Comparison of Quicklime and Hydrated Lime Slurries for Stabilization of Highly Active Clay Soils

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Research is presented that was used to compare the stabilizing effects of quicklime and hydrated lime slurries when applied to three samples of highly active clay soils from each of two geologic formations from North Central Texas. In addition, slurries made of the commercial lime products used in the research were studied and compared. The results obtained included soil properties measured before and after stabilization with these two slurries. These results were compared by using statistical methods to determine the significant differences. It was found that the quicklime slurries had a less detrimental effect on compactibility of the soil, provided somewhat lower swell, caused the soil to have lower plasticity and higher strength, and allowed a lower percentage of lime to be used. In addition, significant differences in time-related changes in properties are discussed in the analyses and conclusions.

Recognizing the severe damage that can be caused to transportation facilities by highly active or expansive clay soils, engineers have often chosen to stabilize these materials. The most common stabilizing agent applied to expansive clays to reduce or eliminate their problematic behavior is lime. This is especially true for the soils, site situations, and climate of the North Central Texas region.

Initially, lime was added to soils as hydrate powder, but as more projects have been built in urban areas, the prudent choice has become slurries of lime and water. Recently, the availability of slurries made in the field with quicklime has raised some questions as to how well these relatively new mixtures stabilize highly active clay soils compared with hydrated lime slurries. There are those who believe that the relatively high-temperature quicklime slurries should perform better, because chemical reactions would be accelerated, but others disagree. The research study reported here was undertaken to investigate the nature of the slurries mentioned earlier and to determine their stabilizing effects when applied to two highly active clay soils of North Central Texas.

SOILS AND LIME REACTIONS

For this study six soil samples were taken from two geologic formations: the Eagle Ford and Austin formations. These were sampled at relatively widespread locations within the Dallas–Fort Worth metroplex. These highly active clay soil samples, which were expected to be lime reactive, were taken from within the top 9 ft of the subgrade. The results for all six samples were combined during analyses, because these samples were thought to be representative of all the metroplex highly active clay soils.

The expected reactions between these clays and the lime slurries included cation exchange, ion crowding, dissolution of clay, flocculation and agglomeration, carbonation, and pozzolanic reactions (*1–5*). These mechanisms would normally cause soils to have reduced plasticity indexes and shrink-swell potentials, increased shear strength and reduced compressibility, increased workability and water repellancy, reduced compactibility, and increased abrasion and erosion resistance. Even though much is known about how these mechanisms cause the foregoing changes in behavior, little has been done to compare how well quicklime and hydrated lime slurries accomplish improvements in behavior.

SLURRY STUDY

In order to provide a basis for understanding how the two lime slurries differ, some of their properties were explored. Other than the apparent differences in the lime materials, there are reported differences in slurry properties. The pH of lime slurries is lowered at higher temperatures because the solubility of lime decreases (*6*). Free calcium cations can exist only when the pH is between 11.9 and 12.4. On the other hand, quicklime slurries are known to cause the evolution of higher heat during slurry formation, requiring that precautions be taken to protect workers. Along with these chemical property differences, there are physical differences.

Physical differences of the two slurries tested were expected but not completely known. Quicklime slurries made in the field have finer gradations than hydrated lime slurries because the slaking process is increased with increasing temperatures. As much as 98.6 percent of lime particles smaller than 5 μm has been measured in quicklime slurries (*7*). These finer particles are expected to have larger specific surface areas, which cause higher reactivi-

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ties. In addition, during this study quicklime slurries were observed to have slower sedimentation rates than hydrated lime slurries. In general, the chemical and physical properties of quicklime slurries just described should make them better stabilizers.

During the beginning phases of this work, a study was conducted on the lime slurries to be used. Sealed cans of fresh commercial pebble quicklime and powdered hydrate lime were made available by members of the Lime Association. These were mixed with distilled, demineralized water to form slurries, the properties of which were then investigated. In order to normalize the results during this slurry study and the subsequent soil-stabilizing study, the slurries used were manufactured to have a specific gravity of 1.200 at normal ambient temperature (72°F), and were tested and utilized at this temperature. This amount of lime was chosen because a solution of 31 percent solids is generally used in the field, and because 40 percent solids is the maximum amount considered pumpable (*8*). The amount of lime in the slurries can be measured in pounds of lime per gallon of slurry (PL/GS), by the specific gravity, or by percent solids. During this study, specific gravity was measured by hydrometer or mud balance or by weighing a specific volume of slurry.

Experiments were conducted to determine the required mixtures of lime and distilled, demineralized water to achieve the needed specific gravity. For every 3.62 lb of hydrated lime used, 1 gal of this water was added. The quicklime slurries were made with 1 gal of distilled, demineralized water to 2.25 lb of quicklime pebbles. It took approximately 1.5 times more hydrated lime than quicklime to produce the same specific gravity of slurry. For each case the percent solids was determined by centrifuge separation of the supernatant and drying of the material remaining. The hydrated lime slurry was found to have 29.14 percent solids, whereas the quicklime slurry had 29.52 percent solids. The difference is believed to be caused by the impurities in the quicklime slurries.

The supernatants extracted from the slurries by centrifuging were tested for their concentrations of calcium by using an atomic absorption spectrophotometer. The results of these readings indicate the presence of 22.18 meq/L of calcium in the supernatant of the hydrated lime slurry, whereas the quicklime slurry had 24.05 meq/L of calcium in its supernatant. The 8.4 percent larger concentration of calcium may very well mean that the quicklime slurry will be more effective at stabilizing.

Following the testing of slurries, the results were used to determine the required percent of each type of lime needed to achieve the lime fixation point. This percent is defined as the lowest percentage of lime needed to fully modify soil behavior, or the lime modification optimum (LMO). The Eades and Grim pH test was utilized to find the LMO for the six soils to be used in the comparison study. In general, this would be followed by a verification of lime reactivity by determination of the stabilized Atterberg limits when compared with those measured for the natural soil. This information will be presented later. Both of these test procedures were performed following ASTM standards.

The results of pH testing are shown in Table 1 for all six soils. Interpretation was done using the lowest percentage of lime that provided sustained pH values, with engineering judgment involved in some cases. The means computed for the percentages of lime were found to be 6.17 percent for the hydrated lime slurries and 5.17 percent for the quicklime slurries.

NATURAL PROPERTIES OF SOILS

The objective of this research was to determine the stabilizing effects of both slurry types on highly active clay soils. The properties chosen for the comparisons included those that would indicate the changes in the total physicochemical nature of the soils. Those measured before and after stabilization included Atterberg limits and indexes, swelling pressure and percent swell, unconfined compressive strength, relationships between dry unit weight and water content, soil pH, cation exchange capacity, pore-water cations, exchangeable cations, and percent clay. Each of these was determined by using standardized test methods as delineated by ASTM or the Soil Conservation Service of the U.S. Department of Agriculture.

TABLE 1 EADES AND GRIM pH TEST RESULTS

	Hydrated Lime		Quicklime	
Soil	Dry Dry Weight	pH	By Dry Weight	pH
GSW	6%	12.53	5%	12.56
Bardin	7%	12.47	6%	12.47
Nath	4%	12.50	4%	12.48
Dallas	6%	12.54	5%	12.56
McKinney	6%	12.44	5%	12.46
Austin	8%	12.47	6%	12.52

Once the natural properties had been determined for each soil, statistical analyses were performed to find their means and standard deviations. The intent was to have a sufficient sample population size to enable statistical inferences to be made as to property changes; therefore, only sample property statistics will be shown in this paper (Table 2). From Table 2 one can note that the mean value for the liquid limit was found to be 56.62 percent, and the mean plastic limit was 27.24 percent. Subtraction of these two values does not provide the mean plasticity index of 29.20 percent because each value was determined for the entire sample population separately. On the basis of the Plasticity Chart and the Unified Soil Classification System, these materials would be classified as CH, inorganic clays of high plasticity (AASHTO classification A-7-6).

Statistical analysis of clay contents shows that the soil

TABLE 2 RESULTS OF NATURAL SOIL PROPERTIES

Property	Mean	Std. Dev.	Range
LMO (%):			
Hydrated Lime	6.17	1.33	4.00 - 8.00
Quicklime	5.17	0.75	4.00 - 6.00
Liquid Limit (%)	56.62	5.38	51.00 - 65.27
Plastic Limit (%)	27.24	3.79	23.55 - 31.90
Plastic Index (%)	29.20	2.88	27.00 - 34.55
Linear Shrink.(%)	17.24	2.34	13.93 - 20.81
Percent Clay	41.01	5.16	35.01 - 47.74
Optimum W.C. (%)	25.77	2.77	22.50 - 29.00
Max. Dry U.W. (pcf)	96.83	3.76	92.00 - 102.00
Percent Swell	8.56	2.09	6.53 - 12.33
Swell Press. (tsf)	2.63	0.24	2.20 - 2.88
Unconfined Str. (tsf)	4.29	0.50	3.54 - 4.82
pH	7.88	0.07	7.76 - 7.94
Pore Water Cations (meq/L):			
Sodium	0.46	0.31	0.187 - 1.046
Potassium	0.41	0.02	0.0001 - 0.055
Magnesium	0.0009	0.0004	0.0003 - 0.0017
Calcium	1.55	0.56	1.01 - 2.44
Exchange Complex Cations (meq/100g):			
Sodium	0.20	0.17	0.08 - 0.50
Potassium	0.29	0.07	0.22 - 0.38
Magnesium	0.01	0.007	0.007 - 0.026
Calcium	12.47	11.67	7.31 - 27.18
Cation Exchange Capacity (meq/100g)	9.75	3.59	6.10 - 15.50

samples tested contained a mean percent clay of 41.01. Based on this value and the mean plasticity index, a high volume change capacity would be assigned to these materials, according to the volume change potential classification for clay soils (*9*). The percentages of clay were not measured for stabilized soils, because this measurement would be highly dependent on the amount of pulverization done.

Further proof of the highly active nature of these soils is the swelling test results. The mean percent swell under 1 psi was found to be 8.56. This occurred as the mean water content in the soils increased from 15.02 to 36.05 percent. The mean swelling pressure was determined to be 2.63 tsf, and the material moisture change was nearly identical to that for the other swell tests, but the mean of the beginning dry unit weights was about 10 percent lower.

Although efforts were made to compact strength test samples at their optimal conditions, slightly lower water contents and dry unit weights were achieved. The mean value of unconfined compressive strength for the soils tested was 4.29 tsf at a mean strain of 7.21 percent.

The mean values of the chemical properties measured indicated that the soils have a nearly neutral pH and cation exchange capacities that are not alarmingly high. The cation analyses indicated that these soils contain predominantly calcium, especially in their exchange complexes. These values are a further indication of how soil chemistry alone cannot be used to predict soil activity and lime reactivity, but may be useful in the understanding of what is occurring in the soil.

STABILIZED SOIL PROPERTIES

The procedures used for testing the stabilized materials were the same as those for the natural soils, with the exception of the addition of the lime slurries and the mixing, mellowing, and curing periods applied. The temperatures of all slurries at the time of application were as similar as possible given the ambient situation of the laboratory. After the lime slurries were thoroughly mixed into the soils, the mixtures were sealed in containers and allowed to mellow. In most cases, 24 hr was used as the mellowing period, but, as will be indicated, this was a variable in some procedures. After mellowing, samples were either compacted before further testing or tested for selected properties uncompacted. Curing of compacted specimens was done under sealed conditions and was varied, depending on the procedure. Each of these variable situations will be outlined as the results are discussed. Because the volume of test results is too large to include in this paper, only important trends will be presented here.

Two sequences were used for Atterberg limits testing. The first was used to verify the Eades and Grim pH test results of LMO at a mellowing period of 24 hr. The other included the use of lime percentages equal to the LMO and varying mellowing periods of 1, 6, 12, 24, 36, and 48 hr. The first sequence provided results that fully verified the LMO, as shown in Table 3. These results indicate that addition of more lime above the LMO does not further modify these soils. The mean values of plasticity indexes developed for various mellowing periods, as displayed in Table 3, show some of the relative effectiveness of these stabilizers. After 1 hr of mellowing, the soils treated with quicklime had experienced a reduction of plasticity index to 7.68 percent, whereas those treated with hydrated lime had decreased to 10.71 percent. This trend is somewhat different after 48 hr of mellowing. The soils treated with quicklime had a mean plasticity index of 4.27 percent and those treated with hydrated lime had a mean of 5.09 percent. Similar results were found when the linear shrinkage of treated samples was measured for differing mellowing periods. Without a test of the statistical significance, it appears that the quicklime slurries were more effective at reducing plasticity.

One of the more interesting behavior patterns found during this study had to do with the effects of these stabilizing slurries on the changes in the compaction characteristics of these soils. The addition of lime is expected to reduce the compacted dry unit weight and increase the necessary optimum water content. These results were observed, but to a different degree for each type of slurry, as shown in Figure 1. It appears that the reduction in compactibility associated with the addition of lime is less when quicklime slurries are used.

The swelling results for stabilized soils indicate greatly reduced tendencies for volume change. The soils stabilized with hydrated lime slurries displayed a mean swell of 0.094 percent with mean changes in water content of 7.27 percent. Those treated with quicklime slurries showed a mean swell of 0.044 percent and a mean water content change of 5.92 percent. The mean water content after swell was some 7 percent higher for the soils treated with the hydrated lime slurries.

The unconfined compression results for stabilized soils

TABLE 3 STABILIZED PROPERTIES: PLASTICITY INDEX

	Hydrated Lime	Quicklime
Percent Lime	P.I. (%)	P.I. (%)
LMO - 2	11.4	11.9
LMO	5.6	5.6
LMO + 2	8.5	8.4
Cure Time	P.I. (%)	P.I. (%)
1 Hour	10.8	7.9
6 Hours	6.9	6.9
12 Hours	6.7	8.0
24 Hours	7.3	6.5
36 Hours	6.0	6.8
48 Hours	5.1	4.3

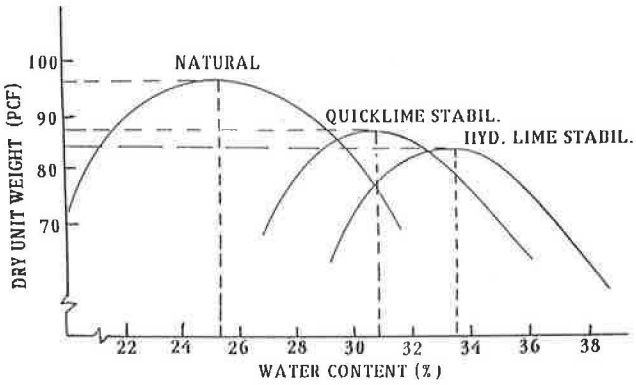

FIGURE 1 Typical compaction test results.

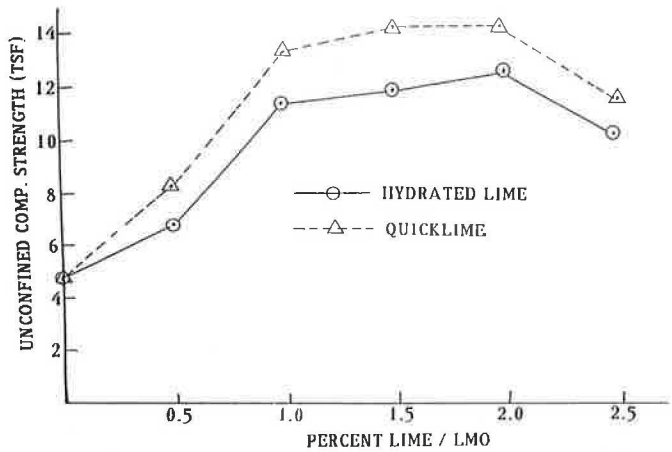

FIGURE 2 Strength comparisons.

showed dramatic increases in strength when the specimens were allowed to cure for 28 days. Both the water content after cure and the dry unit weight after cure were observed to decrease with increasing lime contents. The strength of the mixtures increased almost threefold as a result of the stabilizing action of the lime used. The mean increase in strength versus the percentage of lime added compared with each LMO is shown in Figure 2. The strength increases are most dramatic as the lime percentage reaches the LMO and continue as the amount of lime approaches two times the LMO. Above these percentages of lime there are dramatic decreases in strength. The largest mean strength gains noted were for soils treated with quicklime slurries that provide percentages of lime equal to two times the LMO. As the mean strength increased, the mean strain at failure decreased from 7.2 percent for the natural soils to 1.6 percent for the stabilized soils. This value of twice the LMO may be classed as the lime stabilization optimum (LSO) for these soils.

Soil pH values measured using the supernatants extracted from saturated samples showed little increase of mean values during the first 48 hr of mellowing when the soils were treated with percentages of lime equal to the LMO. Eventually, the mean pH of stabilized soil was found to reach 11.48. No further increases were expected to occur.

Determination of pore-water cations for these soils after stabilization revealed that there were significant increases only in calcium concentrations. The resulting mean levels of calcium in the stabilized soils are shown in Table 4. Increases were noted after just 1 hr of mellowing and continued to increase through the first 12 hr after lime application. It appears that the hydrated lime slurries caused larger increases of pore-water calcium concentrations than quicklime slurries did. On average, this amounted to a 26-fold increase over the natural mean when the percentage of lime added was the LMO.

Changes in the cation concentrations in the exchange complexes of the soils involved both calcium and magnesium. The changes in magnesium concentrations occurred during the first hour of mellowing, including a 56-fold increase for those soils treated with quicklime slurries, and a 71-fold increase occurred in soils stabilized with hydrated lime slurries. These increases are believed due to magnesium impurities in the lime. On the other hand, mean calcium concentrations increased by much greater amounts, as indicated in Table 5. The soils treated with hydrated lime had increases from the natural mean of 12.47 to 189.9 meq/100 g, whereas the concentrations in the quicklime-stabilized soils reached a mean value of 215.8 meq/100 g. These increments occurred when the percentages of lime were at the LMO, and they leveled off at these amounts within the first 6 hr of mellowing. When the lime percentages increased to two times the LMO or to the LSO

TABLE 4 STABILIZED PROPERTIES: CALCIUM IN SOIL

	Hydrated Lime		Quicklime	
Cure (Hrs)	Pore Water (meq/L)	Exch. Complex (meq/100g)	Pore Water (meq/L)	Exch. Complex (meq/100g)
1	20.8	183.6	26.8	189.1
6	34.9	189.9	30.6	215.8
12	43.5	179.7	37.7	204.6
24	41.4	196.1	35.7	204.0
36	52.1	182.4	38.7	194.1
48	42.3	200.6	39.2	203.3

TABLE 5 STABILIZED PROPERTIES: CALCIUM IN EXCHANGE COMPLEX

	Hydrated Lime		Quicklime	
Percent Lime	24 Hr Cure	28 Day Cure	24 Hr Cure	28 Day Cure
0.5 LMO	58.2	78.9	78.2	102.4
1.0 LMO	70.3	99.2	63.7	100.7
1.5 LMO	60.3	119.8	61.3	119.5
2.0 LMO	84.4	131.2	87.9	206.8
2.5 LMO	80.4	128.7	83.3	153.8

NOTE: Data are in milliequivalents per 100 g.

and 24 hr of mellowing was used, the maximum increases in calcium concentration in the exchange complexes were observed. There may likely be some tie between calcium in the exchange complex and strength gain, because these both occur at the LSO.

The data from measurements of the cation exchange capacity (CEC) of stabilized soils revealed three changes. For soils treated with lime percentages equal to the LMO and allowed to mellow 24 hr, there was a dramatic increase in CEC, and this effect was slightly more pronounced for soils stabilized with hydrated lime slurry. This trend was reversed when specimens compacted and cured for 28 days were tested. Finally, a definite decrease in CEC was measured for soils treated with percentages of lime more than two times the LMO.

The properties measured after each type of lime treatment must be compared with those determined for the natural soils in order to determine the actual meaning of the property changes achieved.

STATISTICAL ANALYSES

All experimental data were utilized during statistical analyses of comparison for each population mean difference at various confidence intervals. Hypothesis testing was used to determine the truth or falsehood of each null hypothesis. Student's *t*-statistic was used to investigate the population mean and the mean difference. The 95 percent confidence interval and results of analyses for this level of consideration are shown in Table 6. The following is a summary of the findings for all statistical analyses:

1. Even at a low 75 percent confidence level, no reduction in plasticity index can be proved as a result of using one stabilizer rather than the other.
2. At the 80 percent confidence level, quicklime slurries were found to cause lower swell potential than hydrated lime slurries.
3. At the 90 percent confidence level, quicklime slurries

TABLE 6 RESULTS OF PAIRED EXPERIMENT: *t*-STATISTICS

	Hydrated Lime Treated Values - Quicklime Treated Values			
Property	Mean of Diff.	Std. Dev.	95% Confidence Interval	H_o: U=0
LMO	1.00	0.26	0.48 to 1.50	Reject
PI (%)	0.0	0.88	-1.72 to 1.82	Yes
Max. Dry Unit Weight (pcf)	-3.5	0.68	-4.88 to -2.12	Reject
% Swell	0.05	0.05	-0.05 to 0.15	Yes
Unconfined Str. (tsf)	-1.98	1.20	-4.39 to 0.43	Yes
pH	0.10	0.09	-0.07 to 0.27	Yes
Pore Water Ca (meq/L)	5.68	7.53	-9.49 to 20.85	Yes
Exch. Comp. Ca (meq/100g)	-9.08	11.53	-32.31 to 14.15	Yes
CEC - Ca (meq/100g)	99.67	159.00	-220.71 to 420.05	Yes

were found to produce more strength gain than hydrated lime slurries.

4. At the 80 percent confidence level, after 48 hr of mellowing, hydrated lime slurries were determined to cause higher soil pH than quicklime slurries.

5. At the 75 percent confidence level, within 48 hr of mellowing, hydrated lime slurries were found to provide more calcium cations in the pore water than quicklime slurries.

6. At the 75 percent confidence level, quicklime slurries were determined to provide more calcium cations to the exchange complex than hydrated lime slurries.

7. Even at this low 75 percent confidence level, no difference was found in how these stabilizers affected the CEC of these soils.

8. At the 95 percent confidence level, quicklime slurries are less detrimental to compactibility than hydrated lime slurries.

Space does not permit the listing of all statistical comparisons and results in this paper. Those interested in all the data and the statistical information should contact the authors.

CONCLUSIONS

The objective of this research was the comparison of the stabilizing effects of quicklime and hydrated lime slurries. Statistical analyses were used to test the significance of the differences in the stabilizing effects of these slurries as measured by changes in physical and chemical properties. When the conclusions below are considered, it should be taken into account that 1 percent less quicklime was used for all applications as compared with hydrated lime.

1. The LMOs determined with the Eades and Grim pH test were valid for these lime-reactive, highly active clay soils.

2. Quicklime slurries caused a more reduced plasticity and linear shrinkage, especially after the first hour of mellowing.

3. Quicklime slurries caused these soils to have less reduction in compactibility, as well as less need for water in the curing of stabilized specimens.

4. Quicklime slurries provided more strength gain in these soils, and the maximum strength gain occurred at lime percentages equal to twice the LMO.

5. When a maximum amount of calcium cations is in the exchange complex, there is an accompanying maximum strength gain.

6. Hydrated lime slurries provide more calcium in the pore water, and quicklime slurries provide more calcium to the exchange complex.

7. As short-term effects, quicklime slurries provide a larger reduction in swelling potential, more strength gain, and higher concentrations of calcium in clay soil exchange complexes.

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