Attrition Rates of Soil-Cement Subjected to Water Jets

L.L. LITTON AND R.A. LOHNES

Laboratory erosion tests were conducted on cement stabilized loess-derived alluvium and sand mixtures that had been subjected to 12 cycles of freeze-thaw activity. At a constant water velocity the erosion rate decreased with increasing time and followed a semi-log relationship: the specimens lost 54 percent to 97 percent of their total weight loss during the first 30 min of the 5-hour tests. The attrition rate decreased with increasing relative durability of the soil-cement. Although the results of these tests cannot be used to predict the behavior of this material in the field, the general time-loss behavior appears to be valid. The implications of this study that might be applied to field conditions are (a) soil-cement composed of loess-derived alluvium and sand mixtures will withstand high water velocities, (b) at a given flow rate the erosion rate will decrease rapidly, and (c) the soil-cement will reach a stable configuration relatively early in the flow event.

Soil-cement used in the construction of stream channel grade stabilization structures will be subjected to high erosion forces and may experience considerable material loss. The amount and rate of material loss will depend largely on the relative durability of the soil-cement, the severity of weathering, and the severity of the erosive forces. Weathering severity and erosive forces for a given geometric configuration of a soil-cement structure cannot be controlled; therefore, soil-cement must be designed appropriately to resist field conditions.

Currently accepted mix design methods allow only for the classification of soil-cement as acceptable or unacceptable for a wide range of applications. This method of classification is not useful for risk assessment nor predition of life expectancy for soil-cement structures. Data on the attrition rate of the soil-cement used in a structure are necessary to predict the useful life of that structure. This research was undertaken to study the material loss behavior of soil-cement to be used in constructing stream channel grade-stabilization structures in western Iowa.

FACTORS AFFECTING DURABILITY

The attrition rate of soil-cement under field conditions is determined by combining three factors: the relative durability of the soil-cement, the type and duration of weathering, and the type and duration of loading. These factors are not necessarily independent nor is any one consistently the most important. Laboratory testing of soil-cement must consider all the factors if the testing is to be indicative of behavior in the field.

Relative Durability

The relative durability of different soil-cement mixes is normally the first, and often the only, factor considered in the design of a soil-cement structure. Currently accepted soil-cement mix design procedures make few provisions for the consideration of any other factors.

It has been observed that the relative durability of soil-cement composed of alluvium and sand from western Iowa varies with the percentage of sand in the mix as well as the percentage of cement (1). Similar results, in terms of the relative durability of the soil-cement mixtures, were obtained from the standard wire brush methods and the new erosion test. The erosion tests also show that substantial increases in material loss may occur with increasing water velocity although the relative durability ranking of the mixtures remains much the same. From those results, it is obvious that factors other than relative durability are important for predicting the material loss of soil-cement subjected to erosion.

Weathering

Exposure to repeating cycles of wetting-and-drying and/or freezing-and-thawing causes deterioration of soil-cement both in the field and in the laboratory. The extent of the damage depends on the conditions of exposure (i.e., number and length of weathering cycles, availability of water, minimum temperature of freezing, and so forth) as well as the relative durability of the soil-cement.

Although laboratory methods may be developed to model predicted field weathering conditions, the predictions may prove quite difficult; and the reliability of the predictions without long-term studies is questionable. Judging from the success of the standard soil-cement design methods, the damage induced by the wetting-and-drying and freezing-and-thawing tests outlined in ASTM D-559 and D-560 appears to be severe when compared to field conditions. Packard and Chapman (2) determined that freezing and thawing of specimens submerged in water was more destructive to the specimens than the standard freezing-and-thawing test.

Loading

Soil-cement is used in a wide variety of situations and is subjected to a wide variety of loads. For soil-cement exposed to the elements, the erosive forces acting on the material may be more important than the structural loads. This is especially true for a stream channel grade-control structure where the primary purpose of the soil-cement is to resist the abrasive forces of water and moving sediment. The erosion forces in such a structure may vary greatly with the geometric configuration and location of the structure. For example, the forces on the stilling basin of the drop structure are different than those on a ramp structure, and the erosive forces at the top of a ramp are not the same as those at the bottom of the same ramp. The streamflow over the structure at any given time will greatly affect the magnitude of the forces on the material. If the flow can be estimated, the forces anticipated on various parts of the structure may be determined by analytical methods or by physical modeling.

Laboratory Modeling of Field Conditions

Numerous methods could be developed to test the durability of soil-cement mixes under a wide variety of conditions of relative durability, weathering, and loading; however, to predict field durability, the laboratory tests must either model field conditions or be correlated to field performance. Before prototype field structures are available for the correlation, the only option is to attempt to model field conditions. Field conditions for stream channel grade-control structures are extremely variable and complex thereby making it impossible to reproduce all conditions in proper sequence in the laboratory. Testing under conditions more severe than those anticipated in the field is the conservative approach for these preliminary laboratory tests.

After prototype structures have been constructed and evaluated, the laboratory procedures may be modified to reflect the findings of the field studies.

The relative durability of the soil-cement is the factor controlled by the designer and, therefore, was a primary variable in this study. The relative durability of the test specimens was varied by using different percentages of sand and cement in the mixes. Although the relative durability of identical soil-cement mixtures under similar conditions was determined in Part I of this experiment (1), it was not possible with those data to predict the long term loss of material under erosion.

Weathering, a major factor in the field performance of soil-cement, is extremely variable and, therefore, very difficult to predict for laboratory modeling. Because freezing-and-thawing of soil-cement submerged in water is more severe than the standard freezing-and-thawing method and the standard freezing-and-thawing method appears severe when correlated to field performance, specimens in this study were subjected to submerged freezing-and-thawing before erosion testing.

A wide range of water velocities was investigated in this study so the results could be generalized to various site erosion-control structures and various flood recurrence intervals.

MATERIAL AND MATERIAL PREPARATION

The soil and sand used in this study were obtained from western Iowa and are typical of the loess-derived alluvium and quarried sand found in that locality. The distribution of the grain sizes of the pure materials and combinations of those materials used in this study are shown in Figure 1. The optimum moisture content and associated dry density for the material combinations were determined in accordance with ASTM D-558 and are given in Table 1.

Test beams were molded to maximum density at optimum moisture content, then cured at 21°C (70°F) and 100 percent relative humidity for 7 days. After curing, the specimens were frozen until the beginning of laboratory freezing and thawing. Two days before scheduled erosion testing, the test beams were removed from the freezer and placed in a Logan freeze-thaw cabinet where they were submerged in water and subjected to 12 cycles of freezing and thawing. Erosion testing of the beams usually began immediately after their removal from the cabinet.

Table 1. Optimum moisture density relationships of soil-cement mixtures.

Soil Mixture (% by weight) Sand/Cement	Optimum Moisture Content (%)	Dry Density (gm/cm^3)
0/9	20.4	1.58
25/7	15.8	1.77
40/7	13.6	1.88
55/7	11.6	1.92
100/7	9.0	1.94

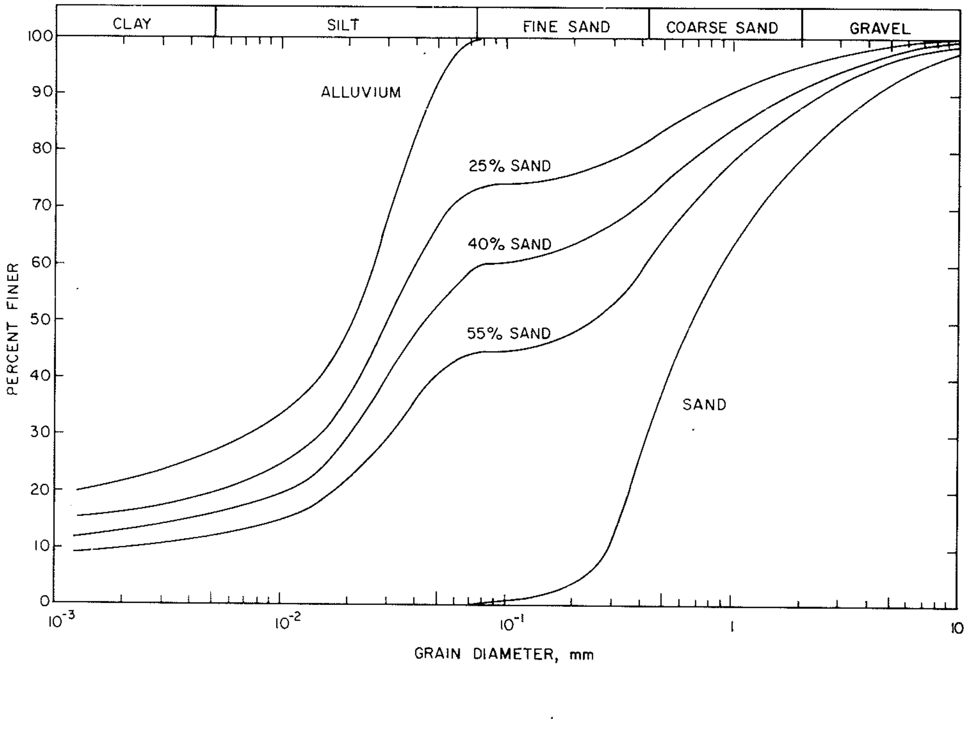
TEST PROCEDURES AND RESULTS

Load Correlation Test Procedure

Two different types of erosive forces are possible in grade-stabilization structures: a force from a free overfall of water impinging on a stilling basin and a force from water flowing parallel to the sides and bottom of a structure. Laboratory experiments were undertaken to determine which flow type is more detrimental to soil-cement and to establish a correlation between the losses under each type of force.

The tests to evaluate the erosion resistance of the cement stabilized soil under the influence of water flowing parallel to the specimen are identified as tractive tests. Specimens were placed in Plexiglas holders and positioned in the test flume so that water would flow over the surface at a rate of 4.72 m^3 per minute per meter of width (380 gpm/ft) for 15 min. The tractive erosion force was caused by the water flowing over the test beams while in this position. The specimens were removed from the flume and weighed to determine the weight loss during this portion of the test. After weigh-

Figure 1. Soil mixture gradation curves.



ing, the specimens were returned to the flume and positioned in such a way that water was allowed to fall from a height of approximately 1 meter onto the surface of the test beams. The beams were then subjected to the free overfall of water supplied at the same flow rate and for the same period of time as in the tractive test. After the overfall portion of the test, the specimens were weighed again to determine the weight loss from water impinging directly on the surface of the specimen.

Load Correlation Test Results

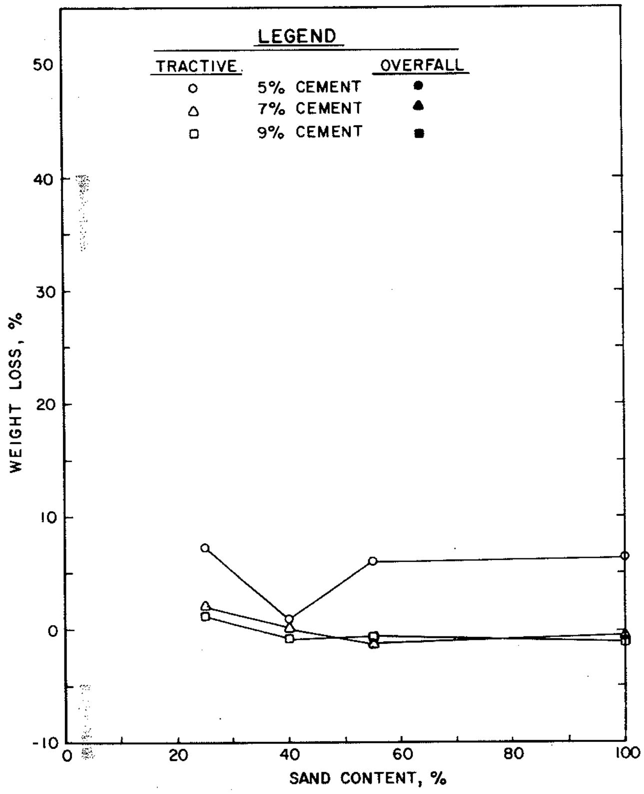
The results of the load correlation tests are shown in Figures 2 and 3 where the percent weight loss is plotted versus the sand content of the specimen. For ease of comparison, the figures are plotted at the same scale. As anticipated, most specimens suffered attrition during the free overfall test in addition to that they sustained during the tractive erosion test. Those specimens with 5 percent cement experienced up to 13 times the tractive test attrition during the overfall test, whereas the specimens with higher cement contents experienced a maximum of four times the tractive erosion during the overfall test (see Table 2). Instances of negative weight loss were presumably caused by water retained by the sample holders.

Because the load correlation tests indicate that an impinging flow is more severe on soil-cement in instances where there was a measurable difference, an impinging jet was used as the erosion mechanism in all erosion rate studies.

Attrition Rate Test Procedure

Test beams were placed under a 12.6 mm- (1/2 in.) wide water jet running transverse to the longitudinal axis of the beam. The more durable specimens of 25 and 40 percent sand were tested with water velocities of 6.0 and 7.5 m/sec (20 and 25 ft/sec) whereas the less durable beams, those with no sand, were tested with velocities of 3.0 and 4.5 m/sec (10 and 15 ft/sec). All test beams were weighed at cumulative time intervals of 5, 15, 30, 60, 120, 180, 240, and 300 min to determine the rate of material loss in each interval.

Figure 2. Weight loss versus sand content for tractive erosion test.



Attrition Rate Test Results

Results of the attrition rate tests on specimens containing no sand are shown in Figure 4 where the cumulative percent weight loss of the test beams is plotted as a function of the duration of testing.

Figure 3. Weight loss versus sand content for overfall erosion test.

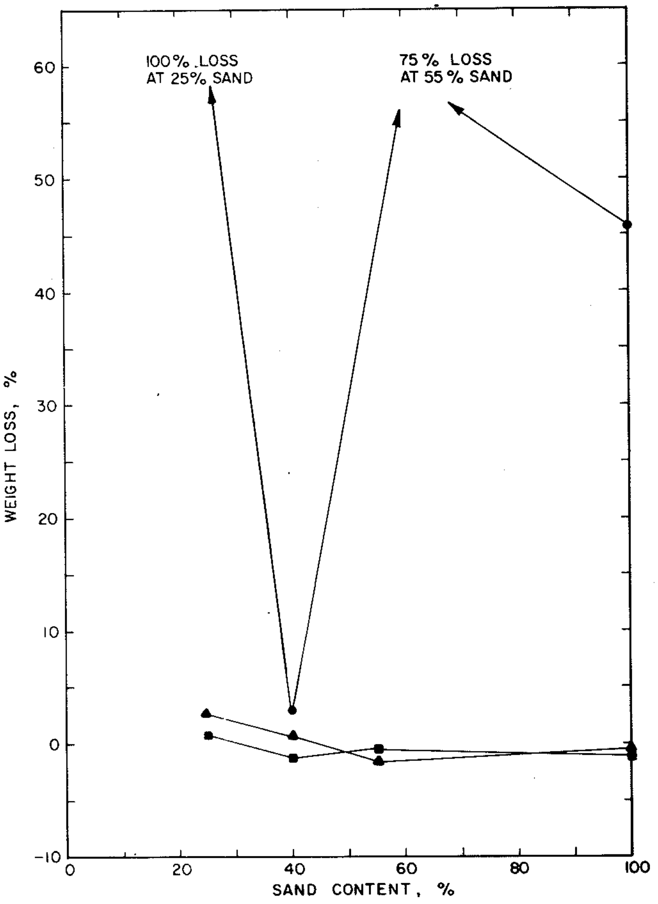
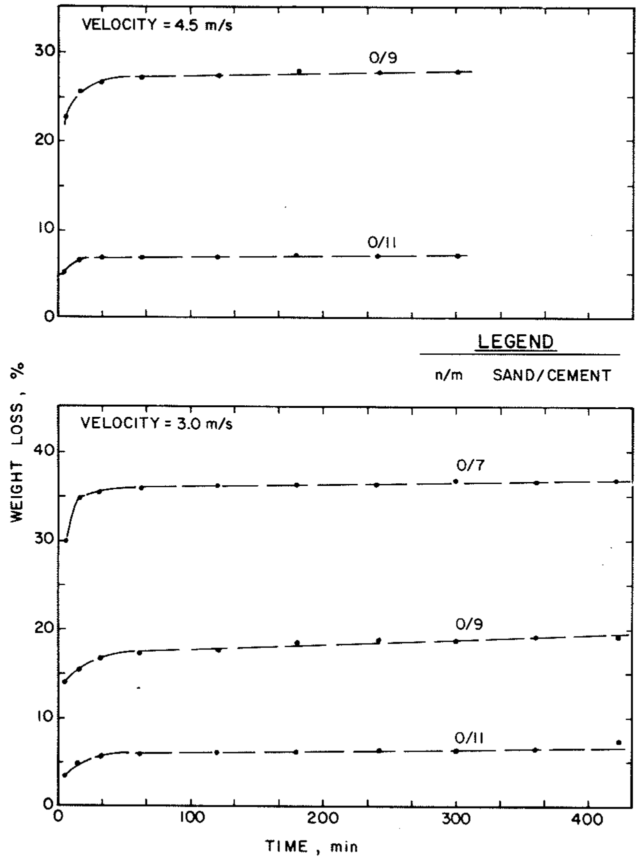


Table 2. Erosion losses for load correlation tests on soil-cement.

Soil Mixture (% by weight) Sand/Cement	Weight Loss (%) Tractive Test (WL_t)	Overfall Test (WL_o)	WL_o-WL_t	$\left(\frac{WL_o-WL_t}{WL_t}\right)100$
25/5	7.3	100	92.7	1270
25/7	2.0	3.0	1.0	50.0
25/9	1.2	1.9	0.7	58.3
40/5	0.9	3.0	2.1	233
40/7	0.2	0.8	0.6	300
40/9	-0.9	-1.0	-0.1	11.1
55/5	6.0	75	69.0	1150
55/7	-1.3	-1.3	0	0
55/9	-0.8	-0.7	0.1	-12.5
100/5	6.4	45.8	39.4	616
100/7	-0.8	-0.6	0.2	25.0
100/9	-1.2	-1.2	0	0

Figure 4. Weight loss versus erosion testing time for alluvium-cement mixtures (1 m/sec = 3.3 ft/sec).



The results are typical of all the attrition rate test results in that the rate of weight loss diminishes rapidly during the first hour of testing. Table 3 lists the portion of the total weight loss (total weight loss is taken as the weight loss after 5 hr) accumulated after 5, 30, and 60 min of testing for each of the specimens. Regardless of the total weight loss experienced during testing, more than half of the attrition occurred during the first 30 min of testing. This behavior suggests a logarithmic rate relationship between the percent weight loss and the time of testing.

Table 3. Percent total weight loss (5-hour erosion test) after 5, 30, and 60 minutes of testing.

Soil Mixture (% by weight) Sand/Cement	Water Velocity (m/sec)	% of 300-Min Weight Loss Cumulative Time (min)			Weight Loss After 300 Min of Testing (%)
		5	30	60	
0/7	3.0	81.7	96.7	97.3	36.6
0/9	3.0	72.1	86.8	90.5	19.0
0/11	3.0	50.0	85.9	89.1	6.4
0/9	4.5	81.7	95.3	97.1	27.8
0/11	4.5	73.6	94.4	94.4	7.2
25/7	6.0	51.0	60.3	83.1	47.9
25/9	6.0	36.5	85.2	93.4	24.4
40/5	6.0	43.8	74.3	80.9	27.2[a]
40/7	6.0	45.2	76.7	86.3	7.3[a]
40/9	6.0	68.8	87.5	100.0	1.6[a]
25/7	7.5	35.1	53.5	62.3	11.4
25/9	7.5	57.1	79.6	83.7	4.9
40/7	7.5	41.7	60.4	68.8	4.8
40/9	7.5	50.0	70.0	80.0	2.0

[a] Erosion losses at 240 min; tests were stopped prematurely.

The results of the attrition rate tests show good correlation when plotted with the percent weight loss as a function of the logarithm of testing time as shown in Figures 5-7. The data for the equation used to calculate these lines, along with the coefficients of correlation, are given in Table 4. The rate of weight loss may be compared by comparing the slopes of the linear semilog plots. The intercepts given in Table 4 represent the weight loss in the first minute of testing.

Too few tests were run for a statistical analysis on the initial losses and the rate of loss; however, trends in the data are noted. The rate and initial loss generally decrease with increasing sand and cement content. The one exception to the trends, i.e., the specimen with 25 percent sand and 7 percent cement, experienced an anomalously low initial weight loss.

Although it was anticipated that higher velocities would result in higher attrition rates, the data do not support this assumption. Only the specimens with 40 percent sand and 9 percent cement exhibited higher attrition rates with increased water velocities. For the specimens containing no sand, this anomaly may be justified somewhat by the higher initial losses experienced by the specimens eroded at the higher velocity. Extrapolation of the data, for illustration only, shows that the percent weight loss for the 9- and 11-percent cement content specimens is estimated to be equal at each water velocity after 2(10)^4 days and 4 days, respectively. The anomaly of higher erosion rates caused by lower water velocities cannot be justified as easily with the specimens containing sand because the lower water velocities also produced higher initial loss

Figure 5. Weight loss versus logarithm of erosion testing time for alluvium-cement mixtures (1 m/sec = 3.3 ft/sec).

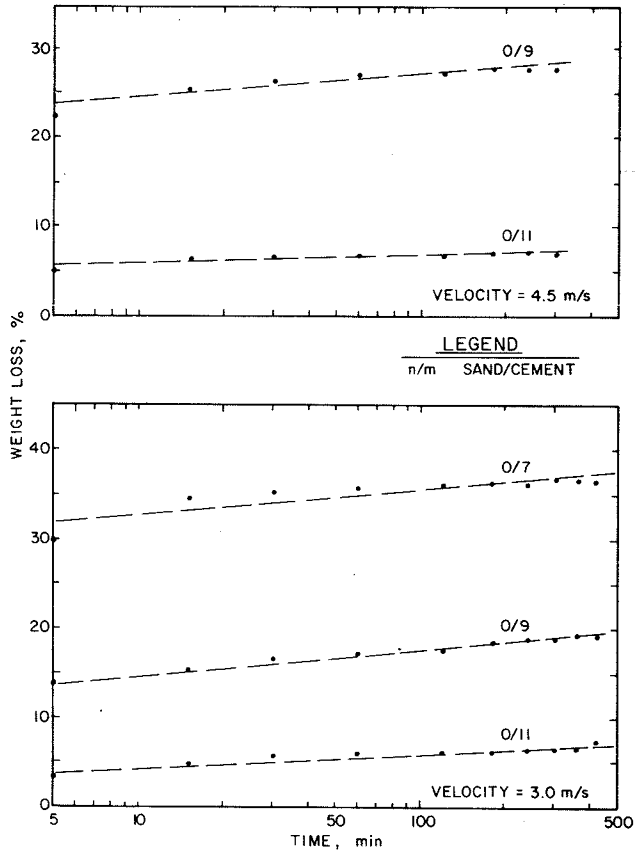


Figure 6. Weight loss versus logarithm of erosion testing time for alluvium-sand-cement mixtures under water velocity of 6.0 m/sec (1 m/sec = 3.3 ft/sec).

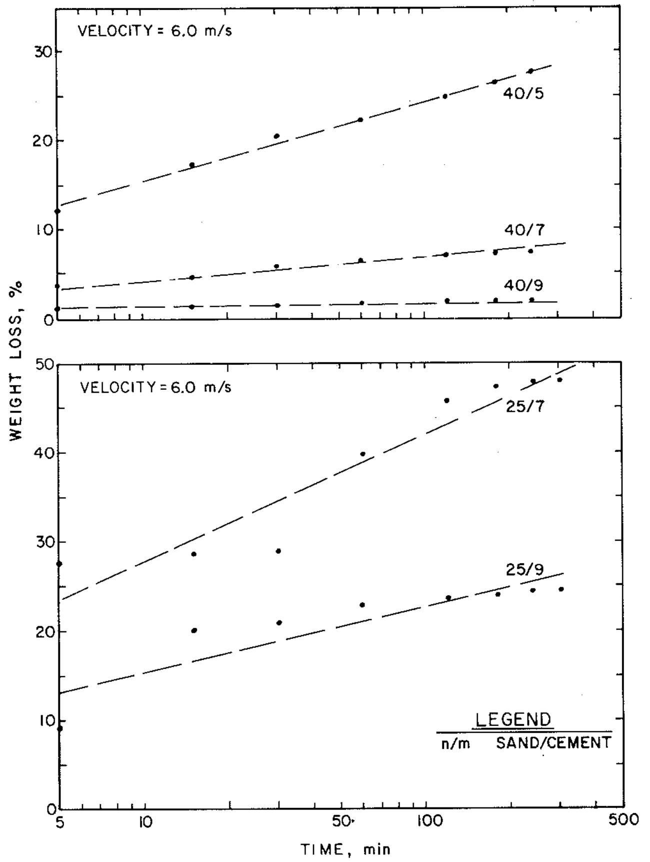
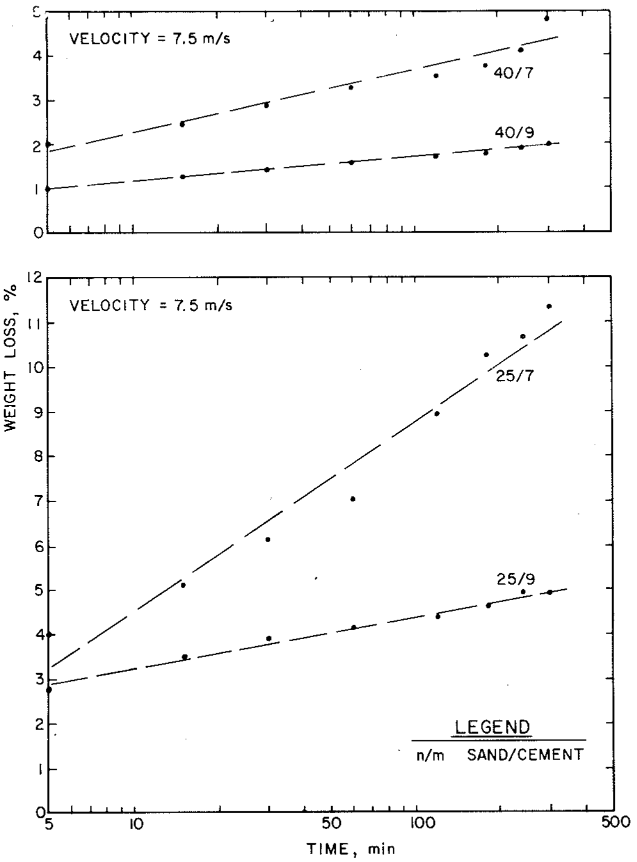


Figure 7. Weight loss versus logarithm of erosion testing time for alluvium-sand-cement mixtures under water velocity of 7.5 m/sec (1 m/sec = 3.3 ft/sec).



in each of these specimens. Because of problems with the equipment, the specimens tested at the higher water velocities were refrozen after the normal freeze-thaw cycle. Consequently, these specimens were cured for an extra 24 hr during the thawing cycle immediately before erosion testing. It does not seem reasonable that the extra curing time could account for all the deviation; therefore, it might be concluded that there is an optimum water velocity for eroding soil-cement. Verification of the preceding results using duplicate specimens is needed.

CONCLUSIONS

Laboratory erosion tests on cement-stabilized alluvium and alluvium-sand mixtures from western Iowa produce attrition rates that decrease with time at a constant water velocity. In laboratory tests, specimens lost 54 to 97 percent of their total weight loss during the first 30 min of a 5-hr test at a constant water velocity. Apparently, the basic soil-cement erosion resistance is greater than any erosive force applied to the laboratory test specimens thus far. The material lost under the erosive forces was presumably that which deteriorated during the freezing-and-thawing cycles, and the reduction in the rate of erosion was a consequence of reaching material that was weathered to a lesser degree. As anticipated, the attrition rate decreased with increasing relative durability of the soil-cement.

Although the results of the laboratory tests cannot be used to predict directly the attrition rate of soil-cement used in a stream channel grade-stabilization structure, the general time-loss behavior is thought to be valid. The implications of the laboratory tests as they relate to field implementation are

1. Soil-cement composed of loess-derived alluvium and sand with alluvium will withstand high water velocities.

2. At any given flow rate, the attrition rate of the soil-cement will decrease rapidly; therefore, the soil-cement will reach a stable configuration

Table 4. Weight loss versus Ln (time) data for attrition rate equations for soil-cement[a].

Soil Mixture (% by weight) Sand/Cement	Water Velocity (m/sec)	Slope	Intercept[a]	R^2
0/7	3.0	1.22	30.0	0.77
0/9	3.0	1.22	12.0	0.98
0/11	3.0	0.68	2.7	0.93
0/9	4.5	1.12	22.0	0.88
0/11	4.5	0.40	5.1	0.85
25/7	6.0	6.16	13.7	0.90
25/9	6.0	3.15	8.1	0.78
40/5	6.0	3.88	6.3	0.99
40/7	6.0	1.06	1.8	0.98
40/9	6.0	0.12	1.0	0.93
25/7	7.5	1.85	0.31	0.96
25/9	7.5	0.51	2.06	0.99
40/7	7.5	0.60	0.90	0.93
40/9	7.5	0.23	0.64	1.00

Note: The general form of the equation used for the curves in Figures 5-7 is % weight loss = slope Ln (Time) + intercept.

[a] Percent of weight loss in the first minute of testing.

relatively early in the flow event and subsequent material loss will be minimal.

Field verification of the conclusions drawn from the laboratory study is needed via prototype structures.

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REFERENCES

1. L.L. Litton and R.A. Lohnes. Soil-Cement for Use in Stream Channel Grade-Stabilization Structures. TRB, Transportation Research Record 839, 1982, pp. 33-38.
2. R.G. Packard and G.A. Chapman. Developments in Durability Testing of Soil-Cement Mixtures. HRB, Highway Research Record 36, 1963, pp. 97-119.

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Design, Construction, and Frost Susceptibility of Lime Stabilized Marine Clay in Highway Subgrade Fill

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A large quantity of wet, soft, silty clay was modified with a low (1.5 to 2 percent) mixture of hydrated high-calcium lime in conjunction with freeway cut and fill grading operations in the Ottawa area. The natural clay derives from a marine saline deposit known locally as Leda Clay. In the project area the in situ moisture and sensitivity of the clay were such that it was unsuitable for conventional roadway fill construction. Adding lime strengthened the soft clay to the point that it could be used as fill within the problem area and conventional production rates of fill construction could be maintained. The modified clay was used as fill up to the subgrade level. Subsequent frost action in the fill areas created distortions so severe that the driving lanes had to be closed. An outline is presented of the design-site and laboratory-investigation analysis, the construction procedures and test data, the performance of the roadway including related climatic data, the site investigation during and after the frost heaving, remedial measures to restore the roadway, and follow-up laboratory testing and evaluation to determine causes of the unexpected frost action. Detailed test procedures and data are provided. Design and construction procedures to be used on projects with similar soft clay problems where lime modification may be an advantage are also discussed. Direct frost-heave-measurement tests on prepared specimens of the modified soil proposed for fill construction are recommended.

An extremely, wet, soft marine clay was modified with a small percentage of hydrated high-calcium lime and subsequently placed in freeway subgrade fills in the Ottawa area (1). After some adjustment of the construction equipment and operations, the contractor succeeded in achieving high-quality, well-controlled fill construction. The lime treatment reduced construction costs by reducing the requirements to dispose of the soft plastic clay and the quantity of imported fill required to construct the fill sections. In the winter and spring following completion, the pavement was opened to traffic, and severe differential frost heaving occurred. Traffic lanes had to be closed and traffic was confined to one lane on the passing side of each of the divided roadways. After the spring thaw, substantial corrective and preventive work was required to restore the roadway.

Outlined in this paper are the laboratory test procedures to determine the stabilizing effects of the lime on the soft clay, the construction procedures used and conditions that existed during the treatment and cut and fill operations, and subsequent site and laboratory investigation to determine frost heaving of soft clay treated with various percentages of high-calcium lime. Also outlined are the remedial measures taken to rehabilitate the roadway.

DESIGN

Pre-engineering samples of the in situ proposed cut material indicated a clay of intermediate to high plasticity. The materials were in an extremely wet condition with natural water contents at or near the liquid limit. Atterberg Limits and the natural water content of the samples before adding lime are given below. The lime necessary to stabilize the natural material is also given.

Property	Percent
Water content (w)	45-52
Liquid limit (W_L)	46-57
Plastic limit (W_P)	17-25
Plastic index (I_P)	29-32
Lime fixation point	1.5-2

According to normal construction practice, it is not practical to use these materials as fill. Three tests were performed to determine the effects of adding lime to the soft clay material (2). These were California Bearing Ratio, Atterberg Limits, and hydrometer analysis to determine the grain-size distribution of the material.

California Bearing Ratio

Details of the California Bearing Ratio (CBR) test procedures may be found in ASTM D 1883-73 (3). Samples of the material were mixed well with the required lime percentages and cured in plastic bags for 24 hr before compaction in the CBR molds. This