Short-Term Active Soil Property Changes Caused by Injection of Lime and Fly Ash

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This paper describes research into the physical and chemical property changes that occur in an active clay soil during and shortly after injection with lime and lime and fly ash slurries. It reports on the changes measured for 20 properties by using 112 samples taken both before and after injection. It describes the design of the experiment, where four treatments were randomly applied in four replications. It describes the property changes noted that were significant and explains how the monitored ground surface elevations changed during the project. The paper describes the processes used for statistical analyses of property changes measured. This description includes two types of analysis of variance and comparison of means before and after treatment. Those properties concluded to have significantly been affected by injection stabilization included water contents, plastic indices, swelling potential, cation exchange capacities, calcium levels in pore water, and calcium levels in the exchange complex. The ground level monitoring analyses presented support the stabilizing effects of lime slurry pressure injection (LSPI). Conclusions include the relative ranking of the treatments applied where a single LSPI followed by a three-staged water injection proved most effective.

The damage to structures caused by change in the volume of active clay soil has been well documented and is estimated to exceed $2 billion annually. This is more than twice the damage caused by other natural disasters combined. Although these problem soils are abundant across the continental United States, they present the most crucial problem to transportation facilities in regions that have semiarid climates. This type of climate provides long periods of drying during which active soils may shrink significantly, followed by periods of intense rainfall when swelling of these soils causes substantial damage. One such area where these problems affect a great number of transportation facilities is the Dallas-Fort Worth metroplex of north-central Texas.

In order to alleviate or eliminate the problems associated with active clay soils, techniques for improvement to the soil site, such as excavation and replacement with inactive materials and stabilization of soils to limited depths, have been recommended by geotechnical engineers. The use of lime or fly ash as stabilizing agents has been popular for some time. Geotechnical engineers would like to understand better how these agents work in active clay soil subgrades, especially when injected under pressure to moderate depths.

Pressure injection of lime was introduced about 20 years ago. Studies have been conducted to determine the changes to the physical properties of soils and soil masses that occur as a result of this stabilization method (1-4). The results of these studies and experience with using lime slurry pressure injection (LSPI) have improved the understanding of how to apply this technique effectively; however, to date there have been no definitive studies that used statistically designed experiments to determine the changes that occur to the physical and chemical properties of active clay soils during and shortly after injection with lime slurries. In addition, no studies have been done to determine the effects of lime and fly ash injection on these soils.

The research reported here was undertaken to provide information about the changes to physical and chemical properties that occur in an active clay soil during and shortly after injection with lime and lime and fly ash slurries. The research site was the Dallas-Fort Worth Regional Airport and the laboratory tests were performed at the University of Texas at Arlington. The majority of material and financial support was provided by the Woodbine Corporation of Fort Worth through the College of Engineering's Construction Research Center. The soils involved in this study were highly active clay soils weathered from the Eagle Ford Shale geologic formation.

RESEARCH PROGRAM

This study uses a statistically designed experiment to report the changes that result in some 20 physical and chemical properties of an active soil subgrade when LSPI stabilization was performed. A site was provided on property of a large transportation facility where 12 areas were treated with four replications of three treatments, and 4 areas were used as untreated control. Prior to treatment, samples were taken to determine the natural properties of the subgrade and, subsequent to treatment, the areas were again sampled to determine property changes. In addition, the movement of the ground surface was monitored for these areas on a monthly basis throughout the duration of the project.

The project site was chosen because of the highly active nature of the clay soil subgrade and because of the highly fractured nature of this subgrade that was determined. This site and the soils profile are indicative of those encountered by transportation facilities in north-central Texas. The site was approximately 2 acres (7000 m^2) in size and was partitioned into 16 areas (called pads) that were squares, 35 ft (10.7 m) on each side. The locations of these pads and of the benchmark found 20 ft (6.1 m) deep are shown in Figure 1.

Design of Experiment

The three treatments and control areas were applied in four replications to the 16 pads. The treatments were selected to represent those currently used in injection-stabilization practice in order to provide relevant information to users of these techniques.

Treatment number one was a single injection, on 5-ft (1.5-m) centers to a depth of 7 ft (2.1 m), of a normally used lime slurry, followed by three similarly spaced and penetrating water injections. The lime slurry contained from 2.5 to 3 lb (1.1-1.4 kg) of hydrated lime and a surfactant at a rate of 1 part to 3500 parts by volume/gal (0.0038 m^3) of slurry. The water injected contained a similar quantity of surfactant. This treatment was labeled as a single LSPI plus three-staged water injection.

Treatment number two was a double-staged injection of the same lime slurry used in treatment number one. The resultant pattern of injections was located at approximate 2.5-ft (0.76-m) centers. There was an approximate one week delay between the stages of this treatment. This treatment was labeled as a double LSPI.

Treatment number three was a double-staged injection of a lime and fly ash slurry performed in the same manner as treatment number two. The fly ash used was obtained from an electric power generating plant by using lignite coal fuel. The contents of

Figure 1. General site layout.

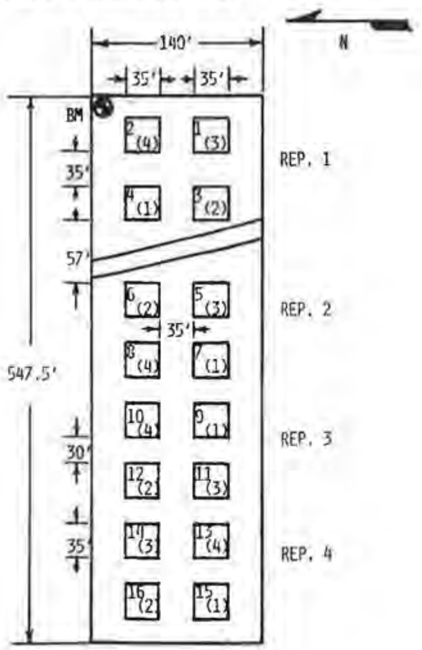
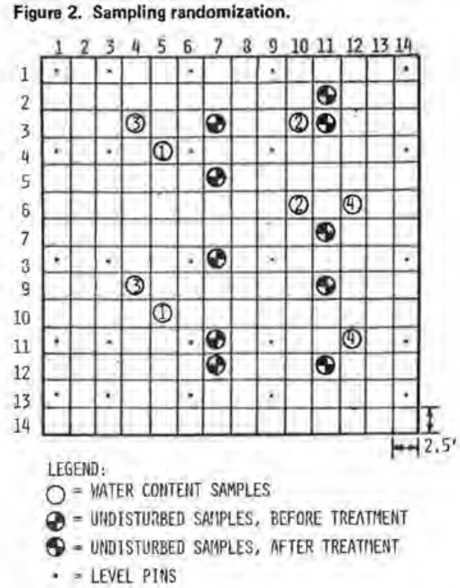


Figure 2. Sampling randomization.



this calcareous fly ash are shown in the table below:

Compound	Average (%)
SiO_2	47.8
Al_2O_3	20.0
Fe_2O_3	6.6
CaO	18.0
MgO	3.3
SO_3	1.5
K_2O	0.7

The lime and fly ash (LFA) slurry contained surfactants in the same quantities as the lime slurry described above, 1 lb (0.45 kg) of hydrated lime and 3 lb (1.4 kg) of fly ash/gal (0.0038 m^3) of slurry. This treatment was labeled as a double lime and fly ash slurry pressure injection (LFASPI).

The total quantities of hydrated lime used for single LSPI on four pads, double LSPI on four pads, and double LFASPI on four, were 59 tons (53 600 kg). The total quantity of fly ash used was 40 tons (36 600 kg).

The fourth treatment, applied to 4 of the 16 pads, was no stabilization. This was done to provide statistically significant information to compare with the stabilization treatments. After injection of stabilizing agents was complete, a 6-in-thick (15.24 cm) surface layer of the subgrade of all pads was mixed thoroughly and lightly compacted.

Twenty-five level pins were placed into the ground of each pad to monitor surface movements. This number was chosen to adequately measure movement but not interfere with sampling or injection procedures. The locations of these pins, shown in Figure 2, were chosen by a random process, which resulted in five columns with five rows of pins. The designation columns were chosen for east-west linear areas between injection points. Rows were designated as north-south linear areas between injection points.

A random selection process was used to apply each of the four treatments to the four pads in each replication. The design chosen was taken from some 20 sets generated to provide as wide a dispersal of treatments to positions within each replication. The pads to which treatments were assigned within the replications are shown in parentheses on each pad in Figure 1. Replications were chosen as groups of four pads in numerical order. This was done because the site topography included some variation in elevation longitudinally and a shallow erosion channel crossing between pads three and four and pads five and six (shown in Figure 1).

Sampling Program

In order to provide information on property changes, samples were taken from each pad before and after treatment. All samples were taken from positions between injection points that were chosen by using a random selection process. Because of expected sampling, 11 sets of positions were chosen so that the samples would be taken in each case within a single column and from selected rows within the column. The use of all samples taken from a single column facilitated sampling operations because a truck-mounted drill could be operated along single lines.

For initial property determination, samples were taken from five borings in each pad. A total of seven undisturbed samples was taken from these five borings. From each hole samples were obtained from 3 to 4 ft (0.91-1.21 m). In addition, to provide some information concerning property change with depth, samples were taken from 4 to 5 ft (1.21-1.52 m) and from 5 to 6 ft (1.52-1.83 m) in the center (number three) boring. The choice of this boring for the deeper samples was to accommodate the limitations of the project and to possibly provide representative information. The samples taken at this time were labeled and sealed in the field to provide identification of the 112 obtained and to preserve the natural properties of the soil. These samples were taken to the civil engineering laboratories of the University of Texas at Arlington for testing, as described later.

In addition to these samples, two sets of disturbed samples were taken during the period before injection for determination of water content only. As in the case of the first, undisturbed samples, these were taken at predetermined locations. In both cases, however, samples were obtained only at the 3- to 4-ft (0.91- to 1.22-m) level from each of

five borings. The second water content samples were taken immediately prior to the injection process. During each of the sampling periods before injection, all holes created in the pads were first filled with a bentonite slurry and then backfilled with soil from the site. This was done to prevent the presence of holes from affecting the injection process or resultant patterns of injected fluids.

The next samples obtained from the subgrade were used to determine the changes in water content that occurred prior to and during the three-staged water injections. On each of four occasions, undisturbed samples were taken from two previously determined borings within the five randomly chosen borings in the set. These samples were obtained by continuous push of shelby tubes to 6 ft (1.83 m). Samples were taken in the field from areas between injection seams and their water content determined in the laboratory. The resultant holes were backfilled with natural soil from the borings and on site.

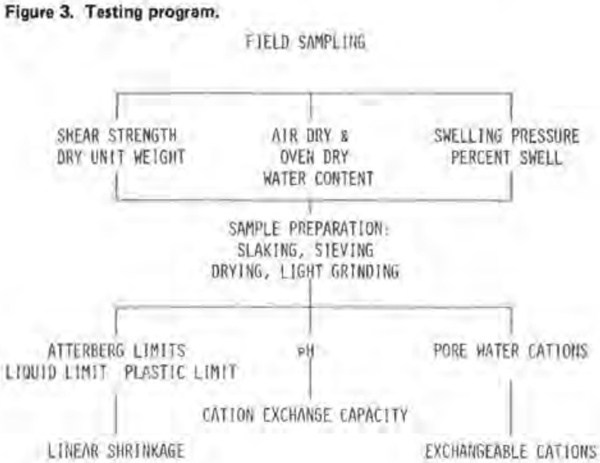
For the final property determination, samples were taken approximately one month after the injections were complete. Some 112 samples were obtained from previously determined random locations in the same manner as were the first property determination samples. These were identified, sealed, and transported to the testing laboratory as were the previously taken samples for property determinations. These samples were tested by using the process described below. The locations within the pads where samples were obtained for property determination before and after injection and for water contents during water injection are shown, along with level pin locations in Figure 2.

Testing Program

Samples taken for property determination before and after injection were tested for 20 properties. The flow chart of the testing program used is shown in Figure 3. The physical properties measured included shear strength, dry unit weight, swelling pressure, percentage swell, air-dry and oven-dry water contents, and selected Atterberg limits and related indices. Soil chemical properties determined included pH, cation exchange capacity (CEC), selected pore water cations, and selected exchange complex cations. Samples tested after injection were taken from between the seams of stabilizing materials in every case.

The testing procedures used for determination of physical property were those recommended by the American Society for Testing and Materials (ASTM).

Figure 3. Testing program.



Swelling tests were started at natural water content and with an initial surcharge load to apply the in situ overburden pressure. The air-dried water content tests were performed by using a temperature of 68°F (50°C) and a relative humidity of 68 percent. The process of sample preparation for Atterberg limits and chemical property testing included removal of seams of stabilizing agents and concretions, slaking in distilled water, wet sieving through a No. 40 series sieve, drying at 140°F (60°C), light crushing of clods to workable size, and reconstitution of moisture to a desirable level for testing. The Texas bar method was used for determination of linear shrinkage.

Determinations of chemical property were performed by using standard procedures specified by the Soil Conservation Service of the U.S. Department of Agriculture (5). The soil pH was determined by using a 1:1 mixture by weight of soil and distilled-demineralized water. Pore water cation extracts were made by using 1:1 mixtures as for the pH test. The CEC was determined by using the calcium replacement method. Exchange complex cation extractions were performed by using amonium acetate and soil mixtures. The concentrations of cation levels were determined by using an atomic absorption flame spectrophotometer.

RESULTS

The results determined during testing for 20 properties for 224 samples are too numerous to include in this report. The properties determined prior to injection have been reported previously, along with the analyses of variance and correlations of those properties (6). The results in this report, therefore, will be directed toward the ultimate purpose of the research project--to compare the changes of properties that occurred due to the injection stabilization treatments. The five samples taken at the same depth were used for all comparisons and analyses, since the other two did not provide sufficient or differing results for analysis.

The changes in the properties measured, the comparison of property means, and the changes that result in these means are of interest. This part of the comparison is normally used by geotechnical engineers when the number of samples is relatively small. A presentation of property means by treatments determined for before and after samples is offered in Table 1. The change to the means may be determined for each property. Note that any comparison of the mean change without statistical analyses, which is possible with the number of samples used in this study, is not complete. It is possible, however, to gain some insight into the basic soil property measurements and the variations present in soils across the site by using this information.

The clay soil at this site is very active, and changes to properties have occurred because of the injection processes applied. Some of the changes are possibly due to changes in personnel who performed the tests and some are due to variation of the soil from which the samples were taken. The analyses of variation, reported earlier (6), for the samples taken before injection showed considerable variation of all properties across the site and significant variances within the pads. Rather than discuss analyses of mean property changes at this point, it would be more significant and useful to proceed to the statistical analyses that were employed and their results. The only conclusion that can be reached after studying the mean property changes presented in Table 1 is that the injection stabilization processes applied significantly re-

Table 1. Mean property values.

Property	Property No.	Treatment 1		Treatment 2		Treatment 3		Treatment 4	
		Before	After	Before	After	Before	After	Before	After
Oven-dry water content (%)	2	24.4	26.8	27.5	27.1	26.9	29.2	27.9	24.7
Air-dry water content (%)	3	14.9	21.1	17.0	21.6	16.3	23.4	18.5	19.4
Plastic index (%)	6	51.0	33.0	50.0	36.0	51.3	40.3	52.8	39.6
Linear shrinkage (%)	7	24.7	21.7	23.9	21.9	24.0	22.6	24.2	21.8
Percentage swell	8	4.0	1.5	5.9	2.4	5.2	1.5	5.9	3.5
Swelling pressure (tons/ft^2)	9	1.4	0.1	1.9	0.4	2.0	0.2		
Shear strength (tons/ft^2)	10	3.9	1.4	3.9	1.9	2.3	1.8	3.4	2.7
pH	11	7.80	7.80	7.71	7.91	7.72	7.82	7.81	8.01
CEC-Calcium (milliequivalence/100g)	12	9.9	25.7	10.4	24.9	15.2	21.4	16.3	21.1
Pore water cations (milliequivalence/L)									
Na	13	14.5	5.5	10.9	7.6	15.5	6.3	13.4	7.1
K	14	0.19	0.49	0.34	0.33	0.67	0.47	0.22	0.36
Ca	15	1.5	2.6	1.4	3.2	1.7	2.5	3.6	2.6
Mg	16	1.77	0.77	1.54	0.84	1.65	0.55	2.63	1.13
Exchange complex cations (milliequivalence/100g)									
Na	17	6.0	5.6	6.4	5.4	9.1	10.8	7.9	8.5
K	18	0.94	1.34	1.12	1.42	0.95	1.35	1.63	1.53
Ca	19	41.4	41.1	58.2	42.2	25.5	42.5	45.7	37.7
Mg	20	4.0	3.6	4.3	3.6	4.0	4.6	4.9	5.8

duced the activity of the soil subgrade under study.

Statistical Analyses

Part of the originally stated purpose of the study was to design and conduct an experiment that would lend itself to statistical evidence of the changes in properties caused by injection stabilization. In fact, statistical significance of research findings is a necessity for such a study. As described above, this experiment was designed by using random selection processes and numbers of samples that provide the best statistical information possible. The selections were made to reduce bias in assignment of treatments, sample locations, and level pin locations and to minimize bias caused by topographic effects on the soil profile and drainage. The statistical analyses of results included analyses of variance, comparison of variances, and comparison of means (7).

The first step in the analysis was to investigate the variance of all property results, including those from both before and after injection samples. The analysis of variance, as it is called, for results from samples taken before injection was reported on previously (6), but two facts from that analysis are pertinent here. The first of these is that, for all properties measured, variance across the sites was significant and exceeded the variance within or between the pads. The second was that, for all properties determined, there was more variance within each treatment set of pads than within or between the pads of each treatment. These results are expected and even preferred from an analysis of variance so that the comparisons of property changes can be accomplished without problems that may arise from unique situations for one or two pads. In addition, these groupings of results for all properties used during studies on changes of properties were tested and found to be distributed essentially normally.

The results from testing of samples taken after injection were put through computer analysis to determine the F-statistics for an analysis of variance. The analysis included consideration of the same data groupings as for the samples obtained before injection. The F-test results were essentially the same for the samples taken after injection as for the samples obtained before injection. Once these analyses of variance were complete and the results as described above were determined, the process for finding the significance of property changes could proceed.

The first step of the property change comparisons and the second part of the statistical analyses was an analysis of variance between properties before and after injection. Each property was investigated for each treatment. The comparison and analysis of mean property changes may not be considered significant when the property values measured are for samples from different statistical populations. In other words, the soil would be a significantly different material.

The distribution of the F-statistic may be used to evaluate variances to indicate independence of populations. When used for this type of study, the computer program used determines probabilities of agreement between F-statistics. The significance level employed in this test is the 5 percent level and the results are shown in Table 2.

The estimations shown in Table 2 indicate that, when variances are significantly different, means may not actually represent average properties for different populations from the same site. Therefore, comparison of means that have significantly different variances may not prove to be a change of property caused by treatments. Ten out of the 19 properties under consideration had probabilities that indicate populations that were nonindependent for treatment one. Nine were nonindependent for treatment two. The results for treatment three property changes showed eight to be nonindependent, and for treatment four only five were found to be nonindependent. These are the possibly significant property changes for each treatment.

The third part of the statistical analyses was the comparison of changes to the mean values for each property and treatment. The first step in this process was to evaluate the significance of the differences in mean values before and after injection. The T-statistic test was used to estimate the difference of a set of mean values (μ_D). In this study, the null hypothesis ($\mu_D = 0$) indicates that there were no changes in properties between the mean values before injection (μ_A) and the mean values after injection (μ_B). The computerized analysis included a 5 percent significance level and P-values (probability) estimated by using a two-tailed test. The results are shown in Table 3.

The estimates shown in Table 3 indicate that about 90 percent of all physical property means were changed significantly. The smallest percentage change resulted in the pads of treatment four. The changes for samples from product treatments one,

Table 2. Analysis of variance results for before and after treatment.

Property	Probability T1	T2	T3	T4
1				
2	0.810[a]	0.500[a]	0.573[a]	0.010[b]
3	0.445[a]	0.108[a]	0.835[a]	0.405[a]
4	0.591[a]	0.783[a]	0.230[a]	0.007[b]
5	0.000[b]	0.002[b]	0.001[b]	0.000[b]
6	0.824[a]	0.050[b]	0.009[b]	0.027[b]
7	0.298[a]	0.781[a]	0.063[a]	0.028[b]
8	0.008[b]	0.005[b]	0.000[b]	0.313[a]
9	0.009[b]	0.001[b]	0.000[b]	0.000[b]
10	0.000[b]	0.000[b]	0.965[a]	0.643[a]
11	0.095[a]	0.166[a]	0.005[b]	0.003[b]
12	0.474[a]	0.028[b]	0.606[a]	0.014[b]
13	0.005[b]	0.088[a]	0.080[a]	0.003[b]
14	0.000[b]	0.007[b]	0.000[b]	0.011[b]
15	0.055[a]	0.000[b]	0.000[b]	0.229[a]
16	0.002[b]	0.014[b]	0.000[b]	0.000[b]
17	0.002[b]	0.072[a]	0.000[b]	0.000[b]
18	0.406[a]	0.374[a]	0.000[b]	0.167[a]
19	0.000[b]	0.000[b]	0.334[a]	0.000[b]
20	0.965[a]	0.140[a]	0.004[b]	0.012[b]

[a]The variance of results before and after injection is not significantly different when P > 5 percent; therefore, nonindependence is shown.
[b]The variance of results before and after injection is significantly different when P < 5 percent; therefore, independence is shown.

Table 3. T-test results for difference of means.

Property	Probability T1	T2	T3	T4
1				
2	0.186[a]	0.793[a]	0.027[b]	0.121[a]
3	0.000[b]	0.000[b]	0.000[b]	0.643[a]
4	0.043[b]	0.144[a]	0.007[b]	0.039[b]
5	0.013[b]	0.008[b]	0.033[b]	0.012[b]
6	0.000[b]	0.002[b]	0.000[b]	0.000[b]
7	0.010[b]	0.015[b]	0.044[b]	0.001[b]
8	0 002[b]	0.003[b]	0.010[b]	0.053[a]
9	0.000[b]	0.002[b]	0.073[a]	0.360[a]
10	0.003[b]	0.013[b]	0.208[a]	0.126[a]
11	0.779[a]	0.029[b]	0.096[a]	0.004[b]
12	0.002[b]	0.001[b]	0.053[a]	0.360[a]
13	0.000[b]	0.040[b]	0.000[b]	0.001[b]
14	0.011[b]	0.910[a]	0.171[a]	0.226[a]
15	0.009[b]	0.010[b]	0.032[b]	0.005[b]
16	0.029[b]	0.127[a]	0.003[b]	0.028[b]
17	0.689[a]	0.436[a]	0.276[a]	0.842[a]
18	0.114[a]	0.120[a]	0.600[a]	0.585[a]
19	0.980[a]	0.036[b]	0.000[b]	0.323[a]
20	0.465[a]	0.209[a]	0.186[a]	0.059[a]

[a]The null hypothesis ($\mu_D = 0$) is accepted when P > 5 percent. This indicates no statistically significant change in the mean values.
[b]The null hypothesis ($\mu_D = 0$) is rejected when P < 5 percent. This indicates that the mean value of samples before and after injection was significantly different ($\mu_B \neq \mu_A$).

two, and three are believed to be caused by the injections. Other changes noted for samples may have been caused by the effects of circumstances and the difference of samples and testing personnel.

The estimates of the differences in mean value in chemical properties are more varied. The most interesting of these are those that have to do with cation concentration changes in pore water and exchange complex extracts. These will be discussed in detail during the final step of the statistical analysis.

The concluding procedure used during the statistical analyses was a combined comparison of variance and change of means values by using the results shown in Tables 2 and 3. Criterion for complete acceptance of the significance of property change caused by injection were developed by using the Fand T-statistical tests together. Some comparisons and analyses that previously resulted in changes that were thought accepted may now be rejected or may be decreased in degree of confidence depending on the combinations of Fand T-statistical combinations. The criterion and results from this combined analysis may be evaluated by using three cases:

1. The variance of the properties for samples taken before and after injection are not significantly different and the means if the properties are significantly different ($\mu_A \neq \mu_B$). For this case, the changes determined were found significant.
2. If the variances determined are not significantly different and $\mu_A = \mu_B$, the changes are not significant (same population, no change).
3. If both the variances and the mean values of properties for couples compared are significantly different, the changes determined may be considered partly significant and the results are not always completely conclusive.

The final determinations of significance for property mean value changes are shown by property and treatment in Table 4. The case that applies is shown for each comparison. The cases that are of most interest and importance are detailed below by property.

Table 4. Statistical significance of treatment methods.

Property	Property No.	T1	T2	T3	T4
Oven-dry water content	2	PS	PS	SS	NS
Air-dry water content	3	SS	SS	SS	PS
Plastic index	6	SS	PS	PS	PS
Linear shrinkage	7	SS	SS	SS	PS
Percentage swell	8	PS	PS	PS	PS
Swelling pressure	9	PS	PS	NS	NS
Shear strength	10	PS	PS	PS	PS
pH	11	PS	SS	NS	PS
CEC	12	SS	PS	PS	NS
Pore water cations					
Na	13	PS	SS	SS	PS
K	14	PS	NS	NS	NS
Ca	15	SS	PS	PS	SS
Mg	16	PS	NS	PS	PS
Exchange complex cations					
Na	17	NS	PS	NS	NS
K	18	PS	PS	NS	PS
Ca	19	NS	PS	SS	NS
Mg	20	PS	PS	NS	NS

Note: SS = statistically significant, PS = partly significant, and NS = not significant.

Water content changes:

Treatment one--Significant increase in air dried, partly significant increase in oven dried;
Treatment three--Significant increases in air dried and oven dried; and
Treatments two and four--No significant changes.

Atterberg limits and related indices--There were significant decreases in PI for all treatments, where samples from treatment one pads had the most significant change, followed by that for samples from treatment two and the least for samples from treatment three and four. There were no significant changes to measured linear shrinkage.

Swelling properties--Partly significant reduction of percentage swell for samples from treatments one, two, and three and almost no change in percentage swell for samples from treatment four. Partly significant reduction in swelling pressure for samples from treatments one and two, and almost no change in swelling pressure for samples from treatments three and four.

Figure 4. Monthly rainfall movement.

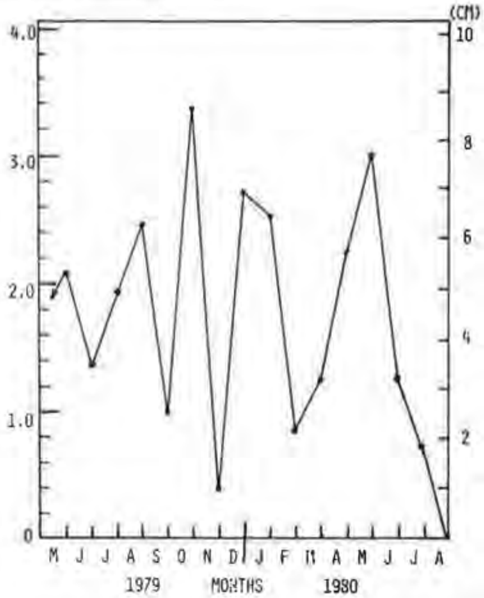
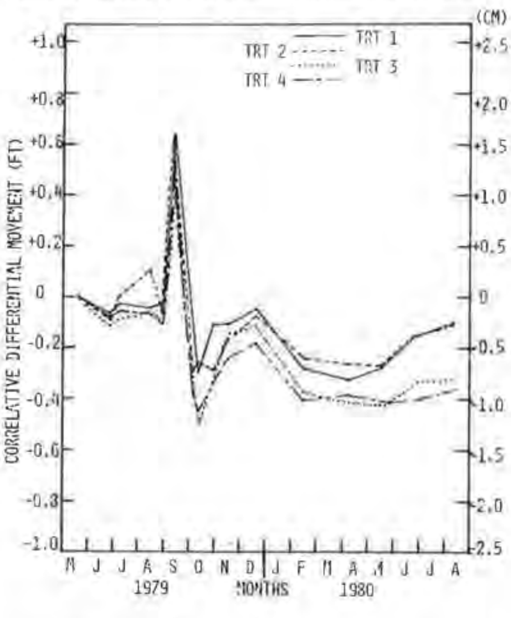


Figure 5. Monthly level differential movement in four treatments.



Shear strength--Partly significant reduction in shear strength for samples from treatment one, two, and three, with the least change for samples from treatment three. Essentially no changes in shear strength for samples from treatment four.

pH--Almost no change for samples from all treatments.

CEC--Significant increase for samples from treatment one, partly significant increase for samples from treatment two and three, and no changes for samples from treatment four.

Pore water cation concentrations:

Sodium--Significant decreases for samples from treatments two and three.

Potassium--Partly significant increase for samples from treatments one and four.

Calcium--Significant increase for samples from treatment one, partly significant increases for samples from treatments two and three, and significant decrease for samples from treatment four.

Magnesium--Partly significant decreases for samples from treatments one, three, and four; no changes noted in samples from treatment two.

Exchange complex cation concentrations:

Sodium--Partly significant decreases in samples from treatment two; no changes noted for samples from other treatments.

Potassium--Partly significant increases in samples from treatments one and two, partly significant decreases in samples from treatment four, and no changes noted in samples from treatment three.

Calcium--Significant increases in samples from treatments three, significant decreases in samples from treatment two, and no significant changes in samples from treatment one and four.

Magnesium--Partly significant decreases in samples from treatments one and two; no changes noted in samples from treatments three and four.

There were no analyses concerning the changes of dry unit weights because this property was not measured for after-injection samples.

Ground Level Movements Caused By Climatic Effects

The ground level movements that occurred before, during, and for approximately one year after injection were monitored by using the 25 level pins placed in each pad. Elevations measured were relative to a benchmark founded 20 ft (6.1 m) deep. Since there was no opportunity to cover the pads, the analyses related to change of elevations of the pad were related to change of elevation of the level pins. The changes in the elevations of the same 100 pins were measured and averaged for each treatment.

The ground surface movements monitored, therefore, were affected by rainfall, temperatures, and the injection processes. The movement should reflect general trends of rainfall and temperature and the specific event of injection. In addition, they should reflect the ability of the subgrade, injected or not, to resist general climatic cycles.

It is possible to analyze the ground surface movements determined by using Figure 4, which shows the monthly rainfall record, and Figure 5, which is a plot of average movement for pads from each treatment. In all cases the ground elevations fell during May and June 1979 because of low rainfall and increase of temperature. The elevations of all pads stabilized somewhat during July because of more rainfall. During July and August 1979 the lime slurry injections were carried out. A notable rise in the ground surface for pads in treatment one occurred when water injections were performed. Treatment one and two had the most affect of swelling the injected soil subgrade. The rainfall in September 1979, coupled with reduced temperatures, is believed responsible for the rise in the ground surface for all pads. The drastically lower rainfall of October 1979 is reflected in the elevation drop in the ground surface for the site. Note, however, that the ground surface movements for pads in treatments one and two were the least; that for pads of treatments three and four were greatest. During the rest of 1979 and until August 1980 the ground movements followed climatic events. In all cases, the movements for pads of treatments one and two were less than those for pads of treatments three and four. The trend supports the other results and substantiates the stabilizing effects of

treatments one and two versus treatments three and four.

CONCLUSIONS AND RECOMMENDATIONS

The objective of the investigation was to determine the property changes that occurred during and shortly after an active clay soil subgrade was injection-stabilized by using three different stabilization application procedures. The objective was realized by obtaining numerous samples before and after treatment. These were tested both physically and chemically. The results were then statistically analyzed for significance.

The results from the testing program, level pin elevation analyses, and statistical analyses indicate the following conclusions.

Treatment numbers one (single LSPI and three water injections) and three (double LFASPI) resulted in significant water change in content. Each caused an increase in mean water content of about 2.5 percent. Treatments two (double LSPI) and four (control) caused no significant change to water content.

Although all four treatments affected the plastic index of the soil subgrade, only treatment one had nonindependent variance and definite change in means. This change amounted to an 18 percent reduction. The results for samples from treatment two were much closer to proving nonindependence than those from treatment three or four, which means that treatment two was more effective in changing the measured plastic index than was either treatment three of four.

Although the statistical analyses resulted in only partial significance, there was significantly less potential of percentage swell for treatments one and three and less for treatment two than for treatment four. The changes in swelling pressure caused by treatments one and two were at least partly significant; the changes caused by treatments three and four were not statistically significant.

The changes in shear strength, although partly significant, occurred mainly where the soil moisture content increased. The stabilizing effects of the fly ash in treatment three probably account for the least loss in strength.

The significant change in CEC that occurred only for treatment one and the partly significant increase caused by treatment two is believed to occur because of the changes in cation concentrations that accompanied these. The less significant change to CEC caused by treatment three is believed to be from a lesser effect on these cation concentrations.

Although some of the stabilizing effects noted were caused by changes in moisture content, the cation concentrations in the pore water changes for each treatment provide insight to how these treatments chemically stabilize the soil:

1. Treatment one caused partly significant reductions in sodium, increases in potassium, and decreases in magnesium; however, it caused significant increases in calcium.
2. Treatment two caused significant reductions in sodium and partly significant increases in calcium.
3. Treatment three caused significant decreases in sodium, partly significant decreases in magnesium, and partly significant increases in calcium.
4. Treatment four caused partly significant decreases in sodium, partly significant decreases in magnesium, and significant decreases in calcium.

One may conclude, then, that treatment one significantly changed the pore water concentrations of calcium to stabilize, and treatments two and three did this to a lesser degree. The highly variant nature of soil pore water chemistry is further supported by these results.

The changes to exchange complex cation concentrations may be summarized by treatment:

1. Treatment one caused partly significant increases in potassium and decreases to magnesium;
2. Treatment two caused partly significant decreases to sodium, increases to potassium, decreases to magnesium, and significant decreases to calcium;
3. Treatment three caused significant increases to calcium; and
4. Treatment four caused partly significant decreases to potassium.

One may conclude that, other than the changes caused by highly variant exchange complex chemistry, the only stabilizing effect was noted in changes to calcium caused by treatment three.

Of the treatments applied during this study, treatment one (single LSPI followed by a three-staged water injection) performed best in stabilizing this soil. The next most effective treatment was number two (double LSPI). Treatment three (double LFASPI) had some stabilizing effects.

One may also state with confidence that LSPI affects the pore water calcium concentrations between the lime seams, especially when followed by water injections. In addition, LFASPI affects the calcium concentrations in the exchange complex of the soil between LFA seams.

The only soil mass effects studied were change in ground surface elevation. Results of these studies support the use of LSPI for reduction of ground surface elevation change caused by climate.

The recommendations offered as a result of the findings of this study are as follows:

1. In order to properly investigate comparisons of soil stabilizing agents and methods, statistical analyses, such as those used in this study, are a necessity.
2. Investigations into the stabilizing effects of chemically acting soil stabilizers should include studies of changes in the soil chemical property.
3. The research reported on in this paper should be extended to optimize injection-stabilization agents and techniques to include injection spacing, injection depths, and agent concentrations.

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Soil-Cement for Use in Stream Channel Grade-Stabilization Structures

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Numerous streams in the loess hills of western Iowa are entrenching their channels, consequently there is a need for economical grade-stabilization structures to control this erosion. Soil-cement has been suggested as a possible low-cost construction material. A study was undertaken to determine the erosion resistance of cement-stabilized alluvium when subjected to water velocities equivalent to velocities over small drop structures in drainage basins that have areas less than 26 km^2 (10 $mile^2$). A second objective was to compare erosion resistance of freeze-thaw specimens with durability as measured by the currently accepted brush test. Erosion and brush tests were conducted on alluvium-cement and alluvium-sand-cement mixtures. Laboratory erosion tests, at jet velocities less than 6.0 m/s (20 ft/s), result in lower weight losses than do brush tests of the same mixtures. The results of the two test methods, in terms of the selection of a cement content, are comparable when the erosion test is conducted at a velocity of 6 m/s (20 ft/s); however, the maximum weight losses are considerably higher for the erosion tests than for the brush test. As anticipated, increasing the sand and cement contents produces more durable soil-cement mixtures regardless of the test method. These laboratory results suggest that anticipated channel flows and velocities should be considered in the economical design of soil-cement for a grade-stabilization structure.

Stream channels in the loess hills of western Iowa have been entrenching as much as five times their original depth since the latter part of the last century. The degradation of the channels has been accompanied by widening as side slopes become unstable and mass movement occurs. For example, the Willow River drainage ditch as constructed in 1919 was 4.6 m (15 ft) deep and 6.7 m (22 ft) wide, but by 1958 the channel was 9.8 m (32 ft) deep and 21 m (70 ft) wide (1). The deepening and widening of these streams has jeopardized highway and railroad bridges by undercutting footings and pile caps, exposing considerable length of piling, and removing soil beneath and adjacent to abutments.

Various types of flume and drop structures have been used to stabilize these channels. Although a need has always existed for economical grade stabilization structures to protect bridges and culverts, the problem is especially critical at the present time because of rapidly increasing construction costs and decreased highway revenues. The cost of reinforced concrete drop structures constructed in western Iowa within the last two years has been as high as \$66 000/m (\$20 000/ft) of fall. Use of riprap is not feasible because of high cost and poor durability of locally available rock. Soil-cement has been suggested as an economical alternate construction material, especially in structures on smaller streams (2).

The use of soil-cement in water control structures dates back to 1951, when a test section was constructed as slope protection against wave erosion on the southeast shore of Bonney Reservoir in Colorado (3). The earliest application of soil-cement for protection against slope erosion in full-scale construction was at Merritt Dam, Nebraska, in 1961. Subsequent water-control applications of soil-cement include reservoir linings, small auxiliary spillways, highway embankment protection along rivers, dam diversion channels, and tailraces (4). The range of cement content used in these structures varies from less than 7 to more than 14 percent by weight of dry soil (3).

A major distinction between soil-cement design in water-control structures and in highways is that, for the former, durability is more important than strength. The durability of soil-cement is normally evaluated by wet-dry and freeze-thaw tests (ASTM D559-57 and D560-57 or AASHTO T135-57 and T136-57). The Portland Cement Association (PCA) recommendation for water-control structures is that the required cement content be 2 to 4 percent greater than the percentage necessary to meet the freeze-thaw and wet-dry criteria for brush loss used for highway applications (5). Research employing water jet and wave tank tests to simulate erosive forces indicates that, if portions of the structure are subjected to milder exposures, cement content may be reduced below the standard requirement (6). Other recommendations regarding soil-cement for water resources applications include central plant mixing, compaction to a minimum of 95 percent maximum density, and limiting the soils to material that contains not less than 55 percent passing the No. 4 sieve and not more than 35 percent or less than 5 percent passing the No. 200 sieve (7).

The need for economical construction material for grade-stabilization structures in western Iowa and the somewhat arbitrary nature of the standard brush test suggest that research on cement-stabilized, loess-derived alluvium is needed. The objective of this research is to determine the erosion resistance of cement-stabilized alluvium under water velocities that are the same as the velocities over small drop structures situated in the smaller watersheds of western Iowa. For drainage basins about 26 km^2 (10 $mile^2$) in area and flood flows that have 10-50 year recurrence intervals, the velocities expected over 0.6- to 3-m (2- to 10-ft) drops range from 4.5 to 10.5 m/s (15-35 ft/s). Normal velocities in the stream channels would be lower so soil-cement specimens were tested at velocities that range from 1.5 to 7.5 m/s (5-25 ft/s).

The loess-derived alluvium selected for testing is a loam typical of a alluvium from western Iowa. None of this alluvium meets PCA gradation requirements. The erosion resistance of silty cement-stabilized soils can be increased by blending the soil with sand (6); therefore, mixtures of sand and alluvium were evaluated. The sand is typical of that available in the study area. If the sand were used in the grade-stabilization structures, it would almost meet the PCA specifications, so tests were run on the sand to provide a basis for comparison. Cement contents of the test specimens ranged from 5 to 13 percent.