

anything approaching this rating beyond 3 or 4 years.

## CONCLUSIONS

It appears that much of the objectionable differentials in the Pierre shale that caused road-surface roughness in the past have been alleviated.

1. It is possible to achieve relatively good density and moisture control by designating the number of roller passes and making frequent moisture tests.

2. The control of special undercutting and soil selection can be managed by the use of specially trained crews assigned to the work.

3. Extreme warping and heaving of the subgrade over narrow fault lines appears to be reduced by deep undercutting of expansive shale and replacement of it with soil having a lower liquid limit.

4. At this time, the ridability of the surfacing is extremely good and better than on similar highways constructed through Pierre shale without deep undercutting and rigid control of compaction efforts and moisture application.

5. The use of lime treatment in the upper 0.15 m (6 in) of the subgrade and a lime-treated base is effective in preserving the moisture content of the subgrade over an extended period of time, which contributes to improved ridability.

6. At the present time, the maintenance costs for the highways listed in this report are very low; however, long-range maintenance costs are time dependent.

Although the methods discussed in this report will not be completely effective in correcting the differentials usually encountered in Pierre shale, the indications, after 5 to 8 years, are that the ridability will generally be much better over a longer period of time at lower maintenance costs.

## REFERENCES

1. Mineral and Water Resources of South Dakota. U.S. Geological Survey, Committee Report to 88th Congress, 2nd Session, 1964, pp. 17-28.
2. Treatment of Expansive Soils for I-90 in South Dakota. Woodward-Clyde-Shemond and Associates, Denver, May 1965.
3. Review and Comments on Woodward-Clyde Report. H. Allen, Bethesda, Md., June 1965.
4. Moisture and Density Control on I-90 Projects I-90-(34) to I-90-(55) (1969-1974). R. Wold, Pierre, S.D., Resumé Repts., 1969-1974.

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# Factors Affecting Unconfined Compressive Strength of Salt-Lime-Treated Clay

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Statistical procedures were used to analyze the effects of salt content, lime content, curing time, curing temperature, molding-water content, and soil type on the unconfined compressive strength of compacted specimens. A modified central-composite, second-order, rotatable experiment design and analysis of variance techniques were used to determine the significant main effects, curvilinear effects, and linear interactions at an alpha level of 1 percent. The following effects and interactions were significant at an alpha level of 1 percent: (a) main effects—salt content, lime content, curing temperature, curing time, molding-water content, and soil type and (b) interactions—lime content and salt content, lime content and curing temperature, lime content and molding-water content, salt content and curing temperature, curing temperature and molding-water content, curing temperature and soil type, curing time and soil type, and lime content and salt content and curing temperature. An engineering interpretation of each is given. A coded multiple regression model was developed to the estimate unconfined compressive strength in terms of the statistically significant main effects and interactions.

A combination stabilization strategy—the use of salt in conjunction with the lime treatment of clay soil—has been studied to determine whether small amounts of sodium chloride can be used to accelerate the stabilization phase

of the lime-soil treatment process. Previous research by Mateos and Davidson (1) indicated that small amounts of sodium chloride are beneficial to the lime-fly ash treatment of Ottawa sand. The relationship between immersed compressive strength and sodium chloride content was parabolic, with maximum strengths at 7, 28, and 120 d curing times at a sodium chloride content of 1 percent. They also reported that 1 percent sodium chloride in conjunction with either calcitic hydrated lime or dolomitic monohydrate lime and fly ash produced higher compressive strengths than those observed for lime-fly ash-treated dune sand and friable silt without sodium chloride. A 6.1°C (43°F) curing temperature was shown to be detrimental to lime-fly ash-sodium chloride treatment of dune sand.

Thornburn and Mura (2), in a review of the literature of salt stabilization, have summarized several studies that used various inorganic salts with lime and lime-fly ash stabilization. This review did not note any specific reference to the effects of sodium chloride on the lime treatment of clay, although other compounds, such as sodium carbonate, have been used successfully to in-

crease the 28-d strength of lime-treated clay (3).

More recent investigations by Marks and Haliburton (4, 5) and by Drake and Haliburton (6) have been specifically designed to study the effects of sodium chloride on the lime treatment of clay soil and have indicated that there is an optimum percentage of salt beyond which further addition decreases the compressive strength. They also reported that small amounts of salt accelerate formation of the stabilization compounds associated with lime treatment. This acceleration of the formation of the pozzolanic compounds would reduce the relatively long time periods required for the development of the cured strength, which is especially significant in areas with short construction seasons and a limited number of months having sufficiently high soil-curing temperatures.

The object of this study was to develop additional information about the effects of mixture design, construction, and environmental variables, and their interactions on the unconfined compressive strength of sodium chloride-lime-treated clay soil.

## MATERIALS AND SOILS

The sodium chloride used was common, noniodized table salt. The lime used was a commercial grade, hydrated, high-calcium lime, processed to have a maximum particle size of 0.037 mm (no. 400 sieve).

Permian red clay (PRC) is a medium plastic, cohesive soil of marine origin found in central Oklahoma with a distinctive red color produced by iron oxide. The PRC used in this experiment was taken from a depth of approximately 3 m (10 ft) below the ground surface on the Oklahoma State University campus in Stillwater, air-dried, and crushed to finer than 0.42 mm (no. 40 sieve). The mineralogical composition indicated that 50 to 75 percent of the PRC is chlorite, 10 percent is mica, and the remainder is illite and smectite.

The Black Belt soils of Alabama are located in a narrow strip running east to west through the south central portion of the state and are characterized by a high volume-change potential. The Houston clay (HC) used in this experiment was sampled at a depth of 38 to 76 cm (15 to 30 in) in a pasture near Downs, Alabama, air-dried, and crushed finer than 0.42 mm (no. 40 sieve).

Houston clay was created by the decomposition of Selma chalk and marine deposits of the Cretaceous age (7) and is visually identified by its grey-yellow color interspersed with modules of calcareous materials and its high plasticity (8). Smectite constitutes about 65 percent of the clay in the Alabama Houston soils and 30 to 45 percent of the whole soil in the Houston profile. Kaolinite is the second most abundant clay mineral, constituting about 25 percent of the clay fraction. Other clay minerals present are mica, vermiculite, small amounts of quartz, and trace quantities of intergrade chlorite (7). The physical properties of the clays used are given below (0.074 and 0.002 mm = no. 200 and no. 10 sieves respectively).

Property	PRC	HC
Specific gravity	2.75	2.72
Liquid limit, %	49.8	61.2
Plastic limit, %	14.2	19.2
Plasticity index, %	35.6	42.0
Percent finer than 0.074 mm	90	90
Percent finer than 0.002 mm	39	36

## EXPERIMENT DESIGN

A modified five-factor, central-composite, rotatable experiment design was used for both soil types (9). A full factorial was selected within this experiment de-

sign so that all main effects, linear interactions, and quadratic effects could be analyzed. This type of experiment design has been successfully used previously (10). The factors and levels used in the experiment are given below [the lime, salt, and molding-water contents are measured as air-dried weight of soil;  $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$ ].

Factor	Level				
	-2	-1	0	+1	+2
Lime content	0	2.0	4.0	6.0	8.0
Salt content	0	1.0	2.0	3.0	4.0
Molding-water content	10.0	12.5	15.0	17.5	20.0
Curing time, d	—	10	20	30	—
Curing temperature, $^{\circ}\text{C}$	—	4.4	23.9	43.3	—

Before completion of the analysis of variance, the estimates of experimental error obtained from the center points were compared for each soil type to determine whether the variances within the two populations were homogeneous. The two estimates of experimental error indicated homogeneity and, therefore, the analysis of variance was pooled. Thus, soil type was treated as a sixth variable, and its main effect and all linear interactions involving it as a quantitative variable were analyzed.

## SPECIMEN PREPARATION AND TESTING

Lime, salt, and soil were weighed out in separate containers at predetermined levels to minimize the time required for specimen preparation. The compacted specimens were prepared by measuring the proper amount of distilled water; selecting the proper preweighed quantities of salt, lime, and soil and dry mixing them; adding the water; and blending by hand until a uniform appearance was attained. Next, the soil was compacted by using a Harvard miniature compaction mold and a scaled model of the ASTM D-698 compaction hammer. The specimens were extruded from the compaction mold, weighed, wrapped to minimize moisture loss, identified, and stored at the desired curing temperature until the test day. Immediately before testing, the specimens were removed from their temperature chambers and weighed. The unconfined compression testing procedure used a strain rate of 1 percent/min. The remains of the entire sample were used to determine its moisture content for the determination of its dry unit weight.

## STATISTICAL INFERENCES

The analysis of variance results are given in Table 1. No quadratic effects were found to be significant at an alpha level of 1 percent. Each significant effect will be individually discussed in the following sections. A multiple regression equation to predict the unconfined compression strength in terms of the mixture, construction, and environmental variables studied is presented.

### Main Effects

#### Salt Content

Figure 1 shows that increasing the salt content from 1 to 3 percent decreases the unconfined compressive strength. Previous research (5) had indicated that an optimum salt content below 3 percent maximizes the unconfined compressive strength obtained in salt-lime treatment, and the data in Figure 1 indicate a similar trend.

Thornburn and Mura (2) have reported that increasing the salt content of a soil increases the dry unit weight, and this experiment indicated a similar trend. Therefore,



an increase in dry unit weight cannot be the reason why an increased salt content caused a decreased strength. A more plausible explanation for the lower strengths associated with higher salt contents is that the excess quantity of salt recrystallizes in the cementitious gels, which may disrupt the crystalline structure of the pozzolanic products and reduce the unconfined compressive strength.

#### Lime Content

Figure 2 shows that increasing the lime content from 2 to 6 percent increases the unconfined compressive strength. The 2 percent level of lime provides an adequate quantity of calcium to modify the soil, but leaves very little for the formation of pozzolanic compounds. The 6 percent level provides adequate calcium for both modification and the formation of strength-producing cementitious compounds.

#### Curing Temperature

As is shown in Figure 3, increasing the curing temperature from 4.4 to 43.3°C (40 to 110°F) causes a large increase in the unconfined compressive strength. Increased temperatures accelerate the rate of the strength-producing chemical reactions between the lime and the soil. The high-temperature curing produces large increases in strength (however, the specimens were wrapped and sealed to minimize moisture loss).

#### Curing Time

Figure 4 shows that as the curing time is increased from 10 to 30 d, the unconfined compressive strength increases, which illustrates the beneficial effect of longer curing periods. However, substantial strengths were developed by the end of 10 d.

#### Molding-Water Content

Figure 5 shows that increasing the molding-water content from 12.5 to 17.5 percent increases the unconfined compressive strength. Because the specimens were sealed, significant amounts of moisture were not lost during curing. The lower level of moisture does not provide an adequate quantity of water for the stabilization reactions; however, the 17.5 percent level of moisture provides the additional water needed for the formation of pozzolanic compounds.

#### Soil Type

As is shown in Figure 6, the two types of soil used in this research have significantly different mean unconfined compressive strengths. Because of differences in clay mineralogy, HC has a much higher cation exchange capacity and a larger specific-surface area than does PRC. This creates several differences in the lime, salt, and moisture requirements of the two soils. First, the quantity of lime required to modify and stabilize HC is greater than that necessary for the modification and stabilization of PRC. Second, because of the differences in the specific-surface areas of the two clays and the different water requirements required to develop the diffused double water layers, it would be expected that HC would require more molding water than does PRC, which has a lower specific-surface area. Therefore, at identical moisture contents, more free water will be available in PRC to participate in the stabilization reactions than will be available in HC.

The confounding effect of the dry unit weight is also

present in these data. The mean dry unit weight of the PRC specimens was 1514 kg/m<sup>3</sup> (94.6 lb/ft<sup>3</sup>) as compared to 1322 kg/m<sup>3</sup> (82.6 lb/ft<sup>3</sup>) for the HC specimens. The difference in dry unit weights will contribute to the increased unconfined compressive strengths observed in the PRC as compared to the HC.

#### Linear Interactions

##### Lime Content and Salt Content

Figure 7 illustrates one of the most important interactions investigated in this research: A 2 percent lime content and a 3 percent salt content produces slightly higher unconfined compressive strengths than does a 2 percent lime content and a 1 percent salt content; however, a 6 percent lime content and a 1 percent salt content produces a much higher unconfined compressive strength than does a 6 percent lime content and a 3 percent salt content. There are several possible explanations for this apparent contradiction. The lower level of lime (2 percent) is very near the quantity required for modification of the soils; therefore, very little if any, calcium will be available for the production of pozzolanic compounds. This suggests that the quantity of salt added would far exceed the quantity of lime available for stabilization of the soil. This excess salt could then only fill the voids, adding strength through increased density, but not through chemical reactions with the soil itself. Also, if the lime content is low, the salt is present in much too great a quantity to act solely as a catalyst in the formation of pozzolanic compounds. At a 6 percent lime content, the decrease in strength of the soil with a corresponding increase in the level of salt strongly suggests that not only is there an optimum quantity of salt, but also that excessive salt can be detrimental to the development of unconfined compressive strength.

##### Lime Content and Curing Temperature

At a lime content of 2 percent, an increase in curing temperature causes an increase in strength (Figure 8), and at a lime content of 6 percent, a change in the temperature from 4.4 to 43.3°C (40 to 110°F) causes a larger increase in the strength of the specimens because the chemical reactions involved in the formation of the pozzolanic compounds are greatly accelerated at the higher temperature. The lime content of 2 percent supplies very little calcium for the formation of these compounds after the modification reactions have taken place. A lime content of 6 percent supplies a surplus of calcium after modification that is available for the chemical reactions that increase the unconfined compressive strength.

##### Lime Content and Molding-Water Content

At a 2 percent lime content, an increase in molding-water content from 12.5 to 17.5 percent increases the unconfined compressive strength (Figure 9). At a 6 percent lime content, the increase in strength as the molding-water content is increased is larger than that at a 2 percent lime content.

This interaction shows the positive effect of increased molding water and lime contents on the unconfined compressive strength. The 17.5 percent molding-water content provides more of the water for the required development of pozzolanic compounds when sufficient calcium is present.

### Salt Content and Curing Temperature

Figure 10 shows that increasing the salt content from 1 to 3 percent at a curing temperature of 4.4°C (40°F) produces little change in the unconfined compressive strength. The same increase in salt content at 43.3°C

Table 1. Analysis of variance for unconfined compressive strength.

Source of Variation	Degree of Freedom	Mean Squares	F-Value*	Significance Level (%)
Total	63	—	—	—
Salt content	1	3 546	17	1
Lime content	1	50 421	245	1
Curing temperature	1	154 814	751	1
Curing time	1	7 151	34	1
Molding-water content	1	14 841	72	1
Soil type	1	25 824	125	1
Lime content and salt content	1	7 884	38	1
Lime content and curing temperature	1	31 964	155	1
Lime content and molding-water content	1	3 234	16	1
Salt content and curing temperature	1	4 132	20	1
Curing temperature and curing time	1	4 124	20	1
Curing temperature and molding-water content	1	11 348	55	1
Curing temperature and soil type	1	16 738	81	1
Curing time and soil type	1	3 242	16	1
Lime content and salt content and curing temperature	1	3 934	19	1
Residual	48	—	—	—
Center points	11	206.31	—	—

\*Critical F-value:  $F(1, 11, 0.01) = 9.65$ .

Figure 1. Effect of salt content on unconfined compressive strength.

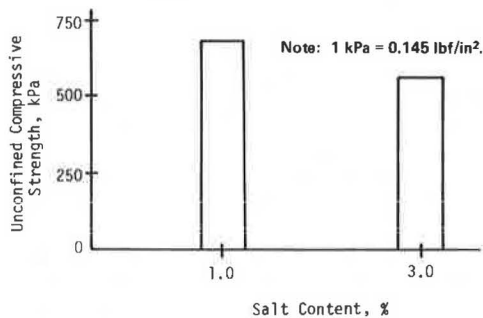
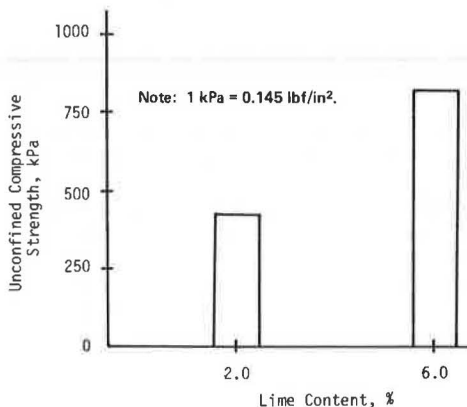


Figure 2. Effect of lime content on unconfined compressive strength.



(110°F) produces a decrease in the unconfined compressive strength. The unconfined compressive strengths for each salt content were higher at a 43.3°C (110°F) curing temperature than at a 4.4°C (40°F) curing temperature, again because the chemical reactions are accelerated at a higher temperature. The decrease in the unconfined compressive strength when the salt content is increased further illustrates the detrimental effect of excessive salt.

### Curing Temperature and Curing Time

As shown in Figure 11, at a curing temperature of 4.4°C (40°F), there is little change in the unconfined compressive strength as the curing time is increased from 10 to 30 d, but at a curing temperature of 43.3°C (110°F), an

Figure 3. Effect of curing temperature on unconfined compressive strength.

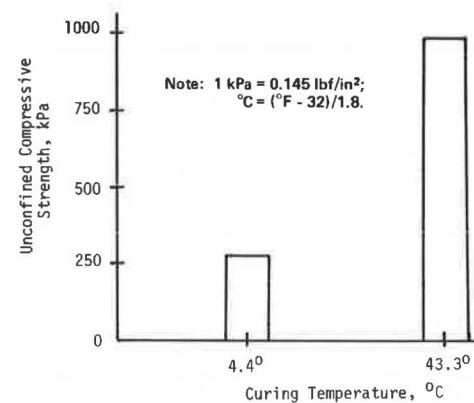


Figure 4. Effect of curing time on unconfined compressive strength.

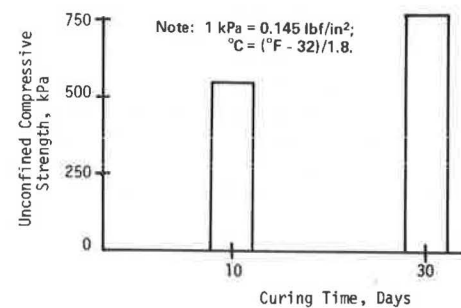
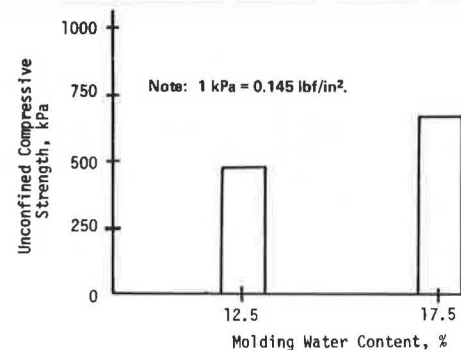


Figure 5. Effect of molding-water content on unconfined compressive strength.



increased unconfined compressive strength is observed when the curing time is increased from 10 to 30 d. This indicates that little chemical activity takes place at 4.4°C (40°F) for the two curing times used and that both increased curing time and increased curing temperature increase the unconfined compressive strength.

Figure 6. Effect of soil type on unconfined compressive strength.

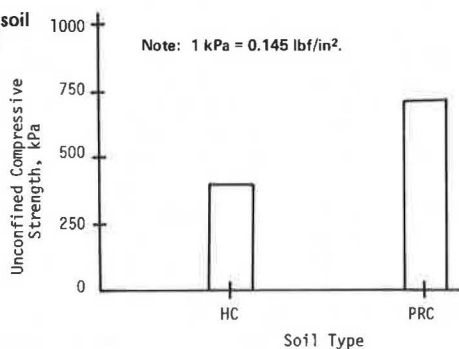


Figure 7. Effect of interaction between lime content and salt content on unconfined compressive strength.

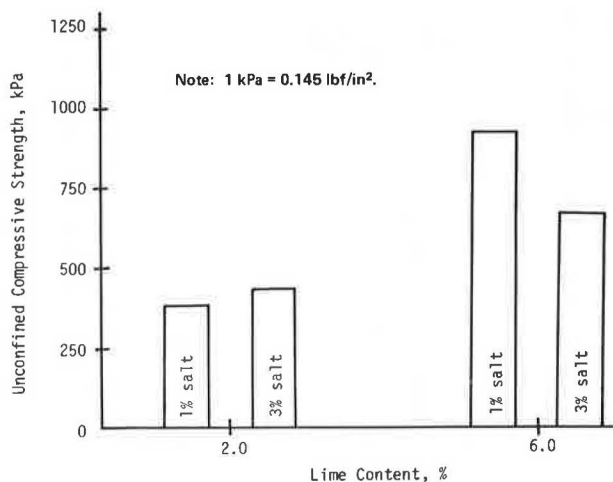
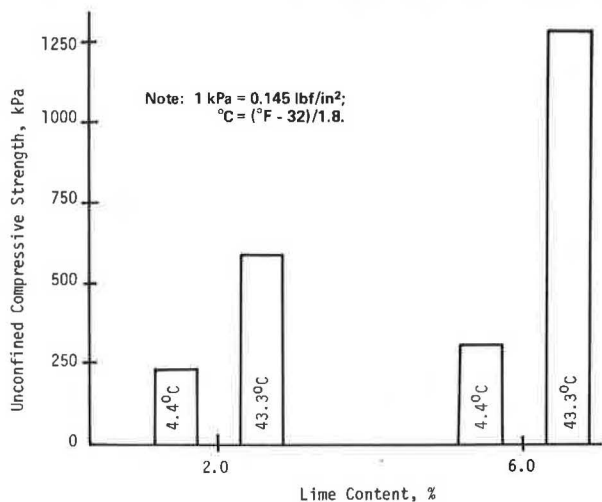


Figure 8. Effect of interaction between lime content and curing temperature on unconfined compressive strength.



#### Curing Temperature and Molding-Water Content

As shown in Figure 12, at 4.4°C (40°F), there is a small increase in the unconfined compressive strength with increased moisture content. However, the unconfined compressive strength substantially increases at a 43.3°C (110°F) curing temperature when the molding-water content is increased from 12.5 to 17.5 percent. As previously discussed, at 4.4°C (40°F), the formation of cementitious compounds is slower than at 43.3°C (110°F). A combination of high levels of molding-water content and temperature produces increased unconfined compressive strength, which illustrates the need for water in the production of the pozzolanic products.

#### Curing Temperature and Soil Type

Figure 13 shows that at 4.4°C (40°F), PRC has a slightly greater unconfined compressive strength than does HC; however, at 43.3°C (110°F), the difference is large.

The difference in the unconfined compressive strengths of the two soils can be partially explained by the differ-

Figure 9. Effect of interaction between lime content and molding-water content on unconfined compressive strength.

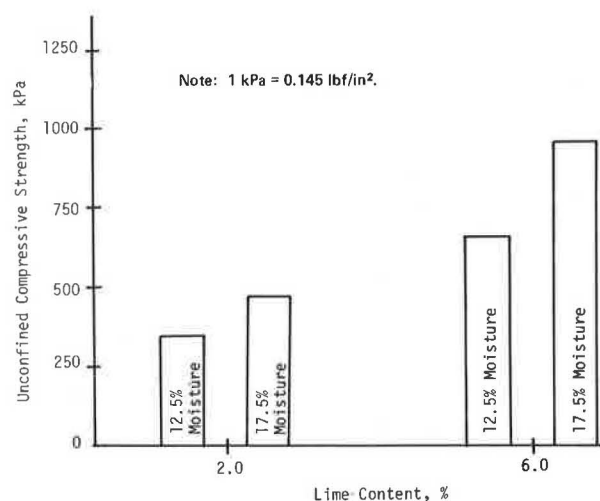
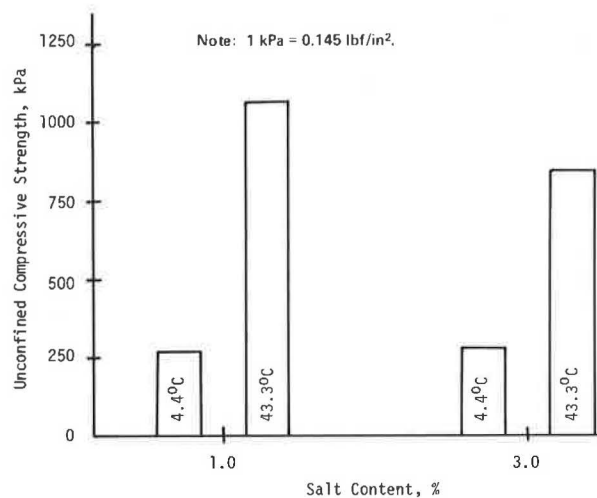


Figure 10. Effect of interaction between salt content and curing temperature on unconfined compressive strength.



ence in their dry unit weights. That difference should explain the difference in their unconfined compressive strengths at low temperatures, even when chemicals have been added, because virtually no strength-producing stabilization reactions take place at 4.4°C (40°F).

At 43.3°C (110°F), the difference between the strengths of the two soils can no longer be explained without considering their mineralogical properties. Because HC could very well have a specific-surface area four to five times larger than that of PRC, one would expect that it would require much more chemical to treat HC than is required for PRC. Hence, the PRC would have a larger increase in the unconfined compressive strength at the higher curing temperature for the levels of lime content, moisture content, and salt content used.

#### Curing Time and Soil Type

As is illustrated in Figure 14 for a curing time of 10 d, PRC develops a higher unconfined compressive strength than does HC. This is also true for a curing time of 30 d, and the difference in strength of the two clays is much greater. This interaction strengthens the postulate that the quantity of lime required to stabilize HC is

greater than that required to stabilize PRC and that soil type is confounded with dry unit weight.

#### Lime Content, Salt Content, and Curing Temperature

At a curing temperature of 4.4°C (40°F), the average unconfined compressive strength increases as the lime content is increased from 2 to 6 percent and as the salt content is decreased from 3 to 1 percent (Figure 15). These increases are very small, but there is a much larger average strength increase at 43.3°C (110°F) as the lime content is increased from 2 to 6 percent and the salt content is decreased from 3 to 1 percent.

This interaction illustrates a response surface among several of the suggested hypotheses. First, lower temperatures retard and higher temperatures accelerate the formation of strength-producing compounds. Second, excessive quantities of salt appear to be detrimental to the stabilization process. The response surface created by the 43.3°C (110°F) curing temperature slopes toward higher percentages of lime and lower percentages of salt for the development of higher unconfined compressive strengths. The major inference from this effect is

Figure 11. Effect of interaction between curing temperature and curing time on unconfined compressive strength.

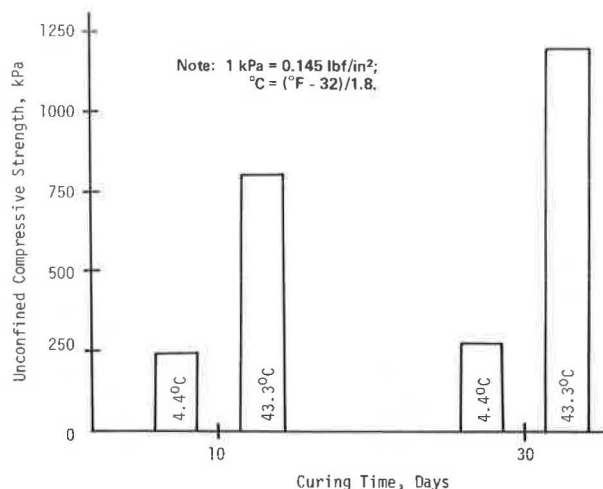


Figure 13. Effect of interaction between soil type and curing temperature on unconfined compressive strength.

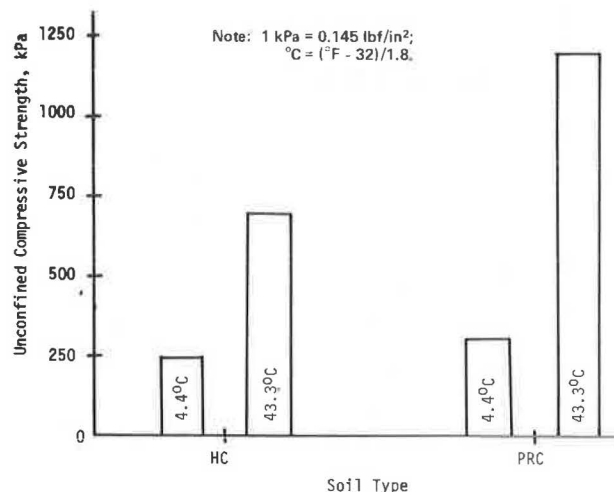


Figure 12. Effect of interaction between curing temperature and molding-water content on unconfined compressive strength.

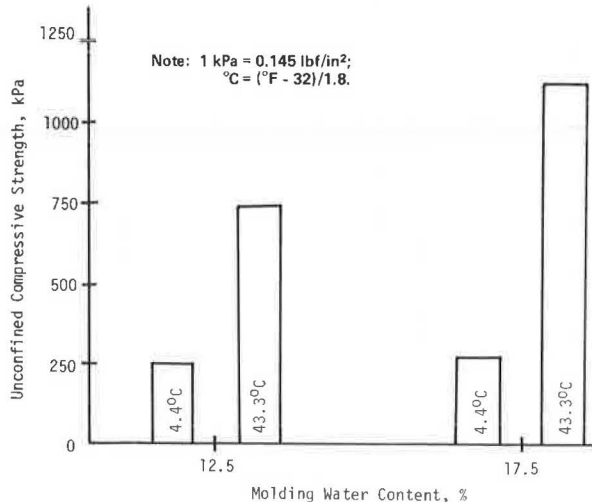


Figure 14. Effect of interaction between soil type and curing time on unconfined compressive strength.

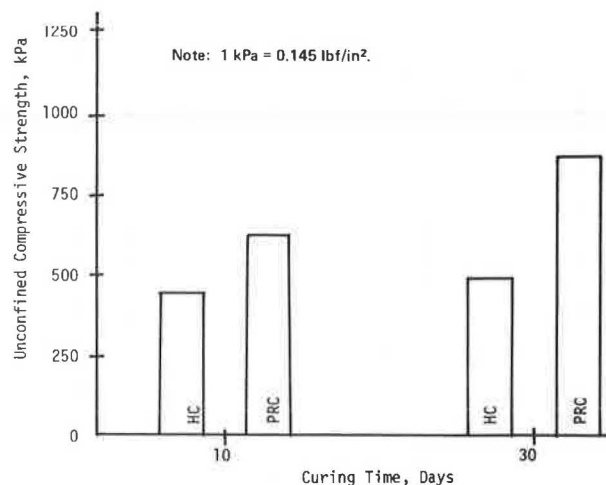
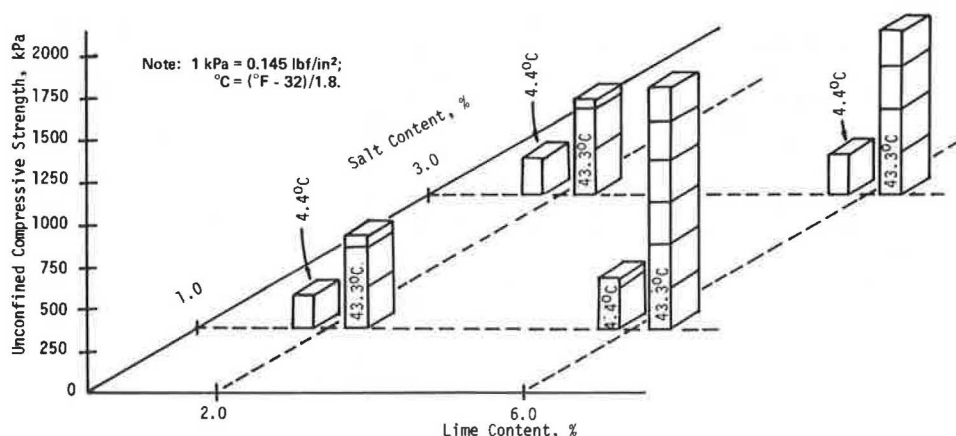


Figure 15. Effect of interactions among lime content, salt content, and curing temperature on unconfined compressive strength.



that there is an optimum salt content that maximizes unconfined compressive strengths in lime-treated clays and that this is probably less than 3 percent if sufficient lime is present for the development of pozzolanic compounds.

#### Prediction Equations

A multiple linear regression was used to generate a coded prediction equation that included all of the main effects, two-factor interactions, and three-factor interactions found to be significant at an alpha level of 1 percent.

$$S = 88.22 - 7.44A + 28.07B + 49.18C + 10.57D + 15.23E + 20.09F - 11.10AB - 8.03AC + 22.35BC + 7.11BE + 8.02CD + 13.32CE + 16.17CF + 7.12DF - 7.84ABC \quad (1)$$

where

S = unconfined compressive strength,  
A = salt content,  
B = lime content,  
C = curing temperature,  
D = curing period,  
E = molding water content, and  
F = soil type.

The coded levels given in Table 1 are used.

The standard error of estimate of the equation is 173.4 kPa (24.9 lbf/in<sup>2</sup>), and  $R^2$  is 0.9246. The equation has a lack of fit at an alpha level of 2.5 percent and is valid only for predictive purposes within the factor space studied, which is a function of the factors and levels studied. Any attempt to extrapolate beyond the factor space with regression equations may introduce conditions that were not investigated and result in erroneous predictions.

#### CONCLUSIONS

All six factors studied in this research were found to be significant as main effects at an alpha level of 1 percent with respect to the unconfined compressive strength. No quadratic effects were found to be significant; however, eight two-factor linear interactions and one three-factor linear interaction were significant at an alpha level of 1 percent. Those main effects and interactions were

1. Main effects: salt content, lime content, curing temperature, curing time, molding-water content, and soil type and

2. Interactions: lime content and salt content, lime content and curing temperature, lime content and molding-water content, salt content and curing temperature, curing temperature and curing time, curing temperature and molding-water content, curing temperature and soil type, curing time and soil type, and lime content, salt content, and curing temperature.

Each of the effects and interactions had a positive regression coefficient except salt content, lime content and salt content, and salt content and curing temperature. A positive coefficient implies that the dependent variable—unconfined compressive strength—is increased as the quantity of the independent variable is increased. For the range of the variables used in this research, the unconfined compressive strength was increased by

1. Increased lime content,
2. Decreased salt content,
3. Increased curing temperature,
4. Increased curing time,
5. Increased molding-water content, and
6. Using PRC rather than HC.

The results of this experiment are indicative of the complexity involved in combination stabilization processes.

#### REFERENCES

1. M. Mateos and D. T. Davidson. Further Evaluation of Promising Chemical Additives for Accelerating Hardening of Soil-Lime-Fly Ash Mixtures. HRB, Bulletin 304, 1961, pp. 32-50.
2. T. H. Thornburn and R. Mura. Stabilization of Soils With Inorganic Salts and Bases: A Review of the Literature. HRB, Highway Research Record 294, 1969, pp. 1-22.
3. C. C. Ladd, Z. C. Moh, and T. W. Lambe. Recent Soil-Lime Research at the Massachusetts Institute of Technology. HRB, Bulletin 262, 1960, pp. 64-85.
4. B. D. Marks and T. A. Haliburton. A Salt-Lime Soil Stabilization Feasibility Study. School of Civil Engineering, Oklahoma State Univ.; Oklahoma Research Program Project Agreement No. 6, Final Rept., 1970.
5. B. D. Marks and T. A. Haliburton. Acceleration of Lime-Clay Reactions With Salt. Journal of the Soil Mechanics and Foundations Division, Proc., ASCE, Vol. 98, No. SM4, April 1972, pp. 327-340.
6. J. A. Drake and T. A. Haliburton. Accelerated Curing of Salt-Treated and Lime-Treated Cohesive Soils. HRB, Highway Research Record 381, 1972, pp. 10-19.



7. Chemical, Mineralogical, and Engineering Properties of Alabama and Mississippi Black Belt Soils. Alabama and Mississippi Agricultural Experiment Stations and Soil Conservation Service; Southern Cooperative Series No. 130, Auburn Univ., Auburn, Ala., Feb. 1968.
8. Soil Survey of Macon County, Alabama. U.S. Department of Agriculture and Alabama Department of Agriculture and Industries, Series 1937, No. 11, 1944.
9. W. B. Cochran and G. M. Cox. Some Methods for the Study of Response Surfaces. Experimental Design, Wiley, New York, 2nd Ed., 1957.
10. R. K. Moore, T. W. Kennedy, and J. A. Kozuh. Tensile Properties for the Design of Lime-Treated Mixtures. HRB, Highway Research Record 351, 1971, pp. 112-114.

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# Laboratory Study of the Effectiveness of Cement and of Lime Stabilization for Erosion Control

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Soils ranging in texture from sand to heavy clay can be rendered effectively resistant to the soil erosion caused by raindrop impact by treatment with as little as 1 percent portland cement or hydrated lime. Erosion resistance was evaluated in a standard rainstorm sequence in which 8.2 cm (3.25 in) of rain was applied for 1 h on each of two successive days. Compacted but otherwise unstabilized soils lost 1 to 2.5 g/cm<sup>2</sup> (0.014 to 0.035 lb/in<sup>2</sup>) of exposed surface, equivalent to 45 to 110 tons/acre, in this standard test. Incorporation of stabilizer and appropriate curing before exposure decreased this erosion loss to about 0.11 g/cm<sup>2</sup> (0.0016 lb/in<sup>2</sup>), equivalent to 5 tons/acre, for fully compacted specimens. Cement-treated soils tested after only modest compaction maintained their erosion resistance, but lime-treated soils were adversely affected by reduced levels of compaction. These laboratory test results do not necessarily predict practical field performance, because the effects of running water erosion, of the incomplete mixing characteristic of field incorporation of stabilizers, and of cycles of temperature change, wetting and drying, and freezing and thawing have not been tested.

Accelerated soil erosion at construction sites is a serious environmental problem in many parts of the United States. The present methods of erosion control are not uniformly effective.

For many years, soils have been stabilized for use as highway or airfield subgrade materials by treatment with portland cement or hydrated lime.

The present work is based on the idea that treatment of soils exposed on construction sites with small amounts of cement or lime might be useful in preventing erosion. The use of these stabilizers would be relatively expensive in terms of the usual costs of erosion control, but it might provide effective erosion resistance and be a useful alternative to conventional methods, particularly where erosion may lead to especially harmful or serious consequences.

## EVALUATION METHODS

Characterizing the erosion resistance of a particular soil or treated soil is, in the final analysis, a field-scale problem. Nevertheless, laboratory assessment based

on measurement of the soil lost in controlled artificial-rainstorm tests should be helpful in screening the effectiveness of various kinds of erosion-control treatments on various soils. The present paper reports the results of tests on a range of Indiana soils treated with small amounts of hydrated lime or portland cement, compacted, and cured to various degrees before exposure to a standardized laboratory rainstorm sequence and discusses the extent to which such laboratory results might reflect field effectiveness.

The apparatus used measured the resistance of 10.2-cm (4-in) diameter test specimens exposed to a standard rainstorm sequence of approximately 7.6 cm (3 in) of rain delivered in 1 h, followed by a 23-h rest period, and then by another rain cycle of the same kind. Equipment quirks prevented the delivery of exactly 7.6 cm (3 in) of rainfall in 1 h, and 8.2 cm (3.25 in) was standardized on. The rainfall device delivered droplets of uniform size and spatial distribution that had a kinetic energy approximating that of the average drop in natural storms of the same intensity.

In the tests, the surfaces of the specimens were maintained at a 5° angle to the horizontal to prevent ponding. Three replicate specimens were exposed simultaneously, and the actual amount of rainfall delivered was monitored by rain gauges between the specimens. The soil removed from each specimen was collected and dried and weighed for the quantitative assessment of the amount of erosion. Erosion was expressed in terms of weight loss per unit area of exposed specimen surface.

The apparatus and test procedures have been described previously (1).

## SOILS AND STABILIZERS USED

Four natural Indiana soils were chosen to provide examples of a full range of textural classes from a heavy, montmorillonite-bearing clay soil to a predominantly sandy soil with only about 3 percent clay. They are described in Table I.