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ERODIBILITY OF A CEMENT-STABILIZED SANDY SOIL

Cement-stabilized soil has been successfully used as facing or lining for highway embankments and drainage ditches to reduce the peril of erosion. However, very little information regarding its erodibility is available. In an effort to characterize the erodibility of compacted cement-stabilized soil under various physical and environmental conditions, both erosion and unconfined compressive strength tests were carried out on a sandy soil mixed with various amounts of cement (1, 1½, 2, and 3 percent of cement by dry weight). The various samples were compacted by kneading to a dry density of 132.4 pcf at a moisture content of 8.1 percent and then cured for 7 days in a constant-temperature moisture room. A specified number of wet-dry or freeze-thaw cycles (0, 3, 6, 9, and 12) were applied to different samples to determine the effect of environmental changes on the mechanical and hydraulic stability of the soil. For the uncycled samples (no treatment) the critical boundary shear stress increased as the unconfined compressive strength (or the cement content) of the sample increased. A simple relationship between the unconfined compressive strength and the critical boundary shear stress was obtained for the range of cement contents used in this investigation. Erodibility characterization of cement-stabilized soil considering the influence of climatic changes is very complex. The critical boundary shear stress is no longer a unique parameter to define the hydraulic stability of the soil. The alternating action of field weathering and erosion is detrimental to the integrity of the soil. However, the nature of the time- and environment-dependent erodibility of the cement-stabilized soil is not fully known; more basic information concerning the interaction among soil, water, and environmental factors is urgently needed.

Severe erosion can develop on unprotected road cuts, drainage ditches, and embankments under the influence of running water. Smith (1) has estimated that uncontrolled erosion in the United States alone produces nearly 4 billion tons of sediment each year. The protection of highway embankments and drainage ditches from severe erosion has justifiably been one of the major considerations in the design and maintenance of highways. During periods of torrential rainfall, particularly in arid and semi-arid regions where soils are sandy and vegetation is scarce, unrestrained erosion of roadbeds and road cuts can effectively paralyze an entire road system. Cement-stabilized soils have been used as facing or lining for highway embankments and drainage ditches to reduce erosion.

Although experience with cement-stabilized soils in road construction has been considerable, most attention has been directed toward strength characterization of cement-stabilized soils subjected to either static or moving loads. Very limited information is available on the erodibility of compacted cement-stabilized soils for slope protection. A laboratory study on erosion and resistance to abrasion of soil-cement, using both coarse-grained (A-1-b and A-2-4) and fine-grained soils (A-4), was reported by Nussbaum and Colley (2). Erosion tests were carried out by subjecting the 7-day cured samples to 12 cycles of treatment. (Each cycle consisted of 17 hours of either drying at 70 F or freezing at -20 F, followed by 7 hours' exposure to a water jet from a ⅛-in. diameter orifice at a pressure of 27 psi.) The abrasion tests were conducted by exposing the 7-day cured specimens to flows of water carrying ⅛- to ¼-in. gravels. The results indicated that satisfactory performance can be expected from hardened soil-cement mixtures containing the amount of cement suggested by PCA for soil-cement slope protection. However, flows not carrying debris were found to have little or no erosional effect on soils stabilized with even minimal amounts of cement (i.e., 1.5 percent for A-4 soil and 0.75 percent for A-1-b soil). Whereas the Nussbaum and Colley study has shown the effectiveness of cement-stabilized soils as erosion-resistant material, it does not provide basic information regarding the influence of various physical and environmental conditions on erosion of cement-stabilized soils in general.

The present study is an effort to characterize the erodibility of cement-stabilized soil under various physical and environmental conditions and to possibly relate erodibility to indexes such as critical shear stress, rate of erosion, and unconfined compression strength so that design guidelines may be established. It is believed that these indexes are more indicative of the hydraulic and mechanical stability of cement-stabilized soils used for slope protection. The results presented in this paper are part of a continuing study on the erodibility of cement-stabilized coarse-grained soils.

EXPERIMENTAL PROGRAM

The strength of cement-stabilized soils comes mainly from the cementitious bonds formed in the hardened mixture. Although the mechanism of soil-cement stabilization for coarse-grained soils is different from that of fine-grained soils, the bond is believed responsible for erosion resistance of all types of cement-stabilized soils and may be considered as a kind of internal bonding or cohesion of the mixture. It thus seems appropriate, in studying the erodibility of cement-stabilized soils, to follow the general approach used for cohesive soils. Erosion studies made on cohesive soils have followed two paths: determination of a permissible noneroding velocity of water flow and determination of maximum allowable shear stress.

Determination of a permissible noneroding velocity of water flow involves the selection of hydraulic variables so that a permissible velocity is not exceeded and undesirable erosion does not take place. The practical use of experimental investigation in this approach is limited because of the lack of a good definition of the channel bed velocity; furthermore, an accurate measurement of that velocity is extremely difficult. Forchheimer (3) summarized most of the available information in the form of tables of critical velocities for different materials.

In the determination of maximum allowable shear stress, a critical boundary shear stress, above which erosion begins, is related to pertinent soil properties and flow variables. Flume tests have been the most widely used method in this approach (4, 5, 6, 7). Carlson and Enger (8) used a well-flushed tank with a rotating impeller to investigate the relation between critical shear stress and soil properties. Dunn (9) and Moore and Masch (10) reported the use of an impinging jet in similar studies. Unfortunately, agreement among various reported results has been poor. The wide variation of test results is due to the absence of a precise definition for the initiation of erosion and the variation of shear stress exerted on samples with respect to time and space. Masch, Espey, and Moore (11) have commented that, with these techniques of testing, "the average tractive force is not uniformly distributed over the sample, and determinations of the critical shear stress from point velocity measurement are not necessarily representative of the shear on the sample." Much information regarding investigations using these techniques is made available by Partheniades and Paaswell (12) and Masch (13).

To determine more precisely the shear stress at which erosion commences and the rate of erosion of a given cohesive soil, Masch developed a rotating cylinder apparatus (11). Use of this apparatus minimizes the effect of variation in shear stress with respect to time and space. The apparatus gives a measure of the erosion rate and the true shear stress independent of such uncertainties as roughness changes and boundary-layer growth during testing. Utilizing this apparatus, Rektorik (14) presented linear relations between the critical shear stress and vane shear strength of a clayey soil. More recently, Arulanandan et al. (15) used a modified rotating cylinder apparatus to measure the shear stress and to study the initiation of erosion on saturated clay soils. Because of its simplicity, reliability, and accuracy the rotating cylinder apparatus was adopted in this study.

Erosion Apparatus

A sketch of the testing apparatus is shown in Figure 1; minor modification has been made for testing stabilized soils. A stationary cylindrical sample fastened by two end plates is mounted coaxially inside a rotating cylinder. A ¼-hp Bodine motor with a Bodine variable-speed control box (speed ranging from 25 to 2,400 rpm) is used to drive the outer cylinder. As an option, two sample sizes can be tested in this apparatus: a 3.0-in. diameter, 3.45-in. high sample with an outer cylinder of 4.2 in. ID; a 4.0-in. diameter, 4.6-in. high sample with an outer cylinder of 5.2 ID. In both cases, the annular space between the sample and the outer cylinder is 0.6 in. The shear force is exerted on the eroding surface by the rotating water filling the annular space between the sample and the outer cylinder. The magnitude of this force is measured through the torsional displacement of a thin brass rod connected to the sample holder. Figure 2 shows the relation between rotating speed and resulting shear stress for the 3.0- × 3.45-in. samples. Because the annular space between the sample and the outer cylinder is a constant and because there is no abrupt change in roughness of the eroding surface, a uniform shear stress at all points on the eroding surface can be assumed.

Materials

The sandy soil used in this study was obtained from the Castaic Dam in California. The grain-size distribution of the soil is shown in Figure 3. The soil is nonplastic and can be described as a uniformly graded gravelly sand having a D_{10} of 0.2 mm and a uniformity coefficient of 7.5. There are about 5 percent fines passing the No. 200 sieve. This material, based on the AASHO classification, can be designated as A-1-b soil. The average specific gravity of the solids is 2.67. A standard AASHO compaction curve is shown in Figure 4 where the optimum water content is 8.1 percent and the corresponding maximum dry density is 132.4 pcf. Commercially available type 2 cement was used in all the samples for soil-cement stabilization.

Cement Treatment Level

Durability test results have indicated that a minimum of 4 percent cement by weight is required to properly produce a hard, durable soil-cement from the Castaic sandy soil. A pilot erosion study made on 4 percent cement samples revealed that these samples were too strong to be used for erosion study within a reasonable time limit. Therefore, cement treatment levels of 1, 1.5, 2, and 3 percent were chosen in this study. Longer term erosion tests on higher cement content samples will be carried out at a later date.

Sample Preparation

An appropriate amount of soil and cement for each sample was first mixed in an air-dry state; the necessary amount of water was then added to the mixture, which was thoroughly mixed for about 5 min. Cylindrical samples were compacted by kneading in two layers in a 3.0-in. diameter by 3.45-in. high steel mold. All samples were compacted to a dry density of 132.4 pcf at a molding water content of 8.1 percent. For samples scheduled for erosion test, a ¾-in. hole was drilled axially. All samples were then cured in a moisture room for 7 days (95 percent humidity and 72 F), after which the samples were grouped and subjected to specified numbers of either wet-dry or freeze-thaw cycles according to the procedure outlined for durability tests (ASTM D 559-57 and D 560-57).

Testing Procedures

Both unconfined compression tests and erosion tests were carried out on samples subjected to various cycles of treatment. The kind of treatment chosen for this study was 0, 3, 6, 9, and 12 freeze-thaw or wet-dry cycles:

1. Unconfined compression tests—Samples tested for unconfined compression were first soaked in water for 4 hours (PCA specification) and then tested to failure on the Tinius Olsen testing machine.
2. Erosion tests—The sample was first fastened to the supporting rod between the two end plates and then soaked in water for 1 hour before being weighed and mounted onto the apparatus. Next, the annular space between the sample and the outer cylinder was filled with water. Tests were started by rotating the outer cylinder at a preselected low speed. Depending on the erodibility of the sample, the running time varied from a few minutes to an hour. During this period the test was stopped at least three times to record the weight loss for a given period of erosion. The speed was then increased and the same process repeated. The test was continued at higher speeds until a considerable amount of erosion on the sample surface was noticed. In this manner, the relationship between weight loss and time of erosion for various rotating speeds can be established by at least three data points.

TEST RESULTS

Unconfined Compressive Strength Tests

The unconfined compressive strength of samples subjected to wet-dry or freeze-thaw cycles is shown in Figure 5. The wet-dry treatment appears to affect only slightly the unconfined compressive strength and, for the 2 and 3 percent cement content, the strength in fact increased during the treatment process. The freeze-thaw treatment on the other hand proves to be far more destructive and shows a decrease in strength with increasing number of treatment cycles.

According to Figure 5, the strength loss due to freeze-thaw treatment is most significant in the first few cycles and then becomes less effective as the number of treatment cycles increases. This phenomenon, however, may reflect the presence of a weakened outer layer formed during the first few cycles of treatment and, not being removed, may have served as an effective buffer against further deterioration of the sample in successive treatment cycles. Removal of this protective layer after each treatment cycle would expose a fresh, unweakened surface to new attack that could yield lower strength values than those shown in Figure 5.

Erosion Tests

The typical erosion test results shown in Figures 6 and 7 represent the relation between soil weight loss per unit surface area and the erosion time for various speeds or equivalent shear stresses. At a given rotating speed, beyond the speed capable of initiating erosion, both the wet-dry and the uncycled samples show that the amount of weight loss per unit surface area increases with increasing erosion time; and, for a given time of erosion, the amount of soil loss increases with increasing rotating speed.

On the other hand, samples subjected to various cycles of freeze-thaw do not always show an increase in weight loss with increasing rotating speed. Substantial weight loss may be expected early in the test as the weakened outer layer, formed during the first few freeze-thaw cycles, is eroded easily at low rotating speeds. Weight loss may then be expected to decrease even at higher rotating speeds as the less erodible, fresh surface is exposed. The erodibility of this weakened layer depends on such factors as soil type, cement content, and the number and type of treatment cycles. The exact nature of this layer, however, is not known at present.

Figure 1. Rotating cylinder apparatus [after Masch and Moore (11)].

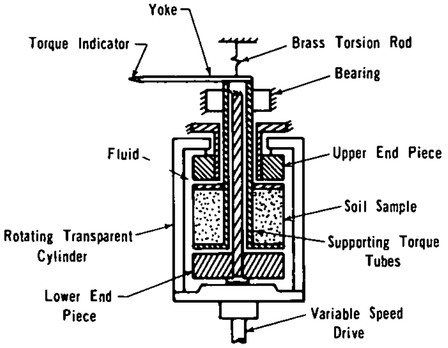


Figure 2. Calibration curve.

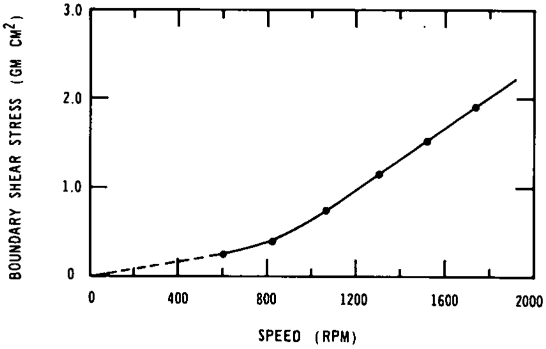


Figure 3. Grain-size distribution.

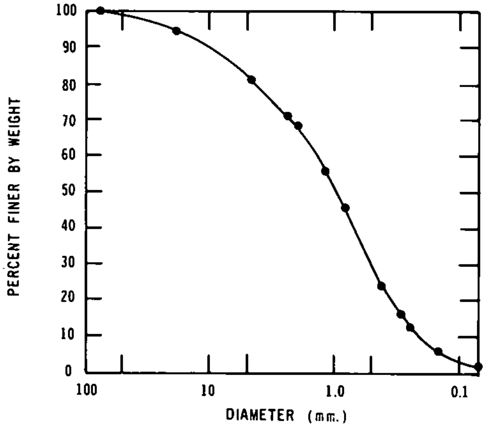


Figure 4. Standard AASHO compaction curve.

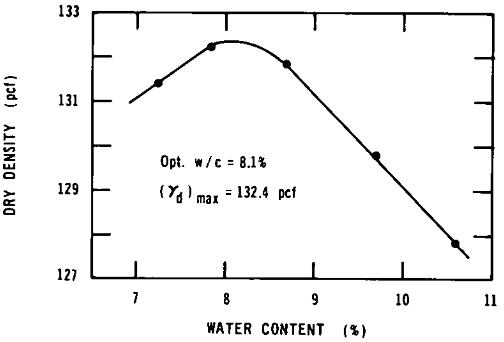


Figure 5. Unconfined compressive strength.

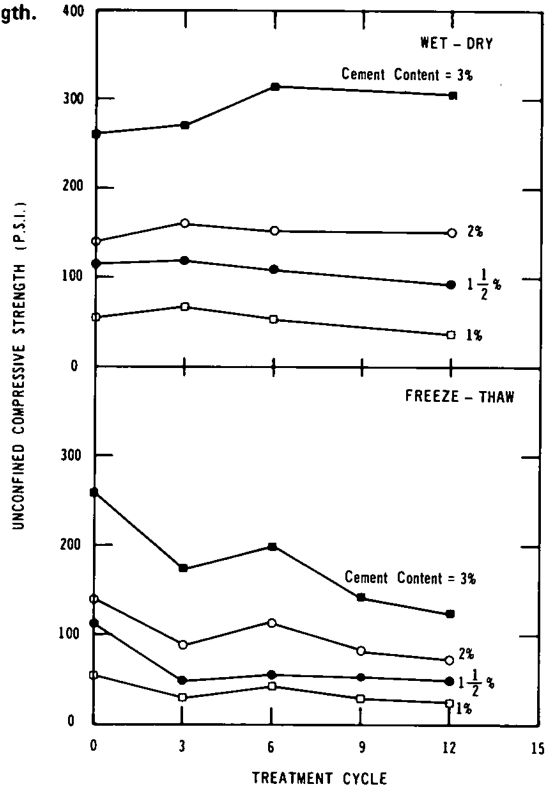


Figure 6. Erosion test results of freeze-thaw samples with 2 percent cement.

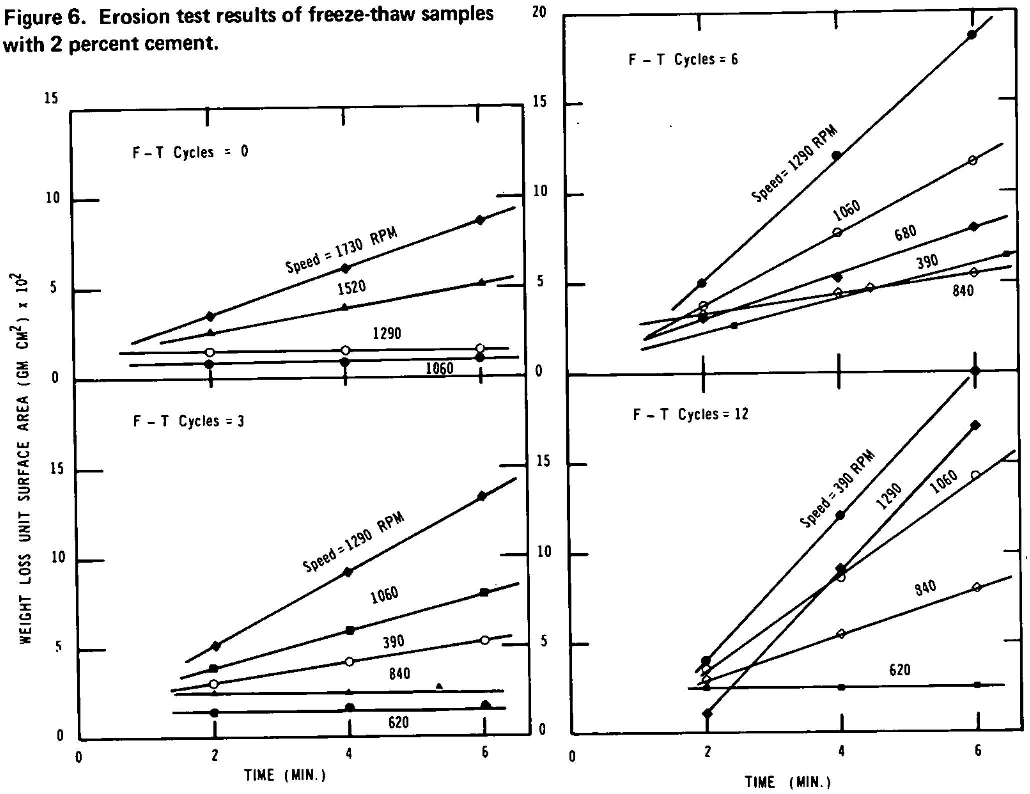
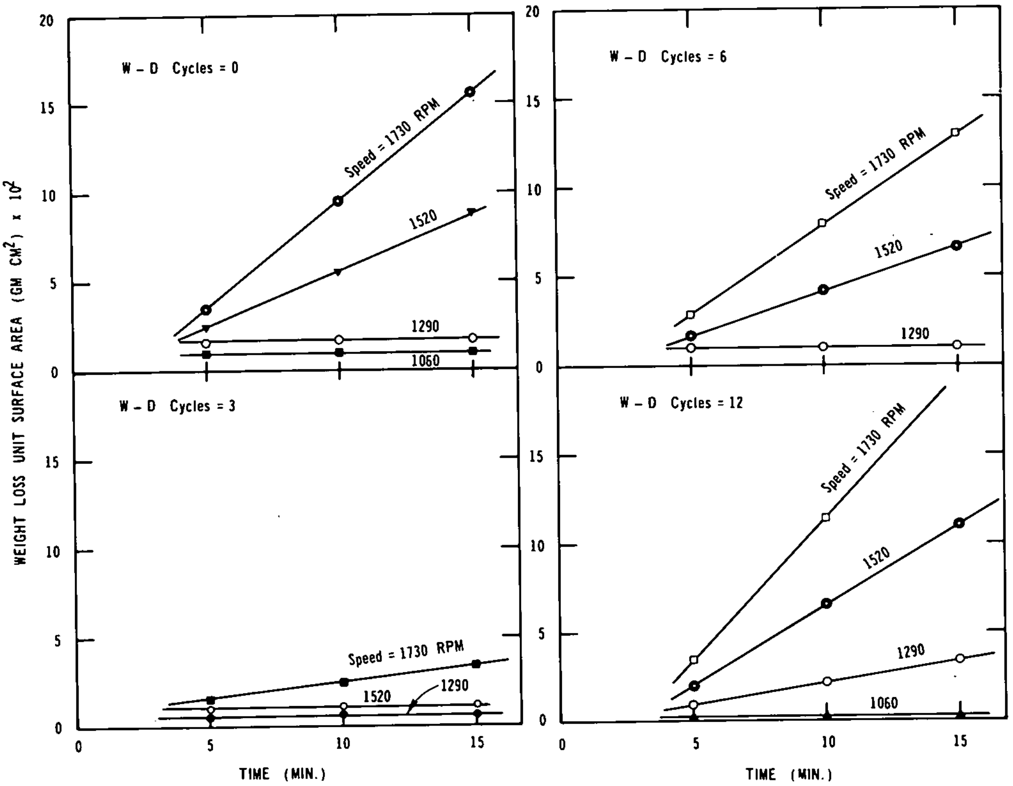


Figure 7. Erosion test results of wet-dry samples with 2 percent cement.



DISCUSSION OF RESULTS

One of the most important considerations in dealing with chemically stabilized soils is that the properties of such soils are affected by environmental forces; therefore, with time, the stabilized soils may be weakened and become unfit as channel lining for erosion protection. If we borrow the suggestions proposed for earth dam facing by Nussbaum and Colley (2), a lined channel may be divided into three exposure zones. The first zone includes the channel bottom and a portion of the bank constantly below the minimum water level. In this zone the adverse effect of freeze-thaw and wet-dry cycles of nature has little impact on the soil properties. The only major eroding force is the flow of water, which is persistent but more or less predictable. The second zone is the zone along the banks where water level fluctuates. This zone is subjected to freeze-thaw cycles in the presence of water, and therefore the environment has a very detrimental influence on the performance of the soil. The third zone is the topmost portion of the channel, which is generally in a dry state. Because of the lack of a sufficient amount of water in this zone, changes in the climatic environment have less ill effect on the soil properties than in the second zone.

To properly design the cement-stabilized soil lining of a channel requires that the erodibility of the soil and the impact of environmental factors on the erodibility of the soil be known. The nature of this problem is highly complex, and currently available information is not sufficient to warrant a reasonable design. The limited laboratory results presented in this report, however, may provide some insight for qualitative discussion.

Erosion Below Water Level

In this region the environmental considerations are less important, and for all practical purposes one could assume that the properties of the cement-stabilized soil remain essentially unchanged with time. One way to characterize the erodibility of a soil is to determine the magnitude of the critical boundary shear stress that would effect no erosion to the soil (zero erosion rate). If we use the data shown in Figure 6, the straight-line relationships of erosion rate versus boundary shear stress can be plotted for various cement contents as shown in Figure 8. The values of critical boundary shear stress can therefore be obtained by extending the straight lines to zero erosion rate (16). It can be seen that, for the sandy soil studied, the higher the cement content is, the higher the critical boundary shear stress is.

The proper selection of an erosion-resistant lining material involves an accurate appraisal of the flow-induced hydrodynamic (shear) forces in a channel. Once this information is available, the desired objective can be attained either by suitably controlling the hydraulic variables so that the induced shear is always less than the critical shear stress of the lining material or by choosing a lining material that has a critical shear stress greater than the stress induced by the hydraulic flow at all times.

For a plane stationary bed, assuming a constant cross-sectional area throughout a given distance and a statically steady-state water flow and bed, the shear stress exerted by the hydraulic forces of the flow is given by Graf (18) as

$$\tau_0' = \gamma DS \qquad (1)$$

where τ_0' is the boundary shear stress, D is the water depth, γ is the unit weight of water, and S is the slope of the energy grade line. For a two-dimensional flume, or in the case of a very wide channel, Eq. 1 is quite correct. However, the more general form of Eq. 1 is

$$\tau_0'' = \gamma R_h S \qquad (2)$$

where R_h is the hydraulic radius.

The shear stress as given by Eq. 2 represents the average value of the shear force per unit wetted area. However, the shear stress in channels, except for a few cases, is not uniformly distributed. One way to find the true values of the shear stress at different locations of various channel sections is to assume a power law for the velocity distribution (17). Membrane analogy and the finite differences method were used to obtain the shear stress distribution shown in Figure 9 in terms of the boundary shear stress obtained from Eq. 1. Therefore, the shear stress at any point on the wetted area might be given as

$$\tau_o = f\gamma DS \tag{3}$$

where f is a coefficient ≤ 1; and, for a given location and channel section, it is a function of the ratio of the width of the bed to the depth of the channel.

The shear stress can be related to the flow speed by using Maning's formula:

$$v = \frac{1}{n} R_h^{2/3} S^{1/2} \tag{4}$$

where v is the flow speed (ft/sec) and n is Maning's coefficient (roughness coefficient). Substituting S from Eq. 4 into Eq. 3 would lead to

$$v = \frac{\tau_o^{1/2} R_h^{1/6}}{\gamma^{1/2} n f^{1/2}} \tag{5}$$

Therefore, it is possible to design a stable channel either by choosing the hydraulic radius so that

$$v < \frac{\tau_{cr}^{1/2} R_h^{1/6}}{\gamma^{1/2} n f^{1/2}} \tag{6}$$

where τ_{cr} is the critical boundary shear stress measured in the erosion test, or by choosing the lining material such that

$$\tau_{cr} > \frac{(v_{max})^2 \gamma n^2 f}{R_h^{1/3}} \tag{7}$$

For materials, where the shear strength is dependent mainly on the cohesive bonds, Graf (18) has suggested

$$\frac{\tau_{cr}}{(\gamma_s - \gamma)d} = C_o \tag{8}$$

where d is particle diameter, γ_s is the unit weight of the lining material, and C_o is the cohesion coefficient of the material. Figure 10 shows the relationship between the critical boundary shear stress obtained in the erosion test and the corresponding shear strength. These results indicate the possibility of establishing a simple relationship as shown in Eq. 8; however, more test results are needed before any general conclusion can be drawn.

Erosion Affected by Environmental Factors

The discussion outlined above is only good for a homogeneous soil layer with its mechanical and hydraulic properties unaffected by the change of environment. This situation is certainly not applicable to stabilized soil located in the second and third zones where changes in climatic environment could weaken the surface of the soil. This weakening process can be identified as a form of weathering that, coupled with erosion due to running water, is detrimental to the stability of the channel. Therefore, for proper design of a channel lining, a thorough understanding of the effect of environmental factors on the mechanical and hydraulic stability of the stabilized soil is essential.

Figure 8. Erosion rate versus shear stress for uncycled samples.

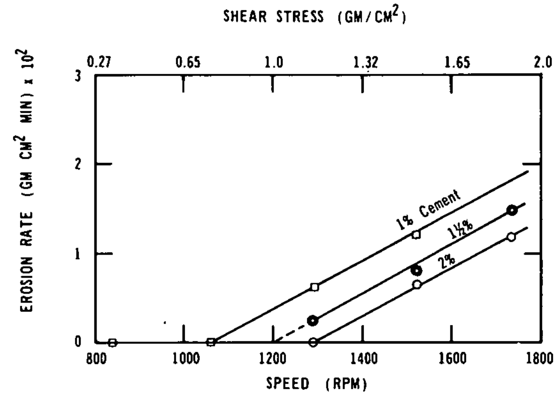


Figure 9. Maximum shear stress in a channel [after Lane (17)].

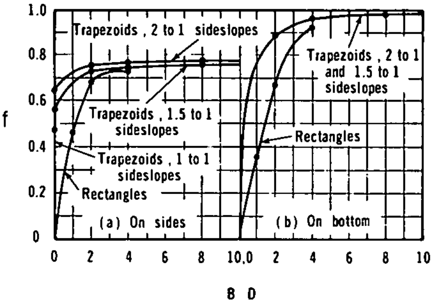
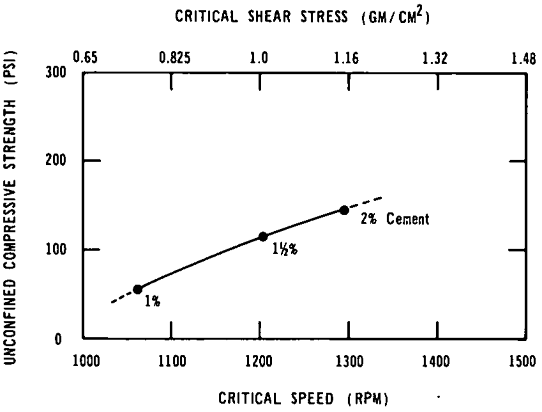


Figure 10. Critical shear stress versus unconfined compressive strength for uncycled samples.



The erodibility characterization of cement-stabilized soil considering the influence of climatic changes is in itself a difficult task. For instance, the critical boundary shear stress can no longer be considered as a unique parameter that defines the hydraulic stability of a stabilized soil. Shown in Figures 11 and 12 are the plots of erosion rate versus rotating speed for samples subjected to different numbers of either wet-dry or freeze-thaw cycles. The scatter at low speeds, shown in Figure 12, is the result of large weight losses in the weakened outer layer of the freeze-thaw samples; however, when straight-line relationships were constructed, these points were neglected. The critical boundary shear stress obtained, therefore, represents the erodibility of the fresh surface of a given sample subjected to a specified type and number of treatment cycles. For a given cement content, the critical boundary shear stress decreases as the number of treatment cycles increases. In the freeze-thaw samples, the buffer is believed responsible for minimizing the role of treatment cycles on the erodibility of the soil. However, in the field, the alternating action of weathering and erosion will continuously affect the hydraulic stability of the soil. If the soil is susceptible to substantial weathering action, its critical boundary shear stress will certainly change with time, and therefore a realistic characterization of the erodibility of a stabilized soil is not possible unless its property changes with time, including environmental factors, are considered.

As an alternative, the lining can be designed strong enough to resist weathering without the formation of the weakened outer layer; therefore, erosion of the lining will not be initiated, and its integrity can be preserved. This can be accomplished by increasing the cement content in the soil-cement mixture, making the soil stronger and less susceptible to environmental attacks. This concept is currently being used in soil-cement facing for slope protection of earth dams, and satisfactory performance has been reported (19). However, except for the work done by Nussbaum and Colley (2) that examined the adequacy of the suggested soil-cement criterion for slope protection, there is a lack of basic information concerning the interactions between the soil, the water, and the environmental factors. It is believed that detailed studies that take into consideration the effects of weathering and erosion on cement-stabilized soils are needed so that a more rational assessment of the criterion can be made.

CONCLUSION

Using the rotating cylinder apparatus, we examined the erodibility of a cement-stabilized sandy soil. In general for the uncycled samples, the erodibility decreases as the unconfined compressive strength (or the cement content in the samples) increases. If erosion due to flowing water is the only consideration, the proper design of a channel lining can be achieved by choosing the material strong enough so that its critical shear stress is greater than the possible maximum shear produced by the hydraulic flow. Results from this study show that a simple relationship between the unconfined compressive strength and the critical shear stress can be established for the range of cement contents used. It is therefore possible to design a stable channel lining by knowing the hydraulic as well as the geometric parameters of the channel and the unconfined compressive strength of the cement-stabilized soil.

A more critical situation is where the erodibility of the stabilized soil is effected by the alternating cycles of weathering and erosion. A realistic characterization of time-dependent erodibility of a stabilized soil is not possible unless the influence of the environmental factors on the changing properties of soil is considered. This system is a highly complex one, being dependent not only on the soil type and the cement content, but also on the hydraulic parameters and the field conditions. More extensive studies are urgently needed; it is hoped that the reported study will stimulate interest and discussion in this area of research.

Figure 11. Erosion rate versus shear stress for wet-dry samples.

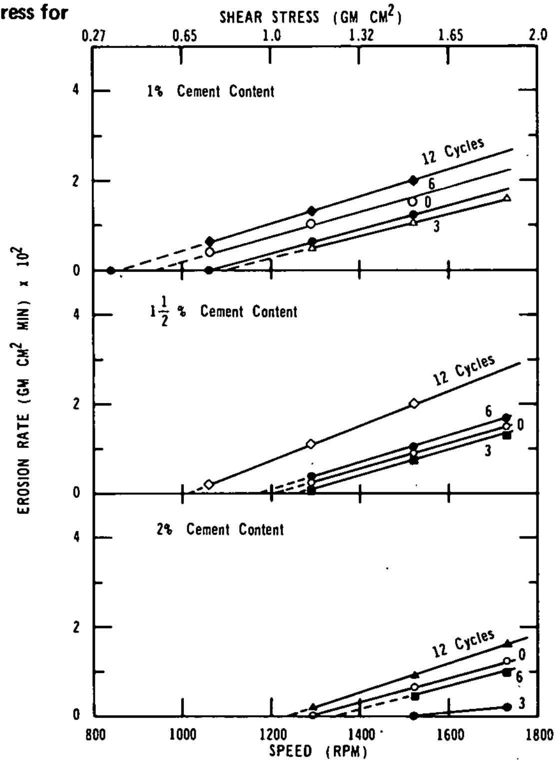
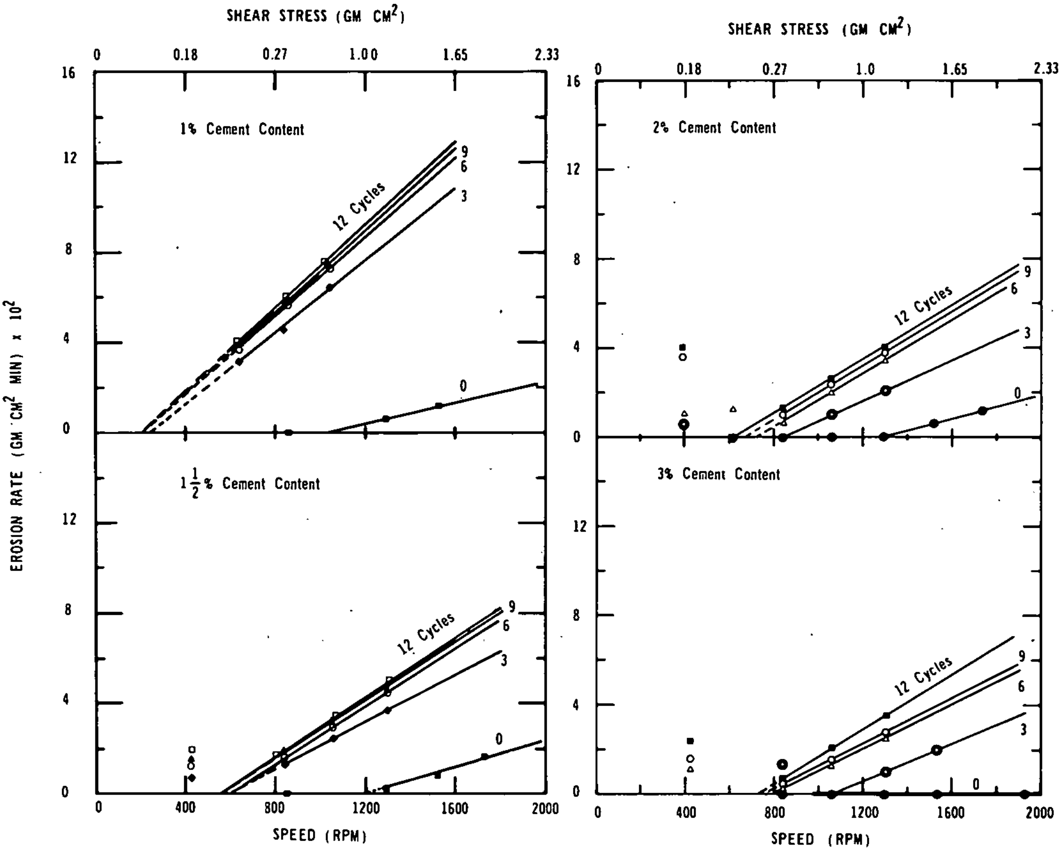


Figure 12. Erosion rate versus shear stress for freeze-thaw samples.



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