Use of Sodium Chloride in Reducing Shrinkage in Montmorillonitic Soil-Cement

JERRY W. H. WANG and ALEXANDER H. KREMMYDAS, Civil Engineering Department, Ohio University

Shrinkage in soil-cement results in progressive cracking and has been the cause of increasing concern. This paper reports the results of an experimental investigation to reduce shrinkage in Na-montmorillonitic soil-cement by using sodium chloride as a trace additive. The mechanism of shrinkage derived from this study was extended to Ca-montmorillonite and was also found generally applicable. Shrinkage was found to decrease greatly with increasing salt content except when used as a form of brine; in one case shrinkage was eliminated completely and actual expansion was observed. Strength reductions in the soil-cement specimens with sodium chloride additions were found to be due only to the increasing coarseness of the additive and not to the amount used. Addition of 1 to 3 percent fine-grained salt was found to produce strength comparable to that of soil-cement. The reduction of shrinkage in soil-cement with addition of salt was found to be primarily due to the ability of salt to reduce moisture loss in the mixture and to provide a more favorable and stable clay basal spacing. Particle reorientation during curing was also believed to be responsible for some of the shrinkage and expansion observed.

•SHRINKAGE IN SOIL-CEMENT is known to result in progressive cracking and has been the cause of increasing concern. This cracking is due to the tensile and shear stresses that are developed when shrinkage is partially or fully restrained. These cracks could conceivably become the cause of poor long-term engineering performance, if left untreated.

Examination of the factors that influence the behavior of shrinkage in soil-cement yields the following (3, 6):

1. Shrinkage results primarily from loss of water due to evaporation. The rate of evaporation decreases with time mainly because of increasing bonding energy of the remaining water with decreasing moisture content and decreasing size of water-filled capillaries. Nevertheless, evaporation of held water causes much greater shrinkage per gram evaporated, because it results in increased internal tensions in the remaining water.

2. Shrinkage of soil-cement is a function of the cement content and, when plotted, it exhibits a minimum at an optimum cement content. Increasing shrinkage of soil-cement with increasing cement content above optimum was presumed to be due to the greater water requirement of the cement to complete hydration. Thus cement hydration results in desiccation and shrinkage, and this shrinkage increases with cement content.

3. The clay content has also been known to increase shrinkage in soil-cement. This is due to the fineness of the -2 micron particles that have a large quantity of bonded water and hence result in large shrinkage as the water evaporates. It is also possible

Paper sponsored by Committee on Soil-Portland Cement Stabilization and presented at the 49th Annual Meeting.

that the clay content constitutes a matrix that is restrained less by the proportionally fewer +2 micron particles that act as rigid inclusions.

4. The kind of clay present in the soil-cement influences the amount of shrinkage; montmorillonite contributes the most for being the finest of all clay minerals. In addition, evaporation of the interlayer water in montmorillonite results in decreasing lattice spacing of the clay mineral. This type of shrinkage is naturally much greater than the shrinkage that results simply from evaporation of pore water.

5. Shrinkage increases with molding moisture wet of the Proctor optimum moisture content. The reason was explained to be that higher moisture contents make the -2 micron particles more apt to change from a cardhouse, flocculated structure to an oriented, dispersed one. When evaporation occurs, the latter structure allows for more shrinkage because of its weakly restrained particles.

The purpose of this study was to investigate the feasibility of reducing shrinkage in montmorillonitic soil-cement based on the concepts of lattice expansion of montmorillonites and retention of moisture with the addition of sodium chloride. Hopefully, it will also help in further delineating the shrinkage mechanism in montmorillonitic soil-cement.

METHODS AND PROCEDURES

Materials

The clay used was a sodium montmorillonite, commercially produced as Volclay by the American Colloid Company. Its exchangeable sodium and calcium cations range from 60 to 65 me/100g and 5 to 10 me/100g respectively (1). Ottawa sand, type I portland cement, and distilled water were the other constituents used together with the Volclay to prepare soil-cement specimens.

Commercially available rock salt for de-icing purposes with more than 99 percent NaCl was used. Different percentages were used in molding soil-cement specimens. The commercial gradation and the gradations of the salt used in the laboratory are given in Table 1.

Preparation and Curing of Specimens

The composition of the control specimens was as follows:

Material	Percent by Weight
Ottawa sand	52
Volclay	32
Portland cement	16

The mixing moisture content was 23.5 percent, based on the total dry weight of solids in the mix. This composition was found to give best workability throughout the process.

Different percentages of salt, based on the dry weight of the control mix, were added to mold soil-cement specimens in order to study the effect of the additive.

Soil-cement specimens of various proportions were molded in batches of 4 specimens. All batches were dry-mixed first for 1 minute to ensure uniform distribution of all constituents. The batches were then wet-mixed for 2 minutes. All mixing was done in a Hobart mixer, Model C-100.

The test specimens were prepared by weighing a constant amount of mix and placing it into a mold. The mold consists of a stainless steel tube (I.D. = 2.00 in.) and 2 end-plungers. The mix was statically compacted into a cylindrical specimen

TABLE 1

GRADATIONS OF SALT

Sieve	Percent Passing			
	Commercial	Coarse	Medium	Fine
⅜ in.	100.0			
¼ in.	69.2	100.0		
No. 4	58.6			
No. 6	24.2			
No. 8	6.7			
No. 10	2.8	0.0	100.0	
No. 40			0.0	100.0

2 in. in diameter and 4 in. in height. This procedure provides a constant dry density of 105 lb/cu ft for all specimens.

After the extrusion of the specimen, a small plate of galvanized sheet metal was attached at one end. At the center of the other end, a small triangular metal chip was attached. These attachments were made to increase accuracy and reproducibility of measurements and were made rigid by using a minimal amount of quick-setting glue.

All specimens were cured at 90 percent relative humidity, ±5 percent, and 25 C, ±1 deg. The curing took place in the cabinet of an incubator.

Measuring and Testing

Changes in specimen height with time were measured by using a dial gage with sensitivity of 0.0001 in. This gage was mounted on a rigid frame that provides a smooth, horizontal base for seating of the specimen. Accurate measurement of the specimen height was taken at the center of its metal chip.

At the end of the specified curing period, all specimens were tested for unconfined compression strength in order to study possible strength reductions caused by the added salt.

X-Ray Diffraction

Determination of changes in lattice spacing was done using a General Electric XRD-5 diffractometer with CuK α radiation. Powder samples were pressed into brass rings using static compaction of 1,000 psi. This helps to obtain dense packing and to eliminate preferred orientation. The ring was also rotated in the X-ray beam to increase reproducibility (7).

RESULTS

Effects of Salt on Shrinkage

Shrinkage versus time graphs are shown in Figures 1 through 7. Each point on the graphs represents the average of readings from 4 specimens cured up to 7 days.

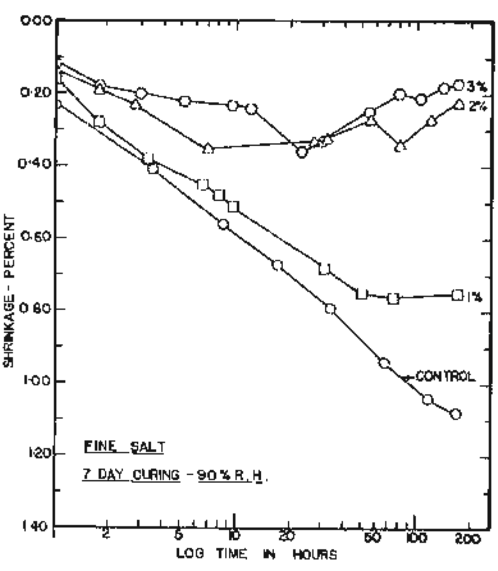

Figure 1. Shrinkage versus time for Na-montmorillonitic soil-cement with various percentages of fine salt and cured under 90 percent relative humidity for 7 days.

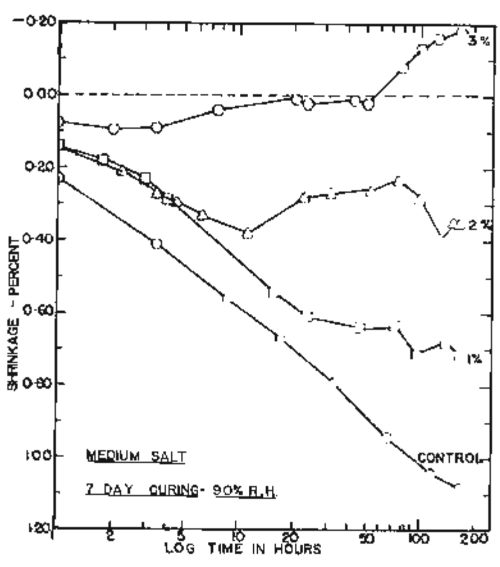

Figure 2. Shrinkage versus time for Na-montmorillonitic soil-cement with various percentages of medium salt and cured under 90 percent relative humidity for 7 days.

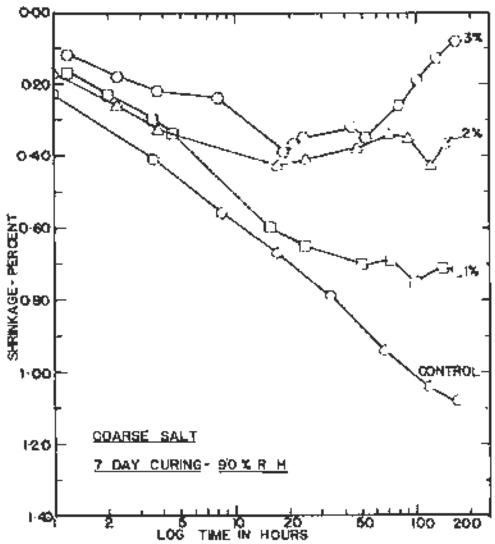

Figure 3. Shrinkage versus time for Na-montmorillonitic soil-cement with various percentages of coarse salt and cured under 90 percent relative humidity for 7 days.

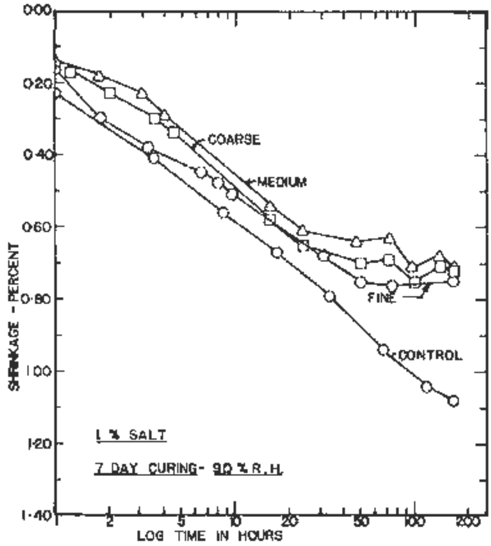

Figure 4. Shrinkage versus time for Na-montmorillonitic soil-cement with 1 percent salt of various gradations and cured under 90 percent relative humidity for 7 days.

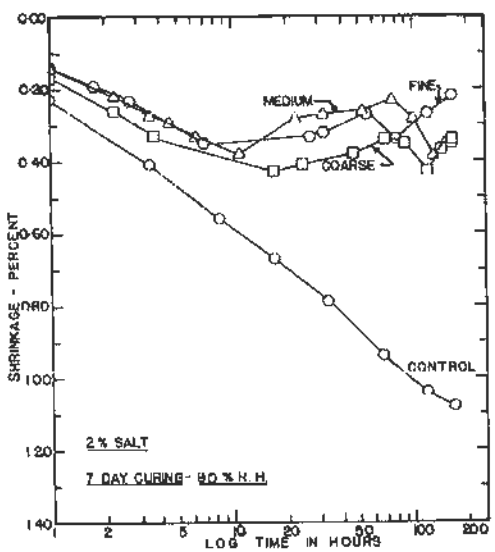

Figure 5. Shrinkage versus time for Na-montmorillonitic soil-cement with 2 percent salt of various gradations and cured under 90 percent relative humidity for 7 days.

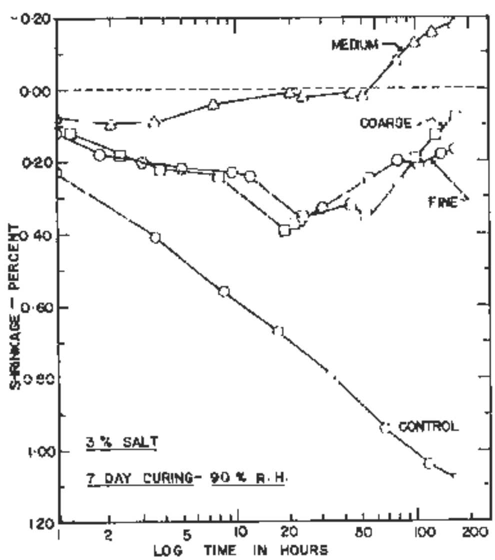

Figure 6. Shrinkage versus time for Na-montmorillonitic soil-cement with 3 percent salt of various gradations and cured under 90 percent relative humidity for 7 days.

Figures 1, 2, and 3 show that shrinkage decreases greatly with increasing salt content of any of the gradations used. Net expansion was observed when 3 percent medium salt was added to the soil-cement specimens. However, different gradations of the same percentages of salt added did not produce a good enough trend of results to allow any conclusions as to their relative effect, as shown in Figures 4, 5, and 6.

Addition of 0.5 percent salt in solution form to the standard specimens did not reduce shrinkage appreciably, as shown in Figure 7.

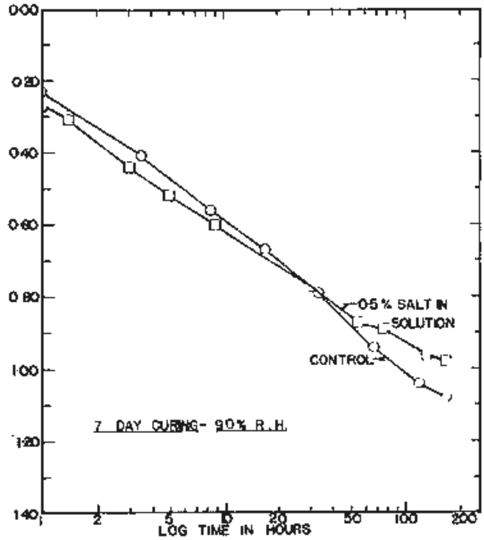

Figure 7. Shrinkage versus time for Na-montmorillonitic soil-cement with 0.5 percent salt added in solution form and cured under 90 percent relative humidity for 7 days.

An analysis of variance study was performed to determine the statistical sign nificance to the effect of salt on shrinkage (2). Bands of 95 percent confidence uncertainty limits were established around the means of 4 specimens of the various batches throughout the curing time. Significant difference in amounts of shrinkage between any 2 batches is indicated by cessation of overlapping and subsequent separation of their corresponding bands. Figure 8 shows this comparison in which 10 hours is the curing time that amounts of shrinkage between the soil-cement control specimens and the soil-cement specimens with 2 percent coarse salt become significantly different. Figure 9 shows calculated times of significant differences in shrinkage between control specimens and specimens

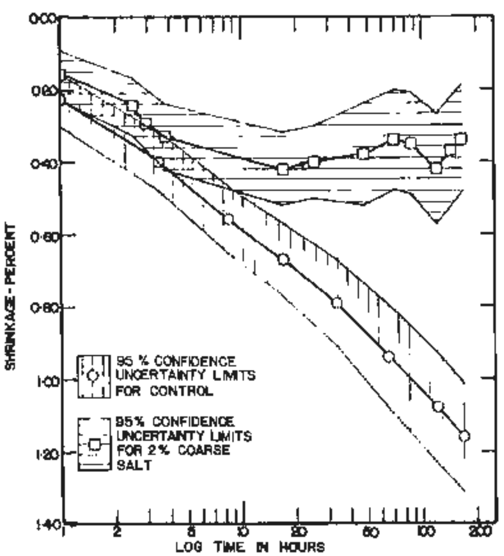

Figure 8. Comparison of 95 percent confidence uncertainty limits for shrinkage versus time.

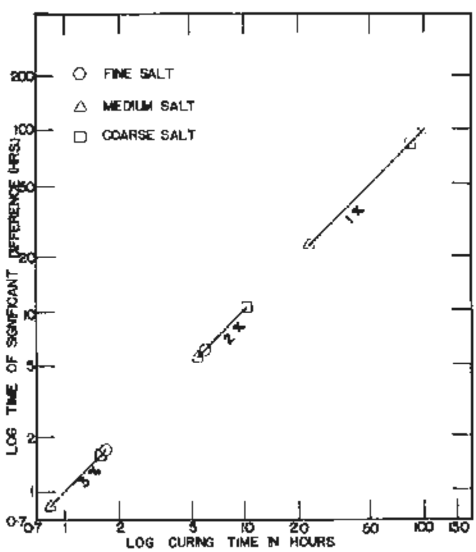

Figure 9. Time of significant difference in shrinkage between soil-cement control specimens and specimens with salt.

with salt. It shows excellent correlation between the time required to significantly reduce shrinkage and the increasing percentage of added salt. Again, no dependable correlation can be drawn for the effect of the specific gradation of salt on shrinkage.

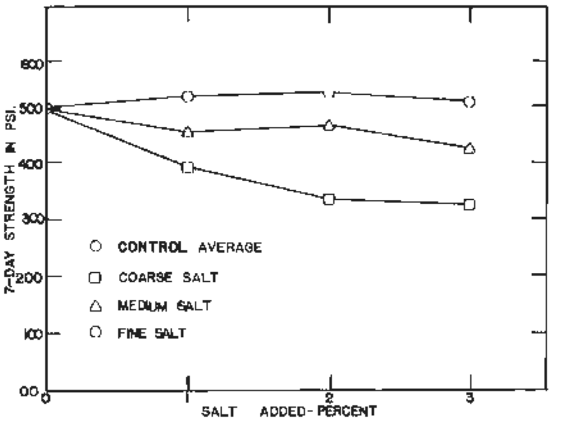

Figure 10. Comparison of 7-day unconfined compressive strength of soil-cement control specimens with specimens containing salt.

Effects of Salt on Strength

The 7-day unconfined compressive strength results are shown in Figure 10. It shows that strength decreases with increasing coarseness of the salt additive. Additions of fine salt (passing No. 40 sieve) show no reduction in strength in comparison with the control specimens in the range of salt contents investigated. However, the additions of 3 percent medium and 3 percent coarse salts resulted in 14 and 34 percent strength reductions respectively.

X-Ray Investigation

Figure 11 shows that while the basal (001) spacing of the montmorillonite in soil-cement specimens with salt remained practically constant, the 001 spacing of the clay in the control specimens decreased steadily throughout the curing period. Similar corresponding behavior was also observed in the variation of moisture content in the specimens throughout the curing period, as shown in Figure 12.

Effects of Immersion and 28-Day Curing

Soil-cement samples containing 3 percent medium salt were also compared with the control soil-cement specimens to investigate the effects of immersion and 28-day curing on shrinkage and strength.

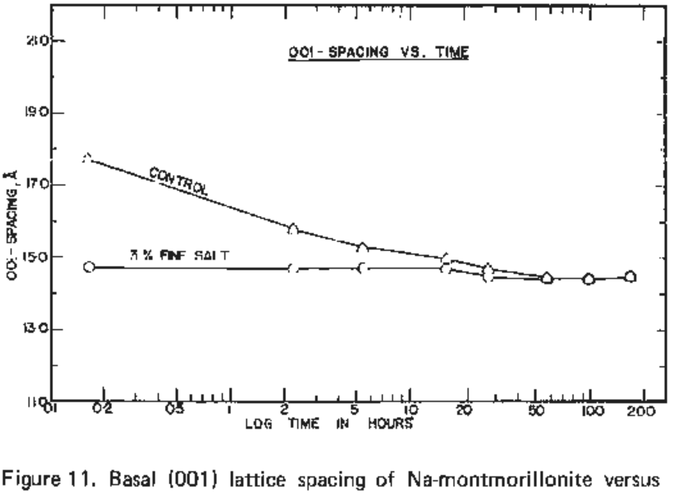

Figure 11. Basal (001) lattice spacing of Na-montmorillonite versus curing time in soil-cement specimens.

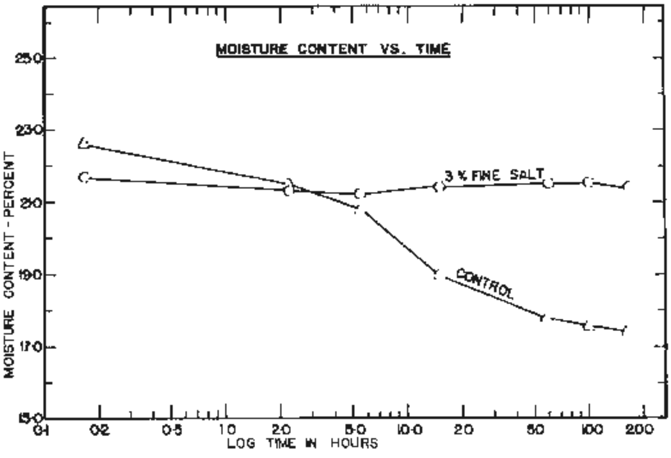

Figure 12. Moisture content versus curing time in soil-cement specimens.

Results have shown that samples with salt continually maintained a lower rate of shrinkage than the control specimens under regular curing at 90 percent relative humidity and 25 C up to 28 days (dotted lines in Fig. 13). However, upon immersion after 7 days of regular curing, the control soil-cement specimens swelled significantly, while the samples with salt were practically unaffected, as shown with the solid lines in Figure 13.

Results also showed that 28-day strengths followed the same order as the 7-day strengths for the regularly cured specimens. However, specimens that were regularly cured for 7 days and then immersed for the rest of the 28-day curing period showed comparable strengths for the soil-cement specimens with and without salt.

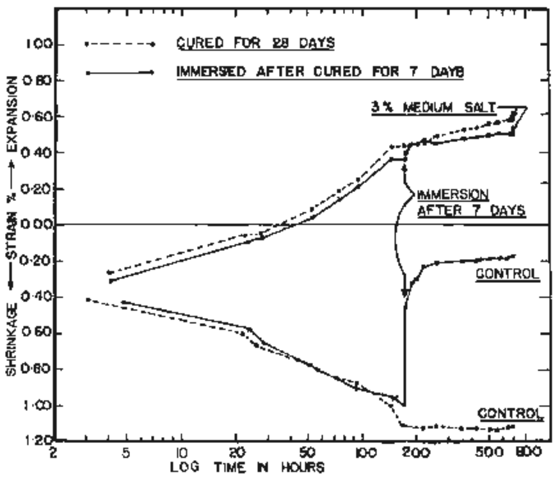

Figure 13. Shrinkage versus time for Na-montmorillonitic soil-cement with 3 percent medium salt and cured under various conditions for 28 days.

Results From Using Ca-Montmorillonite

All the results presented so far have been obtained from specimens molded with Na-montmorillonite. To check the effectiveness of using sodium chloride also as a shrinkage reducing agent in Ca-montmorillonite soil-cement, 0 and 3 percent medium salt specimens similar to those used previsouly were molded using calcium instead of sodium montmorillonite. The Ca-clay used is known as the Panther Creek Southern Bentonite, commercially produced by the American Colloid Company.

Shrinkage and strength results similar to those shown in Figures 2 and 10 were also obtained. Furthermore, soil-cement specimens containing salt again maintained a practically constant moisture content throughout the curing period, while specimens without salt showed a drying tendency similar to that in Figure 12. X-ray diffraction revealed that the moist Ca-montmorillonitic soil-cement mixes with and without salt all initially obtained a 17.7 Å clay basal spacing, approaching the 18.8 Å of the wet clay alone. With the progress of curing, the clay quickly (in a few hours) obtained a stable 14.7 Å basal spacing in specimens with salt with no change in moisture content. On the other hand, in specimens without salt the clay basal spacing decreased very gradually with drying. The results are similar to those shown in Figures 11 and 12. Upon immersion both mixes showed a 001 spacing of about 17 Å.

DISCUSSION OF RESULTS

Shrinkage Mechanism

Figures 11 and 12 suggest that shrinkage in montmorillonitic soil-cement is due mainly to the loss of moisture during curing. This loss causes the clay lattice spacing to decrease, which also contributes an unknown amount of the total shrinkage. The effectiveness of sodium chloride as a shrinkage reducing agent is attributed to the hygroscopic properties of the salt, which, at 3 percent salt content, maintains moisture content in the specimens constant throughout the curing period.

In addition, in Na-montmorillonite the amount of shrinkage that resulted from decreased clay lattice spacing is believed to become less with increasing salt content. This is demonstrated by the fact that the 001 spacing of the Na-montmorillonite in the soil-cement control specimens with 16 percent cement content was found to be 17.7Å soon after wet-mixing, an increase from 11.3Å in the air-dry clay. In the soil-cement specimens with 3 percent fine salt, the spacing was 14.7Å and remained practically constant throughout the curing period (Fig. 11). For 1 and 2 percent fine salt contents, the initial 001 spacings were 17.0Å and 15.0Å respectively. It is believed from these results that the observed increase in shrinkage with decreasing percentages of salt added to the mix was due to the decreasing hygroscopic properties of the mix to maintain the original moisture content and to the weakening abilities of the not-so-plentiful Na^+ cations to prevent calcium saturation of the clay (3, 4, 5) and to achieve lower initial clay basal spacings.

Salt added in solution form is ineffective in reducing shrinkage in Na-montmorillonitic soil-cement (Fig. 7). The reason may be that salt in solution form is more easily going into exchange positions in clay causing expansion of the clay lattice and losing partially its hygroscopic properties to effectively prevent the evaporation of pore waters. X-ray data did show that 0.5 percent salt added in solution form produced an initial Na-clay basal spacing of 17.7 Å, the same as that of the clay in the control soil-cement mix without salt.

Upon immersion, the swelling of Na-montmorillonitic soil-cement without salt (Fig. 13) may be, at least partially, attributed to the increase in clay lattice spacing. X-ray diffraction results did show that the basal spacing returned to 17Å from 14.7Å upon immersion in specimens without salt while the clay in specimens with 3 percent salt maintained at the stable 14.7Å.

In Ca-montmorillonitic soil-cement mixes, the quick reduction of the clay basal spacing from an initial 17.7Å to a stable 14.7Å in specimens with 3 percent salt appears to be due to the exchange of calcium by sodium, as the moisture content remained constant. This quick reduction in clay basal spacing did not produce an apparent effect on shrinkage as the specimens with salt continually showed significantly less shrinkage than the specimens without salt, which, as stated previously, showed gradually decreasing basal spacing with drying throughout the curing period.

Most shrinkage versus time curves (Figs. 1, 2, and 3) show an expanding tendency of salt specimens at longer curing time. X-ray diffraction revealed no sign of recrystallization of salt in the pore spaces, and there was no increase in moisture contents. It is thus speculated that salt might have gradually taken up the exchange position in clay during curing causing dispersing effects of the clay. A dispersed clay structure posseses a larger void ratio and thus results in swelling (8). Similarly, the early shrinkage may be partly attributed to a change to flocculated structures after the dispersing effects of the mechanical molding process.

Effect of Salt Gradations

It was indicated in the previous section that, with a specific salt content, statistical analysis found no significant differences in shrinkage among the various gradations of salt added. However, it is believed that use of a larger number of specimens for analysis would have resulted in greater confidence and, therefore, narrower, nonoverlapping confidence bands. Thus significant differences among some gradations would have been produced, as data shown in Figures 4, 5, and 6 seem to suggest.

Effect of Salt on Strength

The observed reductions in strength in soil-cement specimens with coarser salts are believed to be the result of the salt crystals dissolving, thus leaving "holes" in their places. These holes become areas of stress concentration upon application of load, and the specimen exhibits a lower strength.

CONCLUSIONS

1. Sodium chloride, when used in granular forms, has been shown to be effective in reducing shrinkage in montmorillonitic soil-cement mixtures cured under high relative humidity. The effectiveness increases with increasing salt content and is independent of the gradation of the salt.
2. The reduction of shrinkage in soil-cement with addition of salt was found to be primarily due to the ability of salt to reduce moisture loss in the mixture and to provide a more favorable and stable clay basal spacing. Particle reorientation during curing was also believed to be responsible for some of the shrinkage and expansion observed.
3. Sodium chloride was also found to be effective in decreasing swelling of Na-montmorillonitic soil-cement mixtures upon immersion. A stable, nonswelling clay basal spacing in specimens with 3 percent salt was found responsible.
4. Strength reductions associated with addition of salt to Na-montmorillonitic soil-cement are due only to the coarseness of the additive and not to the amount used. Soil-cement with fine salt added was found to give strength comparable to that of soil-cement specimens without salt.

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Discussion

E. GUY ROBBINS, Portland Cement Association—The authors have presented some very interesting data on the shrinkage of soil-cement with a salt additive. A few general observations are offered for consideration in future research.

The soil used was an active clay mixed with Ottawa sand and a rather high cement factor, 16 percent cement by weight. Salt contents were 1, 2, and 3 percent by weight of materials. This is equivalent to about 6, 12, and 19 percent by weight of cement, which is a high salt content. This suggests soil-cement sodium chloride investigations should be made also with low chloride contents.

In Figures 2 and 6, the mixtures containing 3 percent salt expanded. Figure 10 shows no increase in compressive strength with fine salt and a decrease in 7-day strength with medium and coarse salt. Expansion can indicate some damage to the soil-cement structure, and decrease in strength indicates no improvement in quality. This suggests investigations relating to the durability aspects.

The reduction in shrinkage under moist cure conditions may be due to hygroscopic properties of the salt that could cause the specimens to pick up moisture during curing that would replace moisture lost because of cement hydration, and the net result is less shrinkage. Most shrinkage is associated with loss of moisture.

Volume change studies were made at 90 percent relative humidity. If specimens were dried to, say, 50 percent relative humidity after curing, the volume changes with and without salt admixture may be quite different.

Suggestions for future research include investigations on durability, longer term compressive strength, moisture, and volume change during and after moist curing. Lower salt contents should be investigated with a range of soil types and cement factors.

JERRY W. H. WANG and ALEXANDER H. KREMMYDAS, Closure—The authors wish to thank Mr. Robbins for his interesting discussion and would like to further some of his observations.

It was concluded in the paper that sodium chloride used in granular form was shown to be effective in reducing shrinkage in montmorillonitic soil-cement cured under high relative humidity. For the most part, its effectiveness was due to the hygroscopic properties of salt that make up moisture losses by picking up additional moisture during curing. Inasmuch as NaCl is not capable of absorbing moisture from air at 77 F when relative humidity is below 70 percent, it is anticipated that NaCl would not be very effective in reducing shrinkage at low relative humidity. Nevertheless, the movement of water in the vapor phase and the equivalent relative humidity in a soil-cement mass under normal field conditions are not well understood at this time. Field experimentation is needed to evaluate the limitations of using NaCl as a shrinkage reducing agent in soil-cement.

The magnitudes of critical shrinkage strain that will cause cracking of different soil-cements in the field are also not well known at this time. The high salt contents used in the study were for an active soil showing high shrinkage. It is believed that the amount of salt required to solely prevent cracking can effectively be reduced for most soils and by doing this net expansion will never occur. Again, more studies in the laboratory and in the field are needed in this respect.

The fact that soil-cement with salt would not decrease the strength of soil-cement, provided the coarseness of salt is comparable to the dimensions of the soil-cement mass, is a positive aspect of using salt as a shrinkage reducing agent. In addition, NaCl provides a more favorable and stable clay basal spacing during curing and subsequent immersion for montmorillonitic soil-cement. This fact may offer some practical significance in future soil-cement technology.