

Improvement of Dispersive Clay Erosion Resistance by Chemical Treatment

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Erosion damage caused by dispersive clay soils has created many problems in compacted earth structures and natural cut slopes. Although methods exist for dispersive soil identification, there has been only limited investigation of chemical treatment to improve erosion resistance of these soils. Thus, chemical stabilization of such soils was investigated by using mixtures of hydrated lime, sodium chloride, and aluminum sulfate, which were representative of the calcium, sodium, and aluminum ion groups. This paper describes the effect of chemical treatment on the dispersion potential and erosion resistance of six Oklahoma soils. After a review of literature concerning methods of dispersive clay soil identification and chemical reactions that occur during treatment, experimental test results are presented and discussed. Test results further support the physical erosion test as an adequate means of correctly evaluating the erosion potential of dispersive clay soils. The use of soil engineering properties to determine dispersive erosion potential was evaluated and found to be unsatisfactory. Flocculation through chemical stabilization was an alternative for reducing or eliminating dispersive clay erosion problems. All three chemical stabilizers provided successful treatment and are ranked in order of decreasing effectiveness.

Damage to earth embankments and cut slopes from dispersive clay soil erosion is of increasing interest to geotechnical engineers. A dispersive clay soil erodes in the presence of flowing water, when the particle-to-particle repulsive forces exceed the van der Waals attractive forces. Thus, individual clay platelets are split off (dispersed) and carried away. Such erosion may start in a drying crack, settlement crack, or other channel of high permeability in a soil mass. When water flows through the crack and the clay is eroded at a faster rate than it can swell and close the crack, erosion damage occurs.

Current procedures for identification of potentially dispersive clay soils include several methods of finding their dispersion potential. Although the problem of identifying potentially dispersive soils has received considerable attention and successful identification techniques have been developed, modification of such soils to improve their erosion resistance has received little

attention.

The School of Civil Engineering at Oklahoma State University, Stillwater, has been engaged in a study to determine the effects of chemical treatment on the dispersion potential of cohesive soils. The project was sponsored by the Bureau of Reclamation, U.S. Department of the Interior. This paper presents results obtained during this study, in which hydrated lime, sodium chloride, and aluminum sulfate were used as chemical stabilizers. In addition to discussions of test results, a review of the basic concepts and theories used in the identification and treatment of dispersive clay soils as well as present theories and hypotheses concerning effects of chemical treatment are presented.

LITERATURE REVIEW

Identification of Dispersive Clay Soils

The first widely accepted method of identification of a potentially dispersive clay soil was proposed by Volk (1). His procedure, based on results of tests conducted on dispersive soils from Arizona, involved both qualitative and quantitative measurements of the dispersion potential of a clay soil. Fletcher and Carroll (2), while conducting tests on similar soils, discovered that the soils contained extremely high exchangeable sodium and calcium carbonate. Further research indicated that the dispersion of the clay fraction of dispersive soils resulted from the high percentage of sodium ions surrounding clay particles, relative to other cations (3). Several other researchers investigated the relationship between the concentration of sodium ions and other exchangeable cations present (4, 5, 6, 7). These researchers felt that the relationship involving sodium versus other cations present could be used to predict field behavior.

In 1967, Emerson (8) proposed a test to determine the degree of dispersion based on the observed reaction of soil aggregates immersed in water. The rapid dispersion test or crumb test, which was introduced by Sherard (9) in 1972, was a refinement of the coherence test presented by Emerson. Sherard believed his test was more closely associated with expected field behavior.

A slight modification of the test proposed by Volk is

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the laboratory dispersion test (LDT), which has been adopted by the U.S. Department of Agriculture Soil Conservation Service. The LDT is currently the most widely used method of dispersive clay identification. Based on the LDT, the degree of dispersion is classified according to expected field behavior ranging from non-dispersive to highly dispersive.

After examining previously proposed tests, the authors developed a physical erosion test (PET), to better simulate dispersive soil erosion under field placement conditions (10, 11).

Chemical Treatment

Previous researchers have demonstrated that the difference between a dispersive and a nondispersive soil results from the relative concentration of sodium compared with other exchangeable cations on or surrounding the clay particles. Since the differences are chemical, chemical stabilization might be a solution to the dispersive clay problem. The first chemical treatment considered is the addition of lime (calcium oxide or hydroxide) and its effect on cohesive soils. The effect of lime, when added in the small amounts used in this research study, was to partially modify the soil rather than to stabilize it (12). The addition of lime usually results in the following changes: increase in plastic limit, decrease in plasticity, decrease in number of clay-sized particles, decrease in maximum compacted density, increase in optimum moisture content, decrease in volume change potential, and increase in shrinkage limit (13, 14, 15, 16).

Mechanisms usually presented in literature to explain the changes in physical properties from lime treatment are cation exchange, flocculation, carbonation, and pozzolanic reactions. The last two mechanisms are believed to be long-term effects that control strength gain from addition of lime. Cation exchange and flocculation, which should control soil dispersion potential, have been found to increase with increasing lime content (17, 18, 19, 20). Cation exchange and flocculation are also produced by chemical treatment with sodium chloride and aluminum sulfate.

In the United States, sodium chloride has been widely used in road construction (21, 22, 23). Several changes in the physical properties of soils and soil-aggregate mixtures are thought to occur from sodium chloride treatment (24). The following changes are generally accepted: reduction in volumetric shrinkage, reduction in expansion, decrease in permeability, increase in strength, and increase in compacted density with lower optimum moisture content. The flocculation and exchange capacity of clay soils for sodium ions depends on two factors: original ions associated with the clay mineral and concentration of sodium ions in solution (25, 26).

Use of aluminum sulfate as a chemical stabilizer has received limited attention. To some extent, aluminum sulfate has been used with phosphoric acid to provide metallic ions in soil stabilization (27). The use of aluminum sulfate as a chemical additive was investigated more fully in this study.

MATERIALS, EQUIPMENT, AND SAMPLE PREPARATION

Materials

Materials used in this study were six soils of varying physical properties and geologic histories, native to Oklahoma. Four of these soils were chosen because their soil masses exhibited dispersive clay erosion in the field. The remaining two samples were added to provide a measure of control because they were

known to be nondispersive. Pertinent engineering properties of the samples are given in Tables 1 and 2. The sample locations, geologic histories, and chemical properties of the samples are given elsewhere (10).

High-calcium hydrated lime, reagent grade sodium chloride, and laboratory grade aluminum sulfate were used in the study.

Physical Erosion Test

The physical erosion test (PET) was developed to simulate field situations and to accelerate dispersive erosion so that it could be measured during a relatively short test period (10, 11). PET apparatus, shown in Figure 1, simulates field conditions by back pressure saturation and intermittent flow of water through samples compacted to expected field moisture and density conditions. Erosion testing was accelerated by drilling longitudinal holes in the soil samples. The relationship between the weight of dry soil at the start of the testing sequence and that remaining after testing was used to indicate the percentage of erosion, i. e.,

$$\text{Percentage of erosion} = \frac{\text{initial dry weight} - \text{ending dry weight}}{\text{initial dry weight}} \times 100 \quad (1)$$

PET is believed to give better results than other chemical and engineering property tests currently used to identify potentially dispersive clay soils. Interpretation of PET data used for predicting potential dispersive erosion damage is as follows.

1. Erosion values of 0 to 15 percent indicate that little, if any, erosion should occur.
2. Erosion values of 16 to 35 percent indicate that slight to moderate erosion may occur, probably as a result of slaking or surface erosion or loss of mass structural coherence. Visual observation of PET specimens should help classify the expected behavior.
3. Erosion values of 36 to 50 percent indicate that moderate to severe erosion may occur, primarily as a result of clay dispersion and that there is some lag between construction and the time erosion damage is noted. Visual observation of PET specimens should help to determine the behavior expected.
4. Erosion values of 51 to 65 percent indicate that severe to very severe erosion may occur, primarily as a result of dispersion of a clay binder that contains an appreciable sand-silt fraction with low erosion resistance. If the soil is primarily clay, these values indicate extremely high dispersion potential. Visual observation of the PET specimens will aid predictions of the type of expected field erosion behavior.
5. Erosion values of 66 percent or more indicate soils similar to those in the previous item, except that a faster rate of erosion occurs. Very severe erosion problems should be expected with these soils, during or shortly after construction.

Although the above criteria are tentative, they nevertheless represent our best judgment about interpretation of PET results in evaluation of expected field erosion behavior (10).

Methods based on use of soil engineering properties to predict dispersive soil erosion behavior are usually not valid. For example, a typical engineering relationship developed by Gibbs and Holtz (28), involving natural density versus liquid limit, was evaluated during PET development (10). Data for 21 natural dispersive and nondispersive soils were plotted on the erosion chart of

shown in Figure 2, which indicates PET groups. Because the research samples were received in a disturbed state, standard Proctor maximum dry density was used rather than natural dry density in the graph, but the error is not believed to be significant. When the relationship shown in Figure 2 is examined, both the nonerosive, nondispersive clay soils and the highly erosive dispersive clay soils fall in and along the zone of supposedly highest erosion resistance. Another evaluation of erosion prediction was made by using soil plasticity and the A-line chart of the Unified Soil Classification System (28). The shaded areas in Figure 3 were thought by Gibbs and Holtz to represent the erosion potential of fine-grained cohesive soils. When the results obtained

from PET were plotted according to major groups, no definite relationship was observed between results obtained from PET and those based on soil plasticity.

The data shown in Figures 2 and 3 confirm the newly accepted theory that conventional soil engineering properties may not be used to correctly predict erosion resistance of potentially dispersive clay soils. Soil chemistry techniques have not been completely useful either, but PET (10) is believed to give reasonable predictions. Besides determining the amount of soil erosion expected for given soil placement conditions and worst case erosion water conditions, visual observation of samples during and after testing may give considerable qualitative insight about the type and rate of ex-

Table 1. Engineering properties of research samples.

Sample Number	Specific Gravity	Liquid Limit	Plastic Limit	Plastic Index	Shrinkage (%)		Standard Proctor		Modified Proctor	
					Linear	Volumetric	γ_d (kg/m ³)	ω_{opt} (%)	γ_d (kg/m ³)	ω_{opt} (%)
201	2.76	43	18	25	11	30	1823	12.6	2055	8.6
202	2.73	46	21	25	17	43	1723	13.5	1944	10.0
203	2.75	48	20	28	15	39	1717	13.7	1930	10.3
204	2.75	60	19	41	17	43	1534	20.5	1765	16.9
205	2.72	47	16	31	17	46	1706	16.9	1852	15.0
206	2.70	45	18	27	14	37	1661	19.0	1841	15.4

Note: 1 kg/m³ = 0.063 lb/ft³.

Table 2. Grain size analysis of research samples.

Sample Number	Percentage Passing (sieve size)							
	0.002-mm	0.05-mm	0.02-mm	0.05-mm	No. 200	No. 140	No. 60	No. 40
201	23	33	47	61	80	86	98	100
202	33	51	79	89	92	95	99	100
203	33	54	81	90	93	95	99	100
204	30	73	83	86	87	100	—	—
205	36	51	69	82	86	87	100	—
206	31	41	70	90	97	98	100	—

Note: 1 mm = 0.04 in.

Figure 1. PET apparatus.

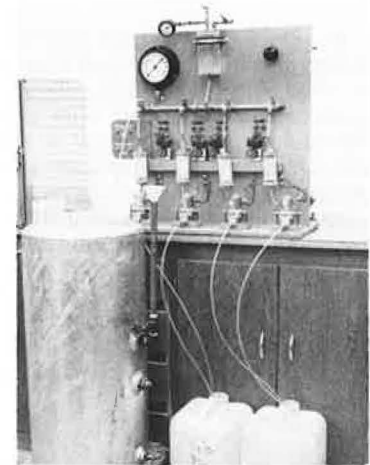


Figure 2. Trends shown by natural density versus liquid limit relationship.

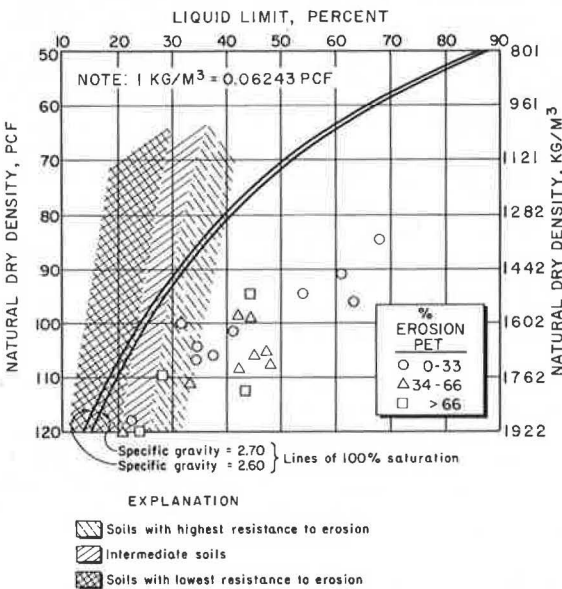
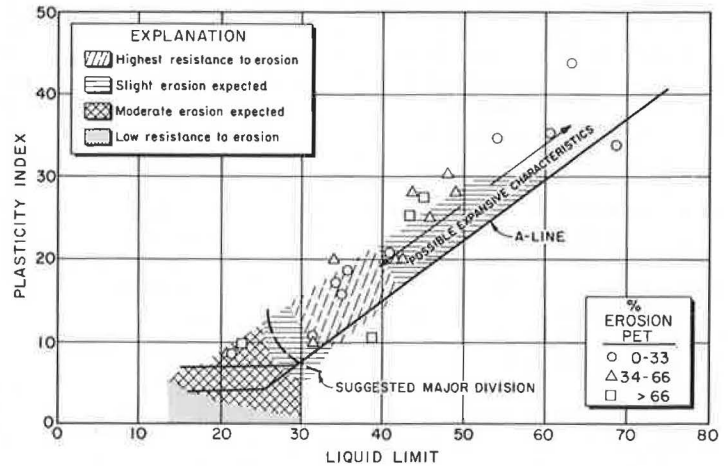


Figure 3. Suggested trend of erosion characteristics for fine-grained cohesive soils with respect to plasticity.



pected field erosion.

Preparation and Curing of Test Specimens

A standard mixing and curing procedure was used for each chemical treatment and produced nearly constant moisture contents and densities. During initial preparation, each sample was oven-dried, ground, and sieved through a No. 40 sieve. Sufficient moisture for complete chemical reaction was ensured by mixing the sample and admixture at 2 percent wet of optimum moisture content for 24 hours before compaction. The samples were compacted to standard Proctor maximum dry density at optimum water content by using a Harvard miniature mold and the Ohio State University miniature impact compaction device. Details of procedures used in sample preparation and curing are given elsewhere (10, 11, 29).

RESULTS

The primary objectives of the investigation involved the effects of lime, sodium chloride, and aluminum sulfate treatment on the dispersive erosion potential of cohesive soils; however, the dispersive erosion potential of the cohesive soils had to be determined without any chemical treatment. In the following sections, the effects of lime, sodium chloride, and aluminum sulfate treatment on six cohesive soils are presented and discussed.

No Chemical Treatment

Each sample was tested for internal erodibility a total of 16 times: 8 times at standard Proctor density and 8 times at modified Proctor density. Test results obtained from samples compacted at both standard and modified compaction and corresponding water contents were approximately the same. The explanation of this is based on a combination of two factors: The increase in dry density as a result of increased compactive effort leads to a decrease in susceptibility to internal erosion, and lower water contents associated with optimum compaction under increased compactive effort tend to increase erodibility. When both these influences on the behavior of a soil mass occurred simultaneously, the result was no general change in the average percentage of erosion.

Lime Treatment

Results obtained from physical erosion testing of lime-treated samples showed a substantial decrease in the percentage of erosion as the percentage of lime was increased, even for the nonerosive control samples.

Figures 4 and 5 show typical effects of lime treatment on erosion of dispersive soil sample 202. These photographs were taken during the pilot study phase, and because little erosion took place at the higher lime percentages, the production research was carried out with 0.5, 1.0, and 1.5 percent lime.

The effects of lime treatment on soil erodibility, as shown by a plot of the percentage of erosion versus chemical treatment for each soil tested, are shown in Figure 6, in which a relationship is seen to exist between the percentage of lime treatment and PET percentage of erosion. Although this relationship is not linear, the percentage of erosion definitely decreases as the percentage of lime treatment increases.

An explanation for the effectiveness of lime as a chemical treatment for dispersive clay soils is based on several factors. One factor is the increase in Ca^{++} cation exchange with the increase in soil pH. Another factor believed to cause decrease in erosion with increase in lime

treatment percentage is compression of the ionic atmosphere around the clay particles. Pozzolanic reactions between the lime and clay particles may also have caused an increase in strength, and the cementation reduces measured erosion. Although this last reaction was observed to occur, it was not directly measured.

Sodium Chloride

Percentages of sodium chloride chosen were 1, 2, and 3 by dry weight of soil. Two methods were used in adding the sodium chloride to the soil sample. One method involved mixing the sodium chloride and the soil before water was added; the other method involved dissolving the sodium chloride in water before it was mixed with the dry soil. The least effective mix procedure in the treatment of dispersive erosion would provide better insight into the use of sodium chloride in either form. Since the wet mix method gave a less effective treatment, as seen in Figure 6, the dry mix procedure was abandoned after three soils had been tested. Relationships between the percentage of sodium chloride, both wet and dry mixed, and the average PET percentage of erosion are shown in Figure 6.

When these results were analyzed, three different patterns of change in erosion were noted when sodium chloride was added. The first erosion pattern was observed in sample 201 in which the percentage of erosion initially decreased, then increased as the percentage of sodium chloride increased. The second pattern was observed in samples 202, 203, and 206, in which the average percentage of erosion decreased as the percentage of sodium chloride increased. The final pattern was observed in control samples 204 and 205, in which the average percentage of erosion increased as the percentage of sodium chloride increased.

The different patterns of erosion may be explained when sodium chloride is considered to act as a peptizing agent. Van Olphen (19) notes that, as the concentration of ions increases when sodium chloride is added, a charge reversal on the clay edges is likely to result because of anion adsorption on the clay edges that causes clay dispersion. Then, according to Mysels (30), further sodium chloride causes the concentration of sodium cations to increase on the clay surface as the adsorbed anions are replaced, and a flocculated structure results.

The behavior of control samples 204 and 205 seems to demonstrate that an initial increase in sodium chloride causes an increase in dispersion potential. These samples possessed an initially low ESP (clay), which is the exchangeable sodium percentage (ESP) (3) divided by the percentage of the clay fraction. ESP (clay) is expressed as a percentage (11). A low ESP (clay) indicates a small amount of adsorbed sodium ions when compared with the total cation exchange capacity of the clay fraction. Although we initially thought that sodium chloride addition should cause additional flocculation of the nondispersed soils, especially at the sodium chloride percentages added, it appeared that the samples exhibit charge reversal and dispersion rather than flocculation from high sodium concentrations in the pore water. However, a point probably exists after which the addition of more sodium chloride will result in flocculation rather than in dispersion.

Samples 202, 203, and 206, which possessed an initially high ESP (clay), demonstrated a reduction in dispersion and thus a reduction in the percentage of erosion as sodium chloride was added. The high initial sodium concentration of these soils had caused a charge reversal on the clay edges; thus when additional sodium was added it became a flocculating agent rather than a peptizing agent.

Sample 201 was observed to first decrease and then

Figure 4. PET observations at start of testing for sample 202 with lime treatment.

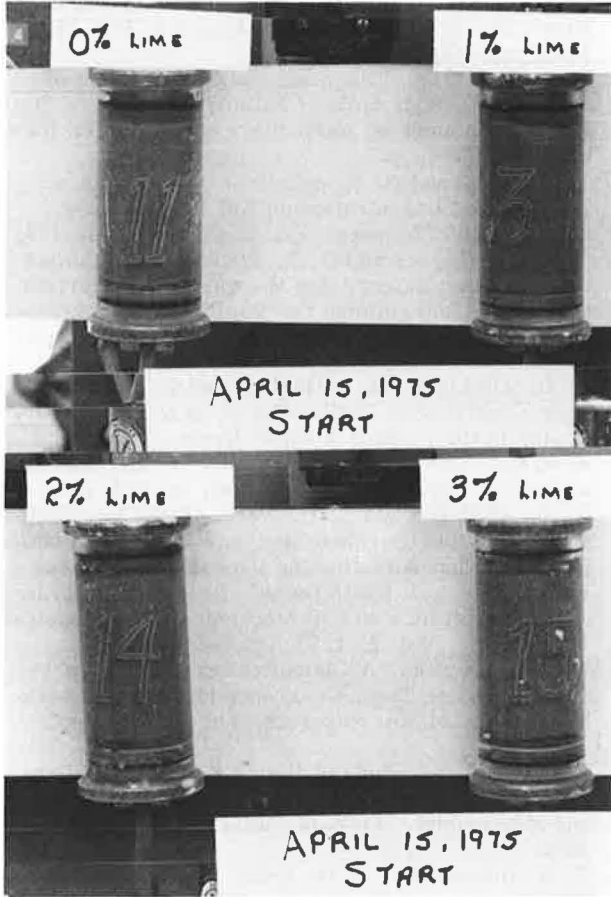


Figure 5. PET observations after 4 hours of testing for sample 202 with lime treatment.

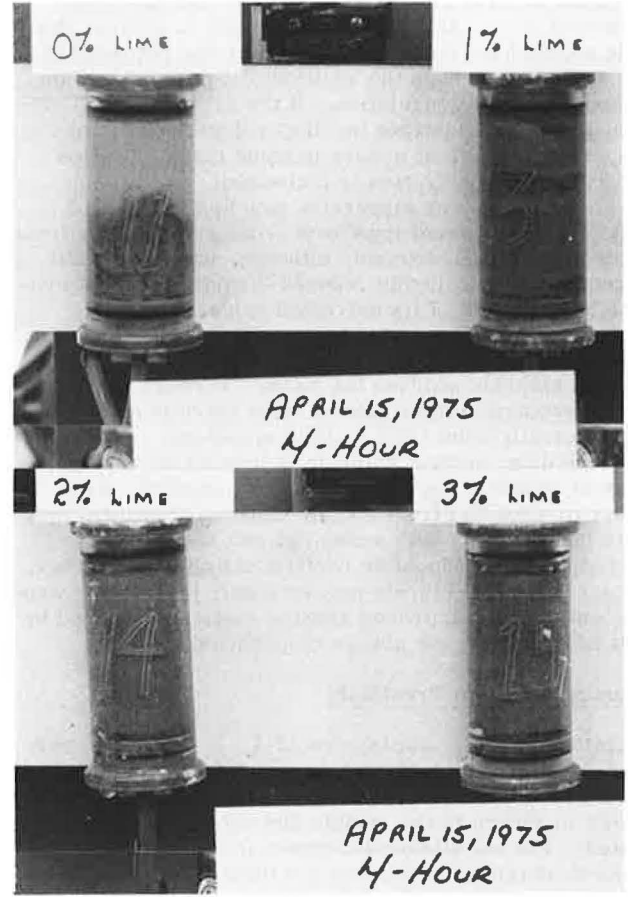
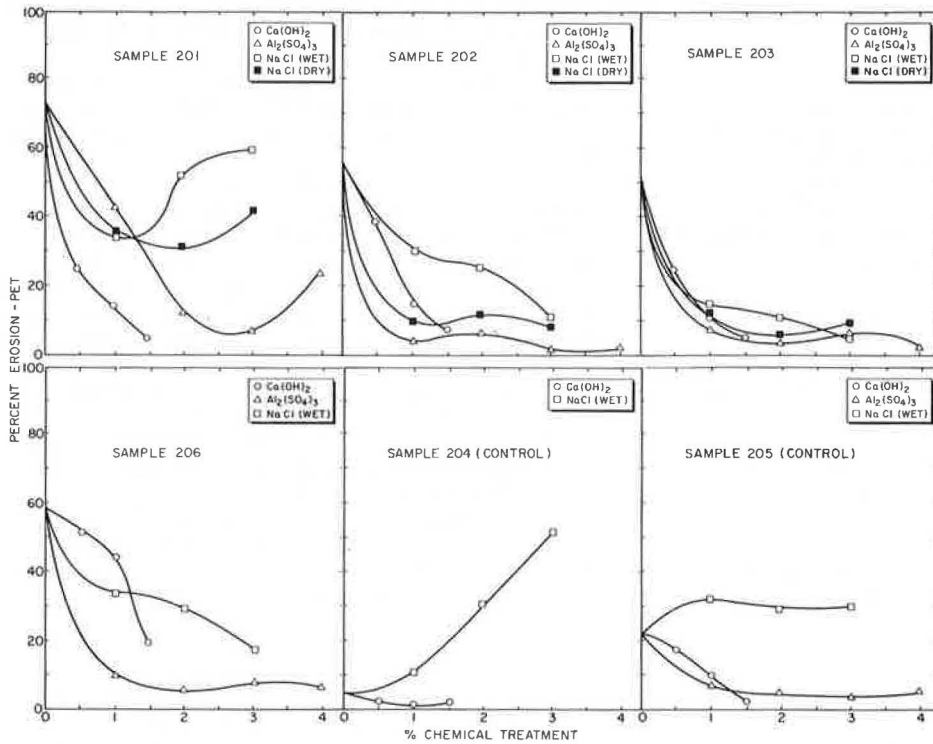


Figure 6. Percentage of erosion, based on PET, versus chemical treatment for each soil sample.



increase in erosion potential as the sodium percentage increased. Sample 201 is the anomaly of the study and is highly erosive as indicated by ESP and ESP (clay) values of zero. Adding a small amount of sodium chloride should have increased the dispersion potential of the soil, and perhaps the addition of 1 percent sodium chloride caused flocculation. If the data are not in error, they may illustrate the dispersion-flocculation-dispersion cycle that occurs in some clays as cation electrolyte concentration is increased.

Three of the four dispersive samples tested (202, 203, and 206) showed improved erosion resistance from sodium chloride treatment, although, for sample 201, 1 percent sodium chloride reduced the percentage of erosion to about half of its untreated value. However, higher treatment percentages caused increased erosion. The two low-sodium control soils were dispersed by sodium chloride addition but as they were not dispersively erosive in their natural state there is no reason to chemically treat them in field situations. According to these data, sodium chloride is less effective than lime in reducing dispersive erosion potential. Also, the behavior expected from sodium chloride treatment may vary considerably with amount of salt used; thus expected behavior should be confirmed by PET. Further, because sodium chloride may be easily leached by seepage waters, the improved erosion resistance caused by salt addition may not always be permanent.

Aluminum Sulfate Treatment

Aluminum sulfate admixtures of 1, 2, 3, and 4 percent by dry weight of soil were used. The effect of aluminum sulfate treatment on erosion resistance is shown in Figure 6; the sample 204 control soil was not tested. The significant decreases in the percentage of erosion shown in the figures are thought to result from flocculation of the soil. Although aluminum sulfate treatment appears to be an effective method of reducing dispersive soil erosion, its unit cost is considerably higher than that of either lime (which works as well or better) or sodium chloride.

CONCLUSION

The objective of this study was to determine whether chemical treatment could be used to adequately prevent erosion caused by dispersive clay soils. This objective was accomplished by evaluating the effectiveness of various chemical treatments on the erosion pattern determined by PET. From the analysis of the data obtained during this study, the following may be concluded:

1. Results obtained from this study further verified that PET is an adequate indicator of potentially dispersive clay soils;
2. Use of soil density or plasticity is not an adequate means of predicting the dispersive erosion potential of clay soils;
3. Flocculation through chemical stabilization is a reasonable alternative for reducing or eliminating dispersive clay problems; and
4. All three chemical stabilizers evaluated, hydrated lime, aluminum sulfate, and sodium chloride, provided successful treatment and are ranked in order of decreasing effectiveness.

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