarded during curing periods.

## Summary

Analyses and discussions of data presented in the previous sections allow some preliminary evaluations concerning the behavior of chemically treated PRC and RMGC, using sodium chloride, calcium oxide and salt-lime admixtures. For all practical purposes, addition of small sodium chloride percentages to PRC and RMGC did not affect Atterberg limits and plasticity indices of these materials. Although Atterberg limits of both cohesive soils were affected by salt treatment, indicating that soil-salt reactions did in fact occur, resulting increases in PI of both soils were negligible with addition of less than two percent salt.

RMGC and PRC were found to respond to lime modification in virtually the same manner. Effects of calcium oxide on liquid limits of both soils was exactly opposite to effects of salt on PRC and RMGC liquid limits. However, plastic limit values were affected by lime modification in the same manner as salt treatment. The more cohesive RMGC required a lime content of 6.0% to reduce its PI to zero whereas PRC only required 4.0% lime to become nonplastic. Thus, based on Atterberg limits tests and plasticity indices determinations, the modification optima for PRC and RMGC are 4.0% and 6.0% calcium oxide.

As was found for sodium chloride treatment alone, addition of salt at modification optima for both soils caused relatively little change in consistency limits of soil-lime mixtures. Addition of one percent sodium chloride to soil-lime mixtures of both PRC and RMGC produced an increase in PI of both soils from zero to 4.0. Increasing percentages of salt did not cause any further change in PI values of either soil. The small increase in PI of both cohesive soil-lime admixtures was a result of a decrease in plastic limits of the soil-lime mixtures. RMGC mixtures were found to have liquid limit values decreases with the addition of one percent salt whereas PRC mixtures revealed very little change in liquid limits with addition of sodium chloride.

Addition of sodium chloride to raw soils in percentages expected to be beneficial, less than two percent, produced little change in the shrinkage of either PRC or RMGC.

Lime modification sharply decreases linear shrinkage of both soils; however, it was found that minimum shrinkage values of 8.4% and 9.5% for PRC and RMGC were unaffected by addition of lime in percentages greater than modification optima. Not only did increasing percentages of lime have little affect on linear shrinkage values above modification optima, but also addition of small percentages of sodium chloride to soil-lime mixtures at modification optima was found to have little affect on linear shrinkage of either soil.

Addition of sodium chloride to raw cohesive soils and soil-lime admixtures at modification optimum lime contents enhanced moisture retention capabilities under selected typical Oklahoma construction season climatic conditions. Relative humidity variation was found to be more critical in moisture retention ability of all mixtures than was dry bulb temperature change. Beneficial effects of sodium chloride addition were found to be more pronounced in early stages of exposure to various climatic conditions. It is during this initial twenty-four hour period that construction moisture control is of most importance.

The following chapter will be concerned with the effects of sodium chloride, lime, and salt-lime treatment on engineering characteristics of PRC and RMGC. These data, in conjunction with those on physical properties just presented, will allow a complete evaluation of sodium chloride as a feasible chemical additive in cohesive Oklahoma soils.

# CHAPTER V

# EFFECTS OF CHEMICAL TREATMENT ON ENGINEERING CHARACTERISTICS OF COHESIVE SOILS

## Introduction

Engineering characteristics of cohesive soil are considered herein to be those properties which directly affect engineering design. Engineering characteristics of raw soils and chemically treated soils which will receive consideration throughout this chapter are compaction properties, unconfined compressive strength, and swelling potential. These are fully described in subsequent sections of this chapter.

Compaction characteristics of selected soils and soil-chemical mixtures will first be discussed. Effects of various additives on compaction properties is of primary concern; however, effects of various compactive efforts on optimum moisture contents and densities of various soil mixtures will also be presented. Effect of variations in compactive effort will be discussed, since development of such data were necessary for unconfined compression specimen preparation.

The section concerning compressive strength is divided into three major portions, according to type of chemical treatment. Strength characteristics of sodium chloride treated soils, lime and salt-lime modified soils, and lime and salt-lime stabilized soils comprise the major portions of the compressive strength section. Although strength gains during lime modification are of secondary consideration, any additional strength obtained from chemical additives would be beneficial. Effects of sodium chloride as a possible chemical additive to be used with lime modification will be presented. Lime stabilization of cohesive soils has as a primary objective substantial and economical strength gain. Since strength gains obtained from lime stabilization are relatively long-term, it is desirable to find a chemical catalyst which might increase the rate of strength gain during stabilization. Influences of sodium chloride on strength gains and rates of strength gain during stabilization will be presented and discussed.

Swelling potentials of selected soil mixtures under direct loading are presented to show effects of chemical treatment with sodium chloride. Swelling data presented are of a relative nature (for comparative purposes only) since the imposed load was derived from an assumed typical highway section.

Because this chapter contains a multitude of ideas and data, the final section of the chapter is devoted to a concise summary of data presented in the Chapter.

## Compaction Properties

Soil mixtures for Standard Proctor compaction tests were prepared by the standardized procedure outlined in Chapter III. Mixing at moisture contents near the plastic limit of respective mixtures was found to produce points on the dry side of optimum moisture content, as a result of some moisture loss during curing.

Standard Proctor moixture-density curves were developed with a Harvard Miniature compaction mold and specially designed hammer. The mold size and hammer weight were reduced in scale proportionally from the Standard Proctor mold and hammer, Proctor tests could therefore be conducted in accordance with ASTM D698-66T (Ref 45). Since all soils and additives used passed the U.S. No. 40 sieve, compaction curves obtained from the Harvard mold were similar to those obtained from full scale Standard Proctor tests.

The effect of sodium chloride treatment on maximum dry densities obtained by Standard Proctor compactions tests was quite different for PRC and RMGC. Increasing percentages of salt added to PRC caused a substantial increase in compacted unit dry weight. Dry density was increased from 106 pcf for raw PRC to 112 pcf with the addition of two percent sodium chloride. Addition of salt in percentages greater than two percent caused no additional increase in the compacted unit dry weight of PRC mixtures. RMGC did not show any response to salt treatment relative to compacted unit dry weight. Effects of sodium chloride treatment on compacted unit dry weights of both soils are shown in Fig 5.1 by curves representing dry density as a function of salt content. Optimum moisture contents of both soils were affected by salt treatment; however, PRC was again found to be more responsive than RMGC. PRC had its optimum moisture content reduced from 18% in the raw condition to a minimum of 16% with addition of two percent sodium chloride. Addition of percentages of salt greater than two percent caused an increase in optimum moisture content back to that obtained for raw soil. RMGC underwent little change in optimum moisture content with addition of salt in percentages up to four percent. Addition of four percent sodium chloride caused an increase in optimum moisture content of 3%. Changes in optimum moisture contents resulting from salt treatment of both soils are shown in Fig 5.2.

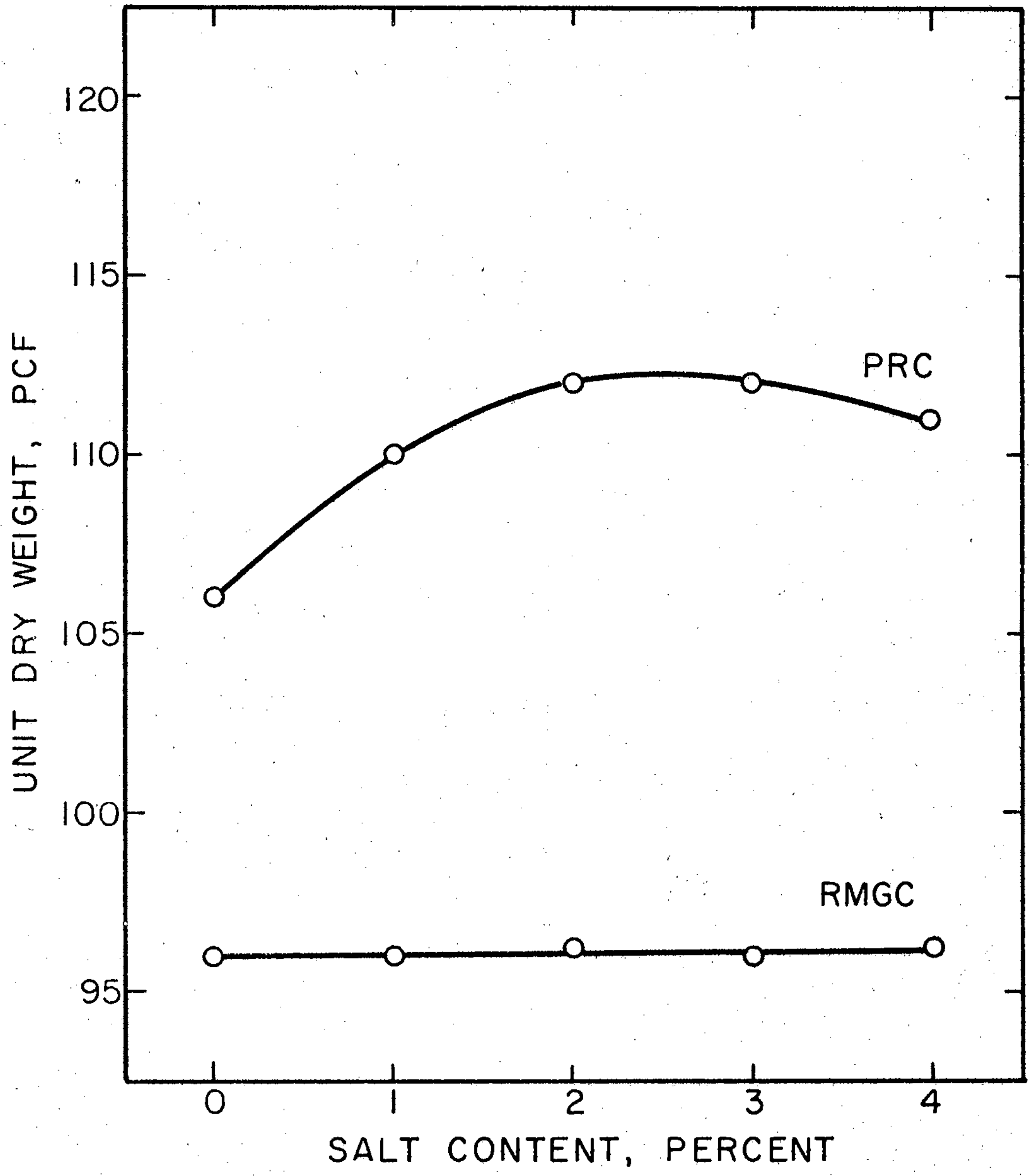


Figure 5.1. Effect of Salt Treatment on Standard Proctor Density

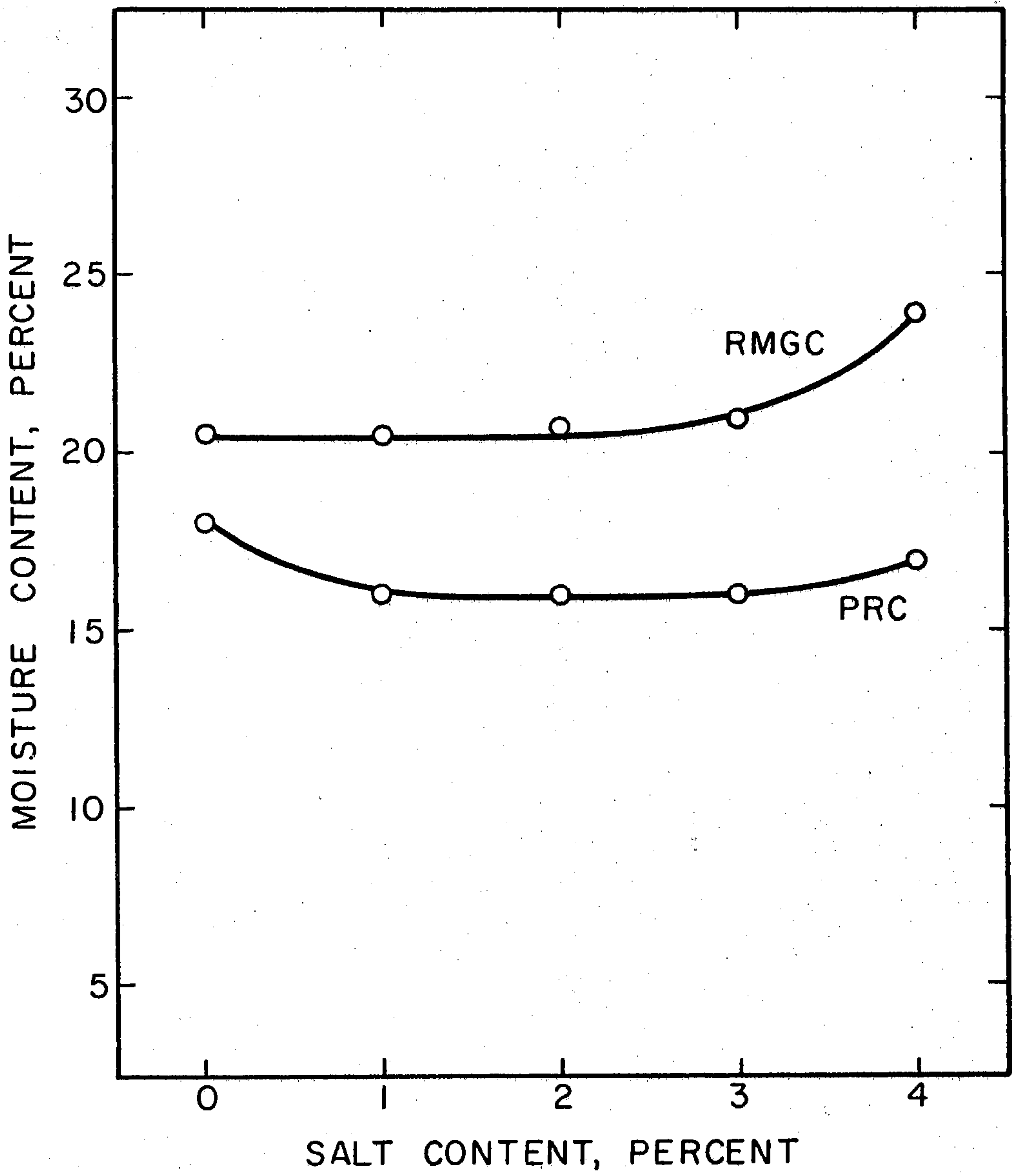


Figure 5.2. Effect of Sodium Chloride on Optimum Moisture Content at Standard Proctor Density

Contrary to effects of sodium chloride treatment on consistency limits of these soils, PRC was found to be more responsive to salt treatment relative to compaction properties than was RMGC. This phenomenon may be a result of stress histories for the two soils. Since PRC has undergone heavy preconsolidation from surcharge and desiccation, it is probable that PRC platelets have a marked parallel orientation. Thus, addition of an electrolyte such as sodium chloride may produce a more nearly random structure from readjustment during flocculation. The more random structure thus produces a higher unit dry weight than the more nearly parallel structure. RMGC, not having undergone so much desiccation, is more randomly oriented in its natural condition, thus addition of the electrolyte has very little affect on compaction characteristics of the material. This behavior is in agreement with arrangement of soil particles during compaction presented by Lambe (Ref 46).

Calcium oxide affected compacted unit dry weights of both soils. Dry densities of both RMGC and PRC were reduced by addition of increasing percentages of lime. PRC was found to undergo much greater loss in compacted unit dry weight than RMGC. PRC unit dry weight was reduced from 106 pcf to 88 pcf with the addition of 9% calcium oxide. RMGC was reduced from 96 pcf to 90 pcf with the addition of 9% lime. Effects of lime treatment on compacted unit dry weights of both soils are shown in Fig 5.3. Optimum moisture contents were found to be substantially increased by lime treatment. PRC was again found to be more sensitive, undergoing an increase in optimum moisture content of 9% (from 17% to 26% moisture). RMGC underwent an increase in optimum

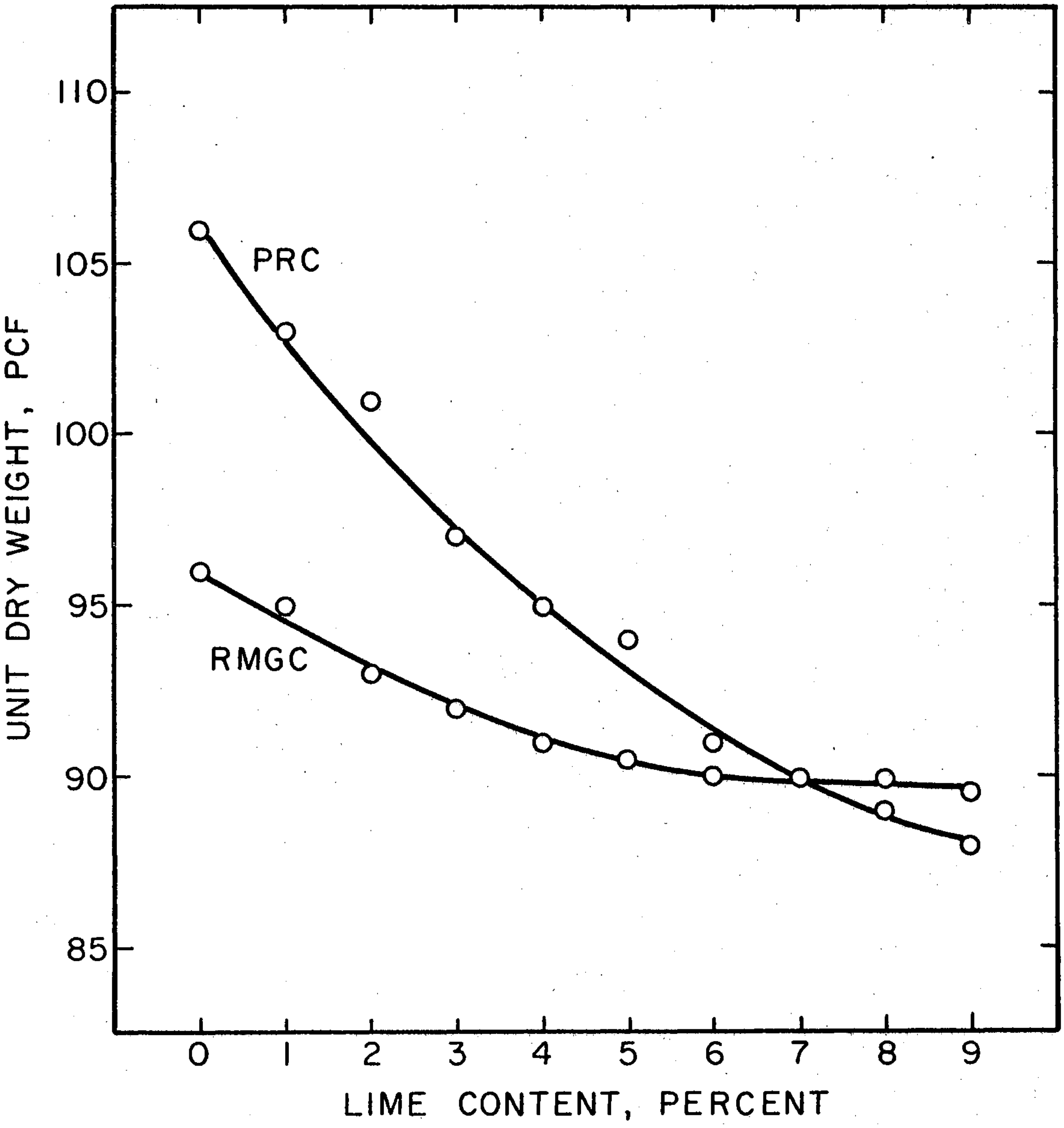


Figure 5.3. Effect of Lime Treatment on Standard Proctor Density

moisture from 20% to 27.5% with the addition of 9% lime. Relative effects of lime treatment on optimum moisture contents of both soils are shown in Fig 5.4.

Reduction in compacted unit dry weight and increase in optimum moisture content of both cohesive soils is a direct result of granulation or aggregation which occurs during lime treatment. Since PRC physical properties are much more sensitive to lime treatment than RMGC, it should be expected that PRC compaction properties would be more sensitive to lime treatment. The granulation effect of lime modification of cohesive soils is clearly illustrated by the shape of moisture-density curves. By comparing compaction curves shown in Fig 5.5, for raw and lime modified soils, it is evident that more granular soils have been produced by lime modification, as evidenced by the sharper peak on lime modified moisture-density curves. It is also apparent from these curves that PRC is less plastic than RMGC, since the latter has a flatter characteristic moisture-density durve than does the former.

Effect of salt-lime treatment on compacted unit dry weights was almost identical to the salt treatment response of both soils. As increasing percentages of sodium chloride were added in conjunction with lime contents near and at modification optimum for both soils, dry density was increased. PRC was again most responsive, passing through a maximum dry unit weight for all lime contents with the addition of one percent sodium chloride. Gains in compacted unit weight were consistent for all lime contents. One percent sodium chloride caused an increase from 96.8 pcf to 102 pcf for 3% lime mixtures, 95.5 pcf to 100 pcf for 4% lime mixtures, and 94 pcf to

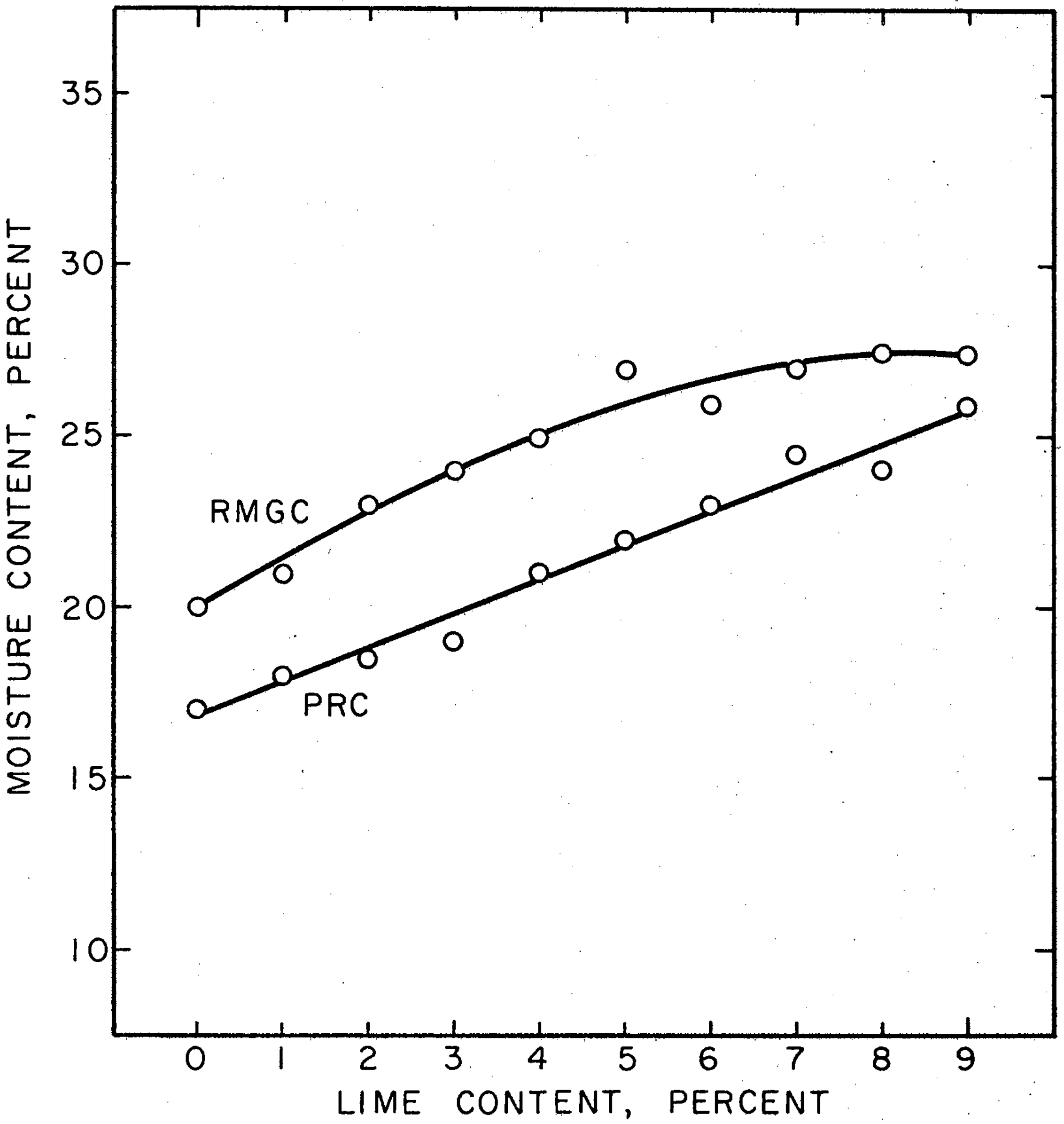


Figure 5.4. Effect of CaO on Optimum Moisture Content at Standard Proctor Density

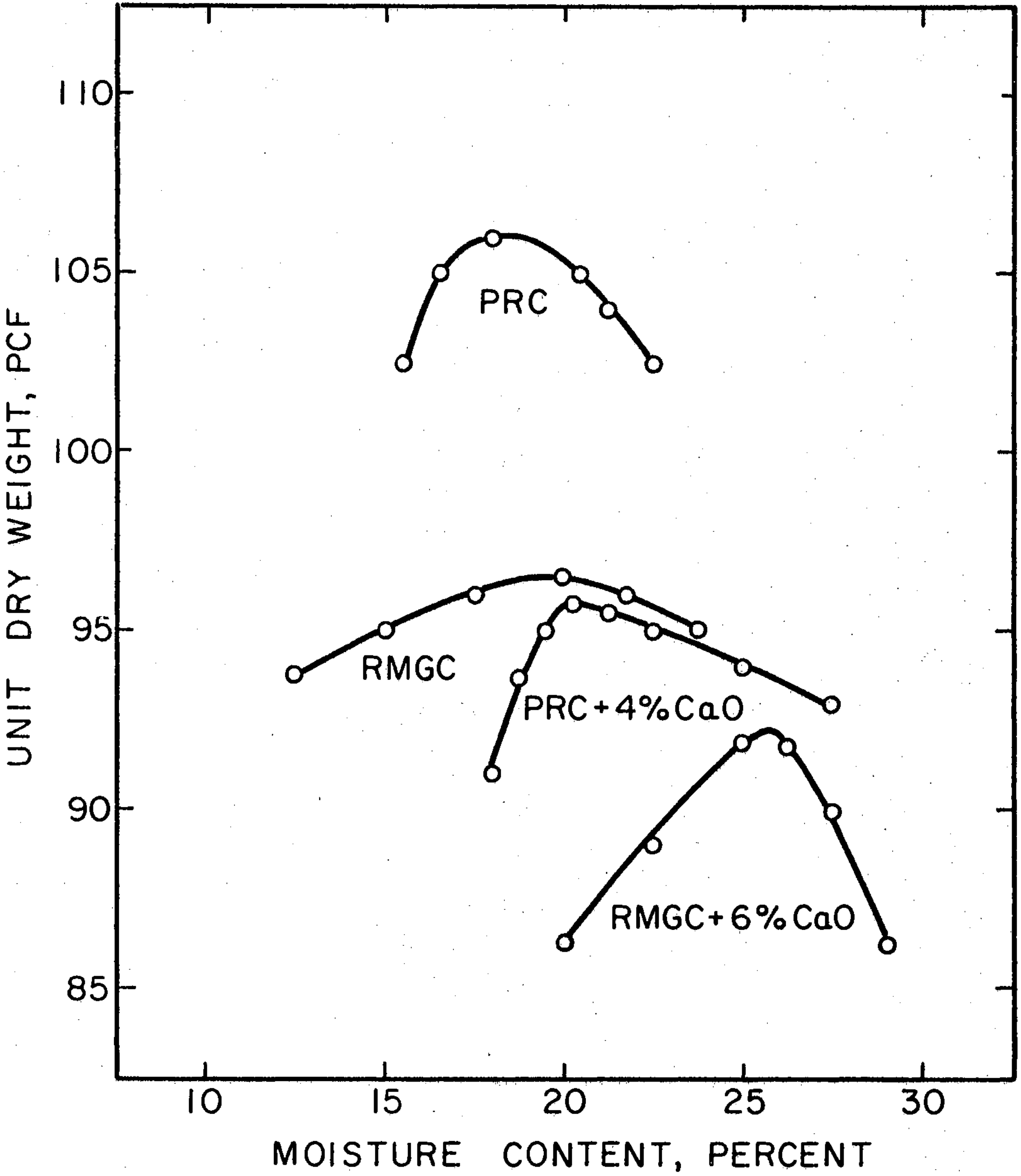


Figure 5.5. Effect of Lime Modification on Moisture-Density Curves of Cohesive Soils

100.5 pcf for 5% lime mixtures. Thus, as shown in Fig 5.6, about one-half of the dry density loss occurred during lime modification was regained by addition of sodium chloride. Optimum moisture contents associated with these maximum compacted densities of salt-lime treated PRC mixtures were found to be reduced with increasing salt content. A minimum optimum moisture content was obtained with the addition of one percent sodium chloride to all lime contents. As indicated in Fig 5.7, reduction in optimum moisture content of PRC salt-lime mixtures was increasingly significant with increase in lime content of the mixtures. However, the minimum optimum moisture content was found to be 18% for all PRC salt-lime modified mixtures.

As in the case of salt treatment, RMGC dry unit weights were affected very little by salt-lime modification. A slight increase in compacted dry density was obtained with increasing salt content of salt-lime mixtures. A maximum dry density was obtained with the addition of two percent sodium chloride in conjunction with all lime contents except 6%, which was modification optimum. As indicated in Fig 5.8, maximum increases in unit dry weights were relatively insignificant, being on the order of 2 pcf. Although RMGC showed little response to salt-lime treatment relative to dry density gains, effects on optimum moisture content were found to be more significant. As increasing percentages of salt were added in conjunction with lime contents near and at modification optimum, RMGC mixture optimum moisture contents were reduced. All RMGC salt-lime mixtures passed through a minimum optimum moisture content at salt contents of 1.5% to 2.0%. As was found for PRC mixtures, the effectiveness of sodium chloride on reducing optimum moisture content was found to increase with increasing

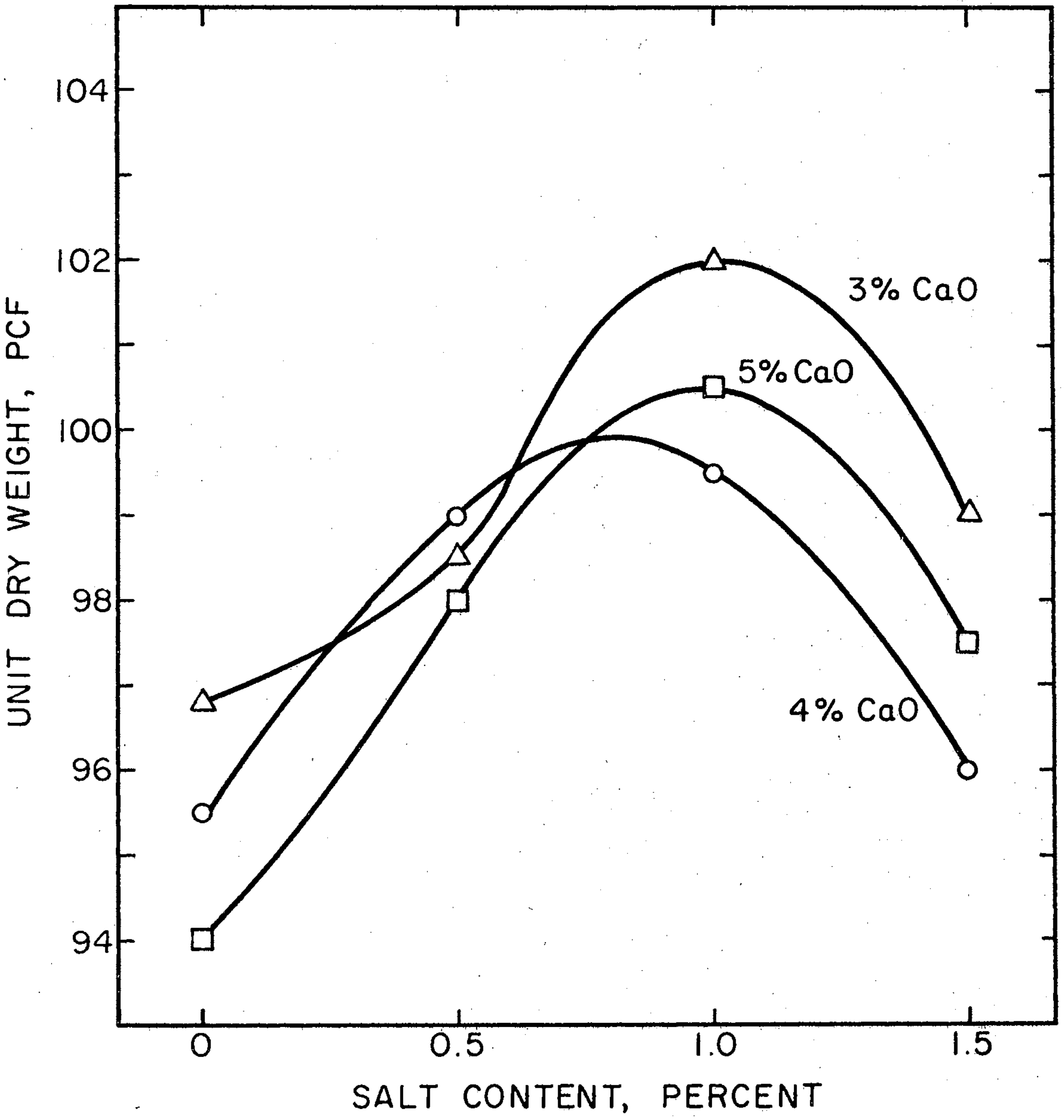


Figure 5.6. Effect of Salt-Lime Treatment on Standard Proctor Density of PRC

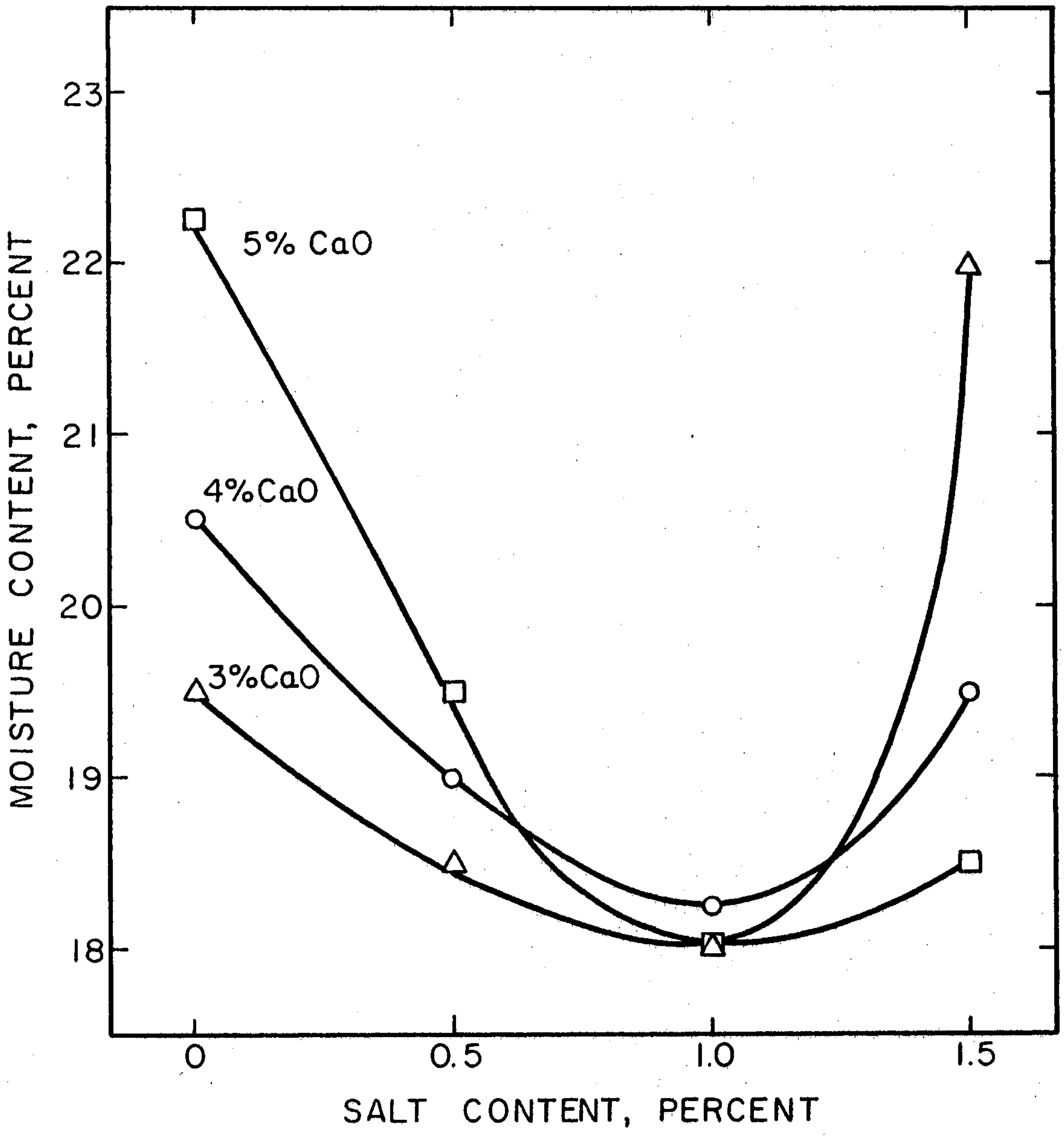


Figure 5.7. Effect of Salt-Lime Modification on Optimum Moisture Content of PRC at Standard Proctor Density

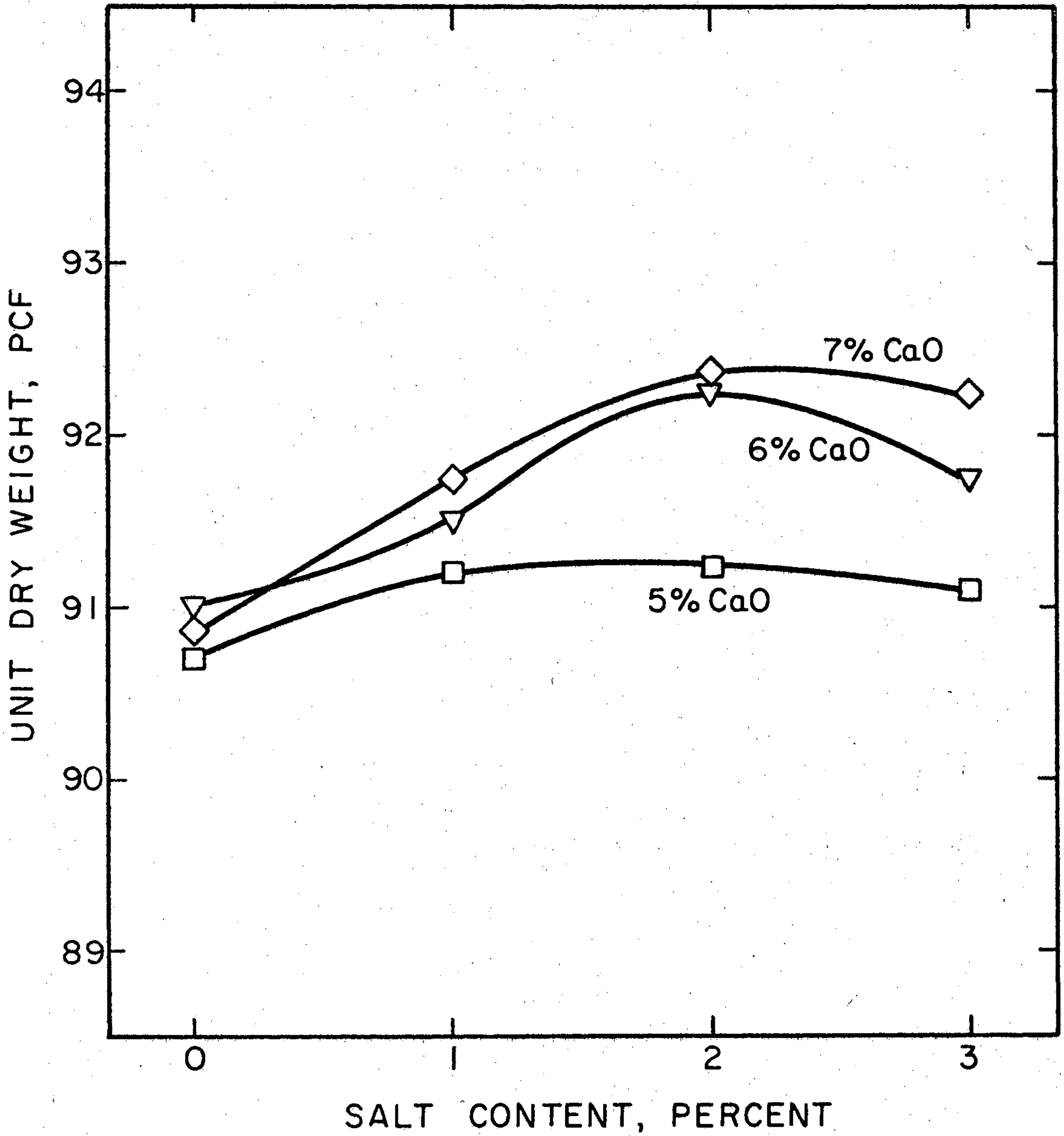


Figure 5.8. Effect of Salt-Lime Modification on Standard Proctor Density of RMGC

lime content. Effects of salt-lime modification on optimum moisture contents of RMGC are presented in Fig 5.9 by curves representing optimum moisture content as a function of salt content for various RMGC salt-lime mixtures.

Since reduction in unit dry weight of RMGC as a result of lime treatment was relatively small and increases in desnity were negligible as a result of salt treatment, it is natural to expect that salt-lime treatment would have little effect on RMGC compacted unit dry weight and optimum moisture content.

Salt percentages of one percent for PRC and two percent for RMGC were found to be most effective in producing desired results when used in combination with calcium oxide.

## Unconfined Compressive Strength of Treated Soils

Soil mixtures to be used for molding of compression test specimens were blended at desired compaction moisture contents by the standardized procedure.

Unconfined compression test specimens were molded by impact compaction of treated soil mixtures in a Harvard miniature compaction mold. This procedure produced test specimens 2.8125 inches in height and 1.3125 inches in diameter. Immediately after compaction, test specimens were weighed and wrapped securely in Saran Wrap. After compacting and wrapping a particular mixture, specimens were sealed by dipping in molten wax. Test specimens were stored for curing in a moist room having a relative humidity of 100% and a dry bulb temperature of 70°F. Unconfined compression tests were conducted at seven day intervals from the date of compaction. Three test specimens from

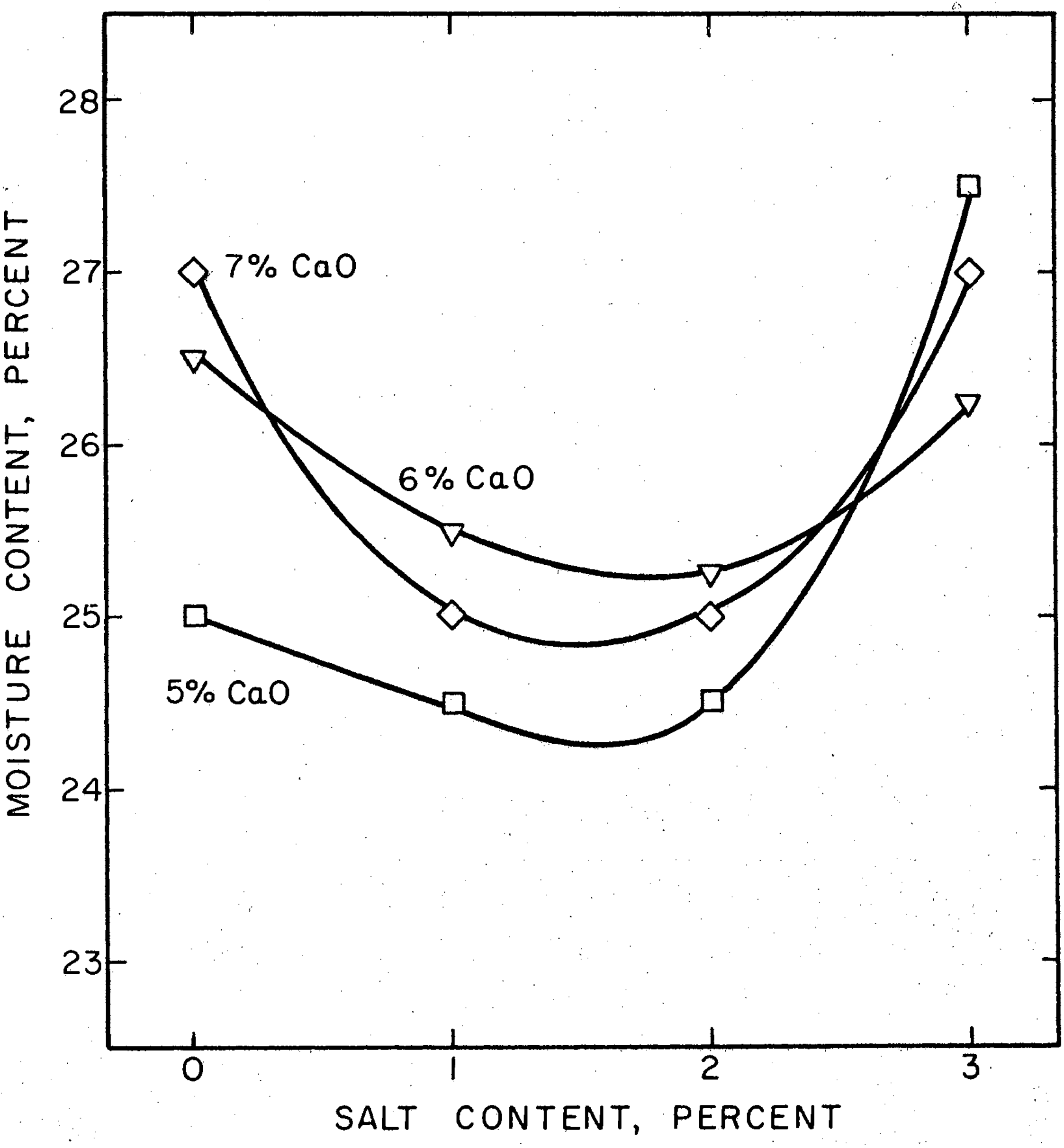


Figure 5.9. Effect of Salt-Lime Modification on Optimum Moisture Content of RMGC at Standard Proctor Density

each mixture were tested on a given test date. Therefore, a total of 12 test specimens were required for each mixture to fulfill the 7, 14, 21, and 28-day test schedule adopted.

Compressive strength of cohesive soils is dependent on existing moisture content and unit dry weight. Elimination of these two variables was accomplished by compacting comparative test specimens at the same moisture content and to the same unit dry weight. RMGC mixtures presented no problem since unit dry weights and moisture contents of all RMGC mixtures were very nearly the same at Standard Proctor maximum density. Therefore, all RMGC mixtures were compacted to 91 pcf at a moisture content of 25% with a compactive effort equivalent to Standard Proctor. PRC mixtures were not so well behaved. As a result of the quite large variation in compacted unit dry weights and optimum moisture contents of PRC mixtures, it was necessary to develop curves relating compactive effort to unit weight and optimum moisture content for various mixtures. Figure 5.10 shows a typical set of curves relating PRC unit dry weight and compactive effort. It is interesting to note that as lime content is increased the effect of increased compactive effort is damped. This is a direct result of granulation which occurs during lime treatment. As soil particles become more nearly granular from lime treatment, impact compaction becomes less effective in producing high compacted unit dry weights, the behavior approaching that of sand. As compactive effort is increased, optimum moisture content is reduced for any given soil mixture, as shown in Fig 5.11. As in the case of unit dry weights, effectiveness of compactive effort in reducing optimum moisture content decreases with increasing lime content. Granulation is also the cause of this behavior.

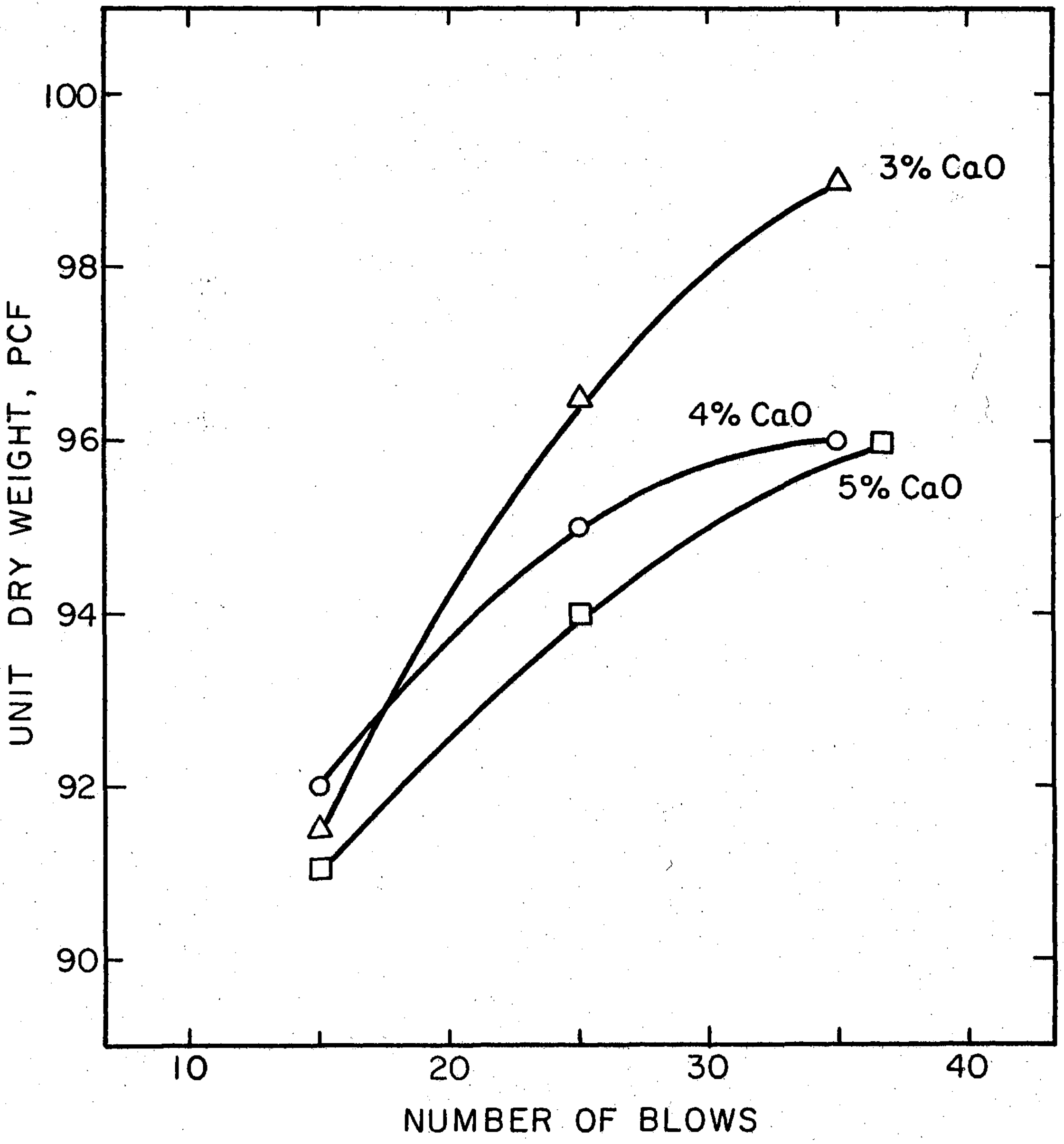


Figure 5.10. Effect of Compactive Effort on PRC-Lime Mixture Density

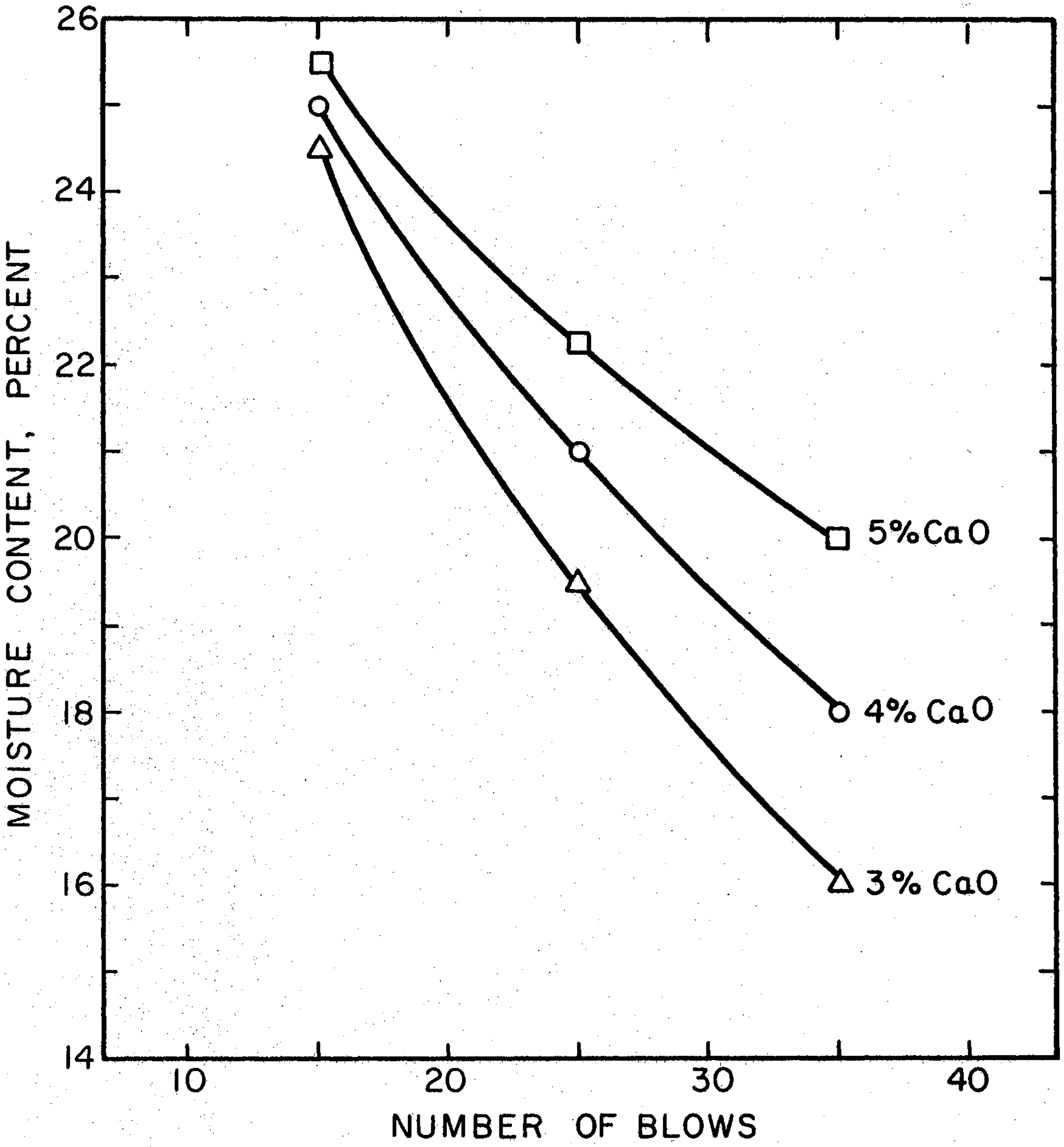


Figure 5.11. Effect of Compactive Effort on PRC-Lime Mixture Optimum Moisture Content

Curves representing compacted dry density and optimum moisture content as a function of compactive effort developed for other PRC mixtures are presented in Appendix B. By reference to these curves it was possible to produce equal moisture contents and dry densities for all soil mixtures to be compared. Required density was obtained at the prescribed moisture content by varying compactive effort for each mixture. Since it was not the purpose of this study to compare strength gains obtained during lime stabilization to those obtained during lime modification, lime and salt-lime mixtures containing modification lime contents were not compacted by the same specifications as those containing stabilization lime contents.

PRC mixtures having lime contents at and near modification optimum were compacted to 96 pcf at a moisture content of 22%. Compactive efforts required to produce these conditions for various PRC mixtures are presented in Table 5.1.

| PRC Soil Mixtures | No. of Blows/Layer |
|---|---|
| PRC | 20 |
| PRC + 2% Lime | 22 |
| PRC + 2% Lime + 1% salt | 22 |
| PRC + 3% Lime | 24 |
| PRC + 3% Lime + 1% salt | 16 |
| PRC + 4% Lime | 35 |
| PRC + 4% Lime + 1% salt | 17 |
| PRC + 5% Lime | 36 |
| PRC + 5% Lime + 1% salt | 15 |

Table 5.1. Compactive Effort Required to Obtain a Unit Dry Weight of 96 pcf at a Moisture Content of 22%

PRC mixtures having stabilization lime contents with and without sodium chloride were compacted to 88 pcf dry density at a moisture content of 18%. Compactive efforts required to obtain density at the specified moisture content for various PRC mixtures are given in Table 5.2.

| PRC Soil Mixtures | No. of Blows/Layer |
|---|---|
| PRC + 7% Lime | 24 |
| PRC + 7% Lime + 1% salt | 15 |
| PRC + 8% Lime | 25 |
| PRC + 8% Lime + 1% salt | 15 |
| PRC + 9% Lime | 26 |
| PRC + 9% Lime + 1% salt | 15 |

Table 5.2. Compactive Effort Required to Obtain A Unit Dry Weight of 88 pcf at a Moisture Content of 18%

Compactive efforts based on control data were often found to require minor adjustment during the compaction process to obtain desired conditions. This may have resulted from some inconsistency in the human element, since variation in the amount of soil put in each lift for compaction was found to be very influential on resulting density. Required adjustments in compactive effort usually amounted to only one or two blows per layer. Compacted densities obtained were found to be quite consistent.

Unconfined compression tests are rapid shear strength tests, for which it is assumed that no moisture loss will occur during the course of the test. In order to approach this condition, a strain rate is required that will produce failure within a relatively short period of time. A strain rate was selected which would produce a 5% strain in the specimen within ten minutes. Specimen heights of 2.8125 inches thus required a loading rate of 0.02 inches per minute.

Immediately after failure, unconfined compression specimens were checked for moisture content. This procedure was adopted to insure that testing moisture contents were approximately the same as compaction moisture contents. Throughout the entire testing program moisture contents existing at the time of testing were found to be within 2% of design moisture contents. By drying the entire specimen for moisture determination, it was possible to obtain a rough approximation of dry density at testing. Density determinations were rough in that loss of one gram of sample during failure reduced the unit dry weight obtained by approximately one pound per cubic foot. Although the method was approximate for dry unit weight determination, unit dry weights of all specimens tested were found to be within 3 pcf of design dry density values.

A computer program was developed to reduce the large amount of data from the unconfined compression tests. The program and a typical output sheet are shown in Appendix C. The program was set up to handle double-ring proving rings and any size test specimen. Variations in loading rate can also be considered, so that the program could be used for reduction of any type compression test data.

In the remaining portion of this section, strength characteristic data and discussions of these data will be presented for both soils. Although qualitative comparisons of compressive strength obtained from chemical treatment of PRC and RMGC cannot be made because of differences in specimen moisture contents and density, some quantitative comparisons of effects of various additives on strength may be inferred.

## Strength of Sodium-Chloride Treated Soils

Analysis of unconfined compressive strength data obtained for sodium chloride treated soils revealed very interesting behavior. Maximum strength gains for both soils were obtained by addition of previously discussed salt percentages that produced maximum dry densities and minimum optimum moisture contents. As shown in Fig 5.12, PRC obtained maximum strength with addition of one percent salt. A maximum strength of 34 psi was obtained, which represents a gain in strength of over 100% above the 16 psi obtained for untreated PRC. Strength gains obtained with addition of one percent salt were not attributable to increased unit dry weight or decreased moisture content, since all sodium chloride treated PRC specimens were compacted to 100 pcf at a moisture content of 18%. For all mixtures this required Standard Proctor compactive effort. As indicated in Fig 5.13, RMGC responded most favorably to two percent sodium chloride treatment. As for PRC, the maximum strength gain for RMGC was in excess of 100%, from 10 psi for raw soil to 23 psi at 28-days by treatment with two percent salt. Since all RMGC mixtures were compacted to 95 pcf dry density at a moisture content of 25%, strength gains obtained as a result of salt treatment cannot be attributed to differences in specimen density or moisture content. These test results indicated that sodium chloride does react in some manner with clay particles. Since strength gains occur within relatively short curing periods, with little increase occurring in latter stages of curing, sodium chloride may affect

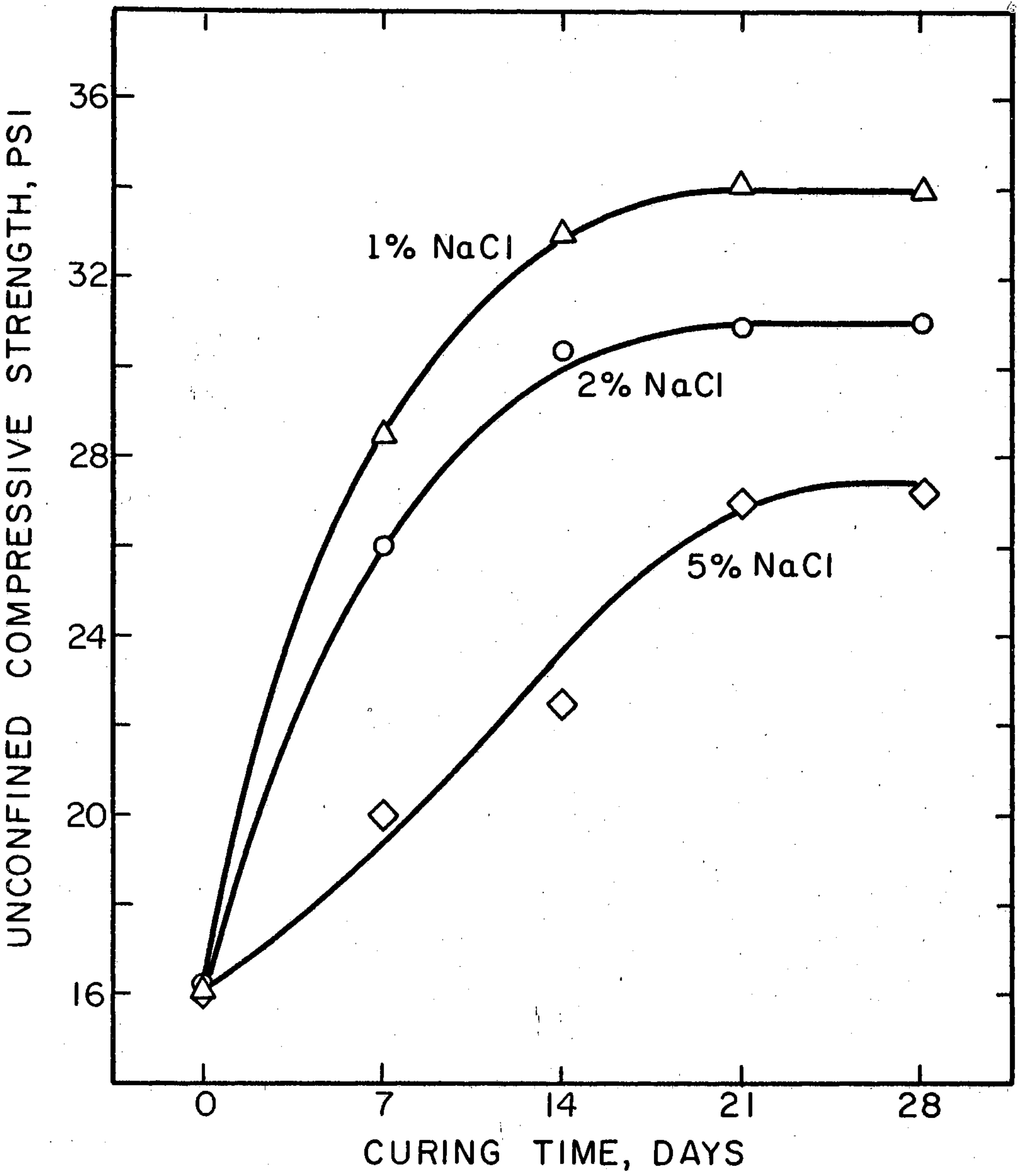


Figure 5.12. Effect of Sodium Chloride Treatment on Compressive Strength of PRC

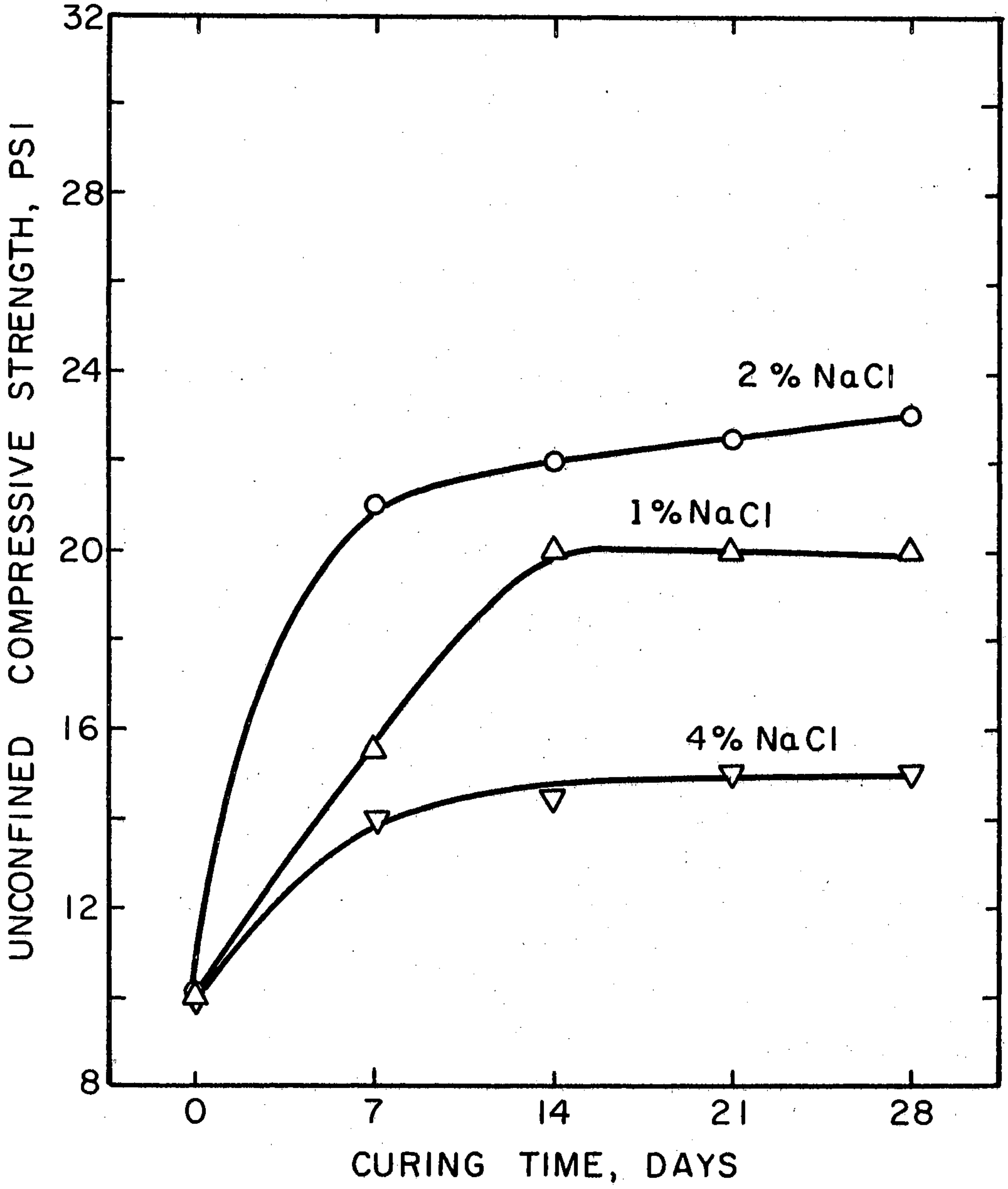


Figure 5.13. Effect of Salt Treatment on Compressive Strength of RMGC

clay particle charges to produce a change in edge to face particle attraction. A phenomenon of this type would occur rapidly and produce high strength gains as more particles were attracted edge to face. No additional strength increase would be expected after this readjustment occurred, which would explain the asymptotic nature of obtained strength curves.

## Strength of Lime and Salt-Lime Modified Soils

Although strength gain is not of primary importance during lime modification, some gain in compressive strength is obtained. These gains in strength are a result of granulation or aggregation of clay particles, which occurs during modification, rather than cementitious bonding by new mineral growth such as that occurring during stabilization. Some very low strength amorphous gels may be formed during lime modification; however, these contribute very little strength. It would be advantageous to obtain higher strengths in shorter periods during lime modification by addition of a chemical additive. In the following portion of this section, effects of sodium chloride, used as a chemical additive in lime modification, on unconfined compressive strength characteristics will be presented and discussed.

Although the modification optimum of both soils had been obtained by PI determination procedures, it was desired to confirm these lime contents by some other procedure prior to strength studies. Confirmation of modification optimum lime contents was obtained by use of the quick test for modification optimum lime content, developed by Eades and Grim (Ref 22). Results of pH tests conducted for modification optimum determinations of both soils are shown in Fig 5.14.

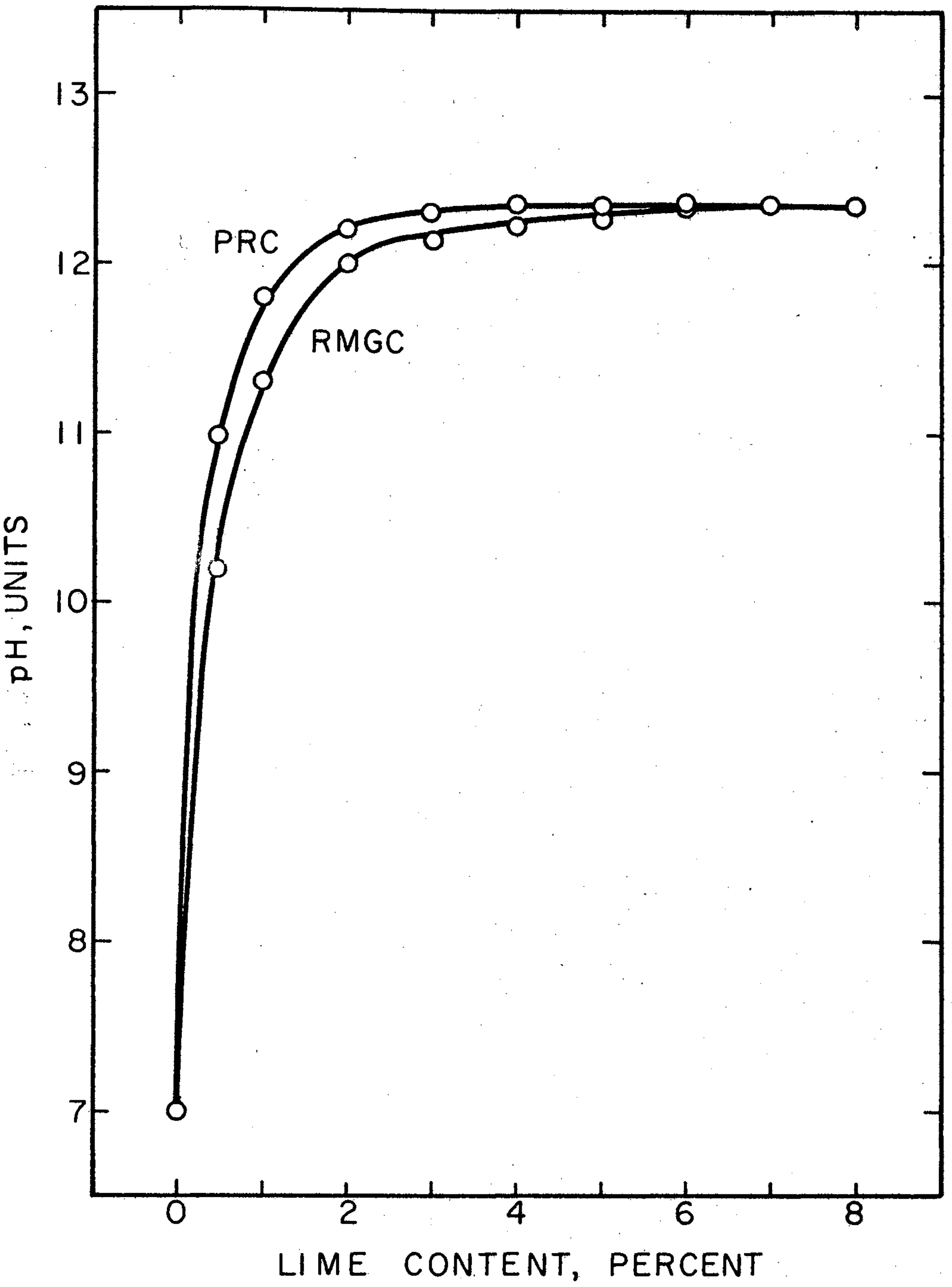
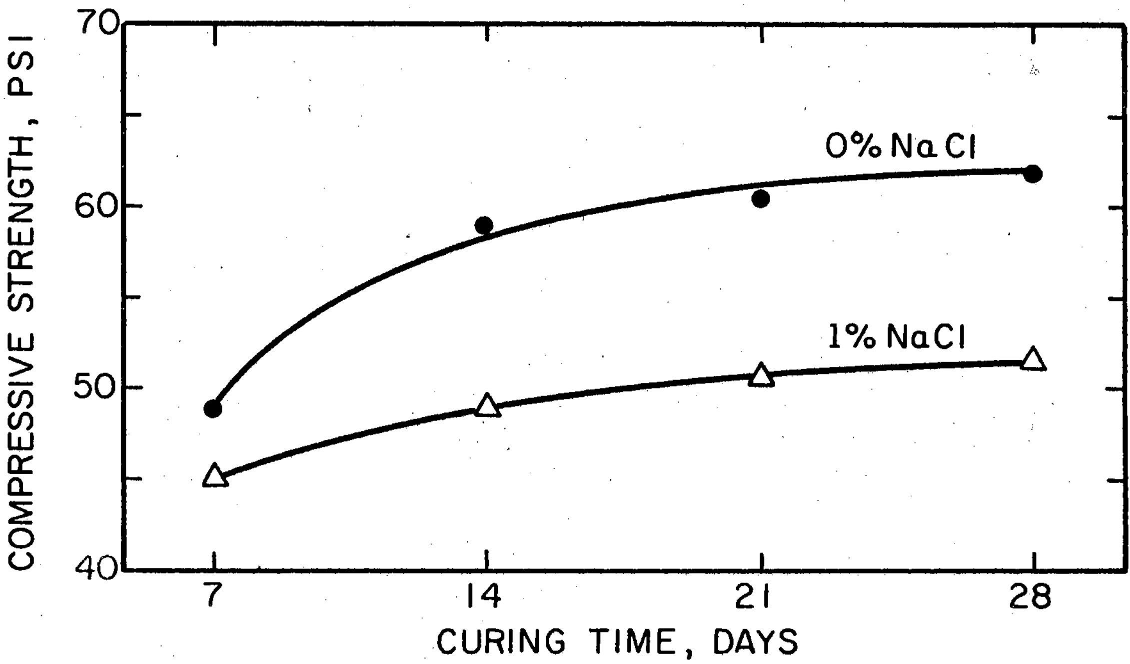


Figure 5.14. Results of pH Test for Determination of Lime Modification Optimum Contents for PRC and and RMGC

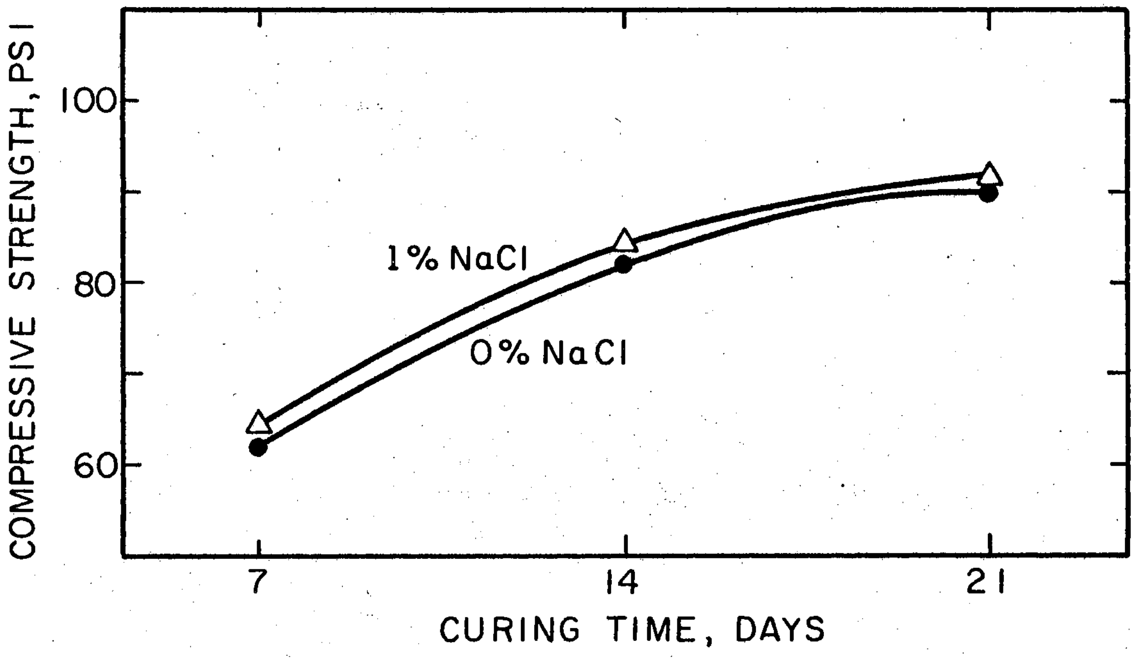
Modification optimum lime contents of 4% for PRC and 6% for RMGC agreed with those obtained by PI determination.

Lime modification of PRC with 2%, 3%, 4% and 5% calcium oxide produced substantial increases in strength over that of raw soil. Major portions of these strength gains were found to occur with the first few days of curing. Addition of one percent sodium chloride in conjunction with modification lime contents produced higher strengths than those obtained with lime alone in all cases except for two percent lime. Sodium chloride was found to increase in effectiveness with increase in lime content of PRC mixtures. Based on 21-day compressive strengths the maximum strength gain was obtained with 4% lime - 1% salt treatment; however, the maximum increase in strength during curing was realized at a lime content of 3%. This lime content is one percent less than modification optimum. Strength values obtained for lime modified PRC mixtures after 21 days of curing were 62.0 psi for 2% lime, 90 psi for 3% lime, 94 psi for 4% lime, and 87.5 for 5% lime. Addition of 1% salt produced strength values of 51.5 psi for 2% lime, 92 psi for 3% lime, 99 psi for 4% lime, and 98 psi for 5% lime. These strength values represented increases of 2.2% for 3% lime, 5.3% for 4% lime, and 13% for 5% lime. A reduction of 16% in compressive strength was obtained with addition of one percent sodium chloride in conjunction with 2% lime. Characteristics of lime and salt-lime modified PRC mixtures are shown in Fig 5.15a through 5.15d by curves representing unconfined compressive strength as a function of curing time.

Modification of RMGC with 5%, 6%, and 7% calcium oxide increased unconfined compressive strength in all cases. Strength gains were

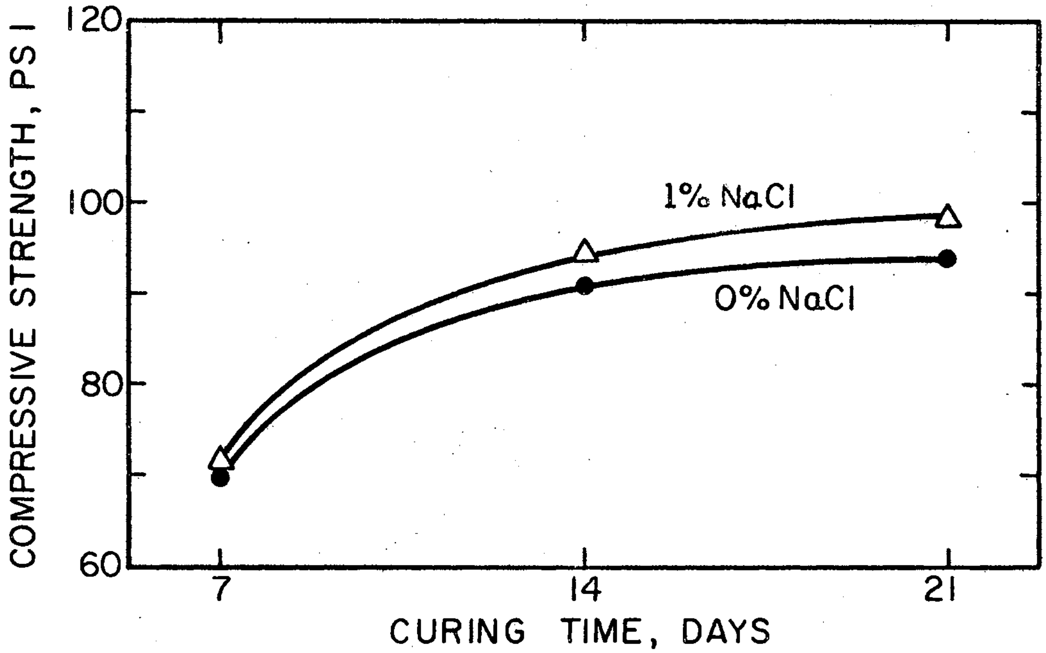


(a) Behavior of 2% Lime and Salt-Lime Treated PRC

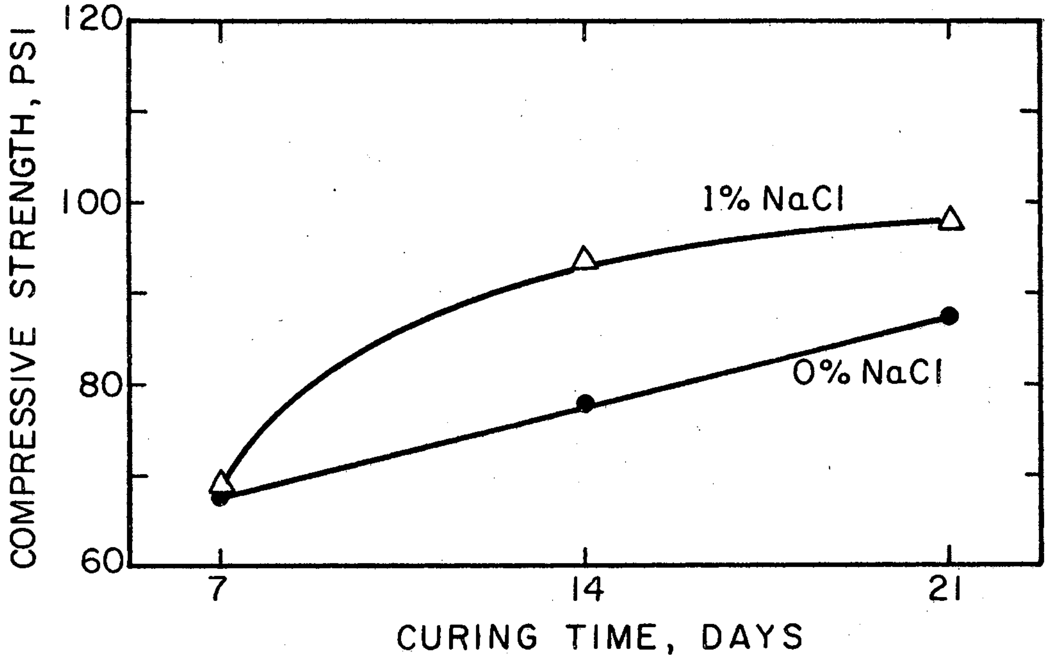


(b) Behavior of 3% Lime and Salt-Lime Treated PRC

Figure 5.15. Effect of Lime and Salt-Lime Modification on Compressive Strength of PRC Mixtures at Constant Moisture Content and Density



(c) Behavior of 4% Lime and Salt-Lime Treated PRC

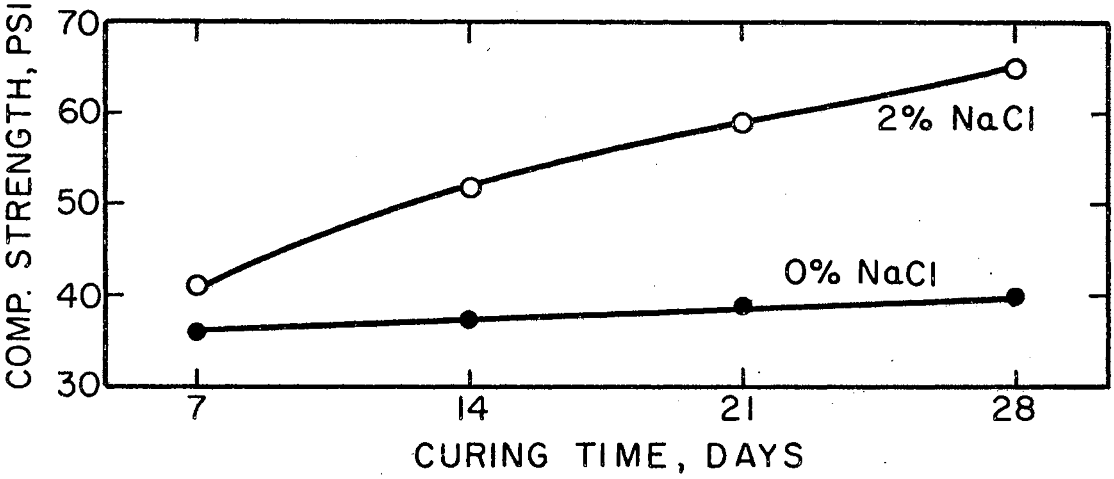


(d) Behavior of 5% Lime and Salt-Lime Treated PRC

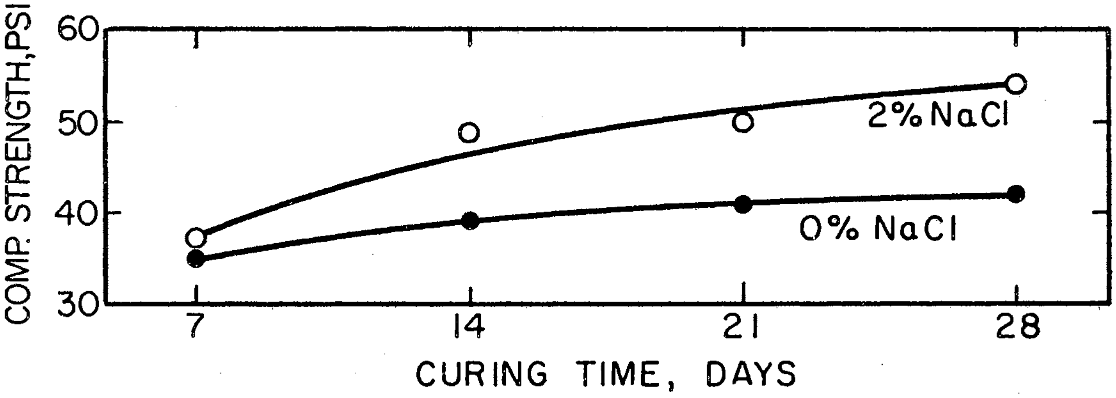
Figure 5.15. Effect of Lime and Salt-Lime Modification on Compressive Strength of PRC Mixtures at Constant Moisture Content and Density

found to occur in short curing periods as with modification of PRC. However, two occurrences were noticed which were very different than behavior noticed in PRC. The 7-day compressive strengths of all soil mixtures were found to be 35 psi. Thus, RMGC did not respond to variation in lime content during early periods of curing. Secondly, curing time was found to have very little effect on strength gains of RMGC mixtures containing only lime. Compressive strengths at 28 days were 40 psi for 4% lime, 41 psi for 6% lime, and 38 psi for 7% lime. Introduction of sodium chloride in conjunction with lime modification was found to affect RMGC mixtures similarly to PRC. Addition of salt with calcium oxide did produce higher strengths for all lime contents than those obtained by lime treatment alone; however, effectiveness of salt was found to decrease with increasing lime content. The rate of strength increase during curing was also found to decrease in salt-lime RMGC mixtures with increasing lime content. Addition of two percent sodium chloride in combination with lime produced increases of 24 psi for 5% lime, 17 psi for 6% lime, and 8.5 psi for 7% lime, over compressive strengths obtained by lime treatment alone. Unconfined compressive strength characteristics of lime and salt-lime modified RMGC are presented in Figs 5.16a, 5.16b, and 5.16c by curves representing compressive strength as a function of curing time.

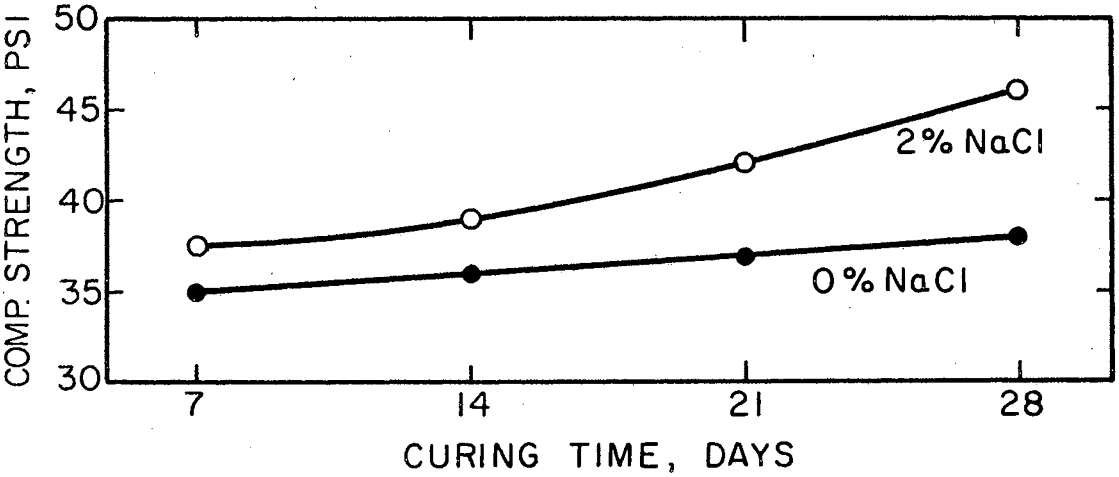
Lime and salt-lime modification effects on unconfined compressive strength of both soils are presented in Figs 5.17a and 5.17b for comparative purposes. These curves, which represent compressive strength as a function of lime content for various mixtures of PRC and RMGC, summarize modification studies based on maximum strength gains obtained at 21 and 28 days of curing.



(a) Behavior of 5% Lime and Salt-Lime Treated RMGC

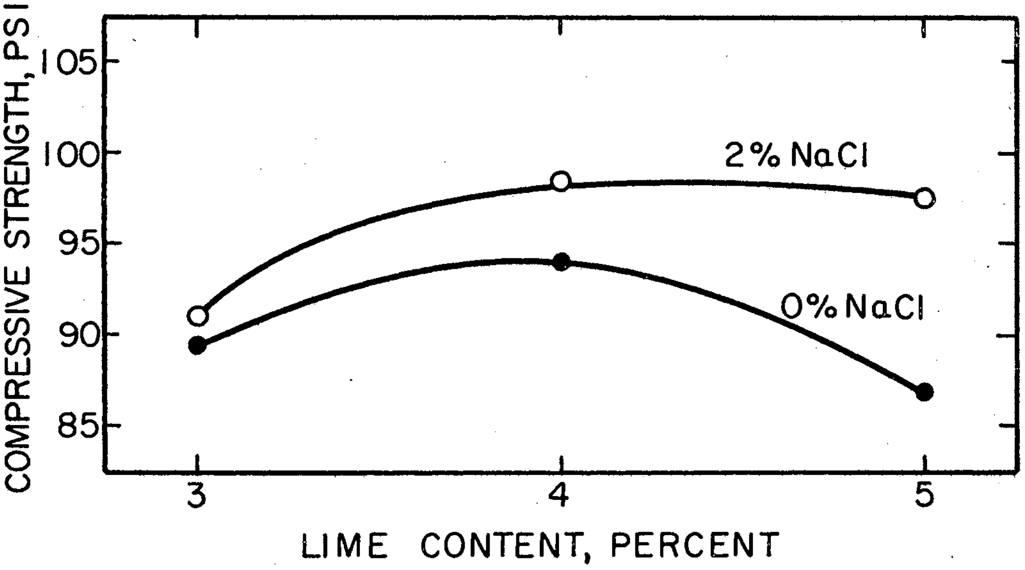


(b) Behavior of 6% Lime and Salt-Lime Treated RMGC

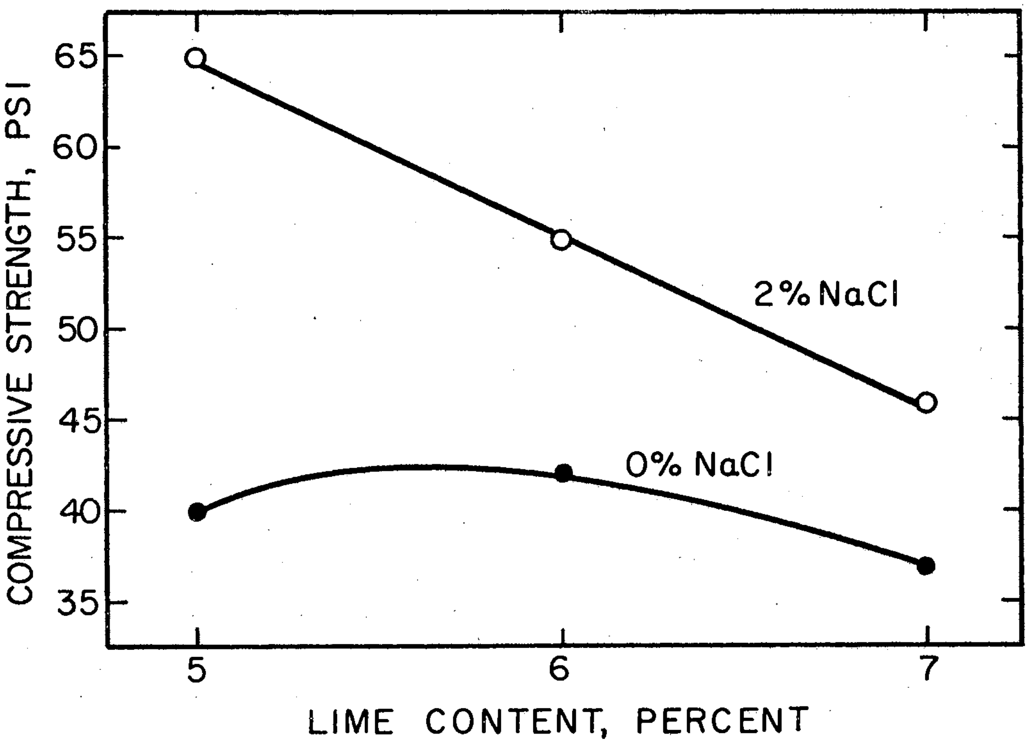


(c) Behavior of 7% Lime and Salt-Lime Treated RMGC

Figure 5.16. Effect of Lime and Salt-Lime Modification on Compressive Strength of RMGC Mixtures at Constant Moisture Content and Density



(a) Lime and Salt-Lime Treated PRC 21-Day Strengths



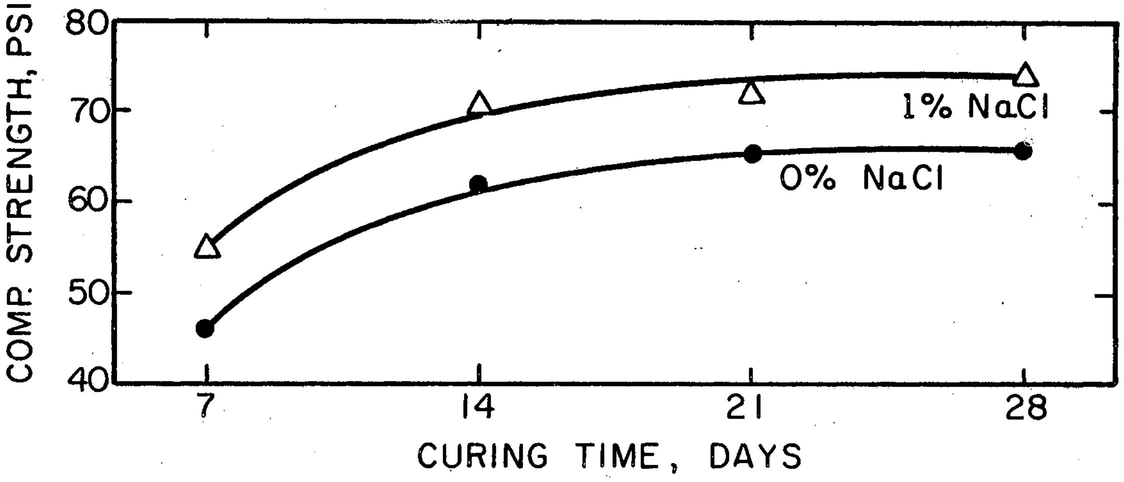
(b) Lime and Salt-Lime Treated RMGC 28-Day Strengths

Figure 5.17. Effect of Lime and Salt-Lime Modification on Compressive Strength of PRC and RMGC Mixtures at Constant Moisture Content and Density

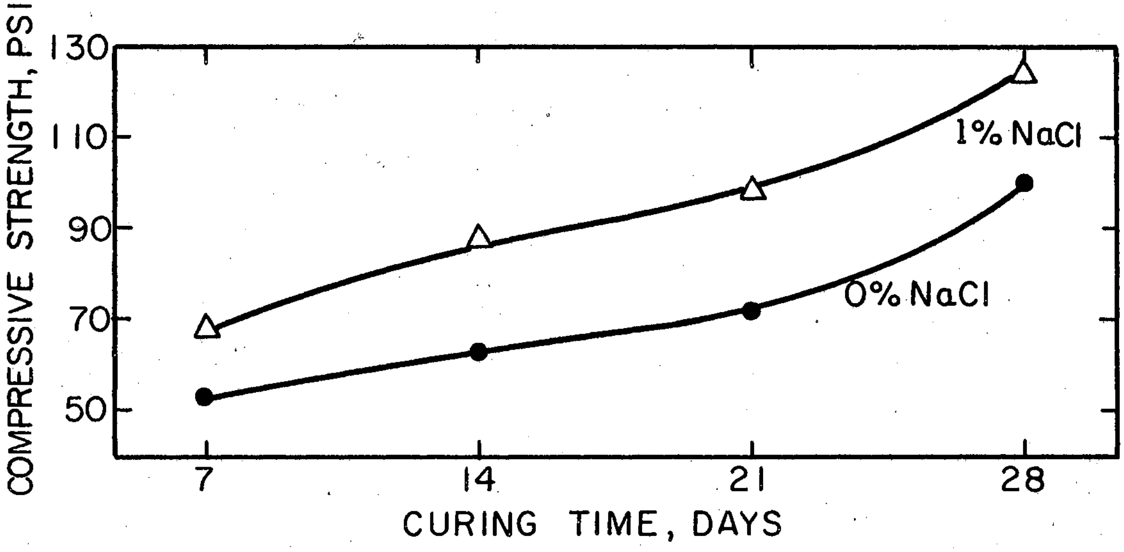
## Strength of Lime and Salt-Lime Stabilized Soils

Stabilization optimum was found to be very distinctive for PRC in analysis of 28-day compressive strengths. Compressive strength curves shown in Figs 5.18a, 5.18b, and 5.18c indicate very clearly the effect of lime content on new mineral growth which produces strength gains in stabilization. Treatment of PRC with 7% calcium oxide, which was found to be one percent less than stabilization optimum, produced a rapid strength gain during early stages of curing; however, strength increase for longer periods of curing was found to be very small. This phenomenon is a direct result of pH conditions in the soil-lime mixture. As pozzolanic reactions occur, pH of the mixture is reduced as calcium silicate hydrate (CSH) is formed. Mineral growth occurs in sequence from softer to more rigid, cementitious crystals often termed CSH I and CSH II, respectively. This process is very pH dependent, thus certain pH conditions must be present to obtain full development of cementitious minerals. As indicated by the curve for 7% lime, CSH I was formed during early stages of curing at a very rapid rate, producing high strength gains.

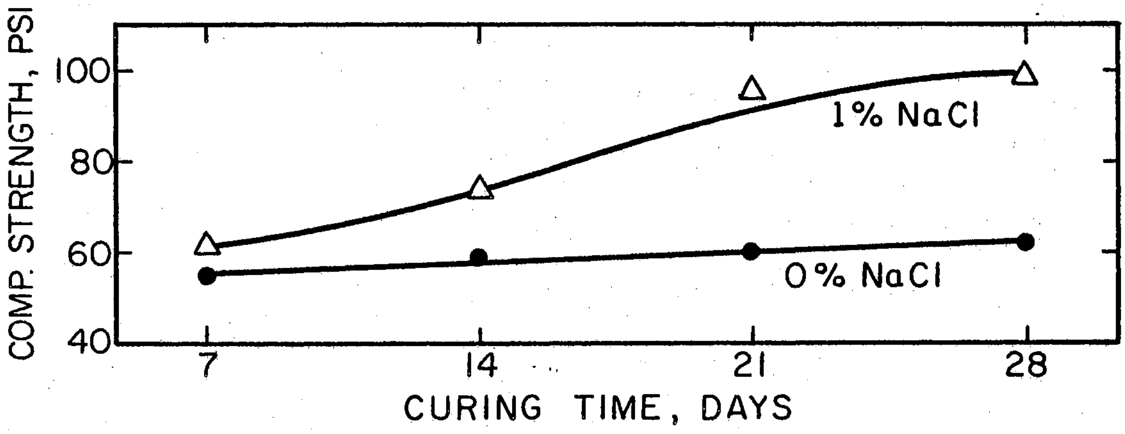
However, as a result of CSH I formation pH values were reduced to the extent that transformation of CSH I into CSH II was not possible and strength gains were essentially halted. In comparison, strength gains during early stages of 8% lime stabilized mixtures were more gradual as CSH I was being formed. Thus, pH conditions were not so drastically affected and accelerated strength gains were obtained during latter stages of curing when CSH I was being transformed to CSH II. Opposite conditions were found to exist for 9% calcium oxide. Because of the abundance of calcium ions, pH is so high that mineral



(a) Behavior of 7% Lime and Salt-Lime Treated PRC



(b) Behavior of 8% Lime and Salt-Lime Treated PRC



(c) Behavior of 9% Lime and Salt-Lime Treated PRC

Figure 5.18. Effect of Lime and Salt-Lime Stabilization on Compressive Strength of PRC Mixtures at Constant Moisture Content and Density

formation is halted. Since CSH I cannot be transformed to CSH II, strength gains during long periods of curing are negligible.

Addition of one percent sodium chloride in conjunction with lime contents near and at stabilization optimum produced greater compressive strengths than lime treatment alone. The rate of strength gain was substantially increased for all mixtures except those containing 7% lime. In this case strengths were consistently higher; however, the rate of strength gain was found to be identical to lime treatment. This behavior coupled with accelerated strength gains found for 8% and 9% lime mixtures indicates that sodium chloride causes an increase in solubility of silica, thus accelerating the formation of CSH I and CSH II. This catalytic type reaction is characterized by the increased rate of strength gain realized during salt-lime stabilization. However, effects of the prevailing pH conditions discussed previously are also reflected in salt-lime stabilization curves, although not as distinctively as with lime stabilization.

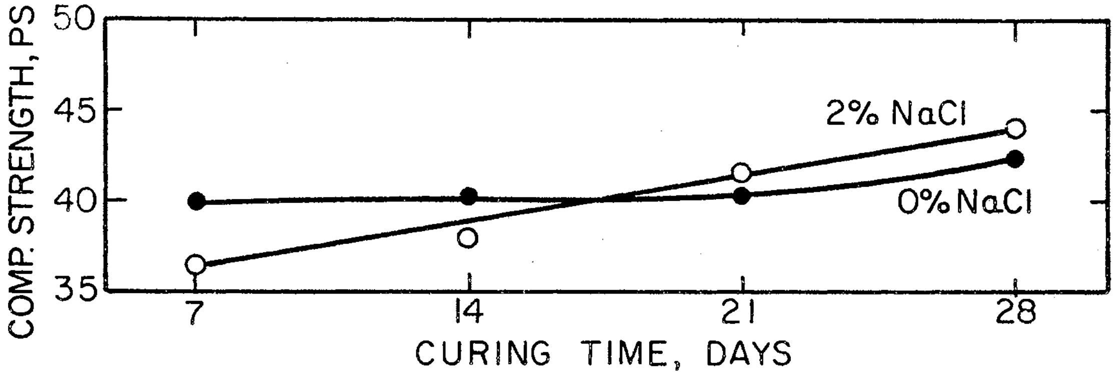
Although much less responsive to both lime and salt lime stabilization with respect to lime content and curing time, RMGC reacted similarly to PRC. Rate of strength gain was substantially increased by addition of two percent sodium chloride in conjunction with lime. Strength gains during the 28-day curing period were not outstanding for any of the RMGC lime mixtures; however, at 11% lime, which was found to be stabilization optimum, the rate of strength gain was substantially higher than the other two percentages. Effects of pH on RMGC were found to be opposite to those with PRC. At low pH conditions (10% lime) strength gains were found to be reduced, similar to behavior obtained for high pH conditions in PRC. High rates of strength increase during early stages of curing with little gain in latter curing periods were found to occur below stabilization optimum in PRC but above same in RMGC mixtures.

Addition of two percent sodium chloride in conjunction with lime produced higher rates of strength gain for all RMGC mixtures, particularly in latter stages of curing. Unlike PRC, RMGC salt-lime mixtures did not have higher compressive strengths during early stages of curing; however, in all cases 28-day compressive strengths were greater for salt-lime mixtures than for RMGC-lime mixtures. Effects of pH were not noticeably reflected in salt-lime treated RMGC compressive strengths, as was found for PRC mixtures. This may be a direct result of variation in silica-sesquioxide ratios of the two soils. Since RMGC probably has a higher ratio, the presence of sodium chloride causes a greater relative catalytic reaction in latter stages of curing for RMGC than for PRC. Comparisons of compressive strength characteristics for lime and salt-lime stabilized mixtures are presented in Figs 5.19a, 5.19b, and 5.19c.

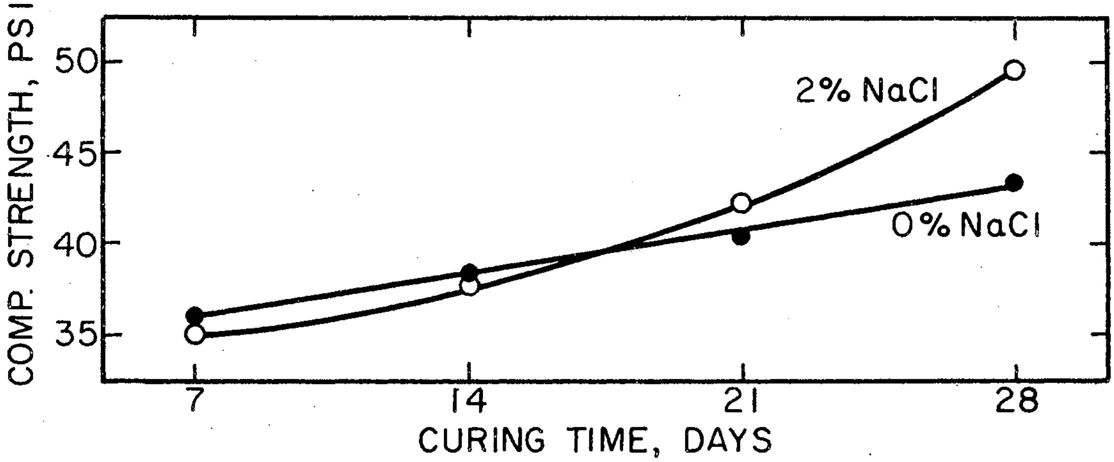
In order to summarize relative effects of salt-lime and lime stabilization of cohesive materials, curves expressing strength as a function of lime content for both PRC and RMGC are presented in Figs 5.20a and 5.20b. From these curves it is evident that 8% lime and 8% lime-1% salt are stabilization optima for PRC, while RMGC requires 11% lime and 11% lime-2% salt to produce maximum 28-day strengths.

## Swelling Characteristics of Treated Soils

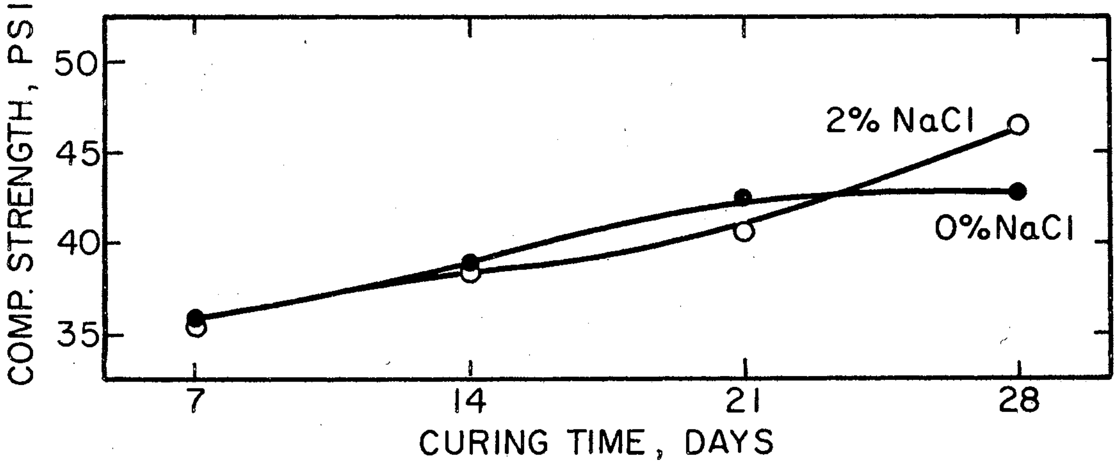
Chemically treated soil mixtures, prepared by standard procedures, were compacted into discs by impact compaction to form swell test



(a) Behavior of 10% Lime and Salt-Lime Treated RMGC

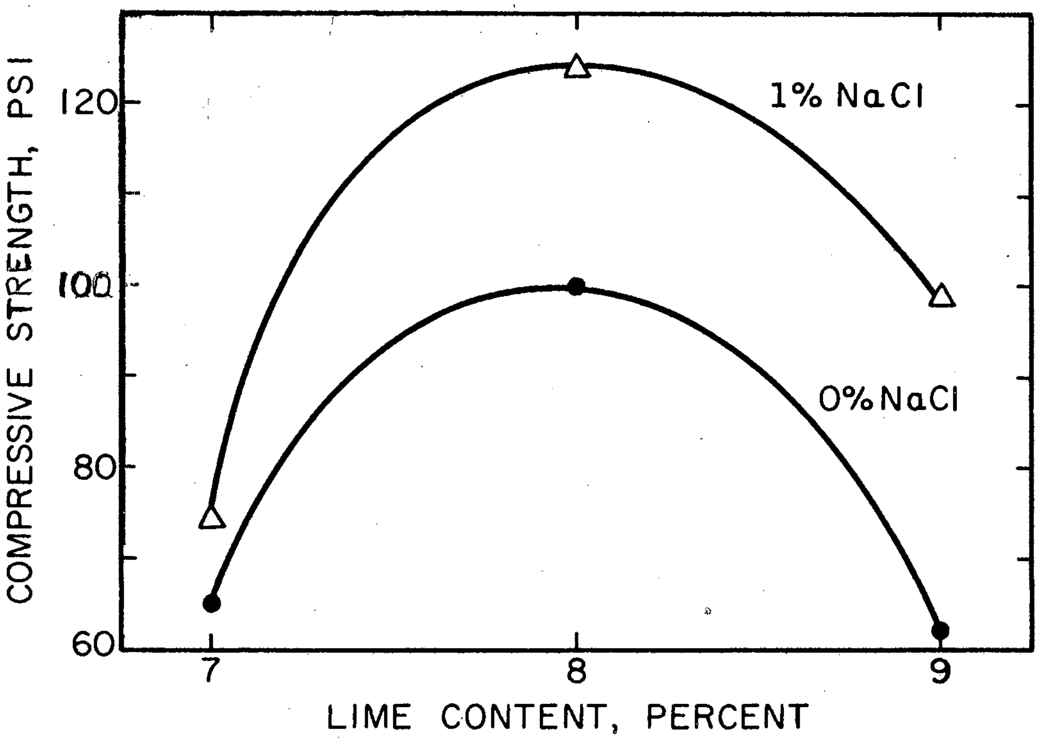


(b) Behavior of 11% Lime and Salt-Lime Treated RMGC

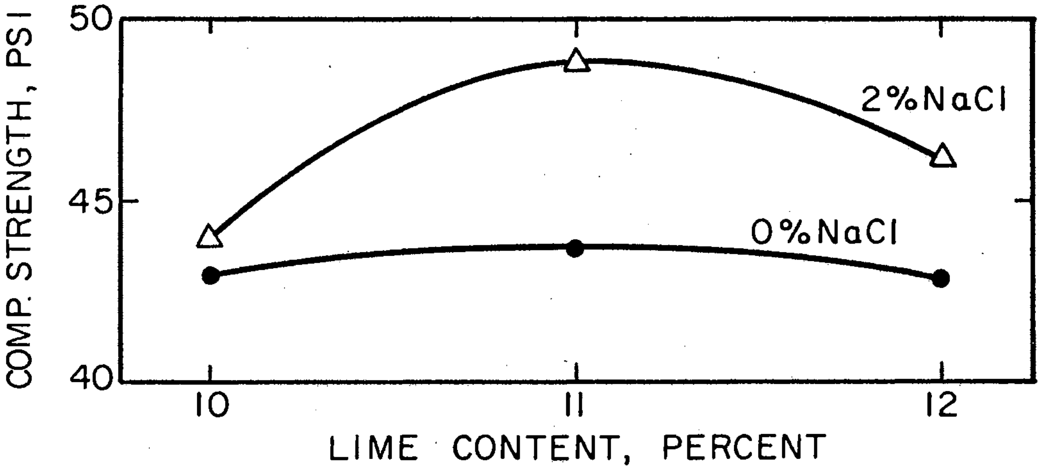


(c) Behavior of 12% Lime and Salt-Lime Treated RMGC

Figure 5.19. Effect of Lime and Salt-Lime Stabilization on Compressive Strength of RMGC Mixtures at Constant Moisture Content and Density



(a) Behavior of Lime and Salt-Lime Stabilized PRC Mixtures



(b) Behavior of Lime and Salt-Lime Stabilized RMGC Mixtures

Figure 5.20. Effect of Lime and Salt-Lime Stabilization on 28-Day Compressive Strengths of RMGC and PRC Mixtures at Constant Moisture Content and Density

specimens. Specimens were made 2.50 inches in diameter and 1.25 inches in height initially by compaction in a specially constructed mold. The compaction mold was made from a 2.50 inch ID seamless aluminum pipe. A segment of the pipe 1.50 inches long was cut and machined. A special compaction head 2.50 inches in diameter was constructed in such a manner so that only 0.25 inches of the head could fit into the mold. Thus with the head in place a void 1.25 inches in height was formed by the mold and head.

All swell test specimens were compacted to the same dry density and moisture content to eliminate these variables. Through preliminary testing, small percentages of lime and salt+lime were found to reduce swelling of both materials under imposed loads to negligible values. Therefore, continued swell testing of lime and salt-lime mixtures was deemed uninformative. Thus salt treated PRC and RMGC specimens constituted the major portion of swell tests conducted. PRC specimens were compacted to 100 pcf at 19% moisture while RMGC salt treated specimens were compacted to 91 pcf at a moisture content of 22%.

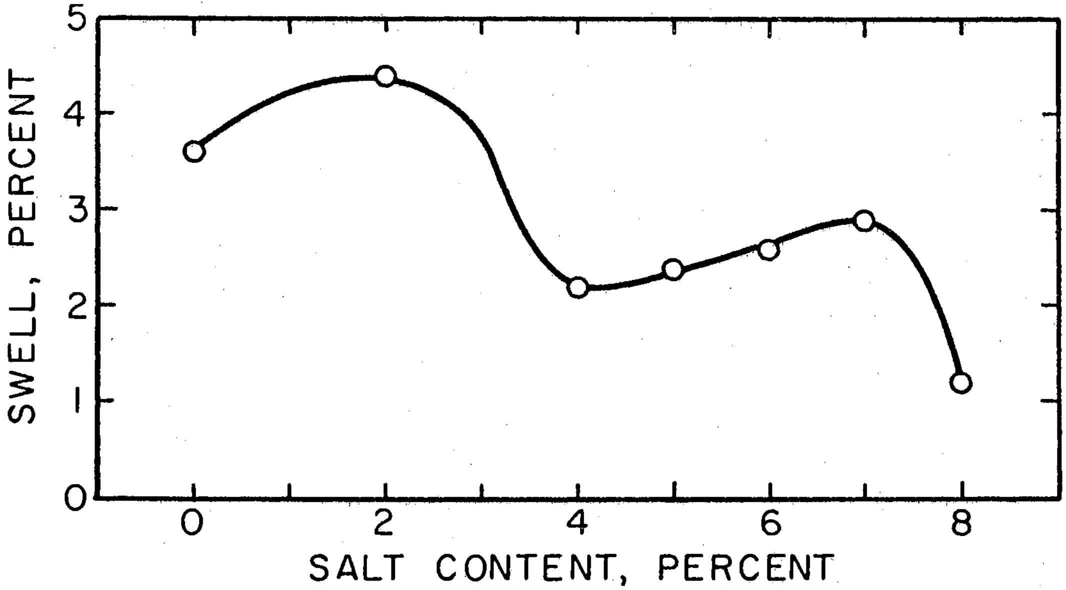
In preparation of compacted specimens for testing, the 1.25 inch discs were placed in 0.75 inch teflon rings. This procedure required that 0.50 inches of the specimens be trimmed. After trimming, necessary wet weights were obtained for determination of initial moisture content of test specimens.

Swell tests were conducted in a direct load frame. Since relative values of swelling were desired, a standard load was adopted to be imposed on all specimens during swelling. Representation of field conditions was desired in arriving at a loading value; therefore, a load was adopted which would impose pressures on swell specimens equivalent to those that might occur in highway subgrades. Specimens were assumed to be located one foot below the subgrade surface in a typical Portland cement concrete pavement section. The assumed cross-section consisted of one foot of Portland cement concrete pavement with a one foot stabilized aggregate base course placed directly on the subgrade. A design load of 0.2 tsf was obtained for soil one foot below the subgrade finished grade. The typical cross-section assumed and calculations of the swell test load are presented in Appendix D.

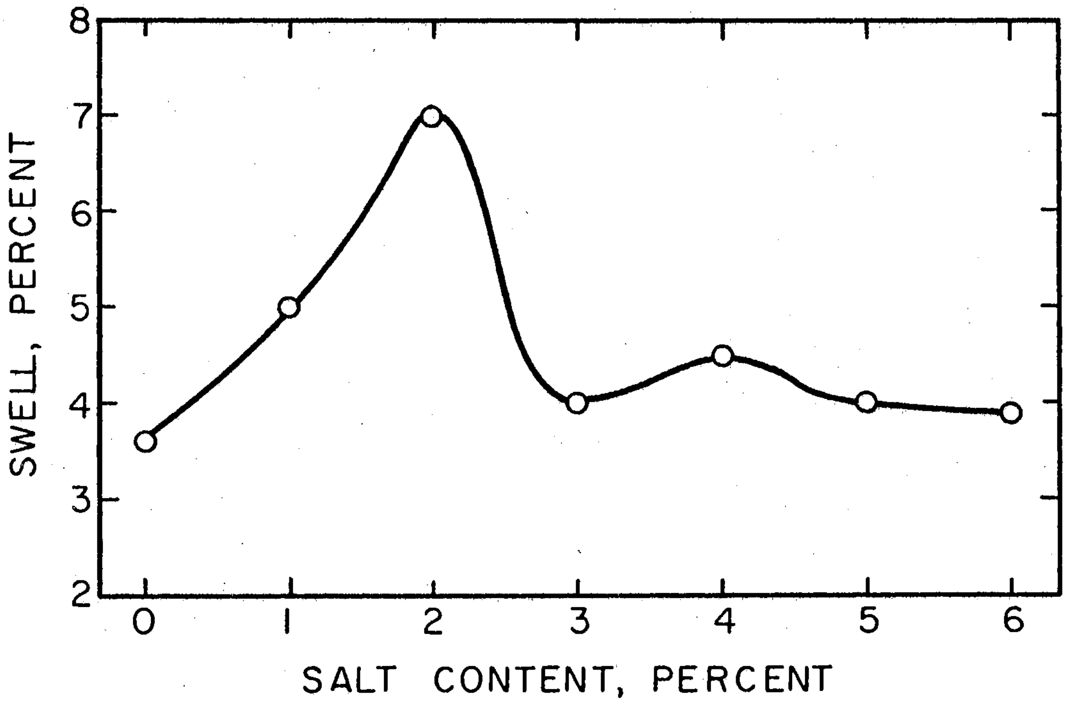
Contrary to expectation, PRC and RMGC underwent the same amount of swelling. It would be expected that RMGC, being more plastic than PRC, would swell more; however, both materials were found to swell 3.6% with respect to original thickness.

Addition of sodium chloride produced increased swelling potential of both soils. Both soils were found to swell a maximum amount with addition of 2% salt. PRC increased from 3.6% to 4.4% swelling with addition of two percent sodium chloride while RMGC increased from 3.6% to 7.0%. Addition of percentages greater than two percent caused a reduction in swelling; however, with addition of percentages greater than four percent swelling was again increased. From 2.2% swelling at 4% salt, an increase of 0.7% swelling was obtained with addition of 7% salt. Eight percent salt treatment reduced the swelling of PRC to 1.2%. Thus, salt treatment of PRC produced a double optimum curve representing swelling as a function of salt content. This curve is presented in Fig 5.21a.

RMGC was found to be more reactive to salt treatment relative to swelling than PRC. A maximum swelling value was attained at 2% salt content with a second optimum occurring at 4% salt. Addition of 6%



(a) Behavior of PRC Mixtures



(b) Behavior of RMGC Mixtures

Figure 5.21. Effect of Salt Treatment on Swelling of PRC and RMGC

sodium chloride reduced swelling to very near that of the raw soil. Percentages greater than 6% did not substantially reduce swelling below that of raw RMGC (3.6%). Swelling characteristics of RMGC salt treated mixtures are presented in Fig 5.21b.

Effect of salt treatment on swelling characteristics of both materials may be explained by analysis of clay particle behavior under various pore water electrolyte concentrations. As increasing percentages of sodium chloride are added to clays, electrolyte concentration increases within the pore water producing flocculation. Submergence of specimens during testing allows dilution of pore water or reduction in electrolyte concentration. Reduction in electrolyte causes deflocculation, which produces swelling as clay particles develop a complete double water layer. At some salt content, found to be 2% for both soils, this phenomenon is maximal. However, with addition of greater percentages of sodium chloride the electrolyte concentration becomes so high that initial flocculation does not occur. Thus, submerged samples do not deflocculate and produce swelling. This phenomenon is characterized by the sudden reduction in swelling potential of both soils with addition of sodium chloride in percentages just over those producing maximum swelling.

## Summary

The foregoing chapter contains data and discussions which are of importance in understanding the behavior of salt-lime treated soils. Principal points are summarized below.

Analysis of salt treatment data indicated that the compaction characteristics of PRC reflected effects of treatment more markedly than did RMGC. Sodium chloride treatment produced a substantial increase in unit dry weight of PRC with a simultaneous decrease in optimum moisture content. RMGC was unaffected (for all practical purposes) by salt treatment with respect to compaction characteristics.

Lime treatment produced reductions in unit dry weights of both soils with corresponding increases in optimum moisture contents. Reduction in unit weight was more pronounced with PRC; however, increase in optimum moisture content was of approximately the same magnitude for PRC and RMGC. These phenomena are direct results of granulation of clay particles, as was clearly demonstrated by comparison of moisture-density curves obtained for raw soils and lime modified soils. Lime modified soils produced sharper moisture-density curves characteristic of granular silty or sandy clay soils.

Salt-lime treatment affected compaction characteristics of both soils very similarly to salt treatment. PRC was more responsive to salt-lime treatment than RMGC. Optimum salt contents of 1% for PRC and 2% for RMGC were found to produce optimum compaction characteristics when used in conjunction with lime. These salt percentages were therefore selected for use in strength studies.

Unconfined compression testing of salt-treated soils indicated that salt percentages which produced most desirable compaction properties also produced greatest strength gains. This behavior was not a result of density and moisture content differences since all specimens were compacted at equal density and moisture content values.

Addition of sodium chloride in conjunction with modification lime contents produced strength gains of 12% for PRC and 62.5% for RMGC over those obtained from 28-day strength tests of lime modified soils, Maximum strength gains were found to occur on either side of modification optimum. PRC and RMGC developed greatest strength with addition of 5% lime and 1% and 2% sodium chloride respectively. For PRC this was above modification optimum while, for RMGC, it was below modification optimum.

Both soils responded significantly to salt-lime stabilization. Maximum strength gains for PRC and RMGC were obtained at stabilization optima of 8% and 11%, respectively. Addition of 1% salt to PRC specimens produced a 28-day compressive strength of 125 psi, which represents a 25% increase over that obtained by lime treatment. A 14% strength increase was realized by addition of 2% salt in conjunction with 9% lime stabilized RMGC.

Swelling of both soils was reduced to negligible values under imposed loads by treatment with very small percentages of salt-lime additives. Salt-lime treatment was found to reduce swelling more than treatment with comparable lime percentages.

Salt treatment was found to increase swelling of both soils to a maximum at 2% sodium chloride. PRC was increased from 3.6% swelling to 4.4% swelling, whereas RMGC was increased from 3.6% to 7.0% swelling with addition of 2% salt. Swelling was reduced back to or below that of raw soil with addition of higher percentages of salt. This behavior is a result of electrolyte concentration conditions of specimens during compaction and submergence.

A complete evaluation of salt and salt-lime treatment of PRC and RMGC will be presented in Chapter VII. Prior to that evaluation some mineralogical effects of chemical treatment are presented in Chapter VI.

# CHAPTER VI

# EFFECTS OF CHEMICAL TREATMENT ON THE MINERALOGY AND CRYSTALLOGRAPHY OF COHESIVE SOILS

## Introduction

Until recent years examination of natural earth minerals by optical methods was impossible. However, with advances in electro-optics, development of the electron microscope enabled researchers to examine the previously unseen. The earlier developed transmission electron microscope was of little use in studying soil minerals because of sample preparation techniques required. Because electrons are transmitted through the sample, thin-sections of materials to be examined have to be made. In soils, this procedure destroys those characteristics which should be examined. Development of the scanning electron microscope opened new doors for soil scientists and clay mineralogists, since relatively large samples with rough surfaces may be examined with very little sample preparation required. Sample preparation procedures which are used do not disrupt the natural state of the clay minerals and crystals contained in the sample.

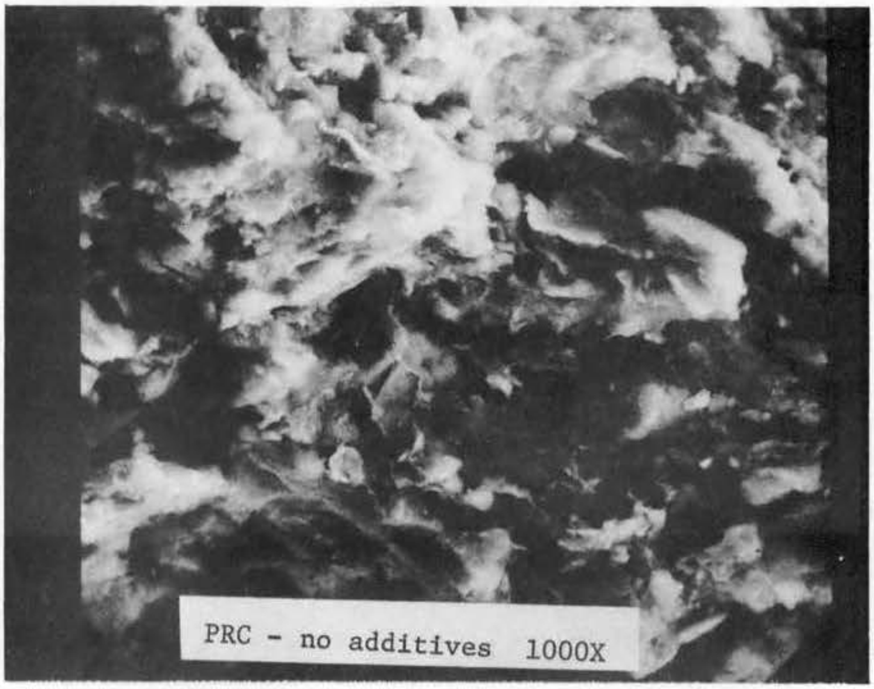
Scanning electron photomicrographs are photographs of images formed by refracted secondary electrons. Secondary electrons are emitted by the sample upon bombardment by the primary electron probe. The primary electron probe is usually 100 Å in diameter at the sample surface. After penetrating the sample, diffusion occurs very rapidly, and thus secondary electrons (which produce the highest resolution image) are emitted from a volume of the sample approximately 100 Å in diameter and 100 Å deep. Optical waves produced at greater depths within the sample produce images of poor resolution (Ref 46).

Sample preparation for examination in the JEOLCO JSM-2 Scanning Electron Microscope was relatively simple; however, specialized equipment was required. Raw soils and chemically treated soil specimens remaining from strength studies were used for scanning electron microscope examination. These specimens ranged in age from nine months to one year, thus mineral growth resulting from chemical treatment was well established. Small pieces of these specimens were oven dried to remove all free moisture. After drying, the samples were coated with a compound of 60% Gold - 40% Palladium. Coating was done by a special technique in a JEOLCO JEE-4C Vacuum Evaporator. Coating of the sample to be examined is required to prevent "charging" by the electron probe during examination. Charging produces static and poor resolution in the optical image.

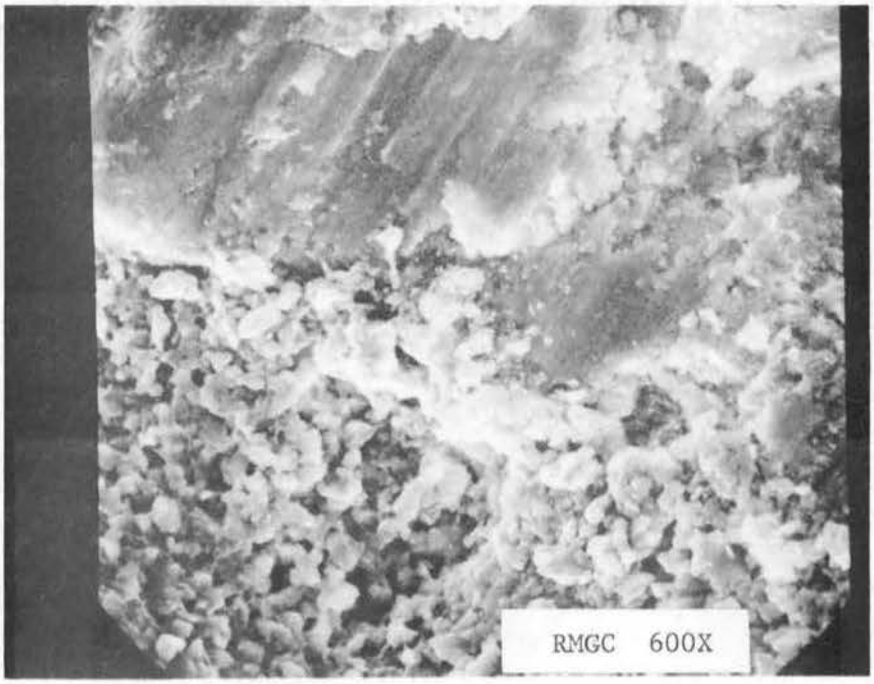
## Scanning Electron Photomicrographs

Examination of photomicrographs of untreated PRC and RMGC reveal some characteristics of these soils which explain the physical properties of these materials. As previously discussed, RMGC contains a lower percentage of fine clay than does PRC; yet, RMGC is more plastic than is PRC, which was somewhat contrary to expectations. Normally, as particle size decreases the plasticity increases with a given clay mineral, thus RMGC must not be composed of the same clay minerals as PRC. In Fig 6.1a a 1000X scanning electron photomicrograph of PRC reveals the very platelike structure of PRC. There appears to be very little orientation of these fine clays; however, orientation which exists is localized in small clay "booklets". Although clay platelets forming these booklets are mutually oriented, orientation of individual booklets is very slight. Contrary to the feathery appearance of PRC, RMGC appears to be "globby" as shown in the 600X photmicrograph of Fig 6.1b. The entire sample does not appear to be clay. Cleavage planes in the upper portion of the figure resemble those of mica sheets. It appears that some highly weathered mica sheets still remain in RMGC, indicating this soil is much younger than the PRC. These photomicrographs show that RMGC does have a smaller percentage of fine clay than PRC. However, the clay minerals in RMGC must have a much higher plasticity than those in PRC.

Effect of sodium chloride on clay minerals was previously discussed in relation to soil chemistry. It has also been shown that salt treatment enhances engineering properties of cohesive soils. Scanning electron photomicrographs of sodium chloride treated PRC and RMGC clearly show these effects of salt on clay minerals. By comparison of Figs 6.2a and 6.2b it is evident that treatment of PRC with 1% salt causes deterioration of the clay minerals. As seen in the first figure, PRC platelets are very distinct and clean in appearance; however, upon treatment with sodium chloride with clay booklets appear very irregular and deteriorated around the edges. No free sodium chloride crystals were found anywhere in the PRC sample containing 1% salt. Treatment of RMGC with 2% sodium chloride was found to cause even more deterioration of minerals comprising this soil. Shown in



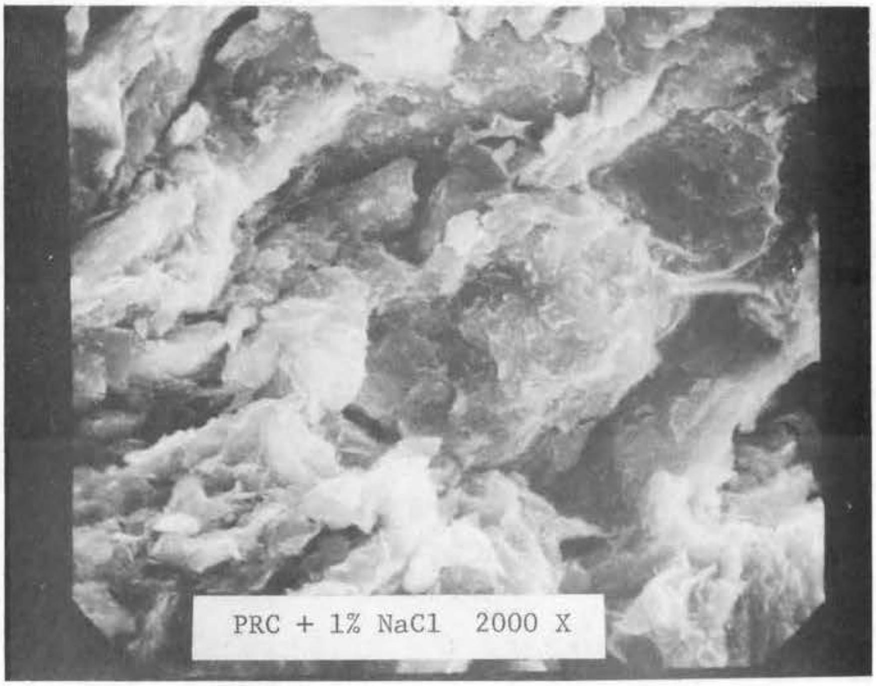
(a) 1000X Photomicrograph of PRC



(b) 600X Photomicrograph of RMGC

Figure 6.1. Scanning Electron Photomicrographs of PRC and RMGC

(a) 3000X Photomicrograph of PRC

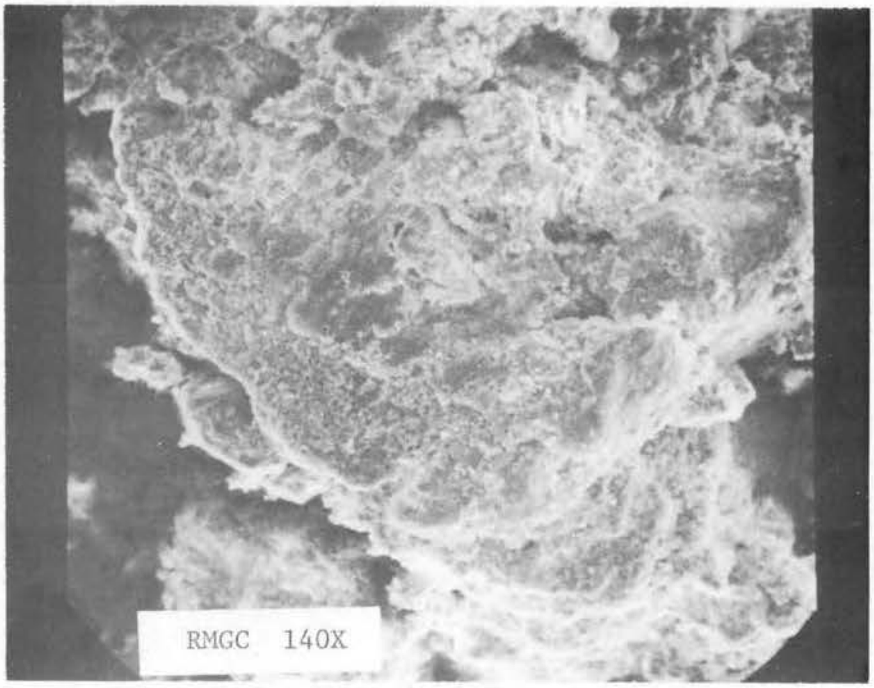


(b) 2000X Photomicrograph of Salt Treated PRC

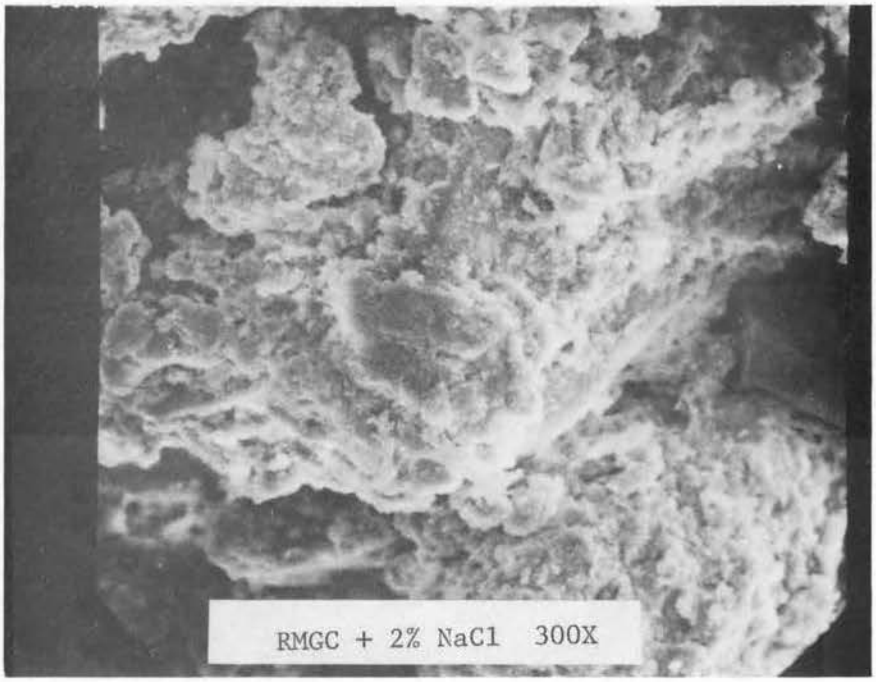
Figure 6.2. Scanning Electron Photomicrographs of PRC and Salt Treated PRC

Fig 6.3a is a low magnification micrograph of the same area previously shown for untreated RMGC. In comparison, the RMGC has been violently attacked by the salt, as shown in Fig 6.3b. Also shown in this figure is the deterioration of small pieces of the weathered mica in RMGC. No free sodium chloride crystals could be found in RMGC specimens even though the clay had been treated with 2% salt.

During lime modification, cohesive soil loses plasticity as a result of clay particle granulation. Scanning electron micrographs of lime modified soils clearly show this phenomenon. PRC appears much more aggregated after lime modification, as shown by Fig 6.4a, compared to the plate-like appearance previously observed. Although the clay has been granulated the individual soil aggregates do not appear to have deteriorated, as was found in salt treated specimens. Some localized mineral growth may be seen in the center portion of the figure. A higher magnification photomicrograph of this area, shown in Fig 6.4b, clearly illustrates the minute spearlike crystals growing in the voids. These minerals are most probably tetracalcium aluminate hydrates which produce quick, very low strength, cementing bonds within the soil. Clearly shown in this figure is the fact that the clay edges have remained very distinct and clean, compared to the deteriorated appearance of salt treated samples. Aggregation of RMGC is not as apparent as in PRC because of its "globby" appearance in the raw condition. However, upon close examination it is evident that the individual soil aggregates have become more angular than observed previously in the raw soil. In the right center portion of Fig 6.5b, which is a higher magnification photomicrograph of the center portion of Fig 6.5a, free calcium oxide appearing as a single

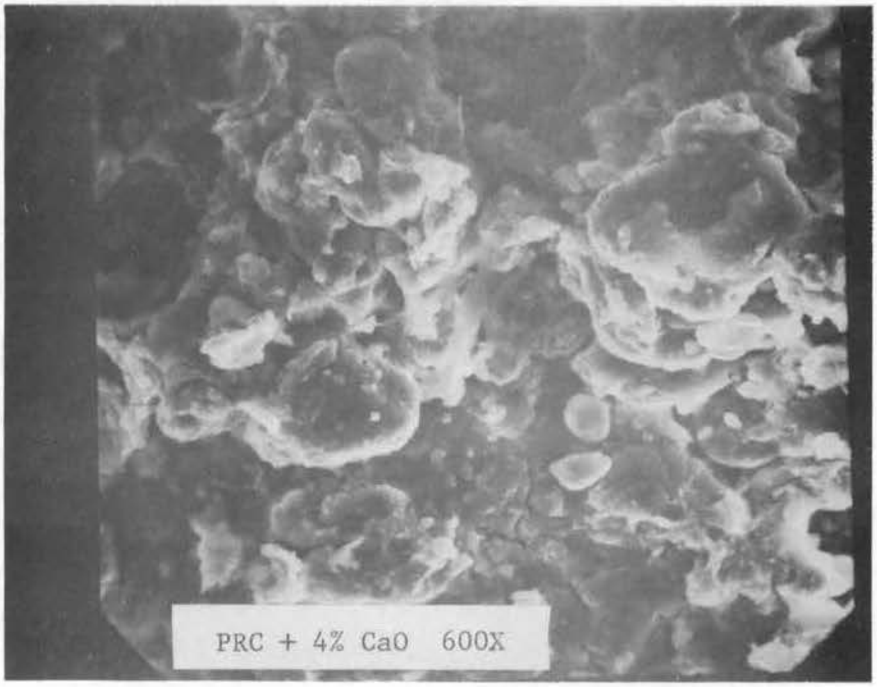


(a) 140X Photomicrograph of RMGC

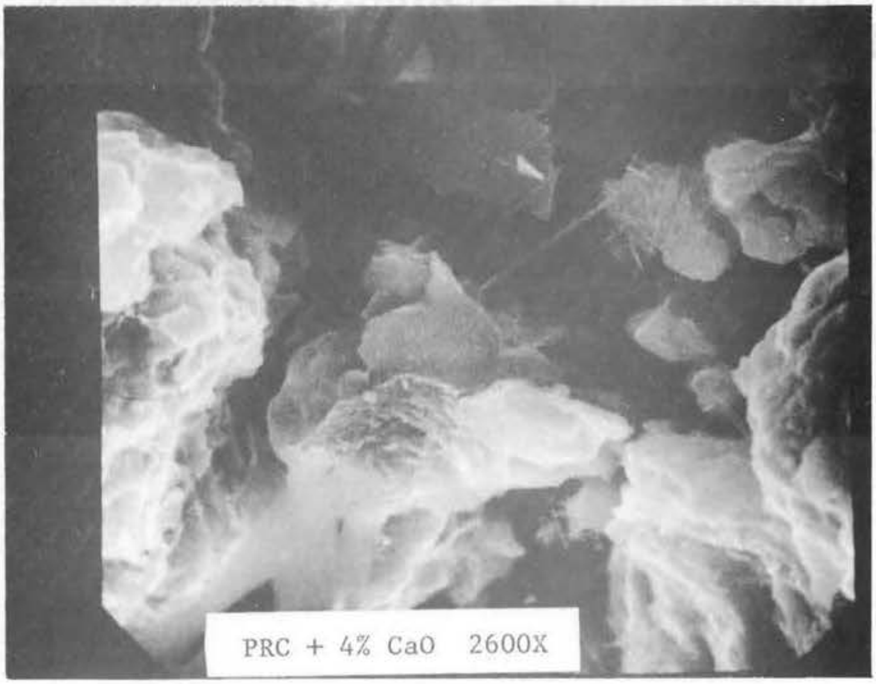


(b) 300X Photomicrograph of Salt Treated RMGC

Figure 6.3. Scanning Electron Photomicrographs of RMGC and Salt Treated RMGC

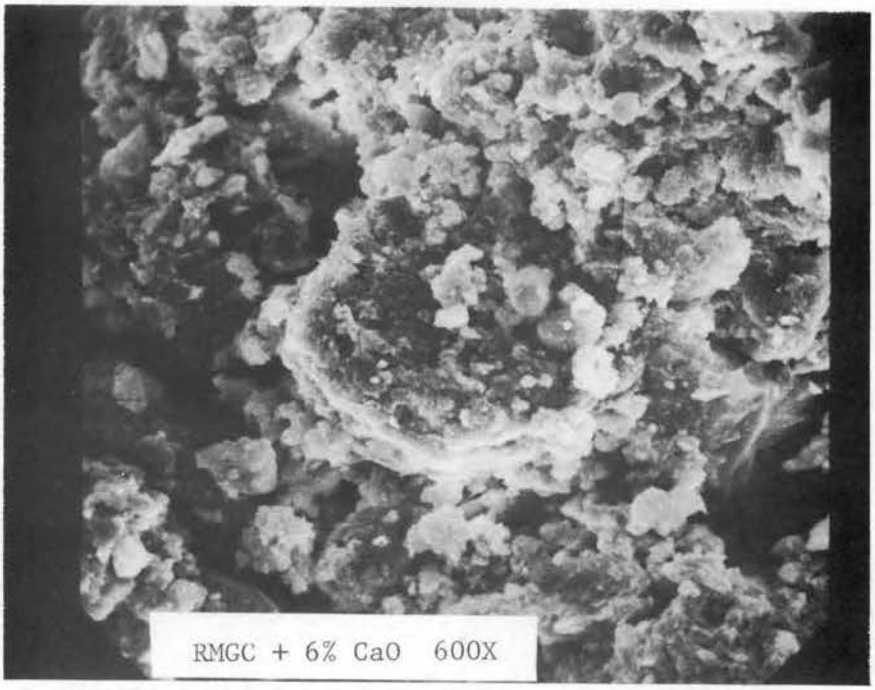


(a) 600X Photomicrographs of Lime Modified PRC

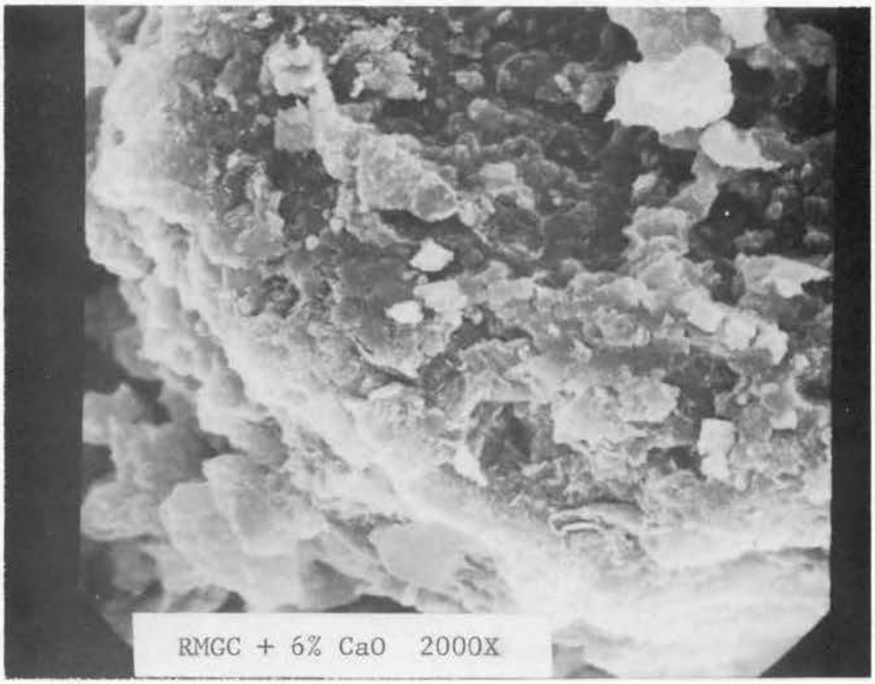


(b) 2600X Photomicrographs of Lime Modified PRC

Figure 6.4. Scanning Electron Photomicrographs of Lime Modified PRC



(a) 600X Photomicrograph of Lime Modified RMGC



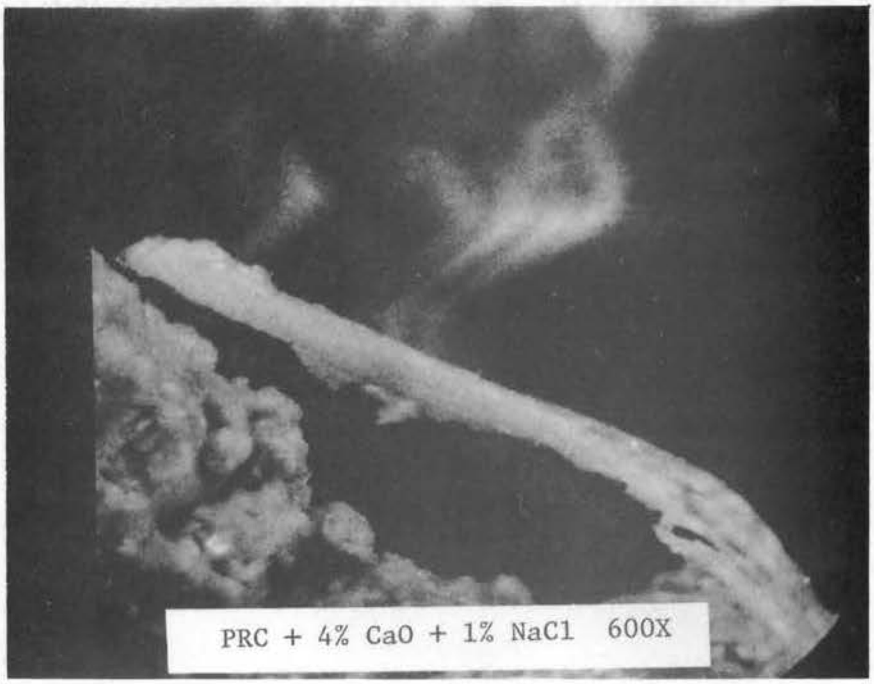
(b) 2000X Photomicrograph of Lime Modified RMGC

Figure 6.5. Scanning Electron Photomicrographs of Lime Modified RMGC

cubic crystal may be seen. Although theoretically no free lime should be present at modification optimum and crystal growth should not be present in any significant amount, it is obvious that this is not true since crystals were found in PRC and free lime was present in RMGC. These findings do not dispute theory but rather the application of theory. It should be evident that absolute dispersion of lime throughout the soil cannot be accomplished by the manual mixing operations employed. Thus in some area an excess of lime will be present while in others a deficiency will exist. Thus, in areas of excess lime accumulation, crystal growth and free lime may be obtained at modification optimum. Since these samples were hand mixed in relatively small quantities in the laboratory, one would certainly expect to find the same behavior in samples obtained from soils which were lime modified in field operations.

The presence of sodium chloride in conjunction with lime modification percentages has been shown to greatly increase compressive strength of treated soils. Examination of scanning electron photomicrographs clearly illustrates the reason for increased strength. As shown in Fig 6.6a addition of 1% salt in addition to 4% lime greatly enhanced the mineral growth. This is not unexpected since salt was found to deteriorate clay minerals. The deteriorating effect of sodium chloride provides a catalytic reaction for formation of new minerals. Also shown in salt-lime treated PRC by Fig 6.6b is the general "mossy" appearance of all clay surfaces, indicating that the clay particles have been fused together in the presence of sodium chloride/calcium oxide additives. The mineral growth shown in these figures does not appear to be the same as that found in lime modified PRC. It is

(a) 300X Photomicrograph of Salt-Lime Modified PRC

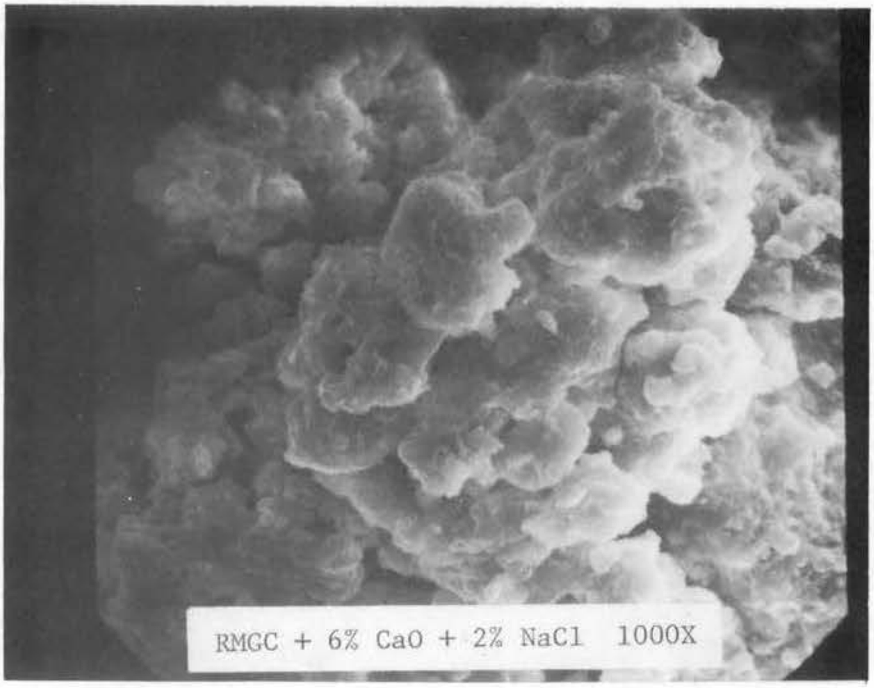


(b) 600X Photomicrograph of Salt-Lime Modified PRC

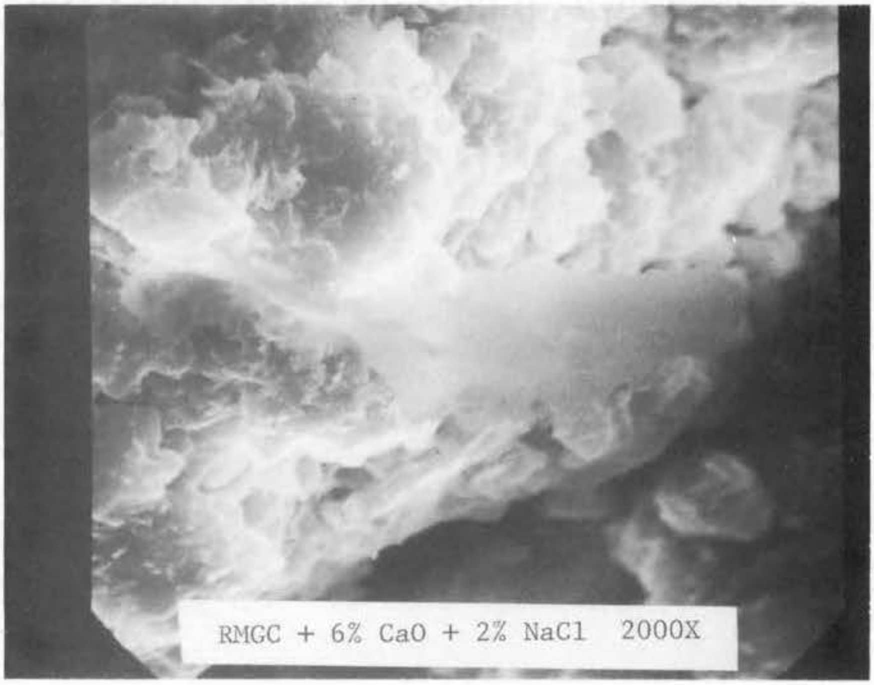
Figure 6.6. Scanning Electron Photomicrographs of Salt-Lime Modified PRC

possible that these crystals are compounds of sodium, calcium, aluminum, and chlorides. Salt-lime modification of RMGC was also found to enhance mineral growth. As shown in Fig 6.7a RMGC platelets appear to be more fused and cemented than was observed in lime modified samples. As in PRC the clays appear to be more deteriorated with 2% sodium chloride present than with only 6% calcium oxide. Higher magnification of the center portion of the photomicrograph, shown in Fig 6.7b reveals some mineral growth. In both salt-lime modified PRC and RMGC, new minerals appear to prefer to grow along clay platelet edges rather than on the flat surface. This may be the result of accessibility of elements required for the formation of these new minerals.

Lime stabilization of cohesive soil provides an ample amount of free calcium to produce high strength calcium silicate hydrate crystals. These tobermonites possess much higher bonding strengths than the tetracalcium aluminate hydrate crystals. These definite mineral forms present in PRC, shown in Fig 6.8a, are very different from those crystals found in localized areas at modification lime content. However, these higher mineral forms do resemble those observed in the salt-lime modified PRC. This would indicate that sodium chloride in conjunction with modification lime contents reacts with the clay in such a manner as to provide amorphous silica for reaction with calcium. Addition of sodium chloride in conjunction with stabilization lime percentages greatly enhances mineral growth in PRC as shown in Fig 6.8b. In this figure it is evident that mineral formation is greatly enhanced. The clay has become fused and tightly cemented to produce greater strength than obtained from lime stabilization alone.

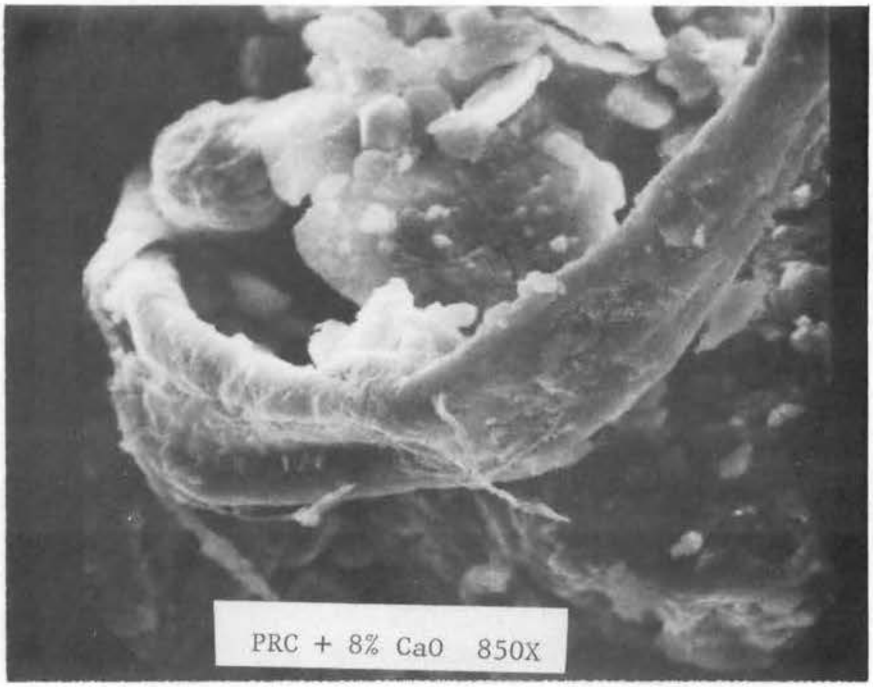


(a) 1000X Photomicrograph of Salt-Lime Modified RMGC

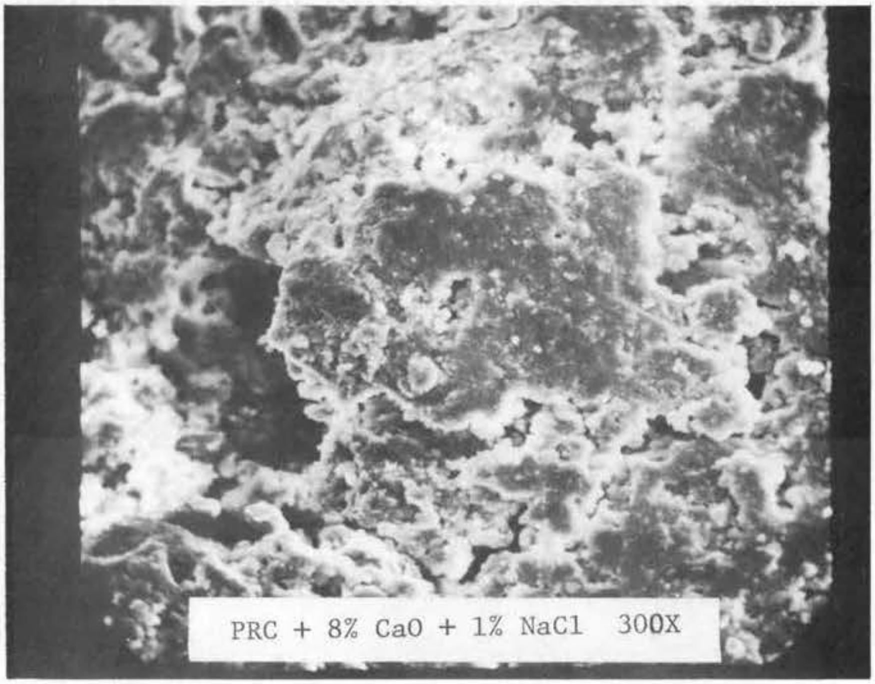


(b) 2000X Photomicrograph of Salt-Lime Modified RMGC

Figure 6.7. Scanning Electron Photomicrographs of Salt-Lime Modified RMGC



(a) 850X Photomicrograph of Lime Stabilized PRC



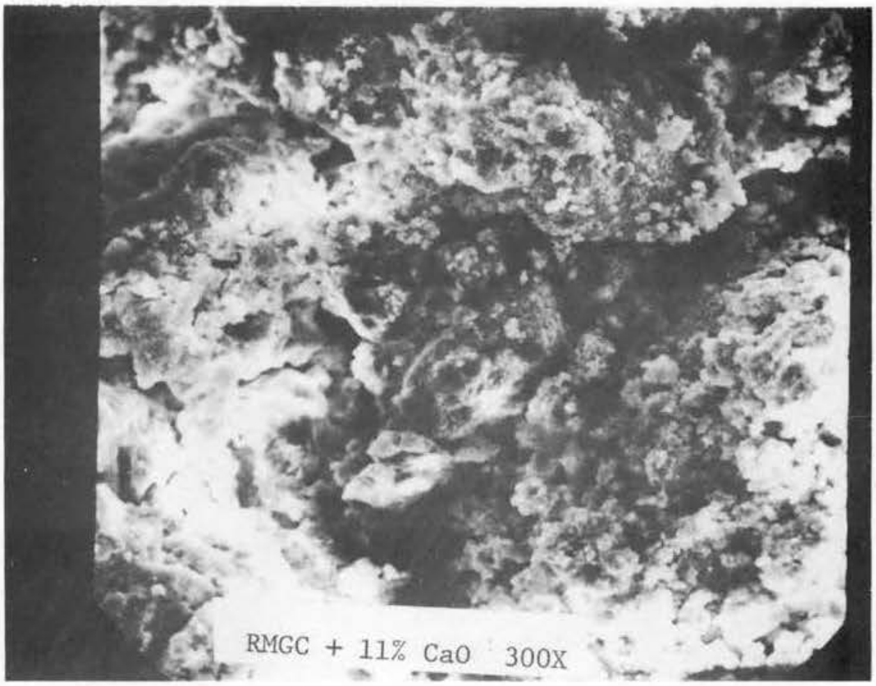
(b) 300X Photomicrograph of Salt-Lime Stabilized PRC

Figure 6.8. Scanning Electron Photomicrographs of Lime and Salt-Lime Stabilized PRC

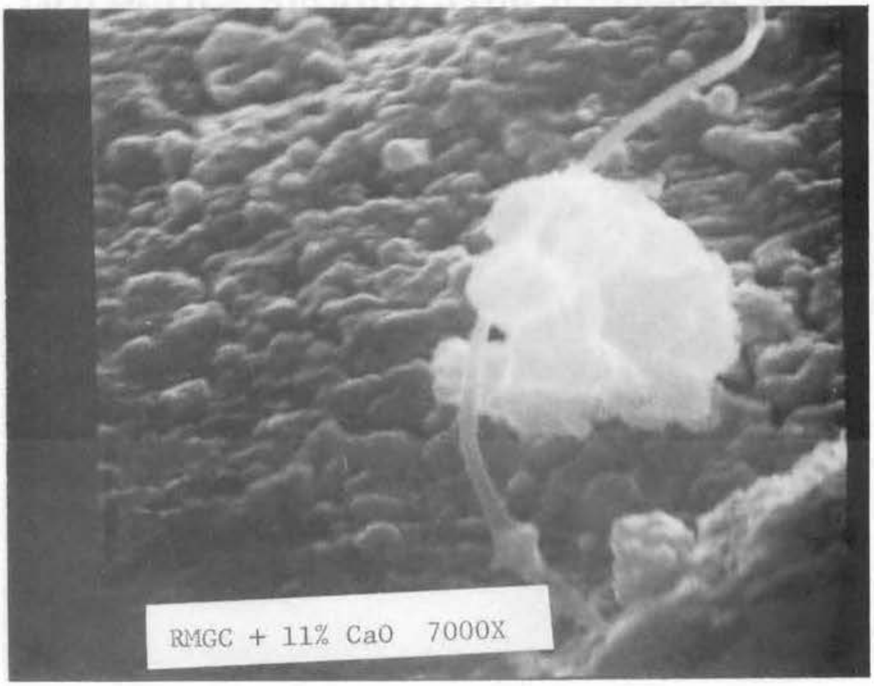
Evidence of the bonding of RMGC platelets by new minerals formed during lime stabilization is found in Fig 6.9a. Upon closer examination of lime stabilized RMGC it was found that the most predominant mineral growth consisted of very fine fibrous minerals which covered the clay platelets. A photomicrograph of one of these minerals is shown in Fig 6.9b. The millions of tiny fibers in some areas resembled a mass of tangled cord or spider web. It appears that not all minerals produced by lime stabilization of clay are identical, but depend upon the mineralogical composition of the clay. This is evident upon comparison of PRC mineral formations and RMGC mineral formation. Acceleration of mineral formation by addition of sodium chloride was more evident in RMGC than in PRC. In Fig 6.10a the mineral growth in RMGC resembles a photograph of coral rather than soil. Upon closer examination of the mineral formations, shown in Fig 6.10b, it is evident that the clay particles have been completely engulfed and bonded together by the maze of newly formed crystalline material.

Although it might be supposed that considerably more evidence of new mineral growth should have been revealed in the photomicrographs, techniques of the procedure are actually rather crude, and fail to reveal or tend to destroy much evidence that may be presumed to have existed in the soil.

Samples for examination by the scanning electron microscope were freshly broken from larger compacted specimens, thus crystal growth along the fracture surfaces was destroyed. Because of the manner in which scanning electron photomicroscope images are produced, only one surface of the sample is examined, thus new mineral formations hidden below the top clay layer are not visible. Therefore, observed

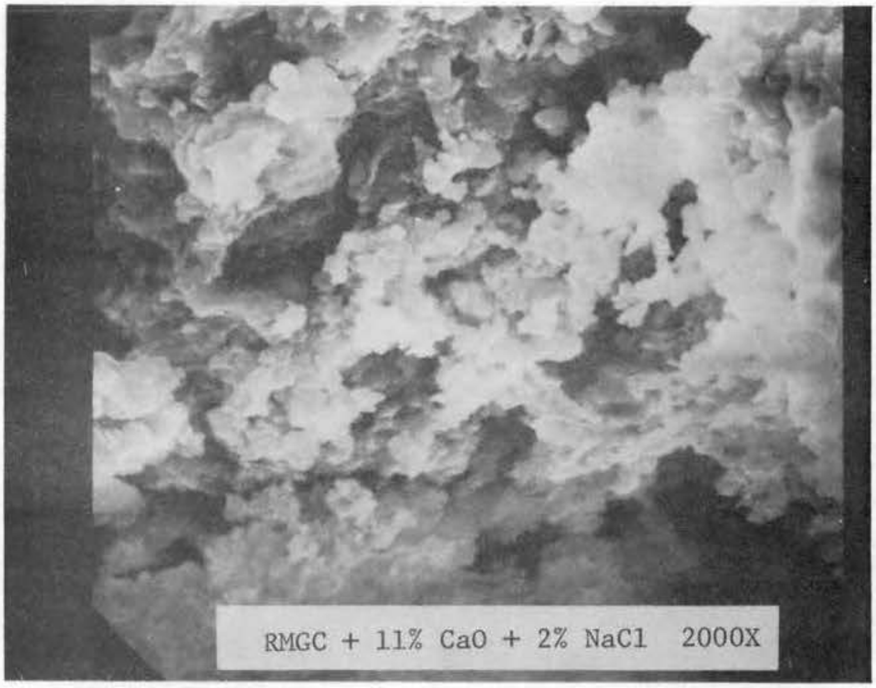


(a) 300X Photomicrograph of Lime Stabilized RMGC

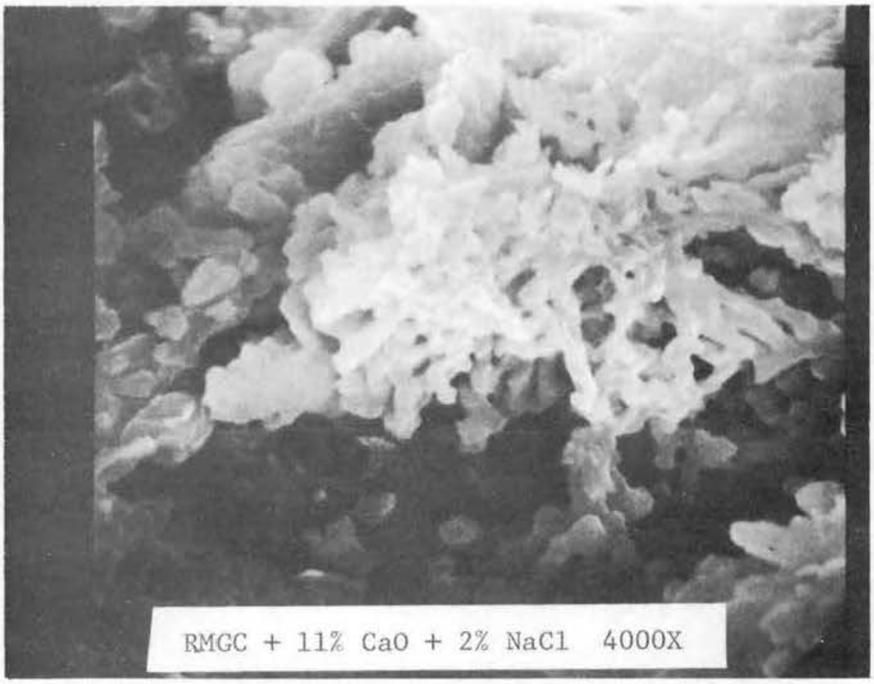


(b) 7000X Photomicrograph of Lime Stabilized RMGC

Figure 6.9. Scanning Electron Photomicrographs of Lime Stabilized RMGC



(a) 2000X Photomicrograph of Salt-Lime Stabilized RMGC



(b) 4000X Photomicrographs of Salt-Lime Stabilized RMGC

Figure 6.10. Scanning Electron Photomicrographs of Salt-Lime Stabilized RMGC

crystal growths must be located in voids of the sample in a plane perpendicular to the electron probe. However, because of the high energy exerted on these crystals by the scanning probe, most of the new mineral formations which grow in the voids are destroyed before a micrograph can be produced. Compounding the problem is the tremendous amount of relief between clay platelets and crystals growing deep within voids. This relief prevents good focusing and resolution of scanning electron photmicrographs. Therefore, obtaining scanning electron photomicrographs of nicely developed crystal formations within chemically treated soils is much more difficult than one may be led to believe at first thought. Considerable time and patience was required to obtain the photomicrographs presented herein.

# CHAPTER VII

# EVALUATION, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter is composed of three sections which discuss previously presented data and inferences drawn from these data. These sections are: 1) evaluation of sodium chloride and sodium chloride-lime additives as feasible chemical agents for treatment of cohesive Oklahoma soils, 2) conclusions reached during the investigation of salt, lime, and salt-lime treatment of cohesive soils, and 3) recommendations for future research in chemical treatment of cohesive Oklahoma soils.

## Evaluation

The following evaluation concerns the feasibility of using sodium chloride as a chemical agent for treatment of cohesive Oklahoma soils or as a chemical additive to be used in conjunction with lime at and near modification and stabilization optima.

1. Although beneficial in enhancing compressive strength and compaction properties, the use of sodium chloride as a single agent for the treatment of highly cohesive subgrades does not appear to be desirable, based on data collected to date. Increase in swelling potential associated with salt treatment at low admixture percentages renders sodium chloride unsuitable for treatment of highly cohesive highway subgrades. However,

salt treatment does produce material which may be useful in construction of impervious membranes in reservoirs or hydraulic fill dam cores. Under these conditions treated soil would remain completely saturated, thus volume change after placement would not present problems. Seepage through the impervious treated clay would be so minute that no leaching would occur.

2. Increased compressive strength, higher compacted unit weights at lower moisture contents, reduced swelling potential, and improved moisture retention characteristics without any increase in plasticity are factors which definitely make sodium chloride feasible as a chemical additive to be used at modification lime contents.
3. Higher compressive strengths as well as increased rate of strength gain make sodium chloride an excellent additive to be used in conjunction with lime stabilization of cohesive Oklahoma soils.

## Conclusions

The following conclusions are those indicated directly or inferred from analysis of data collected throughout the entire investigation. Although directly related to salt and salt-lime treatment, these conclusions are concerned with every aspect of the investigation.

1. Scanning electron photomicrographs and physical properties indicate that RMGC is a much younger soil than is PRC.
2. Differences in clay mineralogy explain differences in the sensitivity of RMGC and PRC to chemical treatment. PRC is

a combination of illite, chlorite, and montmorillonite, whereas RMGC is thought to be predominantly chlorite.

3. Cations present as a result of chemical treatment were found to be more influential on behavior of liquid limits than was variation in soil type.
4. Addition of small percentages of sodium chloride caused little change in plasticity of either soil. The general tendency was an increase in PI with increase in salt content.
5. Calcium oxide treatment caused a reduction in PI of both soils. PRC was found to be more reactive than RMGC. Modification optimum for PRC was 4%, whereas RMGC required 6% lime to reduce plasticity to zero.
6. The pH method of determining the lime modification optimum was found to be in agreement with the PI determination procedure.
7. Addition of small percentages of sodium chloride as a chemical additive at modification lime contents caused negligible increases in PI.
8. Addition of sodium chloride as a chemical treatment agent or as a chemical additive used in conjunction with lime enhanced moisture retention characteristics of loose soil mixtures.
9. Relative humidity was found to be more influential on moisture loss than variation of temperature at a given humidity.
10. The most beneficial effects of sodium chloride in relation to moisture loss were realized within the initial 24-hour period of exposure.

11. Lime treatment of both soils caused reductions in compacted unit weights and increases in optimum moisture content. These effects were more pronounced in PRC than in RMGC.
12. Sodium chloride treatment caused an increase in compacted unit weight of PRC; however, RMGC underwent no change. Optimum moisture contents of both soils were reduced by salt treatment. Two percent salt was found to produce optimum conditions for both soils.
13. Addition of sodium chloride in conjunction with lime increased compacted unit weights and reduced optimum moisture contents for both soils. PRC was found to be more responsive than RMGC. One percent salt was found to produce optimum conditions in PRC mixtures, whereas RMGC mixtures required two percent salt.
14. Unconfined compression tests of salt treated mixtures at constant moisture contents and dry densities indicated the salt content producing optimum compaction characteristics also produced the greatest strength.
15. Strength gains occurring within short periods after lime modification, with little gain in strength during curing, indicate that any strength gains resulting from lime modification are derived primarily from aggregation, which increases internal friction, rather than new mineral formations.
16. Salt-lime modification not only produces higher strengths than lime modification but also increases the rate of strength gain during curing. This would indicate that sodium chloride

acts as a catalyst in the formation of new minerals or reacts with lime and soil to produce minerals foreign to lime modification.

17. The lime stabilization optimum, based on 28-day compressive strength, was more distinct for PRC than RMGC. Stabilization optima were 8% lime for PRC and 11% lime for RMGC.
18. Stabilization optimum was found to be approximately twice the lime modification optimum content for both soils.
19. Addition of sodium chloride at stabilization lime contents not only produced greater strengths, but also increased the rate of strength gain. Thus salt appears to enhance the formation of CSH minerals or other new minerals.
20. Sodium chloride treatment increased swelling potential of both soils with increase in salt content. Maximum swelling potential was obtained at 2% salt content. Salt contents greater than 2% caused swelling to be reduced to that of raw soil.
21. New mineral formations were found to be concentrated in local areas where lime content was high. Thorough distribution of lime by mixing is almost impossible; therefore, some mineral formation will occur at low lime contents during modification, while some clay minerals may not even come into contact with lime, even for higher lime contents used for stabilization.
22. No undissolved or free sodium chloride, which would have been very evident, was found during the scanning electron microscopy studies, in either salt treated or salt-lime treated mixtures.

23. Scanning electron photomicroscopy provides an excellent tool for studying chemically treated soils.

## Recommendations for Future Research

The following topics for investigation are the result of problems encountered during the course of the research or of ideas formulated or inferred from collected data:

1. An accelerated 3-day curing process has already been developed to simulate curing of specimens for one year at normal conditions. Development of a short curing process to simulate 7, 14, 21, and 28-day curing periods would enhance determination of lime and salt-lime stabilization optima.
2. Investigation of a possible relationship between soil properties, modification optimum, and stabilization optimum for many soils may reveal a quick method of determining stabilization optimum.
3. A lime modification and/or lime stabilization study of natural saline soils may provide more information concerning salt-lime modification of cohesive Oklahoma soils now considered useless for any purpose.
4. Differential thermal analysis of salt and salt-lime treated soils may provide more information on new mineral formations obtained by salt-lime treatment.
5. Investigation of the effect of various percentages of amorphous silica and allophane on susceptibility of soils to lime treatment may provide long needed information required for complete understanding of lime-soil reactions.

6. A field study of a salt-lime treated subgrade sections in comparison with lime treated sections may provide information which reinforces the feasibility of salt-lime treatment predicted by this research.

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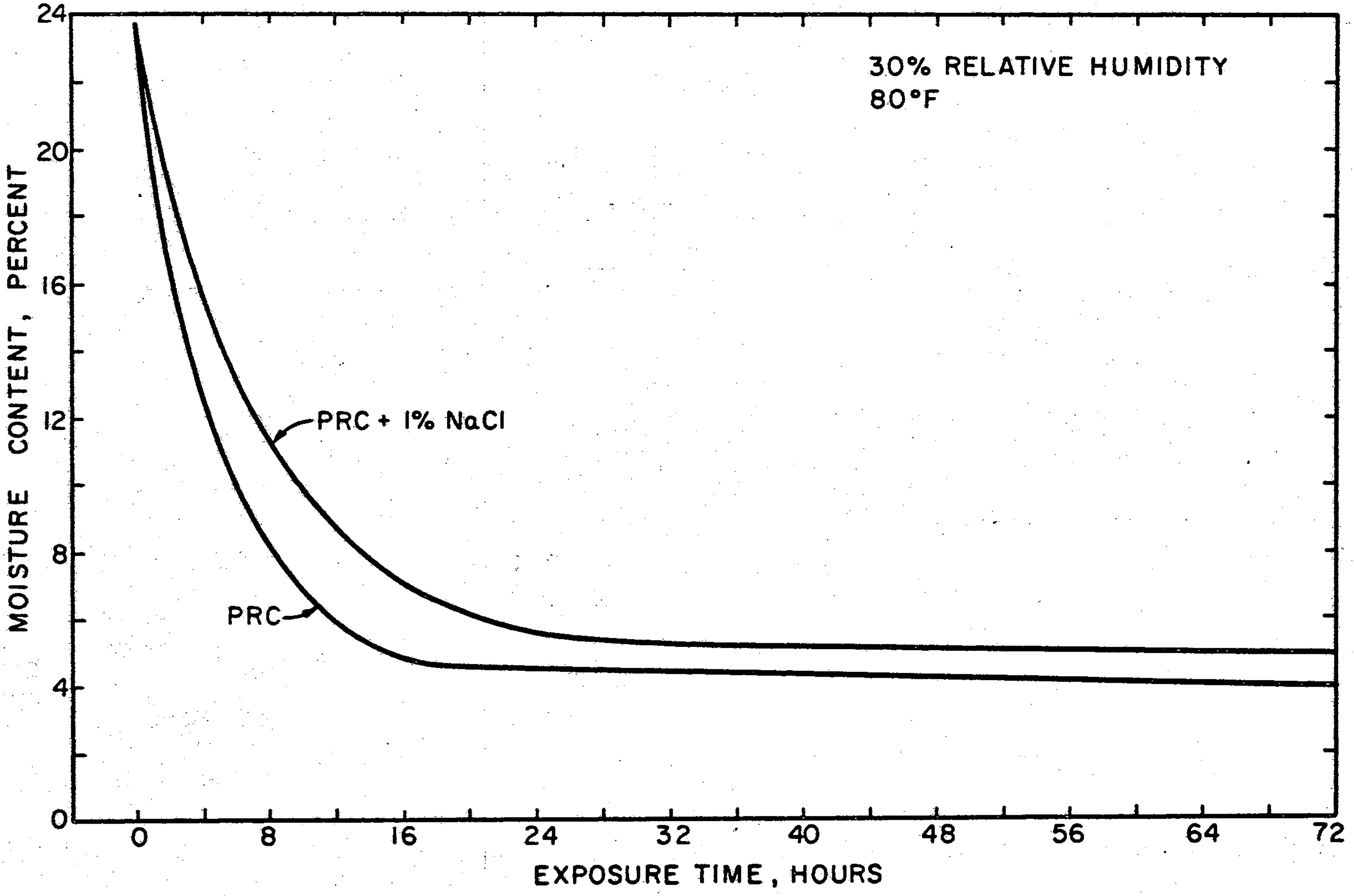
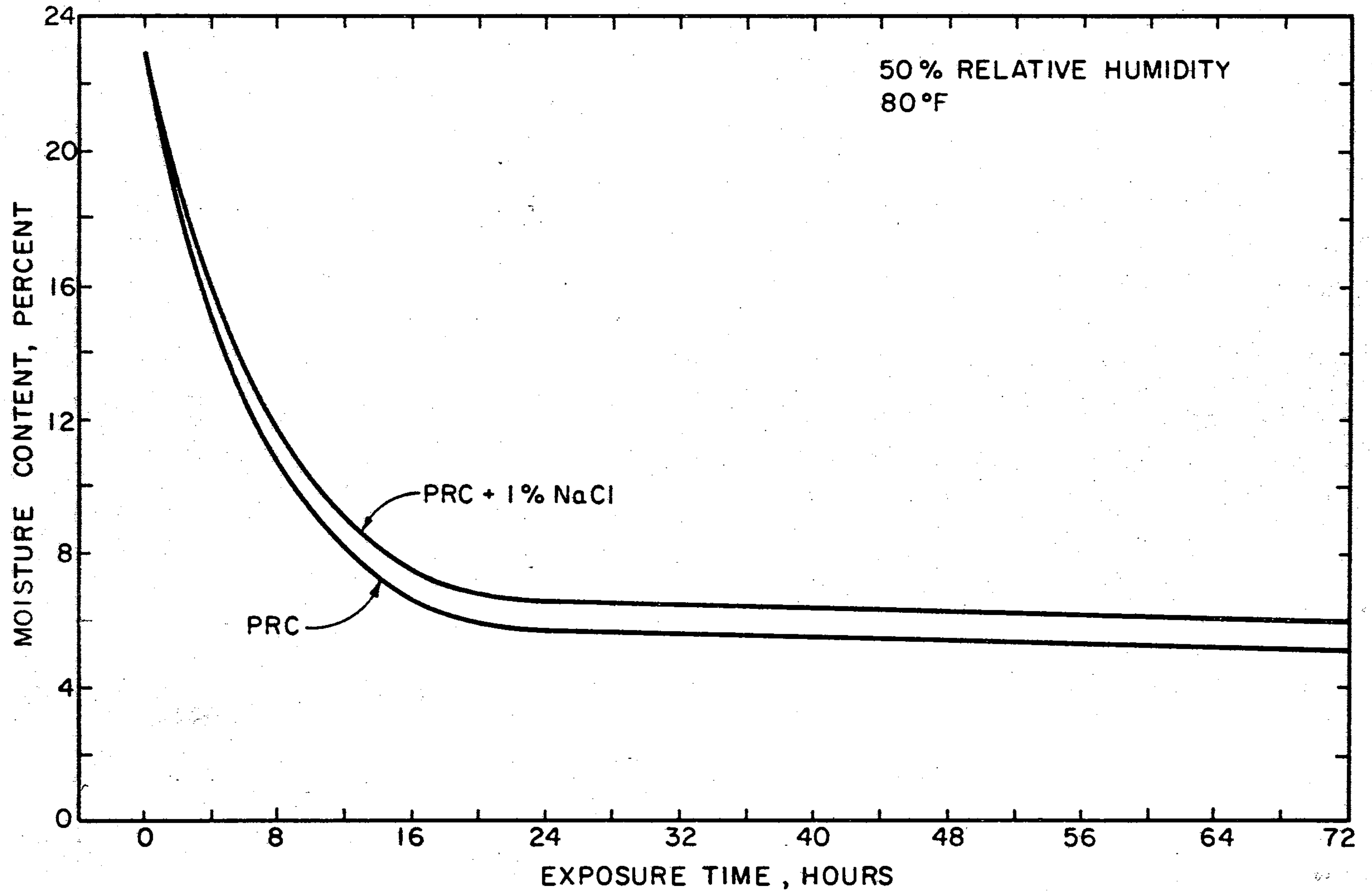
# APPENDIX A

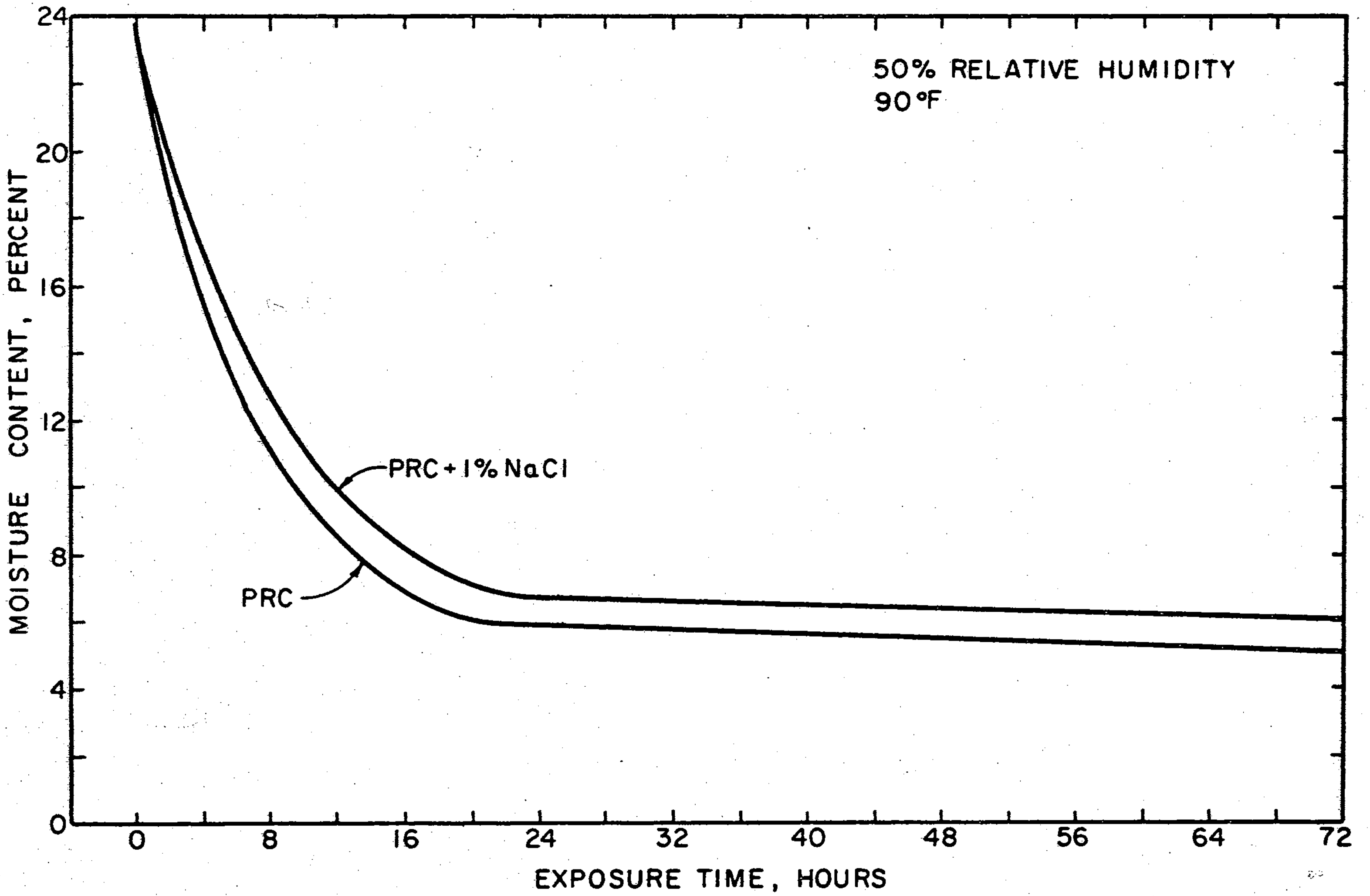
# MOISTURE RETENTION CURVES FOR PRC AND RMGC MIXTURES UNDER VARIOUS CLIMATIC CONDITIONS



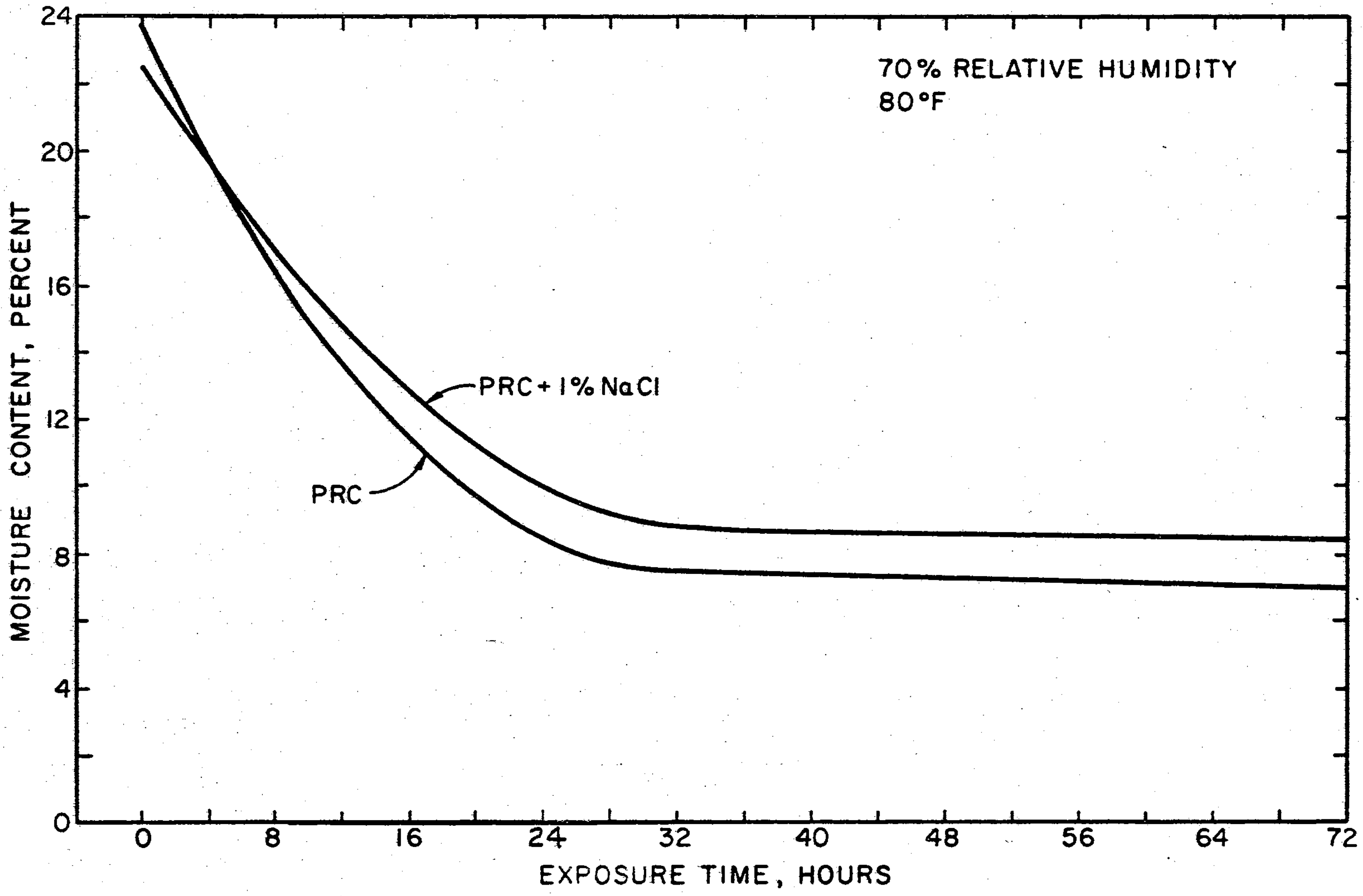
A.1. Moisture Retention Curves for PRC Mixtures at 30% Relative Humidity and 80°F



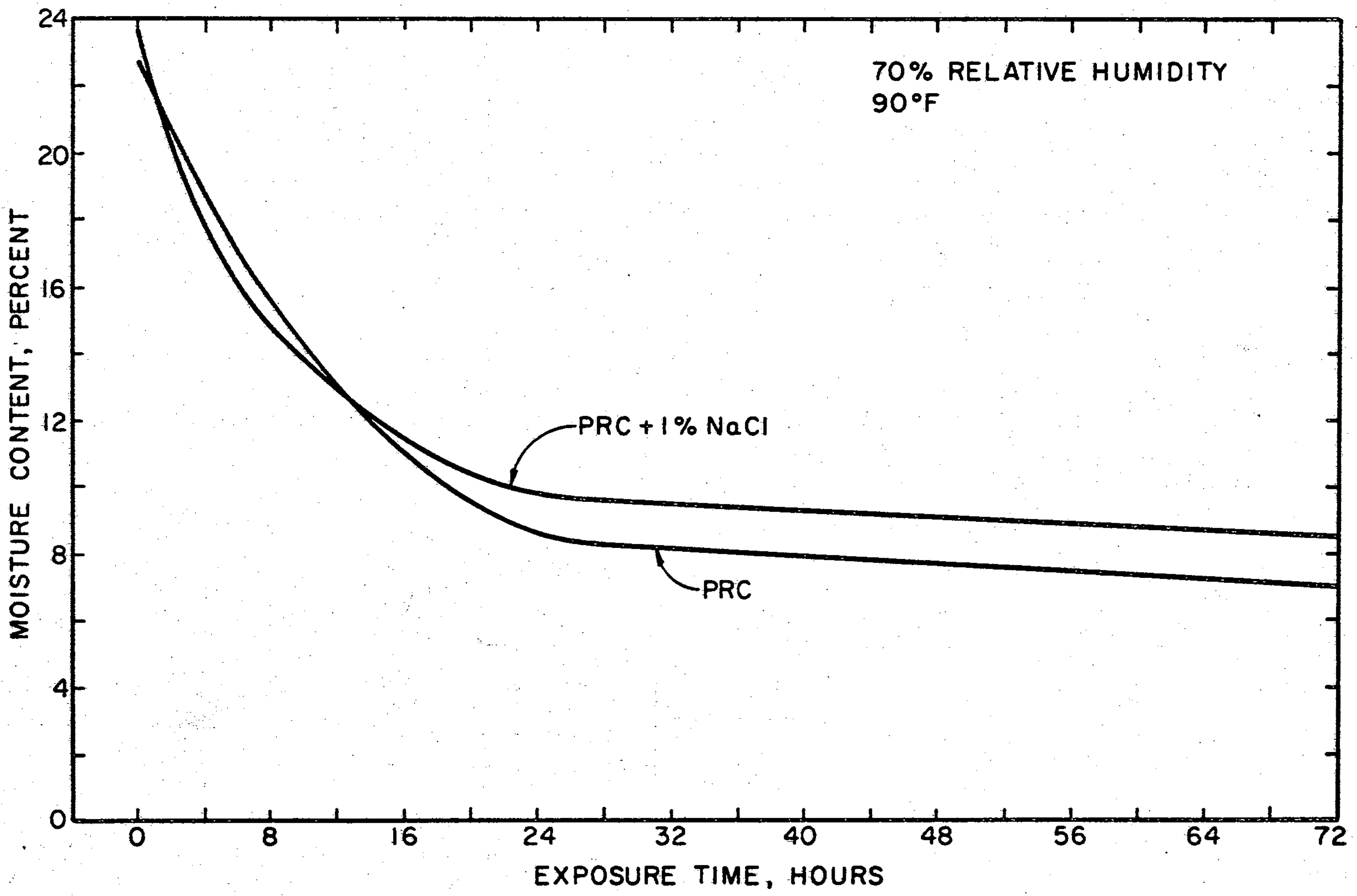
A.2. Moisture Retention Curves for PRC Mixtures at 50% Relative Humidity and 80°F



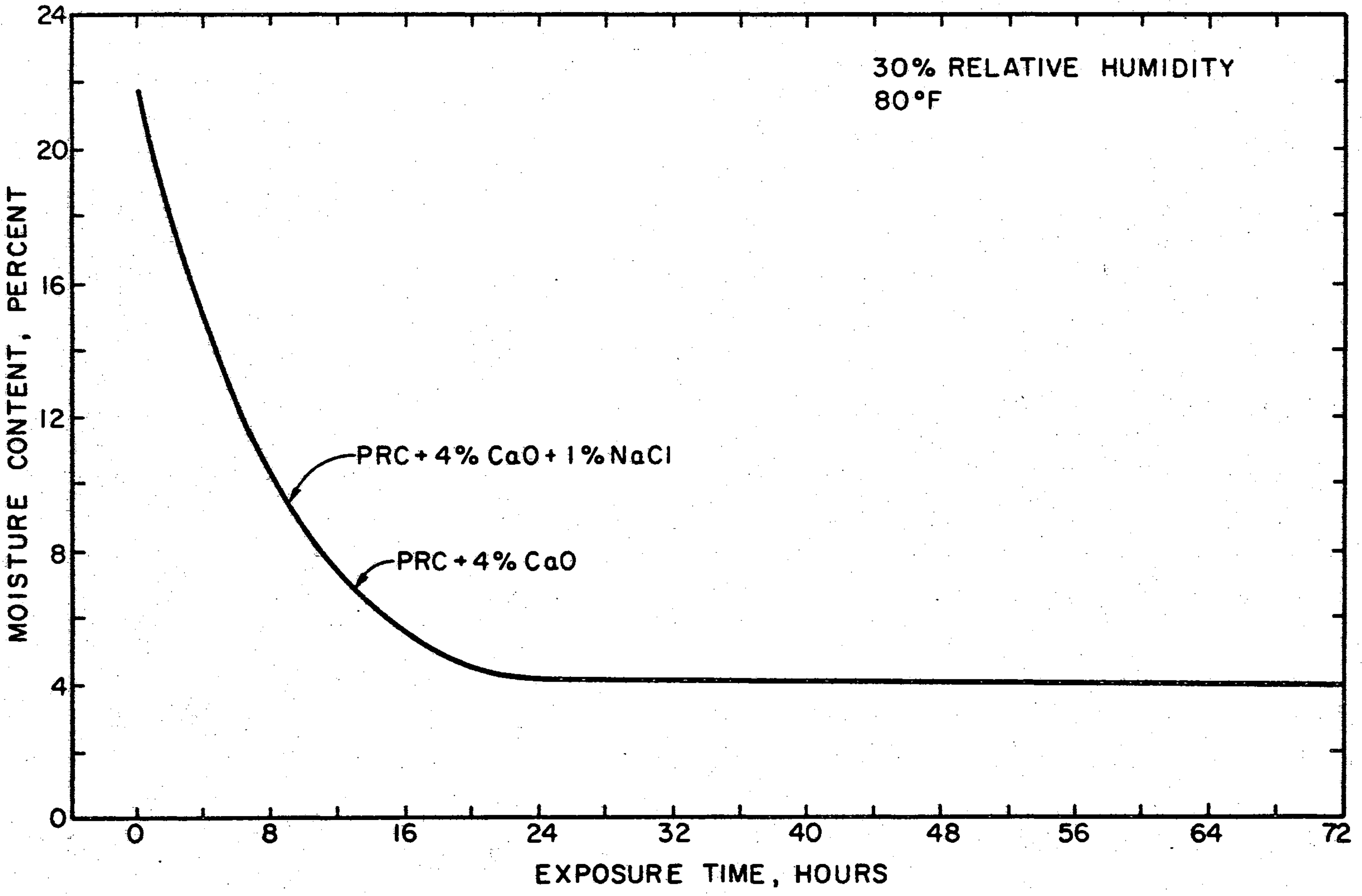
A.3. Moisture Retention Curves for PRC Mixtures at 50% Relative Humidity and 90°F



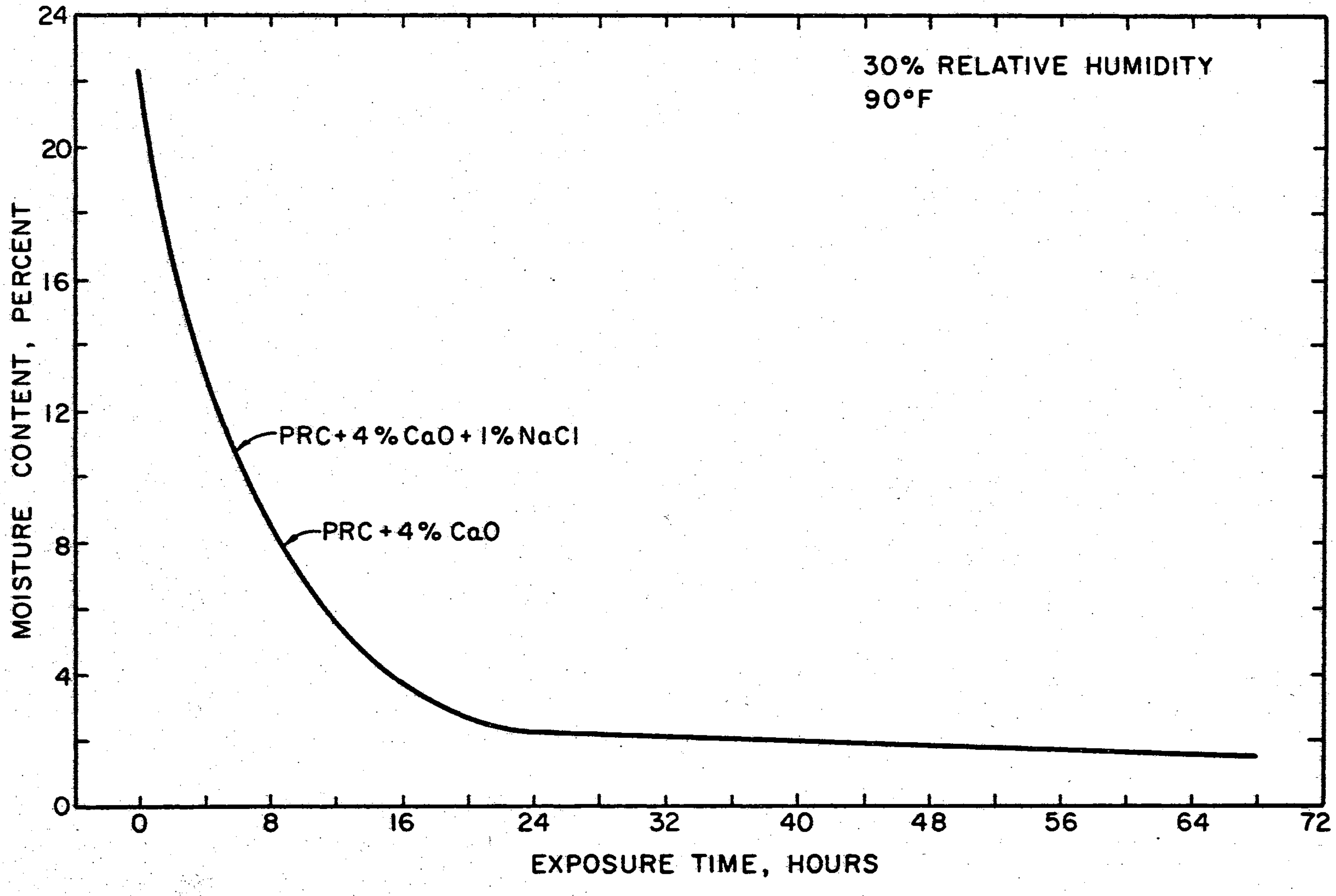
A.4. Moisture Retention Curves for PRC Mixtures at 70% Relative Humidity and 80°F



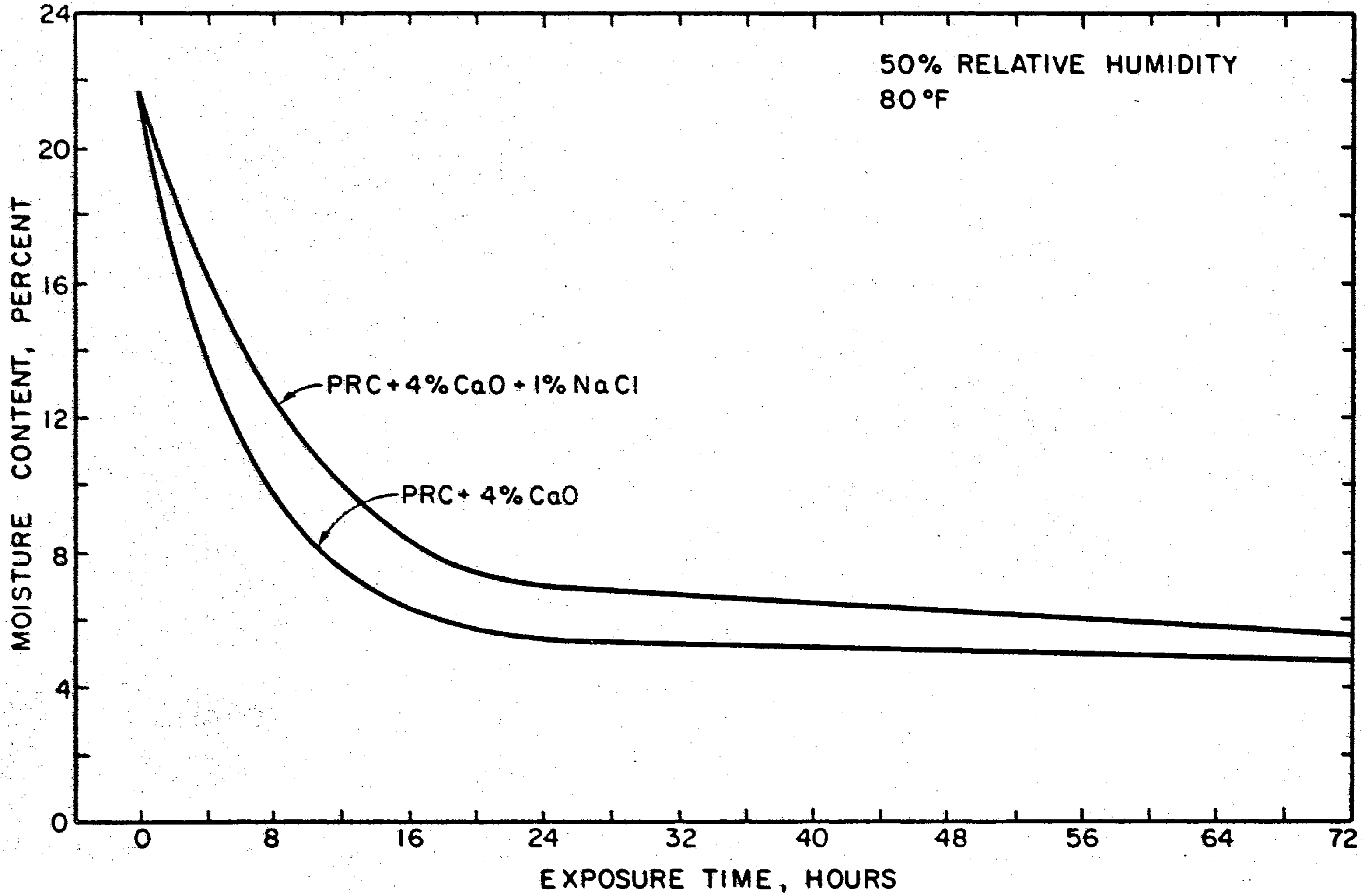
A.5. Moisture Retention Curves for PRC Mixtures at 70% Relative Humidity and 90°F



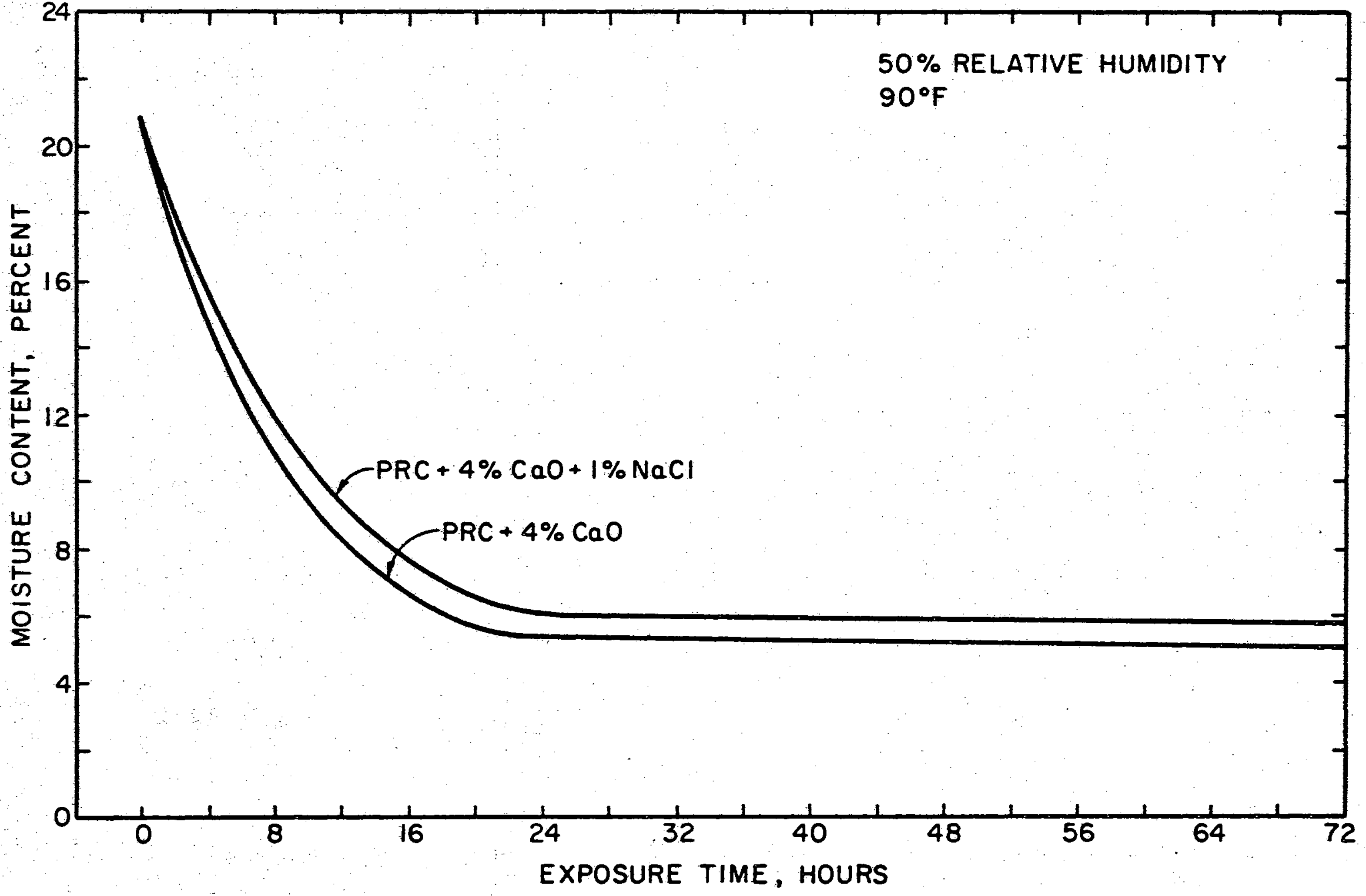
A.6. Moisture Retention Curve for Modified PRC at 30% Relative Humidity and 80°F



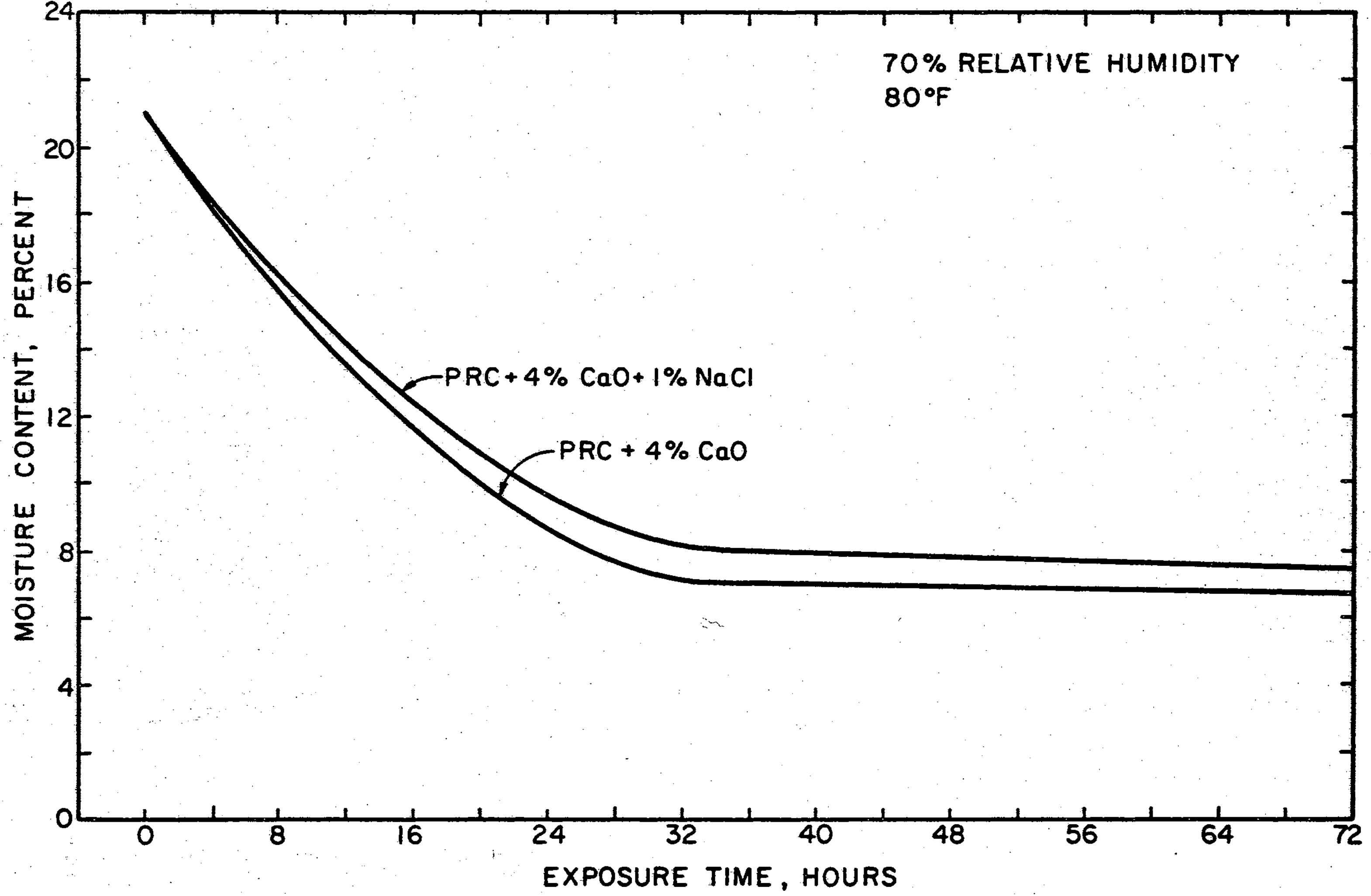
A.7. Moisture Retention Curves for Modified PRC at 30% Relative Humidity and 90°F



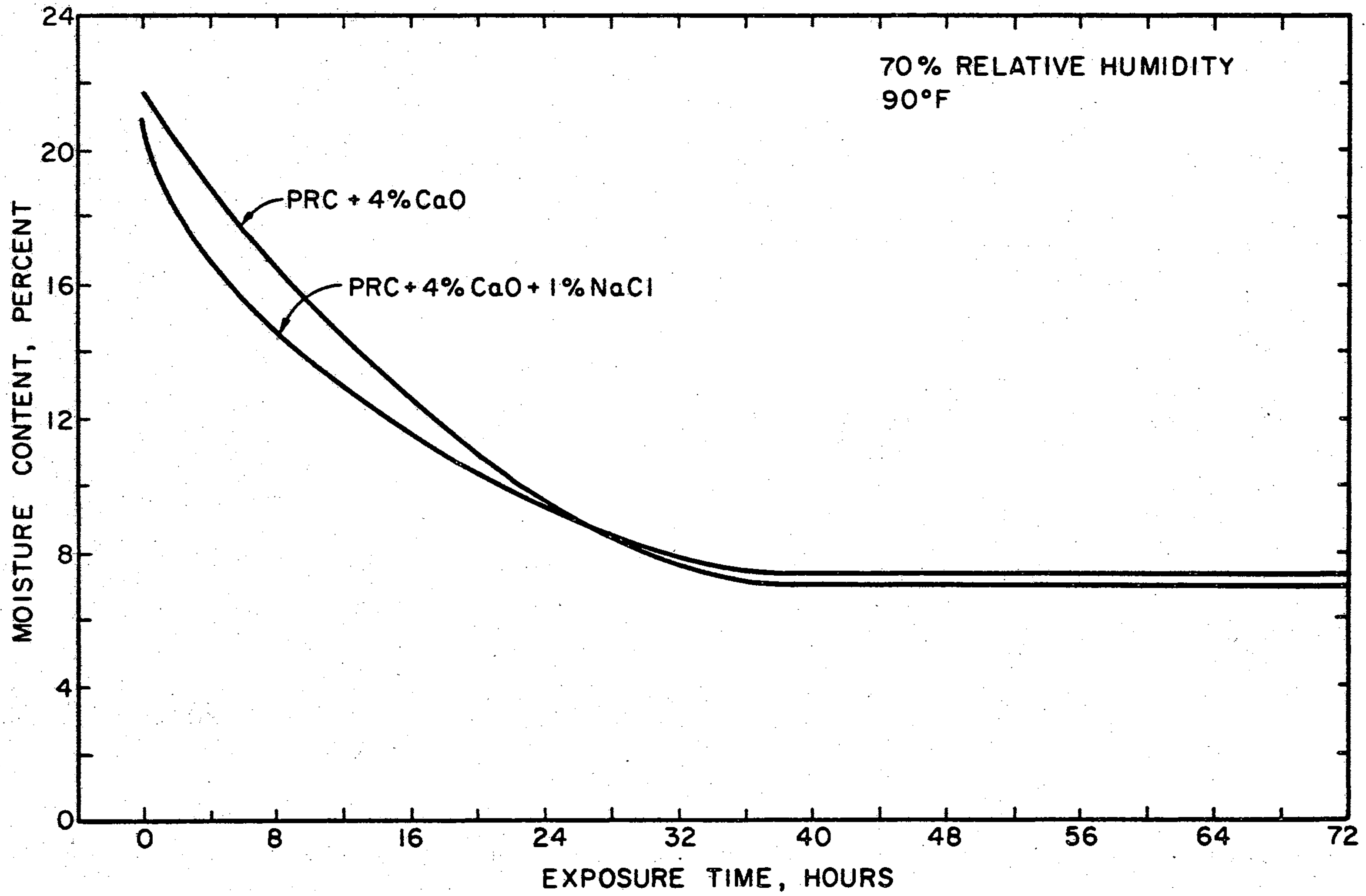
A.8. Moisture Retention Curves for Modified PRC at 50% Relative Humidity and 80°F



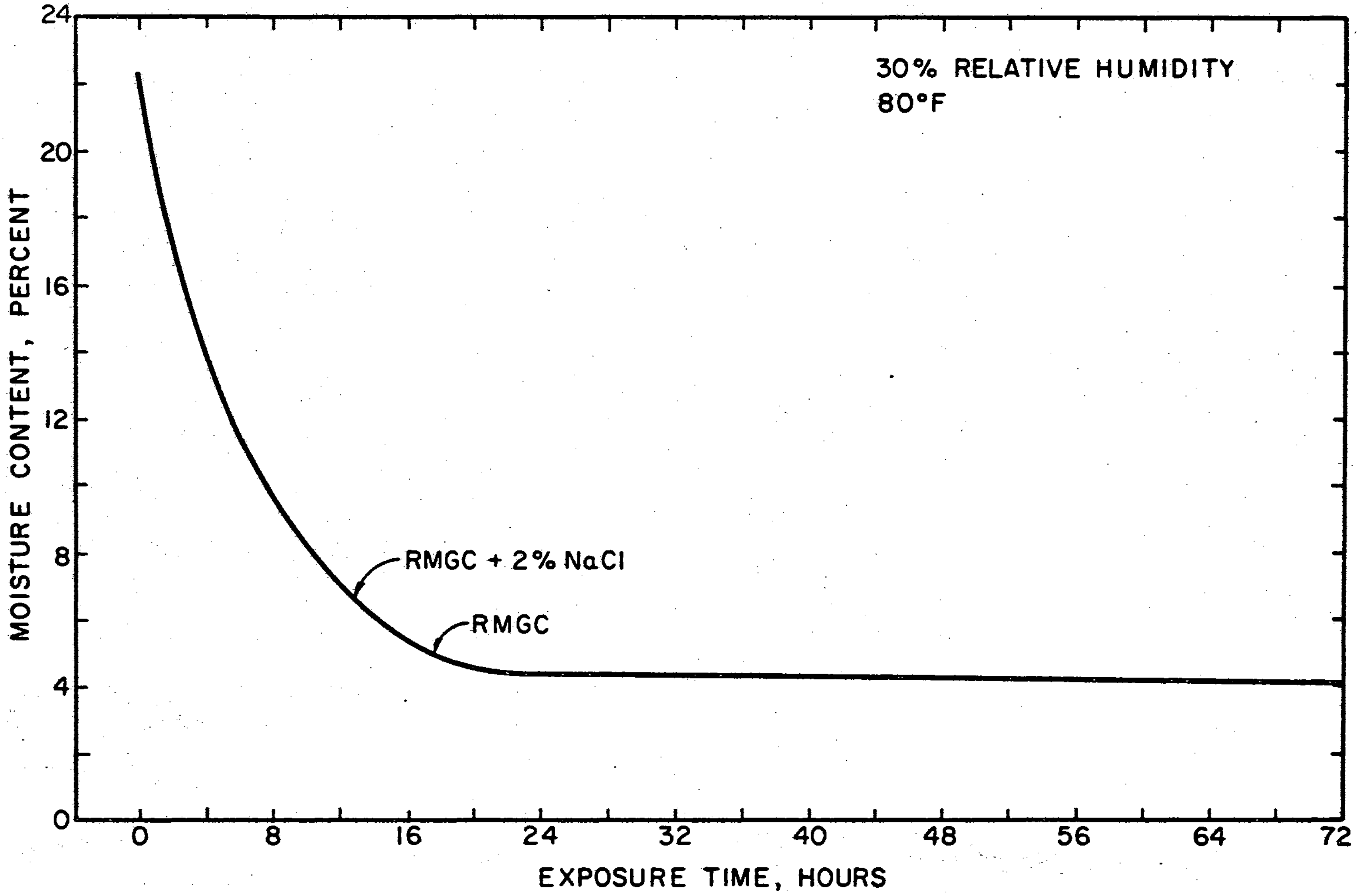
A.9. Moisture Retention Curves for Modified PRC at 50% Relative Humidity and 90°F



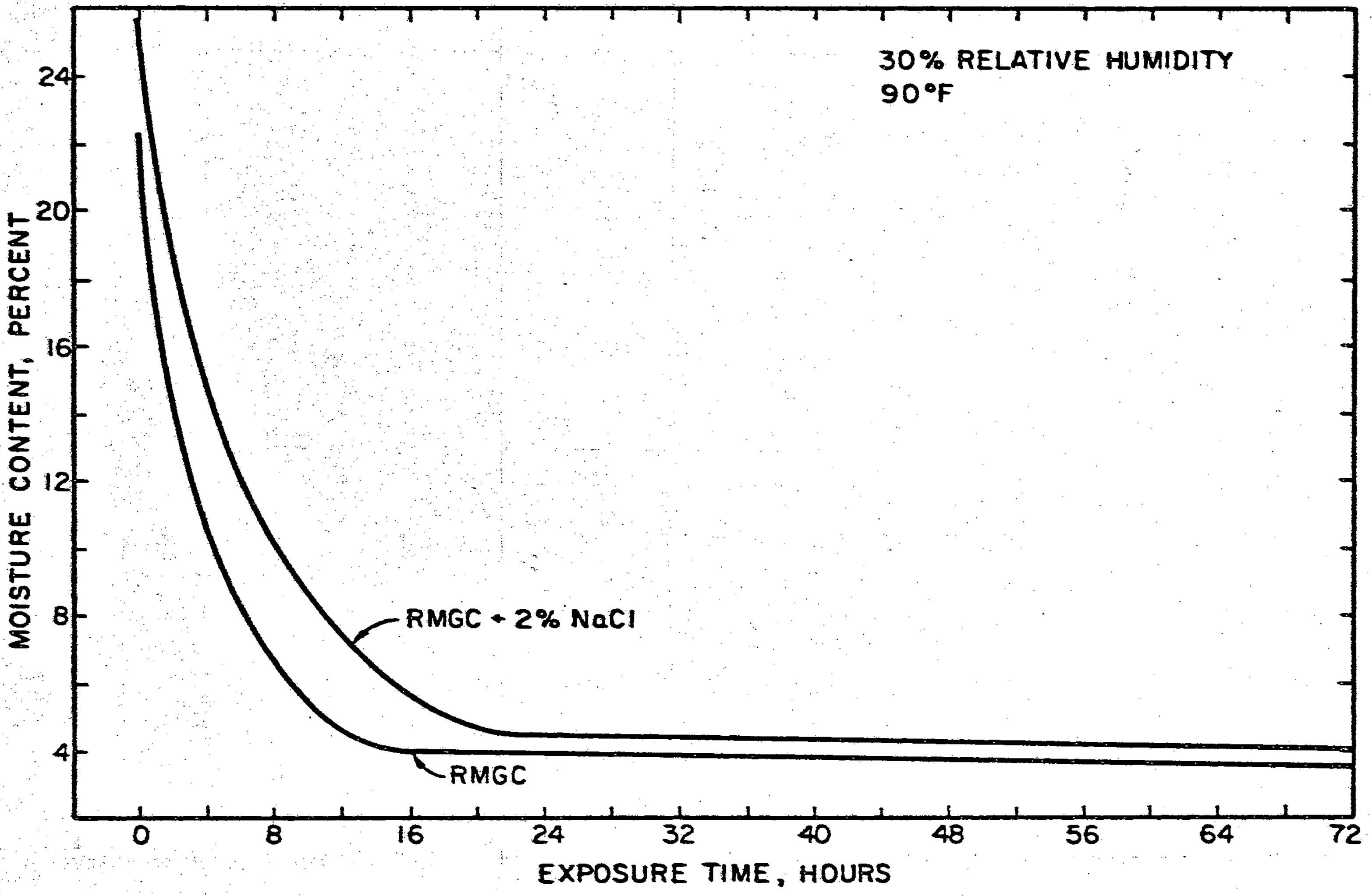
A.10. Moisture Retention Curves for Modified PRC at 70% Relative Humidity and 80°F



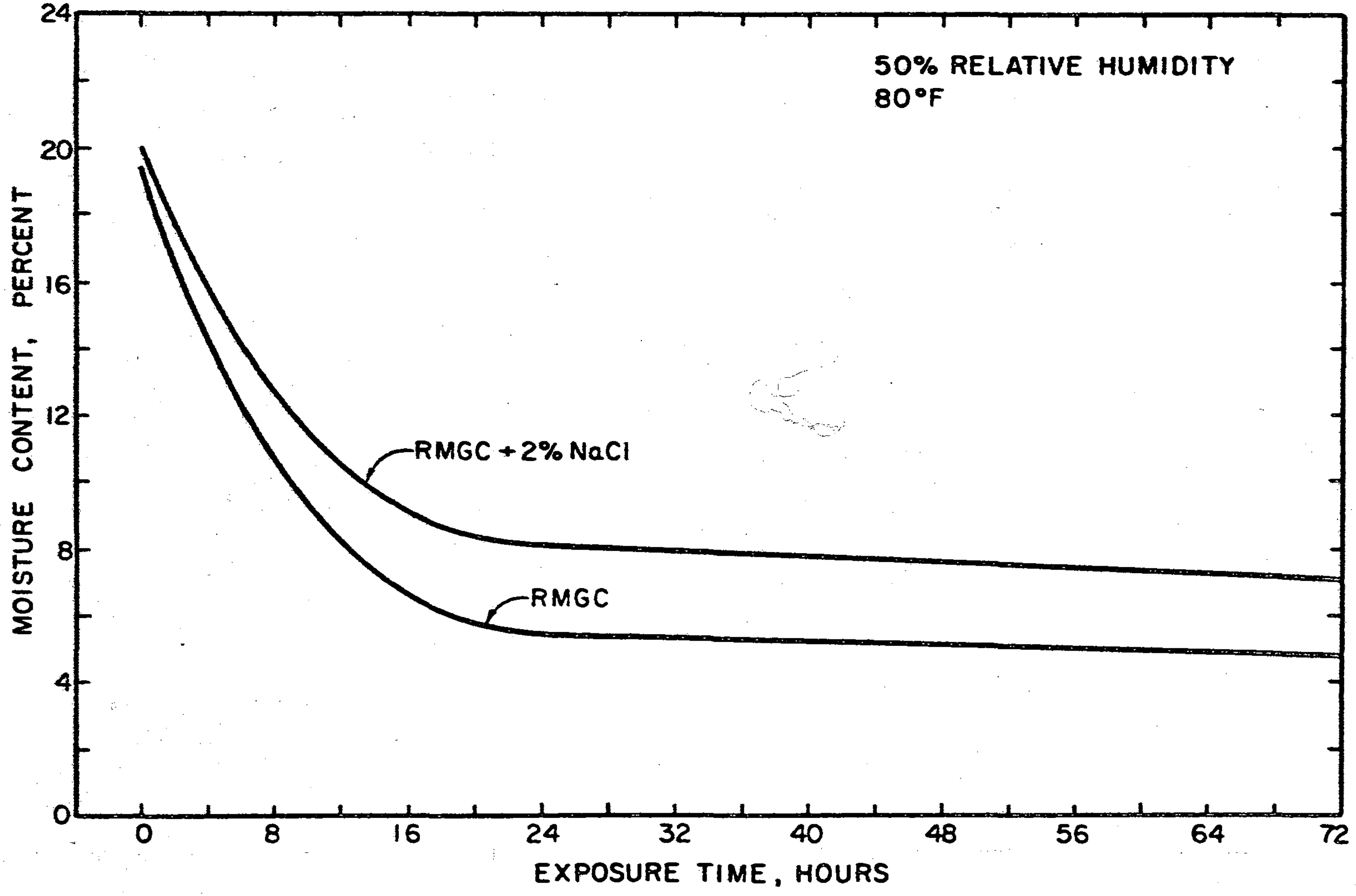
A.11. Moisture Retention Curves for Modified PRC at 70% Relative Humidity and 90°F



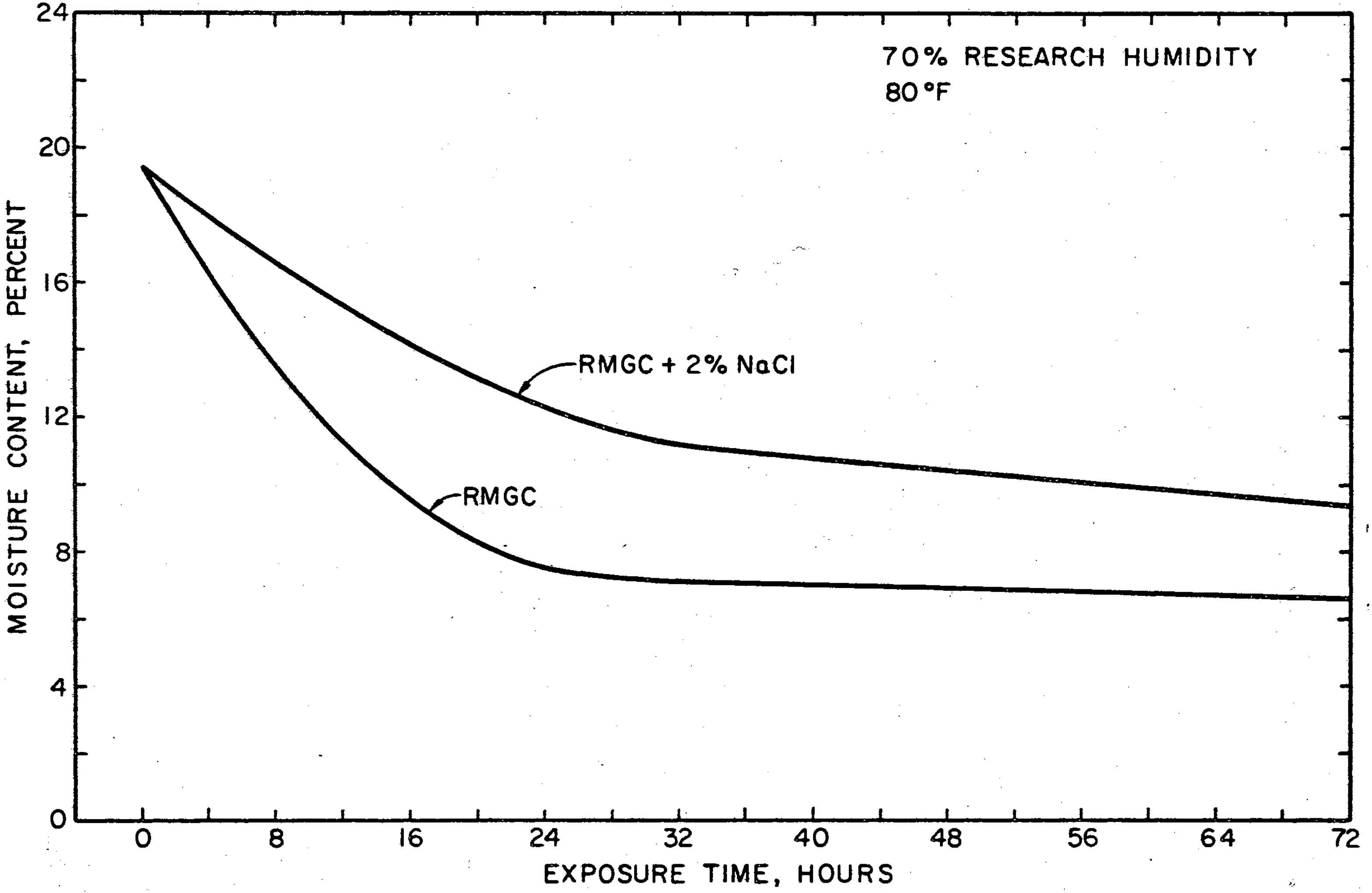
A.12. Moisture Retention Curves for RMGC Mixtures at 30% Relative Humidity and 80°F



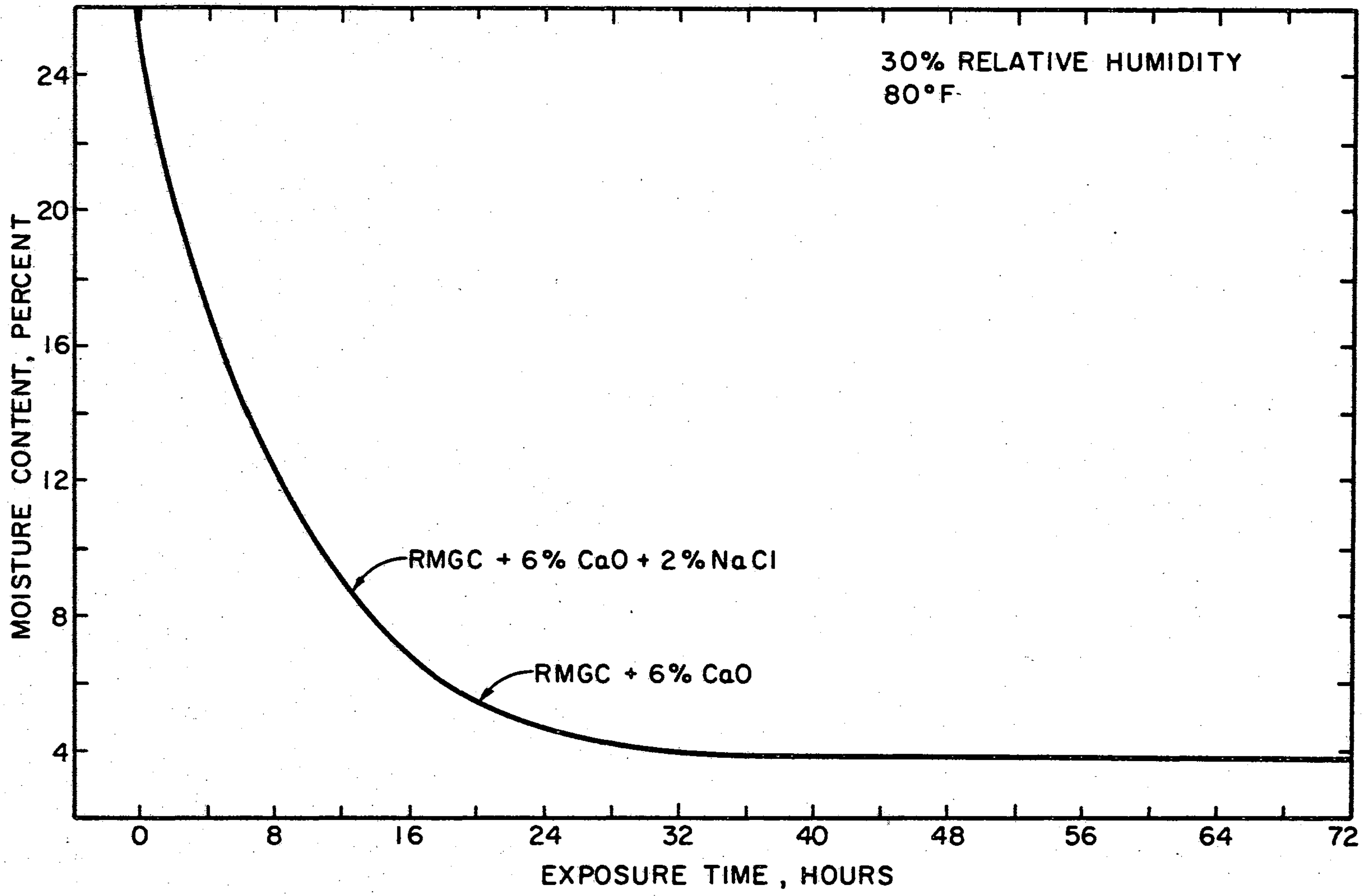
A.13. Moisture Retention Curves for RMGC Mixtures at 30% Relative Humidity and 90°F



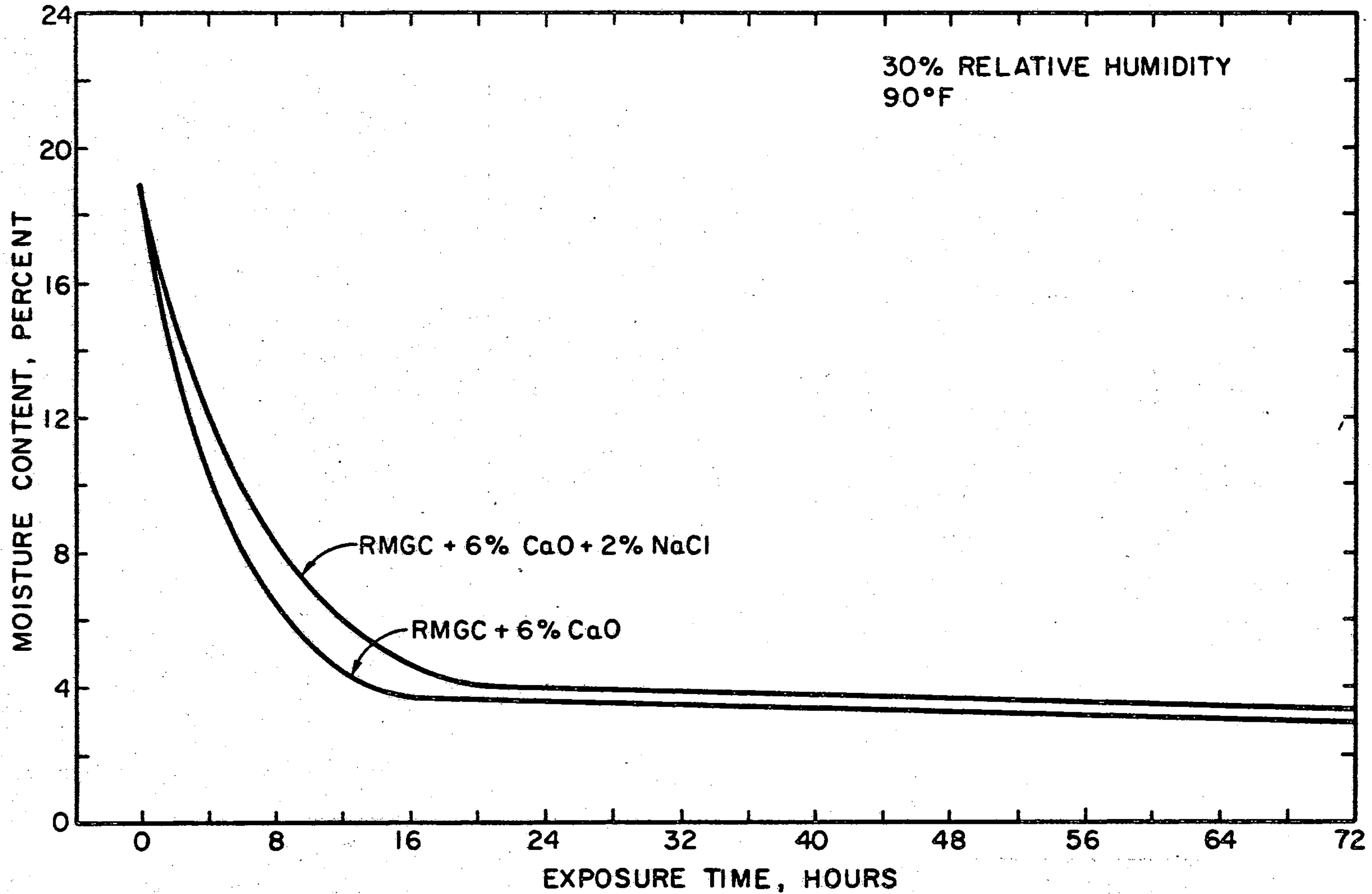
A.14. Moisture Retention Curves for RMGC Mixtures at 50% Relative Humidity and 80°F



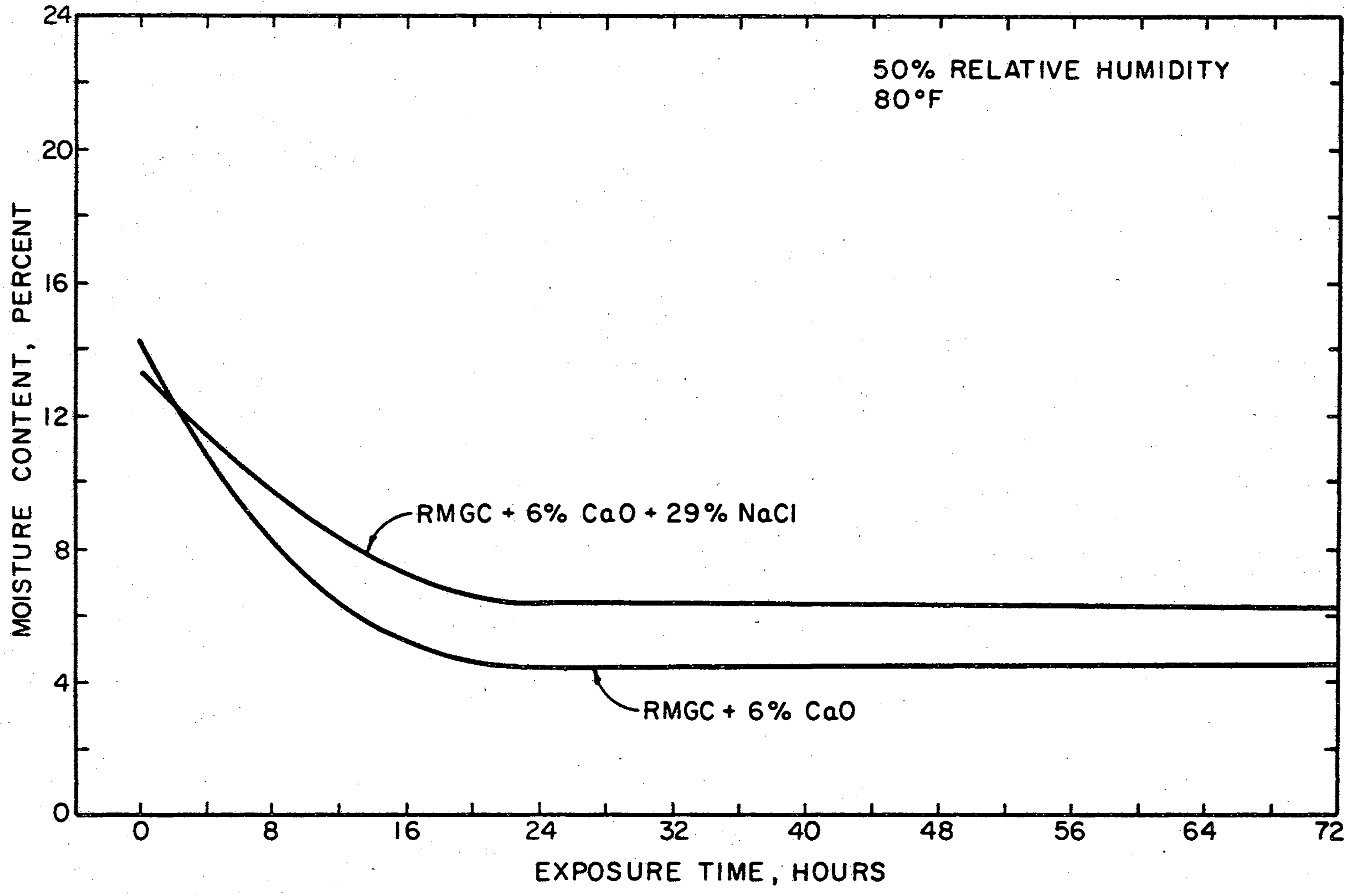
A.15. Moisture Retention Curves for RMGC Mixtures at 70% Relative Humidity and 80°F



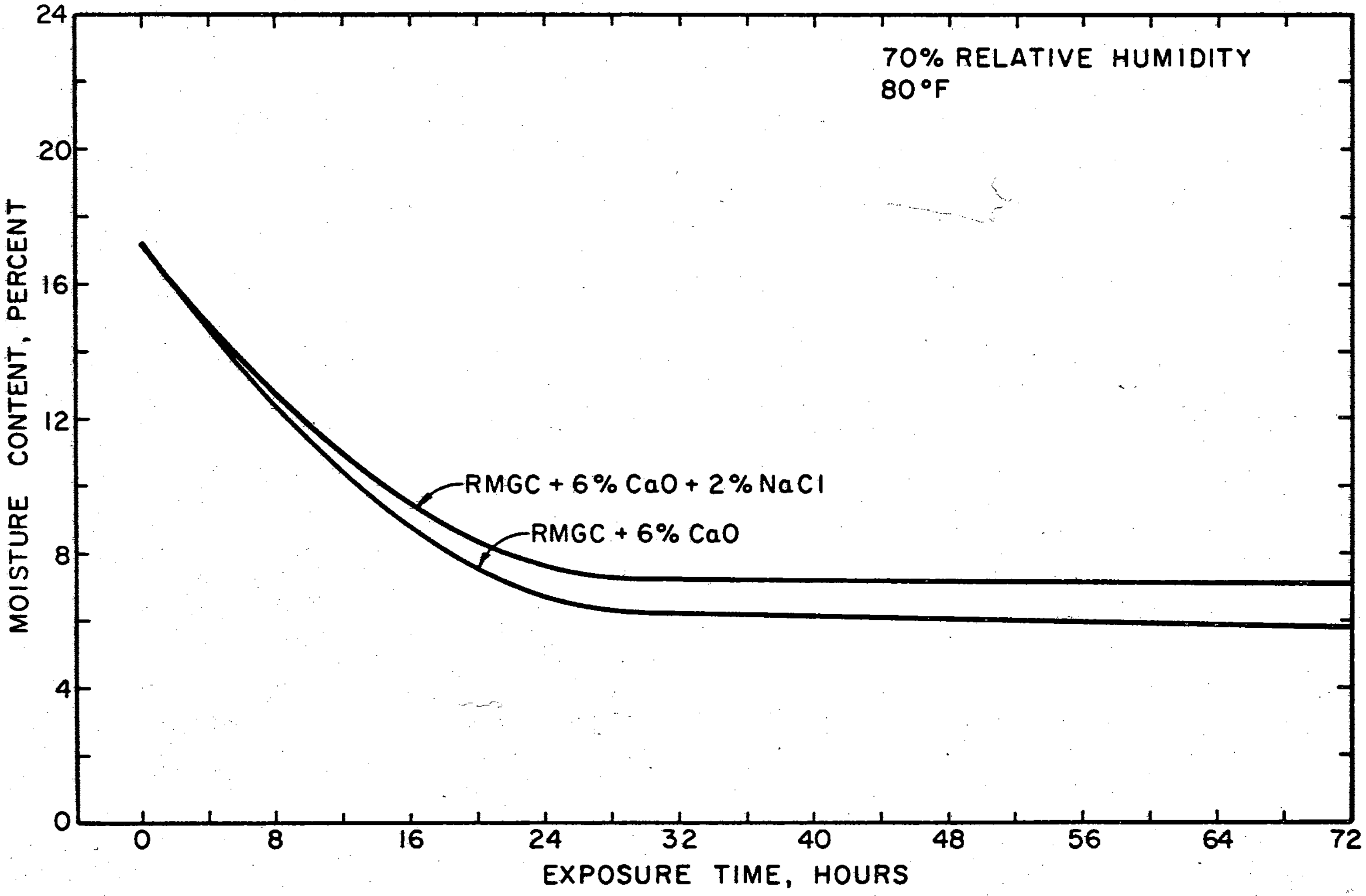
A.16. Moisture Retention Curves for Modified RMGC at 30% Relative Humidity and 80°F



A.17. Moisture Retention Curves for Modified RMGC at 30% Relative Humidity and 90°F



A.18. Moisture Retention Curves for Modified RMGC at 50% Relative Humidity and 80°F



A.19. Moisture Retention Curves for Modified RMGC at 70% Relative Humidity and 80°F

# APPENDIX B

## EFFECT OF COMPACTIVE EFFORT ON UNIT DRY WEIGHTS AND OPTIMUM MOISTURE CONTENTS OF PRC MIXTURES

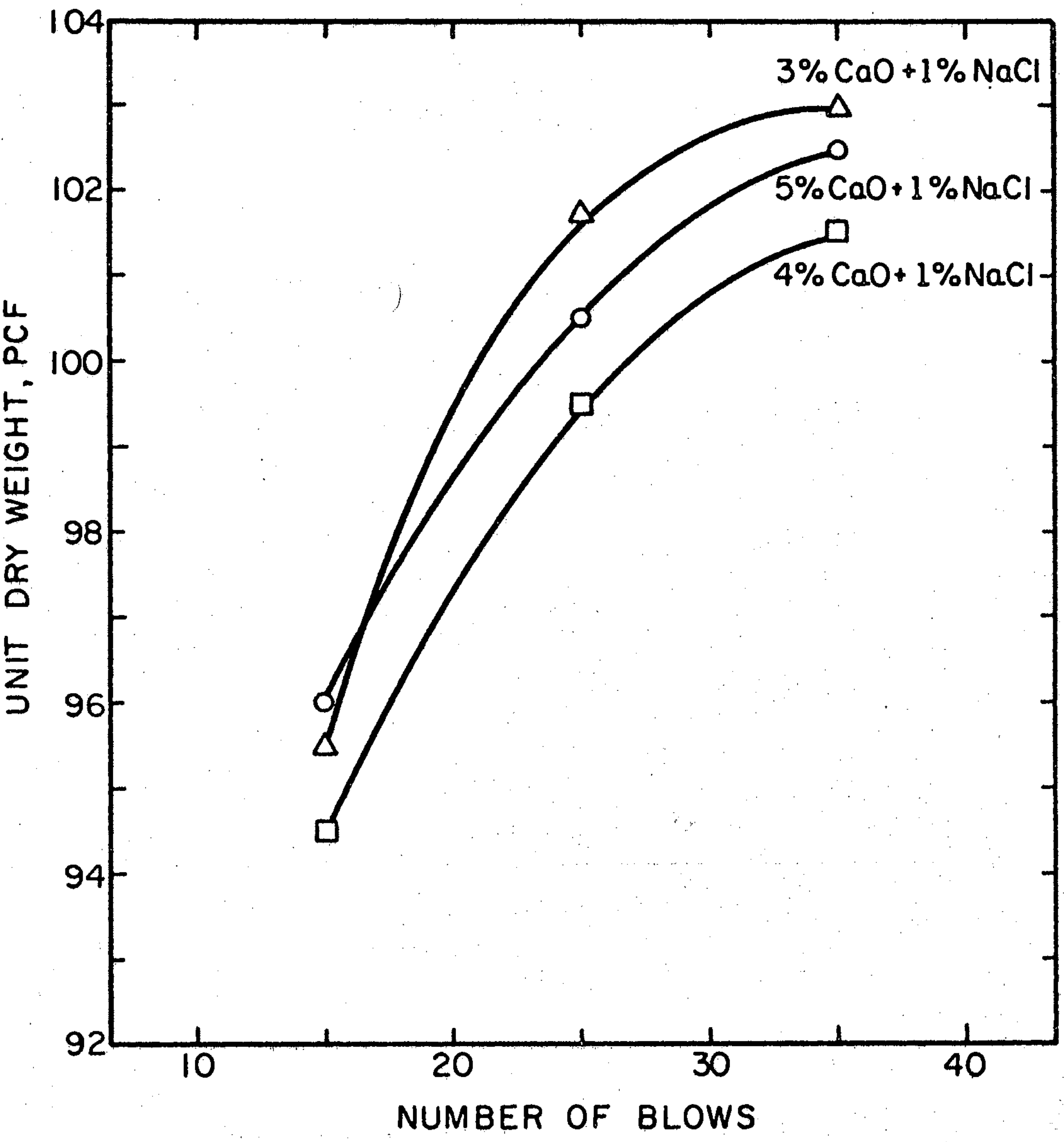


Figure B.1. Effect of Compactive Effort on Salt-Lime Modified PRC Mixture Density

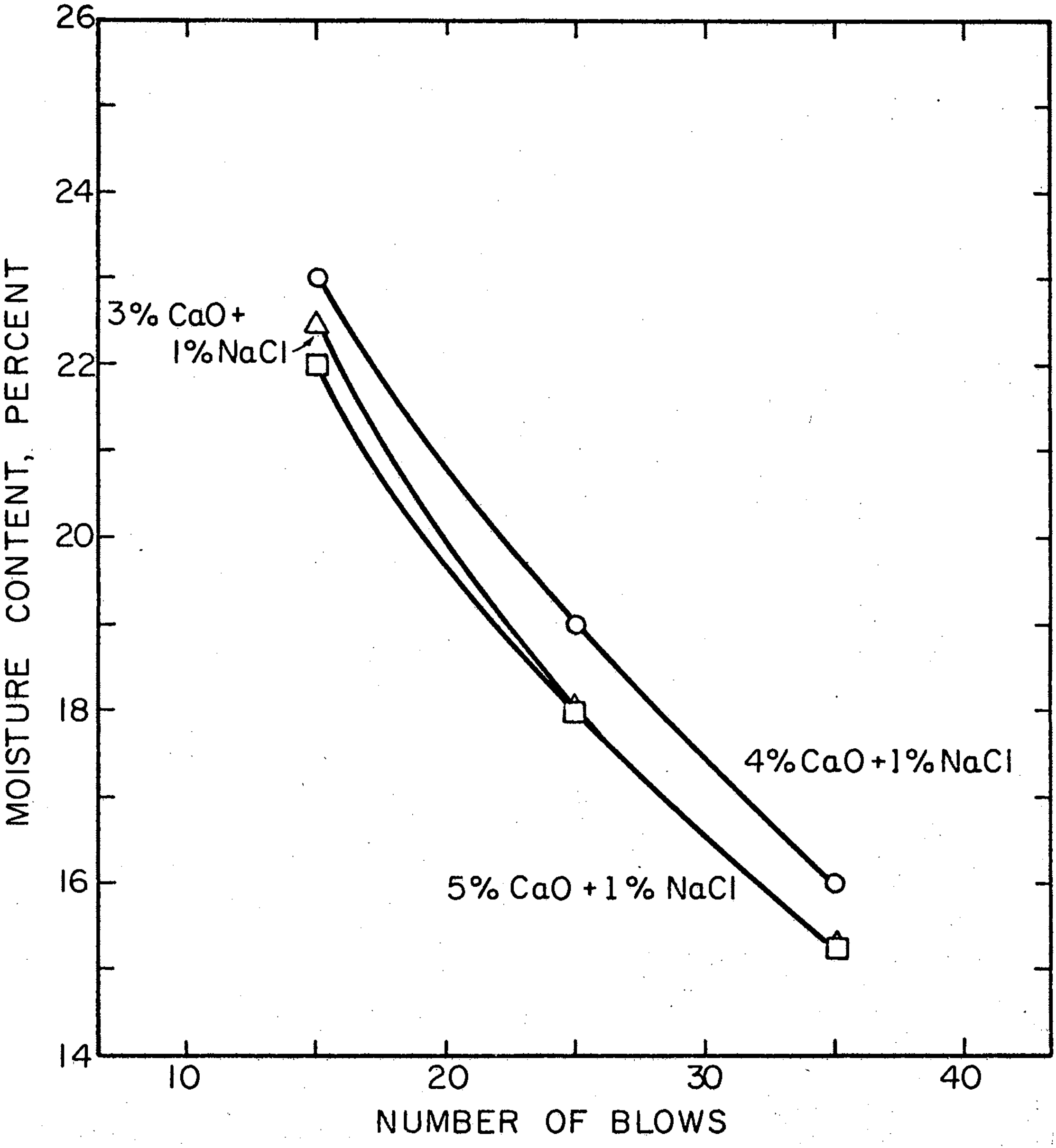


Figure B.2. Effect of Compactive Effort on Salt-Lime Modified PRC Mixture Optimum Moisture Contents

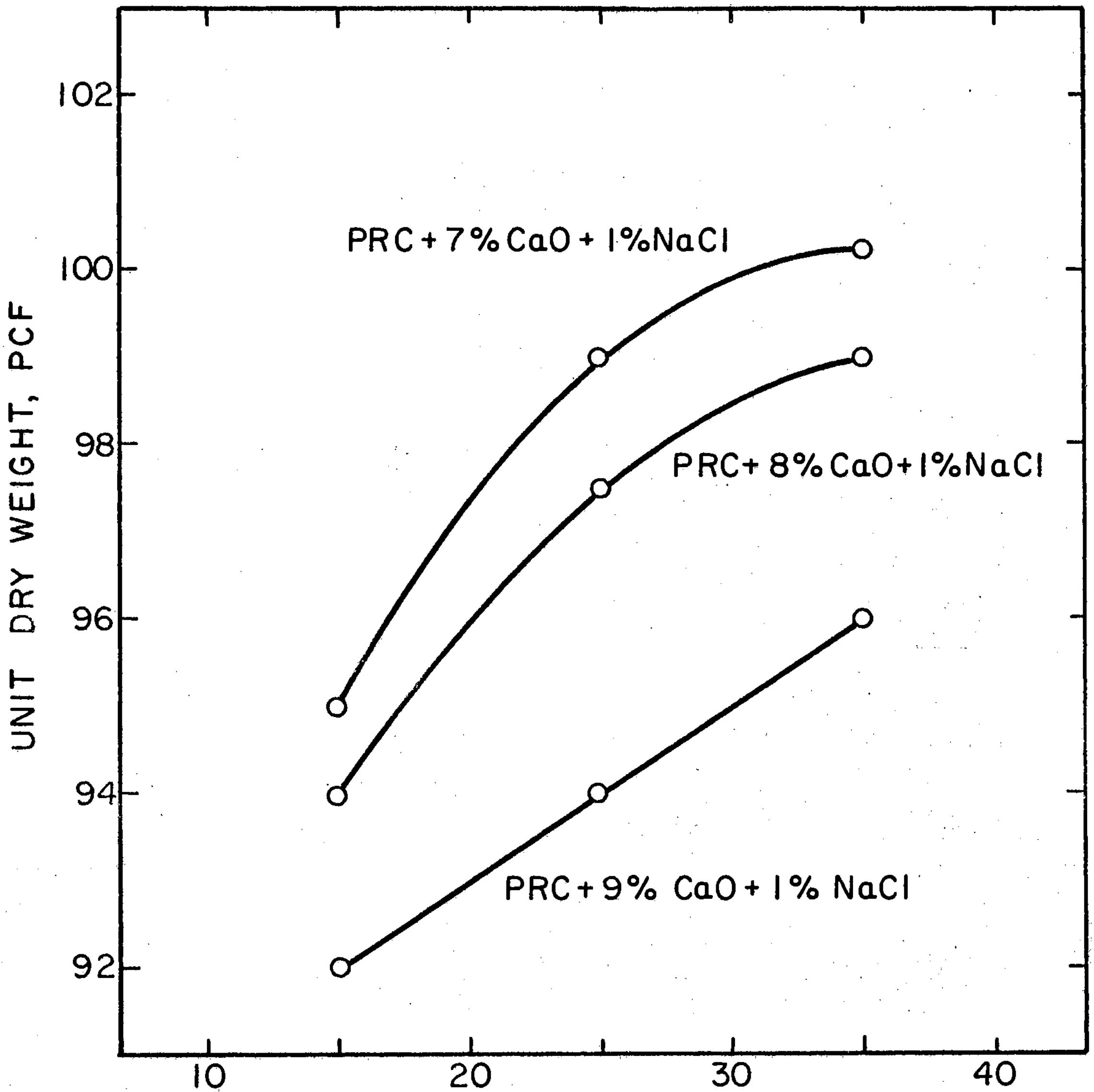


Figure B.3. Effect of Compactive Effort on Salt-Lime Stabilized PRC Mixture Compacted Unit Weights

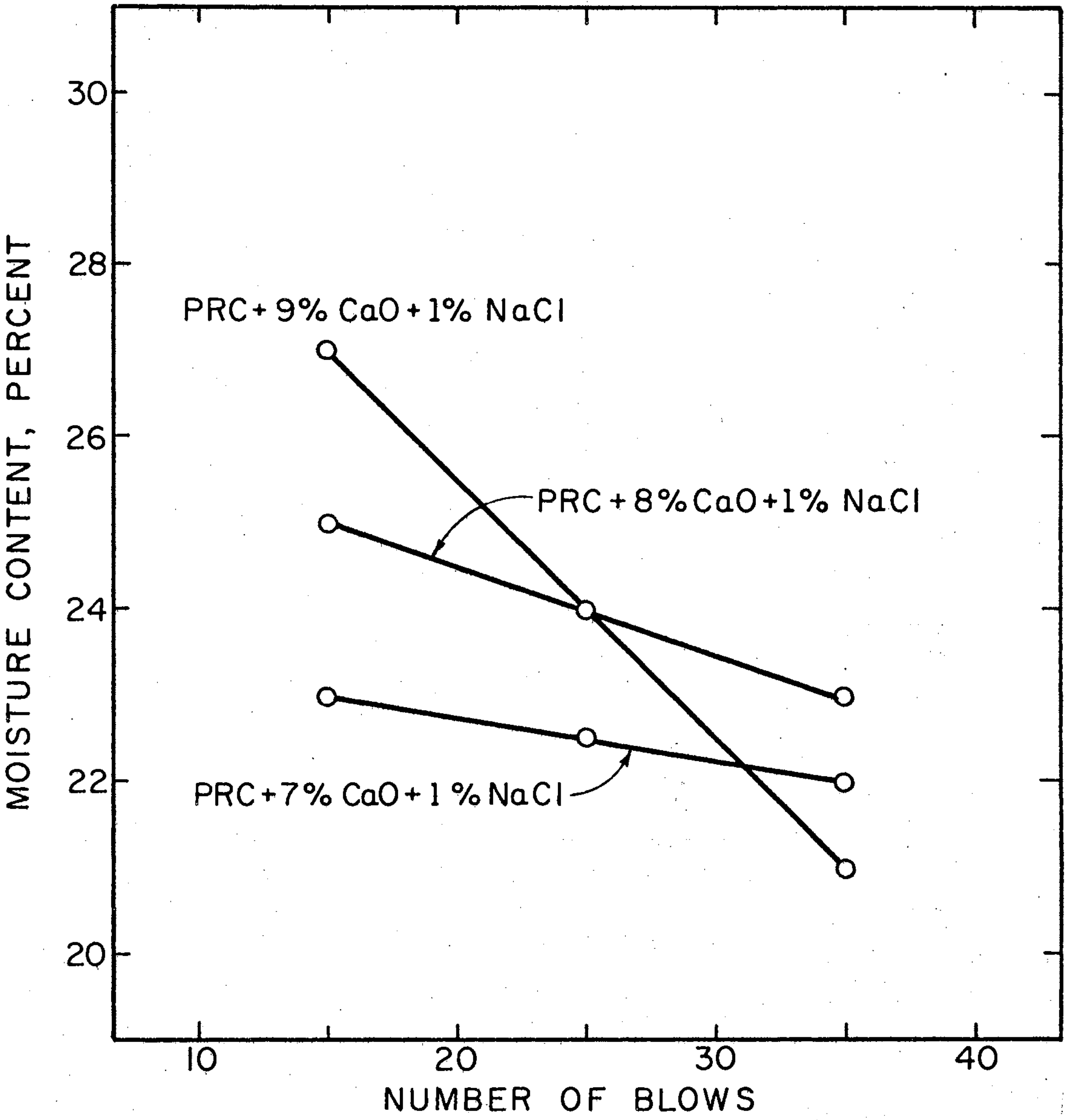


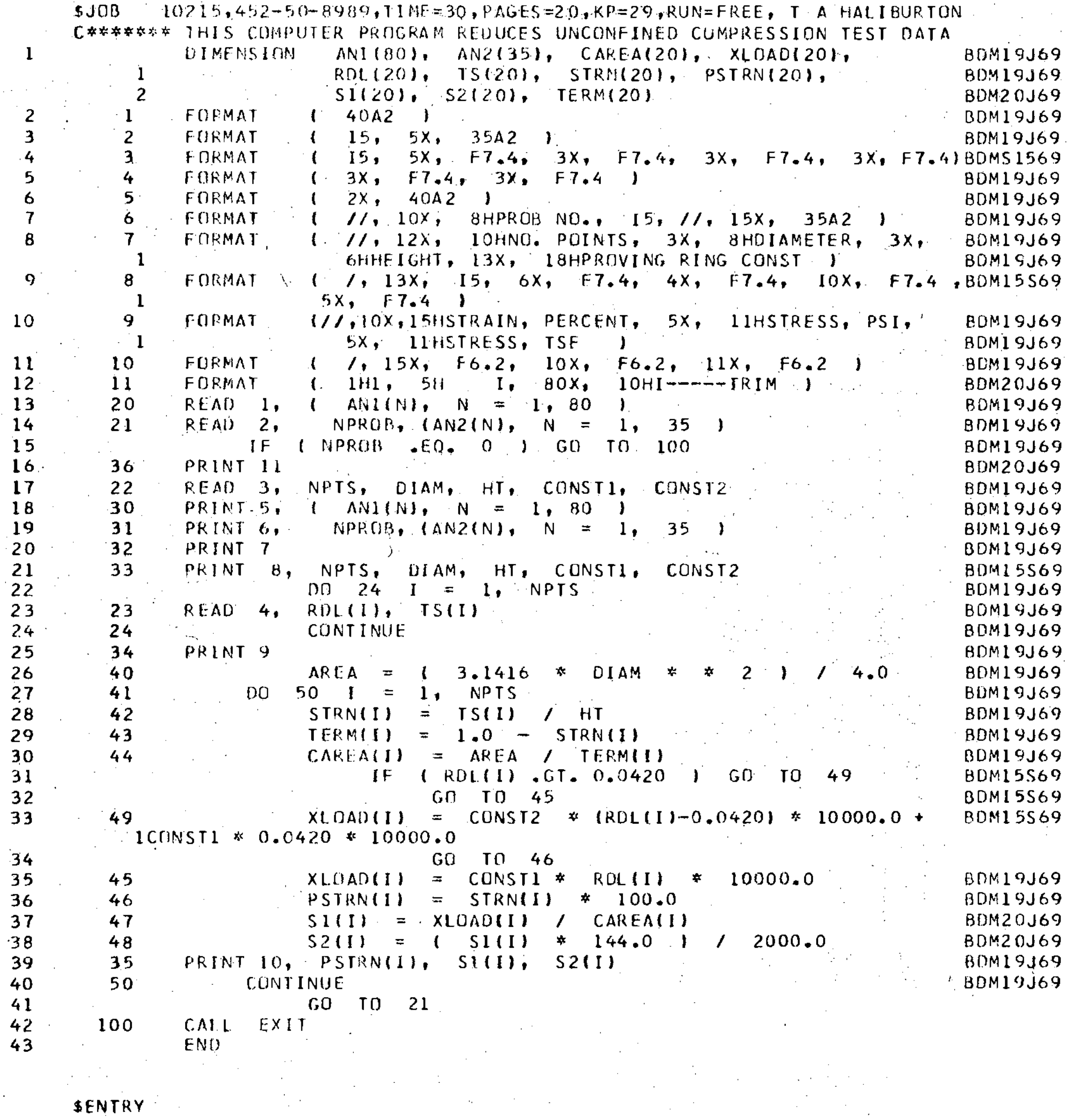
Figure B.4. Effect of Compactive Effort on Salt-Lime Stabilized PRC Mixtures Optimum Moisture Contents

# APPENDIX C

# COMPUTER PROGRAM FOR REDUCTION AND TABULATION OF UNCONFINED COMPRESSION TEST DATA

```
I
 THIS COMPUTER PROGRAM REDUCES DATA OBTAINED FROM UNCONFINED COMP. TEST
  DATA CODED AUGUST 20, 1969 BY DAN MARKS  RUN AUGUST 20, 1969

      PROB NO. 1403

           PRC - DW = 96.0 AT 22.0 PERCENT - ACTUAL = 22.1 PERCENT BROKE 8-19-69

       NO. POINTS   DIAMETER   HEIGHT              PROVING RING CONST

            8       1.3125     2.8125             0.3180       0.0000

      STRAIN, PERCENT      STRESS, PSI      STRESS, TSF

            0.36              12.41             0.89

            0.71              28.00             2.02

            1.07              43.25             3.11

            1.42              57.92             4.17

            1.78              72.26             5.20

            2.13              85.80             6.18

            2.49              96.26             6.93

            2.67              96.08             6.92
```

Figure C.1. Computer Program for Reduction of Unconfined Compression Test Data

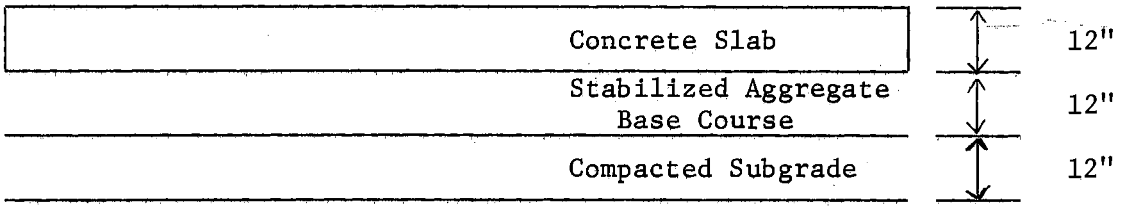


```
$JOB    10215,452-50-8989,TIME=30,PAGES=20,KP=29,RUN=FREE, T A HALIBURTON
C******* THIS COMPUTER PROGRAM REDUCES UNCONFINED COMPRESSION TEST DATA
              DIMENSION    AN1(80),   AN2(35),   CAREA(20),   XLOAD(20),            BDM19J69
      1                    RDL(20),   TS(20),   STRN(20),   PSTRN(20),              BDM19J69
      2                    S1(20),   S2(20),   TERM(20)                             BDM20J69
      1       FORMAT     (  40A2  )                                                 BDM19J69
      2       FORMAT     (  15,   5X,   35A2  )                                     BDM19J69
      3       FORMAT     (  I5,   5X,   F7.4,   3X,   F7.4,   3X,   F7.4,   3X, F7.4)BDMS1569
      4       FORMAT     (  3X,   F7.4,   3X,   F7.4   )                            BDM19J69
      5       FORMAT     (  2X,   40A2   )                                          BDM19J69
      6       FORMAT     (  //, 10X,   8HPROB NO.,  I5, //, 15X,   35A2   )         BDM19J69
      7       FORMAT     (  //, 12X,   10HNO. POINTS,   3X,   8HDIAMETER,  3X,      BDM19J69
      1                    6HHEIGHT, 13X,   18HPROVING RING CONST   )               BDM19J69
      8       FORMAT     (  /, 13X,   I5,   6X,   F7.4,   4X,   F7.4,   I0X,  F7.4 ,BDM15S69
      1                  5X,   F7.4   )
      9       FORMAT     (//,10X,15HSTRAIN, PERCENT,  5X,   11HSTRESS, PSI,         BDM19J69
      1                    5X,  11HSTRESS, TSF    )                                 BDM19J69
     10       FORMAT     (  /, 15X,  F6.2,   10X,  F6.2,  11X,  F6.2   )            BDM19J69
     11       FORMAT     (  1H1,   5H    I,   80X,   10HI-----TRIM  )               BDM20J69
     20       READ  1,   (  AN1(N),   N  =  1, 80   )                               BDM19J69
     21       READ  2,     NPROB, (AN2(N),   N   =   1,   35   )                    BDM19J69
                    IF   ( NPROB   .EQ.  0   )  GO   TO  100                        BDM19J69
     36       PRINT 11                                                              BDM20J69
     22       READ  3,   NPTS,   DIAM,   HT,   CONST1,   CONST2                     BDM19J69
     30       PRINT 5,   (  AN1(N),   N   =   1, 80   )                             BDM19J69
     31       PRINT 6,     NPROB, (AN2(N),   N   =   1,   35   )                    BDM19J69
     32       PRINT 7                                                               BDM19J69
     33       PRINT  8,  NPTS,   DIAM,   HT,   CONST1,   CONST2                     BDM15S69
                         DO  24   I   =   1,   NPTS                                 BDM19J69
     23       READ  4,   RDL(I),   TS(I)                                            BDM19J69
     24                  CONTINUE                                                   BDM19J69
     34       PRINT 9                                                               BDM19J69
     40                  AREA   =   (   3.1416   *   DIAM   *   *   2   )   /   4.0 BDM19J69
     41             DO   50   I   =   1,   NPTS                                     BDM19J69
     42                  STRN(I)   =   TS(I)   /   HT                               BDM19J69
     43                  TERM(I)   =   1.0   -   STRN(I)                            BDM19J69
     44                  CAREA(I)   =   AREA   /   TERM(I)                          BDM19J69
                              IF   ( RDL(I) .GT. 0.0420   )   GO   TO   49          BDM15S69
                                   GO   TO   45                                     BDM15S69
     49                  XLOAD(I)   =   CONST2   * (RDL(I)-0.0420) * 10000.0 +      BDM15S69
     1CONST1 * 0.0420 * 10000.0
                                   GO   TO   46
     45                  XLOAD(I)   =   CONST1 *   RDL(I)   *   10000.0             BDM19J69
     46                  PSTRN(I)   =   STRN(I)   *   100.0                         BDM19J69
     47                  S1(I)   =  XLOAD(I)   /   CAREA(I)                         BDM20J69
     48                  S2(I)   =   (   S1(I)   *   144.0   )   /   2000.0         BDM20J69
     35       PRINT 10,   PSTRN(I),   S1(I),   S2(I)                                BDM19J69
     50             CONTINUE                                                        BDM19J69
                         GO   TO   21
    100       CALL   EXIT
              END


$ENTRY
```

Figure C.2. Typical Computer Program Output for Unconfined Compression Test

# APPENDIX D

# TYPICAL CROSS-SECTION AND CALCULATION OF IMPOSED LOAD FOR SWELL TESTS



Assumed Unit Weights:

| | |
|---|---|
| Concrete | 150 $lb/ft^3$ |
| Base Course | 125 $lb/ft^3$ |
| Subgrade | 125 $lb/ft^3$ |
| TOTAL | 400 $lb/ft^3$ |

Soil Pressure $400\ lb/ft^3 \times 1\ ft = 400\ lb/ft^2$

$= 0.20$ tsf

# VITA

Belve Dansby Marks, III

Candidate for the Degree of

Doctor of Philosophy

Thesis: SODIUM CHLORIDE AND SODIUM CHLORIDE-LIME TREATMENT OF COHESIVE OKLAHOMA SOILS

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Memphis, Shelby County, Tennessee, November 20, 1944, the son of B. D. and Jimmie J. Marks, Jr.

Education: Attended elementary school in Haynes, Arkansas; graduated from Forrest City High School, Forrest City, Arkansas, on June 1, 1962; received a Bachelor of Science Degree in Civil Engineering from Oklahoma State University, Stillwater, on May 28, 1967; received a Master of Science Degree in Civil Engineering from Oklahoma State University, Stillwater, on May 29, 1968; completed requirements for the Doctor of Philosophy Degree in Civil Engineering in July, 1970.

Professional Experience: Employed with Devereax and Finch General Contractors, Forrest City, Arkansas, during the summers of 1962 and 1963; Engineering Aide with the Arkansas Highway Department as Surveyor and Inspector for subgrade, gravel base, and asphaltic concrete pavement during the summer of 1964; Field Engineer and Night Foreman for Dixie Contractors, Inc., Memphis, Tennessee, during the summer of 1965; Laboratory assistant for Civil Engineering Laboratories, Oklahoma State University, Stillwater, September 1965 to June, 1966; Research Assistant, Subgrade Moisture Variations Research Project, Oklahoma State University, Stillwater, July 1966 to July 1969; Research Assistant, Salt-Lime Stabilization Feasibility Study, Oklahoma State University, Stillwater, July 1969 to July 1970; Soils and Foundations Engineer Consultant, Hemphill Corporation, Tulsa, Oklahoma, March 1969 to present.