Influence of Time Between Mixing and Compaction on Properties of a Lime-Stabilized Expansive Clay

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The effectiveness of 4 percent dolomitic hydrated lime as a stabilizer for an organic expansive clay soil has been investigated. This soil is typical of some of the "adobe" soils encountered in California. Samples of treated and untreated soil were compacted to 90 percent of maximum density for each mixture, as obtained by modified AASHO compactive effort, over a range of water contents. The effectiveness of stabilization was measured, in most cases, by triaxial compression tests at various ages after compaction for both soaked and unsoaked samples.

It was found that the time interval between mixing (of the soil, water and lime) and compaction could have a pronounced effect on the properties of the treated soil. For samples prepared using constant compactive effort, a delay of 24 hr between mixing and compaction led to as much as 8 pcf decrease in density and 30 percent decrease in as-cured strength from the values for samples compacted immediately after mixing. The expansion and soaked strength characteristics of treated samples were also adversely affected by a delay between mixing and compaction.

The principal factor responsible for this behavior was found to be the decrease in density (at constant compactive effort) accompanying delays between mixing and compaction. The unsoaked and soaked strength and the swell values for samples compacted immediately after mixing and 24 hr after mixing were essentially the same if the samples were prepared to the same density. Thus, in practice, the beneficial effects of a delay between mixing and compaction in terms of the "mellowing" action of the lime and the consequent improvement in mixing and handling properties may justify an increased compactive effort to maintain the desired density.

A 4 percent lime treatment was found to be an effective stabilizer of the organic expansive clay. Strength improvement in the as-cured samples was not great; however, the effectiveness of lime in reducing the swell of samples soaked under a surcharge pressure of 0.1 kg per sq cm was very marked and resulted in soaked strengths

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of treated samples up to seven times greater than for untreated samples. Peak compressive strength was developed at considerably lower strains for treated than for untreated samples.

A consideration of the data and the results of chemical analyses suggests that, for the soil studied, the beneficial effects of lime treatment are caused primarily by flocculation of the soil structure and a decrease in the water sensitivity of the clay minerals. Cementation effects are believed to be of minor importance in this soil.

● ORGANIC expansive clays, locally termed "adobe," are encountered over large areas of California. Their high water sensitivity leads to a high swell and loss of strength on wetting, and shrinkage and cracking on drying. Thus, in their natural state these soils are undesirable for use as highway subgrade, subbase or base course materials. Effective low-cost stabilization might be expected to have wide application. Lime treatment of such soils for use as secondary road base and subbase courses has been employed in some areas of the state. Although in general the results have been very satisfactory, little specific information concerning the over-all efficiency of lime treatment or the nature of the reactions in these soils is available. Consequently, a laboratory study was initiated for the purpose of better defining the effects of lime treatment. A soil typical of some of the adobes was used.

It was noted early in the investigation that, for a constant compactive effort, the sample densities were sensitive to the time interval between mixing (of the soil, lime and water) and compaction. It has long been believed that one of the practical advantages of lime stabilization is that the time interval between mixing and compaction is not critical, and that the mixed material may be allowed to stand for as long as two days and then be reworked prior to compaction without detrimental effects (1, 2). It therefore appeared desirable to initiate a more detailed study of the effect of time between mixing and compaction, with particular reference to ascertaining whether or not the decreases in densities were accompanied by decreases in strength. Such a study was carried out concurrently with the initially planned investigations by maintaining careful control of sample preparation times throughout the test program.

This paper reports the results of studies both on the effects on properties of the time interval between mixing and compaction and the efficiency of lime as a stabilizer for an organic expansive clay.

Two features of this investigation are considered of particular importance in evaluating stabilizer effectiveness. One of these was that a comparison between treated and untreated samples was made on the basis of identically processed treated and untreated samples, with the untreated samples subjected to the same curing and testing conditions as the treated samples. The use of such a control procedure has the obvious advantage of showing up any effects such as thixotropy in the untreated soil, which, if undetected, might tend to give a false picture of the stabilizer effectiveness. A second feature was to compare treated and untreated samples compacted to essentially the same relative compaction based on their own maximum density for a given compactive effort, rather than samples compacted to the same density. Inasmuch as the addition of lime reduces the maximum density and increases the optimum moisture content relative to the values for untreated soil, this meant comparing samples of treated soil with samples of untreated soil compacted to a higher dry density. Comparison of treated and untreated samples on this basis would appear to more closely duplicate probable field behavior than a comparison on the basis of the same density, because specifications would likely require compaction to a relative density based on the compaction curve for the particular mixture used.

MATERIALS

The clay soil used in the studies was a gray expansive material containing about 8 percent organic matter by weight. It was obtained from the area adjacent to the Soil Mechanics and Bituminous Materials Laboratory of the University of California in

Richmond, Calif. Pertinent characteristics of this soil are summarized in Table 1. It may be noted that on the basis of the plasticity characteristics, the soil would be classified as CL in the Unified Soil Classification System. Analysis of the exchangeable cation complex has shown that calcium and magnesium account for 20.4 milliequivalents per 100 gm of the total exchange capacity of 27.0 milliequivalents per 100 gm. X-ray analyses have indicated a mixture of montmorillonite and illite to be the dominant clay material. The soil possesses undesirable physical characteristics in that it swells and becomes sticky when wet and shrinks excessively with the formation of large shrinkage cracks during dry periods.

TABLE 1

SOIL PROPERTIES^a

 General description: Gray expansive clay containing about 8% organic matter; some small roots, sticky when wet and exhibiting high shrinkage when dried.
Crain size data:

Grain	size	data:

Size, mm	<u>% Finer (by wt)</u>		
0.074	77		
0.005	43		
0.001	26		

3. Plasticity:

		Untreated Soil	Soil + 4% Lin 24 Hr after	Soil + 4% Lime (by wt) 24 Hr after Mixing	
	Liquid Limit	46%	53%		
	Plastic Limit	21%	35%		
	Plasticity Index	25%	18%		
4.	Dominant clay minerals: Illi	te and montmorilloni	te mixture.		
5.	Cation exchange and free cat	ion data:			
	Cation exchange capacity	- 27 milliequivalents/	/100 gm.		
	Specific ion concentration	s: (all values in mill	iequivalents/100 gm).		
	Ion	Exchangeable	Water Soluble	<u>Total</u>	
	Sodium	0.72	0.80	1.52	
	Potassium	0.40	0.22	0.62	
	Calcium + Magnesium	20.4	2.2	22.8	

^aData obtained by Goldberg (3), formerly of ITTE, Univ. of Calif., Berkeley.

The lime used in these studies was a dolomitic hydrated lime having the composition indicated in Table 2. It should be noted that this lime is a commercial agricultural hydrated lime.

EXPERIMENTAL PROCEDURES

The soil was air dried and passed through a No. 8 sieve prior to preparation of any samples. A lime treatment level of 4 percent by weight of oven dry soil was selected for all tests. The appropriate weights of air dry soil and lime were blended in a paddle-type mixer and then sufficient water was added from a spray bottle to give the desired water content. Mixing was continued for 3 min. The mixed samples were then placed in

TABLE 2

COMPOSITION OF DOLOMITIC HYDRATED LIME

Compound	Percentage (by wt)
Calcium hydroxide	37
Magnesium hydroxide	41
Calcium carbonate	22

plastic bags and stored in a humid room until needed for compaction. Compaction was carried out at specified time intervals after the end of the initial mixing period. The samples were hand mixed in the plastic bags immediately prior to compaction.

Large samples (4 in. by 4 in.) were prepared at the beginning of the investigation for determination of compaction curves using modified AASHO compactive effort. Compaction curves were determined for the untreated soil, soil plus 4 percent lime compacted immediately after mixing, and soil plus lime compacted 24 hr after mixing. The samples used to obtain these compaction curves were put aside in an unwrapped condition in shallow pans in a humid room. These samples were later used as a source of supplementary information on the effect of the time interval between mixing and compaction on the properties of the treated soil. At the time these samples were tested they had aged for 215 days, and free water had accumulated in the pans to a depth of slightly more than 1 in. The strength of these samples was evaluated by means of the unconfined compression test using a strain rate of 0.05 in. per minute.

All other samples were prepared by kneading compaction using the Harvard miniature compaction apparatus. Samples were compacted over a range of water contents to a relative density of 90 percent based on the modified AASHO compaction curves. The compactive efforts required to prepare samples to the desired densities were determined by trial for each water content investigated. The resulting samples, which were 1.4 in. in diameter and 3.5 in. long, were carefully weighed and measured and then placed between a lucite cap and base and wrapped with two thin rubber membranes with a layer of silicone grease between. The samples were allowed to cure under water for specified periods of time. At the end of the curing period the samples were removed from the storage tank, unwrapped, weighed, and measured to insure that they had maintained their initial composition during storage. The samples were then rewrapped with new membranes and either tested in triaxial compression under undrained conditions using rate of strain control (0.058 in. per min) and a confining pressure of 1 kg per sq cm, or soaked prior to testing. Specimens to be soaked were placed in triaxial cells with porous stones at each end of the sample. The samples were maintained under a confining pressure of 0.1 kg per sq cm and given access to free water through the porous stones. Soaking was continued for a period of 7 days, after which the samples were weighed, measured and tested in undrained triaxial compression in the same manner as the unsoaked specimens.



Figure 1. Modified AASHO compaction curves for treated and untreated soil.

RESULTS AND DISCUSSION

Density vs Water Content Relationships

Modified AASHO compaction curves for the untreated soil, soil + 4 percent lime compacted immediately after mixing, and soil + 4 percent lime compacted 24 hr after mixing are shown in Figure 1. Two effects may be noted from these curves. First, the effect of lime treatment is to increase the optimum moisture content and decrease the maximum density, a commonly observed consequence of lime addition. This may be attributed primarily to the flocculating effect of lime on the soil structure. The second obvious effect is the lower densities obtained by the modified AASHO effort for the treated samples allowed to age for 24 hr between mixing and compaction in comparison with the densities obtained for the treated samples compacted immediately after mixing.

Effect of Time Interval Between Mixing and Compaction on Density and Strength of Samples Prepared Using Constant Compactive Effort

Series of samples of treated and untreated soil were prepared by kneading compaction at several water contents. For each series a compactive effort was selected such that a sample compacted immediately after mixing would have a relative density between 90 and 95 percent based on the modified AASHO compaction curves (Fig. 1). Samples within any given series were then prepared at different times after mixing, using the same, preselected compactive effort for each sample.

Figure 2 shows the effect of time interval between mixing and compaction on density, and Figure 3 shows the effect of time interval between mixing and compaction on compressive strength. The compressive strengths were determined after a 14-day curing period at constant water content. The same compactive effort was used for the preparation of all samples in any given series.

Figure 2 shows that the time interval between mixing and compaction has little effect on the densities obtained for the untreated control specimens at the two water contents investigated. No explanation can be offered for the slight dip in the density vs time interval curve for samples prepared at 14.6 percent molding water content. On the other hand, the data for the lime-treated specimens show a pronounced decrease in density with increased time intervals between mixing and compaction for all water contents investigated. It may be seen from Figure 3 that, although the compressive strengths of as-cured specimens of untreated soil are insensitive to variations in time between mixing and compaction, the lime-treated samples show a very significant decrease in compressive strength as this time interval increases. On a percentage basis, if compaction was delayed 24 hr the strength decrease was as much as 30 percent of the strength of samples prepared immediately after mixing. It should be kept in mind, however, that these strengths were determined for samples of progressively decreasing density.

The data in Figures 2 and 3 suggest that the magnitude of the detrimental effects of long time periods between mixing and compaction varies with the molding water content. It may be noted, also, that for all treated samples investigated (prepared by kneading compaction) the density decrease resulting from a 24-hr time interval between mixing and compaction is greater than the 2 pcf density decrease observed for samples prepared using modified AASHO compactive effort and impact compaction (Fig. 1). It appears, therefore, that both density and method of compaction may influence the effect of variation in time interval between mixing and compaction on properties.

Additional data on the effect of the time interval between mixing and compaction on the properties of lime-treated samples prepared at constant compactive effort were obtained from a study of the 4- by 4-in. cylindrical samples used to establish the compaction curves shown in Figure 1. As previously noted, these samples had been exposed to a moist atmosphere for 215 days and were resting in about 1 in. of free water at the time they were removed for testing. Thus, the samples had been exposed to rather severe conditions. At the end of the 215 days the samples ranged from very poor to very good condition. The samples of untreated soil prepared at the lower



Figure 2. The effect of time between mixing and compaction on the dry density of lime-treated samples prepared using constant com-



Figure 3. The effect of time between mixing and compaction on the as-cured strength of lime-treated samples prepared using constant compactive effort.

moisture contents were generally soft and mushy. The lime-treated sampes were in better condition, with those that were compacted immediately after mixing appearing much better than those compacted 24 hr after mixing. The samples prepared at the lowest water contents were generally the poorest, with those compacted wet of optimum remaining firm and exhibiting less surface deterioration.

The effects of the storage period on the composition of the samples are shown in Figure 4. The open symbols represent the as-compacted densities and water contents, and the closed symbols represent the density and water content at the end of the aging period. In Figure 5 the volumetric swell and compressive strength are shown as functions of the molding water content. It is immediately evident from Figures 4 and 5(a) that lime treatment had a beneficial effect on reducing the swell and moisture content increase. Figure 5(b) illustrates the marked strength increase effected by lime treatment.

The effects of a 24-hr delay between mixing and compaction on the properties of the treated soil are clearly shown in Figure 5. The water resistance is con-



Figure 5. Effect of lime treatment on the swell and strength characteristics of expansive soil subjected to moist storage.



Figure 4. Effect of lime treatment on water content and density characteristics of expansive soil subjected to moist storage.

siderably impaired by the delay, as reflected by the swell values. This higher swell is undoubtedly one of the principal factors responsible for the lower strengths of the samples compacted 24 hr after mixing as compared with the strengths of the samples compacted immediately after mixing.

Behavior of the type shown in Figures 3 to 5 may be examined in terms of soillime reactions and their effects. The more significant reactions would probably include:

1. Base exchange of calcium (and magnesium if dolomitic hydrated lime such as employed in this investigation is used) for the existing exchangeable cations in the soil (2, 4, 5).

2. A flocculation of the soil structure resulting from both base exchange and increase in free electrolyte content caused by the addition of lime (4, 5).

3. A reaction of calcium and magnesium with available colloidal silica and alumina forming slow-setting cementitious compounds (2, 4, 5).

4. Attack and breakdown of the clay

mineral structure with or without the formation of new crystalline compounds (5).

5. Absorption of CO₂ from the air which reacts with $Ca(OH)_2$ to form $CaCO_3$ which may act as a cementing material (2, 5).

McDowell (2) points out that for reactions 3 and 5 to be fully effective compaction should take place prior to the reaction. It would seem logical that the same should hold true for reaction 4. Because these reactions may be presumed to begin as soon as water comes into contact with the soil and lime, the sooner the mixture is compacted the better. These reactions are probably irreversible and each increment of the reaction uses up a part of the available lime and water. Reaction prior to compaction will result in cementation of particles in a loose structure. Subsequent compaction will break the bonds formed. At the end of compaction there will be less available lime and water to enter into further reactions. Thus, it would be expected that if a significant part of the available lime is consumed by reactions of this type during the early stages after mixing, then the strength of the treated soil will be adversely affected by a delay between mixing and compaction. It should also be noted that cementation into loose aggregates prior to compaction will cause the soil to offer a greater resistance to compaction. Thus, a given compactive effort would be expected to produce lower densities as the time available for these reactions increases.

Due to the relatively high calcium and magnesium content of the exchange complex in the untreated soil (Table 1), base exchange reactions might not play a significant part. Studies by Goldberg (3) show, however, that exchange of calcium and magnesium for sodium and potassium does occur in this soil, but the rate is slow. It should also be noted from the exchangeable cation data in Table 1 that some 5.5 me per 100 gm of exchangeable cations were unaccounted for by the analyses. Calcium exchange for these ions could be important.

Flocculation can have a pronounced effect on the physical properties of a soil. It is known that flocculating a given soil will lead to a higher optimum water content and lower dry density for a given compactive effort. In lime-stabilized soils the effects of increased flocculation might develop slowly due to the low water solubility of lime and other factors, such as the time required for calcium and magnesium penetration between the unit cells of expansive clay minerals. However, the increased flocculation might not have any appreciable effect on strength, because the loss in strength caused by the density decrease could be offset by the strength increase due to the greater degree of flocculation.

It is difficult to attribute the observed strength decreases to one or more specific reactions on the basis of the data thus far examined, because both density and time are variable factors. To evaluate the effectiveness of lime treatment on the expansive



Figure 6. Compactive effort required to obtain 90 percent compaction for limetreated and untreated expansive clay.

clay, however, samples of treated soil prepared 40 min and 24 hr after mixing were studied at essentially the same density. As previously noted, it was originally intended to compare samples at the same relative compaction. A value of 90 percent was chosen, which would mean a density of 98.7 pcf for treated samples compacted immediately and 97.2 pcf for treated samples compacted 24 hr after mixing, based on the curves for modified AASHO compactive effort. Because this difference in densities is not large for this method of compaction, it was decided that preparation of all treated samples to the same density might provide the most information. Consequently, all treated samples for these studies were prepared to an average density of between 97.5 and 98.0 pcf, thus permitting an analysis of

the effect of time between mixing and compaction on strength for samples compared at constant density. Further speculations as to the reactions causing the behavior shown in Figures 2-5 are deferred until after presentation of these additional data.

Effect of Lime Treatment on Strength and Volume Change Characteristics of Expansive Clay

<u>Compactive Effort</u>. —In Figure 6 are shown the kneading compactive efforts required to obtain the desired densities of 97.7 pcf for the treated soil and 105 pcf for the untreated soil. These densities correspond to relative compactions of 89.1 percent for the soil plus 4 percent lime compacted 40 min after mixing, 90.6 percent for the soil plus 4 percent lime compacted 24 hr after mixing, and 90 percent for the untreated soil. As would be anticipated from Figure 2, a greater effort is required to achieve

the desired density for samples compacted 24 hr after mixing than for samples compacted soon after mixing. Figure 6 shows that the compacted effort required to achieve the desired density is much more sensitive to water content for the untreated soil than for the lime-treated soil. This might be anticipated from the shape of the compaction curves in Figure 1, which show steep branches and a sharp peak for the untreated soil and relatively broad, flat curves for the treated <u>soil</u>.

It is also important to note that inasmuch as compactive effort decreased with increasing water content, all samples were prepared dry of the optimum water content corresponding to the compactive effort used for their preparation as shown in Figure 7.

Strength, Volume Change and Water Content Relationships. — The relationships between strength, volume change and water content for samples prepared to a constant density are shown in Figures 8, 9 and 10. In part (a) of each figure is





shown the relationship between as-cured compressive strength and molding water content; part (b) indicates the volumetric swell of the soaked samples as a function of molding water content; part (c) presents compressive strength vs molding water content for samples soaked under a surcharge pressure of 0.1 kg per sq cm for seven days after curing; and part (d) shows soaked strength vs final water content. Values of the as-cured compressive strength are indicated for curing periods of 0, 7, 14, and 35 days. Properties of soaked samples are indicated for curing periods of 0, 7 and 28 days followed by a 7-day soaking period. Figure 8 refers to the results for control specimens of untreated soil compacted to 105 pcf; Figure 9 refers to samples containing 4 percent lime compacted 40 min after mixing to a dry density of 97.7 pcf; and Figure 10 refers to samples containing 4 percent lime compacted 24 hr after mixing to a dry density of 97.7 pcf. (Variations of ± 0.5 pcf were permitted.) Examination of these results show:

1. For both treated and untreated samples prepared at constant density the as-cured compressive strength decreases markedly with increasing molding-water content (Figs. 8, 9, 10(a)).

2. If increase in as-cured compressive strength with time is used as a measure, then thixotropic effects are not large in the untreated soil. Figure 8(a) shows a slight strength increase in the first 14 days after compaction, but essentially the same strength after 35 days as immediately after compaction.

3. The as-cured compressive strength of the lime-treated specimens compacted



Figure 8. Strength, swell and water content relationships for samples of untreated expansive clay.

24 hr after mixing, Figure 10(a), increases significantly with curing time. Scatter in the results, Figure 9(a), does not lead to such a conclusion for samples compacted 40 min after mixing. Reasons for this large scatter are not known; the samples appeared satisfactory in all respects. Perhaps it reflects a non-uniformity in water and lime distribution in the soil as-mixed, which gradully dissipated in the case of samples tempered for 24 hr prior to compaction.

4. The swell under 0.1 kg per sq cm surcharge decreases markedly with both increasing molding water content and increased curing time (Figs. 8, 9, 10(b)) for both treated and untreated samples. The greatest part of the swell reduction occurred during the first 7 days of curing. It should be kept in mind, however, that the uppermost curves in Figures 8, 9, 10(b) refer to samples that started soaking immediately after compaction, and thus the samples were not allowed to cure at constant water content.

5. The strength after soaking increased with molding water content in all cases (Figs. 8, 9, 10(c)). At any water content, both the treated and untreated samples showed an increase in strength with increased curing time.

6. In general, the soaked strength correlates fairly well with the water content after soaking (Figs. 8, 9, 10(d)).

The trends exhibited by these results are reasonable in terms of the behavior of compacted soils in general. The increase in soaked strength with molding water con-



Figure 9. Strength, water content and swell relationships for samples of lime-treated expansive clay compacted 40 min after mixing.

tent is logical, because higher molding water contents lead to less swell, and, consequently, the soaked specimens retained higher densities if compacted at higher water contents. The decrease in swell and increase in as-cured and soaked strength with time for the lime-treated samples would be expected because of the relatively slow rate of the lime-soil reaction.

The increase in soaked strengths with time for the untreated samples follows from the decrease in swell with time. The explanation for the decrease in swell with time for these samples is not readily apparent, particularly because Figure 8(a) shows that the soil does not have appreciable thixotropic characteristics. Evidently some intermal structural alterations—for example, in particle orientations, water structure, ion distribution, or actual chemical change—are occurring with time, which, although not appreciably altering the as-cured strength, reduce the water sensitivity of the soil. Measurements have shown the pH to increase from 5.9 to 6.15 in a period of 24 hr af-



Figure 10. Strength, water content and swell relationships for samples of lime-treated expansive clay compacted 24 hr after mixing.

ter addition of water, suggesting that an actual chemical alteration may be important.

Effect of Time Between Mixing and Compaction on Properties of Lime-Treated Soil for Samples Compared at Constant Density. - Figures 9 and 10 show that essentially the same behavior is exhibited by samples compacted 40 min and 24 hr after mixing. Figure 11 compares directly the as-cured strength, volumetric swell, and soaked-strength values for samples prepared at these two time intervals after mixing. Curves are shown for samples tested 7 and 35 days after compaction. Figure 11 shows that the properties of the lime-treated soil are roughly comparable for both time intervals between mixing and compaction with perhaps some superiority exhibited by the specimens aged 24 hr between mixing and compaction. The as-cured strengths are difficult to compare due to the large scatter of the data for the 40-min samples. The swelling behavior shows a slight superiority for the 40-min samples after 7 days but after 35 days the 24-hr samples appear the better. The strengths after soaking are about the same for each case. It seems reasonable to conclude, therefore, that a time interval of 24 hr between mixing and compaction has no detrimental effect on the swell or strength of limetreated samples of the expansive clay studied in comparison with samples prepared soon after mixing, provided samples are compacted to the same density.

These results may be contrasted with those in Figures 2 to 5 which show the behavior for samples prepared at constant compactive effort. It would appear reasonable to conclude, from a consideration of the behavior at constant density, that the decrease in strength exhibited by treated samples with increasing time between mixing and compaction, Figure 3, is for the most part due to decreased density and not cementation prior to compaction.



Figure 11. Comparison of strength and volume change characteristics of limetreated samples compared at equal densities but compacted at different times after mixing.

If irreversible chemical changes were a primary factor, it would be expected that the greater the delay between mixing and compaction the poorer would be the results obtained for samples prepared at constant density. The lime involved in irreversible reactions during the tempering period would no longer be available for cementation after compaction, and the cementation during the tempering period would be largely destroyed by the compaction process. This is not meant to imply that chemical changes did not occur, but rather that any changes that did occur were insignificant from a cementation standpoint. Chemical analyses of the lime-treated soil by Goldberg (3) show a progressive decrease in undissolved calcium, increase in carbonates, and decrease in available calcium plus magnesium with time after mixing the soil with lime and water. Differential thermal analyses, also run by Goldberg, indicate that the $Ca(OH)_2$ present in the lime is reacted rapidly after addition to the soil, and disappears almost entirely by the end of a week. The Mg(OH)₂, however, reacts much more slowly. The relatively high (8 percent) organic matter content of the soil studied could have been responsible for the consumption of some of the lime as well. Determinations of pH indicate that the addition of lime causes an increase from 6 to 9.5 at high water contents and to 11.3 at low water contents. The pH then decreases slightly with time; the greatest decrease occurring in samples at the lowest water content and amounting to up to 1.5 pH units after 35 days.

It is suggested that the main factor responsible for the decrease in density at constant compactive effort caused by increased time between mixing and compaction is flocculation of the soil structure, which increases with time of exposure of the soil to water and lime. The effect of greater flocculation is to increase the resistance to compaction. The increase in intensity of flocculation with time after lime addition may be attributed to the greater time available for lime to dissolve and other chemical



Figure 12. Strength and swell characteristic of lime-treated and untreated expansive clay prepared to 90 percent relative compaction.

reactions to occur. Penetration of calcium and magnesium between the layers of the expansive clay minerals, with consequent reduction in swelling, and on actual attack and breakdown of the clay mineral structure could be significant factors. The uncompacted soil structure is so affected that greater compactive efforts are required to achieve a given density for greater time intervals between mixing and compaction. Flocculation would also account for the apparent slightly greater strength of the samples compacted 24 hr after mixing, as shown in Figure 11, because for two specimens compacted to the same density, the one with the more highly flocculated structure should be the stronger.

Effectiveness of Lime as a Stabilizer for Expansive Clay Soil. - The over-all effectiveness of a 4 percent lime treatment of the expansive clay from the standpoint of strength improvement and swell reduction may be seen from Figure 12. Test results for untreated samples are compared with those for treated samples compacted 24 hr after mixing. Curves of as-cured strength, volumetric swell, and strength after soaking vs molding water content are shown for samples tested 7 and 35 days after compaction. It is important to keep in mind that densities of treated and untreated samples are considerably different, being 105 pcf and 97.7 pcf for the untreated and treated specimens, respectively, but that these densities represent the same degree of compaction.

It may be seen from Figure 12 that, in general, a 4 percent lime treatment of the expansive clay is quite effective. Figure 12(a) shows that in the as-cured state the strengths of the treated and untreated specimens are roughly comparable at the lower molding water contents. Lime treatment becomes more favorable with increasing water content, the strengths of the lime-treated samples tested after 35 days curing time being three times greater than those of untreated samples at 22 percent molding water content. Although this strength improvement is perhaps not as marked as might be achieved with a greater percentage of lime or with some other type of stabilizer, the as-cured strengths are fairly substantial and, furthermore, the as-cured condition is not the critical condition from the standpoint of field performance.

In the field, the critical condition will generally arise when the treated soil is exposed to water. Figures 12(b) and 12(c) indicate the performance of the lime-treated soil to be markedly superior to that of the untreated soil both from the standpoint of swell and of strength after soaking. It may be seen from Figure 12(b) that at the lowest water contents investigated lime treatment reduces volumetric swell from about 17 percent to about 5 percent for samples soaked immediately after compaction and to about 2 percent for samples permitted to cure for 28 days prior to soaking. It may be noted that the surcharge pressure of 0.1 kg per sq cm used in the tests is comparable to that afforded by a typical pavement. Because of the reduction in swell the strength after soaking remains at a high level. It may be seen from Figure 12(c) that the strength of treated samples after soaking is as much as seven times greater than the strength of untreated samples.

A further point of considerable importance from the standpoint of pavement design and performance, not shown by Figure 12, is the strain required to develop maximum compressive strength. In general, failure of soaked treated samples occurred at axial strains of less than 4 percent, whereas, 15 to 20 percent strain was required to develop the maximum deviator stress for untreated soaked samples. Because for pavement design, strength at low strain is generally the important factor, the beneficial effect of treatment is obvious.

In assessing the probable mechanism of property improvement by stabilization of this soil with lime, it is unlikely that actual cementation of particles is the major factor. Reasons for this conclusion are (a) lime treatment does not cause a large increase in the as-cured strength, (b) a delay between mixing and compaction is not detrimental provided compactive effort is increased to maintain constant density, and (c) the strength loss due to remolding treated samples cured for considerable periods at constant water content is not large. In connection with this latter point, lime-treated samples, compacted to the same density over a water content range from 12.8 to 22.6 percent, were cured at constant water content for 70 days. At the end of this period the samples were tested in triaxial compression in the usual manner. At the end of the test the samples were thoroughly remolded at constant water content, recompacted, and the strength again measured. Results of these tests are summarized in Table 3. It may be seen that the strength loss due to breaking up the structure acquired after a 70-day curing period was very small. The rigidity of the structure was lessened, however, as is indicated by the values for strain at failure.

It is suggested, therefore, that the chemical effects associated with the lime treatment of the expansive clay acted primarily to create a more flocculent and water-resistant structure, rather than to participate in significant amounts of interparticle cementation. Both cation exchange (calcium and magnesium for sodium, potassium and the 5.5 me per 100 gm of unaccounted-for exchangeable cations, Table 1), and increased electrolyte content, as well as alteration of organic matter and attack and breakdown of the expansive clay mineral structure could lead to increased flocculation and lower water sensitivity. Expansion of the montmorillonitic clay minerals would also be limited by the high calcium and magnesium content of the treated soil.

SUMMARY AND CONCLUSIONS

It has long been felt that one of the advantages of lime as a stabilizer is that the properties of the stabilized soil do not depend critically on the elapsed time between addition of lime and water to the soil and compaction of the mixture. The American Road Builders Association (1) points out that the mixed material may cure or age for 24 to 48 hr prior to compaction as long as optimum moisture conditions are maintained. Mc-

Dowell (6) states that soil-lime mixtures may be compacted any time within two days after mixing, with delays of up to 4 days permissible if heavy plastic clays are being stabilized. McDowell (2), the ARBA (1), and Dumbleton (6) point out the helpful action of lime in breaking down clay clods or "mellowing" the mixture on standing. This is an important consideration in terms of the mix uniformity of the final product, because

TABLE 3

EFFECT OF REMOLDING ON STRENGTH OF LIME-TREATED EXPANSIVE CLAY

At End of 70-Day Curing Period			Af	ter Remole	ling and Compac	tion	
Water	Dry	Compressive	Strain at	Water	Dry	Compressive	Strain at
Content	Density	Strength	Failure	Content	Density	Strength	Failure
(%)	(pcf)	(kg/cm ²)	(%)	(%)	(pcf)	(kg/cm ²)	(%)
12.9	97.5	6.9	1.5	12.9	97.0	7.3	3.7
16.1	97.9	7.5	1.3	16.1	96.0	6.8	5.0
19.4	97.8	6.0	3.0	19.4	97.2	5.5	6.5
21.9	98.1	5.6	4.0	21.9	97.7	5.3	12.5

the mellowing action greatly facilitates final mixing. A delay in compaction may reduce the effectiveness of possible cementation and carbonation reactions, however.

The results of the present investigation have shown that for the expansive clay soil studied, a delay between mixing and compaction is definitely detrimental in terms of density, swell and strength for samples prepared using constant compactive effort. Densities were found to decrease by as much as 8 pcf, and as-cured strengths by 30 percent for a 24-hr delay between mixing and compaction. Thus, on the basis of performance of samples prepared at constant compactive effort, it might be concluded that a delay in compaction would be disadvantageous.

On the other hand, for samples prepared to a specified constant density, it was found that the properties of the treated soil after curing, and in the soaked and unsoaked condition, were about the same for samples prepared 40 min and 24 hr after mixing. This indicates, for this soil at least, that delay between mixing and compaction is not detrimental provided extra compactive effort is exerted to maintain the desired density as time between mixing and compaction increases; however, extra compactive effort means increased cost of compaction.

Consideration of probable soil-lime reactions would suggest that a flocculation of the soil structure, which increases with time after addition of lime, is the principal effect responsible for the observed behavior. Quite possibly an investigation of the effect of delay between mixing and compaction using soils in which the soil-lime reactions were predominantly cementation and carbonation would show that large delays produce irreversible detrimental effects.

In practice, the advantages of improved mix uniformity and handling characteristics that may result from allowing a delay between initial mixing and reworking prior to compaction may well offset any losses in density or strength that may result, or may justify the expenditure of more compactive effort to obtain high density.

The investigation has shown a 4 percent dolomitic hydrated lime treatment to be a very effective stabilizer of an expansive clay soil containing appreciable (8 percent) organic matter. Untreated and treated samples have been compared over a range of water contents and curing periods and compacted to dry densities corresponding to 90 percent of their respective maximum densities as determined by modified AASHO effort. This meant a comparison wherein the untreated samples were some 7 pcf denser than the treated samples.

Although the improvement in strength as a result of lime treatment was not marked for samples tested in the as-cured condition, the improvement in properties of specimens exposed to water was very marked. Swell was reduced to low levels (less than

3 percent) immediately after compaction for treated samples prepared to high water contents, and for samples cured for 28 days the swell was reduced to less than 3 percent over the whole water content range. The swell of the untreated specimens ranged from 17 percent at low water contents to 4 percent at high water contents. Soaked strengths of treated samples showed similar improvements over the untreated soil, being increased as much as sevenfold by lime treatment. The improvement in soaked strength follows directly from the decrease in swell afforded by lime treatment.

Because by lime treatment the increase in as-cured strength is not large, a delay between mixing and compaction is not detrimental provided sufficient compactive effort is used to maintain specified density, and the strength loss due to remolding and recompacting treated samples 70 days after original compaction is not large, it is concluded that the observed chemical changes on aging serve mainly to increase the flocculation and reduce the water affinity of the soil. Cementation effects are felt to be of minor importance in the over-all reaction of this soil with lime.

Finally, additional tests have shown a consistent trend for a slight decrease in strength and increase in swell to occur with both treated and untreated samples when the curing time is increased from 35 to 60 days. The cause of this behavior has not yet been established; however, the effects of the organic matter or bacteriological factors are suggested as possibilities.

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