Dispersive Clay Embankment Erosion: A Case History

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A fine-grained soil mapped as the Cupco soil series by the U.S. Department of Agriculture's Soil Conservation Service was used as embankment material on a recent project. The project was located on US-59 in LeFlore County, near Panama, Oklahoma. The work called for embankment widening in the southbound direction. A segment of the completed embankment experienced some characteristic dispersive clay erosional patterns following a period of above-normal rainfall. Representative samples of the embankment material were taken from standard penetration tests, from thin-walled tube samplers, and by hand auger. A laboratory analysis determined the soil classification, in-place density, moisture content, and moisture-density relationships for the embankment material. To determine the dispersive characteristics, the following tests were used: pinhole, double hydrometer, soluble salts in the pore water, and crumb. Statistical analyses were conducted for the different dispersion test results. All four laboratory tests indicated a highly dispersive clay material. Correlations were observed among compaction water content and density and dispersion. The effects of the soluble salts in the pore water and clay dispersion were analyzed. It is believed that the main mechanism that triggered this embankment erosion was rainwater flowing in cracks that had resulted from earlier drying of the clay. Significant contributing factors were found in the plan design and during construction. The damaged embankment was repaired by undercutting and filling holes, gullies, and tunnels; plating with select material; and flattening the design slope.

Certain natural soils tend to disperse in the presence of relatively pure water. These soils are highly susceptible to erosion and piping. The principal difference between dispersive clays and ordinary erosion resistant clays is the nature of the cations in the pore water (*1*).

Dispersive clays contain sodium as the predominant cation in the pore water, whereas nondispersive clays contain calcium and magnesium. The presence of the dominant sodium ions increases the thickness of the diffused, double water layer surrounding the individual clay particles. This leads to a deflocculated structure in which the repulsive forces exceed the attractive forces so that the individual clay particles go into suspension in the presence of water.

Dispersive clays generally have low to very low permeability rates (*2*). As a result, the velocity of water moving through the pores is insufficient to move the soil particles, even under very high heads. However, once a crack or opening occurs, the dispersed clay particles go into suspension and are easily carried away with the water moving through the opening.

The tendency for dispersive erosion in a given soil depends on such variables as the mineralogy and chemistry of the clay. Studies have shown that soils with montmorillonite as the predominant clay mineral tend to be more dispersive than those containing kaolinite and vermiculite (*3*). Further studies have revealed that dispersive clays have at least 12 percent of their particles, computed on a dry weight basis, finer than 0.005 mm as determined by ASTM D422-63 (1990) (*2*). These clays have a plasticity index greater than 4 and tend to have a pH well on the acidic side (*4*).

The soil surveys conducted by the U.S. Department of Agriculture (USDA) Soil Conservation Service in Oklahoma provide a general indication of dispersive clays. The more recent soil surveys in Oklahoma (those published since 1975) contain significantly more engineering and chemical data and indicate the dispersive potential and location of mapped soil units more accurately. Dispersive clays are common in Oklahoma, occurring randomly within residual and alluvial soil deposits derived from shales of the Permian and Pennsylvanian geologic periods.

This paper presents a case history of the geotechnical investigation of the conditions and factors influencing severe dispersive clay erosion of a highway embankment. The project involved widening the existing two-lane section of US-59 between Panama and Poteau in LeFlore County, Oklahoma, to four lanes with a center median. To accomplish this, the existing embankment was widened as shown in Figure 1. The southbound lanes were constructed almost entirely on new fill with a 6:1 roll off slope increasing to a 2:1 side slope down to the toe. A soil type used in the embankment construction from one of the adjacent borrow pits was mapped by the USDA Soil Conservation Service as the Cupco soil series, and it was placed solely in a quarter-mile extent of the embankment, hereinafter referred to as the Cupco embankment. Cupco soils at this site consist of deep deposits of somewhat poorly drained silty clay loams that are strongly to very strongly acidic in the A-horizon ranging to neutral in the B-horizon on broad floodplains of Brazil Creek. The initial phase of the project began with the construction of the southbound embankment starting in September 1990 and ending in November 1990. The pavement surface and base courses and the vegetative mulch and sodding for embankment side slope protection were set aside from December 1990 through August 1991 until the southbound bridges were constructed. The embankment was unprotected for approximately 9 months.

Asphalt pavement construction began in late August 1991 and continued into September 1991. The pavement design called for 0.09 m (3.5 in.) asphalt concrete surface course (Type B) underlain by 0.30 m (12 in.) of a very open graded asphalt concrete base (Type G). The pavement design called for no edge drains. Shortly after the asphalt paving, the embankment slope was treated with a vegetative mulch tracked

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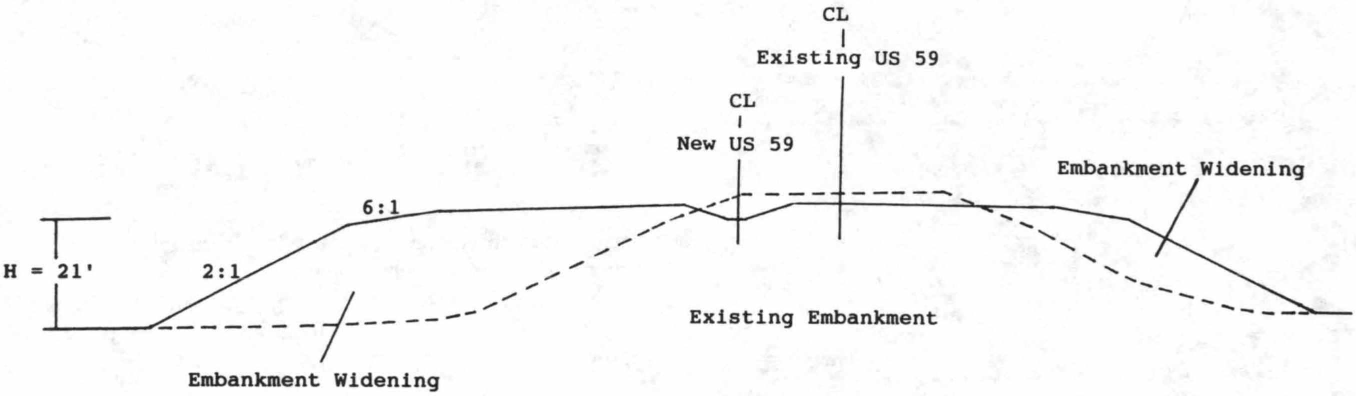

FIGURE 1 New construction for US-59, embankment cross section: Station 1475 + 00 (typical).

in by a dozer because the 2:1 side slope was too steep to use a disk. Rainfall over the 9 months before paving was near normal. However, much heavier total monthly rainfalls occurred in September, October, and November. A total of 0.31 m (12.04 in.) of heavy rain was recorded from October 24 to October 30. Within the next 2 weeks, project inspectors observed the formation of typical dispersive clay erosional features in the form of rills, gullies, tunnels, and jugs within the Cupco embankment.

SITE INVESTIGATION

A geotechnical investigation of the problem began in early November 1991. The most prominent erosional feature, an open hole on the surface, commonly called a jug, leads to an underground tunnel. The extent of the jug was surveyed. The survey identified 242 erosional holes within the extent of the 6:1 roll-out slope within the Cupco embankment that had a minimum dimension of 0.46 m (1.5 ft.). The average jug depth was 1.25 m (4.1 ft.) with a range of 0.46 to 4.48 m (1.5 to 14.7 ft). Additionally, the embankment was heavily rilled and had numerous gullies and tunnels that broke out on the 2:1 side slope. Figures 2 and 3 typify the embankment surface appearance.

Soil samples from the embankment were obtained from the standard penetration tests (SPTs), from thin-walled tube samplers, and by hand auger. Three SPT borings were continuously sampled, and adjacent to the SPT borings at five offsets, three additional borings were made in which 0.61-m (2-ft) thin-walled tube samples were taken at 0.91-m (3-ft) intervals. The appropriate sampling techniques (*5*) applied were D1586-84, D1587-83, and D1452-80, respectively. The SPT and tube samples were taken through the depth of the embankment and into the foundation soil. The length of the embankment was broken into quarters, and these borings were made at the ¼-, ½-, and ¾-point locations on the 6:1 slope. The hand auger samples were taken at random within the top 2 ft of the embankment along the 6:1 and 2:1 slopes.

A review of the 1981 USDA Soil Conservation Service soil survey for LeFlore County shows that the entire embankment and adjacent borrow pit are in a large mapped extent of the Cupco soil series. The Cupco soil series are noted in the LeFlore soil survey to have high sodium content. A pedological soil survey was made by hand auger identifying all horizons at a representative, undisturbed location between the Cupco embankment and the borrow pit. Adjacent hand auger

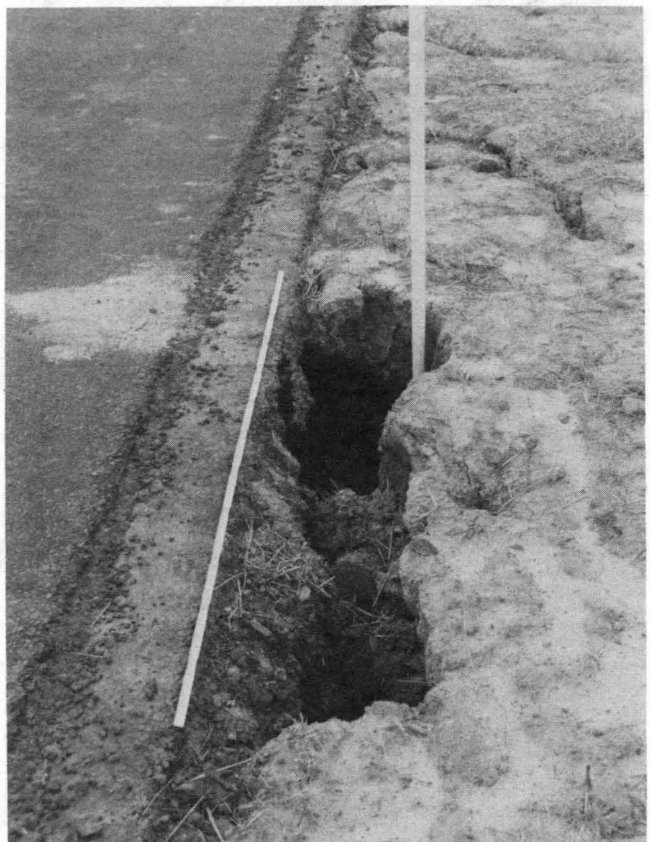

FIGURE 2 Formation of jugs near pavement edge.

FIGURE 3 Gullies, rills, and tunnels on 2:1 slope.

borings and exposures in the borrow pit confirmed the Cupco soil identity.

The embankment appeared to be consistent and uniform in depth, based on the soil color, and in the surface, matching the Cupco soil series.

Water was observed draining from the edge of the (Type G) asphalt concrete base at five locations. As shallow trenches were shoveled perpendicular to the pavement edge, large quantities of oily water flowed from the (Type G) base into the trenches. This process was repeated at various stations along the eroded sections of the embankment, each having the same results.

LABORATORY INVESTIGATION

The laboratory investigation consisted of two parts. The first phase documented the material type classification, moisture content, and in-place density. The second phase identified the clay as dispersive. The four currently recommended laboratory tests used to determine if clays are dispersive are as follows:

- Pinhole test,
- Chemical analysis of pore water extract,
- Double hydrometer test, and
- Crumb test.

A total of 164 samples were tested and classified according to ASTM D4318-94 and D2487-90, respectively. Seventy-six samples were taken from the thin-walled tube samplers, and the in-place densities were measured from chunk density tests according to AASHTO T233-86. Statistical data for the soil classification and in-place moisture and density are presented in Table 1. A family of curves and a line of optimums were developed from 21 Harvard miniature proctor curves for samples of the embankment material. The in-place density and moisture of the embankment material are compared to the backcalculated line of optimums in Figure 4.

To study the dispersive character of these embankment clays, all four recommended laboratory tests were conducted. The pinhole test was performed according to ASTM D4647-87 Method A on 20 embankment samples; the test results are provided in Table 2. Fifty-three samples were analyzed for soluble salts in the pore water using an ammonium acetate saturation extract by a method after Jackson (*5*, p. 85). The saturation extract was analyzed by an inductively coupled plasma apparatus, model Jarrell-ASH 2400, to determine the quantities of the four main metallic cations in the solution (calcium, magnesium, sodium, and potassium) in milliequivalents per liter (meq/L). The results and definitions for this analysis are presented in Table 3. The double hydrometer test was conducted on 89 samples. The test method applied was ASTM D4221-90 (*6*), and the test values are tabulated in Table 2. The crumb test developed by Emerson (*6*) was con-

TABLE 1 Index and In-Place Embankment Soil Property Statistical Summary

Test	Number	Mean	Standard Deviation	Range
LL	164	32	2.3	24 - 38
PI	164	13	2.2	7 - 18
Percent Passing NO. 200 Sieve	164	90.7	5.7	65.5 - 97.4
In-Place Density, Pcf	72	104.0	12.2	96.6 - 113.2
In-Place Moisture, %	72	15.5	1.8	12.5 - 20.8

163 samples classified as CL and one as CL-ML

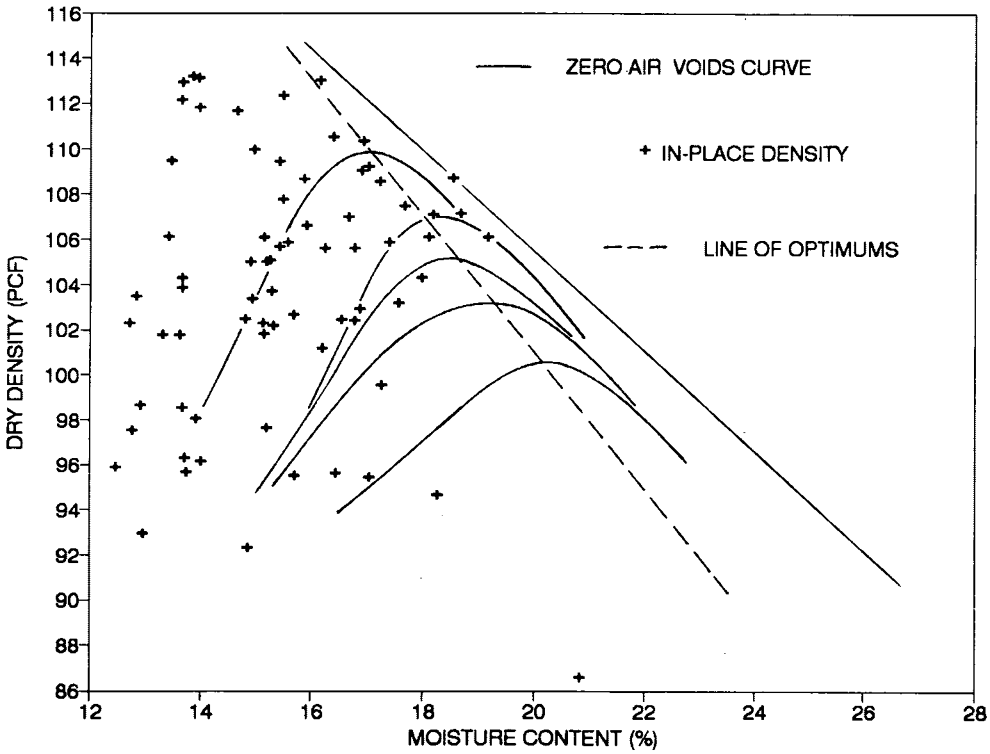

FIGURE 4 In-place densities for southbound embankment.

TABLE 2 Dispersion Test Data Statistical Summary

Test		Number	Mean	Standard Deviation	Range
Pinhole (1)					
Flow (ml/s)		20	0.92	0.30	0.51 - 1.79
Hole Diameter (mm)		20	1.90	0.20	1.50 - 2.10
Double Hydrometer					
6:1 Slope , (%)		22	81.6	20.2	57.5 - 100
Tunnel Locations , (%)		17	79.4	22.6	55.1 - 95.6
Samples with Depth , (%)		50	67.1	26.0	25.6 - 89.0
Crumb					
Rating	4	61			
	3	27			
	2	4			
	1	2			

(1) The effluent for all samples was dark. Eighteen samples were rated D2 and two samples were rated ND4.

TABLE 3 Soil Chemistry Test Data Statistical Summary

Test	Number	Mean	Standard Deviation	Range
pH	53	6.960	0.570	5.740 - 8.540
TDS[2]	53	0.652	0.429	0.129 - 2.407
CEC[1]	53	11.172	3.057	3.355 - 15.975
ESP[1]	53	19.842	6.504	3.259 - 28.768
SAR[2]	53	1.543	0.708	0.487 - 3.340
PS[2]	53	64.177	20.960	18.507 - 93.782

[2]TDS: Total Dissolved Salts = Ca + Mg + Na + K

[1]CEC: Cation Exchange Capacity

[1]ESP: Exchangeable Sodium Percentage = Na/CEC * 100%

[2]SAR: Sodium Adsorption Ratio = $Na/\sqrt{[(Ca+Mg)/2]}$

[2]PS: Percent Sodium = Na/TDS

1 - in terms of meq/100 g
2 - in terms of meq/liter

ducted on 94 samples using demineralized water. Test results are provided in Table 2.

The index, physical, and chemical properties for Cupco soil series were analyzed. The results are provided in Tables 4 and 5.

ANALYSIS AND DISCUSSION OF RESULTS

The consistency of the embankment was very uniform based on the site inspection, soil classification tests, and in-place density. Of the 164 samples tested, all were low-plasticity clays, with 163 being classified as CL and one as CL-ML (Table 1). This analysis was further confirmed by 45 SPT "N" resistance values that had a mean value of 17 and a standard deviation of 4.8.

As noted, 0.31 m (12.04 in.) of rain was recorded after the slope mulch treatment was placed on the embankment slopes. A review of precipitation records at the Poteau Water Works Station, which is located approximately 11.27 km (7 mi) south of the project, indicated that an unusually wet cycle was occurring in the area beginning in September and agreed with records kept at the site. Preceding this wet September and October were 9 months of near-average rainfall. During this period the embankment was left unprotected. As can be seen in Figure 4, the embankment soils were placed considerably dry of optimum. Compaction dry of optimum tends to increase the chances of the formation of surface cracks. There was ample time for crack development during the approximately 9-month period preceding the placement of the asphalt. It has been shown that whenever heavy rainfall and runoff can attack exposed dispersive clays, the surface drying and settlement cracks provide the avenue for dispersion to begin (*7*). This fact was observed over the 4-month investigation by noticing apparently affected embankment sections with cracks slowly degrading. Compounding the problem further the asphalt concrete (Type G) base (with no provision for drainage) was back-calculated to have a coefficient of permeability (k) of approximately 28.22μm/sec (4 in./hr). After observing the amount of water flowing from the asphalt concrete (Type G) base, there is little doubt that water from the rainfall had been

TABLE 4 Cupco Soil Index and Physical Properties

Soil Horizon	Depth (inches)	LL	PL	PI	Percent Passing No. 200 Sieve	Classification (Unified)	Maximum Dry Density (pcf)	Optimum Moisture (%)
A_1	0 - 11	48	28	20	96.1	CL	90.0	26.8
A_2	11 - 21	33	23	10	94.0	CL	102.2	21.4
B_{2t}	21 - 30	30	20	10	92.4	CL	106.3	19.4
B_{22t}	30 - 55	26	19	7	90.5	CL	106.8	18.9
B_3	55 - 83	27	19	8	94.4	CL	107.5	18.5

TABLE 5 Cupco Soil Chemistry Properties

		Cation Concentration meq/litre								
Soil Horizon	pH	Ca	Mg	Na	K	CEC[1]	ESP[1]	SAR[2]	TDS[2]	SODIUM[2]
A_1	5.5	0.157	0.106	0.115	0.001	9.404	0.978	0.317	0.3795	30.303
A_2	5.4	0.101	0.012	0.072	0.001	3.067	3.684	0.679	0.0950	75.790
B_{2t}	6.4	0.008	0.034	0.189	0.025	6.085	12.950	1.306	0.2559	73.935
B_{22t}	6.3	0.011	0.046	0.182	0.029	5.742	9.000	1.080	0.2674	68.025
B_3	6.7	0.013	0.060	0.356	0.040	6.495	18.362	1.854	0.4696	75.724

[1]CEC: Cation Exchange Capacity

[1]ESP: Exchangeable Sodium Percentage = Na/CEC * 100%

[2]SAR: Sodium Adsorption Ratio = $Na/\sqrt{[(Ca+Mg)/2]}$

[2]TDS: Total Dissolved Salts = Ca + Mg + Na + K

[2]SODIUM: Percent Sodium = Na/TDS

1 - in terms of meq/100 g
2 - in terms of meq/liter

trapped beneath the asphalt concrete surface course. Other contributing factors were as follows:

1. The 2:1 embankment slope allowed surface runoff to flow downslope faster than a flatter slope, helping to accelerate the erosion.
2. A drainage ditch was cut at the toe of the slope to allow runoff to drain to Brazil Creek. This ditch let water back up onto the slope and further accelerate the dispersive erosion during heavy rains and flooding of the creek. This event was observed twice during the investigation. On these occasions, it was noted that the erosional exit tunnels lined up slightly below the highwater marks on the 2:1 slope. The tunnels increasingly changed during the course of the rise and fall of the water in the ditch.
3. The tracking in of the slope mulch treatment by a dozer is thought to have broken up the slope surfaces, therefore providing another access for rainfall to enter into the soil. The dispersion of the embankment slopes started occurring and accelerating before the planned 0.15 m (6 in.) treatment of topsoil and sodding could be placed.

All four tests for soil dispersion showed positive results. The percentage of dispersion based on accepted criteria for the samples tested are as follows:

	Percentage
Pinhole test	100
Soluble salts in pore water	75
Double hydrometer	95
Crumb test	94

In the pinhole test, as seen from the data in Table 2, all samples are rated as dispersive. Only two samples were classified moderately dispersive (ND4) according to Method A of the test procedure. It must be pointed out that while 12 flow rates did match exactly the flow rate criteria for Method A, the test procedure does allow for some discretion. Section 5.3 states that the flow rates serve primarily as a guide to proper equipment and specimen performance. Therefore, the cloudiness of the effluent and hole diameter were considered sufficient (two out of three criteria) for Method A classification. If Method B criteria were used, then 19 samples would be classified as dispersive and 1 as slightly dispersive.

A key finding of the analysis for the soluble salts in the pore water is the high percentage of sodium, a mean exceeding 60 percent (Table 3). Generally the percentage of sodium in a saturation extract is a reliable indicator of probable dispersiveness of a soil (*8*). If the percentage of sodium versus the total amount of dissolved salts is plotted on the relationship shown in Figure 5, approximately 75 percent of the samples are dispersive. This relationship (*6*) is based on the pinhole test correlation and experience with erosion in nature. Figure 5 indicates that for these soils, dispersion is possible when the total amount of dissolved salts are less than 1.0 meq/L and the percentage of sodium is high. From these data, it would appear that for these soils the boundaries for Zones A and C of 60 and 40 percent are appropriate for separating potential dispersive clays.

The exchangeable sodium percentage (ESP) and the sodium absorption ratio (SAR) are both good indicators of the stability of clay soil structure to spontaneous dispersion in water (*8*). In this case, from data in Table 3, the ESP values are high and follow the trend seen in the percentage of sodium found. When the ESP for a soil exceeds 2 percent, it is highly susceptible to dispersion in water (*8*). There is evidence that when the ESP is between 10 and 50 percent, the sodium and calcium ions separate into distinct regions within the diffused double water layer. This phenomenon further enhances the dispersiveness of the clay soil (*8*).

A comparison with earlier Australian criteria (*6*) also indicates that when the SAR exceeds values of 1 to 2, there is the potential for a soil to be dispersive. A look at the pH for

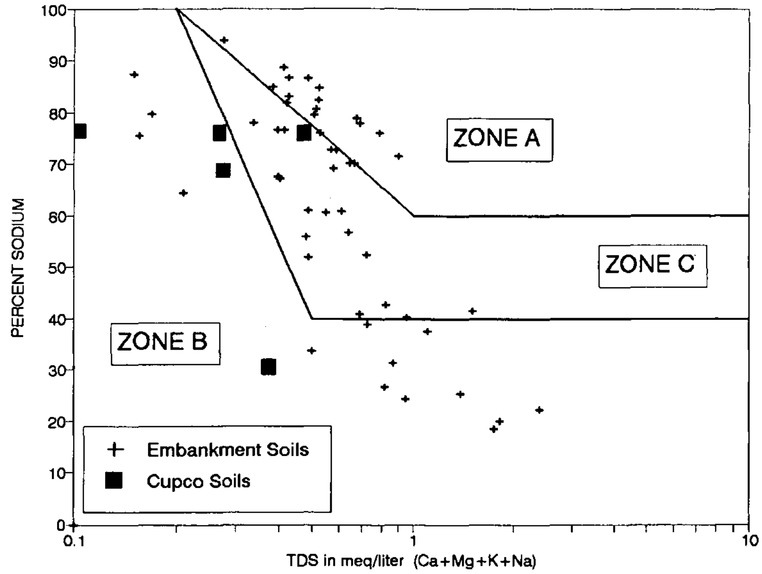

FIGURE 5 Pore water salts analysis.

these soils indicates a range from a slightly acidic to a moderately alkaline environment. As mentioned earlier, the pH in the Cupco series ranges from strongly acidic in the A-horizon to neutral in the B-horizon. The significance of the pH on dispersion is that higher pH values result in higher surface charge densities on the clay particles. Increased surface charge densities cause more concentration of ions in the diffuse double layer resulting in greater particle repulsion. However, for these soils it does not seem that the pH indicates soil dispersion.

The double hydrometer test data results are shown in Table 2 and in Figure 6. This test is good, with an 85 percent reliability for predicting dispersion when the test indicates 35 percent or more. The crumb test, likewise, proved to be a good indicator, with 29 percent showing a moderate crumb rating and 65 percent a strong crumb rating. The percentage of dispersion based on the pinhole and crumb test for the Cupco "B" horizons from the representative undisturbed location is as follows:

Horizon	*Pinhole*	*Crumb*
A1	ND1	1
A2	ND1	1
B2t	D2	4
B22t	D2	4
B3	D2	4

These results match very closely the values for the embankment material (Table 2).

RECOMMENDATIONS

At the outset of the investigation, it was suggested that the dispersive clay erosion could continue to occur underneath

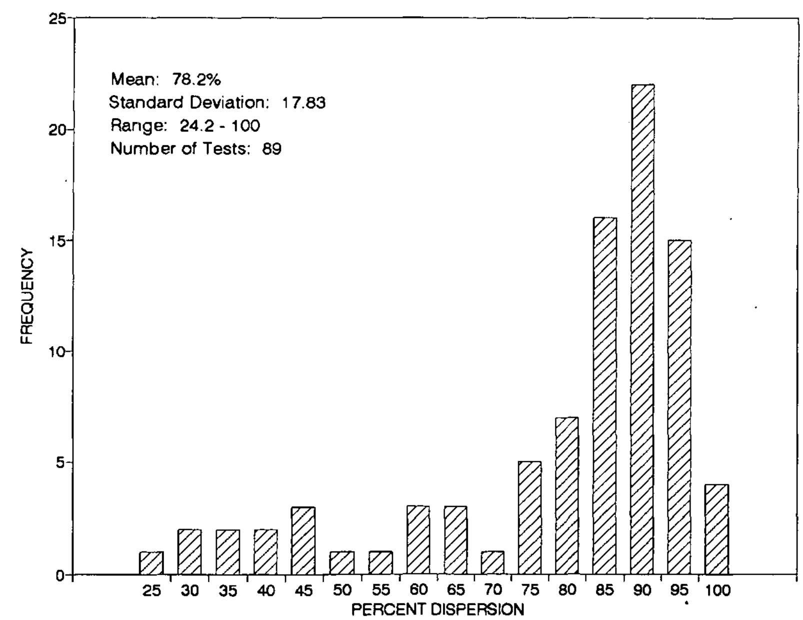

FIGURE 6 Distribution double hydrometer test results.

the newly completed asphalt pavement. However, the construction engineers pointed out that it would be unacceptable to correct this portion of the new embankment (see Figure 1) because it would require completely closing the highway at that stage of the construction. Therefore, only the following recommendations were made:

1. Stage 1 called for filling all of the known holes with a sand-cement grout. This grout was to have a sand-cement ratio ranging from 2:1 to 5:1. It was to be pumped using a conventional grout batch system while limiting the grouting pressure to 5170.5 to 6894.8 Pa (0.75 to 1.0 psi) per 0.30 m (1 ft) of overburden depth. Estimated average quantities of grout were approximately 0.25 m^3 (0.33 yd^3) per hole. Relying on grouting to fill all of the holes along and under the pavement posed a problem because it was not possible to determine the extent of hole development under the pavement.

2. Stage 2 called for lime modification of the top 0.30 m (1 ft) of the roll-off slope soil and the top lineal 3.05 m (10 ft) of the 2:1 slope. This modification would be accomplished in two phases. The top 0.15 m (6 in.) of soil would be excavated and stockpiled while the bottom 0.15 m (6 in.) would be treated in place with 5 percent hydrated lime. Upon completion of the bottom lift treatment, the bottom lift would be scarified, and the top 0.15 m (6 in.) would be returned and treated similarly. In lieu of the lime treatment of the top 0.30 m (1 ft) of the embankment, undercutting and replacing with nondispersive select material was recommended.

3. Stage 3 required filling in any holes along the 2:1 slope that were unable to be grouted. The soil used to fill these areas had to be classified as nondispersive according to double hydrometer analysis (ASTM 4221-90) and the pinhole test (ASTM 4647-87).

4. Stage 4 required flattening the existing 2:1 slope to a 4:1 slope beginning at the 6:1 roll-off slope extending to the toe of the embankment. The soil used in this stage was classified as nondispersive. This new slope construction was benched into the existing slope according to Section 202(c) of the Oklahoma Construction Specifications.

5. Stage 5 called for plating the 4:1 slope and the 6:1 slope with Bermuda grass solid slab sod.

CONCLUSIONS

The field and laboratory evidence conclusively identifies the soils used for embankment construction as high-sodium dispersive clays. Using the four tests described to identify dispersive soil is still considered appropriate practice for positive identification.

The recommendations suggested were accepted by the construction engineers responsible for the project and implemented by the project contractor. The final stage was completed in early April 1992. The side slopes of the embankment have displayed no signs of erosion, but there has been a continuing problem with depressions developing underneath the pavement where no treatment was applied. Inspection of these depressions revealed the presence of large voids under the pavement that had an average depth of 1.22 m (4 ft). This presents a significant maintenance problem as well as a liability problem if these depressions continue to appear. The project is continuing to be monitored.

At the time this study was conducted, the normal practice of the Oklahoma Department of Transportation was to allow unclassified borrow to be used as embankment material to get low contract prices. This process requires only soil classification and moisture-density tests for quality control without any preliminary screening for dispersive soils. The lesson in this case history is twofold:

1. In the reporting of preliminary soils reports, a greater effort will be made to examine the potential for dispersive soils in the highway alignment and potential borrow sources.

2. Where the use of dispersive soils appears to be unavoidable in certain areas of the state, design recommendations will be made to incorporate them in the project earthwork to negate their effect.

ACKNOWLEDGMENTS

The author would like to thank the Oklahoma Department of Transportation Materials Division for its support in this study. Special thanks is expressed to Jeff Dean and Ed Rios for participating in laboratory testing and preparing figures and tables, and to Lorraine Utley for typing.

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Publication of this paper sponsored by Committee on Transportation Earthworks.