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

L.L. LITTON AND R.A. LOHNES

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).

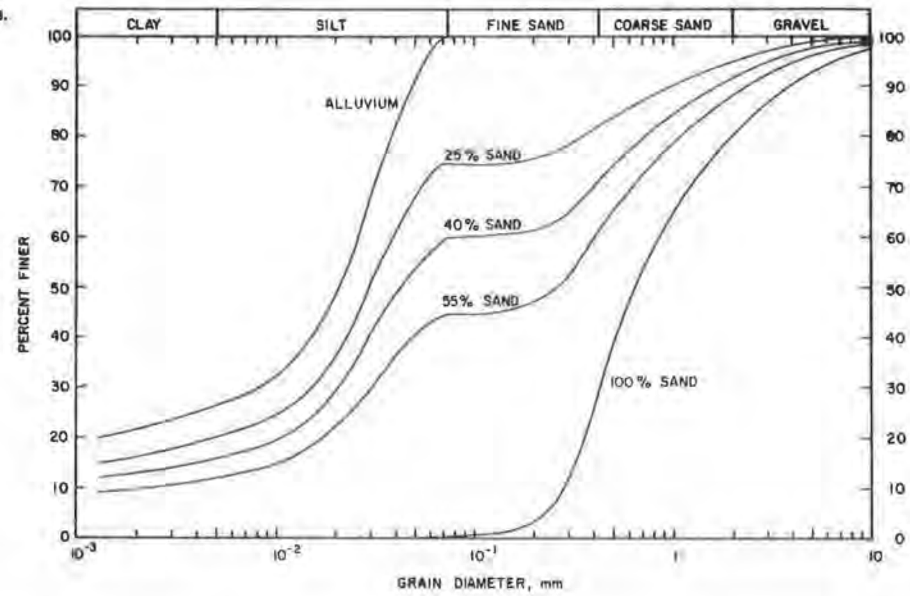
The use of soil-cement in water control structures dates back to 1951, when a test section was constructed as slope protection against wave erosion on the southeast shore of Bonney Reservoir in Colorado (3). The earliest application of soil-cement for protection against slope erosion in full-scale construction 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.

Figure 1. Soil mixture gradation curves.



The stabilized specimens were subjected to both freeze-thaw and wet-dry testing. Hydraulic erosion tests on the wet-dry specimens resulted in negligible weight loss; therefore, only the results of the freeze-thaw tests will be discussed here. Details and results of the wet-dry tests on these mixtures can be found elsewhere (8).

TEST METHODS AND SPECIMEN PREPARATION

The alluvium, with an American Association of State Highway and Transportation Officials (AASHTO) classification of A-6, was obtained from the site of a future grade-stabilization structure. The gradation of the raw materials as well as the alluvium-sand blends used in the testing program are shown in Figure 1. Alluvium-sand mixtures that contained 25, 40, and 55 percent sand as well as sand were used to test the effects of sand content on the durability of soil-cement. Cement contents of 5, 7, and 9 percent, calculated as a percentage of the dry weight of the alluvium-sand mixture, were tested in all blends. The alluvium was tested with 5, 7, 9, 11, and 13 percent cement. The portland cement used in all specimens was type 1.

Rectangular soil-cement beams of the various alluvium-sand-cement ratios were used for the hydraulic load tests. The 76.5x76.5x200-mm (3x3x7-7/8-in) beams were compacted to 100 percent maximum density at optimum moisture content as determined in accordance with ASTM D558. Optimum moisture contents and maximum dry densities are given in the following table (note: 1 gm/cm^3 = 0.004 lb/in^3):

Soil Mixture (% by weight)			Optimum Moisture Content	Dry Density
Alluvium	Sand	Cement	(%)	(gm/cm^3)
100	0	9	20.4	1.58
75	25	7	15.8	1.77
60	40	7	13.6	1.88
45	55	7	11.6	1.92
0	100	7	9.0	1.94

Soil-cement for the test beams was thoroughly mixed by hand before being placed as a single lift in a modified flexural beam mold. Compactive effort was applied from one side with a universal testing machine. After molding, the test beams were cured at 21°C (70°F) and 100 percent relative humidity for seven days.

One set of soil-cement specimens was tested in accordance with ASTM D560 (freezing-and-thawing tests of compacted soil-cement mixtures). Replicate soil-cement test beams were subjected to hydraulic erosion tests. The complete series of beams was subjected to 12 freeze-thaw cycles, each of which consisted of 24 h in a freezer at -20°C (-4°F) followed by 24 h in a humidity room at 21°C (70°F).

The erosion test was designed to simulate the velocities, hence the forces, anticipated from a free overfall of water. The velocities used were 1.5, 3.0, 4.5, 6.0, and 7.5 m/s (5, 10, 15, 20, and 25 ft/s). The relative durability of the test beams was expressed as a percentage weight loss. The beams were surface-dried and weighed after 60 min exposure to the water jet at a constant velocity. A normal testing sequence consisted of subjecting the beams to erosion by the lowest test velocity for a 60-min duration then increasing the velocity for each subsequent test. Long-term tests, up to 7 h, have indicated that 81-97 percent of the total loss occurs within the first hour of testing at a given velocity.

The apparatus used for applying the erosive force is shown in Figure 2. The curved plexiglass side panels funnel the water from the upper tank to the 12.7x406.4-mm (1/2x16-in) discharge slit. The test beams are located 152.4 mm (6 in) beneath the discharge slit in a removable sample box. Water is supplied to the test apparatus from a constant head tank to ensure consistent flow rates. The control valve was calibrated for various flow rates by discharging the flow into a weighing tank.

TEST RESULTS

The results of the brush tests on the freeze-thaw specimens (ASTM D560) are shown in Figure 3, where percentage weight loss is plotted versus percentage cement content. Because the PCA-recommended allowable weight loss for A-6 soil is 7 percent, none of the specimens of cement-stabilized alluvium is acceptable. The maximum weight loss in the brush test is 32 percent from the alluvium with a 5 percent cement content. Although the addition of sand to the alluvium changes its classification, the 7 percent maximum weight loss is used as the criterion

Figure 2. Erosion testing apparatus.

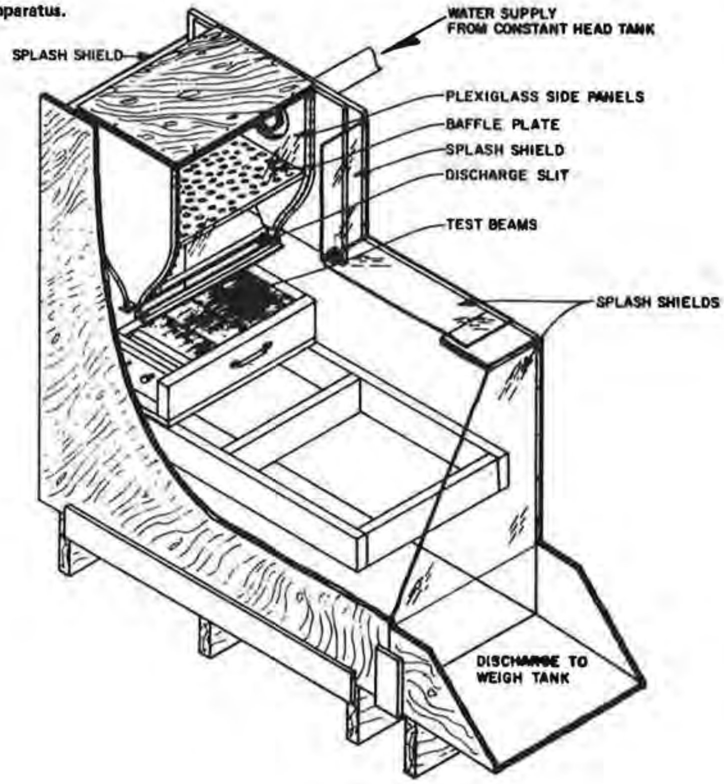
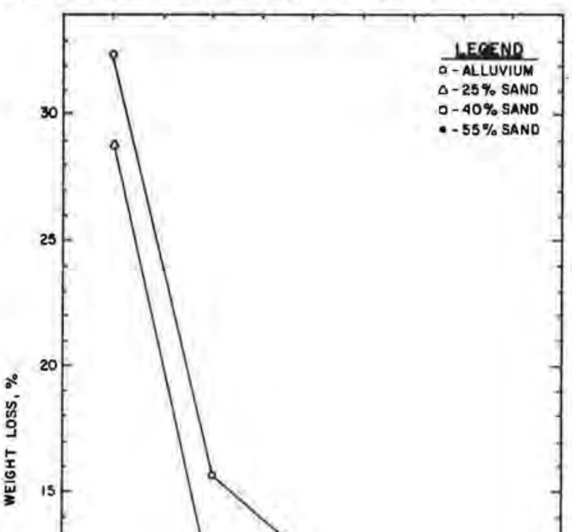


Figure 3. Weight loss versus cement content for brush tests.



for selecting minimum cement content of all the alluvium-sand mixtures. The alluvium-sand mixture that contains 25 percent sand is acceptable with a cement content about 8 percent, and the 40 percent sand mixtures is acceptable at about 6 percent. With 55 percent sand mixed with the alluvium, the mixture shows acceptable weight loss with cement contents as low as 5 percent. In this paper, the minimum cement contents indicated by the brush tests are compared with the results of the erosion tests.

Figures 4 and 5 are graphs of cement content versus weight loss for the stabilized mixtures at various erosion velocities. For a velocity of 6 m/s (20 ft/s), a weight loss of 100 percent occurred for alluvium stabilized with 7 percent cement and a weight loss of 65 percent occurred for alluvium that contains 9 percent cement. These losses are greater than the maximum lost in the brush tests. At a velocity of 4.5 m/s (15 ft/s), weight loss ranged from 28 to 8 percent for cement contents of 5-13 percent. For lower velocities, weight loss meets maximum acceptable levels at about 9 percent cement at 3 m/s (10 ft/s) and 7 percent cement at 1.5 m/s (5 ft/s), as shown in Figure 4.

Figure 4 shows that, at velocities below 3 m/s, all of the alluvium-sand-cement mixtures have weight losses below the allowable limit. At the 4.5 m/s velocity the 40 percent sand mixture has maximum allowable weight loss with about 5 percent cement, whereas the 55 percent sand content has allowable weight losses at all cement contents tested.

The 55 percent sand mixture has acceptable weight losses for all cement contents at 6 m/s velocity and for cement contents above 6 percent at 7.5 m/s (25 ft/s), as can be seen in Figure 5. The 40 percent sand content mixture has acceptable weight losses above 6 percent cement content at 6 m/s and above 9 percent at 7.5 m/s.

For the sand at all velocities and all cement contents, the weight loss was negligible; conse-

Figure 4. Weight loss versus cement content for erosion tests with velocities of 1.5, 3, and 4.5 m/s.

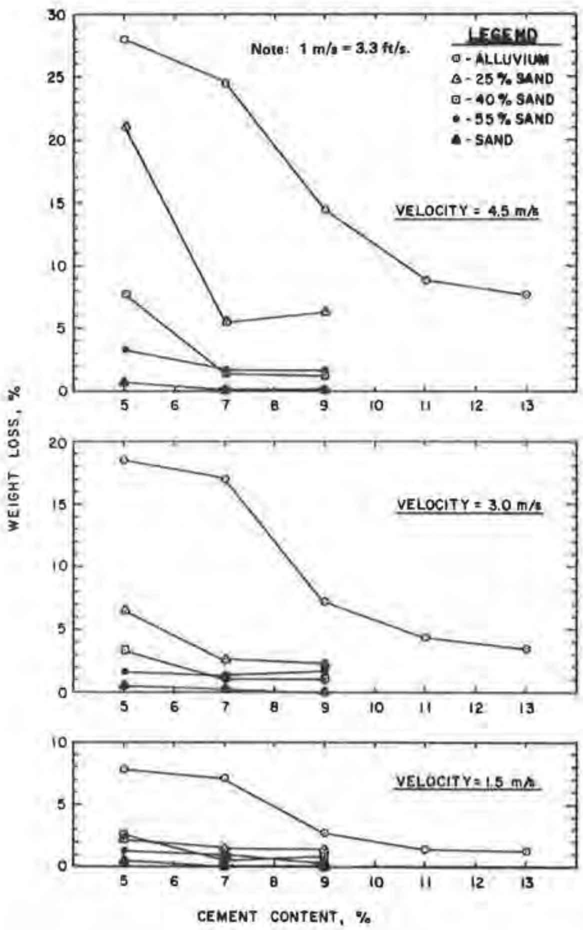
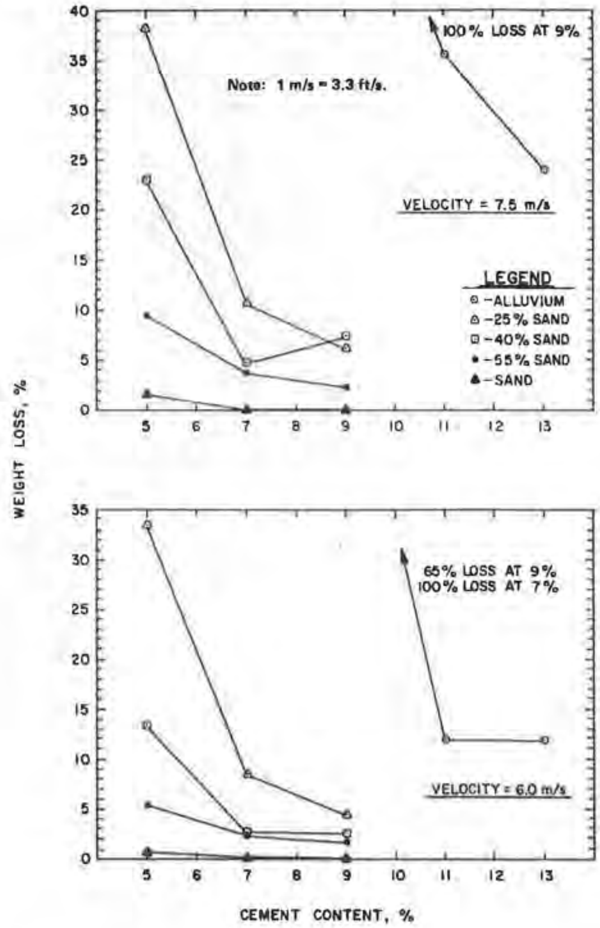


Figure 5. Weight loss versus cement content for erosion tests with velocities of 6 and 7.5 m/s.



quently, the minimum cement content is less than 5 percent. Table 1 summarizes the minimum cement contents as indicated by the brush and the erosion tests at the various velocities. Comparison of the results of the two methods of testing shows that, for velocities less than 6.0 m/s (20 ft/s), the brush test may be too conservative and result in uneconomical design mixes. At higher velocities, the brush method may be a reasonable criterion for selecting a minimum cement content; however, at velocities greater than 6 m/s, the maximum percentage of soil lost in the hydraulic tests far exceeds the maximum lost in the brush tests. This latter observation suggests that the brush test may not simulate the amount of soil lost under more severe channel erosion.

An alternate analysis of the data shows the relationship of erosion velocity to the durability of the soil-cement specimens. Figure 6 is a plot of percentage weight loss versus erosion velocity for the cement-stabilized alluvium at constant cement contents. For specimens stabilized with 5 and 7 percent cement, a nearly linear relation between weight loss and velocity exists up to a velocity of about 4.5 m/s (15 ft/s). Above that velocity the erosion loss increases almost exponentially. Similarly, for 11 and 13 percent cement the rate of loss is lower up to a velocity of 6 m/s, above which the percentage of loss per unit of velocity increases abruptly. A 9 percent cement content test was not run at velocities greater than 4.5 m/s. The relatively low rate of loss for lower velocities indicates the possibility of a threshold velocity below which losses may be tolerable and above which losses become excessive. This suggests the possibility of a more rational criterion for determining the allowable weight loss. Similar trends also appear in Figure 7 for the alluvium-sand mixtures with 5 percent cement. If the higher cement content mixtures have a threshold velocity, it is above the highest velocity of 7.5 m/s (25 ft/s) at which the specimens were tested.

If the PCA criterion of a maximum of 7 percent loss is used as a limiting criterion, a maximum allowable velocity may be defined as the velocity at which the erosion loss for a given cement content equals 7 percent. The maximum allowable velocities are shown in Table 2. The maximum allowable velocity increases with increasing cement and sand content. The foregoing analysis suggests that

Table 1. Minimum allowable cement contents for weight loss of 7 percent.

Soil Mixture	Minimum Allowable Cement Contents (%)					
	Brush Test	Erosion Test Velocities				
		1.5 m/s	3 m/s	4.5 m/s	6 m/s	7.5 m/s
Alluvium	>13	7	9	>13	>13	>13
Alluvium-25 percent sand	8	<5	<5	7	8	9
Alluvium-40 percent sand	6	<5	<5	5.5	6	9
Alluvium-55 percent sand	<5	<5	<5	<5	<5	6
Sand		<5	<5	<5	<5	<5

Figure 6. Weight loss versus erosion velocity for alluvium-cement mixtures.

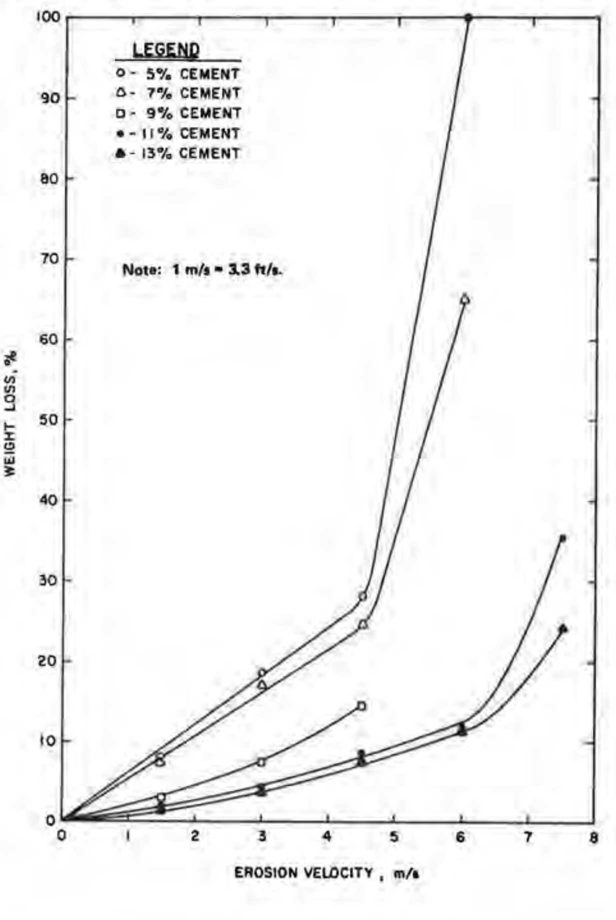
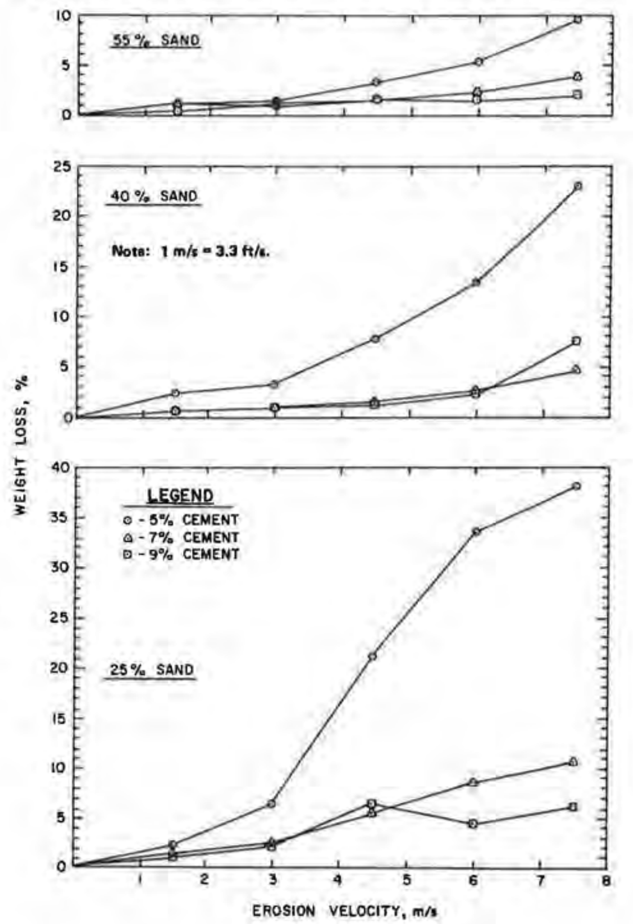


Figure 7. Weight loss versus erosion velocity for alluvium-sand-cement mixtures.



channel velocity is an important variable that should be taken into consideration when designing a mix for soil-cement in grade-stabilization structures.

DISCUSSIONS AND CONCLUSIONS

Current practice limits design of water control structures by using soils stabilized with portland cement to sandy soils. The procedure for selecting cement contents is a modification of the procedure used for highway design. In the case of the grade-stabilization structures designed to retard or stop channel degradation on small streams, current practice may be too conservative and lead to uneconomical structures. On the other hand, if high velocities are expected, current practice may not be conservative enough. A statistical probabilistic approach to design is unacceptable when applied to a dam or bridge in a populated area (9); however, the failure of a grade-stabilization structure on a small stream is unlikely to have immediate, devastating effects. Some consideration should be given to the use of materials that may be unacceptable in a large dam but may provide a reasonably long life and a realistic risk factor for a low-head grade-stabilization structure. The design of such a structure should consider the durability of the materials in terms of flow velocities and recurrence intervals in the channels into which they are placed.

Erosion tests at velocities less than 6 m/s (20 ft/s) on cement-stabilized alluvium and alluvium-sand mixtures from western Iowa result in lower weight losses than do brush tests on the same mixtures. At hydraulic velocity of 6 m/s, the cement contents that produce less than 7 percent weight loss are comparable to cement contents determined from the brush tests; however, at this and higher velocities, the hydraulic tests result in greater maximum losses than the losses produced by brushing. As expected, the addition of sand to the alluvium results in greater durability and less erosion at equivalent cement contents. Current design practice for water-control structure precludes the use of cement for stabilizing western Iowa loess-derived alluvium. However, this study indicates that, at low erosional velocities, cement-stabilized alluvium may be an economical and reliable construction material for grade-stabilization structures in small watersheds.

Table 2. Maximum allowable erosion velocity for weight loss of 7 percent.

	Maximum Allowable Velocity (m/s)				
	Cement Content				
Soil Mixture	5 Percent	7 Percent	9 Percent	11 Percent	13 Percent
Alluvium	1.2	1.5	2.7	4.3	4.6
Alluvium-25 percent sand	3.0	5.2	>7.5		
Alluvium-40 percent sand	4.1	>7.5	>7.5		
Alluvium-55 percent sand	6.5	>7.5	>7.5		
Sand	>7.5	>7.5	>7.5		

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Abridgment

Reaction Products of Lime-Treated Southeastern Soils

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Six soils series (Cecil, Chewacla, Eutaw, Sumter, Tatum, and Wilcox) of the southeastern United States were investigated by using x-ray diffraction analysis, thermogravimetric analysis, and scanning electron microscope. The study compared the natural soil with lime-treated soil (by using 6 percent high-calcium-hydrated lime) after a 48-h accelerated curing period at 49° C (120° F). The compaction specimens were prepared in a Harvard miniature compaction mold by using impact compaction and were sealed in plastic wrap during the curing phase to prevent moisture loss. Lime-soil reaction products of calcium oxide-alumina oxide-hydrate (C_4AH_3), C_3AH_6, calcium-silicate-hydrate (CSH) (gel) and CSH II were identified, although a different mixture of products was associated with each soil. Unknown products were also noted on the thermogravimetric analysis data at 440°, 450°, and 460° C. Both absorbed-solution and through-solution mechanisms appear to be involved in the formation of cementitious material. When compared with lime reactivity (i.e., unconfined compressive strength gain following the accelerated curing), the results for the montmorillonite dominated soils (Eutaw and Wilcox) suggest that excessive specific surface is a detriment to the development of significant cured unconfined compressive strength gains.

Six fine-grained soil series characteristic of those found in the southeastern United States were investigated by using x-ray diffraction, thermogravimetric analysis (TGA), and the scanning electron microscope (SEM) to determine the nature of lime-soil reaction products. Selected soil morphology, engineering physical property, and lime-reactivity data are presented in Table 1 (1-3). The soils exhibit a wide range of lime reactivity with the lowest strength gains noted for the montmorillonitic soils (Eutaw and Wilcox).

PREPARATION OF SOIL-LIME SPECIMENS

Specimens were prepared for SEM, x-ray diffraction, and TGA after an accelerated curing sequence (4). The soils were air dried, then dry mixed by hand with 0, 2, 4, and 6 percent high-calcium-hydrated lime by dry weight of the soil. Distilled water was added to each soil to achieve moisture contents approximately that of optimum for the lime-treated soil. Samples were compacted in a Harvard miniature mold with a 0.53-lb impact compaction hammer in 3 layers by using 25 blows/layer. Immediately after removal from the mold, the compacted specimens were sealed with plastic wrap to prevent moisture losses and then cured at 49°C (120°F) for 48 h.

SOIL TESTING PROCEDURES

X-Ray Diffraction

X-ray patterns for soils before and after treatment with 6 percent high-calcium-chemical lime were obtained by using a Norelco x-ray diffraction unit with a copper tube. For a detailed discussion of x-ray diffraction theory, see Jackson (5).

TGA

A Dupont 951 thermogravimetric analyzer and a Dupont 990 thermal analyzer and record console were used for TGA. About 10 mg of the entire soil sample were used. The sample was heated from 25° to 800°C at a constant rate of 20°C/min. Weight loss was a result of the release of surface water and structural hydroxyls. Minerals loose these hydroxyls within specific ranges of temperatures and at constant percentages of weight. Therefore, some minerals (gibbsite and kaolinite) may be identified quantitatively (5).

SEM

An AMR-100 SEM was used on the soils at various magnifications.

DISCUSSION OF RESULTS

Cecil

A sharp reduction in kaolinite and illite x-ray diffraction peaks indicated some degradation of those minerals. This was supported by TGA results where kaolinite peaks at 500°C were reduced in size. The new peak (reaction products of lime treatment) was identified by Glenn (6) at 140°C to be calcium-alumina oxide-hydrate (C_4AH_{13}), calcium-silicate-hydrate (CSH) (gel), and CSH I. Data by Ruff and Ho (7) preclude the existence of the latter. The peak at 230°C indicates that C_4AH_{13} makes up at least part of the 140°C weight loss. The new mineral found at 320°C was identified as C_3AH_6 (6). The 670°C peak could