Effects of Sodium Chloride and Sodium Chloride-Lime Admixtures on Cohesive Oklahoma Soils

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Sodium chloride has been used for many years as a stabilizing admixture in "select" base course material. However, little if any investigation of the engineering properties of sodium chloride-stabilized cohesive soil has been done. This paper describes the effects of sodium chloride and sodium chloride-lime admixtures on plasticity, compaction, and strength properties of 2 high-volume-change cohesive Oklahoma soils. After review of available literature and discussion of chemical and physical reactions that occur during stabilization, experimental test results are presented and discussed. Small percentages of sodium chloride added to raw soil were found to have negligible effects on soil plasticity while increasing compacted density and decreasing optimum compaction moisture content. Workability and moisture-retention qualities of the raw soil were also enhanced. When small percentages of sodium chloride were added to lime-modified soil, similar results were obtained: Compacted density was increased, optimum moisture decreased, and the workability and moisture-retention properties of the salt-lime mixtures were enhanced considerably over those of lime-modified soil. In addition, salt-lime treatment produced strength gains over those obtained by lime treatment alone, both at the maximum compacted density and optimum moisture for each treatment and when the soils were compacted to similar moisture and density conditions. Reasons for the behavior observed are presented.

•CHEMICAL TREATMENT of subgrade soils to produce more desirable foundation material has gained increasing attention in recent years. Lime, in both hydrated and oxide form, has become one of the most widely used chemical treatments. Although lime treatment produces very desirable results, some undesirable effects also occur. These effects are more evident in lime modification than in stabilization and include reduced compacted unit weight, increased optimum moisture content, and little change in workability during initial mixing operations.

Addition of other chemical additives in conjunction with lime might be an effective way to minimize undesirable effects. The School of Civil Engineering at Oklahoma State University, Stillwater, is presently engaged in a feasibility study to determine effects of sodium chloride and sodium chloride-lime admixtures on cohesive Oklahoma soils. The project is sponsored by the Oklahoma Department of Highways.

This paper presents preliminary results obtained in the study. Theoretical considerations concerning the effect of lime and salt on cohesive soils are reviewed, followed by presentation and discussion of experimental results.

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THEORETICAL CONSIDERATIONS

Addition of lime to cohesive soil usually produces a decrease in plasticity. Chemical reactions that occur during lime treatment are not completely understood but must be hypothesized to explain effects of lime on cohesive soil. As divalent calcium ions are released on addition of lime to cohesive soil, monovalent diffused ions in the double water layer are dissociated. This causes some compression of the double layer and thus flocculation of clay particles. At the point of complete double-water-layer compression, no further reduction in plasticity is possible because the clay surface charge has been brought to equilibrium. The lime content that produces this maximum plastic limit has been termed the "lime-fixation point" by some investigators (1) and throughout this paper will be referred to as "modification optimum," for at this lime content, maximum modification of soil with respect to plasticity reduction has been obtained.

Addition of lime above modification optimum provides more free calcium ions, which are available for formation of new molecules and crystals. Calcium combines with aluminum hydroxyl groups to form tetracalcium aluminate hydrates that produce quick, low-strength cementing bonds within treated soil (2). Higher, long-term strength gains are obtained from formation of tobermorite minerals. These minerals are strongly bound hydrates of calcium and silica. Formation of tobermorites, such as calcium silicate hydrate, by pozzolanic reaction has been found to be greatly enhanced under high pH conditions. A pH in excess of 10.0 increases the solubility of silica, thus acting as a catalyst for new mineral formation (3).

Many factors exist that affect behavior of lime-treated cohesive soils. The effect of particular cations present in soil has been discussed many times; however, because formation of new crystals depends on availability of high valence hydrates, it seems only reasonable to conclude that soil sesquioxide content may be very important in lime reactions. Mattson (4), in some of his early work, found that silica/sesquioxide ratios in clays governed the behavior of these soils in reactions with acids and salts. Because free silica is all-important in the formation of tobermorites, it appears that lime treatment may be more dependent on the soil silica/sesquioxide ratio than any other single factor, as most lateritic soils, having low silica/sesquioxide ratios, react very poorly to lime treatment.

Addition of sodium chloride to cohesive soil has the same effect as addition of any other neutral salt. Phenomena that occur upon treatment of clay with salt may be explained in terms of double-water-layer theory or molecular chemistry. Both approaches produce the same result—a reduction in pH of the soil water system.

Clay particle surfaces are negatively charged, with net charge decreasing as distance from the particle surface decreases. This phenomenon is a result of diffused cations existing in the diffused double water layer. As salt is added to soil, double-water-layer thickness is reduced as a result of concentration of diffused cations. Compression of the diffused double layer causes a more abrupt decrease in charge across the layer, thus reducing the pH of the entire system (5).

Chemically, salt added to soil reacts with aluminum and silica in clay minerals to the extent that the minerals are altered. Addition of salt to clay minerals produces an excess of aluminum ions, which react with anions to form aluminum salts, very acidic compounds (6). The increased solubility of silica in the presence of sodium chloride, as shown by Van Lier, DeBruyn, and Overbeek (7), would enhance aluminum bonding that produces soil acidity.

MATERIALS AND SAMPLE PREPARATION

Materials being used in the study are 2 cohesive soils native to Oklahoma. The first type is a red permian clay (PRC) obtained from a depth of approximately 10 ft on the campus of the Oklahoma State University, Stillwater. The second cohesive soil is a highly plastic gray clay (RMGC) obtained from Roger Mills County in western Oklahoma. The gray clay deposit was found at a depth of approximately 3 ft, above permian deposits in that area. Index properties of PRC and RMGC are given in Table 1. Grain size distribution curves for both clays are shown in Figure 1. It should be noted that RMGC is more plastic than PRC, despite a lower colloidal fraction.

TABLE 1

INDEX PROPERTIES OF PRC AND RMGC

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, percent	12.0	17.8

Quicklime used in the study was obtained from the St. Clare Lime Company, Sallisaw, Oklahoma. Both commercial grade sodium chloride and ordinary rock salt were used in the study, without any noticeable effect on test results. A standard mixing and curing procedure was adopted for all samples prepared, and it was found to produce mixtures with more nearly constant moisture contents and better workability than any other procedure tried. Soil and additives were thoroughly mixed in dry form. Required moisture contents were obtained by sprinkling the entire sample surface with water. Mixtures were then sealed and allowed to cure for 8 to 12 hours at room temperature. This allowed moisture to migrate evenly and naturally through the soil samples.

PRESENTATION AND DISCUSSION OF RESULTS

Primary objectives of the investigation involved effects of sodium chloride and lime admixtures on engineering behavior of cohesive soils; however, it was necessary to determine effects of individual additives on the clays for comparative purposes. In the following sections the effects of salt treatment, lime treatment, and salt-lime treatment on the 2 cohesive soils are shown and discussed.

Effect of Sodium Chloride Admixtures on Soil Plasticity and Compaction

Addition of sodium chloride to both soils had the same general effect on plasticity, being more pronounced in RMGC. Increased percentages of salt caused corresponding increases in soil liquid limits (Fig. 2). A general increase was found to occur in plastic limit values for PRC; however, RMGC had a maximum plastic limit at 1 percent salt content. Plasticity index values for both soils increased with increasing salt content. The

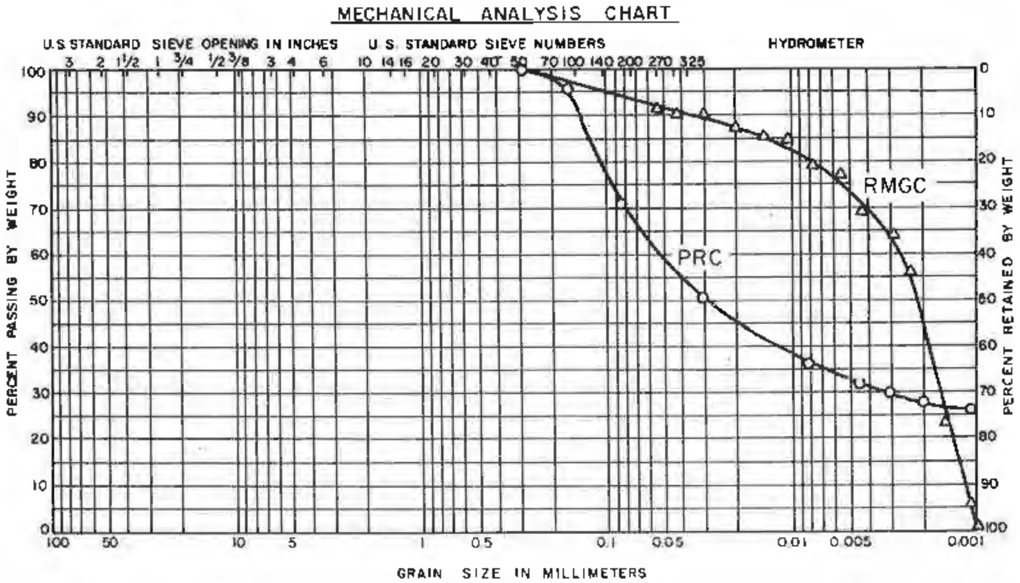

Figure 1. Grain size distribution curves for PRC and RMGC.

maximum increase in PI of PRC was 4.0 while RMGC showed an increase of 14.0, both at 4 percent salt. At salt contents below 2 percent, the effect of salt treatment on plasticity was negligible.

From observed behavior of these widely different soils, it appears that surface chemistry had a large effect on behavior. PRC, high in sesquioxide content, seems to be more stable on treatment with salt than does RMGC. This is reasonable because monovalent sodium ions would have little effect on dissociation of trivalent ions existing near PRC particle surfaces. However, salt treatment would have a greater effect on RMGC because of its low sesquioxide content and the absence of large amounts of high-valence ions near clay surfaces.

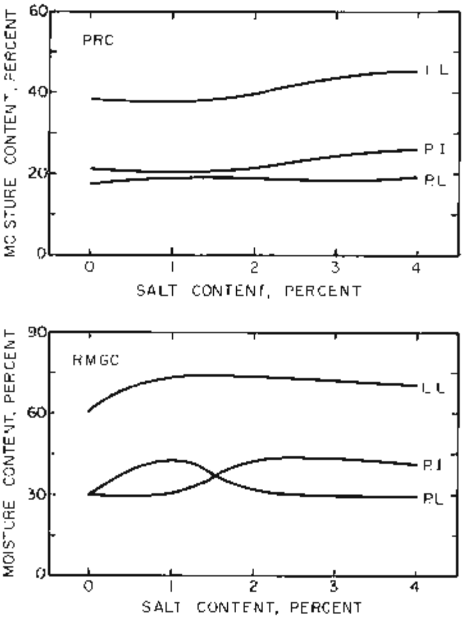

Figure 2. Effect of salt treatment on Atterberg limits of PRC and RMGC.

Standard Proctor density tests conducted on sodium chloride-treated soil produced favorable results in the case of PRC. Compacted unit weight of PRC was increased with increase in salt content to a maximum of 112 lb/cu ft at 2 percent salt, an increase of 6.0 lb/cu ft over that for the raw soil. This gain is much greater than that contributed by the presence of sodium chloride. RMGC produced no gain in compacted unit weight with addition of salt. Corresponding optimum moisture contents were found to be reduced with increase in salt content, passing through a minimum at 2 percent salt. Optimum moisture for PRC decreased from 18.0 percent in raw soil to 15.0 percent with addition of 2 percent salt. RMGC showed no reduction in optimum moisture content with salt treatment.

Because moisture-density curves obtained during compaction tests depend primarily on particle orientation, it would be reasonable to expect thal the flocculating effect of salt affected particle orientation. The authors feel that, for PRC, 2 percent salt produces enough compression of the double water layer to obtain maximum compacted density at the lowest possible moisture content. However, compacted density of RMGC was not affected by salt treatment. This could result from differences in mineral composition, as PRC has a larger colloidal fraction even though RMGC is more plastic.

Quantitatively, moisture retention of salt-treated soils of both types was much greater than for raw soil samples. This was evident in the mixing and curing procedures described previously.

Effect of Lime Admixtures on Soil Plasticity and Compaction

Atterberg limits were run on admixtures of both PRC and RMGC with varying percentages of lime, in order to locate the modification optimum lime content. Modification optima for PRC and RMGC were 4 and 6 percent respectively. To further substantiate location of the modification optimum, the pH test for lime-treated soil was used to locate the optimal lime content, and confirmed the Atterberg limit-obtained percentages.

Standard Proctor density data for the soils at their respective lime modification optima indicated a relatively large reduction in compacted unit dry weight from that of the raw soil, with resulting increased optimum compaction moisture content. Maximum compacted unit dry weight for PRC was decreased from 106 to 95 lb/cu ft by addition of 4 percent lime, while optimum moisture increased from 18.0 to 20.5 percent. For RMGC, 6 percent lime decreased maximum compacted unit dry weight from 96 to 91 lb/cu ft, and optimum moisture increased from 20.0 to 26.5 percent.

Because most undesirable features of lime treatment occur in lime modification of soil, percentages of lime around the modification optimum of each soil were selected to begin study of lime-salt admixture combinations.

Effect of Salt-Lime Admixtures on Soil Plasticity and Compaction

Some preliminary experimentation was conducted to determine if mixing procedure was an important variable. Results indicated that no appreciable difference was obtained by changes in the mixing sequence of salt and lime, nor was there any evidence that mixing either salt or lime in slurry form had any significant effect on soil behavior.

Addition of salt in combination with lime had very little effect on the plasticity of either soil. No case occurred where the addition of small percentages of salt with lime increased the plasticity such that the treated soil became nonselect material, i.e., with a PI greater than 5.0. These small effects of sodium chloride on plasticity of lime-treated soil further indicate that monovalent sodium ions have little effect on dissociation of divalent calcium ions. However, sodium chloride does affect surface chemistry of cohesive soils, as indicated by behavior of salt-lime mixtures during compaction, which is very dependent on surface chemistry and particle orientation.

By varying salt content with 3, 4, or 5 percent lime plus PRC, trends similar to those obtained from standard Proctor compaction tests of PRC plus sodium chloride were obtained. Maximum density was found to be substantially increased, and optimum moisture content reduced. One percent salt appeared to be the optimal salt content for increase of density and reduction of optimum moisture content in lime-modified PRC. Similar results were found to occur with RMGC, although response to the salt-lime treatment was not as pronounced as with PRC. An optimum salt content of 2 percent was found for RMGC mixtures. Results obtained from standard Proctor compaction tests for lime contents at and near modification optimum are shown in Figure 3. Effects of salt-lime treatment on optimum moisture are shown for both soils in Figure 4.

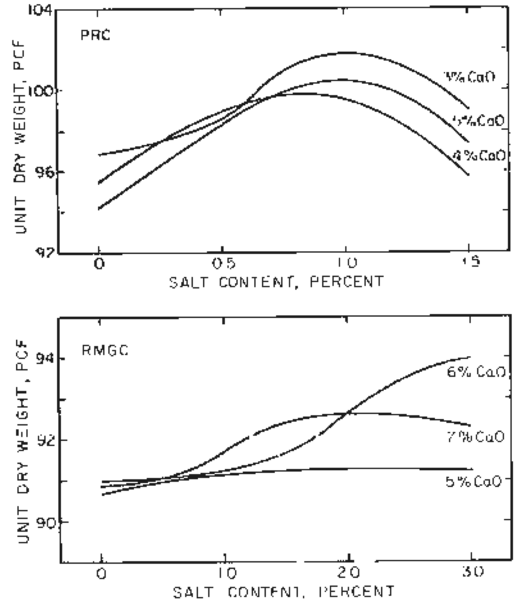

Figure 3. Effect of salt on compacted unit weight of PRC and RMGC mixtures near their lime modification optima.

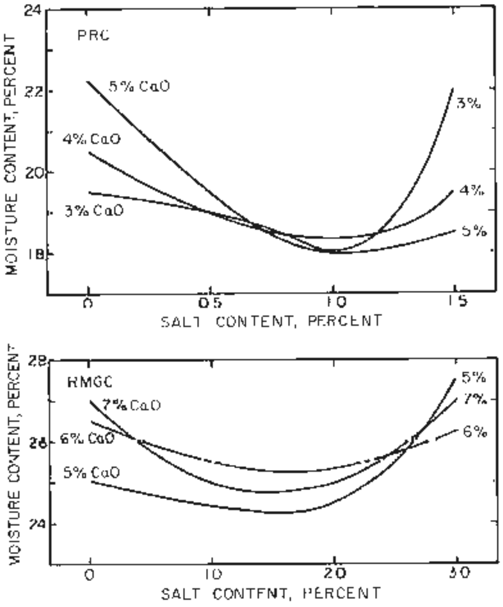

Figure 4. Effect of salt-lime treatment on optimum moisture contents of PRC and RMGC mixtures near lime modification optima.

It is thought that the small percentages required to cause these changes in unit weight and optimum moisture are sufficient to increase particle orientation by additional particle flocculation. Although this seems a sensible explanation, it is somewhat incomplete because flocculation should have occurred completely as a result of the addition of lime. Thus, compression of the double water layer must be enhanced by monovalent sodium ions, plus any dissolution effect caused by the presence of chlorine ions.

Workability of salt-lime mixtures was better than lime-treated mixtures. Added moisture was found to be more evenly distributed and constant after comparable curing times than was found with lime-treated soil. Ability of salt-lime admixtures to retain initial moisture contents was much greater than for mixtures of lime-treated soil.

Effects of Sodium Chloride-Lime Admixtures on Compressive Strength

Throughout this portion of the paper, results obtained from unconfined compression tests on salt-lime-treated soil will be compared with those obtained from lime-treated soil.

The loading rate for all unconfined compression tests was 0.03 in. per minute. This rate was based on a desired 5.0 percent strain in 10 minutes. Unconfined compression test specimens were molded in a Harvard miniature mold. Curing of all samples was accomplished by waxing specimens and placing them in a 25 C moist room for desired curing times. Each data point on all curves represents the average of at least 3 tests.

Initially, all strength tests were conducted on specimens compacted at optimum moisture content and maximum standard Proctor densities. Although differences between optimum moisture content and maximum dry density for the various mixtures will have some effect on strength, results obtained were expected to be more meaningful, for practical purposes, than samples prepared at the same compaction moisture content and unit dry weight.

Unconfined compression test results of samples compacted at optimum moisture contents and maximum standard Proctor densities indicate that the presence of salt increases the strength of both PRC and RMGC above that obtained from lime modification alone. Both lime-treated and salt-lime-treated PRC 7-day strengths passed through maxima as lime content was increased. RMGC mixtures showed a decreasing effect of salt on strength as lime content was increased. PRC showed greater response to salt-lime treatment at standard Proctor density than did RMGC. Results of 7-day unconfined compression tests are shown for both soils in Figure 5.

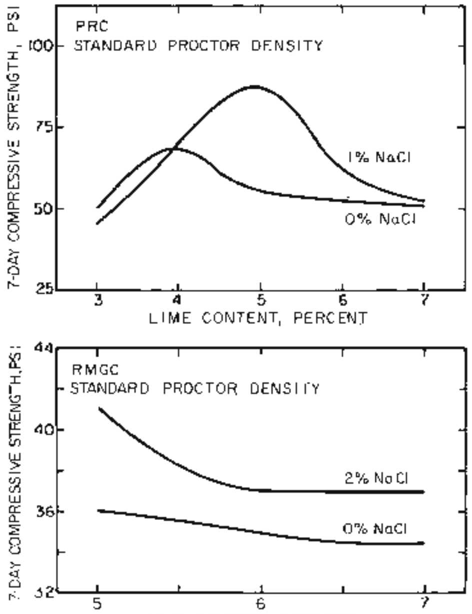

Figure 5. Effect of salt on lime-treated PRC and RMGC strength when compacted to standard Proctor density.

In order to determine the amount of strength gain contributed by salt, it was necessary to eliminate the variables of compacted moisture content and unit dry weight. Moisture-density curves for different compactive efforts were therefore obtained to determine a compaction moisture content and unit dry weight with corresponding compactive effort that could be used for all samples tested.

Samples thus prepared were cured in the manner described previously, with unconfined compression tests conducted after 7, 14, 21, and 28 days of curing. In all cases, admixtures of salt plus lime produced greater strengths than samples treated with lime alone. In PRC mixtures, 5 percent lime with 1 percent salt again showed a greater increase

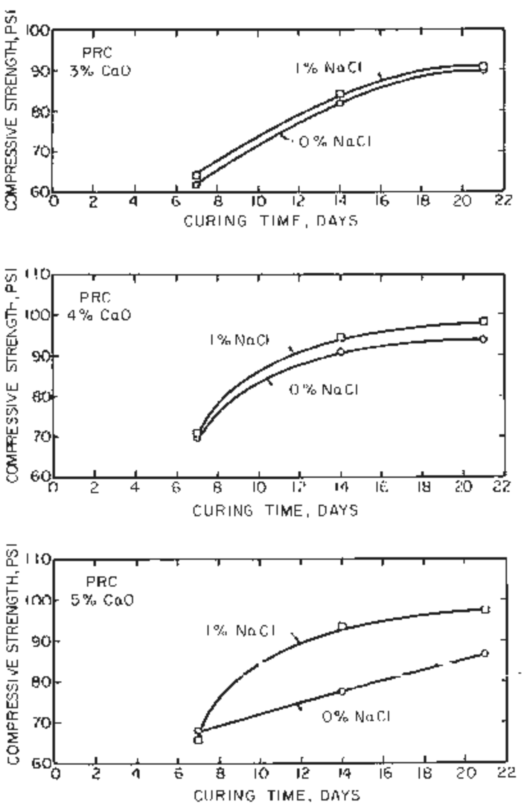

Figure 6. Effect of curing time on strength of salt and salt-lime modified PRC samples under constant moisture and density conditions.

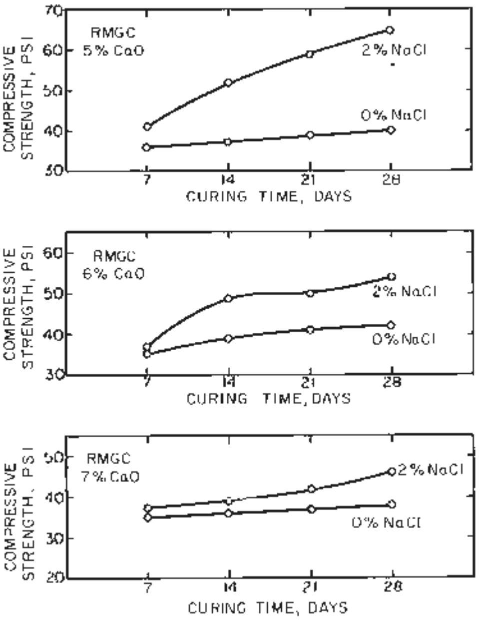

Figure 7. Effect of curing time on strength of salt and salt-lime modified RMGC samples under constant moisture and density conditions.

in strength than did either 3 or 4 percent lime with 1 percent salt. The same was true for RMGC. Mixtures of 5 percent lime plus 2 percent salt showed greater strength gain than did other percentages. The rate of strength gain was reduced as lime content increased. Figures 6 and 7 show strength gain relationships between lime-modified and salt-lime-treated PRC and RMGC respectively. Figure 8 shows the effect of lime content on compressive strength, with and without salt treatment.

Consistent gains in strength from salt-lime admixtures, above those obtained from lime-treated soil, indicate that salt may produce other effects besides flocculation in cohesive soil. Reaction of clay minerals with sodium chloride may create a situation where aluminum is more accessible to chemical reaction with lime. Because early strength of lime-treated soil results from formation of tetracalcium aluminate hydrates, sodium chloride may act as a catalyst in formation of these cementitious molecules. Increased solubility of silica or quartz in the presence of salt may well be the reaction that accelerates crystal growth, producing strength gain.

Discussion of salt-lime admixture strength thus far has been confined to lime percentages near the modification optimum for both soils. In this region of lime percentage, strength gain is usually of secondary consideration; however, it has been shown that strength gains obtained by addition of salt at modification lime contents are of fairly large magnitude. The next item to be discussed involves the benefit of adding small percentages of sodium chloride at lime contents around the stabilization optimum. At these lime contents strength is the primary, rather than secondary, concern.

In the case of PRC, a lime content of 8 percent was found to be stabilization optimum. Experiments were conducted with admixtures of lime and salt plus lime, 1 percent on either side and at optimum lime content. The greatest effect of salt on strength was

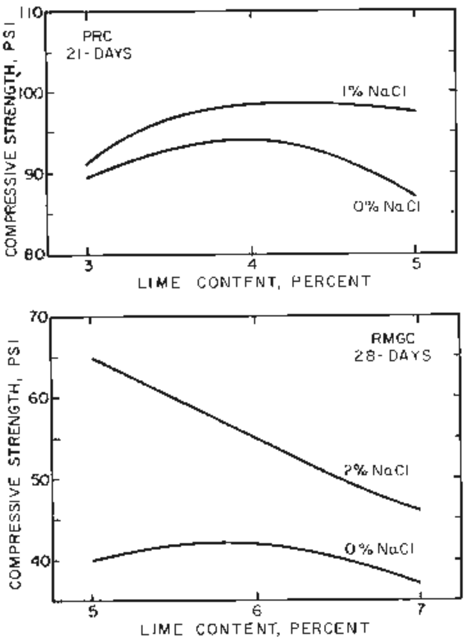

Figure 8. Comparison of lime and salt-lime compressive strength for PRC and RMGC near their lime modification optima under constant moisture and density conditions.

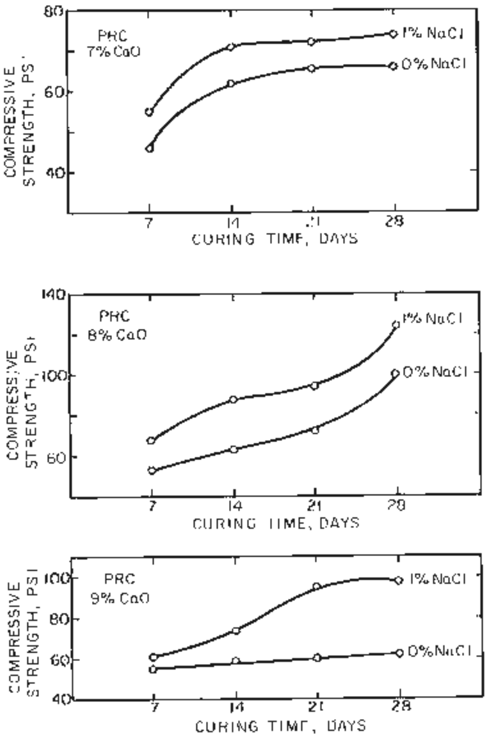

Figure 9. Effect of curing time on strength of lime and salt-lime stabilized PRC mixtures under constant moisture and density conditions.

found to occur at 8 percent lime content. The rate of strength increase was also found to be greatest at this lime content. Figure 9 shows the effect of curing time on strength for the 3 lime and 3 salt-lime mixtures tested. Addition of 1 percent salt at optimum lime content produced a compressive strength of 122 psi, which represents a 22 percent increase over lime alone.

RMGC was found to behave similarly to PRC, with maximum benefits obtained at a stabilization optimum of 11 percent lime. Although the rate of strength increase was substantial for RMGC mixtures, the total increase in strength was not as high as for PRC. The rate of strength increase is shown in Figure 10, which shows compressive strength as a function of curing time for all RMGC mixtures. The maximum strength, obtained at a lime content of 11 percent with 2 percent sodium chloride, was 49 psi, a strength increase of 11.5 percent over lime treatment alone. Thus, the effect of salt on strength gain is almost twice as much for PRC as for RMGC; however, because of the lower strengths obtained with RMGC, the latter increase may be of more importance. A summary of strength as a function of lime content, with and without salt, is shown for both soils in Figure 11.

The fact that the rate of strength gain was increased by addition of salt at all lime percentages would indicate that some type of catalytic reaction occurs during curing.

At this time, 2 purely hypothetical explanations are being considered. The first is that the sodium chloride reacts with clay minerals and upsets aluminum bonding in the clay, producing a condition where calcium ions may more easily unite with aluminum and silica to form new minerals, thus increasing the rate of strength gain. This reaction would have an effect on soil pH and charge equilibrium at the clay particle surface.

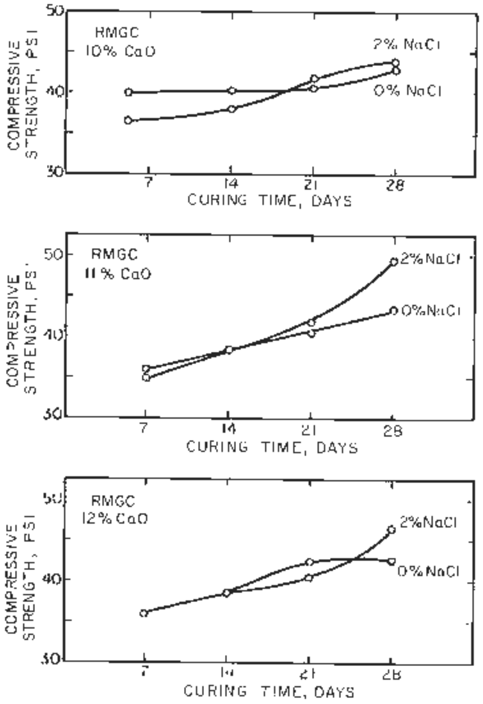

Figure 10. Effect of curing time on strength of lime and salt-lime stabilized RMGC mixtures under constant moisture and density conditions.

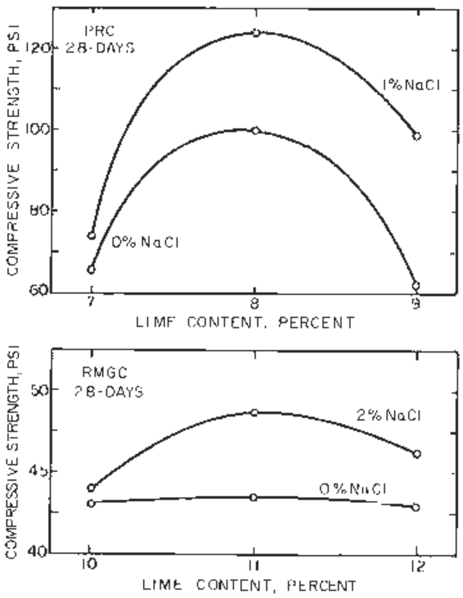

Figure 11. Effect of lime content on PRC and RMGC compressive strength without salt and at optimum salt content under constant moisture and density conditions.

The second explanation would be the increased solubility of silica in the presence of sodium chloride. By increasing the solubility, silica is available for reaction with calcium at a much greater rate than occurs in normal lime treatment.

SUMMARY

Based on data presented in this paper, the following preliminary conclusions are presented concerning effects of sodium chloride and sodium chloride-lime admixtures on the engineering behavior of cohesive soil. Results were obtained on 2 Oklahoma clay soils, but should be indicative of behavior for cohesive soils of similar origin and engineering properties.

1. Plasticity of cohesive soil is increased by addition of sodium chloride; however, PI increase at salt contents less than 2 percent is negligible.
2. Addition of sodium chloride was found to produce a substantial increase in compacted unit weight and corresponding decrease in optimum moisture content in the lower plasticity PRC, while the more plastic RMGC showed no response in compaction properties by addition of sodium chloride.
3. Both cohesive soils showed higher compacted unit dry weights and lower optimum moisture contents for salt-lime mixtures than for lime-treated soil.
4. Addition of small sodium chloride percentages with lime near modification optima did not increase plasticity sufficiently to change the material to nonselect subgrade soil.
5. Strength gains at both modification and stabilization optima were substantially increased by addition of small percentages of salt; thus sodium chloride increases the rate of strength gain and total strength associated with lime treatment.
6. Workability and moisture retention properties of both raw soil and lime-treated soil were enhanced by addition of small percentages of salt.

Sodium chloride may have use as a compaction aid, a moisture-retention agent, and a catalyst in increasing the strength of lime-modified and stabilized cohesive soils. Also, addition of small salt percentages counteracted the reduced unit dry weights and increased optimum compaction moisture contents associated with lime treatment of cohesive soils. Research currently in progress is expected to obtain more data concerning engineering behavior of salt and salt-lime-treated cohesive soils, and also to provide reasons for the behavior observed.

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