Effects of Pulverization on the Strength and Durability of Highly Active Clay Soils Stabilized with Lime and Portland Cement

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This paper presents the results of a laboratory investigation exploring the effects of varying degrees of pulverization, from laboratory-quality gradations to field gradations, on the strength and durability of highly plastic clay soils stabilized with lime and portland cement. Background information is presented on the mechanisms of stabilization and on previously reported studies of other materials. A 6-yd^3 sample was used to provide 198 large specimens, which were tested in unconfined compression and wet-dry tests. Considerable differences were found in the strength of a highly active clay soil, depending on the gradations used to make specimens. Significant differences were found in the durabilities of specimens, depending on the stabilizer and the gradations used. Lime appears to be a more effective stabilizer for durability and portland cement more effective for strength, provided the gradation is fine enough. Recommendations, subject to further research, include longer curing times and the use of field gradations for all mix designs.

One of the additives frequently used to stabilize heavy clay soils successfully has been high-calcium lime. There has also been some successful experimentation in the laboratory with portland cement as a stabilizer. However, the majority of this research has been performed on finely pulverized samples, usually having 100 percent passing the No. 4 sieve. The main drawback with using this type of gradation is that it does not accurately reflect the kinds of pulverization specified in the field. The differences between laboratory and field gradations are great enough that the stabilized materials in each case have vastly different properties. These differences are most critical for highly active clay soils, especially when they are exposed to cycles of wetting and drying.

The purpose of the research reported here was to investigate and evaluate the effect of soil preparation (pulverization) on the strength and durability of highly plastic clay soils that have been stabilized with lime or portland cement. This was done using materials that were pulverized according to field and laboratory gradations, then compacted and subjected to strength and durability testing.

BACKGROUND

The objective of soil stabilization by the addition of lime or portland cement is to modify the physicochemical properties of fine-grained soils to improve strength and durability. Much has been reported about how these agents affect soil physical and chemical properties, yet there has been little investigation of the effects of differences in pulverization.

The responses of soil to treatment with hydrated high-calcium lime are complex and often dramatic (*1*, *2*). With the addition of lime to a fine-grained soil, several reactions occur. Cation exchange and flocculation-agglomeration reactions occur rapidly and produce immediate changes in soil plasticity and workability, and the immediate incurred strength and load deformation properties. Pozzolanic time-dependent reactions may occur, depending on the soil being stabilized. These pozzolanic reactions result in the formation of various cementing materials that increase mixture strength and durability. The exact products formed during stabilization with lime will vary depending upon the type of clay and the reaction environment, especially temperature and pH.

The stabilization of clay soils with portland cement is a two-stage process. The hydrolysis and hydration of cement, with the resulting soil hardening, are regarded as the primary processes. The cement particles bind the adjacent soil grains together to form a more-or-less continuous skeleton of hard material enclosing a matrix of unaltered soil (*3*). The clay itself participates in the secondary process by combining with the calcium ions produced by the hydration of the cement and forming new cementitious materials. Although minimal, the calcium generated during cement hydration reacts with the clay in much the same manner as if added as the stabilizing agent. The amounts of calcium hydroxide available decrease as the cement-soil reactions progress. The hardening of the soil-and-cement combination is primarily due to the hydration of cement, but it is also the result of physicochemical reactions between the soil and cement particles (*3*).

The inclusion of large clay lumps in stabilized soil has long been considered detrimental to the stabilization process and to the corresponding strengths and durabilities. Granular soils and light clays have been successfully pulverized in the field with the aid of lime and cement stabilizers. However, pulverizing heavy, highly plastic soils to meet the same specifications is difficult, and often the specifications cannot be met. Furthermore, there is very little information available or research reported concerning the durability of coarsely pulverized stabilized soils.

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Portland cement and lime stabilizers react differently to soils with gradations that are coarser than the typical laboratory gradation (*4–9*). Construction specifications normally stipulate different gradations for portland-cement- and lime-stabilized soils, with cement-stabilized soils having a finer gradation. For example, the U.S. Department of Transportation (DOT) recommends the same degree of pulverization as that used by the Texas Department of Highways and Public Transportation: 100 percent passing the 1-in. sieve and a minimum of 80 percent passing the No. 4 sieve (*7*). In contrast, the Portland Cement Association recommends that the minimum passing a 1¾-in. sieve be 100 percent and that the minimum passing a ¾-in. sieve be 75 percent.

Felt (*5*) studied the factors influencing the physical properties of soil and cement mixtures; he used many different types of soil, from nonplastic fine-grained silts to highly plastic clays. He prepared specimens of stabilized soils that had different percentages of lumps larger than a No. 4 sieve. In some specimens these lumps were wet and in some they were dry. As the specimens were subjected to wet-dry and freeze-thaw tests the ones with dry lumps were destroyed upon contact with water. Felt concluded that the quality of the mixture was adversely affected if less than 80 percent of the clay soil was pulverized to pass a No. 4 sieve and the large lumps were dry of optimum water content.

In another study, Grimer and Ross (*6*) investigated the effects of the degree of pulverization on the quality of heavy clay soils stabilized with portland cement. Specimens were prepared using aggregations of continuous grading (retained on British Standard No. 14 sieve to retained on B.S. No. 200 sieve) and various proportions of single-sized 3/16-in. extruded aggregations. All specimens were cured in wax for 7 days and then immersed in water for 7 or 28 days before being tested in unconfined compression. Grimer and Ross found that the strength of the stabilized soils increased with decreases in aggregation size. In addition, the ratio of the strength after immersion to that after cure decreased with an increase in the percentage of the large aggregations. The considerable increase in strength found with increased pulverization suggested that pulverization, much more than mixing, was the main factor governing the strength of portland cement clay mixtures.

In a recent study, Kennedy et al.(*7*) investigated the effects of pulverization on portland-cement-treated, highly plastic clays. They compared the unconfined compressive strengths in both the wet and dry conditions of both unpulverized and well-pulverized samples. The unpulverized soils had gradations with 85 percent passing the No. 4 (U.S. series) sieve, and 15 percent passing a 1½-in. sieve and retained on a ¾-in. sieve. The well-pulverized samples had gradations with 100 percent passing the No. 4 sieve. The strengths of the mixtures of unpulverized clay and portland cement were substantially lower than those of the comparable well-pulverized materials when tested in a dry condition, a situation that was more pronounced for those in the wet condition. The study concluded that for portland-cement-modified, highly plastic clay soils, even small amounts of unpulverized materials are detrimental to the overall strength of the mixture.

Through the years efforts have been made by those who thought that lime migration into soil clods or aggregates would eventually stabilize these soils to make construction more economical by reducing the required pulverization of lime-stabilized soils. These beliefs were often been supported by field observations.

During a study by Davidson et al. (*8*), the diffusion phenomena and the effect of coarse gradations were investigated on combinations of gradations containing from 20 to 100 percent lumps passing the 1-in. sieve in a matrix of soil passing the No. 4 sieve and appropriate amounts of lime. The specimens made were cured from 7 to 270 days and tested in unconfined compression. The results of these tests showed that the presence of lumps in compacted soil-lime mixtures decreased the strength of the mixture, but that after about 150 days of curing time the strengths of all mixtures were approximately equal. This change of influence by the lumps was believed to have been caused by lime movement, which occurred in sufficient quantities to cause a pozzolanic reaction within the mixture.

Additional support for the theory of lime migration was found by Stocker (*9*). In his study specimens were prepared using field gradations. Three percent and 15 percent lime was added, and the compacted samples were cured for up to 122 days. The specimens were then alternately wetted and dried under suction while their volume changes were observed. Specimens cured 122 days showed no sign of distress, and Stocker concluded that lime migrates into the soil lumps and stabilizes them.

The majority of studies on lime and portland cement as stabilizers for plastic soils have regarded strength as the primary quality-control check. Few have investigated the relationships between strength and durability and degree of pulverization. The intent of the study reported here was to explore these relationships.

PRELIMINARY TESTING PROGRAM

The program of research reported here contained initial testing to evaluate the materials used and to determine the optimal percentages of the agents to use. Following these activities, gradations for further testing were prepared, and the compaction characteristics of both natural and stabilized materials were determined.

The soil profile for the test sample was that of soils weathered from the Taylor geologic formation at an industrial park just west of Greenville, Texas. The suitability of these soils was initially determined using Shelby tube samples taken from two 25-ft-deep borings. After the soil plasticity indexes were found to be at least 60 percent, approximately 6 yd^3 of soil was excavated from the lower A and upper B horizons at depths of 1.5 and 7.0 ft, respectively, using a front-end loader; loaded on an 8-yd^3 truck; and transported to the laboratory. These materials were randomly sampled and tested to ensure that their plasticity indexes were equal to or greater than 60. Typical values of the Atterberg limits of these materials, which are classified as inorganic clays of high plasticity, are shown in Table 1. These tests were performed according to ASTM methods on soils that were wet-processed and passed the No. 40 sieve.

X-ray diffraction tests were performed on samples of the soil that had passed the No. 40 sieve. The primary constituents were as follows:

Mineral	Percent
Quartz	50
Montmorillonite	40
Calcite	10
Feldspar	<1
Illite	<1
Kaolinite	<1

Samples that were utilized for the Eades and Grimm lime-soil pH test, the lime percentage-PI series test, and the portland cement percentage-PI series test were processed as for Atterberg limit testing. These procedures were performed in accordance with ASTM methods. The optimum lime content based on the lime-soil pH series was selected from the curve at a pH of 12.4, which occurred at 10 percent lime content. The results of the tests in which plasticity indexes were determined for various lime additive rates indicated that the maximum reduction in the plasticity index occurred at a lime content of 10 percent, when the plasticity index was 16.8. The same type of testing, when performed on portland-cement-treated soils, resulted in an optimum portland cement additive rate of 12 percent, which corresponds to a maximum reduction in the plasticity index to 12. It was clearly evident that this soil was both lime and portland cement reactive, so the testing could proceed.

Once the suitability of the soil had been determined, the clay was air dried and sieved by hand and with a large mechanical shaker to pass the sieves chosen, forming coarse, medium, and fine gradations as follows:

Coarse:
Minimum passing 1 ¾-in. sieve = 100 percent
Minimum passing No. 4 sieve = 60 percent

Medium:
Minimum passing 1-in. sieve = 100 percent
Minimum passing No. 4 sieve = 80 percent

Fine:
Amount passing No. 4 sieve = 100 percent

TABLE 1 ATTERBERG LIMITS TEST RESULTS

Sample No.	Liquid Limit	Plastic Limit	Plastic Index
1	82	17	65
2	94	22	72
3	86	22	64
1	96	19	77
2	91	23	68
3	99	31	68

It was necessary to prepare these gradations at moisture levels slightly lower than the soil's plastic limit to prevent coalescence of individual aggregations. All the graded soils were placed in metal barrels and sealed to retard or prevent moisture loss.

The relationships between moisture and unit weight were determined for all gradations of both raw and stabilized soil. To enable the use of these coarser gradations and the highly plastic soils, a modified compaction method was chosen based on the TEX-113E testing specification. This specification was used to best represent the expected field situation, especially to prevent overcompaction. To achieve the 6,912-ft-lb/ft^3 energy level, a 6-in.-diameter mold 4 in. high was used with a 5.5-lb hammer falling 12 in. Three layers and 30 drops of the hammer per layer were used.

Moisture-unit weight relationships were determined for portland-cement-treated clay mixtures containing the optimum amount of cement as indicated by the PI reduction method. The proper amount of cement was mixed with the soil, water was added in varying amounts, and the soil mixture was immediately compacted. Similarly, soil-lime mixtures were prepared using the optimum lime contents determined from both the PI reduction and pH test methods. These mixtures were allowed to cure in sealed plastic bags for 24 hr before compaction testing. The optimum moisture contents and maximum dry unit weights determined from these compaction tests are shown in Table 2. These results seem to indicate that the addition of lime had little effect on the compaction characteristics of this soil and that portland cement acted as an apparent compaction aid, providing an increased maximum dry unit weight and lower optimum water content.

SPECIALIZED TESTING PROGRAM

The major testing program included a series of unconfined compressive tests and wet-dry tests on compacted mixtures of lime- and portland-cement-treated soil. Strength and durability testing was performed on a total of 198 cylinders of soil (6 by 12 in. each) compacted using six layers and the compactive effort explained earlier. Three specimens were prepared for each gradation and type and amount of stabilizer, which were cured for various periods in a moist

TABLE 2 RESULTS OF TESTS ON MOISTURE AND UNIT WEIGHT

Stablizer (%)	Gradation	Optimum Dry Unit Weight (lb/ft^3)	Moisture Content (%)
Raw	Coarse	79.4	34.0
Raw	Medium	76.9	33.6
Raw	Fine	75.4	35.0
7 (cement)	Coarse	86.5	29.5
12 (cement)	Medium	89.1	26.0
12 (cement)	Fine	87.8	28.6
10 (lime)	Coarse	79.0	32.0
10 (lime)	Medium	78.0	34.0
10 (lime)	Fine	75.3	36.5

environment before unconfined compressive testing. The levels of stabilizer used included the optimum and 3 percent above and below the optimum.

Two specimens were made for each gradation and type and amount of stabilizer for the wet-dry testing, as follows:

1. At the end of the cure period, the specimens were submerged in tap water at room temperature for 5 hr.
2. The specimens were removed from the water and allowed to drain.
3. Each specimen was weighed to the nearest 0.1 lb and measured to the nearest 1/16 in.
4. Each specimen was then placed in an oven set at 160°F for 42 hr and removed.
5. The specimens were again weighed and measured.
6. The previous five steps constituted one cycle of wet-dry testing.

All materials used for these tests were prepared using the same procedures as those for the compaction tests and at optimum conditions. The amounts of lime or portland cement stabilizer and the curing methods used depended on the testing situation, as will be explained later.

The procedure for the unconfined compressive tests was the same for all specimens. After they had cured for the specified length of time, which was 0, 7, or 28 days, in a wet concrete-curing room, the specimens were removed, weighed, and measured. They were then tested to failure at a constant strain rate of 0.1 in./min. The ultimate load was recorded for each of the specimens, and their moisture content was found after failure. The test results are shown in Figures 1–3. For each case of stabilizer and cure period the resulting average unconfined strength is plotted versus the percent stabilizer. On each graph a separate curve is drawn according to the gradation, which is plotted to best represent the variations in strength.

Figure 1 and the top part of Figure 3 show how lime

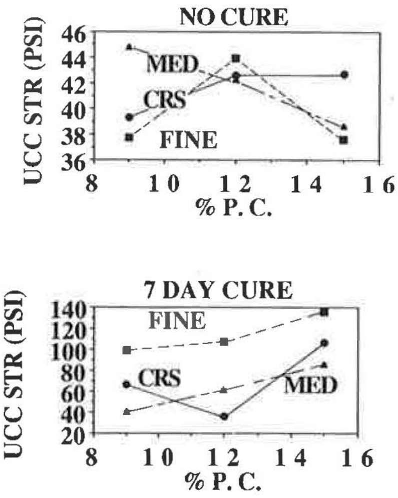

FIGURE 2 Unconfined strength of portland-cement-treated soils: 0- and 7-day cures.

treatment affected the strength for each length of curing time. Figure 2 and the lower part of Figure 3 show these same features for the portland-cement-treated soils. The results for unconfined strength following a 28-day curing period are shown for both stabilizers in Figure 3 to facilitate comparisons.

If one considers only the effects of changes in gradation, the resulting strengths measured depended greatly on the curing period involved. For both stabilizers and for immediate testing of specimens without curing, the amount of pulverization appears to have had little effect on the strength developed. After a 7-day curing period the effects of degree of pulverization on the resulting strength were mixed. The lime-treated specimens that were made from more finely pulverized materials displayed more strength. This trend was not as clearly evident for the portland-cement-treated specimens, although the most finely pulverized materials provided the specimens with highest strengths. For those

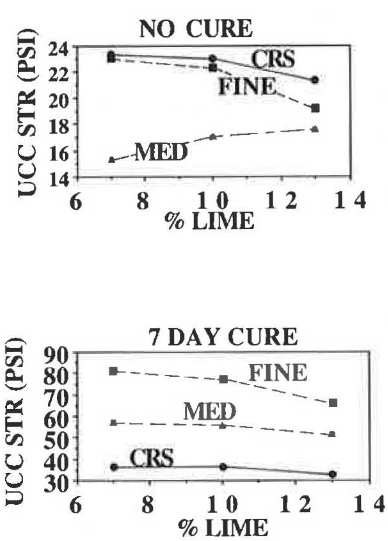

FIGURE 1 Unconfined strength of lime-treated soils: 0- and 7-day cures.

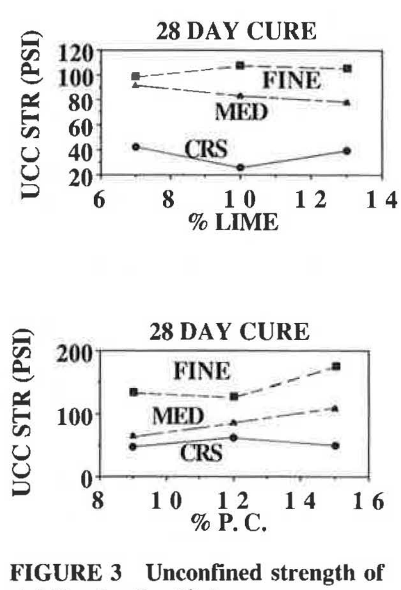

FIGURE 3 Unconfined strength of stabilized soils: 28-day cure.

specimens cured for 28 days before strength testing, strengths were very dependent on the degree of pulverization of the material before treatment and compaction. Those specimens that had been made with the most finely pulverized soil had significantly more strength than those made from the medium and especially the coarse gradation materials. The benefits of finer pulverizations are clearly evident in Figures 1–3.

Consideration of how the measured unconfined strengths of specimens changed with added amounts of the stabilizers revealed the effects of curing. Without curing, specimens stabilized with both agents had little or mixed changes of strength as the percent of the stabilizer increased. The lime-treated specimens, which had been cured for 7 days, displayed generally decreasing strengths as the percent of lime was increased. This trend was different when the lime-treated specimens were cured for 28 days. In this case the measured strengths increased as the percent of lime was increased to the optimum but remained unchanged as the lime content was increased further. The portland-cement-treated specimens, when cured for either 7 or 28 days, exhibited increases of strength as the percent of cement was increased. The largest strength gains noted were for portland-cement-treated specimens with 15 percent cement cured for 28 days.

Overall, the cement-stabilized specimens displayed higher strength than the lime-stabilized specimens, with differences ranging between 10 and 70 psi. This trend became more evident as the curing times and the percent of stabilizer increased. The most significant increases in unconfined strengths were noted in specimens made of soils stabilized by both agents as the gradations of materials used to make the specimens became finer.

Specimens to be tested in the wet-dry procedure were first cured for 7 days in the wet room. These specimens were tested according to a modified version of ASTM D 559-82. The specifics of the procedure were given at the beginning of this section. This procedure was repeated at least 12 times, or until the specimens failed, either during the wetting cycle or the drying cycle. All specimens that completed these wet-dry cycles were tested in unconfined compression.

The results of wet-dry testing revealed much about the durability of compacted stabilized materials with various gradations. The portland-cement-treated soils did not appear to perform well during this testing. After the first cycle of wet-dry testing on the cement-stabilized soils with coarse gradation, all the specimens slaked heavily. This occurred when they were stabilized at optimum, below optimum, or above optimum percent cement and during the 5-hr soaking period. At the end of the 42-hr drying period all cement-stabilized specimens crumbled as an attempt was made to remove them from the oven.

After the first 5-hr soaking period for the soil specimens prepared with medium gradation and cement treatment, those with below-optimum percentages of cement fell apart and were discarded. The remaining specimens in this category crumbled after the prescribed period of drying.

The cement-stabilized specimens made with the fine gradation soil completed one full cycle of the wet-dry test. However, when removed from the oven, all of those with 9 percent, one with 12 percent, and one with 15 percent cement crumbled. The remaining two specimens, one with 12 percent and the other with 15 percent cement, slaked to total failure after 5 min of the second soaking cycle.

Specimens stabilized with lime were much better able to endure the wet-dry testing cycles. The benefit derived from finer gradations was very apparent during this part of the testing also. All lime-stabilized specimens made with coarse gradation soil completed two cycles of the wet-dry tests. After the third soaking period, however, these samples had slaked so heavily that they crumbled when removed from the soaking tank.

The lime-stabilized specimens compacted using medium gradation soil varied in their durability to the wet-dry testing. The specimens with 7 percent lime crumbled after the fourth cycle. The samples stabilized with optimum lime contents (10 percent) completed seven full cycles of wetting and drying, and those with above-optimum percentages of lime (13 percent) completed the full 12 cycles of the test. However, after the 10th cycle, there was only one specimen with 13 percent lime to continue testing. At the end of the 12 full cycles, the remaining specimen was not considered testable in unconfined compression because it was heavily slaked.

The most durable of the lime-stabilized specimens were those made with the fine gradation. Those stabilized with below-optimum percentages of lime completed seven cycles of the wet-dry tests before disintegration. The specimens with optimum and above-optimum lime contents successfully completed all 12 cycles of the wet-dry tests. One specimen with 10 percent and one with 13 percent lime were accidentally broken before strength testing. Two viable specimens remained, one with 10 and one with 13 percent lime. They were soaked again and tested for their unconfined compressive strength. The specimen with the optimum percent of lime had a strength of 14.1 psi and the one with above-optimum lime had a strength of 33.1 psi.

The weight loss for all specimens was fairly consistent. This varied from approximately 0.5 to 1.0 lb of material per cycle lost in soaking until the specimens slaked to failure. Figure 4 shows how this weight loss occurred for a fine-gradation specimen stabilized with the optimum percent of lime.

DISCUSSION OF RESULTS

When all the results described above are considered, it becomes clear that the way in which a stabilizing agent works with and within the soil influences the way in which the stabilized soil will be affected by differences in the amount of pulverization before treatment. The results achieved for very finely pulverized samples used for the Atterberg limits and reactivity testing seem to indicate that these stabilizers are roughly similar in their stabilizing effects. Indeed, the samples treated with portland cement appeared

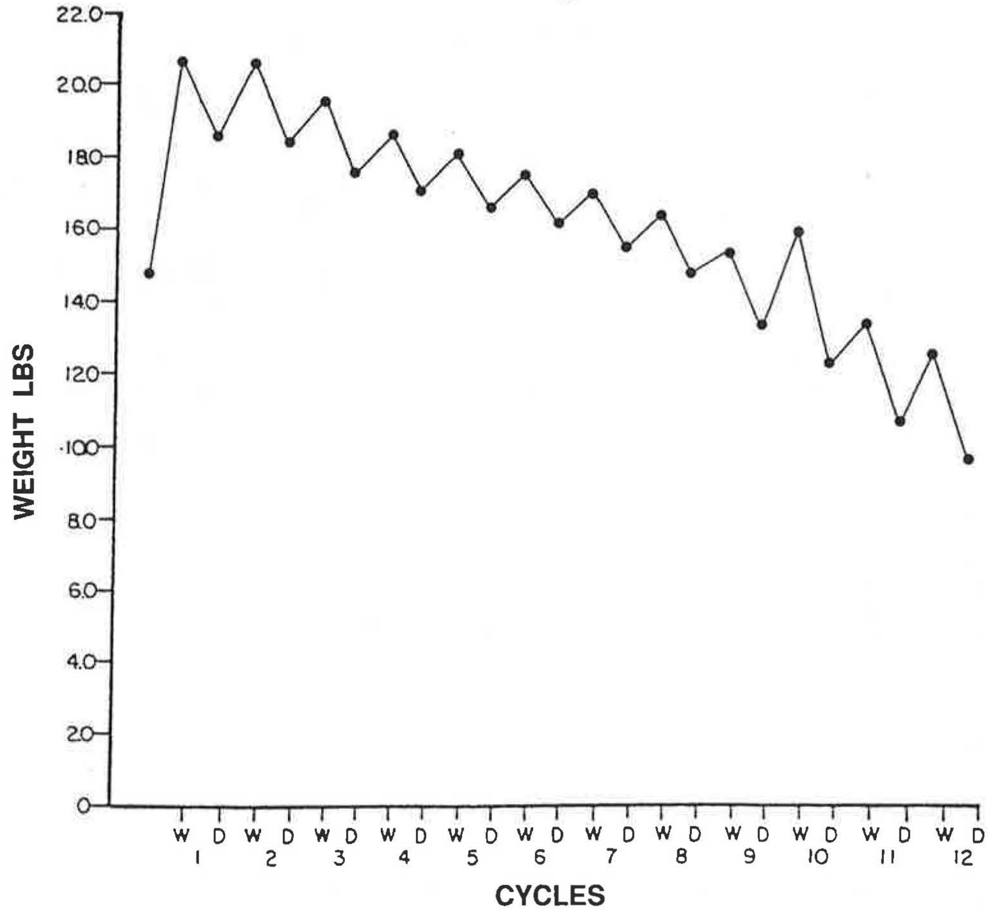

FIGURE 4 Weight variation per wet-dry cycle, 10 percent lime, fine gradation.

to be more stable as far as their PIs would indicate. However, these results did not indicate clearly what would occur during later testing.

The effects of the coarse gradation on the stabilized soil were caused primarily by the presence of large clods or aggregations of highly active clay particles that were left relatively untreated. After tests had been completed, the destroyed specimens were inspected and the following observations were made.

1. The specimens stabilized by lime had large aggregations in which the outer layers reacted with lime to form a coating that provided a degree of waterproofing but little strength. This may be the reason for the small strength gain in these samples. However, even this small amount of lime migration provided definite protection during wetting and drying cycles.

2. The specimens treated with portland cement contained large aggregations held together by the cement coatings but not fully coated to a level where they were waterproof and resistant to conditions leading to shrinking and swelling of the clods. This condition led to little strength gains for these soils and ineffective waterproofing. The strength displayed by all coarsely graded specimens was most likely dependent only on the shear strength of the clay clods or aggregations.

As the gradations became finer, stabilizing effects increased and the materials gained strength and durability. The maximum stabilizing effects occurred for the finest gradation. Those specimens stabilized with portland cement had higher dry unit weights and significant strength gains from about 39 to 176 psi. Better compaction for the cement-treated specimens may have occurred because of less flocculation than occurred in the lime-treated soils and some lubricating effects. The cementitious effects of cement hydration in forming a skeleton of binding material were also evident. On the other hand, it is evident that the waterproofing capacity of portland cement is questionable, especially where it affects the shrink-swell phenomena in clay particle aggregations.

The lime-stabilized materials displayed the kind of waterproofing needed for durability against wetting and drying. However, these materials did not display as much strength gain as those stabilized with cement. It is very possible that a good part of the difference in strength gain is because of the lower dry unit weights in the lime-stabilized soils. When the strength gains realized are nor-

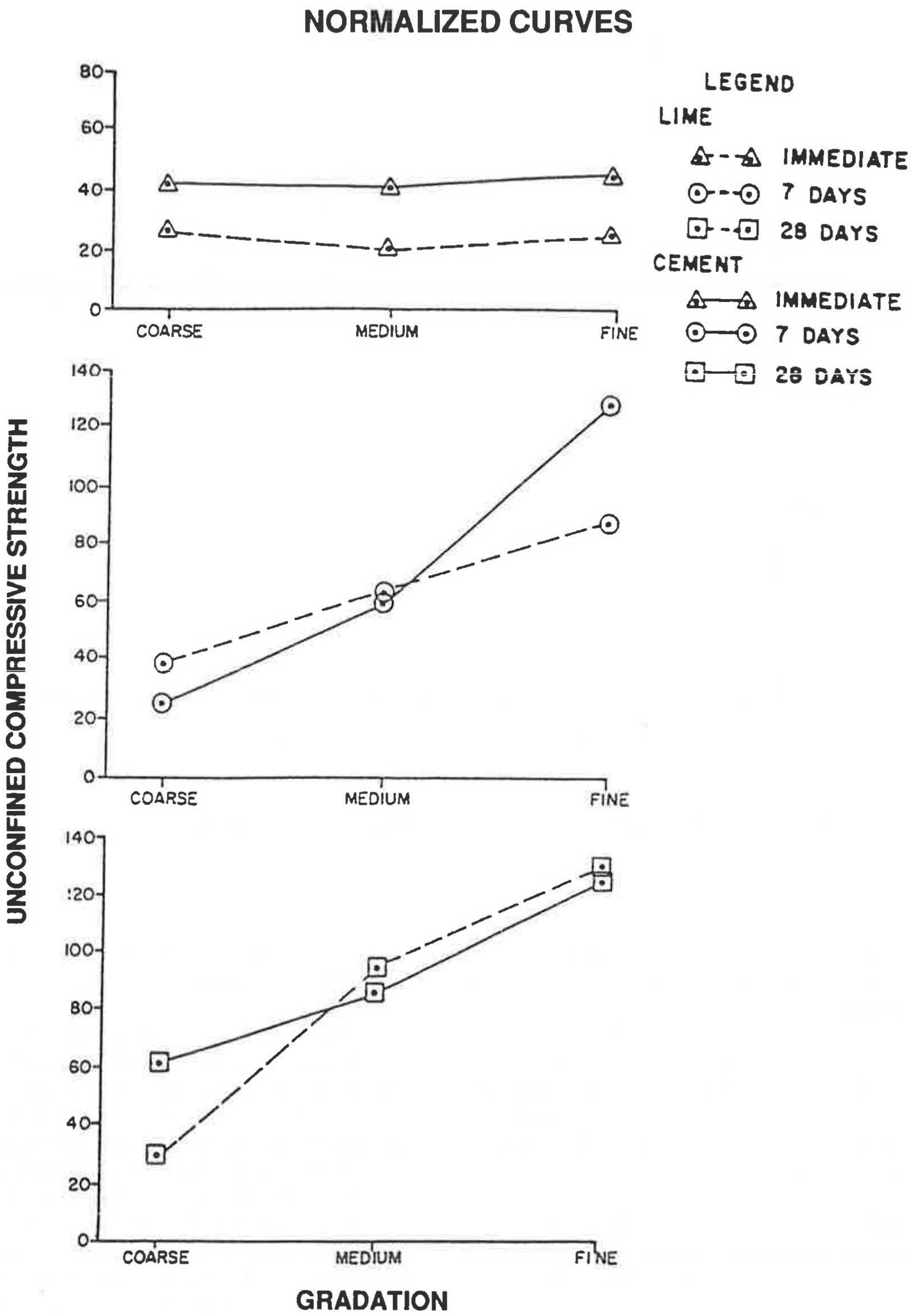

FIGURE 5 Strength versus gradation, 10 percent lime, 12 percent cement.

malized by differences in dry unit weights, the type of curves shown in Figure 5 results. It is believed that the coating and migrating effects of the lime lead to greater overall stability for these highly active clays. As the gradation approached that used in the initial laboratory testing, the strength gain effects of these stabilizers became similar.

It became evident that the differences in behavior and response to different gradations can be tied to the difference in stabilization effects of the lime and portland cement. The physicochemical action of lime provides more stability for these materials than the primarily mechanical (e.g., cementing) action of portland cement. It is interesting to note that after 12 cycles of wetting and drying and one of saturation, specimens made with the fine gradation had significantly higher unconfined compressive strengths than the untreated soils.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this investigation was to determine the effect of pulverization on the strength and durability of highly plastic clays stabilized with lime and portland cement. The objective was reached through an extensive program of testing. The conclusions are as shown below.

1. With regard to long-term durability, lime stabilization produced a better product for all gradations tested.
2. Portland cement produced a stabilized material that had better compaction characteristics and better strength, provided the gradation was fine enough.
3. Lime stabilization of coarsely graded materials required longer curing time than did fine-graded materials to reach attainable strength and durability.
4. Portland cement is not an effective stabilizer for highly plastic soils under field gradation situations. The strengths vary and are probably very dependent on the shear strength of the clay.

The following recommendations, which should be supported by further research, are a consequence of this investigation.

1. Laboratory tests for stabilizing soils should be conducted using field gradations.
2. When wet-dry tests are conducted on 6- by 12-in. specimens, the soaking and drying times should be extended to ensure complete saturation and drying.
3. Curing periods should be extended to obtain more realistic strength values for specimens made with coarser gradations.

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Publication of this paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization.