Effect of Lime on Highly Plastic Clay with Special Emphasis on Aging

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A laboratory study was undertaken to evaluate the effect of aging on the properties of Regina clay treated with 2 and 4 percent quick lime. Aging is generally referred to as the time interval between the addition of lime and water to the soil and the compaction of the mixture. Regina clay, a highly expansive clay, was selected for this study because it forms a common subgrade material in Saskatchewan. As a result of this study, it was found that aging had a pronounced effect on the properties of the treated soil. The properties also depended on the percentage of lime. The results indicate that both density and strength decreased as a result of an increased aging period for the treated samples prepared using constant compactive effort. However, the reduction in strength could be eliminated or could even result in an increase if the treated specimens with low percentages (e.g., 2 percent) were subjected to an increased compactive effort. Nevertheless, the results show that increasing the compactive effort could not eliminate the reduced strength for samples treated with higher percentages of lime (e.g., 4 percent) and increased aging (e.g., 24 hr). Increased compaction may well lead to a lower strength as a consequence of overcompaction. Aging appears to have had no significant effect on swell for treated samples prepared by both constant and increased compactive efforts, and little effect as well on the plasticity index.

Lime has been used for more than 20 years on Saskatchewan highways to improve the engineering properties of subgrade soils. However, use of lime in Saskatchewan is relatively limited because of the costs involved and some unsatisfactory experiences in the past. Lime has been used on a few full-scale experimental test sections throughout the province and on some small projects. Consequently, little information is available concerning the performance of lime-treated soils in Saskatchewan. In particular, there is limited information available on the long-term performance of lime-treated highway pavement.

PURPOSE AND SCOPE

In an attempt to develop a fuller understanding of the behavior of lime-treated clays native to Saskatchewan, the Saskatchewan Highways and Transportation Department is committed to sponsoring a 3-year lime research program at the University of Saskatchewan; the program began in 1986. The main purposes of the research program are twofold: (a) to investigate the behavior of the lime-treated clay native to Saskatchewan under the influences of various design and environmental factors, and (b) to develop appropriate methods for predicting the long-term strength and durability of the lime-treated native clay, a highly plastic material referred to as Regina clay.

The following research program has been established in order to accomplish the foregoing purposes. The program consists of (a) a literature search and synthesis of data, (b) a laboratory testing program, (c) an evaluation of the field design mix and construction procedure, and (d) the study of a full-scale field test section.

The purpose of the literature search and synthesis of data was to critically examine the past literature pertinent to lime-treated soils. The literature review was used to help establish a relevant laboratory testing program to investigate the behavior of the lime-treated native clays under the influence of various design and environmental variables. An attempt was made to establish appropriate testing procedures for predicting the strength and durability of the lime-treated clays on a long-term basis. Upon completion of the laboratory program, design and construction procedures specific to Saskatchewan climate conditions will be proposed. The proposed procedures will then be evaluated by studying a field test section through a long-term monitoring program.

The laboratory investigation began in the spring of 1986. It consisted of a short-term and long-term property evaluation of a lime-treated native clay. In the short-term property evaluation the effects of variables such as lime percentage, initial water content, aging period, and compactive effort on lime-treated clays were studied. The long-term property evaluation emphasizes the influences of the environmental variables on lime-treated clays. The variables studied included curing, wetting and drying, and freezing and thawing. This paper contains the results of the short-term property evaluation; the research findings of the long-term property evaluation will be presented in a separate paper.

BACKGROUND

Considerable research has been conducted during the past few decades on the behavior of lime-treated soils. The literature review indicated that efforts have concentrated mainly on evaluating variables such as soil type, lime type, lime content, and curing. However, the influence of aging

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has not been thoroughly examined (*1*). Aging is generally referred to as the elapsed time between the addition of lime and water to the soil and the compaction of the mixture. This term has also been referred to as "rotting" and "mellowing."

It appears that researchers have not believed that aging critically affects the properties of lime-treated soils. McDowell (*2*) and Dumbleton (*3*) pointed out that aging was helpful in breaking down clay clods, which provided a better mix uniformity and workability. However, Taylor and Arman (*4*) reported that most of the failures associated with lime-treated bases in Louisiana were due to improper mixing and delayed compaction after the initial mixing of the soil and lime.

Mitchell and Hooper (*5*) performed an investigation to study the effect of aging on an expansive clay treated with 4 percent dolomitic hydrated lime. It was found that aging was detrimental in terms of density, unconfined compressive strength, and swell characteristics for samples prepared using a constant compactive effort. It was reported, however, that the detrimental effects related to aging could be eliminated if extra compactive effort was provided to compact the aged samples to the same densities as the unaged samples.

Other properties affected by aging are permeability and suction. Fossberg (*6*) reported that the addition of lime decreases permeability and increases soil suction. Klym (*7*) used a longer aging period than Fossberg and showed that the addition of lime resulted in an increase in permeability and a decrease in suction.

The effect of aging on the durability of lime-treated soils has not been thoroughly investigated, possibly because of an earlier understanding that aging only provides better mix uniformity and workability. O'Flaherty and Andrews (*8*) performed a series of freezing and thawing tests, and concluded that aging has a deleterious effect on the durability of lime-treated soils.

Aging not only influences the physical properties of the soil but also plays an important role in the field construction procedure. This is particularly true for highly plastic clays native to Saskatchewan. It therefore appeared desirable to initiate a thorough laboratory study to better define the effects of aging and compaction. The initial phase of the study, which evaluated the short-term properties of lime-treated native clays, emphasized the influence of aging and compaction.

MATERIALS

Soil

The soil selected for this study was Regina clay, a material commonly used for highway subgrades in Saskatchewan. Its relevant properties are summarized in Table 1. The soil consists of approximately 80.0 percent clay and 20.0 percent silt. The average liquid limit is 86.0 percent and the average plasticity index is 58.8 percent. The soil is classified as CH in the Unified Soil Classification System.

The average specific gravity of Regina clay is 2.83. The maximum ASTM standard proctor density is 1.42 Mg/m^3 at an optimum water content of 30.0 percent. The maximum modified ASTM density is 1.66 Mg/m^3 at an optimum water content of 21.8 percent.

X-ray analysis indicates that the soil has a mixture of smectite and illite clay minerals. The soil swells excessively when wet and shrinks when drying, forming large shrinkage cracks.

Lime

The lime used in this study was a commercial calcitic quick lime (CaO) having the composition and gradation indicated in Table 1. It was kept in sealed containers until immediately before use to prevent carbonation with the carbon dioxide in the air.

SAMPLE PREPARATION

To prepare the material for the various tests, Regina clay was air dried and pulverized using a Los Angeles abrasion resistance machine. The soil was then sieved, and material passing the 2.00-mm (No. 10) sieve was used for the density, unconfined compression, and swell tests. Material passing the 0.425-mm (No. 40) sieve was used for the plasticity index testing. Before lime was added to the soil samples, distilled water was added to the air-dried soil to achieve the desired initial water content (7 or 15 percent). The samples were placed in a moist room for at least 2 days. The quick lime was then added to the soil samples and dry-mixed for several minutes. Distilled water was added to the soil-lime samples to achieve the desired aging water contents of approximately 25, 30, or 35 percent. After being mixed by hand for several minutes, the samples were mechanically mixed for 3 to 5 min to ensure complete and thorough mixing. The samples were then placed in sealed double plastic bags and allowed to age for 1, 4, or 24 hr. Immediately after aging, the soil-lime samples were tested for density, unconfined compressive strength, percent swell, and plasticity. It should be emphasized that no curing period was permitted; only initial values were measured. The curing portion of the research program is to follow.

A large number of samples was required to complete this portion of the study (approximately 300). In order for each variable to be studied, only one sample for each particular combination of aging water content, lime percentage, aging period, compactive effort, and initial water content was prepared. Thus for the tests of unconfined compressive strength and percent swell, only one sample was prepared for each data point. The density data are a result of three tests, because compaction was required for preparation of the unconfined compressive strength and swell tests. One test per point was also performed for the plasticity index results. No statistical comparisons were made.

TABLE 1 MATERIALS

REGINA CLAY			
		CLAY MINERALOGY	
LIQUID LIMIT	86.0%	ILLITE/SMECTITE MIXED LAYER	48.0%
PLASTIC LIMIT	27.2%	ILLITE	9.0%
PLASTICITY INDEX	58.8%	KAOLINITE	10.0%
% CLAY	80.0%	QUARTZ	33.0%
% SILT	20.0%		
OPTIMUM WATER CONTENT AND MAXIMUM DRY DENSITY			
STANDARD PROCTOR: 30.3%, 1.415 Mg/m^3			
MODIFIED PROCTOR: 21.8%, 1.658 Mg/m^3			
CHEMICAL ANALYSIS			
SOLUABLE SULFATE	2050 ppm (.205 %)		
ORGANIC CARBON	10000 ppm (1.0 %)		
LIME ANALYSIS		% BY WEIGHT	
CaO plus MgO		96.35%	
MgO		01.45%	
IMPURITIES		03.65%	
GRADATION		% BY WEIGHT PASSING	
2.00 mm		100%	
0.16 mm		100%	

LABORATORY TESTS

Plasticity Index

The plasticity index tests were performed according to ASTM D424-59 (1971). The soil-lime samples that were tested for plasticity were aged at a water content of 30.0 percent.

Density Tests

Standard Compaction

After mixing and allowing the soil-lime samples to age, compaction was performed according to ASTM D698-78. Compaction was achieved with a mechanical dynamic compactor. The soil was compacted in three layers with a 2.49-kg (5.5-lb) rammer and a 305-mm (12-in.) drop. A standard 101-mm (4-in.) proctor mold was used to form the specimens.

Increased Compaction

Figure 1 shows a plot of dry density versus number of blows per layer for various lime percentages and aging periods. Each point represents a lime-treated soil compacted by using a mechanical dynamic compactor with a 2.49-kg rammer and a 305-mm drop. Three compaction layers were used; however, the number of blows per layer varied for each specimen. A maximum dry density of 1.4 Mg/m^3 at a water content of 30.0 percent was desired. This density is equivalent to the maximum dry density of untreated Regina clay according to ASTM D698-78. Figure 1 shows the required number of blows per layer to achieve 1.4 Mg/m^3 for a particular aging period and lime percentage. The increased compactive effort required to achieve the

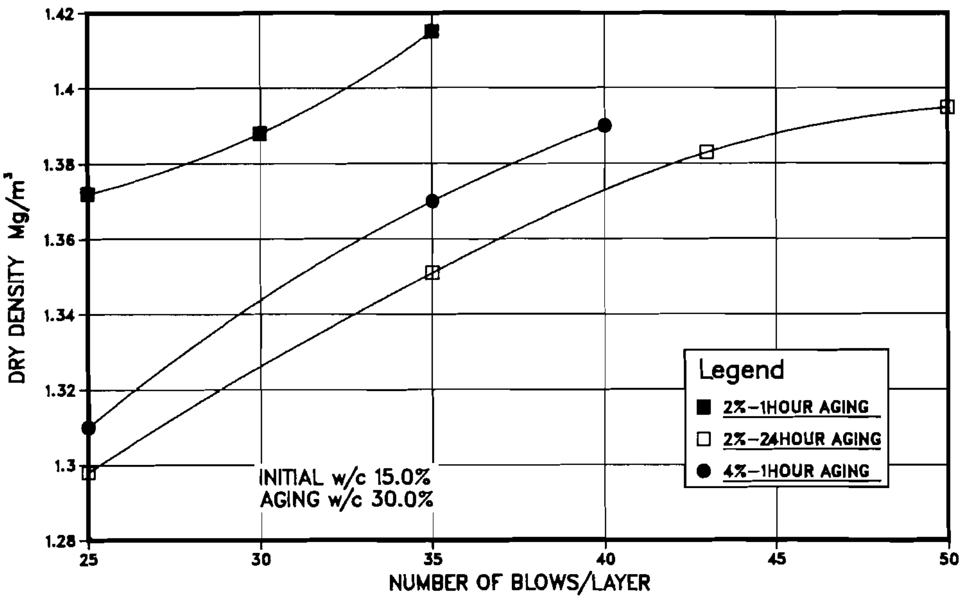

FIGURE 1 Number of blows per layer versus dry density for 2 percent lime-modified clay aged for 1 and 24 hr and 4 percent lime-modified clay aged for 1 hr (initial water content 15 percent and aging water content 30 percent).

constant density was then used to prepare the specimens for the unconfined and the swell tests.

Unconfined Compression

Unconfined compression tests were performed according to ASTM D2166-66 (1979), with a constant strain rate of 1.0 percent and a length-to-diameter ratio of 2.4. To obtain a sample for the unconfined compression test, the soil-lime specimens were compacted in the proctor mold, either to standard proctor density or untreated density (1.4 Mg/m^3). A 50.8-mm (2-in.) diameter Shelby tube was then hydraulically pressed through the compaction specimen. Extruding the sample from the Shelby tube resulted in a specimen 47.2 mm (1.9 in.) in diameter and 117 mm (4.6 in.) long. This sampling technique proved successful, resulting in minimal sample disturbance.

Swell

Swell tests were conducted according to ASTM D4546-85, with a 64-mm (2.5-in.) diameter steel ring and a vertical overburden pressure of 7 kPa (1 psi). The swell test specimens were formed by manually pressing the 64-mm steel ring into the compaction specimen; they were then trimmed. The specimens were allowed to swell in one-dimensional odometers and then loaded back to the original void ratio. The swelling pressures were determined by reloading the specimens to their original void ratio. However, only the percent swell results are reported in this paper.

RESULTS AND DISCUSSION

Effect of Aging on Lime-Treated Samples Using Constant Compactive Effort

The effect of aging on the lime-treated Regina clay was assessed in terms of Atterberg limits, the relationship between water content and density, unconfined compressive strength, and swell characteristics. All compacted samples were prepared using a standard compactive effort.

Atterberg Limits

Figure 2 shows the effect of aging on the plasticity characteristics of lime-treated Regina clay. In general, the results indicate that the plasticity index decreases only slightly with increasing aging period. The difference is so small that no conclusions can be drawn without additional tests. Nevertheless, the effect of aging on plasticity index tends to increase with increasing lime content.

The relationship between lime content and the plasticity characteristics of lime-treated Regina clay aged 24 hr is shown in Figure 3. As can be seen, the addition of lime results in a decrease in the liquid limit and an increase in the plastic limit. The net effect is a significant reduction in plasticity index, a commonly observed consequence of lime addition. In addition, the results show that the largest reduction in plasticity index occurs at the first addition of lime. With the addition of only 2 percent lime, the plasticity index is reduced dramatically from 58.8 to 20 percent. However, the decrease with a further increase in lime content is reduced.

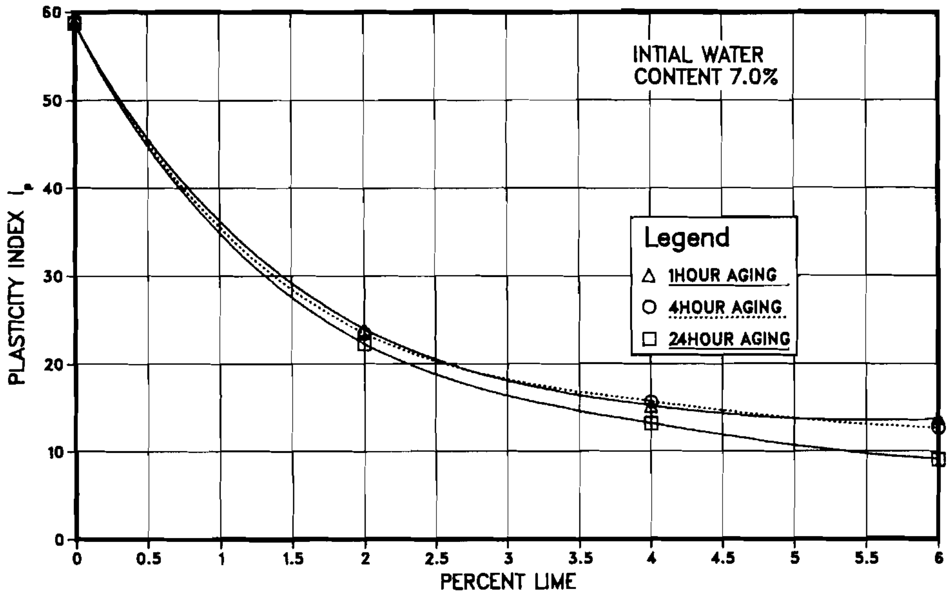

FIGURE 2 Percentage of lime added versus plasticity index for 1-, 4-, and 24-hr aging.

Water Content Versus Density

The standard compaction curves for the untreated clay with 2 and 4 percent lime aged for 1 hr and the clay treated with 2 and 4 percent lime aged for 24 hr are shown in Figure 4. These curves indicate the following trends.

1. The effect of aging on lime-treated Regina clay is to reduce the density. It is generally agreed that the initial stage of the soil-lime reaction, which is referred to as immediate amelioration, begins upon the addition of lime. It is believed that the immediate amelioration, which takes place before compaction, will result in the cementation of particles into a loose structure (*9*). Cementation that has developed at the points of contact between the edges and the faces of adjacent clay particles in the house-of-cards type of structure will cause the soil to offer a greater resistance to compaction. Therefore, for a given compactive effort, a lower density would be expected as the time available for this reaction increases. However, the extent to which aging affects density is related to aging water content. At low aging water content (24 to 26 percent) the difference in density between samples aged for 1 and 24 hr is small irrespective of lime percentage. The difference in density increases with increasing aging water content. This may be attributed to the fact that the lime hydration

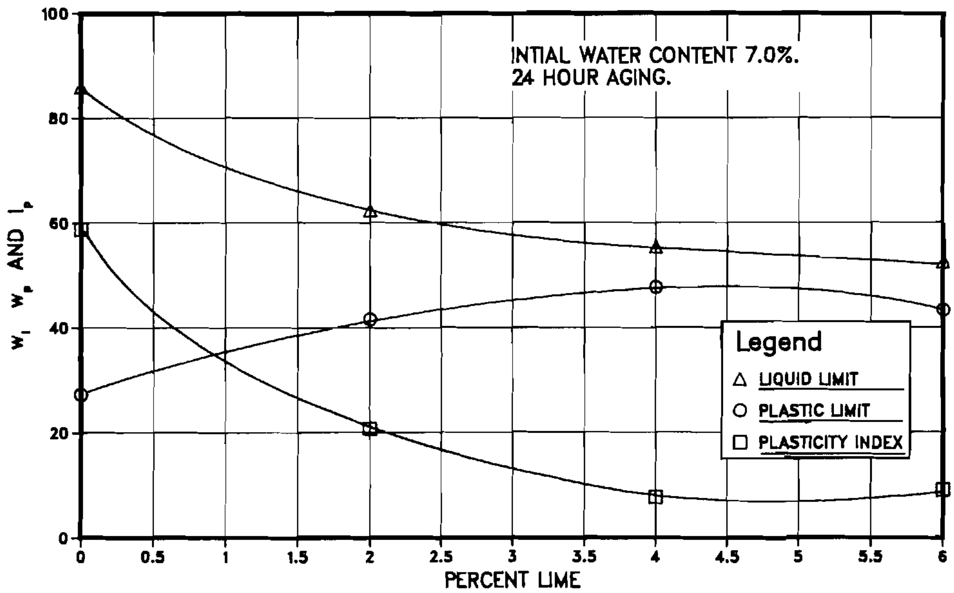

FIGURE 3 Percentage of lime added versus liquid limit, plastic limit, and plasticity index for 24-hr aging with 7 percent initial water content.

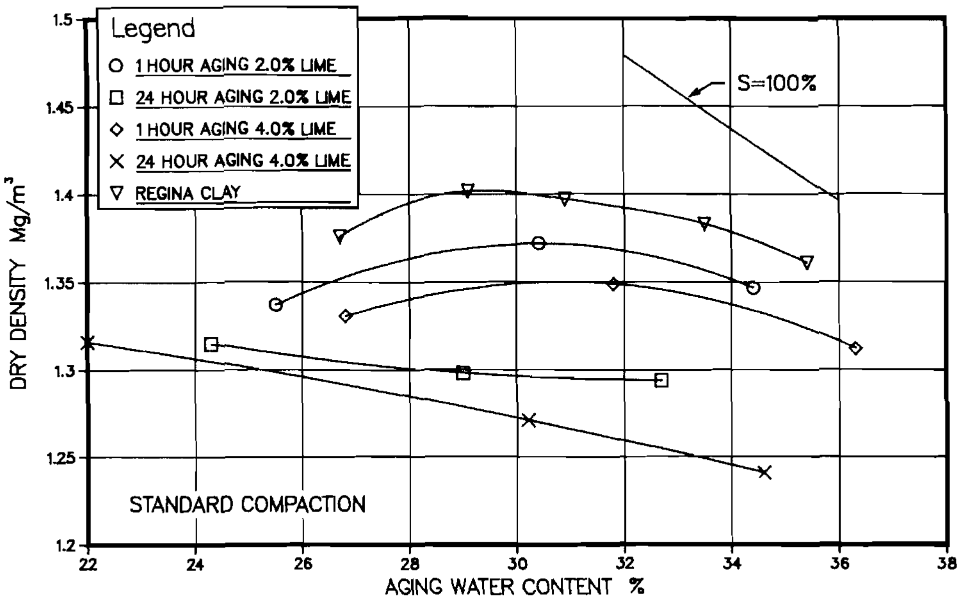

FIGURE 4 Aging water content versus dry density for 2 and 4 percent lime-modified samples aged 1 and 24 hr, with standard compaction and 15 percent initial water content for 2 percent samples and 7 percent initial water content for 4 percent samples.

process cannot occur freely without sufficient water. On the other hand, the effect of aging becomes more pronounced if adequate water is added to the lime to satisfy its initial chemical affinity for water.

2. Aging not only reduces density but also affects the shape of the compaction curve, depending on the duration of the aging period. The results indicate that the effect of short-term aging (e.g., 1 hr) is to produce a lower dry density and higher optimum water content for a given compactive effort. The shape of the compactive curves for soil treated with 2 and 4 percent lime and aged for 1 hr is comparable with that of the untreated soil. As the aging

TABLE 2 SUMMARY OF TEST RESULTS UNDER CONSTANT (STANDARD) COMPACTIVE EFFORT

		COMPRESSIVE STRENGTH (kPa)			PERCENT SWELL %		
LIME %	INITIAL w/c,%	AGING w/c,%	1 HOUR AGING	24 HOUR AGING	AGING w/c,%	1 HOUR AGING	24 HOUR AGING
2	7	23.55	285.3	260.8	23.95	3.62	2.00
2	7	27.85	344.1	264.2	30.65	1.11	1.45
2	7	32.40	374.7	249.7	33.80	0.24	0.84
2	15	24.75	287.3	234.0	25.50	3.70	3.30
2	15	29.70	393.7	353.7	29.80	1.95	2.40
2	15	33.30	269.0	280.5	34.65	0.67	1.11
4	7	23.80	295.3	224.2	24.50	1.64	0.34
4	7	28.15	366.9	228.0	31.25	1.02	0.78
4	7	32.60	333.8	307.9	36.15	0.84	0.40
4	15	25.30	262.0	-	26.80	2.39	-
4	15	30.70	336.0	-	30.30	0.92	-
4	15	34.60	202.6	-	35.20	0.83	-

(-) tests not performed

period increases from 1 to 24 hr, the compaction curves appear to become flatter with no definable optimum water content.

3. The influence of aging on density is more pronounced than that of lime percentages, particularly at higher aging water contents. For example, soil samples treated with 2 percent lime and prepared at 30 percent (aging) water content indicated a reduction in density by as much as 75 kg/m³ when the aging periods were increased from 1 to 24 hr. The density decreased by only 30 kg/m³ when lime treatment was increased from 2 to 4 percent for soil specimens prepared at the same water content with a 1-hr aging period. It is known that the addition of lime will reduce the maximum density and increase the optimum water content relative to values for the untreated soil. These effects are similar to the effects of aging under short duration.

Unconfined Compressive Strength

The unconfined compressive strength test results on the lime-treated soil specimens under 1- and 24-hr aging periods are compared and presented in Table 2. The results show that the unconfined compressive strength decreases as the aging period increases. However, it should be noted that one value is contrary to this trend.

A typical plot of aging water content versus unconfined compressive strength of lime-treated specimens aged for 1 and 24 hr is shown in Figure 5. The unconfined compressive strength of the untreated Regina clay is also included in Figure 5 for comparison purposes. As indicated in Figure 4, an increase in aging period leads to lower unconfined compressive strengths for a given compactive effort. Herrin and Mitchell (*10*) indicated that the immediate amelioration will take place rapidly, particularly when the soil-lime mixture is in a loose state. Thus, it would be expected that a significant portion of this reaction would take place if there were a prolonged delay between mixing and compaction. As previously discussed, the reaction before compaction results in the cementation of particles, which, in turn, increases the strength. However, this appreciable increase in strength is likely to be overshadowed by the loss in strength caused by the decrease in density as a result of the delay between mixing and compaction. Subsequent compaction can destroy the bonds between the particles. Therefore, the net effect is a reduction in strength.

The effect of aging on strength is also related to aging water content. Figure 5 shows that the effect of aging on strength becomes more pronounced as the aging water content increases. This trend appears to lend support to the fact that sufficient water must be added to the soil-lime mixture in order to hydrate the lime before the soil-lime reaction can proceed.

Swell Characteristics

The effects of aging water content on the percent swell of the specimens treated with 2 and 4 percent lime and aged for 1 and 24 hr are shown in Figures 6 and 7 along with the swell characteristics of the untreated Regina clay. The results of the swell tests conducted using constant compactive effort are also summarized in Table 2.

The beneficial effect of lime treatment on the reduction in swell is shown in Figures 6 and 7. The reduced swell characteristics may be attributed to the decreased affinity for water of the flocculated calcium-saturated clay, the formation of which is caused by the increased electrolyte content of the pore water and the cation exchange of the clay to the calcium form as a consequence of the addition

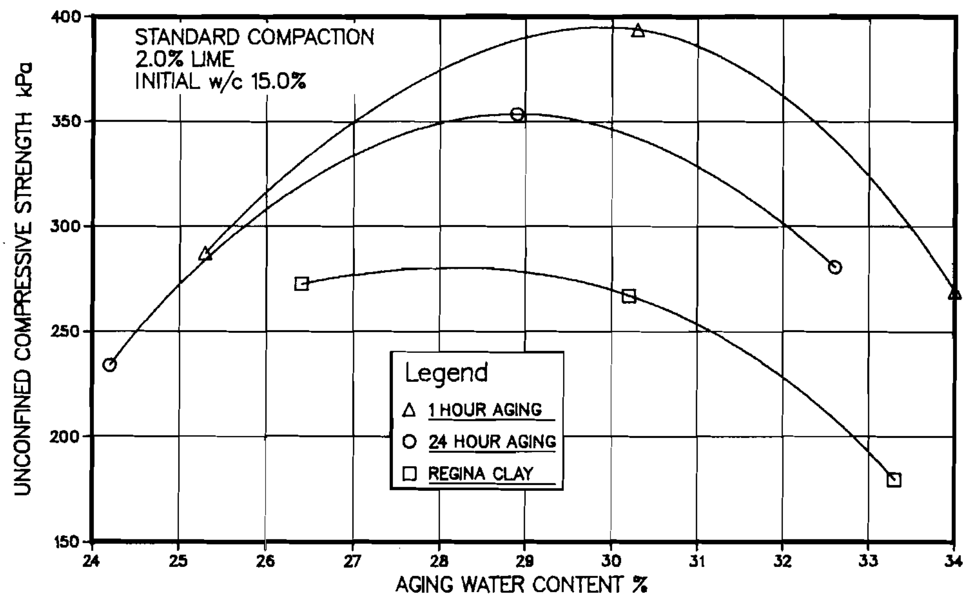

FIGURE 5 Aging water content versus unconfined compressive strength for 2 percent lime samples aged for 1 and 24 hr, with standard compaction and 15 percent initial water content.

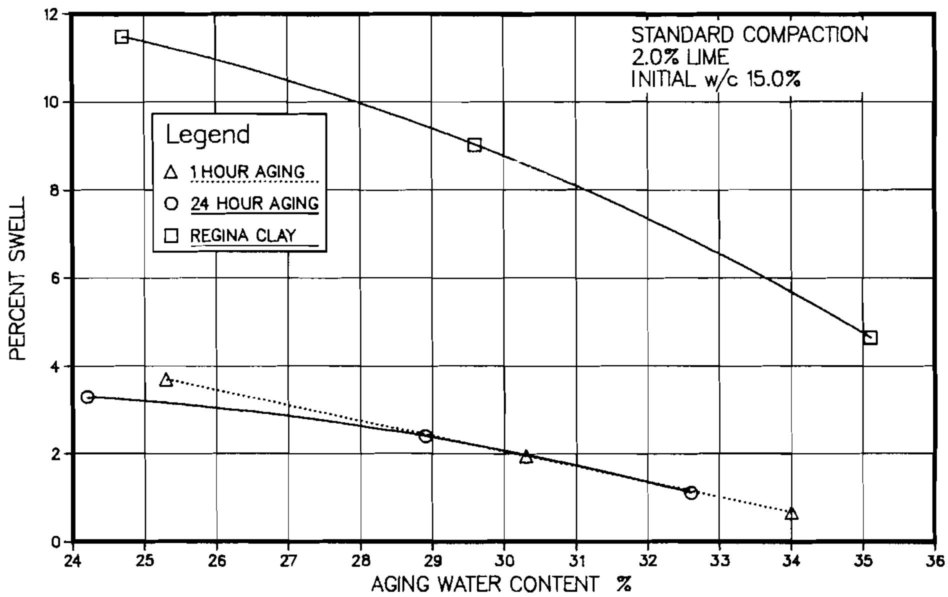

FIGURE 6 Aging water content versus percent swell for 2 percent lime samples aged for 1 and 24 hr, with standard compaction and 15 percent initial water content.

of lime. Figures 6 and 7 show that the reduction in swell percentage is more significant with the addition of smaller percentages of lime.

Figures 6 and 7 indicate that the aging water content at which compaction is carried out has an important influence on swell percentage. At the same compactive effort, the soil fabric becomes increasingly oriented with increasing water content. Soil samples compacted dry of optimum have flocculated structures, whereas samples compacted wet of optimum have a more oriented or dispersed structure. The compacted clay soils with a flocculent structure tend to swell more than those with a dispersed structure. Figures 6 and 7 show that the swell percentage decreases with increasing aging water content regardless of the aging periods. Aging appears to have no significant effect on swell for the soil studied.

Effect of Aging on Lime-Treated Specimens Using Increased Compactive Effort

The influence of aging examined thus far is based on constant compactive effort. In order to compare the effect of

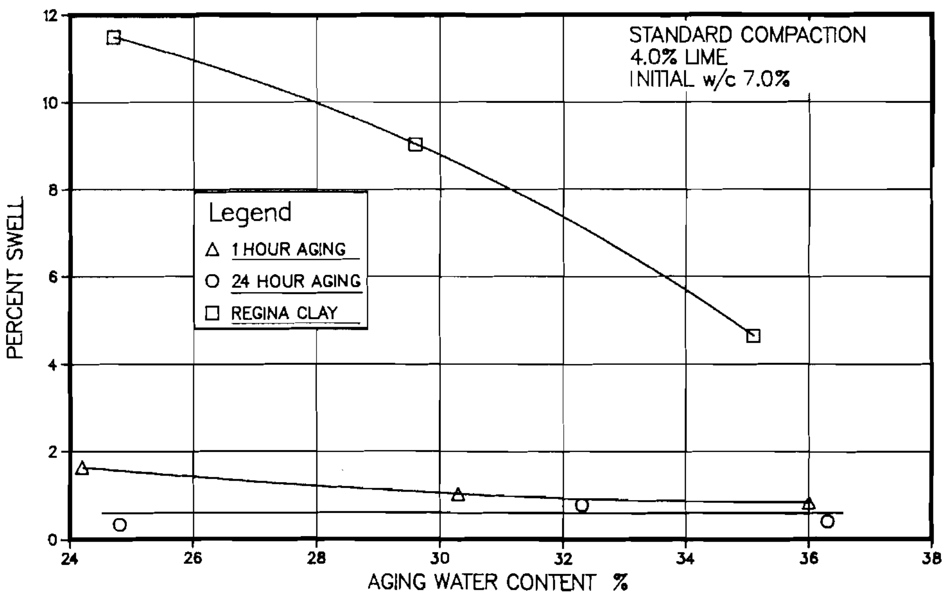

FIGURE 7 Aging water content versus percent swell for 4 percent lime samples aged for 1 and 24 hr, with standard compaction and 15 percent initial water content.

aging on lime-treated specimens at equal densities, specimens were prepared at densities equal to those of the untreated specimens.

Unconfined Compressive Strength

Figure 8 indicates that if specimens were treated with 2 percent lime and compacted to equal densities, the samples aged for 24 hr showed a greater unconfined compressive strength than those aged for 1 hr. However, an increase in compactive effort was required to achieve the required density. The increase in strength may be attributed to the flocculated soil structure.

The results shown in Figure 8 can be compared with those in Figure 5, which shows the influence of aging on strength of lime-treated specimens prepared at constant compactive effort. The decrease in strength with increasing aging period is mainly due to the decrease in density. A similar conclusion was reached in the study conducted by Mitchell and Hooper (*4*).

An increase in compactive effort does not always result in a greater strength in the case of samples treated with higher lime contents and aged for longer periods. There is probably a greater degree of flocculation under these conditions, which offers greater resistance to compaction. However, a greater compactive effort must be provided to attain the desired density. Overcompaction may cause the specimens to become weak and friable, resulting in sampling problems. Some test results were considered to be nonrepresentative because of the poor condition of the specimens after sampling (Table 3).

Swell Characteristics

Figure 9 shows that aging has little or no effect on swell characteristics of lime-treated samples prepared using an increased compactive effort. As previously noted, similar behavior was found at a constant compactive effort (Figure 7). The insignificant effect of aging on swell, as indicated by the two different compactive efforts, would suggest that the main factor responsible for the decreased swell characteristics is due to flocculation and agglomeration of the soil structure and not cementation before compaction. If cementation were a primary factor, it would be expected that the longer aging period would result in greater swell for samples prepared using both constant and increased compactive efforts. As explained by Herzog and Mitchell (*11*), the flocculation and agglomeration are caused by the increased electrolyte content of the pore water and cation exchange of clay to a calcium form following the addition of lime to the soil. As a consequence of this series of reactions, the original clay is changed to a flocculated calcium-saturated clay that has the tendency to reduce swell because of its decreased affinity for water.

CONCLUSIONS

1. An increasing aging period does not significantly affect the plasticity index results. More tests would have to be performed in order to confirm that longer aging periods decrease the plasticity index slightly, especially at higher lime contents.
2. Aging produces a lower density and a reduced strength for specimens prepared using a constant compaction effort.

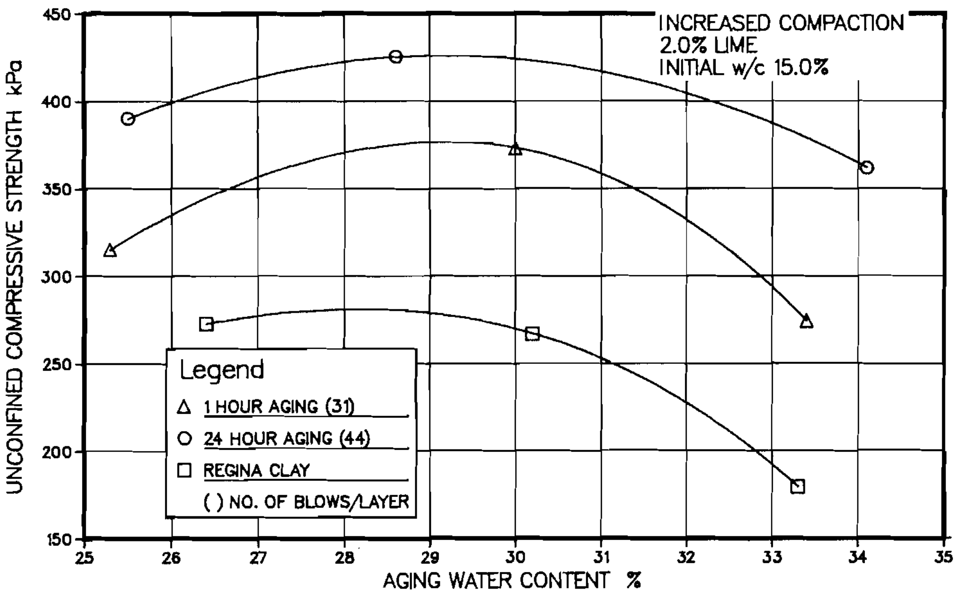

FIGURE 8 Aging water content versus unconfined compressive strength for 2 percent lime samples aged for 1 and 14 hr, with standard compaction and 15 percent initial water content.

TABLE 3 SUMMARY OF TEST RESULTS UNDER INCREASED COMPACTIVE EFFORT

		COMPRESSIVE STRENGTH (kPa)			PERCENT SWELL %		
LIME %	INITIAL w/c,%	AGING w/c,%	1 HOUR AGING	24 HOUR AGING	AGING w/c,%	1 HOUR AGING	24 HOUR AGING
2	7	24.90	369.7	492.5	25.75	2.50	4.60
2	7	29.70	449.4	545.3	30.40	0.98	1.70
2	7	34.15	304.4	247.5	34.05	0.54	0.65
2	15	25.40	315.2	390.1	-	-	-
2	15	29.30	373.0	425.4	29.8	1.60	1.40
2	15	33.75	274.3	361.6	-	-	-
4	7	24.05	365.1	346.6	27.40	1.40	1.00
4	7	29.80	524.5	511.6	31.25	0.28	0.63
4	7	35.60	319.2	*	35.80	0.85	0.11
4	15	25.50	384.6	-	26.10	2.40	-
4	15	30.00	430.0	-	30.50	0.79	-
4	15	34.80	207.1	-	34.60	0.59	-

(-) tests not performed
* specimen too weak to be sampled

The extent to which aging affects the density and strength depends on the aging water content at which the specimens were compacted. The reduction is small at low aging water contents, but it becomes more pronounced at higher aging contents.

3. The reduction in strength as a result of aging can be compensated for or even improved upon by using an increased compactive effort for specimens treated with low percentages of lime. However, an increased compactive effort does not always produce higher strengths when the specimens are treated with higher percentages of lime and aged for longer periods. In other words, increased compaction may cause a reduction in strength.

4. Aging appears to have no significant effect on the

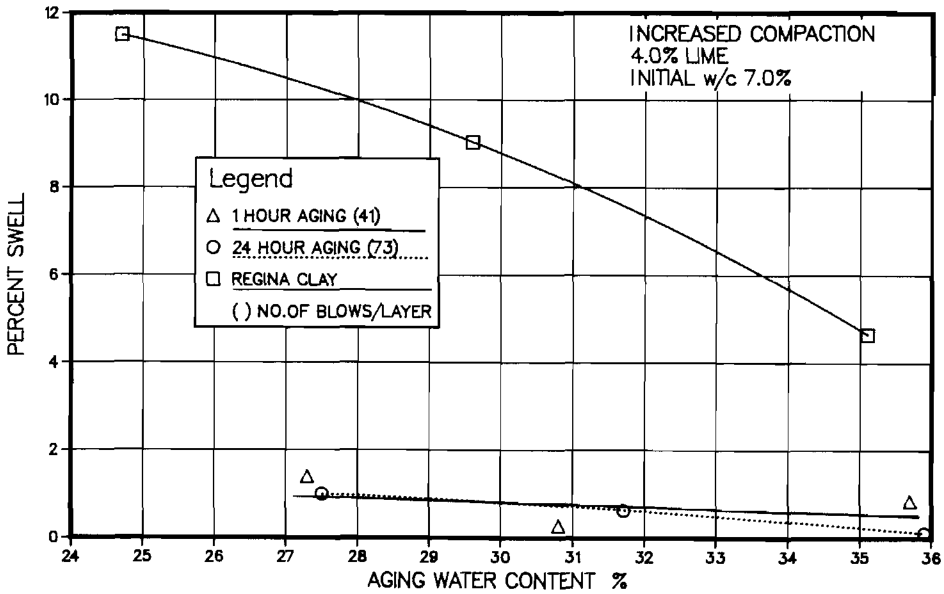

FIGURE 9 Aging water content versus percent swell for 4 percent lime samples, with increased compactive effort and 7 percent initial water content.

swell of treated specimens prepared with constant and increased compaction.

5. The influence of aging on lime-treated Regina clay has been examined in terms of plasticity, the relationship of water content to density, unconfined compressive strength, and swell. These are referred to as short-term effects. This investigation did not take into consideration such variables as curing, wetting and drying, and freezing and thawing, which are known to have a significant influence on the behavior of lime-treated soils in a long-term basis. Therefore, further studies are now being conducted in order to better define the effect of aging in a long-term basis.

ACKNOWLEDGMENTS

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