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SOIL EROSION: Causes and Mechanisms Prevention and Control

Highway Research Board
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SPECIAL REPORT 135

SOIL EROSION: Causes and Mechanisms; Prevention and Control

Proceedings of a Conference-Workshop
Held January 26, 1973,
Washington, D.C.
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Highway Research Board
Division of Engineering
National Research Council
National Academy of Sciences
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Washington, D.C.
1973

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FOREWORD

The papers for this Special Report originated as part of the 1-day Conference-Workshop on Soil Erosion cosponsored by the Highway Research Board and the National Science Foundation. The workshop was held at the Sheraton-Park Hotel on January 26, 1973. The report is presented in two parts: Part I, Causes and Mechanisms of Soil Erosion, contains the state-of-the-art report by R. E. Paaswell along with the papers that provided the basis for panel and open forum discussions held in Session I. Part II, Methods of Preventing and Controlling Erosion, contains the state-of-the-art report by D. B. Chittenden along with the papers that provided the basis for the panel and open forum discussions in Session II.

The rationale for the workshop is clear. Soil erosion is occurring at accelerated rates in many places where man has disturbed or modified the surface of the ground. An important and serious consequence of accelerated erosion is sedimentation downstream from the point where erosion occurs. Thus, erosion damage is not confined just to the site where it occurs; its effects are felt at points far removed in space and time.

Sediment from soil erosion is conceded by most authorities to be the largest single stream pollutant. Physical damages from sediment include reservoir silting and resulting loss of storage capacity; filling of harbors and navigation channels; altering of morphology and stability of stream channel systems; and clogging of drainage ditches, culverts, and underflows along highways. Sediment restricts recreational use of water and disrupts stream ecology. Ultimately, erosion and sediment are expensive problems.

America's 4 million miles of roads contribute an estimated 56 million tons of sediment annually to streams. Although not the largest contributor of sediment on an absolute scale, highways do have one of the highest rates of sediment production on a unit area basis relative to other sources. The nature and magnitude of soil erosion and the contribution of roads and highways to the problem are discussed in detail in Part II of the proceedings.

The conference-workshop was intended to facilitate exchange of information on soil erosion and its causes, cure, and prevention. These proceedings provide an up-to-date publication on significant research findings and information on these topics. They should be of interest to both researchers and practitioners alike. Part I of the proceedings is aimed more at the research worker. Soil erosion involves the process of both particle detachment and transport. The papers in Part I explore the mechanics of this process and the parameters that affect it. Part II should be of particular value to the highway transportation engineer who must contend with the problem.

This Conference-Workshop on Soil Erosion was planned by representatives from the following HRB committees: Physicochemical Phenomena in Soils, Chemical Stabilization, Roadside Development, and Environmental Factors Except Frost. The contributions of C. R. Anderson, K. Arulanandan, R. C. Deen, L. F. Erickson, J. K. Mitchell, R. E. Paaswell, J. J. Ryan, D. A. Sangrey, and W. G. Weber, Jr., are especially acknowledged.

The assistance and financial support of the National Science Foundation are gratefully acknowledged.

Donald H. Gray

Part I

CAUSES AND MECHANISMS

HANS F. WINTERKORN, Princeton University

EXPERIMENTAL STUDY OF THE ATTACK OF WATER ON DRY COHESIVE SOIL SYSTEMS

The mechanism of water attack on dry cohesive soil systems was studied by means of simple slaking tests on specimens prepared from five soils and a number of their homoionic variants as well as on sand-clay specimens manufactured from these soils and crushed limestone and flint sands. The observed slaking pictures and rates were analyzed with reference to such soil parameters as Atterberg limits, types and percentages of clay and organic matter, heats of wetting, and presence or absence of a granular bearing skeleton. For the natural soils, a simple exponential relationship was found between the shrinkage limits and the slaking times; however, the slaking pictures were different for expansive and nonexpansive soils and also for expansive soils possessing relatively large secondary aggregates that were protected by wetting-resistant organic films. Analysis of all the data obtained on the natural soils, their variants that gave maximum and minimum slaking times, and corresponding sand-clay systems yielded information on the mechanism and time rate of water attack on a wide range of soil systems. Analysis also suggested a possible sequence of events that cause a gradual loss of mechanical stability of mine waste dumps due to internal weathering under acid conditions and may lead to their ultimate catastrophic failure.

The interaction of soil and flowing water that leads to sheet and gully erosion may also be accompanied by or result in the usually more severe and often catastrophic phenomena of slaking and sloughing off of river banks and mud flows, especially if dry cohesive soils or similar materials such as piles of mine tailings and other mineral industrial wastes are involved. Attempts at understanding the basic mechanism of water attack on dry cohesive soil systems are germane to the purpose of this workshop. Because of the numerous physical and physicochemical factors involved, there is little hope for a truly analytic solution at the present state of theoretical development; and, if such a solution were possible, the apparatus and skill required to determine the pertinent fundamental parameters would forbid its use in most practical cases. Under these circumstances, the most promising engineering approach is the simple slaking test in combination with the commonly performed Atterberg or other simple routine test and an evaluation of the test results in accordance with present understanding of their physical meaning.

GENERAL THEORETICAL CONCEPT

It may be postulated that rate and picture of reaction depend on the relative magnitudes of the driving and resisting forces (aside from geometrical factors) whereby the sum of the driving potentials equals the total suction potential composed of the matrix and ion hydration potential (related to the heat of wetting) and the osmotic potential. Among the resistance factors are the resistance to water permeation (the inverse of permeability), the resistance of the internal soil surface to wetting (as

caused by surface films of certain types of organic matter), the bonds between primary and secondary particles, and the air in the soil pores augmented, as the case may be, by previously adsorbed air released by the advancing wetting front.

Of special importance with regard to the reaction picture is the relation between the rate of water penetration and the rate of destruction of interparticle bonds. If the rate of bond destruction equals or exceeds that of water penetration, the result will be a progressive, orderly slaking and separation of primary or secondary constituent particles. If, on the other hand, the rate of bond destruction is much smaller than that of water penetration (assuming sufficient air venting to prevent building up of gas pressure), then the system may fail only after a prolonged period of water saturation and may do so catastrophically without any apparent immediate reason.

METHOD OF TEST

Of the available methods, one originated by Russian pedologists was employed. In this method, the test specimens are formed at moisture contents slightly above the plastic limit in molds normally used for making tensile test specimens for cement mortar. After careful drying to avoid the formation of shrinkage cracks, they are coated with paraffin except for a center strip ¼ in. wide (or other adopted width) around their narrow portion. The specimens are then suspended, completely immersed in water, and the reaction picture as well as the time necessary for complete separation of the upper and lower portions is recorded. For a detailed description of specimen molding and testing see Winterkorn (2).

SOIL MATERIALS EMPLOYED

Marshall, Putnam, and Cecil subsoils and loess Pampeano topsoil and subsoil, as well as eight homoionic variations of each soil were employed. Physical, physiocochemical, and chemical parameters characterizing the natural soils are given in Table 1; for those of the homoionic variants see Winterkorn (2). The organic content of the Pampeano topsoil not only is high but also possesses a marked water resistance, as shown by the low heat of wetting (H_w) of this soil.

RESULTS OF SLAKING EXPERIMENTS

Results are given for the reaction picture and the time required for the destruction of the natural soil specimens; data on the homoionic soils are introduced only insofar as they illustrate or illuminate specific points. The reaction pictures of the natural soils were as given in Table 2.

TIME REQUIRED FOR DESTRUCTION OF NATURAL SOIL SPECIMENS

Figure 1 shows plots of the logarithms of the slaking times of the natural soil specimens versus their respective LL, FME, PL, SL, and H_w values as well as the percentages of organic matter and -1μ clay contents. For easier visualization, data for the same parameters are connected by straight lines without a priori assumption of linear relationships.

The soils seem to form two distinct groups: the loess Pampeano, Marshall, and Putnam subsoils on one hand and the loess Pampeano topsoil and the Cecil subsoil on the other hand. In the first group, the slaking times decrease with increasing LL, FME, and PL values, whereas the opposite seems to hold for the Pampeano topsoil and the Cecil subsoil. In the plot of slaking time versus the -1μ clay fraction, only the Cecil soil stands alone. In view of the high content in relatively water-resistant (low heat of wetting) organic matter of the Pampeano topsoil, it may be concluded that this soil actually belongs to the first group and that its greater slaking time is due to the protection of its secondary aggregates by films of organic matter.

This is in agreement with the slaking picture. Accordingly, the Cecil soil stands alone as confirmed by the low SiO_2/R_2O_3 ratio, which shows its lateritic character by the practical absence of organic constituents and by the reaction picture. The only plot that does not show a reversal is that of SL versus slaking time, although there is a discontinuity between the Putnam subsoil and the Pampeano topsoil.

For both behavioral groups, the relation between SL and slaking time can be expressed by

$$\text{Log}\ (t) = \frac{SL - 10}{C} + \log t_{SL=10}$$

where

t = slaking time for specimen with shrinkage limit SL,
$t_{SL=10}$ = slaking time of specimen whose shrinkage limit equals 10, and
C = difference in shrinkage limit per decade of time.

C was the same for both groups, whereas $t_{SL=10}$ was 16 min for the first and 7.5 min for the second group.

This relationship held only for the natural soils and not for their homoionic variants. However, there seems to exist a general relationship between the slaking time and the LL/SL ratio of the homoionic variants. Plots of the pertinent data permit the drawing of straight lines for the homoionic variants of the Pampeano topsoil and the Putnam, Marshall, and Pampeano subsoils. The angles of these lines with the LL/SL base line decrease with increasing clay content of the respective soils. The homoionic variants of the Cecil soil give a shotgun pattern.

The slaking times of the variants giving maximum and minimum values are given in Table 3 together with those of the natural soil specimens. Also given are slaking data obtained on mixtures of the same soils with flint and limestone sands prepared according to ASTM specifications for sand-clay. For details see Winterkorn and Choudhury (4).

DISCUSSION OF DATA OBTAINED ON NATURAL AND IONIC SOIL VARIANTS

Interestingly, the longest slaking times were found for those variants whose exchange ions tended to have a dispersing effect on the particular soils—Na-ion in all but the Cecil soil and H-ion for the Cecil soil. This is important inasmuch as the level of water resistance under otherwise equal conditions increases with increasing shrinkage limit, i.e., with increasing tendency to flocculated structure formation. To complete the paradox, we found that the flocculating Fe- and Al-ions brought about the lowest slaking times in all but the Cecil soil.

It is possible that by dispersing a portion of the secondary clay aggregates a better gradation of effective particle sizes was obtained with consequent lowering of permeability. The same result would be obtained by covering the secondary aggregates with a film of dispersed particles. Flocculating ions would have an opposite effect. It is noteworthy that the greatest absolute increase (Na-ion) and decrease (Fe-ion) in slaking times were obtained in the case of the Pampeano topsoil. Additional evidence for the proposed explanation is the great water resistance of the oven-like bird-nests that crown almost every fence and other post in the Argentine pampas. These nests are constructed by the hornero (ovenbuilder) bird of masticated Pampeano topsoil.

SOME COMMENTS ON HOMOIONIC WHOLE SOILS

Theoretically, homoionic soils appear to be ideal media for fundamental studies on the real physical and physicochemical meaning of the various consistency and other parameters normally determined and used in soil engineering. Unfortunately, homoionic variants are not so well defined, physically and chemically, as would be desirable and as is often assumed.

Table 1. Physical properties of natural soils.

Property	Loess Pampeano Subsoil	Marshall Subsoil	Putnam Subsoil	Loess Pampeano Topsoil	Cecil Subsoil
LL	67	52	35	40	75
PL	31	24	18	27	38
PI	36	28	17	13	37
SL	12.8	13.7	15	21	32
FME	44	37	23	33	41
H_w	5.5	2.8	2.8	0.69	2.02
Water intake	0.96	0.69	0.68	0.69	0.88
Percentage <No. 40					
0.05-0.005 mm	39	55	55	53	9
<0.005 mm	50	37	33	27	76
<0.001 mm	30	22	12	10	62
SiO_2/R_2O_3	3.6	3.2	3.2	3.1	1.3
Organic matter, percent	1.95	2.2	<1	4.5	0
Slaking time, min	25	30	38	49	328

Note: H_w is measured in cal/gram of dry soil; water intake in cc H_2O/gram of dry soil.

Table 2. Reaction picture of soils tested.

Soil	Reaction Picture
Loess Pampeano subsoil	Rapid corrosion and dispersion into very small particles; water muddy
Marshall subsoil	Swelling of the specimen and disintegration into small secondary and primary particles
Putnam subsoil	Rapid corrosion and dispersion into small secondary particles; some swelling of specimen
Loess Pampeano topsoil	Disintegration into soil aggregates of intermediate size; some swelling
Cecil subsoil	Specimen keeps integrity until clean fracture separation of lower from upper portions

Figure 1. Slaking times of natural soil specimens versus various parameters.

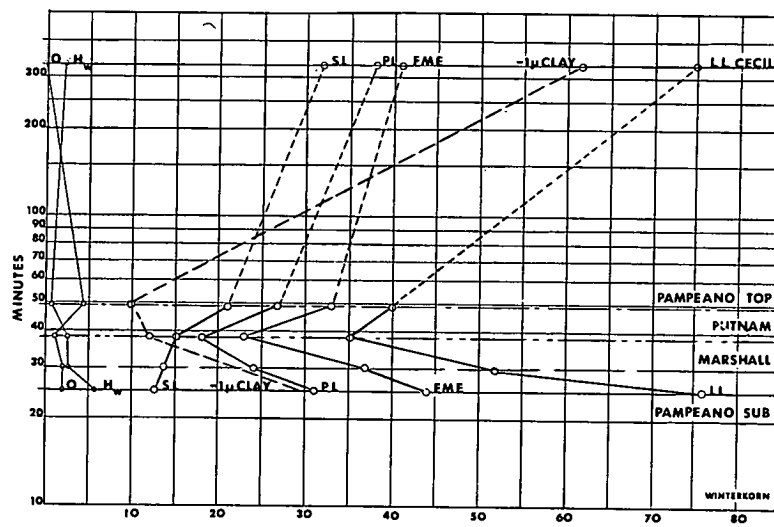

Table 3. Slaking times of natural soils and their ionic variants.

Soil	Time (min) t_{nat}	t_{max}	t_{min}	Range of t_{max} to t_{min} / t_{nat}
Pampeano subsoil	25	28 (Al)	8 (Al)	0.80
Plus limestone sand	13	179 (Na)	7 (Al)	13.2
Plus flint sand	6	55 (Na)	4 (Al)	8.5
Marshall subsoil	30	159 (Na)	17 (Fe)	4.7
Plus limestone sand	17	355 (Na)	10 (H)	20.3
Plus flint sand	6	360 (Na)	4 (K, Al, Fe, H)	59.0
Putnam subsoil	38	138 (Na)	20 (Fe)	3.1
Plus limestone sand	17	255 (Na)	<5 (K, Al)	14.7
Plus flint sand	13	240 (Na)	6 (H)	18.0
Pampeano topsoil	44	266 (Na)	6 (Fe)	5.9
Plus limestone sand	15	92 (Na)	7 (Fe)	5.7
Plus flint sand	10	39 (Na)	3 (Fe)	3.6
Cecil subsoil	328	360 (H)	188 (Mg)	0.5
Plus limestone sand	114	209 (Mg)	59 (Na)	1.3
Plus flint sand	54	110 (Na)	39 (H)	1.3

In the preparation of homoionic variants either by percolation with aqueous solutions of salts of the desired exchange ion and subsequent washing with distilled water (and often water-alcohol mixtures) or by making first H-soils by the use of acid solutions or of electrodialysis with subsequent neutralization by hydroxides of the chosen cations, large amounts of saline or acid solutions or both and of distilled water or water-alcohol mixtures are employed. Their use deprives the original soils of soluble inorganic or organic constituents or both that may have a marked or even critical effect on soil behavior. Also, it is well known that the effect of different exchange ions on the normally determined physical soil parameters is essentially an indirect one through modification of the state of aggregation of the primary soil constituents, i.e., the soil structure. The latter is also affected by the entire past history of a specific soil sample, which may differ for the different ionic variants. These facts must be taken into account in the evaluation of data obtained on homoionic soil materials.

DISCUSSION OF DATA OBTAINED ON SAND-CLAY SPECIMENS

The purpose of this phase of the investigation was to obtain some idea about the interaction of cohesive silt-clay soils with bearing skeleton forming larger grains, the possibility and degree of bond formation, and the influence of volumetric relationships on the slaking phenomenon. To reduce the influence of grain shape as much as possible while providing a variable in mineral type required the use of crushed flint and limestone sands of the same gradation.

The data given in Table 3 translate into the following picture. If we assume in first approximation that the rate of advance of the wetting front into the specimens made of the natural soils and of the soil-sand mixtures was the same, then the water resistance of the effective interparticle bonds was reduced by the limestone sand admixture to a fraction of from 0.57 to 0.34 and by the flint sand admixture to one of 0.34 to 0.16 of the value for the natural soil. The greatest reduction was obtained by the combination of flint sand with natural Cecil soil.

Considering the cationic soil variants that by themselves gave longest slaking times (Na-ion for all but the Cecil soil), we see that admixtures of both types of sand markedly decreased the slaking time of the Cecil soil and even more that of the Pampeano topsoil. It should be remembered that the natural Cecil soil and its ionic variants had the longest slaking times and greatest water resistance of interparticle bonds of all the soils tested, whereas the Pampeano topsoil held second place with respect to slaking time though its slaking resistance was governed by a different mechanism.

In the case of the Na-variants of the Pampeano, Marshall, and Putnam subsoils, provision of an interconnected granular bearing skeleton by the sand admixtures increased the slaking times a considerable extent. However, a great numerical difference between the effects of the two types of sand was evident only in the case of the Pampeano subsoil, the limestone sand being more than three times as effective as the flint sand.

In the systems giving longest slaking times, differentiation between several behavior groups may be made:

1. Among the Cecil soil variants, the natural soil as well as its cationic variants develop characteristic interparticle bonds of great water resistance. These bonds are disturbed and weakened by the admixture of either type of sand; the provision of a granular bearing skeleton does not appear to have any beneficial effect on the slaking behavior of these soils.

2. The protective mechanism possessed by the Pampeano topsoil (films of wetting-resistant organic matter over secondary particle aggregates) is weakened or even destroyed by the sand admixtures (more by the flint than by the limestone sand). As in the case of the Cecil soils, there seems to be no special advantage to the presence of the granular skeleton.

3. In the case of the Marshall and Putnam subsoils, the very presence of the granular skeleton appears to be the dominant factor regardless of the type of sand mineral involved. Obviously, the intergranular spaces not occupied by the skeleton are sufficient to accommodate the swelling of the clay particles caused by the advancing water front. This swelling decreases the permeability of the soil system and increases the slaking times.

4. In the case of the Pampeano subsoil, there appears to be a combination of bond-forming tendency with the limestone sand and swelling accommodation in the intergranular spaces of the bearing skeleton. The importance of such swell accommodation for soil stabilization has been discussed by Winterkorn and Choudhury (4), who also developed pertinent equations for the advance of the water front into specimens showing different types of slaking.

DISCUSSION OF SYSTEMS EXHIBITING MINIMUM SLAKING TIMES

With perhaps one exception (Fe-Pampeano topsoil plus limestone sand), all ionic soil variants that gave minimum slaking times gave even shorter ones in combination with the sands; those with limestone sand had somewhat better slaking resistance than those with flint sand. With the exception of the Cecil soil systems, the general slaking behavior of these soil and soil-sand systems resembled more that of rapidly corroding silts than that of normal cohesive soils. This seems to be paradoxical inasmuch as the Al-, Fe-, and H-cations that pushed all but the Cecil soil into silty behavior might have been expected to make the soils whose clays possessed a SiO_2/R_2O_3 ratio of more than 3 behave more like the Cecil soil. In addition to other important factors, there exists a great difference in the pH environment in which Fe and Al soil variants are produced in the laboratory and that of normal genesis of clays of low SiO_2/R_2O_3 ratios. Whatever the detailed explanation is, the fact is that, by treatment with acid Fe- and Al-salt solution followed by one or more drying and wetting cycles, cohesive clay soils may shift toward silty behavior. This may be very important with regard to the stability of certain soil structures in which such changes occur. Let us consider the following example.

Coal mine overburden and tailings of shaly character are dumped into piles of sufficiently loose packing to provide relatively easy access to air and precipitation water. This looseness is attested to by Schmidtalbers (1), who observed and recorded that during dumping the material in such piles behaved as macromeritic liquids (5). In their new exposure to weathering conditions (permeating water and air, temperature, and wetting-drying cycles), the mechanically produced secondary shale particles gradually return to their original clay character. At the same time the always-present pyrites and other sulfides produce acid Fe- and Al-salt solutions that react with these clay materials and produce the corresponding cationic variants at the surface of the original shale particles. In the end, these systems have lost the granular character of the original comminuted shale and have acquired the characteristics of soft aggregates covered by a layer of silt-like material. At this stage, soaking of the pile by prolonged precipitation may result in a condition similar to that caused in an earth dam by rapid draw-down of an adjoining water reservoir. The final event may be a catastrophic failure of the waste dump.

CONCLUSIONS

1. Simple slaking tests in combination with the common Atterberg limit tests are valuable tools for the study of the attack of water on dry cohesive soil systems.

2. Of special significance with regard to the strength of interparticle bonds in natural cohesive soils not possessing a granular bearing skeleton and the rate of destruction of these bonds by an advancing wetting front is the position of the shrinkage limit. The higher this limit is, the longer is the time required for slaking or other type of specimen failure.

3. At comparable clay contents, shrinkage limits and water resistance increase with decreasing SiO_2/R_2O_3 ratio of the clay fraction.

4. Relatively high shrinkage limits and corresponding slaking times may also be obtained in natural soils whose secondary aggregates are protected by a film of wetting-resistant organic matter.

5. The slaking times of homoionic variants of natural soils show certain vagaries that are probably due to loss of some mineral or organic constituents by true or colloidal solution in the large amounts of liquids employed in their preparation. An additional factor is the different treatment history of the ionic variants, which leaves its imprint on their secondary structure.

6. Exchange ions that have a dispersive tendency generally increase the slaking times of whole soils, whereas flocculating ions tend to decrease them.

7. Sand-clay systems prepared from the natural and homoionic soil variants may exhibit longer or shorter slaking times than the corresponding soils. Decrease occurs when strong original interparticle bonds are replaced by weaker ones with the alien sand admixture without beneficial effect due to the presence of the granular bearing skeleton. Increases in slaking times occur when the intergranular space can accommodate the swelling of the clay fraction with a resulting decrease of the permeability of the system. This essentially geometric or volumetric effect may be modified by bond formation between the clay particles and the surfaces of the sand grains.

Other more specific conclusions were presented in the text of this paper.

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RICHARD W. CHRISTENSEN, Dames and Moore, Chicago
BRAJA M. DAS, Walter Lum Assoc., Honolulu

HYDRAULIC EROSION OF REMOLDED COHESIVE SOILS

This study was undertaken to gain a better understanding of the erosion of cohesive soils and to determine the relationship between rate of erosion under steady flow conditions and critical tractive stress. Tests were conducted on soils containing kaolinite and grundite, and Ottawa sand was used as an additive in some of the samples. Three series of tests were conducted to determine the effects of test duration and tractive stress, density and moisture content, and temperature of water flow on hydraulic erosion. The first series revealed that there are three distinct stages of erosion under a given tractive stress. In series II, the samples were prepared at varying densities and moisture contents. Molding the samples at high moisture contents produced smoother samples; thus, it appeared that decreasing surface roughness was more important than increasing density. When the temperature of the water flow was varied in series III, it was observed that the rate of erosion increased significantly with increasing temperature. It was concluded that erosion rates are dependent on soil composition, surface roughness, flow rate, temperature, and duration of flow.

In recent years increasing emphasis has been placed on the study of erosion characteristics of cohesive soils. Knowledge of the rate of erosion is especially useful in the design of noneroding canals and maintenance of highway embankments and other man-made structures.

Erosion of cohesive soils under steady flow conditions has been considered for this study. The resistance to erosion of cohesive soils is generally attributed to the interparticle forces and the electrochemical forces between the clay particles. The rate of erosion is a function of the hydraulic tractive stress that causes erosion, of temperature of the flowing water, and of several other soils parameters such as density, moisture content, clay type, percentage of clay fraction, and cation concentration.

An improved understanding of the effects of these parameters has been developed by several researchers (2, 3, 4, 12, 14, 15, 16, 17, 18). However, definite relationships between rates of erosion under steady flow conditions and critical tractive stress are still lacking. This study was conducted for the purpose of supplementing the understanding of erosion processes in cohesive soils.

EXPERIMENTAL STUDIES

Materials

Tests reported in this study were conducted on soils containing kaolinite and grundite as basic clay minerals. Ottawa sand was used as an additive to the clay minerals in some of the soil samples. A description of the soils tested is given in Table 1. All samples were tested in the saturated condition.

Testing Apparatus

A majority of the studies on erosion of cohesive soils in the past have been done by the use of the shear flume. The experimental procedure adopted in this study involves lining the inside of a brass tube (1-in. inside diameter, 4 in. long) with the clay to be tested and maintaining a steady flow of water through the clay linings. The thickness of the clay linings was kept at $\frac{1}{8}$ in. for all the tests conducted.

A schematic diagram of the laboratory experimental setup is shown in Figure 1. Desired rates of flow through the clay linings were maintained by an overhead tank and two flow adjusters. The pipes leading from the overhead tank into and out of the clay-lined brass tube were kept at the same inside diameter as the clay lining ($\frac{3}{4}$ in.) to avoid turbulence.

Sample Preparation

The assembly for lining the inside of the brass tube with clay is shown in Figure 2. It consists of an outer brass tube having an inside diameter of 1 in. (sample tube), an inner molding tube ($\frac{3}{4}$-in. outside diameter) with a socket head at the top and semicircular openings at the bottom, two end pieces, and a plunger.

The clay samples were molded by placing the assembly under a static compression device with the plunger inside the socket head of the inner tube (Fig. 3). When pressure is applied to the plunger, the clay is pushed in and forced through the semicircular holes at the bottom of the inner tube into the $\frac{1}{8}$-in. thick annular space between the inner and outer molding tubes. The plunger is removed and more clay is added into the socket head as required. This process is continued until threads of clay begin to emerge from the small hole in the side of the outer tube. If the emerging threads are observed, the presence of any voids can be detected. After compaction is complete, the plunger is removed, the inner tube is slipped out, and the end pieces are removed. This process produces a smooth clay lining $\frac{1}{8}$ in. thick with a $\frac{3}{4}$-in. inside diameter and 4-in. length on the inside of the outer brass tube.

Samples prepared in this manner proved to be very consistent and reproducible. It is expected that the orientation of clay particles would remain practically the same for samples made from the same type of clay at the same moisture content. After visual examination, disturbed samples were rejected, inasmuch as rough linings would affect the test results.

The weight of the outer brass tube was recorded before the start of the molding procedure and again after the tube was lined with clay. The difference in these two weights gives the weight of the clay used in the lining. If the moisture content during molding is known, the dry weight of the clay can be determined.

Hydraulic Tractive Stress

With a steady rate of flow of water through the sample tube, the hydraulic tractive stress on the surface of the clay lining can be expressed as

$$\tau_H = \frac{f\rho}{8} V^2 \tag{1}$$

where

τ_H = hydraulic tractive stress on the surface of the clay lining,
f = friction factor for the surface of the clay lining,
ρ = density of water, and
V = average velocity of flow through the clay lining.

The friction factor f in Eq. 1 was evaluated by the use of the Moody diagram (11) as a function of Reynolds number and relative roughness of the material, ϵ/D, where ϵ is a measure of the size of the roughness projection for the surface of the clay lining and D is the inside diameter of the clay lining.

Because the kaolinite and grundite soils used for this study are more than 95 percent finer than 0.045 mm and the innner molding tube used for surface

Table 1. Description of soils tested.

Soil	<No. 40 Sieve (percent)	<No. 200 Sieve (percent)	<2 Microns (percent)	Liquid Limit	Plastic Limit	Plasticity Index
Kaolinite	100	100	53	43	29	14
Grundite	100	96	62	51	30	21
Ottawa sand	2	—	—	—	—	—

Figure 1. Schematic diagram of laboratory erosion test setup.

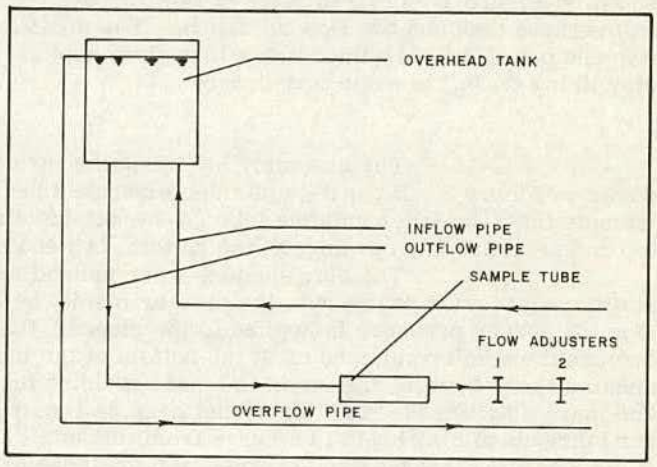


Figure 2. Assembly for clay lining inside brass tube.

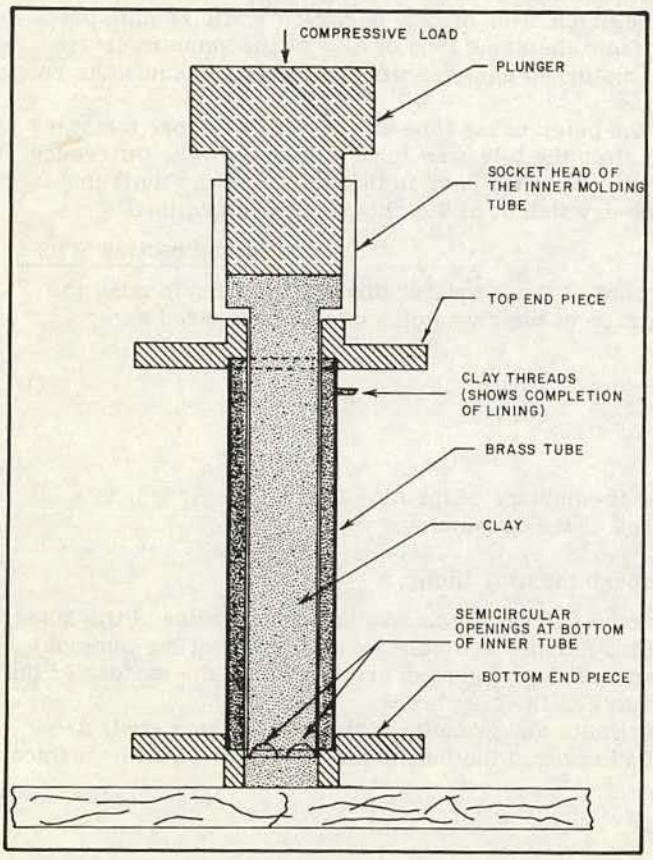
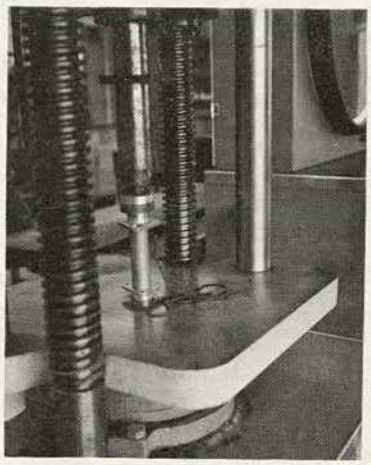


Figure 3. Compaction process for clay lining inside brass tube.



finishing was drawn brass tubing, the inside surface of the clay lining is expected to be very smooth. Hence, the value of ϵ for the clay samples can be expected to be within the range of wrought iron and drawn tubing.

The rate of flow during all the tests was adjusted in such a manner that the Reynolds number remained in the range of 4,000 to 8,000.

Table 2 gives the range of friction factors for wrought iron and drawn tubing for a ¾-in. inside diameter at Reynolds numbers of 4,000 and 8,000. It can be seen from Table 2 that, for the given diameter and with the range of Reynolds number between 4,000 and 8,000, the maximum difference in friction factor between wrought iron tubing and drawn tubing is about 12 percent. It may be noted that the friction factor versus Reynolds number plot for the drawn tubing approaches that of smooth pipe flow within the range of Reynolds numbers considered.

The original surface of the clay lining prior to testing should be no rougher than that of wrought iron. During testing, after large amounts of erosion have taken place, the surface tends to become quite rough. However, the test data were disregarded when erosion became excessive. Therefore, if the hydraulic shear stress is computed on the assumption of smooth pipe flow, the results will not be in error by more than 12 percent at the maximum and about 5 to 6 percent on the average. The equation relating Reynolds number and the friction factor for smooth pipe flow may be expressed in the form

$$\frac{1}{\sqrt{f}} = 2 \log_{10} R \times \sqrt{f} - 0.8 \qquad (2)$$

where R = Reynolds number.

Equations 1 and 2 were used for calculation of hydraulic tractive stress on the surface of the clay linings.

Controlled Variables

The effect of three major variables that influence the rate of erosion of cohesive soils, i.e., hydraulic tractive stress on the clay lining, molding moisture content, and temperature of flowing water, have been studied for the two types of clay described. In each series of tests, one of the variables was changed while the others were kept constant. The sequence of laboratory testing is given in Table 3.

TEST RESULTS

Series I

This phase of the investigation was designed to study the erosion of the soil samples for various test durations and hydraulic tractive stresses. The durations of the tests for kaolinite samples were ¼, ½, ¾, and 1 hour, and those for the grundite samples were ½, 1, 2, and 3 hours. The hydraulic tractive stress was varied by changing the flow rate. The molding moisture content, density, and the test temperature were kept constant for each soil under consideration. The amount of erosion under varying test conditions is shown in Figures 4 and 5.

It can be seen from these figures that, for each soil, there are three distinct stages of erosion under a given hydraulic tractive stress. These three stages are more distinguishable in the case of grundite than kaolinite. In the initial stage, the rate of erosion decreased with time, followed by what appears to be a steady-state condition during which the rate of erosion remained constant. At the end of the steady state, the rate of erosion increased rapidly. During the latter stage, the eroded soil particles were much larger, indicating a rapid deterioration of the clay surface. The shapes of the curves shown in Figures 4 and 5 suggest that, in the early stages of the tests, loose particles left on the surface are eroded away first, followed by a steady-state condition of fairly short duration; and finally, after the surface has been significantly roughened by the previous erosion, the rate of erosion accelerates rapidly, and the surface deteriorates badly in a short period of time. The entire process bears a

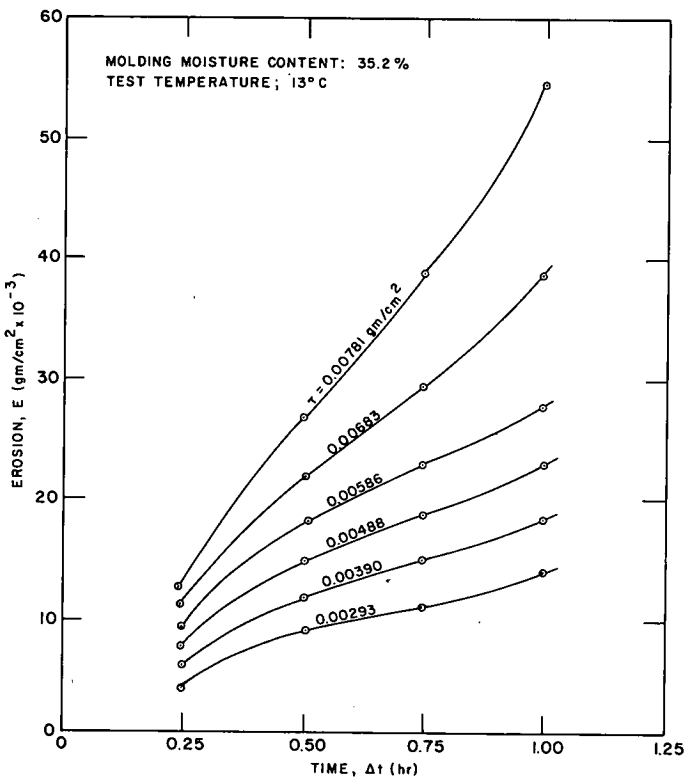
Table 2. Friction factors for wrought iron and drawn tubing.

Material	ϵ (ft)	Reynolds Number	D (ft)	ϵ/D	f	Difference (percent)
Wrought iron	0.00015	8,000	1/16	0.0024	0.036	11.7
Drawn tubing	0.000005	8,000	1/16	0.00008	0.0324	
Wrought iron	0.00015	4,000	1/16	0.0024	0.042	5.0
Drawn tubing	0.000005	4,000	1/16	0.00008	0.040	

Table 3. Parameters of the three test series.

Series	Variable Parameters	Controlled Parameters
I	Hydraulic tractive stress on clay lining, duration of test	Density of compaction, molding moisture content, temperature of water
II	Molding moisture content	Hydraulic tractive stress on clay lining, duration of test, temperature of water
III	Temperature of water	Hydraulic tractive stress on clay lining, duration of test, molding moisture content

Figure 4. Erosion versus time at constant temperature and moisture content for kaolinite.



marked resemblance to creep behavior of cohesive soils at stress levels large enough to eventually cause failure.

Figures 6 and 7 show the steady-state rate of erosion as a function of the hydraulic tractive stress for kaolinite and grundite. These curves demonstrate that the steady-state rate of erosion rapidly increased beyond a certain hydraulic tractive stress level for each soil. This point seems to delineate the onset of mass erosion from the surface. The corresponding stress level is termed the "critical" hydraulic tractive stress τ_{cr}. Stress levels higher than τ_{cr} lead to severe erosion of the clay surface in a very short period of time.

Series II

It is generally assumed that, under similar conditions, the rate of erosion will decrease with increasing density. However, the evidence in previous studies has not been conclusive (4, 17, 18).

For this phase of the laboratory investigation, saturated soil samples were prepared at varying densities and moisture contents and subjected to a constant hydraulic tractive stress. Because the soil samples were saturated, the density decreases with increasing moisture content. The duration of the test and the temperature of the water were kept constant for each type of soil.

The laboratory test results, shown in Figures 8 and 9, exhibit a sharp decrease in erosion with increasing moisture content. Visual observation of the samples prior to testing indicated that molding the samples at higher moisture contents produced a smoother surface on the clay lining. It was also observed that the linings containing sand were rougher than those without sand at the same moisture content. From the results obtained in this series of tests, it appears that decreasing the surface roughness is more important than increasing the density from the standpoint of reducing erosion.

Series III

Grissinger (4) has reported that erosion rates are influenced by temperature. In this series of tests, erosion of kaolinite and grundite samples was observed with the flowing water adjusted to various temperatures. Because the clay linings were only ⅛ in. thick, it is assumed that the temperature of the clay quickly adjusted to the temperature of the flowing water. The configuration of the testing apparatus did not allow direct temperature readings in the clay; therefore, it is not definitely known whether the temperature of the clay completely adjusted to the temperature of the flowing water within the duration of the tests. During this series of tests the molding moisture content, hydraulic tractive stress, and test duration were held constant.

The effects of varying water temperature are shown in Figures 10 and 11. It may be observed that the rate of erosion increased significantly with increasing temperature and that the erosional response to temperature changes is typical of thermally activated processes. It should be noted that the data shown in Figures 10 and 11 may be somewhat in error due to the possibility that the temperature in the clay may not have reached complete equilibrium with the temperature of the flowing water during the time the tests were in progress. Correction of the temperature data, if any is required, would result in a steepening of the slopes of the lines shown in Figures 10 and 11; i.e., a more pronounced temperature effect than that shown.

INTERPRETATION OF RESULTS

The test results obtained in this study bear a striking similarity to those obtained from creep tests on saturated cohesive soils under constant shear stress. Therefore, it may be postulated that, although direct proof would be difficult, particles or clusters of particles are eroded from a clay surface as a result of shear stress transmitted by the flowing water. If so, it should be possible to interpret the erosion behavior of cohesive soils within the same framework as that used to explain steady-state creep behavior.

Figure 5. Erosion versus time at constant temperature and moisture content for grundite.

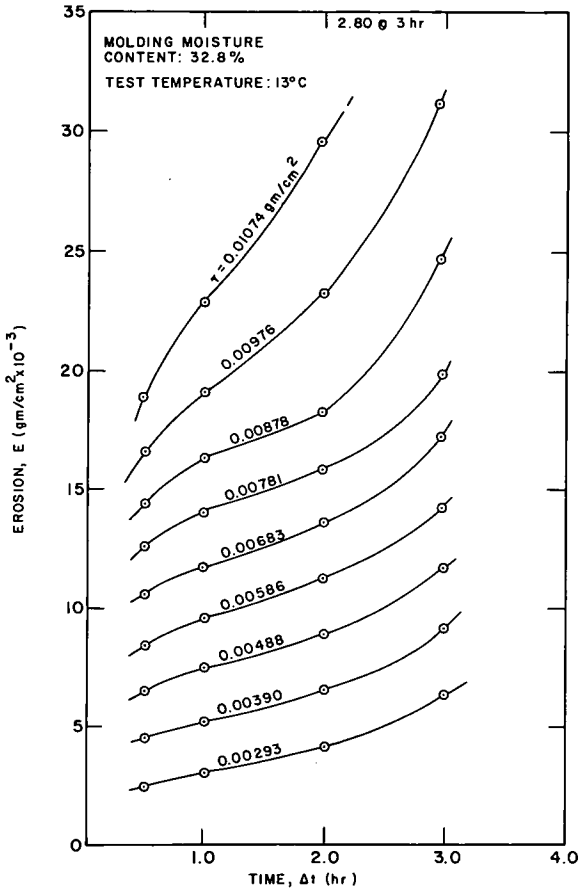


Figure 6. Log E versus hydraulic shear stress at constant temperature and moisture content for kaolinite.

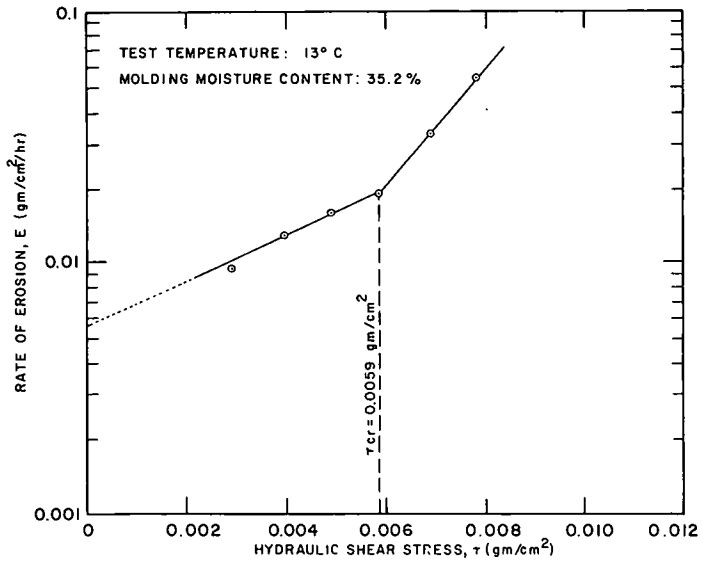


Figure 7. Log E versus hydraulic shear stress at constant temperature and moisture content for grundite.

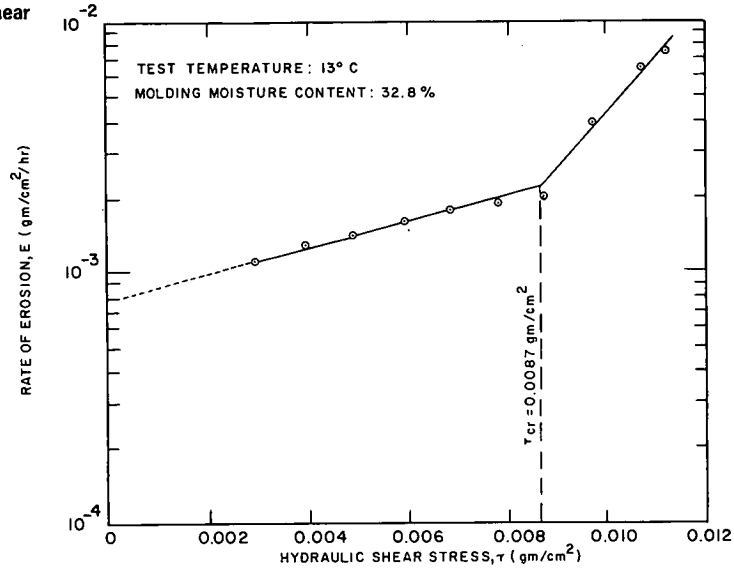


Figure 8. Erosion and dry density versus moisture content at constant temperature and hydraulic shear stress for kaolinite and kaolinite-sand mix.

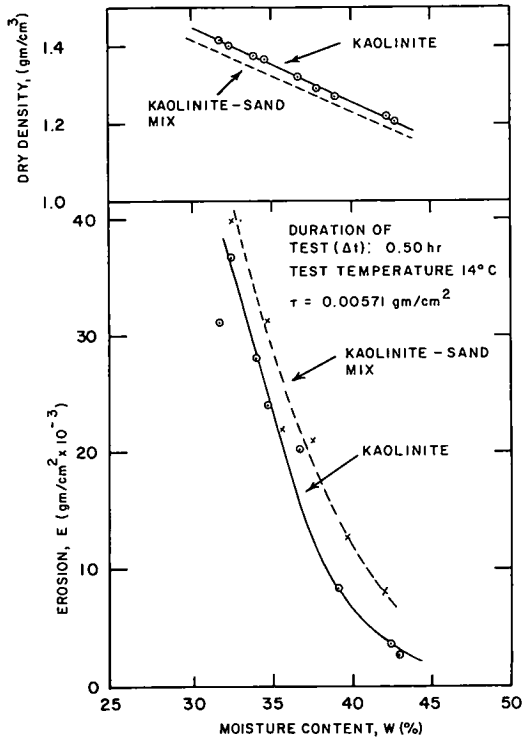
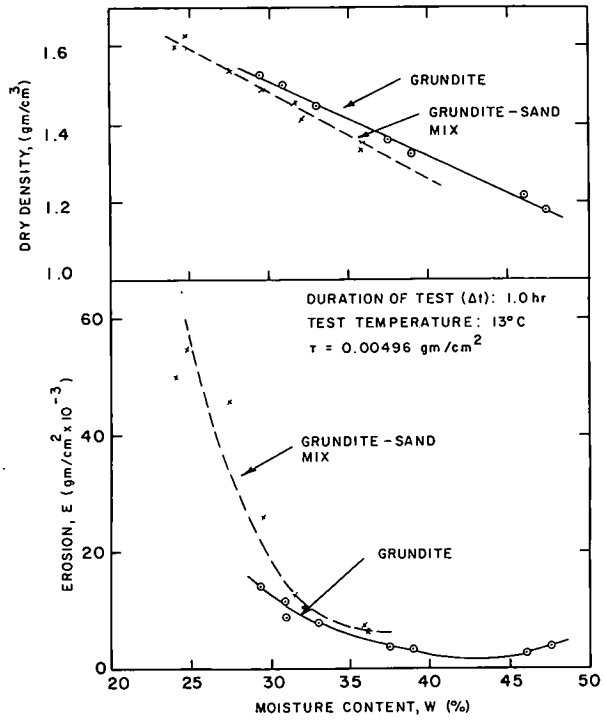


Figure 9. Erosion and dry density versus moisture content at constant temperature and hydraulic shear stress for grundite and grundite-sand mix.



Mitchell et al. (10) recently considered bonding mechanisms and strength of soils in terms of rate process theory, using steady-state creep data as a basis for their hypotheses. The equation for creep rate is given in the form

$$\dot{\epsilon} = \chi \frac{kT}{h} \exp\left(-\frac{\Delta F}{RT}\right) \exp\left(\frac{\lambda\tau}{2SkT}\right) \tag{3}$$

where

$\dot{\epsilon}$ = creep strain rate,
τ = shear stress causing creep,
k = Boltzman's constant = 1.38×10^{-16} erg/deg K,
h = Planck's constant = 6.624×10^{-27} erg/sec,
T = absolute temperature, deg K,
R = universal gas constant = 1.98 cal/deg K,
ΔF = free energy of activation, cal/mole,
χ = a function that depends on the number of flow units in the direction of deformation and the average component of displacement in the same direction due to a single surmounting of the energy barrier,
λ = separation distance between successive equilibrium positions, and
S = number of flow units per unit area.

If the mechanism of erosion is similar to that of creep, it follows that the expression for erosion rate should be of the form

$$\dot{E} = \beta_E \exp(\alpha \tau_H) \tag{4}$$

where

$\beta_E = \sim T \exp\left(-\frac{\Delta F}{RT}\right)$ and

$\alpha = \frac{\lambda}{2SkT}$.

The exponential dependence of erosion rate on the hydraulic shear stress predicted by Eq. 4 can be seen from Figures 6 and 7.

From Eq. 4,

$$\frac{\partial \ln\left(\frac{E}{T}\right)}{\partial\left(\frac{1}{T}\right)} = -\frac{1}{R}\left(\Delta F - \frac{\lambda N \tau_H}{2S}\right) \tag{5}$$

where $N = \frac{R}{k}$ = Avogadro's number. Figures 10 and 11 show that the form of Eq. 5 correctly describes the effect of temperatures on the steady-state erosion rate.

The values of the rate process parameters have been computed from the data shown in Figures 6, 7, 10, and 11 and are given in Table 4. These values may be compared with those obtained by Mitchell et al. (10) to determine whether the rate process hypotheses developed from creep studies are applicable to erosion.

The number of bonds per unit area S computed from the erosion data is of the order of 5×10^5, which is approximately five orders of magnitude smaller than typical values reported for creep (10). However, Mitchell et al. (10) have also shown that the number of bonds is inversely proportional to compressive strength (or shear strength, τ_{max} in gm/cm^2); e.g., for remolded illite,

$$S \simeq (8 \times 10^7)\, \tau_{max} \tag{6}$$

The erosion tests indicated that, when the hydraulic tractive stress exceeded the critical value, significant shear failures were occurring, causing large clusters of soil to be removed from the clay lining. If the critical hydraulic tractive stress is interpreted as the shear strength of the soil at the exposed face of the lining, then, according to

Figure 10. Erosion rate as a function of absolute temperature for kaolinite.

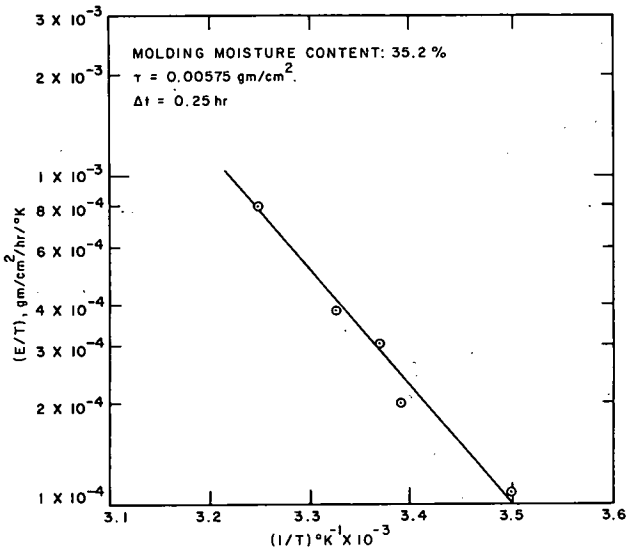


Figure 11. Erosion rate as a function of absolute temperature for grundite.

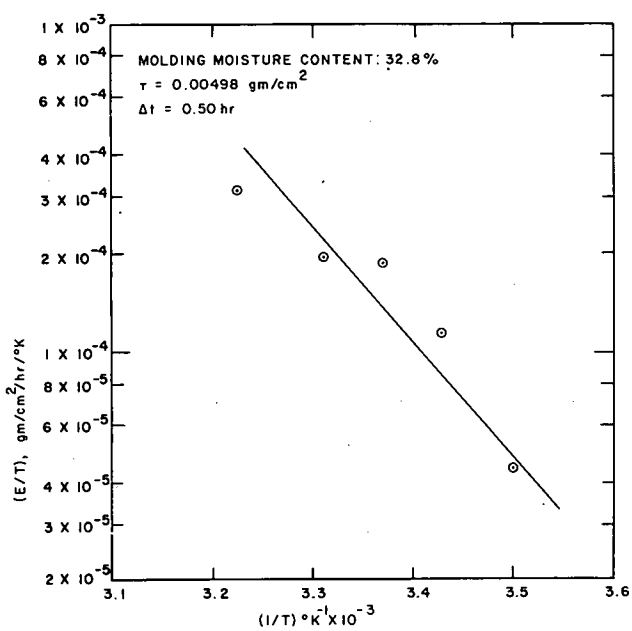


Table 4. Values of rate process parameters for kaolinite and grundite.

Soil Type	α (cm^2/gm)	β_ϵ ($gm/cm^2/hr$)	S (cm^{-2})	$\Delta F - \frac{\lambda N \tau_K}{2S}$ (cal/mole)
Kaolinite	200	5.8×10^{-3}	5.75×10^5	16,300
Grundite	120	8.1×10^{-4}	3.45×10^5	15,400

Eq. 6, S should be of the order of 10^5. Interpreted in this light, the apparently small number of bonds per unit area and the correspondingly high value of α are consistent with the concept of bonding proposed by Mitchell et al.

The experimental activation $\left(\Delta F - \frac{\lambda N \tau_H}{2S}\right)$ was computed from Eq. 6 and the data are shown in Figures 10 and 11. The values obtained for erosion are substantially lower than those reported for creep (10). As discussed previously, part of the discrepancy may be attributed to the fact that the accuracy of temperature control and measurement in this study were relatively crude for the calculation of activation energy. Therefore, it is quite possible that the actual values of activation energy should be higher than those calculated. However, it should also be noted that, by the very nature of the erosion process, data cannot be obtained until failure conditions are imminent at the surface of the clay lining. Hence, the experimental activation energy computed from the erosion tests pertains to conditions very near failure. Mitchell et al. (9) have shown that the experimental activation energy tends to decrease as failure is approached. Moreover, any contribution to the activation energy due to restraint of deformation caused by mechanical interaction between neighboring particles would be almost totally lacking in erosion from a free surface, whereas such effects could be significant in a typical creep test where the planes of deformation pass through the body of the specimen.

CONCLUSIONS

1. Erosion rates are highly dependent on soil composition. Both clay content and clay type are important variables.
2. Other important variables of soil erodibility appear to be surface roughness, flow rate, i.e., hydraulic tractive stress, and duration of flow.
3. There is a sharp point of demarcation at which the steady-state erosion rate rapidly increases with increasing hydraulic tractive stress. This point provides a convenient working definition for critical tractive stress.
4. In saturated soils, increased density does not necessarily increase resistance to erosion. Other factors related to placement conditions such as surface roughness may overshadow the effects of increased density.
5. Although more than one interpretation is possible, it is postulated that erosion of saturated cohesive soils is basically a shearing process that can be explained in terms of the rate process theory. By use of this approach, the values of the rate process parameters (activation energy and number of bonds) are consistent with those obtained for steady-state creep.

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W. H. WISCHMEIER and L. D. MEYER, Purdue University,
West Lafayette, Indiana

SOIL ERODIBILITY ON CONSTRUCTION AREAS

Forty years of research in the U. S. Department of Agriculture has identified the major factors in soil erosion and established their functional relationships to soil loss. The relationships were combined in an empirical erosion equation that is now widely used on farmland and can be adapted to sediment prediction and erosion control planning on construction areas. Soil erodibility is one of the six major factors that determine soil-loss rate at a particular site. In this narrow sense, the term denotes the inherent susceptibility of a soil to detachment and transport by rainfall and runoff. Results of an intensive field, laboratory, and statistical study of the relations of soil properties and interactions to a soil's erodibility are briefly summarized in the report. Use of the soil-erodibility factor and the erosion equation to predict construction-site sediment yields is illustrated. The other factors in the equation evaluate effects of rainfall pattern, slope length, slope steepness and shape, cover and management, and conservation practices. They are interpreted relative to construction-site conditions, and sources of information for their locality evaluation are discussed. Recent tests of cover and management effects on construction sites are reviewed.

Soil erosion by water is a complex process that involves the interrelations of many factors. Some of these influence the capability of the erosive agents, rainfall and runoff, to detach and transport soil material. Others influence the ability of the soil to resist the forces of the erosive agents. Extensive research by the U. S. Department of Agriculture and land-grant universities has identified the major factors that influence soil erosion and has established functional relationships of soil, rainfall, topography, cover, and management to soil loss.

The term soil erodibility has several possible connotations. At the Agricultural Research Service (ARS), it has been used to denote the relative susceptibility of different soils to erosion when other factors are essentially equal. By this interpretation, erodibility is a function of soil properties only and, therefore, a soil parameter. On the other hand, expressions such as soil erodibility on a construction area are more likely to connote the expected soil-loss rate or sediment yield from a particular site. To predict erodibility in this broader sense requires that the effects of local rainfall pattern, slope length, slope steepness, land cover, and management practices be evaluated along with the soil factor.

This report will consider soil erodibility in the narrower sense, as a function of soil properties, but will also discuss its role as one of six major factors that combine to determine the amount of soil eroded from a particular site.

The factor relationships were derived from statistical analyses of soil loss and associated data obtained in 40 years of research by ARS and assembled at the ARS runoff and soil-loss data center at Purdue University (11). The data include more than a quarter-million runoff events at 48 research stations in 26 states, representing about 10,000 plot-years of erosion studies under natural rain. They also include supplemental data obtained with rainfall simulators (4) on field plots and from fundamental studies in the laboratory.

Several developments at the ARS data center have provided convenient working tools for farmland erosion control planning that can be adapted to conditions at the construction site as well. These developments include (a) a new rainfall-erosivity index EI, (b) a more informative parameter to describe soil particle-size distribution, (c) a soil-erodibility nomograph, (d) a slope-effect chart, (e) a technique for evaluating cover and management effects in relation to specific rainfall patterns, and (f) the universal soil-loss equation. The first five developments were incorporated in the sixth.

ERODIBILITY AS A SOIL PARAMETER

The dimensional soil factor K, derived for the universal soil-loss equation (17), is usually expressed in tons per acre per unit of rainfall EI, under conditions of 9 percent slope 72.6 ft long, continuously fallowed. (EI is defined later.) The K-value for a particular soil can be obtained directly from soil-loss data and is independent of geographic orientation. For the major soils on which the erosion plot studies were located, K ranged from 0.30 to 0.69. The more than 20-fold range in its magnitude emphasizes the importance of the soil factor in gross sediment prediction. Empirically determined, K combines the effects of the soil's water intake capacity and its susceptibility to detachment and transport by rainfall and runoff.

ARS recently conducted an intensive study of the relation of a soil's erodibility to its physical and chemical properties. Rainfall simulators were used in three physiographic regions to apply identical rainstorms to identically prepared, fallowed field plots on widely differing soils. The experimental design allowed interactions between soil parameters to exert their normal influence on the measured erodibilities. Topographic and surface-condition variables were measured, and the soil profile was described at each test site. Physical and some chemical properties of each soil were determined by standard laboratory methods (16). Regression analyses were used to explore the relative predictive capabilities of numerous soil properties individually and collectively. Terms to evaluate the effects of various factor interactions were included in the regression models.

A 24-term equation, derived from data for 55 widely varying Corn Belt soils, accounted for 98 percent of the variance in observed K-values (16). The equation did not fully meet the requirements of a field working tool, but it showed some interesting factor interrelationships that influence the erodibility of a soil. Some of them will be discussed later. Further exploratory analyses, which included five additional soils, resulted in development of new relationships that were combined in the soil-erodibility nomograph shown in Figure 1 (15). The nomograph is a convenient tool for graphical computation of the erodibility of a specific topsoil or subsoil horizon.

Factor Relationships That Influence a Soil's Erodibility

Standard textural classes as defined in the USDA Soil Survey Manual (9) were poorly correlated with soil erodibility. Soils classified as silt loams, for example, ranged all the way from moderately to very highly erodible. Mechanical analysis data, based on the USDA classification system, accounted for less than 25 percent of the soil-loss variance for the fallowed plots. This system classifies particles smaller than 0.002 mm as clay, those from 0.002 to 0.05 mm as silt, and those from 0.05 to 2.0 mm as sand. In very general terms, the silt-size particles were eroded most easily, and soils became less erodible as either the sand fraction or the clay fraction increased. The rate of increase in erodibility with additional increments of silt-size material became less as either organic matter or the clay-to-sand ratio increased. The rate of decrease in erodibility with increased clay content declined with higher organic-matter content or higher aggregation index. Aggregates of appreciable size washed off.

Analyses of the rainulator and natural rain soil-erodibility data showed conclusively that particles classified by the USDA system as very fine sand (0.05 to 0.10 mm) behave more like silt than like larger sand. When silt was redefined to include particles from 0.002 to 0.10 mm and sand was redefined as 0.10 to 2.0 mm, the

prediction values of the two parameters were substantially improved. This grouping approaches AASHO (1) and ASTM classifications but does not quite coincide with them.

Even with the improved mechanical analysis classification, the relation of erodibility to percentage of silt depended very much on the clay-to-sand ratio and associated levels of other properties of the particular soil. Development of a statistical parameter that adequately describes the whole particle-size distribution for a given soil greatly enhanced the predictive capability of mechanical analysis data. The new particle-size parameter (15), which was designated as M, is

$$M = (\text{percentage of } 0.002 \text{ to } 0.10 \text{ mm}) \times (\text{percentage of } 0.002 \text{ to } 2.0 \text{ mm}) \qquad (1)$$

where the first group is percentage of silt and very fine sand and the second is percentage of silt plus sand (or 100 minus percentage of clay).

The parameter M accounted for 85 percent of the variance in observed K-values for the 55 rainulator-tested soils in a curvilinear relationship. Some of the individual soil predictions, however, still deviated rather widely from the observed values. Three more parameters were required to account for these deviations: soil organic-matter content, structure, and permeability.

Organic-matter content was inversely related to sediment content of the runoff and was directly related to the amount of rain needed to initiate runoff and to the final infiltration rate. The inverse relations of erodibility to organic-matter level and water-stable aggregation were strongest for silts, silt loams, loams, and sandy loams and declined significantly as clay content increased. Percentages of organic matter were determined by a modified Walkley-Black method (10). They are roughly 1.7 times the percentage of soil carbon.

Soil structure apparently bears a close relation to several soil properties that influence erodibility. When a soil-structure index (9) was included with the particle-size parameter M and organic-matter content, it significantly improved the accuracy of individual erodibility predictions. Structure codes shown in Figure 1 are as follows:

Structure Index	Definition
1	Very fine granular
2	Fine granular
3	Medium or coarse granular
4	Blocky, platy, or massive

The only additional parameter needed to obtain prediction accuracy within the range of practical needs was the standard permeability classification (9). The six permeability classes are as follows:

Permeability Class	Definition
1	Rapid
2	Moderate to rapid
3	Moderate
4	Slow to moderate
5	Slow
6	Very slow

Many other parameters were tested. Water-stable aggregation was inversely related to erodibility and, in simple regressions, accounted for about 6 percent of the soil-loss variance. Because of its interrelation with particle-size distribution and organic-matter content, however, the aggregation index proved of no additional value in the multiple-term relationship on which the erodibility nomograph is based. Bulk density and the dispersion ratio proposed by Middleton (7, 8) were omitted from the final equation for the same reason. The relation of pH to erodibility

seemed to depend on the soil's structure and silt content. The data were not adequate to establish dependable relationships between phosphorus and potassium contents and erodibility.

Nomograph

The soil-erodibility nomograph (15) shown in Figure 1 graphically solves an abridged equation that incorporates the new particle-size distribution parameter M and the revised definitions of silt and sand. The parameter M appears in the nomograph as the unidentified horizontal scale in the left section. The scale does not need identification because M is computed in the first step of the nomograph solution.

The five moves in the graphic solution are shown in Figure 1. All entry values, except permeability, apply to the upper 6 or 7 in. of soil, regardless of whether it happens to be an original topsoil or a scalped subsoil.

For soils with silt (0.002 to 0.10 mm) fractions less than 70 percent, the nomograph solves the equation:

$$2.1(10^{-4})(12 - O)M^{1.14} + 3.25(S - 2) + 2.5(P - 3) \qquad (2)$$

where O is percentage of organic matter, M is the particle-size parameter, S is the structure index, and P is the permeability class. Changes in the relationships of Eq. 2 when the silt fraction exceeds about 70 percent are introduced by the inflections in the curves of percentage of sand.

The error of estimate based on the data used for derivation of the nomograph indicates that, of 100 K-values obtained by its solution, 68 would be within 6.4 percent of the true values, 90 within 11 percent, and 99 within 17 percent. When the nomograph was applied to descriptive data for bench-mark soils on the erosion research stations, all the solutions were well within accuracy requirements for practical use.

Because the soil surface is often unprotected during construction periods, the soil factor assumes even greater relative importance. C horizon subsoils exposed by bulldozing were tested with a rainulator on two construction sites: a Miami loam subsoil and a compacted, calcareous loam till underlying a Wingate silt loam. In each case, the measured K-value was within 0.02 of the value predicted by the nomograph. Soil-loss data from mechanically desurfaced plots in erosion studies of the 1930s and 1940s on Shelby loam in Missouri and Marshall silty clay loam in Iowa were equally reassuring. Also, nomograph readings for wide range of hypothetical subsoils, including textural extremes, predicted K-values that appear quite realistic. However, further studies are under way at Purdue University to explore possible influences of chemical properties and to test the validity of the nomograph for subsoils extremely high in clay content.

The erodibility nomograph can be especially helpful for sediment prediction and erosion control planning on construction sites because it can predict the changes in erodibility when different subsoil horizons are exposed in the reshaping process. For example, assume that a residential development is being planned on an eroded rolling phase of Enon silt loam in Fairfax County, Virginia. From soil classification data, the planner obtains a detailed description of his soil (except the K-values) as given in Table 1. Using first the information for the A_p horizon, he enters the left scale of Figure 1 with the 71 percent silt + vfs (0.002 to 0.10 mm), moves horizontally to the curve for 15 percent sand, vertically to the OM = 2 percent curve, horizontally to structure = 2, and vertically to permeability = 4. On the scale to the left of this point he reads K = 0.45. Following a similar procedure for each soil horizon, he obtains the other four K-values given in Table 1.

By definition of K, soil losses from the respective soil horizons, if exposed on similar slopes and under similar rainfall, would be directly proportional to the K-values. On this site, a 3-ft cut would expose a C horizon that is nearly twice as erodible as the B_3 horizon exposed by a 2-ft cut. On other soils, the B horizon may be substantially more erodible than the topsoil or the C horizon. Information on the subsoil K-values not only shows the depths of cut that would result in the most or the least sediment yield potential but also shows whether return of stockpiled topsoil on the exposed subsoil would be profitable on the particular site.

The nomograph solution, although quantitative, reflects only the effect of the soil on gross erosion. The universal soil-loss equation combines this soil parameter with effects of five other factors to predict gross sediment from specific farm or construction-site areas.

The soil-loss equation, A = KRLSCP, computes average annual soil loss A as the product of the soil factor K discussed above, a rainfall factor R, and dimensionless factors for the effects of slope length L, slope steepness S, cover and management C, and conservation practices P (18). The factors R, L, and S combine to describe the potential of the erosive agents to detach and transport soil material; K reflects the susceptibility of the soil to detachment and transport by the forces of the erosive agents; C and P describe the effectiveness of land cover, management techniques, and conservation practices for protecting the soil's surface against the erosive agents.

The factor R is the rainfall-erosivity index EI. For a given rainstorm, EI is the product of the storm's rainfall energy and maximum 30-min intensity (12). For a season or year, it is the sum of the individual storm values. This product appears to evaluate satisfactorily the combination of rainfall kinetic energy available for detachment of soil particles and associated runoff available to transport them and to detach others.

On the basis of published drop size and terminal velocity data, the kinetic energy of rainfall is related to rainfall intensity by the following formula:

$$Y = 9.16 + 3.31 \log_{10} I \tag{3}$$

where Y is energy in hundreds of foot-tons per acre-inch and I is intensity in inches per hour (17). The rainstorm is divided into increments of approximately uniform intensity, and the energy for each increment is computed using Eq. 3 or the published energy-intensity chart (17) derived from it. The sum of these incremental values is the E-component of the EI parameter. The I-component is maximum 30-min intensity, in inches per hour.

Locational values of EI (factor R) throughout the 37 states east of the Rocky Mountains may be obtained from a published iso-erodent map (13, 18) derived from 22-year rainfall records. This map, with the county lines omitted, is shown in Figure 2.

Topographic factors L and S adjust the soil-loss prediction for effects of differences in length and steepness of land slope. The capability of runoff to detach and transport soil material increases rapidly with increases in runoff velocity. Runoff velocity increases as runoff rate increases, as the flow concentrates, or as the slope steepens. Therefore, the erosive potential of runoff increases substantially as slope length or steepness increases. On slopes not exceeding 20 percent and of moderate length, average slope effect is expressed by

$$A = C\lambda^{0.5} \tag{4}$$

$$A = 0.43 + 0.30s + 0.043s^2 \tag{5}$$

where

A = soil loss,
λ = slope length, in feet,
s = percentage of slope, and
C = a function of soil, rainfall, and land use.

Dimensionless factors L and S of the soil-loss equation are obtained by expressing Eqs. 4 and 5 relative to their solutions for the basic plot dimensions of 9 percent slope, 72.6 ft long. The topographic factor LS is then expressed as

$$LS = \lambda^{0.5}(0.0076 + 0.0053s + 0.00076s^2) \tag{6}$$

In practice, the applicable LS-value may be conveniently obtained from a published slope-effect chart (18) derived by this formula.

When a slope is concave, convex, or irregular, the average steepness does not accurately predict the slope effect. The soil-loss rate near the toe of a convex slope (steepening toward the bottom) is greater than on a uniform slope of equal elevation change (3, 20). On a concave slope it is less. These relationships are shown in Figure 3 and can be very significant in reducing sediment yields from reshaped land at construction sites. The magnitude of the effect of the curvilinearity can be approximated by dividing the slope into segments.

Information is not available to evaluate the factor LS on very steep slopes, such as 2:1 or 3:1 roadbank slopes, in relation to soil and rainstorm characteristics. Use of Eq. 6 or the published slope-effect chart on slopes steeper than 5:1 would be speculative and is not recommended. Beyond some critical steepness, not yet identified, the formula would probably overpredict soil loss.

Practice factor P, on farmland, reflects the runoff control and erosion-reducing effects of superimposed practices such as contour farming, terracing, or contour strip-cropping. The effectiveness of terraces or diversions, which reduce effective slope length and runoff concentration, should be similar on construction sites. Benefits derived from denuding only alternate strips along a construction area slope at any one time or from contoured mulch strips should be comparable to those from strip-cropping.

The cover and management factor C, on farmland, is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from tilled, continuous fallow (which is the basic condition on which the soil factor K is evaluated). C ranges in value from near zero for excellent sod to 1.0 for continuous fallow. On construction sites, C reflects the influences of various types and rates of mulch, methods of revegetation, chemical soil stabilizers and loose and compacted fills. Some of these effects have been studied by operating a rainfall simulator on construction site conditions. Others can be estimated from field plot data.

The graph in Figure 4 shows how soil loss was influenced by various rates of straw mulch on several soils and slopes (2, 5, 6). The data are from rainulator storms applied at 2.5 in./hour for 1 hour on 2 successive days on 35-ft slope lengths. The study on Fox loam of 15 percent slope was on untilled oat land from which all residue had been removed with a scraper. The Xenia and Wea soils had been plowed and disked. The Wingate and Miami subsoils had been mechanically denuded prior to mulching. The Wingate subsoil on 20 percent slope was highly erodible, and substantial rilling occurred beneath the 2.3 tons of straw mulch per acre. The studies showed that even small rates of mulch may greatly reduce soil loss but that larger rates are required for adequate erosion control. They also showed that the mulch rate required for control increases as the erosion hazard increases and that in some situations even a heavy straw mulch would not adequately control erosion.

Figure 5 shows the results of a study of stone and wood-chip mulches for erosion control on construction sites (2). This study was on the 20 percent Wingate subsoil. Surface mulches of crushed stone, gravel, and wood chips showed great potential for erosion control on short, denuded slopes.

After 5 in. of rain had been applied in standard tests, inflow was added at the upper ends of the plots to obtain runoff rates equivalent to those from slope lengths of 75, 115, and 150 ft respectively. Figure 6 shows the results for several of the treatments. With the added inflow, soil losses from the poor treatments were extremely high. However, the stone mulch treatments at 240 and 375 tons/acre, and wood chips at 25 tons, had nearly clear runoff. Even at 135 tons/acre, a depth of less than 1 in., the stone mulch treatment lost only 10 percent as much soil as the 2.3-ton straw mulch treatment at an equivalent length of 150 ft on this 5:1 slope. Stone mulch at 135 tons/acre can be delivered and spread for about 1 cent/sq ft, and wood chips are becoming a common waste material because of restrictions on burning.

Broadcast seeding of grass after the tests gave excellent stands on the plots mulched with 240 or 375 tons of stone, 12 tons of wood chips, or 2.3 tons of straw per acre. Stands were very poor on the no mulch and on the 15-ton rate of stone mulch.

Figure 1. Soil-erodibility nomograph.

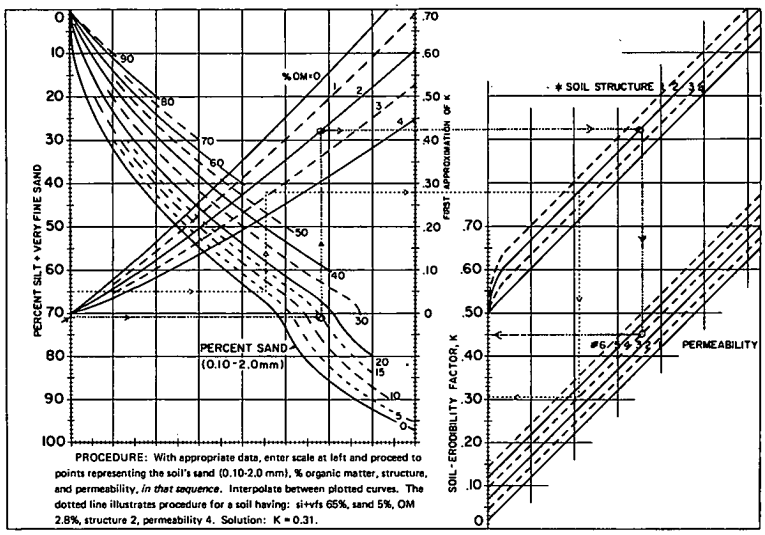


Table 1. Soil horizon data for deriving K-values.

Soil Horizon	Depth (in.)	Texture Class	Particle Size (mm) 0.002-0.10 (percent)	Particle Size (mm) 0.10-2.0 (percent)	Organic Matter (percent)	Structure Index	Permeability Class	K
A_p	0 to 6	sil	71	15	2.0	2	4	0.45
B_1	6 to 9	sicl	60	7	0.6	4	4	0.42
B_2	9 to 20	sic	51	7	0.4	4	4	0.33
B_3	20 to 32	c	38	5	0.3	4	4	0.22
C	32 to 42	sicl	61	9	0.2	4	3	0.43

Figure 2. Average annual values of rainfall intensity (17).

Figure 3. Influence of land slope shape on sediment load.

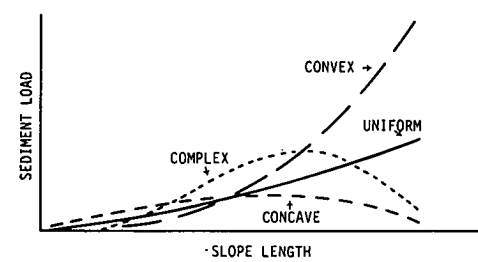


Figure 4. Soil losses from 5 in. of intense simulated rain, as affected by straw mulch cover (intensity = 2.5 in./hour; slope length = 35 ft).

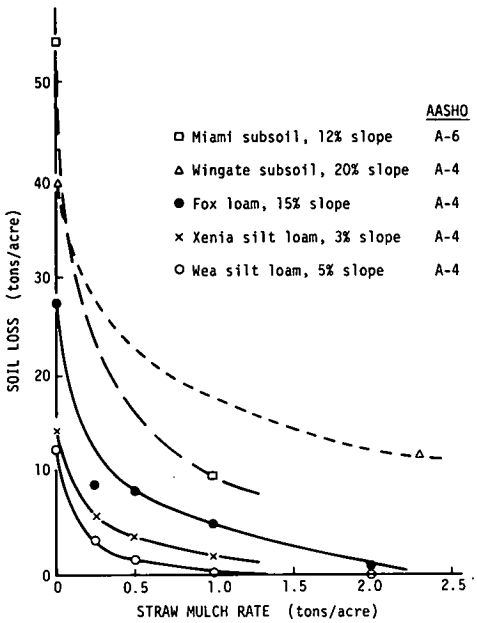


Figure 5. Influence of several mulch types and rates on soil loss from 5:1 construction side-slope (rain intensity = 2.5 in./hour; total applied = 5 in.; slope length = 35 ft).

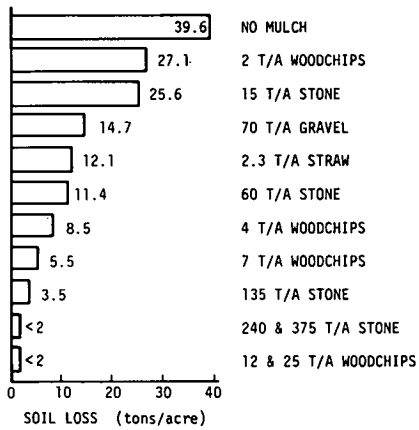
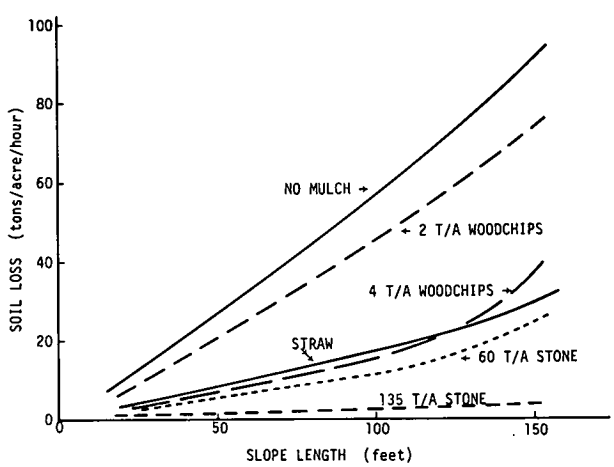


Figure 6. Influence of slope length on erosion rate for several mulch types and rates (5:1 slope).



Predicting Specific-Site Erosion

Effects of the six major factors discussed above are methodically combined in the universal soil loss equation to predict gross erosion from specific sites and in relation to specific planning alternatives. For illustration of the procedure, assume the construction-site situation used earlier to demonstrate application of the erodibility nomograph, and assume that the site is on a 10 percent slope about 200 ft long.

Consulting the detailed iso-erodent map (18) shows that, in Fairfax County, R = 200. For a 10 percent slope 200 ft long, Eq. 6 indicates that LS = 1.93. The erosive potential of the expected annual rainfall and associated runoff is R times LS, or 200 x 1.93 = 386 RLS units.

In the nomograph illustration, the planner found that for the A_p horizon of his soil K = 0.45. This means that he should expect 0.45 ton of soil loss per acre for each RLS unit or an annual total of 386 x 0.45 = 174 tons, if the surface were continuously in a condition equivalent to bare fallow. If the soil were scalped so as to expose the B_2 horizon, the estimated loss would be 386 x 0.33 = 127 tons and so on for the other horizons.

EI probability tables (18) show that at this site the planner faces a 5 percent probability of an R-value equal to or greater than 136 for a single rain event and an annual total of 336 or more in any 1 year. Using these values for R, he finds that he has a 5 percent likelihood of at least 118 tons of soil loss per acre from a single rain or 292 tons in 1 year. The latter would be about 200,000 cu yd of sediment per square mile.

If the topography were shaped to a convex slope, he could expect gross erosion from the area to exceed these estimates; if finished to a concave shape, it should be less. The amount of deviation expected would depend on the degree of slope curvature and the relative erodibilities of the subsoil horizons involved.

The potential sediment predicted by the RLS combination could be reduced by application of one or more of the practices discussed under factor C. For example, a straw or hay mulch at the rate of 3,000 lb/acre would have a C-value of about 0.10. The expected sediment yield from the A_p horizon, mulched at this rate but without use of diversions, would be RLSKCP = 200 x 1.93 x 0.45 x 0.10 x 1.0 = 17.4 tons/acre. The results of each of many alternative management decisions could be similarly predicted. The technique has been described more fully in other publications (14, 18).

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M. R. AKKY and C. K. SHEN, University of California, Davis

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)].

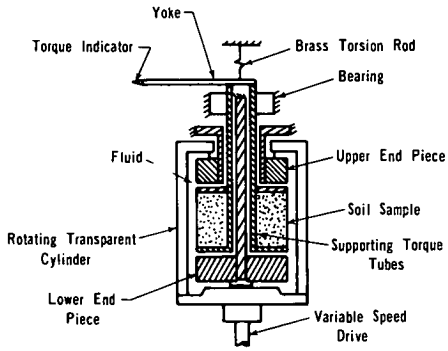


Figure 2. Calibration curve.

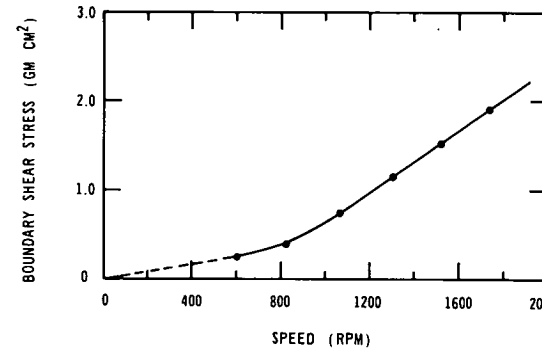


Figure 3. Grain-size distribution.

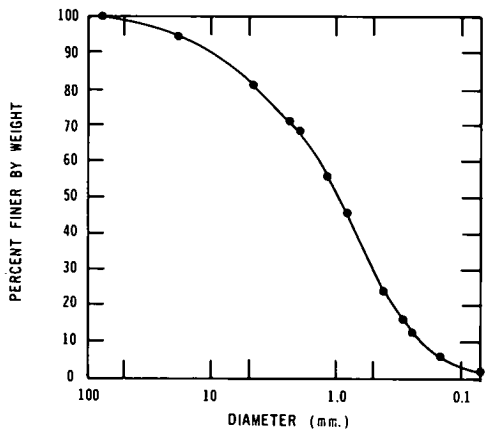


Figure 4. Standard AASHO compaction curve.

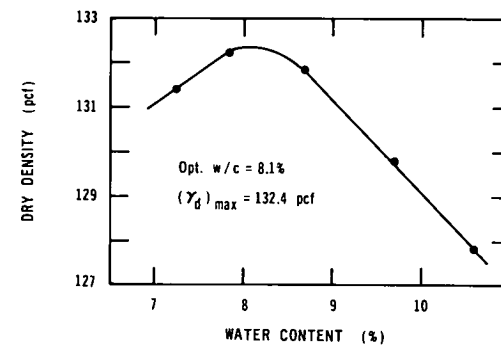


Figure 5. Unconfined compressive strength.

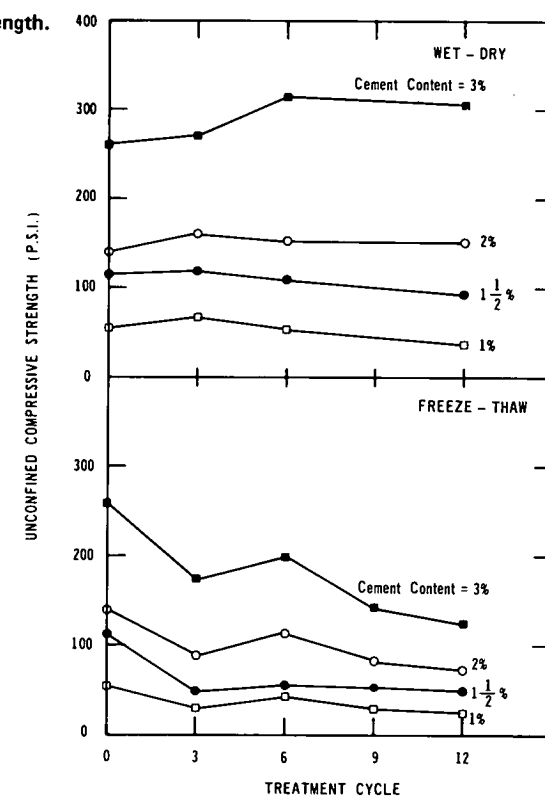


Figure 6. Erosion test results of freeze-thaw samples with 2 percent cement.

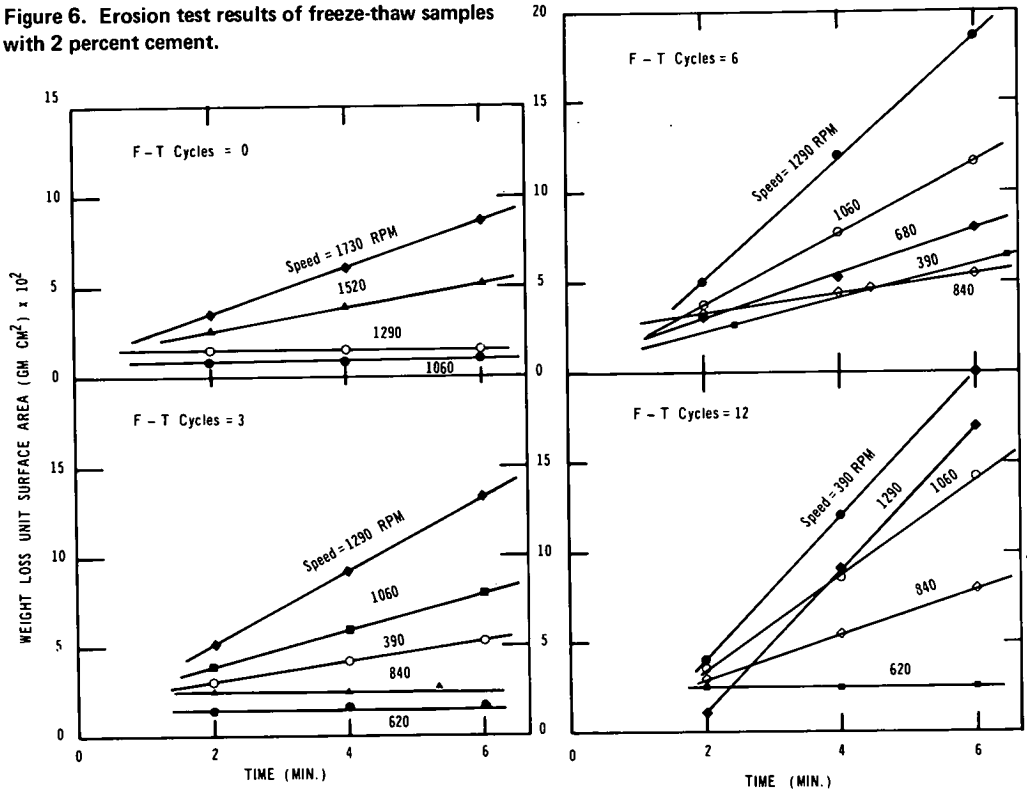
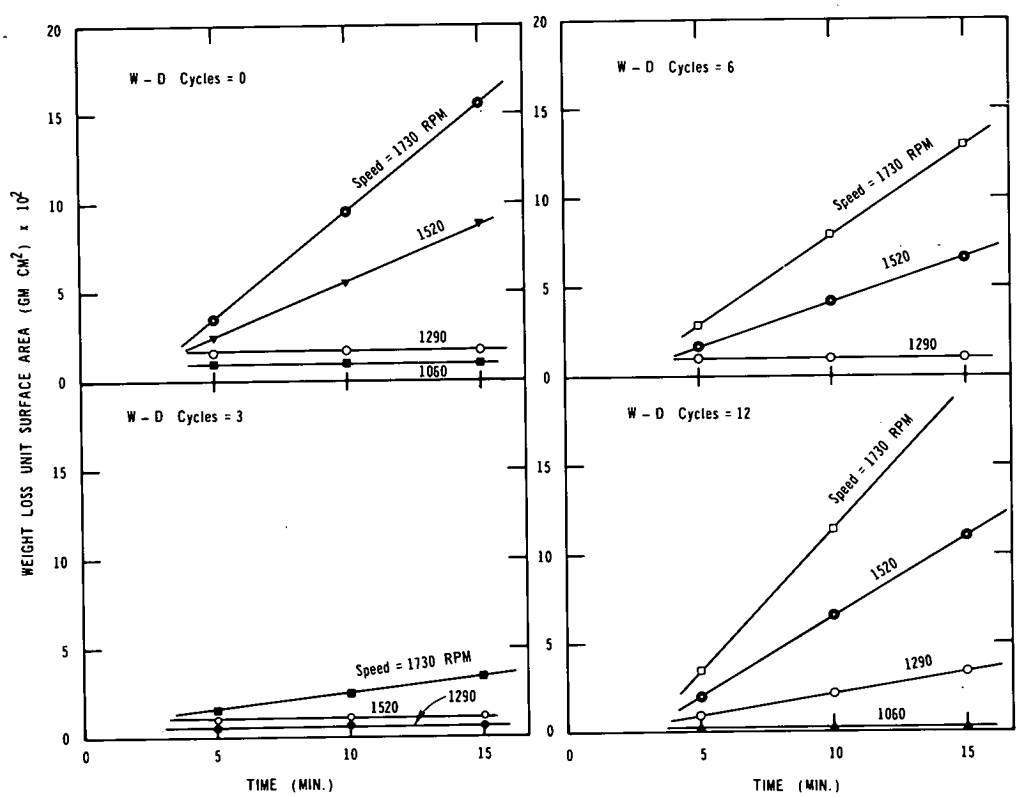


Figure 7. Erosion test results of wet-dry samples with 2 percent cement.



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

$$\tau_o' = \gamma DS \tag{1}$$

where τ_o' 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

$$\tau_o'' = \gamma R_h S \tag{2}$$

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.

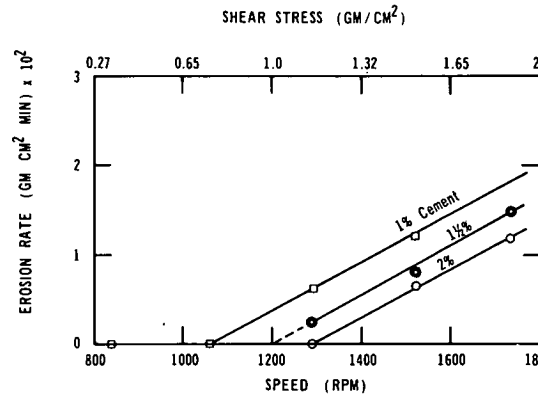


Figure 9. Maximum shear stress in a channel [after Lane (17)].

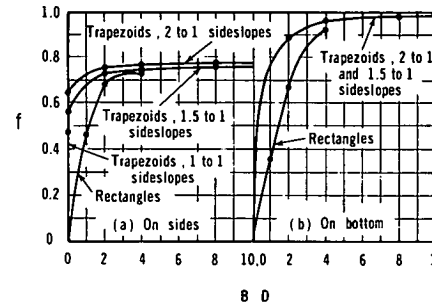
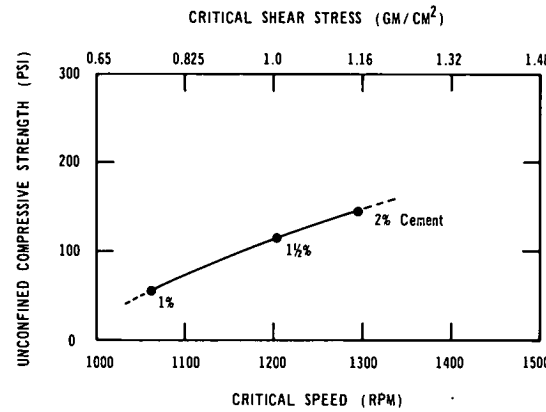


Figure 10. Critical shear stress versus unconfined compressive strength for uncycled samples.



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.

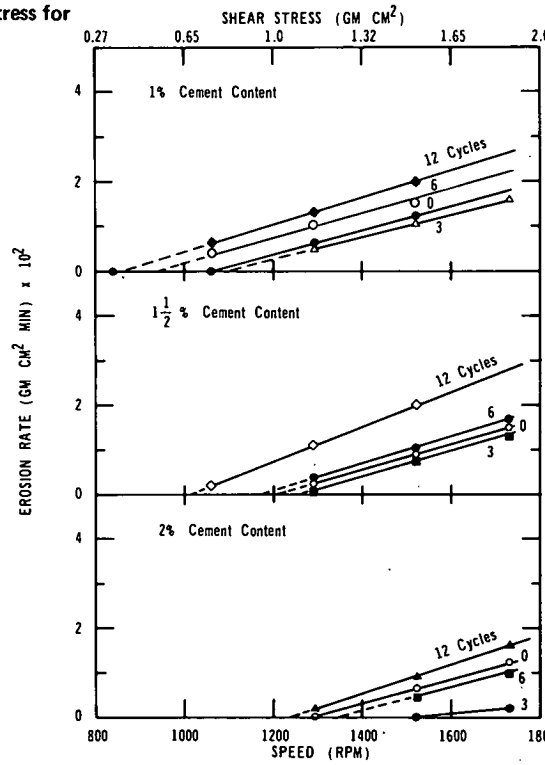
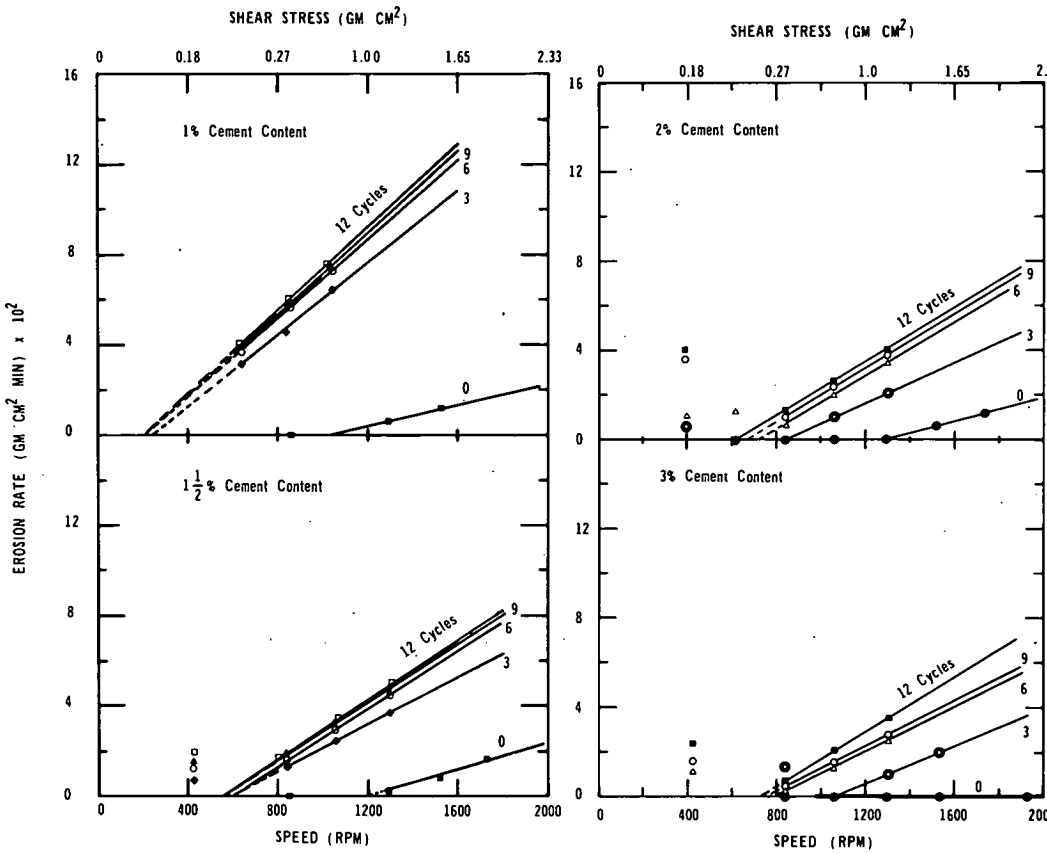


Figure 12. Erosion rate versus shear stress for freeze-thaw samples.



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K. ARULANANDAN, A. SARGUNAM, P. LOGANATHAN, and
R. B. KRONE, University of California, Davis

APPLICATION OF CHEMICAL AND ELECTRICAL PARAMETERS TO PREDICTION OF ERODIBILITY

The laboratory study of the erosive behavior of remolded soils shows that the shear stress required to initiate erosion is significantly affected by the kinds and concentration of ions in the pore and eroding fluids and types of clay minerals. The kinds and amounts of clay minerals have been shown to be described by the dielectric dispersion of saturated samples. The composition of the pore fluid is described by the electrical conductivity and sodium adsorption ratio. A method for measuring the hydraulic shear stress necessary to initiate erosion has also been developed. This paper presents experimental data that demonstrate that the shear stress required to initiate erosion depends on sodium adsorption ratio, electrical conductivity, and the magnitude of dielectric dispersion.

Problems of potential erosion are found in unprotected road cuts, drainage ditches, embankments, and other surfaces from which vegetation has been removed. Resulting erosion and waterborne sediments restrict the capacity of the drainage system, and great amounts of water are lost by seepage and channel instability. Hence, factors affecting the erodibility of soil need study in order to identify, predict, and prevent erosion.

Table 1 gives a chronological listing of research performed on the effect of soil properties on the hydraulic erosion of soils. Some results indicate that erodibility depends on the bulk properties of soil (e.g., vane shear stress and soil density), whereas other results (14) indicate that surface erosion is independent of shear strength. Partheniades and Paaswell (27) hold that vane shear strength and plastic index do not accurately convey the state of soil at the surface and therefore are poor parameters for evaluating erodibility.

A widespread incidence of subsidence and piping failures was reported by Ingles and Aitchison (18), Aitchison and Wood (19), and Sherard, Decker, and Ryka (20). Such erosion behavior in the field was correlated with the composition of the pore fluid. The types of ions in the pore fluid have been quantified in terms of sodium adsorption ratio (SAR), which is calculated as

$$SAR = [Na]/\sqrt{0.5\,[(Ca^{++}) + (Mg^{++})]}$$

where (Ca^{++}), for example, indicates the concentration of individual ions in milliequivalents per liter. The amount of ions in the system is expressed by the conductivity of the soil extract.

Although subsidence and piping failures of embankments and canals have been explained in terms of SAR and pore fluid concentration and numerous studies have been carried out to study the influence of various soil properties on hydraulic erosion of soils, no systematic laboratory study has been reported to determine the influences of pore and eroding fluid compositions nor of type of clay mineral on soil erodibility.

This paper summarizes available laboratory data on the influence of pore and eroding fluid compositions on the erodibility of a soil (21, 22) and presents new data on the influence of the type of clay mineral on erodibility. A possible functional relationship among the shear stress required to initiate erosion, the composition of the soils, and the types of ions in the pore fluid is discussed. The erosion mechanisms for partially saturated clays, however, may be different and are not considered in this paper.

SAMPLES FOR TESTING

Materials

Results reported in this study were obtained on a local natural soil called Yolo loam. Its composition is 46 percent sand, 35 percent silt, and 19 percent clay. X-ray analysis showed that montmorillonite, kaolinite, mica, and vermiculite were the clay minerals present. The cation exchange capacity was 19.8 meq/100 grams of soil, and the pH was 8.2. Other properties of Yolo loam are as follows:

Property	Value (percent)
$CaCO_3$	0.4
Saturation	33.9
Liquid limit	46
Plastic limit	23

The extractable cations, in meq/100 grams of soil, are Ca^{++}, 9.7; Mg^{++}, 10.6; Na^{+}, 6.2; and K^{+}, 0.3. The water soluble ions, in meq/1 saturated extract, are Ca, 1.3; Mg, 2.4; Na, 6.6; and K, 0.1.

Yolo loam particles smaller than 50μ in size were replaced by kaolinite (hydrite R), illite grundite, and montmorillonite in order to examine the effect of the type of clay mineral on erodibility.

Sample Preparation

Samples of soil of 1.5 kg were mixed in 20-liter bottles containing 10-liter solutions of various SAR and salt concentrations. Samples were agitated from time to time to facilitate equilibrium between soil and solution. For samples of very high SAR, the soil was initially equilibrated with a higher concentration of NaCl than the final concentration to displace as much adsorbed Ca and Mg as possible and then filtered and equilibrated with the proper concentration of NaCl. The samples were filtered and consolidated for 2 weeks with increasing loads up to 32 kg. The effluent from the consolidated samples was used in analyzing the concentrations of Na, Ca, and Mg. The total electrolyte concentration was determined by measuring the electrical conductivity of the effluent solution. A portion of the consolidated samples was taken for determination of moisture content.

Chemical Analyses

Concentrations of Na, Ca, and Mg in the effluent solutions were determined with a Perkin-Elmer Atomic Absorption spectrophotometer, Model 303, equipped with a digital concentration readout unit. All solutions were made up to contain 500 ppm Cs, 0.2 percent La, and 1 percent HCl as the supporting interference-suppressing electrolytes. An air-acetylene flame was used for Ca and Mg, whereas an air-propane flame was used for analysis of Na.

TESTING PROCEDURE

Erosion Measurement

The erosion apparatus used is a modification of the rotating cylinder test apparatus of Masch, Espey, and Moore (26). Cylindrical specimens, 3 in. in diameter by 4 in. long, were prepared by consolidation from slurries. The specimen

was supported by a mandrel and placed concentrically in a plastic outer cylinder. A photograph and a cross section of the apparatus are shown in Figures 1 and 2. The annular space between the sample and the outer cylinder is filled with the eroding fluid, which in this study is distilled water. The outer cylinder is then rotated at a uniform speed for a measured time, and the shear stress τ on the surface of the sample is determined by the torsional displacement of the inner cylinder.

Erosion was determined from the difference in weight before and after the applied stress. Fresh eroding fluid was used after each weighing. Erosion was measured after various periods at each speed of rotation (shear stress), and the erosion rate was computed from a graph of erosion versus time (Fig. 3). This was repeated at increasing speeds of rotation to determine erosion rates for different shear stresses. The relation between erosion rate and shear stress obtained on samples of Yolo loam is shown in Figure 4. This figure shows that the data do fit a linear relationship, suggesting that the eroding mechanism is the same over the range of applied stresses. Figure 5 shows specimens before and after erosion.

The shear stress required for zero erosion rate, which is the intercept on the applied shear axis, is defined as the critical shear stress τ_o.

Method of Measuring the Type and Amount of Clay Minerals

A method of describing the amount and type of clay without destroying the soil sample has been developed in our laboratory (23, 24). This method makes use of the electrical properties of a soil sample, such as dielectric dispersion $\Delta\epsilon_o$. The dielectric dispersion is the difference in the dielectric constant measured at, say, about 10^6 and 10^8 Hz. Dielectric constants of various clay-sand mixtures and various clay types are shown in Figures 6 and 7. These and other data show that different clays and different sand-clay mixtures have different amounts of dielectric dispersion in the frequency range at which the measurements were carried out. It has also been shown that the dielectric dispersion is nearly independent of the water content of the sample as shown in Table 2. Table 3 shows that $\Delta\epsilon_o$ is a function of the amount of clay and type of clay.

RESULTS OF EROSION MEASUREMENTS

Effect of the Type and Amount of Sorbed Ion on Erodibility

The critical shear stresses obtained from the intercepts of plots such as that shown in Figure 4 are shown in Figure 8. Figure 8 shows the effects of both the salt concentration in the pore fluid and the SAR on the shear stress required to initiate erosion of Yolo loam when distilled water was used as the eroding fluid. A detailed study of this nature might yield a relationship of the form $\tau_o = f(\text{SAR}, \sigma_p)$, where σ_p is the conductivity of the pore fluid (a measure of the salt concentration).

Data shown in Figure 8 indicate that τ_o increases with a decrease in SAR of the salt concentrations of the pore fluid studied. Further, τ_o increases with increased salt concentration in the pore fluid at any SAR. These effects are expected if one considers the degree of flocculation of the soil. As SAR increases or total salt concentration in the pore fluid decreases, soil flocculation decreases, with interparticle bonds weakening and surface soil particles detaching more easily (21).

Effect of Composition of the Eroding Fluid

Figure 9 shows how the NaCl concentration of the eroding fluid affects erosion rates. The soil sample used in each case was a saturated Yolo loam having the same SAR, the same NaCl concentration in the pore fluid, and the same water content. τ_o increased as NaCl increased in the eroding fluid. This result shows that erosion rates depend also on the composition of the eroding fluid. Hence, $\tau_o = f(\text{SAR}, \sigma_p, \sigma_e)$, where σ_e is the conductivity of the eroding fluid. These results show that erosion also depends on the osmotic pressure gradient between the pore and eroding fluids.

The effects of the amount and types of ions in the pore and eroding fluids on erosion are discussed further elsewhere (21).

Table 1. Research performed on the effect of soil properties on hydraulic erosion of soils.

Investigator	Soil Properties Studied
Lutz (1)	Physical properties of soils that affect permeability and dispersion
Anderson (2)	Dispersion ratio
Sundborg (3)	Particle size
Dunn (4)	Vane shear strength
Smerdon and Beasley (5)	Plasticity index, dispersion ratio, mean particle size, percentage of clay
Laflen and Beasley (6)	Effect of compaction-void ratio
Moore and Masch (7)	Scour index (as function of Reynolds number)
Partheniades (14)	Surface erosion independent of shear strength
Flaxman (9)	Unconfined compressive strength
Carlson and Enger (10)	Vane shear strength, plasticity index, soil density
Abdel-Rahman (8)	Plasticity index, dispersion ratio, particle size, percentage of clay
Rektorik (12)	Moisture content at compaction, vane shear strength, void ratio exchangeable calcium-sodium ratio
Berghager and Ladd (13)	Effect of cohesive intercept (shear strength for zero effective normal stress at failure)
Grissinger (15)	Bulk density, temperature, antecedent water, type of clay, orientation of clay materials
Mirtskhulava (16)	Eroded aggregate size, cohesive force, effect of water weight on particle
Liou (17)	Influence of electrolyte concentration, pH, and temperature on hydraulic erodibility of pure clays

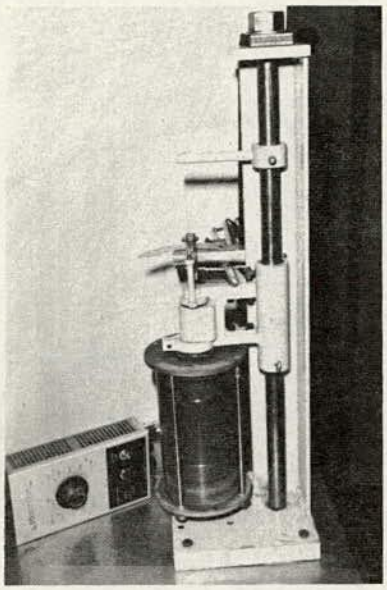


Figure 1. Rotating cylinder erosion test apparatus.

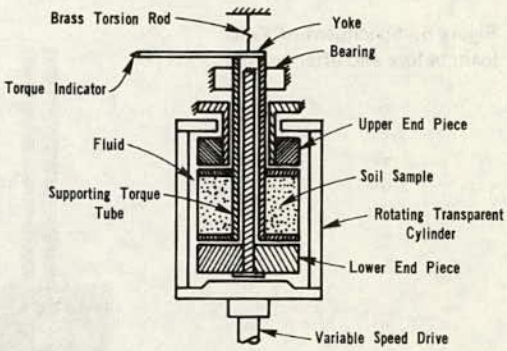


Figure 2. Cross-sectional view of the rotating cylinder test apparatus.

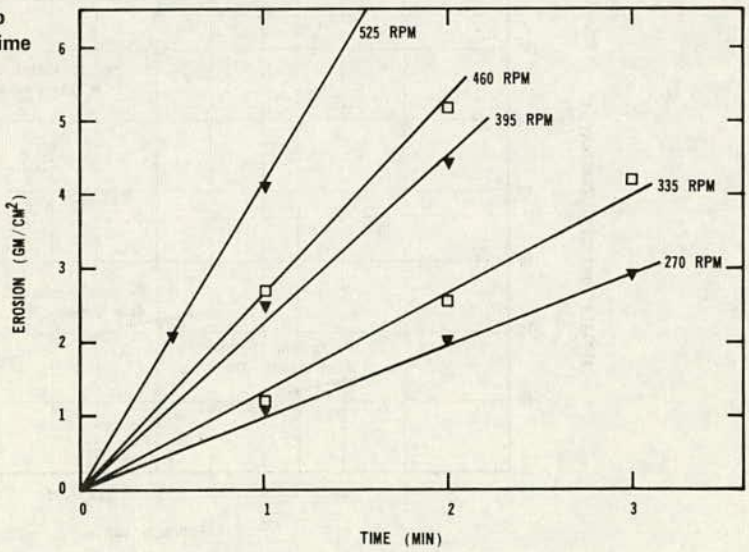


Figure 3. Relationship between erosion and time at different speeds of rotation (Yolo loam, 0.006N, SAR = 1.6).

Figure 4. Relationship between erosion rate and shear stress for different SAR (Yolo loam, ~0.1N, water content ≈28 percent).

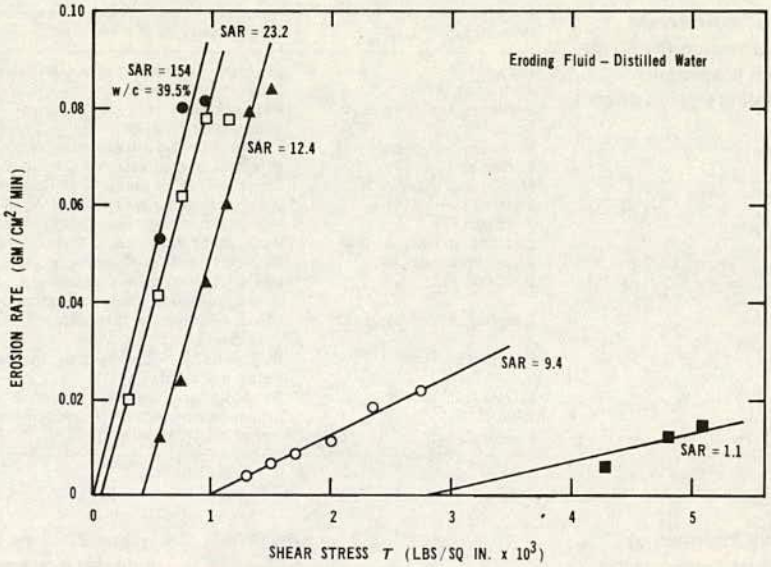


Figure 5. Specimens of Yolo loam before and after erosion.

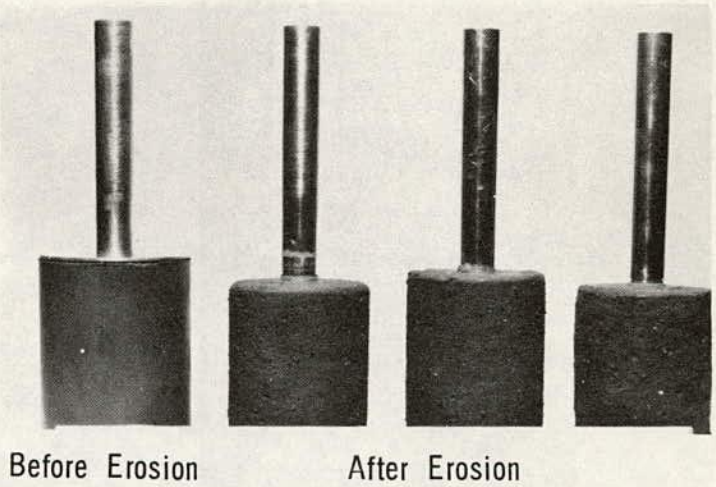


Figure 6. Effect of clay type on electrical dispersion.

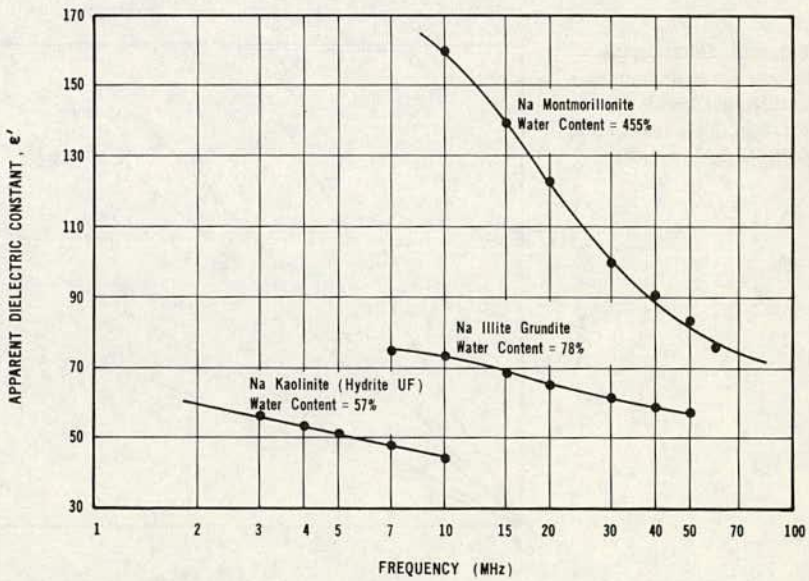


Figure 7. Effect of clay content on dielectric dispersion of illite grundite.

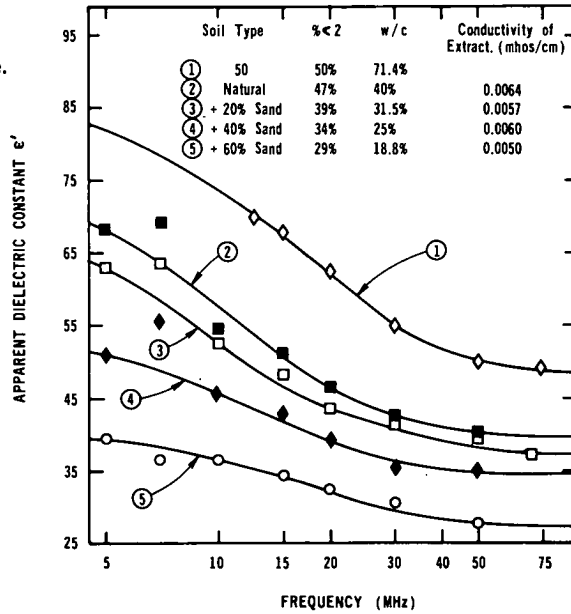


Table 2. Effect of water content on dielectric dispersion.

Soil Type	Water Content (percent)	$\Delta\epsilon_o$
Montmorillonite	260.0	127.0
	361.0	128.0
	455.0	112.0
Illite grundite	48.6	24.0
	52.0	26.0
	78.0	25.0
Kaolin UF	51.2	16.0
	81.0	17.5
	80.2	14.5

Table 3. Effect of type and amount of clay on dielectric dispersion.

Soil Type	Water Content (percent)	$\Delta\epsilon_o$	Percentage of Clay
Montmorillonite plus sand	260.0	123	100
	230.0	103	80
	255.0	98	60
	182.0	57	20
Illite grundite plus sand	40.0	30	47
	31.5	27	39
	25.0	17	34
	18.8	12	29
Kaolin UF plus sand	70.0	14	100
	45.0	4	80
	39.3	5	60
	35.4	8	50

Figure 8. Relationship between critical shear stress and SAR for different concentrations of Yolo loam.

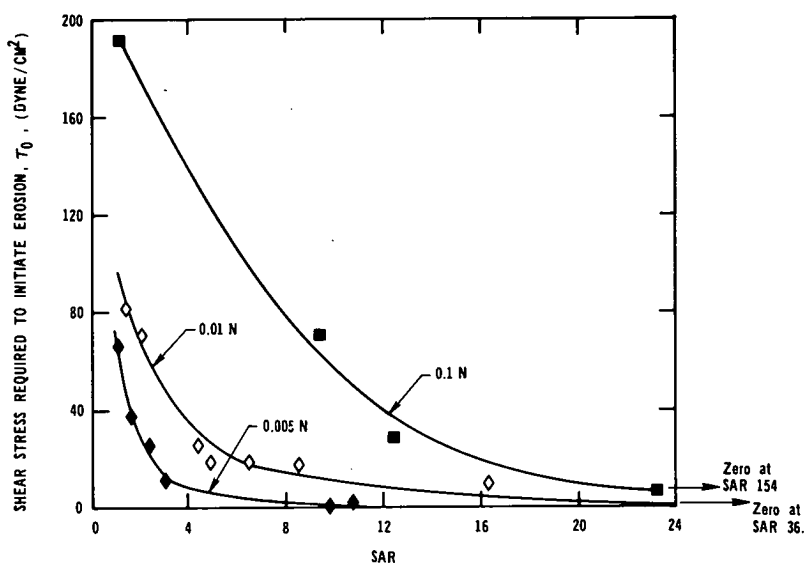


Figure 9. Relationship between erosion rate and shear stress for different concentrations of eroding fluid (Yolo loam, SAR ≈35, σ = 2.0 mmho/cm, pore fluid = 0.02N, water content = 40 percent).

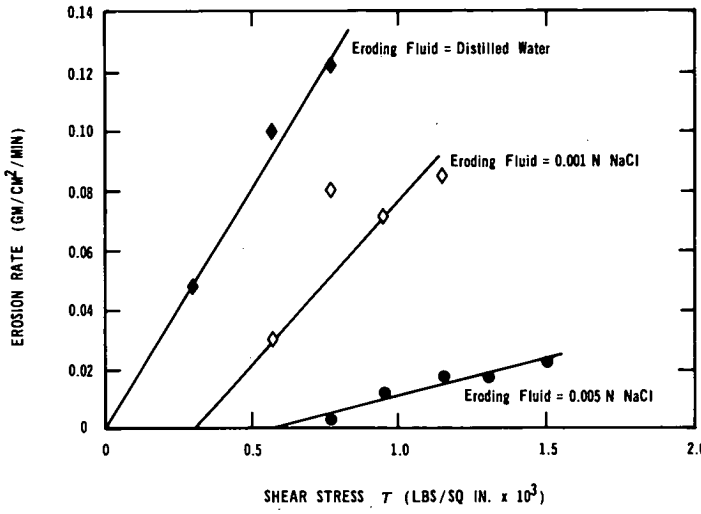


Figure 10. Effect of clay type on dielectric dispersion.

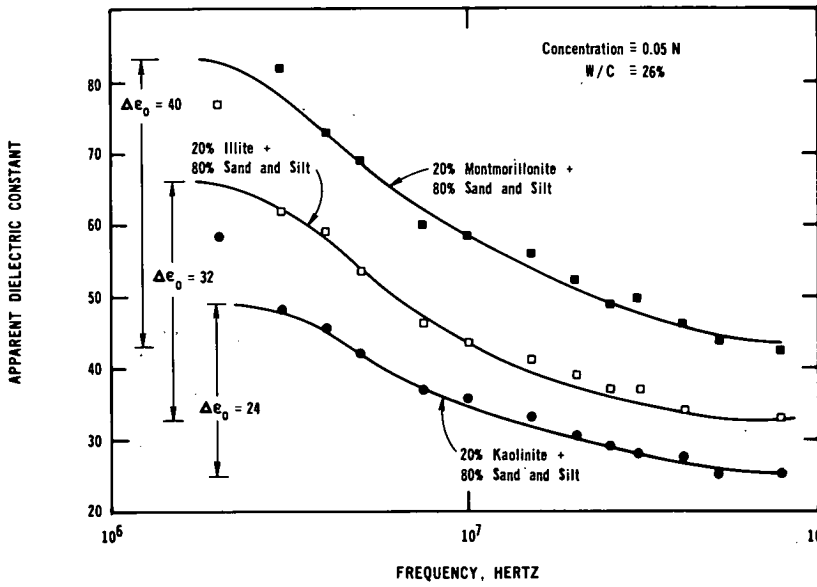


Figure 11. Relationship between τ_o and SAR for different clay types.

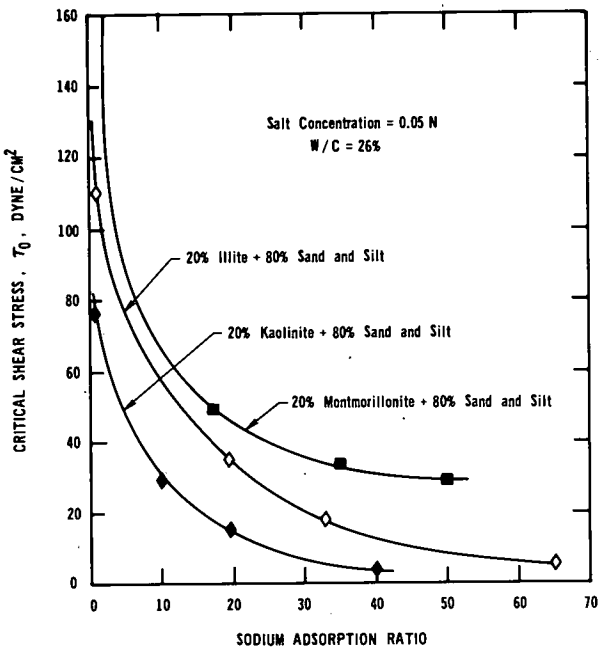
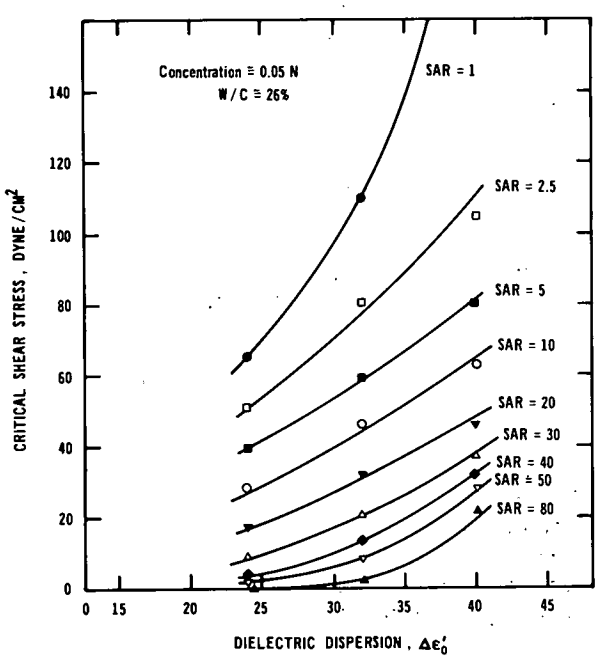


Figure 12. Relationship between dielectric dispersion and critical shear stress as a function of SAR at one typical concentration.



Effect of the Type of Clay Mineral on Erodibility

The type and amount of clay minerals, structure, and particle orientation can be characterized by electrical properties (24) as indicated by the results shown in Figure 6. The magnitude of dielectric dispersion $\Delta\epsilon_o$ for the kaolinitic, illitic, and montmorillonitic clays used in this study are 24, 32, and 40 respectively (Fig. 10). The magnitude of dielectric dispersion is a measure of the average compositional and environmental property of clay-water-electrolyte system, which can be used to characterize a soil without destroying or separating the soil mass into different sizes. Existing methods such as the use of plasticity index or activity or both cannot, however, evaluate the average compositional and environmental property of consolidated intact or undisturbed soils.

The results shown in Figure 11 demonstrate the effect of SAR on the shear stress required to initiate erosion (τ_o) for the three different types of clays at a water content of 25 percent and concentration of pore fluid of 0.05 N. The results show that a highly swelling montmorillonitic clay at a given SAR and concentration and at this composition is less erodible than an illitic or kaolinitic clay.

Relationship Between Dielectric Dispersion, Sodium Adsorption Ratio, and Critical Shear Stress

A quantitative evaluation of the type and amount of clay is made in terms of the electrical parameter, $\Delta\epsilon_o$; the type of ions in the pore fluid is determined by SAR; and the value of τ_o is determined from erosion measurements. The relationship between SAR, τ_o, and $\Delta\epsilon_o$ for a given water content and concentration of pore fluid is shown for the three clays in Figure 12. The results show that, as the value of $\Delta\epsilon_o$ increases and SAR decreases, the resistance to erosion increases at a given concentration of the pore fluid.

The results presented in Figures 8 and 9 show that the concentration of electrolyte in the pore and the eroding fluids will have significant influence on the results shown in Figure 12. The effect of the most important parameters on erodibility has been shown by the data presented, and it would appear that a nomograph that could be used to predict the erodibility of a soil based on SAR, $\Delta\epsilon_o$, conductivity of pore fluid σ_p, and conductivity of eroding fluid σ_e could be developed.

CONCLUSIONS

The erosive behavior of consolidated cohesive soils was studied. It was found that both the types and concentrations of ions in the pore and eroding fluids and types of clay minerals have dominant effects on soil erosion.

The types and amount of clay minerals and soil structure can be determined by dielectric dispersion measurements; the type and amount of pore and eroding fluid compositions can be determined by SAR and electrical conductivity. Functional relationships between τ_o and $\Delta\epsilon_o$, SAR, σ_p, and σ_e are currently sought in order to develop a nomograph for prediction of erodibility of soils and also for use in model analysis of erodible areas.

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ROBERT E. PAASWELL, State University of New York at Buffalo

CAUSES AND MECHANISMS OF COHESIVE SOIL EROSION: THE STATE OF THE ART

The processes of erosion of cohesive soil are examined through a study of basic soil index properties, soil structure and fabric, and physicochemical interaction of soil and water. Reported studies are evaluated to determine the factors that initiate and sustain erosion. A wide variety of test procedures are studied, including jets, rotating cylinders, tube flow, flumes, and field data. It is found that generally used soil classification indexes have not proved useful as erosion predictors. Structural indexes and indexes describing the quality of the pore fluid and eroding fluid must be established for each case. Internal and external force systems are defined to establish the rate and initiation of erosion. The paper concludes with a brief study of some current methods used to stabilize erodible soils in the field.

In recent years as we invest more in our constructed environment, we turn our attention more to the quality of the land that we use and that is available. All too often we find that problems caused by water erosion coexist with other construction and land use problems. Of special concern are problems related to erosion of cohesive soils. Understanding the erosion process and defining ways to limit erosion are growing disciplines. Lyle and Smerdon (26) have stated, "The properties of a soil which govern or dictate its resistance to water erosion are numerous and difficult to understand." This paper is concerned with the influence of cohesive soil properties on the erosion process.

The phenomenon of erosion occurs when fluid flow-induced shearing stresses on a surface reach values great enough to cause particle removal from that surface (Fig. 1). The difficulties in modeling and predicting this behavior can be classified as follows:

1. Defining the true state of stress induced by the fluid at the soil-water interface in the flow field, and
2. Establishing the parameters of the soil that control its behavior as a bed material potentially susceptible to erosion.

To develop valid theories of behavior or even to interpret currently available data on erosion requires that the characteristics of soil behavior be examined. This requires defining those parameters and properties involved with this problem. This paper is concerned with the following:

1. Basic soil properties currently noted in available literature are briefly defined and analyzed as to their relevance to the erosion phenomenon.
2. The distinction between natural and compacted states of soil is made in light of soil structure and fabric and influence of depositional mode. In addition, the importance of the electrolytic properties of fluid is discussed.
3. The nature of physicochemical interaction of soil and water influencing the water-particle force system is reviewed.
4. Analysis of possible erosion mechanisms is based on a critical review of the current state of knowledge of cohesive soil erosion.

The first three items lay the fundamentals for the last item. The puspose of the paper is to analyze the nature of control cohesive soil has on the erosion process by using reviews of previous studies.

BASIC SOIL PARAMETERS

Soil parameters of interest can be separated into those that define the physical characteristics of the soil and those that define aspects of mechanical behavior. These parameters, many of which have been postulated by researchers to have an effect on erosion, are given in Table 1 and discussed later in light of their relevance to the erosion phenomenon.

Vanoni (48) has stated that "shear strength and plasticity index and clay content have an important bearing on the phenomenon, but do not describe it completely. The chemical and environmental factors must also be considered." Because there are apparent disparities among previous workers in the field in measuring both the forces causing erosion and the rates of erosion under measurable flow, it became crucial to delineate all those properties of the soil that have some bearing on the observations in order to make comparisons in theory and also to design experiments that will give interpretable and reproducible results.

PHYSICAL CHARACTERISTICS

Naturally deposited soils are usually a mixture of soil types, i.e., clays, sands and silts, and clay minerals; artificially compacted soils can be controlled for variety and distribution of clay type. The first soil parameter examined in this study is the percentage of clay by weight in the soil investigated and the classification of this percentage according to mineralogical composition. Clay particles are of colloidal size, have large ratios of surface area to thickness, and are generally (for the most common clays) plate-like in shape (47). The mineralogical origin will specify the relative degree of activity of the clay, that is, whether the clay is a two- or three-layer clay and whether the clay lattice is expandable as noted below, this being an index of its ability to attract, hold, and replace surface ions.

The most common clays are two- or three-layer clays. These are bonded units of silica tetrahedra, T, and alumina octahedral, O, sheets. The most inert clay is two-layer OT, bonded together by hydrogen bonds, with strong attraction between O and T and with little isomorphous substitution within the lattice structures. These soils, kaolinites, are relatively inactive and show little or no ability to absorb water within the lattice, which can cause swelling.

Three-layer clays, TOT, that show such surface activity due to large-scale isomorphous substitution and that show great abilities to absorb water within the lattice are montmorillonites. Illites are of the same form as montmorillonites but, because of the large potassium ion present between the T and O sheets, strong bonding occurs and the swelling potential is greatly reduced. In these soils, swelling can occur as water enters the weakly bonded interlays of the montmorillonite, whereas the strongly bonded interlayers of illite reduce the swell potential. The importance of swelling may briefly be envisioned if we consider an unsaturated embankment that exists at a given density (void ratio), which predetermines the structural (particle-to-particle) arrangement of the soil. If suddenly saturated, such an embankment, if composed of an active clay, would swell, thereby increasing the void ratio. This reduces the interparticle forces and makes the embankment more susceptible to erosion.

The isomorphous substitution of lower valence ions for higher valence ions within the lattice of the clays leaves charge deficiencies at the surface of the clay particle, resulting in a net negative charge at the surface. The magnitude of the charge depends on the degree and type (valence) of ionic substitution. Particles of colloidal size with highly charged surfaces respond to laws of electrical attraction and repulsion to an equal or greater degree than they do to ordinary Coulombic attraction (gravity) between layer bodies. The greater the percentage (by weight) of clay in a given soil is, the greater will be the overall effect of the surface behavior.

A widely used index for establishing the quality of the clay soil is the plasticity index (PI). PI is defined as the difference between the liquid limit (LL) and the plastic limit (PL) of a clay soil. Whereas the LL test is essentially a constant shear strength test, the PL test is not, showing higher limiting shear strengths as the plastic properties of the soil increase. Because the PI of sands and silts is zero, an increase in PI from zero indicates that the range of moisture contents over which a soil shows plastic behavior increases as the ability of the soil to absorb stress through deformation at specific values of shear stress (i.e., nonzero values, such as water) without brittle failure increases. This increase is due to (a) an increase in the percentage of clay mineral (by weight) of the total soil fraction and (b) the variance in the type of clay mineral. Both factors indicate that the strength of the soil becomes less dependent on the structure of the interparticle contacts and more dependent on the intercolloidal force structure as a function of such factors as surface charge density, arrangement of particles, and quality of the electrolyte.

Defining activity as follows (40, 41) gives more understanding to the significance of the concept of plasticity index:

$$\text{Activity} = \frac{\text{(change in) plasticity index}}{\text{(change in) percentage by weight of clay fraction}} \tag{1}$$

Activity as noted actually combines the two factors that influence the resultant limits of plastic behavior of the soil as noted above. By comparing activity with the swelling characteristics of clay soils, Seed (40) found this to be a "reasonably reliable index of... swelling coefficient." Proper use of the defined activity will allow this parameter to be a basic one in predicting regions of behavior for a given clay soil, for (40) "activity will accurately classify the soils with regard to their liquid limit versus clay content relationships, or with regard to their swelling potentials regardless of the clay mineral composition of the clay fraction."

It is important to establish certain aspects of soil behavior that the activity index does not cover. The PI is based on two tests at limiting moisture contents, neither of which has been generally used in erosion studies. In most erosion studies, the soil has been compacted or exists naturally at some moisture content other than the LL or PL. Furthermore, because the tests are based on soil remolded to existing conditions (19), they can in no way predict density or strength of the soil used. Activity serves to aid in classifying soil types, and thus its inherent value is its use as a comparative index or a grouping index to rate soil for its potential erosion resistance.

The structural indexes previously defined are indicators of the net interparticle force system that exists in the colloidal-size clay particles.

The true distribution of forces between individual clay particles has not yet been mathematically defined. Because of the highly complex geometry (even in the most disperse systems) and variations in structure (from flocs to pacs), plus the general level of the stability of the system, accurate mathematical formulation of the interparticle forces has been made nearly impossible.

This interparticle force system shall in the future be referred to as the internal system. This system is viewed on the atomic level and is defined as the resultant stresses established by the electrochemical behavior of the particle surface. The factors that control the strength of this potential field are valence and size of adsorbed ions, percentage and type of dissolved salts in the electrolyte, temperature, original particle orientation, and stress level (potential geometry).

The nature of the internal stress system can be illustrated if we consider the pressure between two parallel plates subject to a repulsive potential ψ (x) established by the existence of similar charge densities on each plate (47). The total excess pressure, p_e, between the plates is given by

$$p_e = p_d - p_H = 2nkT\left(\cos h \frac{v_e \psi_n}{kT} - 1\right) \tag{2}$$

where

p_d = pressure at a distance d midway between the plates,
p_H = hydrostatic pressure of fluid not influenced by particles,
v = valence,
n = concentration of electrolyte,
k = Boltzmann constant,
ϵ = electrostatic unit of charge, and
T = absolute temperature.

The attractive potential (A) is considered basically a Vanderwaal-London force and is dependent on the volume of the attracting mass, its geometry, and the distance of separation for clay plates and, compared to repulsive forces, can be assumed constant for a given environmental condition. The net force acting between particles is then more strongly dependent on the relative magnitude of the repulsive force (R) and can be illustrated for combinations of (R-A) as follows:

(R-A) < 0, net attraction-tendency toward flocculation
(R-A) > 0, net repulsion-tendency to dispersion
(R-A) = 0, equilibrium position

This internal force system can be symbolized by a net force that is actually a difference between the R-forces and the A-forces acting between particles. The R-forces are highly susceptible to changes in the environment, whereas the A-forces are relatively stable. The net force is important in determining both initial structure and structural changes that occur when the soil is subject to applied stresses. This system itself is established by the type and distinction of the principal clay minerals, the net surface charge on these minerals, and the quality of the electrolyte surrounding them. Because of the ability of the net force to vary widely depending on the environment, the soil, during its process of formation, can assume a variety of structures. It is the nature of the geometry of these structures and their inherent stability that determine the ability of a soil to resist imposed stresses.

MODES OF DEPOSITION

There is evidence that the physical structure of the cohesive material plays a major role in erosion resistance, and the characteristics of that structure are determined by the initial mode of deposition or compaction. Deposition (natural) takes place through a body of water (sedimentary) where the particles are subject to Brownian motion and surface electrical forces as moderated by the quality of the water (character of dissolved salts, etc.). For example, Grissinger (14) found that the erosion rate of several clay soils was dependent on the formation technique, including the amount of moisture at compaction and the compaction method.

Interparticle orientation varies from highly random with many edge to force (EF) positions (flocculated) to highly oriented with parallelism of the particles and a parallel orientation to the bed surface (disperse) as the predominant structural pattern. Particles can also form packets first, which are groups of parallel-oriented particles held together by high local forces, and these packets can then form parallel or random structures. Residual soils, weathered in place from parent bedrock, show different structural patterns, which are a function of the degree of weathering the rock has been subjected to. Compacted cohesive soils (man-made) have structural characteristics quite different from the others described.

Natural Deposition

In fresh water there is a large diffusion of low amounts of salts (if any) and of hydrogen ions in and out of the water surrounding the particle. This diffusion allows the zone of electrical force (or potential) to extend some distance away from the particle, resulting in a high degree of repulsion between adjacent particles. Fresh-water depositions result in a disperse interparticle structure, where the void ratio will decrease as the magnitude of the original surface charge decreases, allowing

particles to come closer together (30). The porosity of surface or near-surface deposits is also influenced by the rate of deposition and size of particle (30); porosity is greater for rapid deposition and less for greater particle size.

Nonsalt flocculation (20), most prevalent in kaolinite, can also occur as the strong positive edge charges are attracted by the negative force charges (EF). This gives a more or less perpendicular arrangement between the particle, resulting in an open structure with high porosity. Slight increases in the salt concentration reduce the magnitude of the face charge potential, resulting in a more disperse structure.

Saltwater deposition (NaCl, $MgCl_2$, and $CaCl_2$) usually results in flocculated structures due to suppression of the repulsive force leaving a net attractive force between particles. This flocculation can be particle edge to face (EF) or face to face (FF) in an open network. Finer clays such as montmorillonite also form domains or pack clusters, and these domains then establish themselves as a flocculated system. During the process of deposition it is also possible for flocs to form during settling in the fluid. This total structure (Fig. 2) has a very high porosity (low total density) and is relatively weak. In all cases any loading of the sediment, due to either further deposition or some external physical loading, tends to create more parallelism between the particles, which breaks down the flocs.

The distance at which the particles are separated is a function of mineral type and fluid quality. If attractive forces predominate, it is possible to have actual EF contact, whereas with repulsive forces predominating it is most likely that the bound water layer will physically separate the particles. An understanding of the nature of particle-to-particle orientation and the associated surface force is essential for interpretation and evaluation of eroding forces.

Compacted Deposits

Soils that were deposited and then compacted in place, or natural deposits that are artificially compacted, have structural characteristics significantly different from soils that are naturally deposited and untouched. For soils that are remolded (or molded) and mechanically compacted, any natural interparticle bonding that occurred in the parent material is destroyed. The entire strength depends on the initial physical structure of the material created by compaction and to a lesser degree on subsequent bonding that may occur as the deposit is stressed. The structure that the soil will assume depends on the compacting moisture content (20). As the moisture content at compaction increases, the structure becomes more oriented. In addition, whereas it is possible to have flocculated structures (generally associated with low moisture contents of compaction), it is unlikely to form a structure composed of flocs that have the large void ratios (porosity) associated with naturally deposited materials. The nature of composition serves as an index of subsequent amounts of swelling (41), flocculated soils tending to swell to a much greater degree than the more oriented soils. Inasmuch as swelling reduces the structure (which increases the voids), if erosion is considered a surface phenomenon, it is evident that any swelling can only have an adverse effect on resistance to erosion.

Several basic studies that use both natural and artificially compacted soils (Table 2) have been made. As mentioned earlier, the variance in structure due to compaction state is the key to success or failure of a channel to resist erosion.

In both the deposited and compacted states, the structure of the sample has great influence on the relative erodibility of the sample. The structure reflects the interparticle force system and is established by the nature of the internal force system.

The erosion problem considered here is that of surface, and not deep-seated, shear. For this reason, any factors that minimize the surface interparticle forces and simultaneously minimize the stability of the surface layer (as realized through the geometry or potential energy configuration) maximize the erosive conditions. There are two distinct stress systems that control the resistive behavior: external and internal.

Figure 1. Mode of erosion.

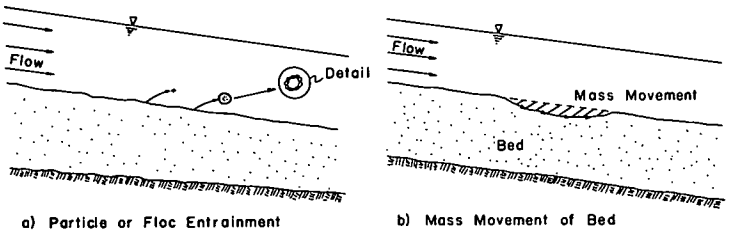


Table 1. Soil parameters used in evaluating erosion of cohesive beds.

Characteristic	Parameter
Physical	Soil type (clay mineral) Percentage of clay Liquid and plastic limits and activity Specific gravity
Physicochemical	Base exchange capacity Sodium adsorption ratio Pore fluid quality Pore fluid environment
Mechanical properties	Shear strength (surface and body) Cohesion Thixotropy Swelling and shrinkage properties
Conditions of environment	Weathering (wet-dry) Freezing and thawing Prestress history

Figure 2. Open network system formed by floc deposition.

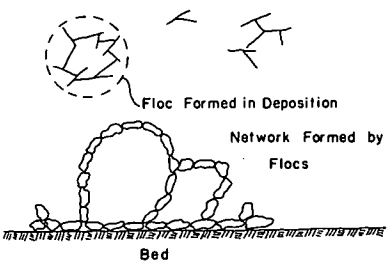


Table 2. Summary of selected studies on cohesive soil erosion.

Investigator	Mode of Placement of Sample	Mode of Measurement of Erodibility
Lutz (25)	Comparison of physical tests with erosive properties of natural soils	Use of qualitative physicochemical analyses
Peele (38)	In-place topsoils	Soil loss and runoff tables
Anderson (5)	In-place topsoils	Correlation of erodibility with shear measurements
Dunn (11)	Remolded, subjected to jet	Jet to produce erosion; visual measures
Smerdon and Beasley (45)	Slightly recompacted natural soil, top leveled	Visual observation of bed movement
Laflen and Beasley (18)	Remolded at unspecified percentage of water, then saturated	Visual correlation or erosion with calculated inactive stress
Flaxman (13)	Natural soils	Correlation of permeability and unconfined compressive strength with natural erosion (channel measures)
Moore and Masch (33)	Remolded and natural (trimmed) jet	Measurement of scour depth and weight loss
Abdel-Rahman (1964)	Remolded in duct	Visual; measurement of erosion depth
Partheniades (36)	Remolded natural deposited (salt water) in duct	Measurement of suspended sediment concentrating with time
Grissinger	Remolded in channel	Rate of erosion by weighing
McQueen (1965)	Remolded	Weight comparison
Masch, Espey, and Moore (28)	Unspecified but trimmed as hollow cylinder	Weight loss versus rotating shear; visual correlated with shear
Ben Zvi (1965)	Remolded in ring	Visual and measurement of sample surface
Mirtshkulava (31)	Remolded in flume	Weight of floc loss
Liou (22)	Remolded in flume	Point-gauge measurement of erosion depth
Liou (23)	Remolded in flume	
Coad and Paaswell (1968)	Naturally sedimented and consolidated in duct	Sediment concentration measurement
Akky and Shen (2)	Molded in ring; stabilized soil	Weight comparison
Arulanandan et al. (3)	Molded in ring	Weight comparison
Christensen and Das (9)	Remolded in tube	Weight comparison
Grissinger (15)	Natural samples remolded in channel	Rate of erosion by weighing
Wischmeier and Meyer (50)	Natural data	Weight of runoff

The external system is the stress system that is the total system imposed on the deposit during and subsequent to its formation. The previous stress history of the soil, if normally consolidated, is simply a function of the weight of overburden in place. If man-placed, the soil can be considered to have some properties that are functions of the energy input. The external system exerts much influence on the soil particle geometry, for, as the loads increase, the particles in the structure attain a higher degree of orientation and the interparticle spacing decreases. Under great loads there may be much interparticle contact with resultant formation of strong bonds. The influences of the structural geometry and location of the particles are shown in Figure 3. Particles on the surface are subjected to fewer net forces than are particles somewhat below the surface. Due to natural processes of compaction, the void ratio decreases with depth. A decreasing void ratio implies a more complicated structural matrix inasmuch as there would be greater physical particle interaction. Added to the fact that the soil surface is subject to constantly flowing water with fluctuating shearing stresses and the associated particle deformations is the fact that the surface particles would be in an energy state of less stability than particles below the surface.

In summary, the complexity of the forces holding a clay together can be seen through the historical development of the deposit. The type of mineral(s) determines the surface charge and then establishes the net repulsive force. The mode of deposition or compaction establishes the structural geometry as influenced by the net interparticle forces (internal system). Continual stressing (external system) causes further changes in the internal system through changes in interparticle spacing and orientation.

CHARACTERISTICS OF A CLAY BED FLUID AFFECTING EROSION RESISTANCE

The quality of the fluid during the process of deposit formation and the subsequent process of erosion must be accurately determined. This includes determination of dissolved salts (type and quantity), other impurities that may perhaps exist as cementing agents, and pH of the fluid.

A change in the ions in the electrolyte can lead to a change in the adsorbed ion and then to a change in the physical properties of the clay, i.e., liquid limit, plastic limit, and strength (47).

In a study of the erodibility of clay beds, Liou (22) demonstrated that pronounced changes in the stability of the soil deposit will occur when the type of chemical additive in the eroding and mixing fluid is changed. Partheniades (35) found that the presence of iron ions in the water was sufficient to cause cementing action on the surface of the bed, substantially changing the critical shear stress from values obtained when iron ions were not present.

MECHANICAL PROPERTIES OF CLAY BED

Measurement of mechanical properties is essential to establishing the specific stress deformation relationships that characterize clay soil behavior for a given set of environmental conditions.

Erosion is incipient when individual particle or small particle clusters (flocs) are worked loose from the parent mass and entrained in the moving fluid (Fig. 1). Note that in a geologic sense erosion is considered to take place even if large planes of the material are worked loose at once. The latter phenomenon is essentially a mass stability or mass movement problem and is different from the first.

The soil shearing strength is the resistance that the material can mobilize to imposed shearing stresses. In a clay soil it is, everywhere, a combination of interparticle assemblage (dilitation and friction components) and the net interparticle chemical forces as defined earlier. A plane of failure will develop when the shearing stress along that plane exceeds the mobilized shearing strength of the material, interparticle bonds are broken (N is exceeded), and particles are moved around or along each other. This plane can be readily visualized within a mass due to boundary stresses

acting on the mass. In the case of surface shear stresses (erosion stresses) where the nature of confining the total soil mass is quite different, the factors constituting the resistance to shear are not so readily defined. This is essentially resistance to shear at zero confining stress (7).

One parameter contributing to the net shearing resistance is cohesion. Cohesion can be considered as a measure of the actual interparticle bonds consisting of both chemical forces and cementing between particles. The amount of cohesive strength that can be developed is a function of original deposition conditions, minerals present, and the stress history of the soil. It is important to distinguish between normally consolidated and overconsolidated beds. A normal state is one in which the existing stress on the mass is the original stress on the mass and has never been exceeded. An overconsolidated state is one in which the current state of stress on the mass is less than some previous stress in the history of the material. The following examples illustrate the difference between the two states:

1. A bed whose surface has been recently deposited, whose deposition is continuing, and where no erosion has taken place (normal); and
2. A bed whose upper surfaces have been eroded away to some extent and whose current surface once existed some distance away from the previous surface (overconsolidated).

The resistance to erosion shear in these samples (even if of the same clay deposited initially under the same conditions) will be different.

Thixotropy is the strength regain with time of a compacted or disturbed clay and is due to particles being removed from an equilibrium condition (relative minimum energy position) and then reattaining a new equilibrium position under the imposed conditions. It is generally associated with the formation of flocs. A knowledge of the time-strength history of compacted clays is essential for evaluation of the bed and surface strength of the compacted clays at the time of erosion both in the laboratory and in man-made channels. According to Mitchell (32), thixotropy occurs as the excess of energy in the attraction term in the net internal force system is dissipated and equilibrium occurs through particle readjustment (slight) and changes on the structure of the adsorbed water.

An understanding of thixotropic behavior is important in using laboratory tests to predict field behavior. In laboratory testing, samples placed in ducts, flumes, or rotating devices are subject to thixotropic strength regain with time. This has been clearly shown by Grissinger (14, 15).

INFLUENCE OF SOIL STRUCTURE ON EROSION MECHANISMS

Although a most important variable of erosion control is soil structure, there is no one fundamental parameter that uniquely describes structure. Variables describing structure, such as void ratio, moisture content, percentage of clay, plasticity index (activity), and cohesion, must be isolated in any experimental analysis.

To interpret previous evaluations of variation of soil variables on erosion requires that critical shear, so widely used by hydraulic engineers as an index of inception of erosion, be defined. The critical shear stress τ_c is the empirically determined shear stress at which erosion is either imminent or actually taking place. In all equations defining τ_c, the velocity of flow is one essential factor that must be evaluated experimentally (6).

ISOLATION OF SOIL PARAMETERS INFLUENCING ERODIBILITY

To establish that any currently used soil parameters can be used as indexes to predict erosion, we must review previous studies made on a variety of soil types. In an early study, Lutz (25) compared two soils of different plasticities. These natural soils, one of high plasticity (D) and the other of lower plasticity (I), were noted to be quite different in their resistance to erosion. The high-plasticity soil was

nonerosive, whereas the lower one was highly erosive. In the analysis of erodibility it was noted that the permeability of the A horizon of the D soil was 34 times that of the I soil. It is also noted that in its natural state the soil is relatively friable. He concludes that the coefficient of permeability is a controlling variable in that it determines the rate of infiltration of water into the soil, resulting in less energy available for erosion. Inasmuch as the D soil does contain a higher percentage of clay, saturation of the soil subsequent to flow would reduce the friability, increase the surface activity, and increase the resistance to erosion. Chemical tests indicated that the D did not swell and that its suspension rapidly flocculated. I soil was more readily dispersed and exhibited swelling. These factors of swelling and flocculation are the most significant results reported with regard to soil influence on erosion. The measurement of permeability here is seen to be no index in the manner expected, inasmuch as the D had a coarse structure and higher permeability. Permeability can be used as an index of structure, and it is seen that a structure alone is not sufficient to predict the susceptibility. Permeability is a key to the rate at which a nonsaturated material can be wetted when subject to overland or channel flow.

Anderson (5) related the observed relative erodibility of six basic soil types to dispersion and erosion ratios. He measured erosion ratio by evaluating and comparing the quantity of suspended sediment of a specified size as a percentage of total silt and clay sizes in a very crude hydrometer type of test. Correlation is good inasmuch as the two comparisons are essentially the same. An increasing dispersion ratio implies that the fines as a percentage of the total soil in suspension at a given time increase. Dispersion ratio refers to a change in gross size of particle groups (clusters or aggregates, given as a ratio to the absolute quantity of soil and clay size). With this understanding, it becomes somewhat less than intuitive that critical shear stress will decrease as dispersion ratio increases. This correlation in fact is made by Smerdon and Beasley (45).

Smerdon and Beasley established from selected soils the following regression equation relating critical shear τ_c and dispersion ratio D_r:

$$\tau_c = AD_r^{-b} \tag{3}$$

where A and b are constants and D_r is the dispersion ratio. Smerdon and Beasley for a group of 11 soils related τ_c to each of several soil properties including PI, mean particle size, and percentage of clay. The dependence of these parameters on each other can be shown by an example: According to the regression laws developed at a critical tractive force of 0.02 psf, a soil could have PI = 8 or a dispersion ratio of 40. Yet soil No. 1 has a greater PI (10.2) and a smaller τ_c (0.0199 psf). There is no question then that more insight into the relative cause and effect of the above-mentioned parameters on erosion can be provided if some form of multiple correlation is made. The essential problem is to correlate the internal force system that D_r and PI actually reflect.

The effect of the factors mentioned above that influence the net force system, hence surface stability of the material, has been noted by several investigators. Moore and Masch (33) noted the possibility that "...the shear producing fluid may influence the clay chemistry of the soil so as to affect the cohesive bond and thus the scour resistance." By using glycerine as the erosive fluid, they found that a scour-resistant layer of material was being formed on the surface. Exposed surfaces of increased stiffness could be attributed to the hygroscopic qualities of glycerine. A change in the surface adsorption characteristics of the soil with glycerine causes a change in the interparticle force system also. Moore and Masch's results may suggest that glycerine water may be used in erosion control, but they highlight the difficulties in substituting a liquid for water in the model tests. The viscosity and density of glycerine (100 percent glycerine has a specific gravity of 1.26 and viscosity of 1,400 at 20 C)are significantly different from water, which produces different flow properties (e.g., N_R, shear) at the same fluid velocities. Only at mixtures of 75 percent H_2O and 25 percent $C_3H_5(OH)_3$ can glycerine be used to model water with less than a 25 percent error in viscosity and density measurements. The difficulties in using a polar organic

compound to study flow (hydraulic) characteristics can be seen in the resultant change in soil characteristics.

In addition to the type of fluid, essential changes in erosive characteristics can be brought about by the type and quantity of dissolved salts in water. It is necessary to differentiate immediately between two roles water plays in the problem: (a) It is a medium for saturating the soil and plays the determinant role in its composition or consolidation, and (b) it is the erosion medium. It is quite possible that fluid characteristics in each of these cases are somewhat different. A soil may be deposited in a salt environment and may be eroded by fresh water. Thus, these roles must be completely distinguishable in any analysis. These roles were analyzed by Martin (27), who indicated that changing the salt concentration of the fluid surrounding the clay would have noticeable effect on the strength of the clay in both its natural and remolded states. If erosion is considered as a surface phenomenon and the characteristics of the eroding fluid are different from those of the saturating or depositional fluid, changes in the interparticle force system can be brought about by a displacement of the saturating by the eroding fluid.

The general effects of electrolyte replacement on strength were considered by Bjerrum and Rosenqvist (8), who established that clays deposited in a saline environment and then subsequently leached with pure water will suffer a decrease in shear strength and a reduction in the liquid and plastic limits. The strength change occurs although there is no further change in moisture content. Their analysis also indicated that changes akin to weathering occurred during a 2-month period in the laboratory, resulting in an increase in shear strength. The weathering effect, coupled with thixotropic effects, is a variable of great importance in the control of laboratory investigations. This effect may illustrate that freshly deposited samples (in the laboratory) are weaker and, hence, more subject to erosion forces than would be an identical sample in a natural channel that has existed for some period of time.

INFLUENCE OF INTERNAL STRUCTURE ON EROSION RESISTANCE

Studies of the influence of chemical additives on the erodibility of cohesive soil have been made by several investigators. In tests by Liou (23), Na_2CO_3 and $Ca(OH)_2$ were added to soil to permit ion exchange before erosion took place. An attempt made to correlate vane shear strength of the soil with erodibility for different weights of chemical additives was successful only with Na_2CO_3. Liou concluded that a higher potential swell pressure (see Eq. 2 for example), which would result in a high total vane shear strength, would also result in a low resistance to erosion under flow conditions. There was no correlation between vane shear and critical tractive force for the soil with $Ca(OH)_2$ added. There is some indication that critical tractive force decreases rapidly to a minimum value as vane shear strength of the Ca-montmorillonite increases due to increasing availability of the Ca ion and then increases rapidly above this minimum as Ca availability increases. Further data points are needed to substantiate this trend. Liou described the physical process for erosion of the Na-montmorillonite as "the mixture of water dispersed small clay particles and some chemicals;... the soils were eroded away, layer by layer, approximately uniformly across the soil sample." For the Ca-montmorillonite, "... the soils treated with 2.0 percent and 5.0 percent $Ca(OH)_2$ additives were eroded away in large flocs.... The soils were eroded away locally." The influence of the structrure of the clay as evidenced by its particle orientation and potential swell characteristics is clearly seen in these tests through an analysis of erosion rates. The Na-montmorillonite displayed a sustained erodibility that increased as concentration of sodium ion increased. The Ca-montmorillonite showed erodibility over a range of a low-percentage additive but showed an abnormal peak at 5 percent Ca additive. This of course corresponds to the minimum critical tractive force required to erode the 5 percent Ca sample as described above. Liou suggests that the variation in erodibility between the Na- and Ca-montmorillonites occurs from the structure, flocculated or dispersed, that is established by the quantity of salt added. A further interpretation of the high Ca erodibility

peak may be that the structure is one of large flocs whose internal strength comes from suppression of the strong repulsive forces but whose interfloc strength is still weak enough to permit easy particle separation. As the percentage of Ca ion is increased, the interfloc repulsive forces are reduced, with the result of a regain in total structural stability or erosion resistance.

The relationship of erosion susceptibility to water quality is clearly shown in the study of Arulanandan et al. (34). Water quality of both the pore fluid and the eroding fluid was changed in a series of rotating-cylinder shear tests. The rate of erosion was measured under varying surface shears for soils in which the sodium adsorption ratio was varied and the internal structure of the soil was affected. The eroding fluid also had NaCl concentrations varying from 0 to 0.1 N. The results of these tests [shown in Figure 8, p. 47 (3)] can be interpreted in terms of the effects of fluid quality on external and internal force systems. As the adsorbed sodium ratio increases (i.e., as the replacement of calcium or magnesium ions or both by sodium increases), the critical shear stress decreases. The rate of decrease is a function of the salt concentration in the pore fluid. With low concentration of salt in the pore fluid, high shear stresses are resisted only when little of the original Ca or Mg ion has been displaced. When the pore fluid contains much salt (0.1 N) the resistance to initial erosion is sustained to much higher sodium adsorption ratios. Arulanandan et al. attribute this to the ability of the soil to form strong flocculated structures with either higher valence exchange ions or high concentrations of salt in the pore fluid. This affirms the mechanistic theories that relate erosion initiation to the surface conditions.

The eroding fluid can also be used to stabilize the soil [shown in Figure 9, p. 48 (3)]. Increasing concentrations of salt in the eroding fluid resulted in lower erosion rates. Thus, a quality of 0.005 N NaCl was enough to reduce the erosion rate to 20 percent of distilled water acting on the soil. The combined effect, that is, salt in both the eroding fluid and pore fluid, demonstrates the dynamic effects of the mechanism of erosion. In cases where the NaCl concentration in the pore fluid is greater than the eroding fluid, erosion can be expected; whereas, when the reverse is true, erosion is not expected. These show that the laws of diffusion cause surface changes affecting the internal force system. Reduction of salt concentration at the surface of the soil relaxes the internal forces and permits erosion to commence. There is one extremely important application apparent here. In many coastal areas and near many industrial sites, the quality of the groundwater is changing through diffusion of salts. Where channel erosion may have taken place prior to diffusion at low rates (pore and eroding fluids being of the same quality), erosion rates may be significantly changed, depending on the nature of the eroding fluid and the time allowed for erosion. Diffusion through the pores of soils under eroding conditions is a function of the concentration differences and the temperatures of the fluids. The conclusions of the work of Arulanandan et al. are particularly valid in field conditions where steady-state conditions can be developed.

Partheniades (36) found in flume tests using salt water that, after a period of 4 months and remolding of the soil bed, the erosion rates had significantly decreased (50 to 25 percent of corresponding rates for original bed and velocities of 1.32 and 2.31 ft/sec). This was attributed to a "possible increase of the electrochemical attraction and to the possibility of some cementation due to dissolved iron oxide in the water." The study by Bjerrum and Rosenqvist also suggests that particle weathering may account for increased stability of the soil. Partheniades' soil, a San Francisco Bay mud, was a highly plastic (PI = 55 percent) mixture of montmorillonite and illite clays, silt, and sand, with high ion and magnesium contents. Increased weathering of active particles will strengthen the interparticle bond (cohesion), creating an increase in total shear resistance.

Further study into the causal relationships, though examined on a macroscopic level, was made by Grissinger (14). Grissinger evaluated the relative erodibility of clays of various activity placed on a relatively small (5.04 x 12.5 cm) mold and subjected to flow normal to the orientation of the direction of packing of the material. The soil was compacted in either a flocculated or disperse nature, depending

on initial moisture content. The sample was allowed to adsorb water subsequent to compaction but did not necessarily reach a saturated state. The measured variable was rate of erosion (grams/min). The first study evaluated the effect of aging on erosion rate; and, as can be expected by thixotropic behavior, as aging time increased from no aging to overnight (12 to 24 hours), the rate of erosion decreased considerably. The various soils were made by mixing a predominantly silt soil with various mixtures of kaolinite, illite, Na-montmorillonite, and Ca-montmorillonite.

Grissinger found that, as the percentage of clay in the soil increased, the erodibility decreased with the exception of Ca-montmorillonite. The Ca-montmorillonite was the only soil in fact that showed (except at high density) decreasing stability with increasing clay content. This is consistent with Liou's results if the montmorillonite particles are forming large flocs loosely held together.

As the antecedent moisture content increases, resistance to erosion decreases. The soils were formed in a more disperse state with the main particle orientation parallel to the eroding water. In this manner, the particles are more resistant to shearing forces, inasmuch as the force system and structure are relatively well developed along the surface. As the antecedent water content increases to high values, the rate of erosion again increases, which indicates that swelling must be taking place. As swelling takes place, the net internal force system would decrease as the interparticle spacing increases. Swelling might also cause slight changes in the orientation: Small rotations of the particles occur, and the particles deviate from the generally horizontal disperse structure. In a less disperse form, the particles would be more susceptible to shearing forces than the more oriented particles as indicated by an increasing erosion rate.

Because of the wide range of PI and the overlapping of PI among the various sample mixtures, no correlation of PI with erodibility could be made.

Grissinger (15) later extended this test procedure to a wider range of natural soils. From these tests he related erosion rate to the rate of sample wetting. This empirical relationship is given by

$$ER = b_1 p(\Delta \text{ water/time}) \tag{4}$$

where

ER = erosion rate,
b = regression constant, and
p = sample porosity.

Molded samples were aged for a specified time and eroded in a small flume. The test results were presented in terms of erosion rates at fixed velocity. As noted the erosion force was not determined, so resistance to initial erosion or critical shear stress is not available. These can be thought of as tests on already eroding systems. The samples fell into classes that were established according to water pH, pH difference between water and clay, PI, and percentage of clay. The influence of differences in eroding fluid and clay quality is seen to have effect where the pH values are small for a slightly acid soil and where pH values are large for a water pH in the neutral to alkaline range. Grissinger applied this analysis to a field sample and developed a chart relating eroding velocity to eroding rate and delineating areas of stability.

FLUME STUDIES

Model tests of cohesive soils placed in a flume are worthy of extensive discussion because they clearly illustrate the strong influence of physicochemical forces acting in cohesive soils. The tests by Abdel-Rahman (1) were made on an expansive clay and clearly illustrate the influence of expandability in erosion. Mirtskhulava (31) studied the relationship between critical velocity and floc size and cohesion of soil in an attempt to define stability. Partheniades' tests (36) were also made on active clay but were different from previous tests inasmuch as they are deposited in water at ocean salinity.

Abdel-Rahman performed his tests on material compacted at a variety of moisture contents, varying first the fluid velocity for a series of tests at constant moisture content and then the moisture content for a series of tests at constant flow velocity. The material was compacted by a hammer, which tends to cause some orientation normal to the direction of the applied force, and the surface was subsequently trimmed to a desired level. Because the material was compacted at moisture contents less than the saturated moisture content, submergence in the flume caused additional amounts of water to be absorbed, generally resulting in swelling. The amount of swelling increased as the original moisture content decreased, which is of course expected for compacted materials (40). The swelling was of the order of 4 percent.

Because there were no moisture-density tests performed, it is difficult to determine whether the soil was compacted wet or dry of optimum moisture. The high moisture contents (30 percent) and, in the second series of tests, the large decrease in vane shear strength with increasing moisture content would imply that the material is near or greater than optimum. For this reason, the particle structure would tend more to be disperse than flocculated, this fact being somewhat borne out by the erosion pattern. The soil strength in each case was measured by the vane shear test. It should be noted that the soil tended to swell continually, usually reaching its maximum expansion after 60 to 100 hours after the test had proceeded. As moisture content increases and as the structure expands, the vane strength decreases. In series 2 the vane shear strengths varied initially from 1.026 t/m^2 (w percent = 36.05) to 7.260 t/m^2 (w percent = 24.40) and decreased to 0.90 t/m^2 (w percent = 37.8) to 2.814 t/m^2 (w percent = 29.94) respectively (Table 3).

As noted there are two basic series of tests in which the influence of the hydraulic parameters (velocity and bed shear) and soil parameters (shear strength and moisture content) are isolated. The time patterns of erosion in both are similar, and to relate the erosion phenomenon requires that the tests be discussed in some detail. For low values of hydraulic shear stress ($\tau \leq 1.54 \times 10^{-4}$ t/m^2; $S_r \approx 1$ t/m^2) or for high values of vane shear strength ($S_r \geq 2$ percent; $\tau = 2.6 \times 10^{-4}$ t/m^2), swelling and erosion were of somewhat the same order of magnitude. Erosion apparently took place from time t = 0 and increased rapidly until a steady-state condition was reached. Finally a point of no erosion was attained. Abdel-Rahman cites continuing erosion until the water becomes "cloudy," which is an extremely vague term. The implication here is that there is some local surface shear initially and that after some time there is a greater large-scale surface shear more representative of the general surface condition. He notes that "the smaller the tractive stress, the larger the time needed for the water to become cloudy." This is consistent then with the concept of the time effect of shear. The nature of treatment of compaction and of leveling the surface causes a preferred orientation of the particles, especially on the surface, this orientation being parallel to the bed. Pulling the trimmer over the surface somewhat amplifies surface irregularities and inhomogeneities (mainly in density), causing the nature of erosion as shown in his photographs. The flat pieces are those clusters weakly held to the bed and easily removed by any surface shear force. Further breaking up of these particles is mainly a hydraulics problem. The greatest depths of erosion (hence greatest erosion rates) occur for minimum combinations of τ_o and S as mentioned above, indicating that the soil material possesses a certain inherent strength that will resist erosion below these values.

No scour or steady-state conditions were reached for specific values of stress. This indicated that, the more erodible the soil was, the longer the time necessary to reach steady state would be. Because the erosion mechanism is essentially the same, varying the hydraulic or soil parameters has the following effects: Increasing the tractive stress causes greater boundary shear and greater particle reorientation with surface disruption, thus permitting erosion to continue until the bed adjusts to the flow conditions; greater vane shear indicates a denser, more oriented bed. Thus, as the erosion process continues, more resistance is encountered below the surface, especially as the particles are oriented parallel to the direction of shearing, thus decreasing the time to steady state. In both cases steady state would

be reached because of a continued particle reorientation under the steady influence of the bed shear. This orientation tends to parallelism with the direction of shear. Furthermore, because erosion takes place below the surface, the internal system becomes greater because it has had more time to stabilize (thixotropic effect) and because it was initially in a position of greater stability. Of great interest would be the increase in velocity needed to sustain the maximum rate of erosion as the erosion depth increases. Abdel-Rahman also mentions a "gluey" substance forming on the bed (probably oxides of iron and other metals that become disoriented from the soil due to flow through the upper surface layer). However, the consistent time-depth pattern would tend to sustain the self-limiting aspects of erosion due to the limiting stability conditions of the material.

It may be concluded from Abdel-Rahman's study that, for a soil with a given PI, a wide range of erosion conditions is possible. The bed shear strength can serve as an index to a limiting amount of erosion possible for a given tractive stress. Conversely, for a given bed strength, there may be a lower limit to the tractive stress necessary to cause substantial erosion. Neither of these clarifies the conditions that initiate erosion. It would seem that the initial surface condition will determine the initial modes of erosion, and these of course will determine subsequent patterns; i.e., a naturally deposited material will behave somewhat differently from a compacted soil. Local inhomogeneities may precipitate erosion through the existence of weak planes between the inhomogeneity and the overall bed, which are susceptible to shear forces that will cause movement of the material and which are of orders of magnitude less than shear forces that cause general erosion. This was clearly shown by the flat plates being moved along the bed. Because overall surface erosion can only take place by increasing interparticle (or interfloc) distances, which reduces the interparticle strength, the time of clouding in Abdel-Rahman's tests would seem to represent the actual initiation of general erosion. This has already been discussed in some detail.

Erosion of flocs was also noted by Mirtskhulava in his study of erosional stability. Of significance was his relation of measurable soil parameters to velocity causing erosion. A plot of his data (Fig. 4) indicates that, as cohesion and particle mass (proportional to d^3) increase, the velocity to cause erosion also increases. As the internal stability increases, greater stresses (velocities) are needed to erode the particles. Mass erosion, i.e., large floc erosion, will occur as weak planes between the flocs develop. Cohesion and floc size would be interdependent, for greater cohesion is representative of a stronger internal force system or fewer potential weak planes.

Partheniades' tests examined the influence of velocity (surface traction) to other variables on erosion rate for a basically montmorillonitic clay deposited in salt water. Three series of tests were performed on a remolded sample, at field moisture, that had undergone some chemical change and on an artificially flocculated sample. (The relative shear strengths of the beds taken near the surface are given in Table 4.) Partheniades' significant findings were that the initiation of erosion occurred in all samples over a small range of water velocities, 0.6 to 0.8 fps. Thus, some yield stress must be overcome before erosion can be initiated. Data given in Table 4 also show that erosion rates decrease even though the shear strength of the bed decreases.

This would imply that there are essentially two controlling factors for the soil behavior in these tests. The first factor is that the initiation of erosion occurs by the same mechanism in each case, as explained by Partheniades. The second factor is that the substance of erosion at a constant velocity becomes more difficult as the test series goes from the naturally deposited soil to the artificially flocculated soil.

One explanation may be that the natural clay deposited through a greater depth of water may have had initially a more highly random structure than the artificially deposited clay, which under constant shearing stresses in the fluid develops a more preferred orientation, though perhaps a looser density. The natural clay over a long period of time would also develop strong interparticle bonds and would be more stable than the artificially deposited soil. However, the preferred orientation of the soils in test series 3 would tend to resist erosion more because the plane of the parti-

cles is more aligned with the direction of shear. Ladd (17) illustrated the formation of flocculent structures that consist of clusters of individual groups of particles, some of which have formed domains. He states that the factors that control the formation are the type of clay mineral and the fluid environment and notes that "domain formation is generally restricted to the montmorillonites and some illites...."

The marine clay in its initial environment was probably deposited in an extremely dilute suspension, whereas the artificially sedimented material would be deposited in a more concentrated solution and would tend to form aggregated structures. The shear strength data give evidence that either the structure of the two materials is quite different or the internal force systems have evolved differently as noted. It is quite important to establish some criterion by which the surface orientation of the deposit can be established and to determine the surface strength at a given time as a function of its long time strength.

Flume studies have also been carried out on naturally consolidated laboratory samples (34). Kaolinite samples were deposited and consolidated in a 4-sq ft consolidometer (2 × 2 ft) to various levels of prestress and then subjected to flow in a 4-ft long by 1-ft wide test section of a 30-ft long duct. The test section is shown in Figure 5. Preliminary results (2) are consistent with other studies showing an initial period of high erosion rate, followed by a steady-state period. The erosion rate was measured using concentrations of fluid taken from the duct. Typical results are shown in Figure 6 where the preconsolidation pressure was 1,030 (10).

TRACTION FORCE AND EROSION IN OTHER MODELS

In an attempt to define a relationship between erosion and tractive force, several investigators worked with submerged jets acting on prepared surfaces, hoping to better define the relation of a relatively small area of tractive stress to erosion rate (or depth). Dunn (11) based his measurements on the assumption that the total force causing erosion consisted of, in his analysis, turbulent form drag and viscous drag, most of the force being caused by the latter. The force resisting shear was taken to be the Coulomb failure criterion in which it is necessary to assume some value of ϕ (friction angle) and c (cohesion), which have been shown to be approximations of some true failure criterion (9). By assuming that the Coulomb failure criterion is operative, Dunn postulated that the mechanism of erosion failure at the surface can be defined in the same manner as deep-seated failure criterion. By providing a subsequent redefinition of c, he reinterpreted the failure mechanism without redefining the law controlling this mechanism. The results indicate that the critical shear stress increases in some fashion with the vane shear strength of the bed (a deep-seated phenomenon). This would imply that the surface shear must also be linerarly correlated with the vane shear, a fact that is yet to be demonstrated.

Dunn went on to relate erodibility to PI and percentage of fines, through the failure criterion, noting that, as PI and percentage of clay increase, resistance increases. It is necessary to examine his methodology before commenting on his results. The soils were remolded and subsequently consolidated in a saturated environment. No density measurements were made. The maximum PI was 15.6, and, of seven cohesive samples, three had PIs less than 10. This suggests that the samples consisted of relatively inert clay minerals and that the soil itself was not subject to adverse swelling. Dunn limited his correlation between PI and tractive resistance to those soils with PI > 5. Thus the correlation is made for soils with a range of PI of approximately 6 to 16.

The advantage of using activity instead of PI can be seen in a very brief examination of two studies. Reports by Dunn and Smerdon and Beasley isolate clay portion and PI and compare these with their defined critical shear stress. Whereas general relationships can be deduced from curve fitting, the resultant equations or curves are limited, in Dunn's case, to a very small range of soils with relatively low plasticity ($5 \leq PI \leq 16$) or a large degree of scatter, in the case of Smerdon and Beasley. Table 5 gives Dunn's data in terms of activity and shows the relatively small range of activity of soil investigated and, as would be expected, a small range of τ_c (critical

Figure 3. Surface force distribution.

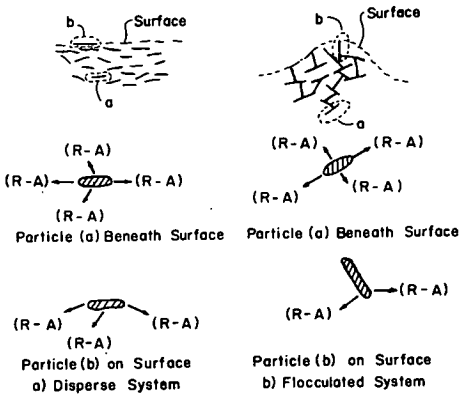


Table 3. Hydraulic and soil parameters influencing erosion (1).

Test	w_i (percent)	Δw (percent)	ΔS (percent)	S_r (t/m^2)	t_{max} (cn)	τ_i/τ
1-1	33.55	3.45	14.72	1.000	0.450	1.00
1-2	34.10	2.88	14.30	1.080	0.300	1.57
1-3	34.50	2.88	14.00	1.085	0.391	2.06
1-4	34.10	2.75	14.00	1.085	1.345	3.46
1-5	34.16	2.44	13.50	1.110	3.990	5.90
2-1	36.03	1.77	12.30	0.90	1.410	1.00
2-2	30.50	3.51	51.00	1.31	1.045	1.00
2-3	27.56	3.16	55.50	2.00	0.610	1.00
2-4	24.40	5.54	61.50	2.81	0.493	1.00

Note: t_{max} is with swelling.

Figure 4. Influence of aggregate size and cohesion on erosion velocity (31).

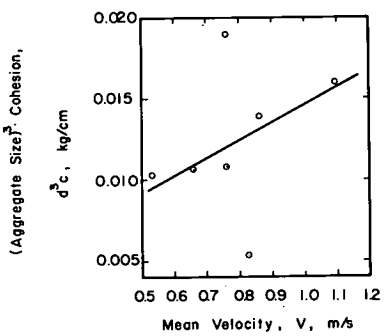
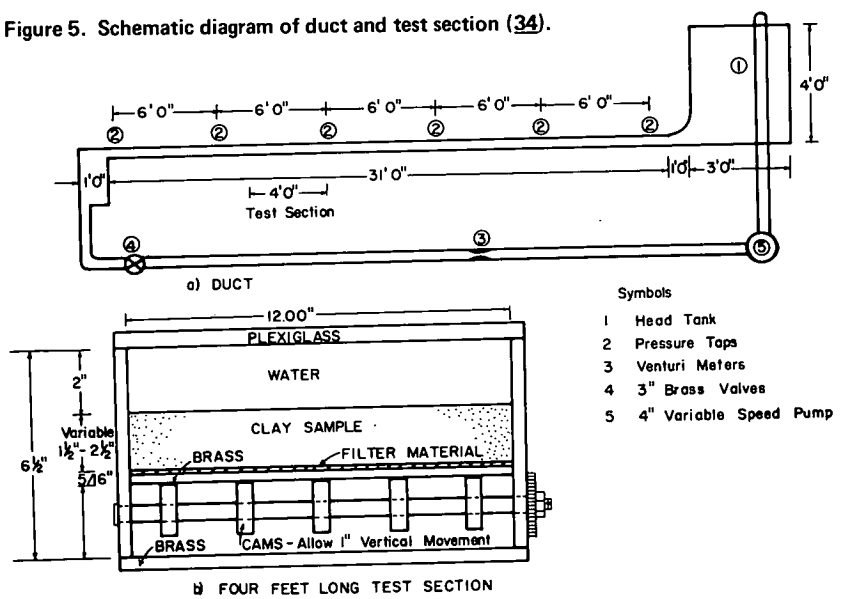


Table 4. Initiation of erosion in Partheniades' study.

Test Series	Velocity of Flow (fps)	Erosion Rate (grams/ft²/hour)	Apparent Shear Strength of Bed ÷ Shear Strength of Series I	Shear Stress on Bed (psf)
I	0.8	0.05	1.0	0.0023
I	1.34	0.338	1.0	0.0103
I	2.34	1.67	1.0	0.0278
II	1.32	0.174	0.6	0.0100
II	2.31	0.674	0.6	0.0272
III			0.0074	
III	1.27	0.506	0.0074	0.0091
III	1.46	0.252	0.0074	0.0120

Figure 5. Schematic diagram of duct and test section (34).



shear stress). For these soils Dunn gets good correlation between tractive resistance and tractive force. If PI and vane strength are isolated, it must be assumed that there is a great deal of similarity in the structure of the soils and in the mechanism of erosion. The soils were recompacted and consolidated similarly and were most likely in a disperse state. In describing the manner of erosion, Dunn notes that the first material removed was that disturbed by the upper plate and that at a particular point, when the jet velocity was increased, the water became cloudy. Removal of the first particles would then be somewhat independent of the shear strength of the mass, inasmuch as these particles have been initially disturbed, have undergone some tensile stress, and evidently are not in a position of great stability. Under the tensile stresses, the bonds between particles (or particle groups) are weakened as the particles are moved further apart, making them more susceptible to erosive forces. Furthermore, removal of the cap would cause a geometric rearrangement in these upper particles so that their orientation is neither so uniform nor necessary predominantly in the same direction as the particles below the surface.

The erosive forces that act on the more stable layers are somewhat different in the case of parallel flow. The jet has components both tangential and normal to the bed so that with both components orientation of the bed particles becomes of less importance than it is for the case of just parallel flow. For a disperse system with particles oriented parallel to the surface of the bed, normal components of stress would tend to deform and cause rotations about the axis, and, coupled then with tangential components, through movement and rotation the bonds would loosen and erosion would occur (Fig. 7).

This is also shown in the tests of Moore and Masch who were able to cause scour to some depth in samples under jet tests. Under the influence of the jet they observed nonuniformities in scour because large pieces would be eroded away as the scour continued. This again can be attributed to a highly nonuniform force field acting on a surface that is somewhat nonuniform to begin with but whose degree of inhomogeneity increases under the influence of the surface forces.

Leitch and Yong (21) showed that under shearing stresses (deep-seated) there is marked reorientation of particles on the failure plane; the particles became aligned in the direction of movement of the plane. This is clearly shown in electron microphotographs taken of kaolin under shear (44).

Although the behavior of surface particles due to the shear forces of the fluid is different from deep-seated shear, the nature of reorientation of particles cannot be neglected. The reorientation or rotation at the surface, in order to cause erosion, must permit a general loosening of the structure. If the particles are subject to a tensile field (surface drag forces) or if under the influence of bending a particle separation can take place, the net interparticle energy field is reduced. Reorientation of a cluster will cause this same phenomenon along the small shear plane, allowing the entire cluster to be removed. This is shown schematically in Figure 8.

Moore and Masch presented many conclusions from their studies that can be extended to flume tests. Unfortunately, none of the plastic properties of the soils is given, nor is the method of preparing the sample for placing in the test apparatus given. The scour rate index, a measure of the rate of erosion, has an apparent linear relationship with Reynolds number N_R or velocity of flow, hence surface shear stress. Further, there is a limiting N_R below which scour does not take place. This in effect confirms the existence of a yield stress that the soil possesses, this yield stress being a function of the internal force system. For a given velocity and at an N_R sufficient to cause erosion, the rate (or depth) of erosion increases in some linear fashion with time. This is shown in Figure 9 for the three samples tested. If the data as presented are extended back to the time axis, it is seen that the initiation of erosion does not take place immediately and that, the lower the Reynolds number is, the longer is the time before initiation of erosion.

The large discontinuities in these curves are attributed to sudden erosion or large clusters of soil. It seems evident that two mechanisms are working simultaneously: first, the surface mechanism yielding a steady deterioration of surface resisting stresses due to general reorientation at the unconfirmed upper surface and,

Figure 6. Eroding soil concentration versus time (10).

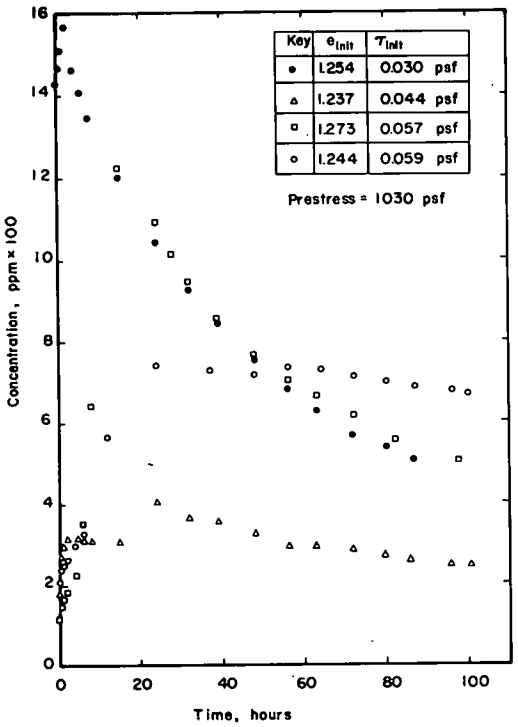


Table 5. Critical tractive stress versus activity (11).

Activity[a]	$T_c$min	$T_c$max
0.054	0.30	0.33
0.062	0.19	0.32
0.110	0.30	0.45
0.127	0.43	0.48
0.161	0.48	0.49
0.164	0.40	0.41
0.165	0.48	0.49

[a]Because soil is classified according to percentage of silt and clay ((0.06 min), the actual clay content ((0.002 min) will be less than given. This is an approximation, the true activity being greater for smaller percentages of clay.

Figure 7. Suggested mechanism of erosion in vertical jet tests.

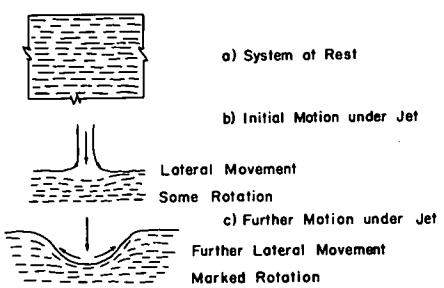


Figure 8. Mechanisms of erosion caused by reorientation or relocation of particles.

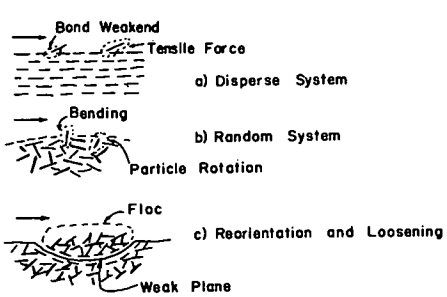
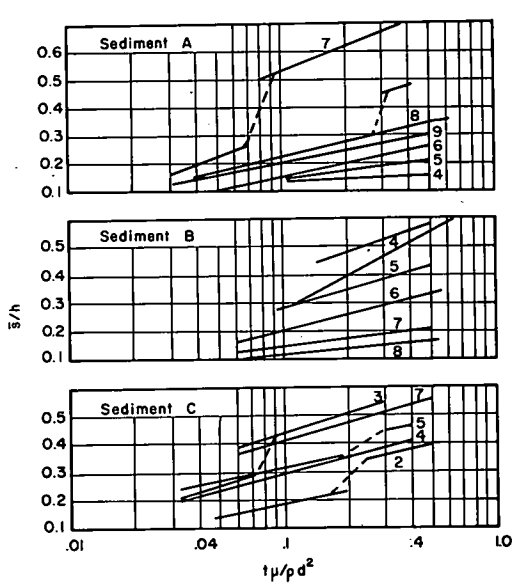


Figure 9. Scour depth versus time (33).



second, the deep-seated shear most likely acting along weak planes that may exist due to natural inhomogeneities in the soil. This would seem likely because there is no consistent pattern of deep-seated shear although in all cases the surface erosion proceeds for a given period of time $\left(t \geq 0.07 \frac{\rho d^2}{\mu}\right)$ before deep-seated shear occurs. This is entirely consistent with the fact that the shearing process in soil is highly time-dependent (21).

Christensen and Das (9) developed a unique test method in which samples were placed inside a brass tube as a lining. The clay was actually compacted by being squeezed into a tube [Figure 2, p. 10 (9)]. The surface was made smooth by removal of the inner tube, which also affected the orientation of the particles at the surface. It should be recognized that this technique allows comparison of erosion parameters for similar samples but would not be representative of field conditions. Molding moisture content, flow velocity, and temperature of the eroding fluid were varied. When eroded, the samples showed patterns consistent with other observers, i.e., an initial rate followed by steady-state conditions. After steady state, a rapid erosion again took place. This is due to the nature of the changing boundary forces as the surface becomes rougher and particle reorientation continues.

The significant contribution of these authors is their approach to a mechanistic model:

$$\dot{E} = \beta_E \exp(\alpha \tau) \quad (\tau < \tau_c) \tag{5}$$

and

$$\dot{E} = E_{CR} \exp\left[\alpha_1^{(\tau - \tau_c)}\right] \quad (\tau > \tau_c) \tag{6}$$

where

$\dot{E}$ = steady-state erosion rate,
τ_c = critical stress, and
α and β = soil and test parameters.

This model makes possible the understanding of erosion as an internal/external energy system, where E can be a measure of the work done on the system, reflected in τ actual, and α and β represent measures of the internal energy developed by the samples. α is related to the bonding energy and β to the weight of the eroded particles. In the form of the relationships given, α, related by the authors to energy, is analogous to the term (constant/T) in the activation process where increasing temperature loosens internal bonds. For erosion, as interparticle bonds are relaxed, external forces would have greater effect on changing particle geometry, thus intensifying the erosion process. The authors noted that, as molding moisture increased, total erosion weight decreased. It should be noted that, as molding water content (above optimum) increases, density or soil particles per unit volume decrease rapidly. Thus a plot of eroded soil in grams versus moisture content is not so meaningful as erosion weight in grams as a percentage of total original weight. If possible, reconstruction of this curve as particle volume lost per unit of area, as a function of original particles per unit area, would perhaps aid in the explanation and would most likely show results more consistent with other investigators.

The importance of the effects of temperature on erosion has also been amplified in a study made by Enger (12). The rate of increase on boundary shear of water from the city supply on the soil sample was 0.0036 psf/deg C. Because the critical boundary shear as measured in these tests ranged from 0.010 to 0.065 psf, the strong influence of temperature is clearly shown. However, other than a series of three tests evaluated to calculate temperature effects, no further temperature correlation was reported, although the report maintains that temperature records were kept.

APPLICATION TO FIELD CONDITIONS

The paper by Wischmeier and Meyer (50) relates the data developed since 1930 by the U.S. Department of Agriculture on runoff and erosion to properties of detachability and transportability of the soil. Dealing with field erosion, the erodibility factors are classified as: "those that influence the capability of the erosive forces, rainfall and runoff, to detach and transport soil material, and those that influence the capability of the soil surface to resist the erosive forces." The authors present the soil loss equation in terms of these factors, which is useful in predicting total weight of soil loss from climatic, geographic, and soil properties. In further multiple regression work, they found that significant parameters affecting erosion were soil texture, organic matter content, aggregation, surface pH, and permeability of surface seal. This was utilized in construction of an erodibility monograph. The monograph is of significance in predicting the erodibility of soil at construction sites from soil parameters easily obtained through surface sampling.

Akky and Shen (2) examine the influence that cement stabilization has on reducing the potential erodibility of a given soil. One to 3 percent cement was added to a sandy soil (nonplastic). Although they were concerned with cohesive soils, the implications of stabilization are important to understanding erosion control. The stabilized material was tested in a rotating cylinder apparatus. "Unweathered" samples showed increasing resistance to erosion with increases in unrefined sample strength. This is to be expected inasmuch as the bonding produced by the cement, which causes strength increases, would be reflected in surface resistance to erosion. This is analogous to increasing erosion resistance found in cohesive soils as percentage and activity of the clay material increase. The effects of weathering, freezing and thawing, or wetting and drying cause surface changes, again analogous to weathered clays. The process of weathering changes the surface through fissuring or bond relaxation through increased wetting. Greater surface areas exposed to the eroding forces make prediction of erosion on weathered surfaces more difficult than on nonweathered surfaces. The processes of stabilization of erodible surfaces need further research. Research in this area would give a needed link between understanding the theory of erosion mechanisms and the nature of control of erosion processes.

Stabilization by other methods including natural cementing agents such as iron oxide and the use of bentonite has been proposed by Partheniades and Paaswell (37).

CONCLUSIONS

It is possible here to summarize brief conclusions from the large amount of research. For example, PI (or activity) can serve as a group index telling whether a class of soils is more likely to be eroded than another class. That is, all other conditions being equal (fluid and density properties), it would be more likely that soils with a high PI would be less erodible than soils with a low PI. However, a given soil (i.e., PI fixed) may or may not be erodible depending on its structure. Thus, PI is not a primary index of erosion and actually serves the purpose of being a means of identification only. However, physicochemical indexes such as sodium adsorption ratio give better information on soil structure necessary to interpret potential behavior.

Other conclusions follow:

1. Generally used soil classification indexes have not proved useful as erosion predictors.

2. Structural indexes must be defined in order to establish relative erodibility of a given soil and comparison with other soils. This index should give an indication of particle orientation, separation (void ratio), stability (strength on a thixotropic scale), previous stress history, and ability to swell. These latter two items become extremely important when laboratory and field tests are compared. A soil that will swell appreciably may have done so in the natural stabilizing processes that take place. Thus such a soil may erode only at a higher velocity than that evidenced in the laboratory.

3. The external and internal force systems must be evaluated to determine rate and initiation of erosion. Surface erosion begins as a particle-by-particle phenomenon, due to the relative instability of a particle (or domain) compared with the remainder of the surface. This instability can arise from orientation, poor bonding, structural defects, or, when subject to a peak in a fluctuating shear field (or else after a time), being rotated in a fluctuating shear field and being subject to some stress less than the peak would be pulled away. Because the soil bed may not be everywhere parallel to the flow direction, the force vectors acting on the bed may have normal as well as tangential components. The normal stresses may have beneficial effects in that they cause more stabilization or harmful effects in that they cause reorientation into the flow field. The internal force field is created by the initial mode of deposition, predominant clay mineral type, and previous stress history. Soils stabilized over a period of time, perhaps prestressed, with orientation parallel to the flow direction will obviously be less erodible than soils with more flocculated orientations of recent deposit.

The research cited here has shown how complex the cohesive soil erosion problem is, but continued developments on soil fabric analysis and more sophisticated techniques in physicochemical analysis should help in solving the aspects of soil behavior under flow.

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Part II

PREVENTION AND CONTROL

WILLIAM M. BRIGGS, Soil Conservation Service,
Madison, Wisconsin

INVENTORY OF ROADSIDE EROSION IN WISCONSIN

Along the 87,000 miles of Wisconsin roads, there are 21,000 sites that produce sediment. If these sites were placed in one continuous strip, it would extend from Madison to New York City and then westward to Los Angeles measuring 3,711 miles long and 16 feet wide. A report on erosion in Wisconsin revealed these facts. In 1967, the Wisconsin chapter of the Soil Conservation Society of America initiated a statewide inventory of erosion on all state, county, and town roads. We are told that this was the first detailed survey of roadside erosion in the nation. The findings were surprising to many: Nearly three-fourths of the sediment-producing sites occurred along town roads. Nearly one-fourth of the sites were found along county roads. Only 3 percent were on state highways. These revelations pinpointed the problem. The increased awareness and understanding of roadside erosion by many people and organizations proved to be one of the most rewarding results of the inventory. Awareness of the problem led to action programs. Today, approximately 50 hydroseeders and mulchers purchased by soil and water conservation districts are helping to accomplish the needed vegetation of the 21,000 identified silt-producing areas. Counties and townships are enacting ordinances and developing policies and procedures for vegetating new highway construction and maintaining established roadsides. Procedures used, results obtained, and expected benefits are briefly outlined.

Highways and highway rights-of-way occupy publicly controlled land, of which we are all stewards. Highways have an important effect on our environment. Runoff from highways frequently drains directly into lakes and streams. For years observers recognized roadside erosion caused by construction and maintenance as one of the principal contribution factors to sedimentation.

Five years ago the extent of roadside erosion was inventoried on all 87,000 miles of Wisconsin highways (1). The survey was an eye-opener. Over 21,000 silt-producing sites were found! On the average, one site for every 4 miles of roadside was found to need erosion control of some kind.

The Wisconsin chapter of the Soil Conservation Society of America (SCSA) initiated the study in 1967. A subcommittee of the Natural Resources Council of State Agencies known as the Roadside Stabilization Working Group was formed. It was made up of representatives from the Wisconsin SCSA; Wisconsin Division of Highways, Department of Transportation; U. S. Soil Conservation Service (SCS); Department of Natural Resources; University of Wisconsin Extension Service; and the Department of Local Affairs and Development. The study included an inventory of all rural state, county, and town roads.

Each county organized a local committee also. Participants in the local committee included county extension agents, soil and water conservation district

supervisors, and personnel from the county highway commission, the Soil Conservation Service, the Department of Natural Resources, the U. S. Forest Service, the county Agricultural Stabilization and Conservation Service (ASCS), and the Farmers Home Administration. Other local, state, and federal agency people frequently helped. The SCS District conservationist usually served as chairman. A number of county rural development committees, then known as technical action panels, chose this as a special project. Several state training sessions were conducted for key leaders. Each county then held training sessions.

Tabulations of sediment-producing areas included length, width, and total area in square feet. Surveyors marked the location in plat books that are now filed in SCS work unit offices. Compilations by townships were prepared (Fig. 1) and sent to the state committee for checking. All 72 counties were summarized on a county and state basis.

Yes, roads are a vital part of America. Roads help us appreciate and understand our natural resources—our soil and our water including lakes and rivers. Our timber, wildlife, mountains, and state parks can likewise be better appreciated.

Published in 1969, the report reveals many interesting facts. If all the erosion sites along roadsides in Wisconsin were placed in one continuous strip, the strip would extend from Madison to New York City and then westward to Los Angeles and would measure 3,711 miles long and over 16 ft wide.

Findings surprised many. Town and county roads account for 97 percent of all roadside erosion. Nearly three-fourths (73 percent) occurs along town roads, and county roads contribute one-fourth (24 percent). The remaining 3 percent exists along state roads where, in general, vegetation is excellent (Fig. 2). In fact, the survey reveals 95.5 miles of every 100 miles of highway have good erosion control.

The published report gives a state summary and details of the findings in each county. Tables include extent of erosion along all roads—town, county, and state roads. One table ranks the 15 counties with the most erosion. This table indicates that one-third of all roadside erosion is found in six counties. It also reveals that over half of the erosion in the state occurs in 15 counties. A map shows quickly where the problems are.

Erosion sites are pinpointed. Town roads, where little or no attention is given to establishment of vegetation, are the worst offenders (Fig. 3). County roads also contribute to the problem. State roads are doing a great job, but some sediment-producing sites were found.

The following benefits are expected from the roadside erosion control program:

1. Improvement in the quality of our environment,
2. Reduction in lake and stream sedimentation,
3. Improvement in highway safety,
4. Enhancement of natural beauty and wildlife habitat, and
5. Reduction in maintenance and reconstruction costs.

Using their best collective judgment, persons making the inventory indicated the erosion control needed. Total figures show that more than half (54 percent) could be controlled by fertilizing, seeding, and mulching. Over one-third (37 percent) required sloping, fertilizing, seeding, and mulching. The remaining 9 percent needed "the works," which includes structures, sloping, fertilizing, seeding, and mulching (Fig. 4).

Erosion was found in every county and in nearly every township. About one-third (36 percent) of the sites were along roads less than 2 years old, whereas the remaining two-thirds were on roads 2 years old or over. The probable causes of erosion were listed as construction, 58 percent; maintenance, 33 percent; and other causes, 9 percent. Many local committees pointed out that considerable erosion was occurring on roads under construction (Fig. 5).

Only areas measuring over 100 sq ft were inventoried. Therefore, the amount recorded does not represent all of the roadside erosion. The state committee prepared individual county supplements to serve town and county officials better.

Figure 1. Sample of township roadside erosion survey.

Township: NORTH BEND

County: JACKSON

Page 1 of 1 pages

ROADSIDE EROSION SURVEY (on Public Roads)

Col 1	Col. 2	Col. 3		Col. 4			Col. 5			Col. 6			Col. 7		Col. 8
No.	Location Record number on plat-book. Mark location in red.	Dimensions		Total Area in Sq. Ft. Recorded by Type of Highway. Post when recorded			Control Needed			Causes			History		Note
		Width	Length	Township	County	State & Fed'l	Fert. Seed Mulch	Slope Fert. Seed Mulch	Structure Slope Fert. Seed Mulch	Construction	Maintenance	Other	New-Under 2Y	Old-2Y & More	
1	North Bend Sec 23	20	150			3000		3000		✓				✓	
2	" "Sec. 33	12 10	400 200	4800 2000				6800			✓		✓		
3	" " 33	—	—												Cattle lane on highway - a problem
4	" " 17	20	300	6000			6000				✓		✓		
5	" " 7	20	600		12000			12000		✓				✓	
6	" " 5	20 40	100 400		2000 16000		2000	16000		✓				✓	
7	Example only	20	100		2000				2000			✓	✓		Kickapoo R. Stream-bank erosion - Rip Rap needed.
8	" "	16 20 16	100 300 300	1500 6000 4800				12300		✓				✓	
9	" "	3	2600	7200			7200			✓	✓		✓	✓	Easily controlled
	Totals			32,300	32,000	3000	13,200	50,100	2000	5	3	1	4	5	

SAMPLE

Figure 2. Distribution of roadside erosion in Wisconsin.

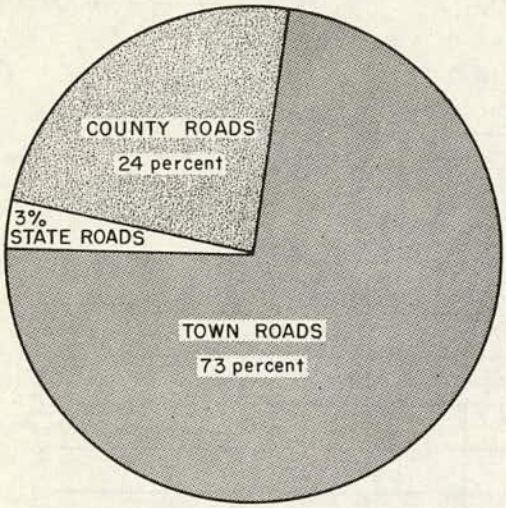


Figure 3. Example of erosion on town road (source: SCS).

Figure 4. Example of roadside needing structure, sloping, fertilizing, seeding, and mulching.

Figure 5. Example of erosion along road under construction.

These supplements tabulate erosion along town, county, and state roads on a legal township basis.

One of the most rewarding results of this inventory was an increased awareness and better understanding of the roadside erosion problem by many individuals and organizations. All of the state's news media widely publicized this study and its findings.

Awareness of the problem led to action programs. Action programs beyond our expectations started as people and organizations woke up. Today, about 50 hydroseeders and mulchers are helping to accomplish the vegetation and revegetation job along Wisconsin roadsides. Soil and water conservation districts and counties are purchasing these labor- and time-saving machines. Counties and townships are enacting ordinances and developing policies and procedures for vegetating new highway construction roadsides and for maintaining established roadsides.

The widely distributed report urges local, county, and state officials to take corrective action as soon as possible. Recommendations include the following:

1. Local agencies and organizations are encouraged to develop and are developing action programs, giving consideration to adopting timetables for achieving adequate control.
2. Soil and water conservation districts and county highway officials should seriously consider the purchase and use of specialized seeding and mulching equipment. As mentioned, about 50 hydroseeders and mulchers have been purchased and are now in operation.
3. Concerned highway departments should control every site reported that is a major source of sediment in Wisconsin's surface waters within the next 5 years. Good progress is being made.
4. State and county officials should consider incentive funds as a way to help speed up roadside erosion control. A committee is working on this. On a statewide basis, county needs can now readily be determined for correcting erosion if and when public works funds are available.
5. Town and county officials are urged to establish vegetation on all newly constructed road cuts and fills. Waiting for natural seedings to occur takes too long. Provisions should be made in some cases to secure wider rights-of-way. Exellent progress is being made.
6. Sediment retention systems should be included in all new construction and should be maintained until permanent structures and vegetation achieve adequate control. As a result of people's concern for the quality of the environment, progress has taken place much sooner than anticipated.
7. All agencies concerned with land use problems on or near highway rights-of-way are encouraged to make use of the report as a basis for arriving at solutions.
8. The state group should organize and make a comparable survey within 10 years to appraise progress and arrive at additional needs for roadside erosion control in Wisconsin.

SUMMARY

The Roadside Erosion Survey in Wisconsin was a great eye-opener to many people. It started an action program for erosion and sediment control. We have the technical know-how to prevent and control erosion along highways. We encourage other states to involve local people in similar activities. Another generation will be here tomorrow. Control of roadside erosion starts in our own backyards. It can be accomplished when everyone works together. SCS is glad to have taken an active part in the statewide inventory of erosion on Wisconsin roadsides.

REFERENCE

1. Erosion on Wisconsin's Roadsides—A Report to Wisconsin Citizens. Wisconsin Chapter of SCSA, Sept. 1969.

LARRY M. YOUNKIN, Bucknell University

EFFECTS OF HIGHWAY CONSTRUCTION ON SEDIMENT LOADS IN STREAMS

Highway construction is often held responsible for significant increases in suspended sediment yield in adjacent streams. Little factual information has been available to objectively evaluate the validity of this accusation. A study has been conducted to obtain the relationship between highway construction and change in suspended sediment yield in stream systems. A field investigation was carried out in a drainage basin, through which an Interstate highway was being constructed, to collect data necessary for the development of a prediction method. This paper describes an investigation of the effects of rainfall, construction phases, and proximity of construction to the stream system on the quantity of sediment transported. Field data for the analysis were collected at four rain gauge sites, at eight stream stations, and over approximately 5 miles of highway construction. A regression equation relating the observed variables to the sediment yield is presented and discussed. Results indicate that the sediment supply to the streams increases with rain energy, clearing and grubbing, embankment work, and proximity of construction to stream. It is concluded that the results of the study may be employed as a means of predicting whether highway construction would be a significant pollution source for a particular site, a criterion to be considered by an engineer during location studies, and a basis to evaluate the effectiveness of attempts to control sediment yield from construction areas.

Sediment transport and sedimentation resulting from the erosion of soil materials are serious polluters of the aquatic environment. Although the movement of sediment is a natural part of the hydrologic system, highway construction is often considered one of the major sources of sediment in streams. Actually few data are available that can establish the exclusive contribution of an area undergoing highway construction, and a method of predicting this contribution has not been developed.

A general method for predicting sediment yield in a stream system from uncontrolled highway construction could be used in many ways. It could be employed simply to determine whether highway construction would be a significant pollution source at a particular site, and, as such, it could be one of the criteria considered by an engineer during location studies. It would define the variation of sediment yield with the construction process, which would allow necessary abatement works to be phased with the construction rather than requiring completion of controls before construction could begin. Thus construction would not be delayed, and the result would be savings of time and money for the public. The predicted values would be useful as the required capacity in the design of desilting basins or sediment traps. It could also be employed as the basis for comparison to determine the effectiveness of attempts to control sediment yield from highway construction areas.

A tremendous amount of work has been performed in the past 40 years to develop prediction methods for rainfall-erosion soil losses from agricultural areas. The results of much of this work have been combined into the USDA universal soil loss equation (1), which includes as independent variables rainfall, soil erodibility, slope length and gradient, cropping management, and erosion control practice factors. But highway construction usually exposes to rainfall slopes steeper than those found in agricultural applications, which results in greater quantities of runoff at higher velocities. Soils in embankments are placed at near optimum compaction, resulting in lower infiltration rates and greater runoff. Subsoils are exposed that may have erodibility factors different from those of the topsoils studied in agricultural work.

In the past several years, reports (2, 3) have been published that extend the application of the universal soil loss equation to construction areas. The methods require that assumptions be made relative to the cropping management and erosion control practice factors and to the extrapolation of slope length and gradient factor from previous results to the conditions encountered in construction. They incorporate the results of recent research (4) on the soil erodibility factor for subsoils. It should be noted that the result of the application of these methods is the soil loss from a construction area and not the sediment yield in the stream system draining from the area.

Vice, Guy, and Ferguson (5) reported on a study conducted in northern Virginia of suspended sediment transport in a stream that drained an area undergoing extensive highway construction. They related the sediment yield to mean storm flow, duration of storm runoff, area of construction, and a seasonal factor. The rainfall effect was not directly considered in the study, and the intensity and dispersion of the construction, as well as the location of the construction relative to the stream system, were not included.

This paper reports on the development of an equation that may be used for computing the suspended sediment load carried by a stream system during periods of rainfall-induced erosion of disturbed soils common to highway construction. The equation was derived from data collected for a study during the construction of an Interstate highway through a drainage basin in central Pennsylvania during the period 1968 to 1970. The basin is drained by White Deer Creek, which empties into the West Branch of the Susquehanna River approximately 15 miles upstream of its confluence with the North Branch of the Susquehanna River at Sunbury, Pennsylvania.

BASIN CHARACTERISTICS

The White Deer Creek drainage basin extends from the mouth of White Deer Creek at the West Branch of the Susquehanna River, 440 ft above sea level, westward about 26 miles to its source, 1,900 ft above sea level. It has a total drainage area of approximately 46 square miles.

The terrain of the basin is typically a deep synclinal valley, bounded on the north by South White Deer Ridge and on the south by Nittany Mountain. The flanks of the valley are covered with a coarse colluvium, ranging up to boulder size. The stream runs through coarse-graded alluvium in the center of the valley and nearly coincides with the axis of the syncline. Fluvial and detrital deposits cover certain areas of the valley floor, primarily in the western part of the highway project area, and contain a higher percentage of finer constituents than the talus material that covers the mountain slopes.

The underlying bedrock is composed principally of shales of increasingly younger age, from the gray, brown-weathering Clinton shales on the west to the red shales of the Bloomsburg formation on the east, with Tuscarora sandstone on the upper hillsides and crests. These formations are all of Lower Silurian age. Also present are the more deeply underlying Juniata and Bald Eagle formations consisting of sandstone with shale interbeds, both of the Upper Ordovician age.

Topography in the basin is relatively steep, with slopes from ridges to streams averaging about 25 percent. Slopes in the valley from mountain base to

stream range up to 10 percent. Stream slopes range from about 1 percent on White Deer Creek to as high as about 7 percent on Mile Run, a tributary of the creek.

The climate in the basin is characterized as continental and inland, with prevailing winds from the west and southwest. Warm summers and moderately long winters are typical of the area. The valley has a freezing depth of approximately 30 in. The mean annual temperature is 50.2 F with a winter mean of 27.9 F and a summer mean of 71.0 F. The average frost-free season is 161 days, although frost may occur as late as May 29 and as early as September 3. The mean annual precipitation is 41.7 in., fairly uniformly distributed throughout the year.

Essentially all of the land in the basin is occupied by forests on both the steeper slopes and the flatter areas in the valley. There are only a few small buildings along the streams, most of which are hunting and fishing cabins occupied only on a seasonal basis. There is no farming activity in the basin.

THE HIGHWAY

After crossing the West Branch of the Susquehanna River, Interstate 80 swings in a northwesterly direction as it enters the White Deer Creek drainage basin. It crosses the creek approximately 2.7 miles upstream of its mouth and then proceeds in a westerly direction along the north side of the valley along the base of the South White Deer Ridge as shown in Figure 1. About 8.8 miles upstream of the crossing, the highway leaves the main valley and closely follows Sand Spring Run, a tributary of White Deer Creek, for approximately 3.4 miles before leaving the basin.

Only the western 5.4 miles of highway construction were included in this study. The construction included four box culverts for the tributaries Lick Run, Mile Run, Kurtz Gap Run, and Sand Spring Run; an overpass for a local road near the Sand Spring Run crossing; and a diamond interchange at Mile Run. Upslope drainage is collected in lined channels at two points and conveyed beneath the highway. Some relocation of the channel was required for Sand Spring Run in the vicinity of its crossing.

The highway consists of two dual-lane roadways, each 24 ft wide. The shoulders adjacent to the median are 8 ft wide including a 4-ft wide stabilized portion. The outside shoulders are 12 ft wide and have a 10-ft wide paved portion. The side slopes in the cut or fill areas are 6:1 for 0- to 4-ft depths, 4:1 for 4- to 10-ft depths, and 2:1 for depths over 10 ft. The median width varies from 84 to 200 ft with the natural vegetation undisturbed everywhere possible.

THE RESEARCH PLAN

The problem of determining the suspended sediment yield in a stream system resulting from rainfall on an area undergoing highway construction may be divided into three phases. The erosion process is that involved with the detachment of soil particles and their movement from the construction area. Rainfall is one of the most important factors affecting erosion inasmuch as it is responsible for the detachment of soil particles. The ease of detachment is a function of the soil and its erodibility characteristics and the condition of the soil surface as related to its compaction, which, in turn, is related to the phase of construction and the intensity of the construction activity. The transport of particles over the exposed surface is a function of the slope length and gradient. Finally, the total yield is related to the area of the soil exposed by the construction.

The second phase is the movement of sediment from the construction area to a definite stream channel and is called the overland transport process. The slope length and gradient of the natural ground surface between the construction site and the stream are of prime importance. The antecedent moisture in the natural ground will affect the infiltration rate of the overland flow and is a factor in the quantity of sediment reaching the stream rather than being deposited on the ground surface. The density and nature of the vegetation and debris on the surface are factors with ability to trap the sediment prior to its reaching a stream.

The final phase is the stream transport process, which relates to the ability of the stream to carry the sediment load it receives from the first two processes. The variables pertinent to this phase include the discharge of the stream, channel cross-sectional characteristics, channel slope, boundary roughness, size distribution of suspended sediment, and average suspended concentration.

To study the sediment yield under a number of different conditions relative to the three problem phases required that eight stations be established on the White Deer Creek stream system as shown in Figure 2. Three of the stations, F, G, and H, were located upstream of the construction area to measure the natural sediment load transported into the reach of the stream affected by the construction.

Four continuously recording rain gauges were located within the drainage basin. Gauge 1 was located adjacent to the construction downstream of the area shown in Figure 2. Gauge 4 was located near the centroid of the basin of the upper branch of the White Deer Creek away from the construction activity. Gauges 1, 2, and 3 had approximately equal spacing along the construction area, negating the necessity of applying weighting factors to the data collected by each.

Series of soil samples were collected from the construction area at random locations. Mechanical analysis and determination of other soil properties for these samples were conducted by project personnel. From these results, approximately 50 percent of the samples were classified in the A-4 group (AASHO classification), and the remainder fell within the A-1-b and A-2-4 groups. The different soils were found throughout the construction area so that the effect of soil erodibility could not be analyzed.

The construction process was divided into several phases: clearing and grubbing, structures, embankment, drainage, and seeding and mulching. The data describing these phases were obtained from the field notes of Pennsylvania Department of Transportation inspectors and were frequently checked by site inspection by project personnel. The clearing and grubbing phase commenced in June 1968 and was completed by mid-April 1969. The bulk of the operation was completed during the summer of 1968 as shown in Figure 3. The field notes compiled the clearing and grubbing progress by highway stations. This longitudinal measurement was converted into area units by scaling widths of cleared area from aerial photographs.

The embankment work began in August 1968 and was completed by October 1969. About one-half of the total fill material was placed during the fall of 1968, whereas most of the cuts were done during the summer of 1969 (Fig. 3). The embankment progress was compiled in the field notes as the number of cubic yards of earth both removed and placed by stations. Thus the cut-and-fill operations were accurately defined as to quantity and location. The structures and drainage work data were compiled but were considered too localized to have a measureable effect on the sediment yield and are not considered in the analysis.

Final grading, seeding, and mulching began in the study area in June 1970 and was completed by August 1970. The field notes described the progress of this phase by stations, allowing accurate definition of the completion of the task. But the transition from freshly seeded and mulched surface to protective vegetative cover is not well defined. Also, some reseeding and touch-up work was performed during and following the major seeding operations, but no record was maintained of this work.

The purpose of selecting five stream stations for sediment yield measurement was to permit the study to consider different conditions of the overland transport phase. Stations B and C, located on Lick Run and Mile Run respectively (Fig. 2), received sediment directly from the construction area with no overland transport. Station D, located downstream of station E on Sand Spring Run, station A, located on White Deer Creek, and station E all received sediment from overland flow, with each having a different average distance from construction to stream. The average slope gradient of the natural ground for each of these three stations was obtained from topography maps but was not considered to be of sufficient variation for consideration in the analysis. The antecedent moisture conditions are a function of time between

Figure 1. White Deer Creek drainage basin.

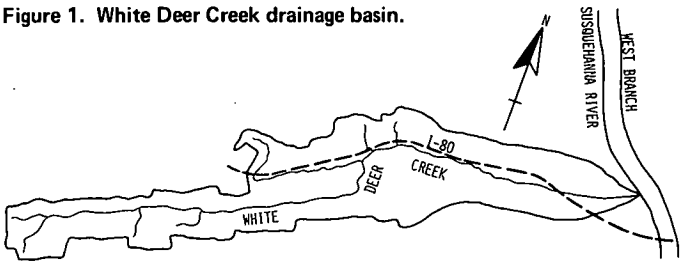


Figure 2. White Deer Creek study area.

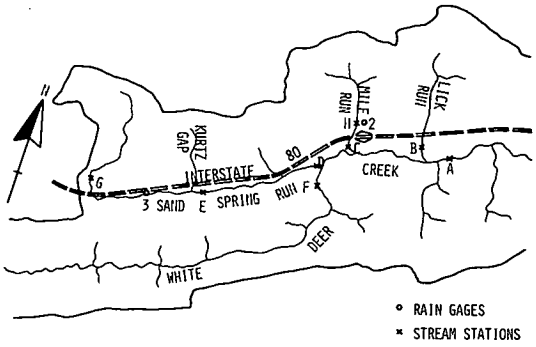
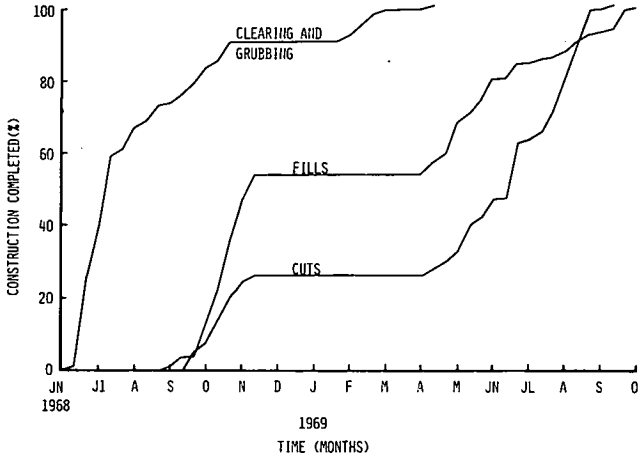


Figure 3. Construction progress.



storms, data available from rain gauges. Because the White Deer Creek drainage basin is entirely wooded, the natural ground cover factor was considered a constant for all stations and was not considered in the analysis.

Visual observations of the channel bottom at many locations in the stream system indicated that there was no accumulation of sediment as a result of the highway construction. For this reason, the only variables that were necessary for measurement of the suspended sediment load were the discharge of the stream and the average suspended sediment concentration at the measuring stations. Continuously recording stage gauges were operated at stations A, D, E, and F to yield the variation of the stage at each for every storm. These stage readings were converted to discharge by employing rating curves that had been developed by an extensive stream gauging program. The discharge hydrographs at stations B, C, G, and H were simulated from those obtained at station D. The suspended sediment concentrations during storm runoff events were obtained from sediment samples collected periodically throughout the event. They were collected with a depth-integrating, hand sampler and analyzed by project personnel. Hand samples at station A were supplemented during the summer of 1970 by samples collected every 30 min during storm events by a stage-actuated, automatic sediment sampler. The suspended sediment yield in tons at each station for each sampled storm was obtained by planimetering the areas under the sediment flow curves. The ordinates of these curves were the sediment flow rates in tons per hour obtained by multiplying the concentrations by corresponding water discharges and the appropriate conversion factor. Sediment flow and water discharge graphs at station A for three storms are shown in Figures 4, 5, and 6.

INDEPENDENT PARAMETER DEVELOPMENT

It was noted in the previous discussion that some variables important to the physical problem of sediment yield from highway construction areas could not be considered in the development of the prediction equation due to conditions in the study area. The soils were found to be relatively uniform and their effect on erosion was considered constant. Certain localized construction phases were considered to have a negligible effect on the net yield in the stream system and were ignored. The slope gradient and the natural cover of the area between the construction and the stream were considered constant in the study area. Because the stream system was apparently capable of transporting the imposed sediment load, the hydraulic properties of the channels and the size distribution of the suspended sediments were not included as variables. The remaining variables mentioned previously were measured, and their effect on sediment yield was analyzed.

Wischmeier and Smith (6) have found that the best single rainfall variable related to soil loss is the product of the total rainfall energy of a storm and its maximum 30-min intensity. They defined a rainfall factor, R, as

$$R = \frac{RE \cdot I}{100} \tag{1}$$

where RE is the total rainfall energy for the storm in foot-tons/acre and I is the maximum 30-min intensity in in./hour. The rainfall occurring during each 15-min increment of each storm for each of the four rain gauges located in the study area was compiled from the respective recording charts. These data were substituted into the equations of Wischmeier and Smith to determine rainfall factors for each gauge.

The total suspended sediment yield is obviously a function of the area of the exposed surface affected by the rainfall. For this study, area A, in acres, was that exposed by the clearing and grubbing phase of the construction. Data describing the condition in the drainage basin of each stream station at the time of a storm were obtained from the compiled construction data.

The slope length and gradient of exposed surfaces have been shown (1) to be of prime importance in soil loss computations. Highway construction is responsible for radical alterations of natural slopes with its cut-and-fill operations. An

attempt to establish a representative slope length and gradient factor for the long, narrow areas over varying terrain common to this construction would be very difficult. Recognizing that side slopes are generally standardized, it was reasoned that average depth D, in yards, of cuts and fills would be a measure of slope characteristics. The transient average depth of embankment work in the drainage basin of each stream station was computed by the equation

$$D = \frac{0.00021\ E}{A} \tag{2}$$

where E is the total volume of earth moved, in cubic yards, and the constant is necessary to convert the area from acres to square yards. The embankment quantity was obtained from the compiled construction data. The minimum value of the average depth, D = 0, occurs after clearing and grubbing have begun but before embankment work is undertaken.

From the discussion of the overland transport phase of the problem and its treatment by the research plan, it remains, for the conditions of this study, to develop a measure of the proximity of the construction area to the stream system. A nondimensional parameter, proximity factor P was rationalized as being an excellent measure of this relationship. It was defined as

$$P = \frac{A_o}{A} \tag{3}$$

where A_o is the surface area between the upslope side of the construction and the stream, in acres. The overland surface area for each stream station was obtained by planimetering highway location plans. The minimum value of the factor, P = 1, occurs when a stream crosses a construction area so that the sediment contribution is direct with no overland flow.

DERIVATION OF THE PREDICTION EQUATION

The objective of this study was to develop a mathematical description of the relationship between the increase in suspended sediment yield in a stream system and highway construction occurring in its drainage basin. Due to the nature of the problem, which defies theoretical analysis, it was anticipated that the relationship would be established by the multiple regression analysis of the data collected in the White Deer Creek drainage basin during the construction of Interstate 80 through it.

The prediction equation to be developed from these data would generally be assumed to be of the form

$$Q_s = K\,R^a\,A^b\,D^c\,P^d$$

where Q_s is the suspended sediment yield at a stream station, in tons, and K, a, b, c, and d are empirical constants. Rational study of the several independent factors permits some modifications of this form of equation. Sediment would be transported by the stream following clearing and before embankment work, when D = 0. It is observed that the model would not satisfy this requirement. Thus, the D^c factor was converted to the form c^D, for a new model. A preliminary plot of log Q_s versus log A, while maintaining the other factors constant, indicated that the relationship was not exponential but approximately logarithmic. Therefore, the A^b factor was converted to the form $(\log A)^b$. Examination of the expected relationships between Q_s and the independent variables shows that Q_s should increase with increasing R, A, and D and decrease with increasing P. Thus, the signs of the exponents a, b, and D should be positive and the exponent of d negative.

The new model equation for relating the chosen variables is rationally of the form

$$Q_s = \frac{K R^a (\log A)^b c^D}{P^d} \tag{4}$$

The multiple regression analysis was performed with the logarithmic transformation of Eq. 4.

$$\log Q_s = \log K + a \log R + b \log (\log A) + D \log c - d \log P \tag{5}$$

Before the regression equation was developed, several special considerations were applied to the data. Some storms were omitted for the following reasons as presented by Brokaw (7):

1. Exclusion of all storms combining rain and snow,
2. Exclusion of those storms with R less than 0.5 foot-ton-in./acre-hour and/or less than ¼-in. of measured rainfall,
3. Exclusion of all storms occurring when the soil was saturated with frost,
4. Exclusion of all storms separated by less than 48 hours, and
5. Inclusion of storms separated by less than 24 hours as one event.

In addition, some storms were omitted due to an insufficient number of suspended sediment concentration values that were necessary for the determination of Q_s.

Rainfall factor values for each storm were generally determined for station A by averaging R values from rain gauges 1, 2, 3, and 4; for station B by averaging R values from rain gauges 1 and 2; for C by using R values from 2; for D by averaging the R values from 2 and 3; for E by using R values from 3; for F by using R values from 4; for G by using R values from 3; and for H by using R values from 2 (Fig. 2).

The measured values of Q_s at the stations affected by the construction were adjusted by subtracting the natural loads as measured at the stations away from construction. For example, the adjusted suspended sediment loads at station E were found by subtracting the measured values at station G from the measured values at station E. Generally, the natural loads measured at stations G and H were insignificant.

Vice, Guy, and Ferguson (5) adjusted their sediment yield data for the seeding and mulching conditions. They assumed that sediment yield was reduced 50 percent upon application and further reduced by 80 percent as a fairly well-established sod cover developed. The sediment data for this study were similarly adjusted beginning with seeding and mulching in June 1970 and continuing until the end of the study period.

Following the noted exclusions and adjustments, the number of sets of data for the various stream stations noted below was available for the analysis:

Station	Data Sets
A	22
B	14
C	12
D	19
E	19
Total	86

A graphical multiple regression analysis was performed with these 86 sets of data using Eq. 5 as the model. The solution was transformed back to the form of Eq. 4, yielding

$$Q_s = \frac{0.034\ R^{1.5}\ (\log A)^{2.45}\ (3.0)^{D}}{P^{0.72}} \tag{6}$$

which was found to have a standard error of estimate of 24 percent. Equation 6 is the prediction method for suspended sediment yield in a stream system from rainfall-induced erosion of soil exposed by highway construction.

DISCUSSION OF RESULTS

The general validity of the relationship developed in Eq. 6 may be questioned relative to the adequacy of the range of independent variable values tested in the field study. Table 1 gives the magnitudes of pertinent parameters for each of the stream stations affected by the highway construction. Wischmeier and Smith (1) have compiled the expected magnitudes of single-storm rainfall factors for representative points throughout the United States. Interpolating from values listed for Pennsylvania to the White Deer Creek valley, the return period for the maximum measured R would be approximately 2 years. The range of exposed area included in the analysis was from 3.3 to 168.75 acres, which would appear to be adequate for general representation. Obviously, larger D values may be encountered at other construction sites, but the range tested in this study, from 0 to 3.2 yd, would include conditions encountered at many locations. Interstate 80 is relatively near White Deer Creek as indicated by small proximity factor values. As the sediment yield decreased with increasing proximity factor, the more important conditions were tested.

Of the four independent variables included in Eq. 6, the rainfall factor has the greatest effect on the sediment yield from the physical problem viewpoint. The magnitude of R will be relatively large, and the exponent value greater than one in the equation indicates its importance. The exposed area and average depth of embankment factors describe the magnitude and intensity of the transient construction activity. As such, they indicate the erodibility potential available to the rainfall factor. Again from the physical problem view, the A term is the most significant with the D factor acting to modify its effect. D indicates the construction activity on an exposed area that must exist first. The three terms in the numerator of Eq. 6 indicate a measure of the quantity of sediment leaving the construction area. This quantity is modified by the conditions that effect the overland transport process. The proximity factor P quantifies the reduction of sediment reaching a stream through this process. It would be a very important factor to the engineer during highway location studies.

The discussion of the overland transport process in an earlier section included the effect of antecedent moisture in the natural ground. Unfortunately, there were not a sufficient number of samples to discern the effect of this variable. It undoubtedly was responsible for some of the scatter that was measured by the standard error of estimate.

The constant coefficient in Eq. 6 includes the effect of the particular type of soil that was found on the construction area in the White Deer valley. To extend the application of this prediction method to other areas, it will be necessary to evaluate the soil erodibility effect. It may be possible to incorporate the soil erodibility factor developed for the universal soil loss equation into the coefficient of Eq. 6. That factor was evaluated so that, if all other conditions are constant, its effect on soil loss was linear. Recent research (8) has generalized the factor for all types of soils. Data are currently being collected at three other drainage basins in Pennsylvania, which should permit the evaluation of the soil erodibility effect.

The constant coefficient in Eq. 6 also includes the effect of the slope gradient and the nature of the cover of the natural ground between the construction area and the stream system in the White Deer Creek drainage basin. The data being

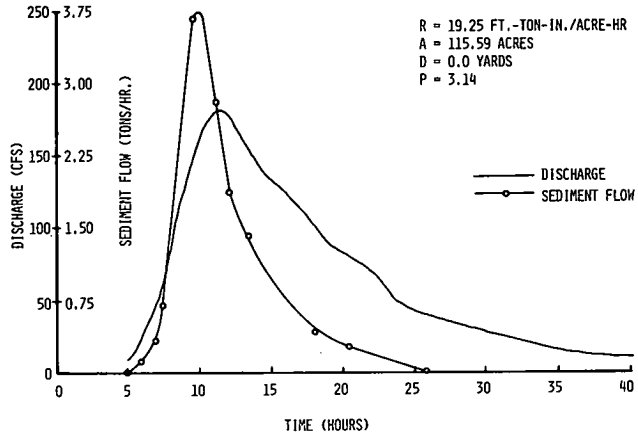


Figure 4. Discharge and sediment flow at station A, September 6, 1968.

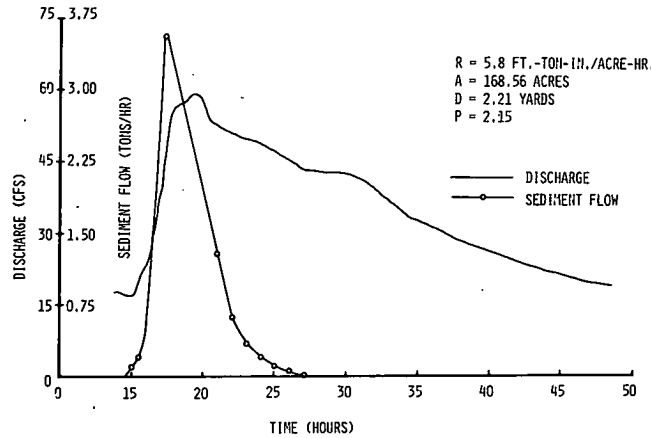


Figure 5. Discharge and sediment flow at station A, August 19, 1969.

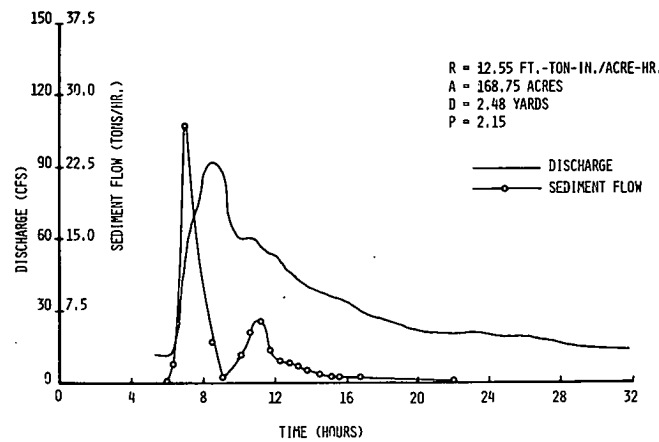


Figure 6. Discharge and sediment flow at station A, August 21, 1970.

Table 1. Extreme parameter values from the study area.

Stream Station	R(ft-ton-in./acre-hour) Maximum	R(ft-ton-in./acre-hour) Minimum	A Maximum (acres)	D Final (yards)	P Final	Highway Length Upstream (miles)
A	24.7	0.70	168.75	2.48	2.15	5.42
B	28.1	2.15	5.95	2.67	1.0	0.28
C	28.1	2.15	4.93	3.2	1.0	0.19
D	21.7	0.58	110.93	2.7	2.16	3.38
E	21.7	0.52	59.65	2.17	1.09	1.75

collected in the other three basins may be utilized to establish the effect of these factors. These areas each have different terrain and land uses from those found in White Deer Creek.

CONCLUSIONS

An equation has been developed that may be employed to predict the suspended sediment load carried by a stream system during the period of rainfall-induced erosion of disturbed soils common to highway construction. Equation 6 considers the effect of the erosive power of the rainfall; the effect of the important construction phase parameters, area of exposed soil surface, and average depth of embankment; and the effect of the proximity of the construction to the stream system.

It may be employed for the prediction of sediment yield from construction areas in other drainage basins if they have soils, terrain, and land use similar to those found in the White Deer Creek valley. The effects of these three factors are contained in the constant coefficient of Eq. 6. Evaluation is currently being undertaken by similar studies in three additional drainage basins.

Highway development often occurs in conjunction with the construction of housing developments, shopping centers, factories, and other urban expansions. These sites are often blamed for the pollution of adjacent waterways with highways receiving the brunt of the accusation. This equation may be used to define the portion of the sediment yield caused by the highway construction. An engineer may establish the location of a proposed highway in a drainage basin for minimum sediment yield by application of Eq. 6. Increasing the distance from a stream increases P but would usually increase D, due to rougher terrain. An optimum location, from the sediment yield aspect, could be found. Sediment control on construction sites is receiving increasing attention. Equation 6 was developed for the condition of uncontrolled construction and thus could be used as the basis for comparison to evaluate the effectiveness of control methods.

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R. C. BARNES, JR., Soil Conservation Service,
Washington, D. C.

EROSION CONTROL STRUCTURES

Erosion and excess runoff are products of many factors: soil type, plant cover, cropping practices, climatic zones, rainfall amounts and intensities, and degree and length of slope to name a few. Water erosion usually occurs as sheet erosion, which is the periodic removal of thin sheets of soil over an area, or as gully erosion that forms incised channels. The end product is sediment. It is in the construction stage that natural conditions such as topography, natural cover, soil conditions, and drainage patterns are being disrupted due to manipulations by man and machines. It should be the goal of each design and construction engineer to control these results within reasonable limits during the construction stage and finally to permanently stabilize the area for control of erosion and runoff upon completion of the job. There are a number of basic principles for controlling runoff and erosion that have proved sound over the years for other land uses and that can prove to be just as useful for highway construction. These include such things as proper attention to soil, foundation, and topography in site selection; minimum exposure of bare areas by control of clearing and grading operations; diversion of water away from critical areas; flattening slopes; reducing slope lengths; use of temporary cover; and control of equipment access and travel ways. A number of structural measures are discussed that may be used as either temporary or permanent installations. These include such things as grassed or paved waterways, buried pipe outlets, diversion terraces, benches, various types of grade control structures, retarding structures, chutes, inlets, and debris basins.

The techniques of controlling water erosion both during and after construction are generally well known and have been well proved for other land uses. These can include both temporary and permanent measures. The basic principles and some of the physical structures for erosion control that may be adapted to highway construction are presented here.

Erosion involves the movement of soil particles by water and wind. It is the result of many factors, the most important of which are soil type, plant cover, climatic zones, rainfall amounts and intensities, degree and length of slope, and conditions brought about by man's activities.

Water erosion of land surfaces is of two types, sheet erosion and gully erosion. Sheet erosion is the removal of thin sheets of soil over an area. Gully erosion is that that forms incised channels. These may vary in size from small rills that can easily be obliterated to those large enough to seriously affect project costs.

The end product of erosion is sediment. This can fill road ditches; cover road surfaces; pollute and fill rivers, streams, and lakes; increase costs due to damage to the construction site; and degrade the aesthetics of the area.

Projects are most vulnerable to these ravages of nature during the construction period. It is in this stage that rapid changes are being made in natural

conditions, such as vegetative cover, topography, soils, infiltration, and drainage due to manipulation by man and his machines. It should be the goal of each design and construction engineer to control these changes within reasonable limits. This will involve protecting the area during the construction stage and permanently stabilizing the area to control erosion and runoff as the final step in completing the job. Needless to say, it must be recognized where problems will occur, and plans must be made in advance to overcome them. This may require a hard sell directed to those responsible for project planning, design, and construction. It must also be recognized that needed erosion control measures may significantly increase project costs.

There are a number of basic principles for controlling runoff and erosion that have been proved sound. Attention must be given to soil and foundation conditions in route selection, design, and construction. Soils with severe limitations for this particular use, if they cannot be bypassed, will require special attention. Local Soil Conservation Service (SCS) offices will usually have soil survey data and interpretations for use on most areas where new roads are being planned or old ones being reworked.

Erosion problems can be reduced by making the best use of topography. For example, erosion problems may be decreased by site location along the contour rather than up and down the slope.

Drainage patterns and conditions are important. Problems usually increase in about the same proportion as disruption in natural drainage patterns. Subsurface drainage problems should be anticipated inasmuch as they will influence slope stability, drainage needs, construction methods, and finally the success of stabilizing the area with vegetation.

Consideration needs to be given in the planning stage to the effect of the road on existing erosion control and water management systems and, conversely, the effects these systems will have on the road project. Most farmland will have some type of conservation system already installed. These may involve things such as terraces, waterways, drainage ditches, or irrigation pipelines and canals.

Other basic principles include clearing and grading to reduce areas and time of exposure, handling excess water generated by the operations, reducing degree and length of slopes, and control and routing of equipment.

TYPES OF STRUCTURES

There are a number of structural measures that may have a place either as temporary or as permanent installations. These include diversions, grassed or paved waterways, buried pipe outlets, bench terraces or berms, numerous types of grade control structures, chutes, inlets, retarding structures, debris basins, and others.

For some of these measures, where and how they may be used and location and design criteria will be discussed. For most of these the SCS has handbooks and standards that cover design criteria and procedures (1).

Diversions

Diversions are designed, graded channels with a supporting ridge on the lower side, constructed across the slope. Their purpose is to intercept surface or subsurface water and to lead it to an outlet where it can be safely disposed of. These structures may be temporary or permanent and graded or level. Graded terraces move water in a planned direction at a nonerosive velocity; level terraces have closed ends and retain the runoff.

Diversions are useful above cut slopes, borrow areas, and gully heads. They can be constructed across cut slopes to reduce slope length into nonerosive segments and can be used to move runoff water away from critical construction sites. They may be built both on and off site.

Diversions should be located so that water will empty in established disposal areas, natural outlets, or prepared individual outlets. Individual outlets may

be designed grassed or paved waterways, chutes, or buried pipe. Diversions should be designed to handle runoff from a 10-year frequency rain.

Berms

Berms are steps or benches in steep slopes. They are modifications of and serve about the same purpose as diversions. Properly located and designed, they reduce slope lengths and divide the volume of runoff water into workable slugs that are more easily handled. Capacity to carry the volume of water is obtained by grading the berm so that the outside edge is higher than the edge adjacent to the cut slope. Runoff water may be removed from the berm by use of paved waterways or buried pipe.

Waterways

Waterways serve as outlets for diversions, berms, or other structures. They may be natural or constructed, shaped to required dimensions, and vegetated or paved for disposal of runoff water. Usually they are constructed to one of three general cross sections: parabolic, trapezoidal, or V-shaped. Where they are to be vegetated, parabolic waterways are the most commonly used. This is the shape ordinarily found in nature.

Successful function of a waterway depends on protection from erosion. This can be done by designing for flow velocities that are nonerosive for the grass that will be used or by paving with concrete or rock. Waterways should be designed to carry runoff from a 10-year frequency rain, as a minimum.

Pipe Outlets

Pipe outlets also may be used to remove water from diversions and berms. If the retarding principle is used, which is to design to empty the structure in a 24- to 48-hour period, a small-diameter pipe may be used. The SCS uses a perforated vertical riser to get the water into the pipe. An orifice plate is designed for the bottom of the riser so that channel rather than pressure flow is maintained in the pipe. The advent of corrugated plastic pipe has made installation rather simple. Pipe outlets are designed to remove runoff volume from a 10-year, 24-hour storm, as a minimum. This may be removed in a 24- to 48-hour period depending on conditions.

Retarding Structures

Retarding structures consist of an earth embankment, a principal spillway, and an emergency spillway. They may be constructed on or off site. Their purpose is to store runoff temporarily, releasing it at a slow rate to protect the area below. They can reduce runoff peaks, permitting use of smaller culverts and bridges. When they are constructed on site and fill is used for the roadbed, they can eliminate bridges and may reduce costs. Because, in any one of the structures, there are numerous community benefits—flood prevention, grade control, and water for livestock, recreation, and irrigation—cooperation from local people and organizations such as soil and water conservation districts is very good. A number of state highway departments have memorandums of understanding with their conservation agencies that encourage this type of cooperation.

The principal spillway usually consists of a reinforced concrete riser and a horizontal pipe or monolithic concrete outlet through the earth fill. It is usually designed to empty the retarding storage area in 10 days or less. The emergency spillway, as a minimum, should handle the routed runoff from a 25-year frequency storm or from a storm with a frequency equal to the design life of the structure, whichever is greater.

The retarding storage should be able to contain the runoff expected to occur at a frequency consistent with the level of protection to be provided.

Grade Stabilization Structures

Grade stabilization structures stabilize grade or control head cutting in natural or artificial channels. They reduce channel grade and flow velocity and literally step runoff water down a slope at a controlled velocity. Grade stabilization

structures may consist of earth embankments with pipe spillways or mechanical structures of concrete, masonry, steel, aluminum, or treated wood. Design depends on site conditions, but ordinarily these structures should handle runoff from a 25-year frequency storm.

Mechanical Structures

Mechanical structures retain, regulate, or control the flow of water. They have a place in grade stabilization and in retardation. Most structures are made up of four major parts: earth embankment, spillway inlet, spillway conduit, and spillway outlet. The three principal types of mechanical spillways are drop, drop inlet, and chute.

The embankment directs the flow of water through the spillway. The embankment for a drop spillway or chute generally extends from the spillway to high ground or to a vegetative spillway. In a detention pond, the embankment detains and impounds water as well as forces storm flow through the spillway.

Water enters the spillway through the inlet, which may be in the form of a box, a weir in a wall, or a culvert. The box may be straight, flared, or curved. The culvert entrance may be round, square, or rectangular, with a square edge, hood, or flared entrance.

Vertical walls extending into the soil foundation under the inlet are known as cutoff walls. Their main purpose is to prevent water seepage under the structure. Similar walls extending laterally from the inlet to prevent seepage and erosion around the ends of the structure are called headwall extensions.

The conduit receives water from the inlet and conducts it through the structure. The conduit may be closed in the form of a box or pipe or open as in a rectangular channel. Cutoff walls or antiseep collars are usually constructed as a part of the conduit to prevent seepage along its length.

Water leaves the structure through the outlet, which discharges water into the channel below at a safe velocity. The outlet may be a cantilever (propped) type, a plain apron outlet, or an apron with any type of energy dissipator to minimize the erosive effect of the discharge. Vertical walls known as toe walls extend below the front of the apron to prevent undercutting. Wing walls are vertical walls extending from the outlet into the channel banks to protect against the swirling effect of the water as it leaves the structure. Types of spillways are given below.

Straight Drop Spillway

The straight drop spillway is a weir structure in which flow passes through the weir opening, drops to a level apron or stilling basin, and then passes into the downstream channel. It may be constructed of reinforced concrete, rock masonry, sheet steel piling, timber, or prefabricated metal.

Box Inlet Drop Spillway

A box inlet drop spillway is a rectangular box open at the top and downstream end. Runoff directed to the box and headwalls enters over the upstream end and the two sides. The flow drops to an apron and leaves through the open downstream end. An outlet structure is attached to the downstream end of the box.

Drop Box Culvert

The drop box culvert is a rectangular box inlet drop spillway placed at the upstream end of a culvert. It may be built as an integral part of a new culvert, or it can be fastened by dowel bars to the upstream headwall of an existing culvert. This is an excellent device for reducing channel grade.

Concrete Chute Spillway

The concrete chute spillway is an open channel with a steep slope in which flow is carried at supercritical velocity. It usually consists of an inlet, a vertical curve section, a steep-sloped channel, and an outlet. Most of the drop in water

surface takes place in a channel. Flow passes through the inlet and down the paved channel to the floor of the outlet.

Formless Concrete Chute

The formless concrete chute is a spillway constructed of concrete without special forming. The earth subgrade is excavated to the dimensions and contour of the structure. Concrete is placed against the subgrade to the depth required and troweled into shape.

Sod Chute Spillway

The sod chute spillway is a steep, sodded section of a water course constructed to conduct the design flow at a safe velocity. It is adapted to small drainage areas and sites where good, dense sod can be developed and maintained. When the channel below the chute is narrow or conditions at the lower end are not favorable for establishment of vegetation, a toe wall drop spillway should be used. The toe wall raises the end of the sod chute above the unfavorable conditions, such as poor soil or wet or rocky conditions, and permits maintenance of a good sod.

Drop Inlet Spillway

A drop inlet spillway is a closed conduit generally designed to carry water under pressure from above an embankment to a lower elevation. It may be constructed of monolithic concrete or of pipe. Metal pipe drop inlet spillways and sod chutes are ordinarily designed to handle runoff from a 10-year frequency storm. Those of concrete are ordinarily designed to handle flow from a 25-year frequency storm. More complex or expensive structures may be designed to handle a 50- to 100-year frequency flow.

Debris Basins

The debris basin is a structure that temporarily detains runoff water carrying heavy loads of silt, sand, or gravel. It usually consists of an earth embankment and a perforated pipe principal spillway. Runoff water slows upon entering the impoundment. A large part of the debris settles out, and the water is automatically drawn out through the principal spillway. The structure should be designed to store the expected debris yield for the life of the structure, or provisions should be made for periodic cleanout. Debris basins may be permanent or temporary. Those to trap debris generated by construction are usually temporary and are removed once the job is completed and the area stabilized.

CONCLUSIONS

Erosion and sediment production both during and after construction can be controlled. Control must be planned in advance. Some of the structures discussed may be used either as a part of the main water disposal system or to stabilize side drainage entering the road system. A number of state and local highway departments are finding some of these principles and measures useful, especially on secondary and rural road systems.

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JOSEPH W. TURELLE, Soil Conservation Service,
Washington, D.C.

FACTORS INVOLVED IN THE USE OF HERBACEOUS PLANTS FOR EROSION CONTROL ON ROADWAYS

Roadway construction annually reshapes thousands of acres of land in the United States. High rates of soil loss and resulting sediment yields from construction sites have caused a serious erosion problem. Although an excellent job is being done to stabilize and beautify Interstate and primary highways, secondary roads remain a problem. Numerous soil materials are being exposed that commonly have physical and chemical properties unfavorable to plant growth, thereby making roadway stabilization difficult. The basic principles for establishing vegetation are presented along with a recommendation that, where feasible, slopes steeper than 3:1 be flattened. Various planting methods and requirements for selecting plant species are discussed, emphasizing the necessity for mulching and maintaining established vegetation.

Soil management, soil and water conservation, landscape engineering, and plant ecology are all essential for controlling erosion and sediment on road construction sites. Thousands of acres of land in the United States are being reshaped annually by roadway construction. High rates of soil losses and subsequent sediment yields from these construction sites often cause serious problems. There is a high risk of runoff and erosion associated with major land modification, and, even when road builders are concerned, they may not be aware of the magnitude of soil losses. On highway cuts, annual losses of up to several hundred cubic yards per exposed acre were measured by Diseker and Richardson (1). Barnett, Diseker, and Richardson (2) measured 62 percent runoff and soil losses of almost 85 cu yd/acre from a single storm of 2.7 in. of intensive rainfall on a bare 2.5:1 highway cut.

An excellent job is being done in stabilizing and beautifying Interstate and primary highways, but much remains to be done on secondary roads. In one state there are 12,000 miles of secondary roads that need erosion control work. In another state there are 9,000 miles that need treatment. The need to stabilize secondary roads is urgent. Perhaps state highway departments and other agencies with a common interest should concentrate on this problem.

The Soil Conservation Service (SCS) can help solve these problems. It provides technical assistance in soil, water, and plant conservation through conservation districts (CDs), which are legal subdivisions of state governments. Boards of supervisors or directors of CDs are elected and are responsible for leading and coordinating the use and management of land, water, and plant resources within the district boundaries. These districts may be called soil conservation districts, soil and water conservation districts, or natural resources districts.

SCS technical assistance is available to any unit of government or group undertaking roadside stabilization projects. SCS specialists assist with detailed

erosion control plans based on scientific research and field experience. Alternative treatments are often suggested in the development of such plans. These technical assistance procedures are sometimes supplemented with more detailed agreements between interested groups. Examples of such agreements follow:

1. Memorandums of understanding between SCS and state highway departments—Such agreements are currently in effect between SCS and state highway departments in Oklahoma, Kansas, Montana, and many other states. The objective of these agreements is to have SCS furnish technical assistance in developing erosion control and pollution abatement plans on designated sections of federal-aid primary and secondary highway projects.
2. Project measure work plan agreements such as that between the Washington County soil and water conservation district in Ohio, the Washington County Commissioners, and the SCS—This plan covers roadbank seeding in the Buckeye Hills Resource Conservation and Development Project.
3. Cooperative technical agreements between SCS, CDs, and state highway departments—Agreements of this kind exist in New Mexico.

There are numerous examples where CDs, SCS, and highway departments are working together to stabilize and beautify highway corridors.

SOIL FEATURES AFFECTING ROADWAY STABILIZATION

Numerous kinds of soil materials are exposed during highway and road construction. They are formed from many different materials including glacial deposits, alluvial deposits, limestone, granite, gneiss, shale, sandstone, loess, and so on. These soil materials commonly have unfavorable physical and chemical properties and features such as steep slopes, south and west exposures, shallowness to rocks, high acidity or alkalinity, infertile subsoils, poor soil structure, high bulk density, slow aeration and permeability, shrink-swell potential, high clay or sand content, instability, low organic matter, and erosion susceptibility. The variations in parent materials and soil properties often adversely affect plant growth, making roadway stabilization difficult. These and other interacting soil features operate simultaneously to ensure the success or failure of establishing vegetation on roadside cuts and fills.

Soil surveys furnish much information on the extent of these interacting features. Such surveys have been made and published by USDA for more than 70 years. SCS has the federal leadership for making soil surveys, which include soil mapping, and has published them for about 2,000 counties and areas. Soil surveys and mapping are being prepared or updated in more than 3,000 soil conservation districts in the 50 states, Puerto Rico, and the Virgin Islands. Detailed soil surveys and maps are not yet available for all counties but less detailed soil surveys and maps are available and can be helpful in making soil interpretations of a general nature. SCS, working with the more than 3,000 soil conservation districts, usually has some kind of soils information available.

PREDICTING SOIL LOSSES

In the 19th century, the noted British scientist, Lord Kelvin, made the statement (3): "If you can measure that of which you speak, and can express it by number, you know something of your subject; but if you cannot..., your knowledge is meager and unsatisfactory." This axiom can be applied to soil losses on roadway construction sites. Such losses can be predicted by using the empirical universal soil loss equation or, as it is often called, the rainfall erosion equation. This formula was developed by the Agricultural Research Service and many state experiment stations in cooperation with the SCS. SCS has been using this formula in 37 states east of the Rocky Mountains for over 15 years to estimate soil losses on farmland. It provides the basic data for scientific farm planning for soil and water conservation, showing those factors that cause loss of soil by water and those that help to reduce such losses.

Estimated soil losses on construction sites can also be made by using the universal soil loss equation. The main advantage in its use on construction sites is to make a reasonable estimate of soil losses at a given location prior to actual construction. Such predictions may influence the degree of planning and treatment required for proper control of erosion. Soil losses on a construction site may be predicted for a whole or part of a year, or they may be predicted on the basis of "probability" storms and magnitudes of single storms.

The universal soil loss equation takes into account rainfall intensities (maximum 30-min intensity storm x kinetic energy of the storm), erodibility of soil, length and steepness of slope, supporting conservation practices, and vegetative ground cover (4).

Another equation has been developed to predict soil losses by wind erosion. This equation considers susceptibility of a given soil to movement by wind, soil surface roughness, climate (wind velocities, temperature, and soil moisture), maximum unsheltered distance along prevailing wind erosion direction, and the kind, quantity, and orientation of vegetative cover (5). Again, a predicted soil loss by wind can influence the degree of planning and treatment required for control of erosion.

HERBACEOUS PLANT ESTABLISHMENT

Principles and Criteria for Establishing Vegetation

We have already mentioned that highway construction may expose many soil properties and features unfavorable to plant growth such as subsoil and substrata materials that are infertile, steep, weakly structured, droughty, poorly aerated, and low in organic matter. Such conditions, if possible, need to be corrected.

Plant species that will suit climate, site conditions, and purpose of plantings must be used. It is also necessary to adhere to other general principles such as preparing a stable seedbed so seed and seedlings can remain in place long enough to grow; applying needed fertilizer, lime, or other soil amendments; using proper planting techniques; and covering the surface with mulch. Other considerations are to grade down to flatter and shorter slopes, if possible, and to spread topsoil when economically and technically feasible. Always avoid leaving land bare longer than absolutely necessary. Until permanent seedings can be made, seed fast-growing, temporary vegetative cover with or without a mulch or use mulch only. Mulching material may be vegetative or synthetic. Practice selective clearing by sections. Control water with interceptor ditches, grassed waterways, drop inlets, and the like.

Slope Stabilization for Establishing Plants

Cuts and fills are inevitable accompaniments of highway construction. These slopes present many erosion hazards and soil stabilization problems. Unless the surface is protected with vegetation or some form of mulch, considerable soil loss occurs from rainfall, flowing runoff water, or wind. Steep slopes make the establishment of vegetation difficult. Best slopes for seeding herbaceous plants and legumes, with tractor-drawn equipment are 3:1 or flatter. Slopes that are steeper than 3:1 may require hydroseeders, mechanical mulchers, or hand labor.

Vegetated slopes often need help from structural or mechanical practices, which may include retaining walls, protected outlets for water, diversions, berms, terraces, downspouts, ditch lining, furrows, and internal drainage facilities. Unstable soils will cause a vegetated slope to slip.

Topsoiling for Plant Establishment

Topsoiling is an expensive practice that should be used only when topsoil is readily available or stockpiled for respreading at the appropriate time. Topsoiling is usually required when soil material exposed for seeding is of extremely poor quality.

A study of soil profile characteristics should be made to determine the need for saving existing topsoil or bringing it in from an outside source. Many subsoils have desirable physical properties although they may be low in fertility. Satis-

factory stands of vegetation are usually obtained on such subsoils by applying sufficient amounts of fertilizer, soil amendments, and mulch. Critical soil areas, however, may need special care and management to maintain satisfactory plant cover.

The use of topsoil may be justified if the soil is extremely permeable, very fine textured, poorly aggregated, highly acid or alkaline, or very shallow and underlain with impervious layers. Care must be exercised in the latter case inasmuch as topsoil, when saturated, will slide. When topsoil is used, it should be friable and loamy in character. It should be capable of producing good stands of grasses, legumes, or other kinds of vegetation. A pH range of 5.0 to 7.5 is most desirable, and soluble salts should not exceed 500 ppm. A soil survey, incidentally, will often rate soils for topsoiling qualities.

Selection of Plant Species

The ability of a plant to grow in a given environment is mostly dependent on its inherent characteristics and its growing needs. There are numerous requirements that need to be considered in selecting species for highway stabilization. These include the plant's capabilities to fulfill the purpose of the planting; geographical, soil, and climatic adaptations; growth habits and longevity; ability to spread; pH, altitude, and winter-killing potentials; cool- or warm-season growing characteristics; susceptibility to drought or wetness; tolerance to inundation, shade, and traffic; seed dormancy properties; ability to grow on steep slopes; rate of growth; need to use hulled or scarified seed; hard seed content; inoculation requirements; needed level of maintenance; and aesthetic qualities.

Herbaceous plants that should not be overlooked for roadside stabilization are the native grasses. SCS plant materials centers and cooperating state experiment stations have developed improved strains of these grasses, and seed for most of these strains is available.

Two advantages of using native species are lower maintenance requirements and costs. These kinds of grasses need little or no fertilizer. They are competitive with weeds and are long-lived plants.

Techniques in Establishing Plants

Herbaceous plants are established from seed, planting stock, sprigs, or sod. Seeding is much less expensive than other planting methods. Commonly used methods of seeding highway construction sites are grass/grain drills; cultipackers or corrugated rollers with grass seeding attachments; hand-operated cyclone seeders; truck-mounted broadcast seeders; and hydroseeders.

The use of plant crowns, clones, or plugs for plant propagation is usually expensive because of higher costs of plant materials and increased labor required for planting. These methods are seldom used but may be feasible on hard-to-get-to sites.

Sprigging is used to propagate stolon herbaceous plants. Sod of stolon grasses is lifted, chopped, or shredded to provide sprigs 6 to 8 in. long. These are set promptly in well-prepared, moist seedbeds. Caution must be used to prevent drying or heating between lifting and planting.

Sodding is done in three possible ways: spot, strip, or solid. Spot sodding is planting small pieces of sod at more or less regular intervals; plants will grow and fill in blank spaces. This method is practiced with plant species that spread rapidly. Strip sodding, which is often done on slopes, is the laying of parallel strips at prescribed intervals. Spaces between strips may be seeded or sprigged to hasten complete ground cover. Solid sodding is complete coverage of an area. This method is used when immediate surface protection is required on critical areas such as drop inlets, grassed waterways, and steep slopes.

Soil acidity, salinity, and low fertility levels are common limiting factors in establishing plant cover on highway construction sites. Soil tests can identify these conditions, and corrective amounts of lime, soil amendments, and fertilizer can be applied. In the absence of soil tests, general recommendations used in the local area may suffice for applying these ingredients to the soil.

Mulching

Mulching is necessary in establishing plants on construction sites. Mulch protects soil, seed, and fertilizer from erosion by wind and water and markedly affects the microclimate and moisture relations in the soil by reducing extremes in moisture supplies and temperatures. Conditions under mulch are more uniform and favor germination and more rapid establishment of seedings. Mulch is essential if a proper seedbed cannot be prepared, if seeding is made outside commonly accepted seasons, if soil is highly erodible, or if slopes are steep.

Mulch should be applied uniformly and held in place by proper anchoring. Anchoring should be done simultaneously with the application of the mulch, or immediately after mulch is spread. Anchoring methods vary and include the use of tractor-drawn implements such as disk types of machines, cultipackers, sheepsfoot rollers, or pick chains; hydromulcher combined with asphalt emulsions; pegs, staples, or twine; and punching or slitting mulch with a square-edged spade. Common types of mulch materials are hay, small grain straw, wood chips or wood-based mulches, jute matting, cotton and paper netting, fiberglass netting, plastics, rubber compounds, polymers, and asphalt products.

Much research has shown that vegetative mulches such as straw or hay are very effective in reducing erosion and runoff on steeply sloping soils. The results of one study of a plot of Fox loam on an unplowed, 15 percent slope 10.7 m long are given in Table 1 (6). (The mulch rate and soil loss rate are given in metric-tons per hectare.)

Grassed Waterways or Outlets

Vegetation-lined waterways are used on construction sites to carry runoff water safely to a disposal point. The vegetation serves a dual purpose: It keeps down the speed of flowing water, and it provides a liner to protect the waterway from eroding.

In selection of grasses for a waterway lining, those that germinate quickly and grow rapidly are desirable. Early establishment of a complete grass cover is important. The most critical period for a waterway is during grass establishment. Rains may cause rilling of waterway bed and wash out seeds and seedlings. Sod grasses are preferred to bunchgrasses for waterway linings because the dense and uniform sod reduces turbulence of the water. Grass in a waterway should withstand bending and beating by flowing water without breaking. The grass plant should recover its normal growing position after the flow or it may rot in the waterway bed. The grass should also withstand some sedimentation. Under some conditions, soil is deposited in the channel, so established grass should be able to grow up through a layer of sediment that is not excessively thick. Grasses in a waterway may be established by sprigging or sodding. These are more expensive methods of lining a waterway, but the control is expedited.

If a new waterway is to be constructed and soil material left after construction is not suited for planting, topsoil should be stockpiled and replaced uniformly over the surface when the channel is completed. Mulch or netting over a heavy seeding will help protect the newly graded waterway from splash erosion and excessive runoff. Solid sodding down the center of a new waterway may retard cutting of the waterway bed during the grass establishment period.

Table 1. Effect of straw mulch rate on erosion rate and runoff velocity.

Mulch Rate (MT/ha)	Soil Loss (MT/ha)	Runoff Velocity (cm/sec)
0	62.3	13.9
0.56	20.1	7.1
1.12	19.4	6.9
2.24	11.5	5.6
4.48	2.5	–
8.96	1.5	–

Irrigation for Plant Survival

Water is essential to plant growth. In some regions, such as humid areas, plants will grow satisfactorily without irrigation because necessary soil moisture is supplied by rainfall. In other regions, during some years the rains may supply water needed by plants, but during other years this source is not

adequate. Where low rainfall is common, it may be necessary to apply irrigation water to ensure plant growth and vigor.

Maintenance of Plants

Establishing herbaceous plants on highway construction sites is only the beginning of the stabilizing process. The growth must be vigorous, dense, and visually pleasing for many years after construction is concluded. It is usually less costly to carry on a maintenance program than it is to make repairs after an extended period of neglect.

Maintenance should be consistent with favorable plant growth, kind of soil, and climatic conditions. This involves regular seasonal mowing, fertilizing, liming, watering, fire control, weed and pest control, reseeding, and timely repairs. It also requires prompt removal of debris, protection of vegetation from unintended uses or traffic, and special attention to critical areas. Well-maintained plants provide a comfortable margin of reserve that will carry through emergencies. A preventive maintenance program anticipates requirements and allows the accomplishment of work when it can be done with least effort and expense.

Mowing may be necessary once or twice a year to prevent erosion, eliminate fire hazards, and promote safety. The use of growth regulators is becoming more and more publicized. Some of the advantages attributed to this practice are reducing the frequency of mowing, cutting down on volume of clippings, reducing labor requirements, lessening fire hazards, and reducing potential for vehicle accidents.

A major input to proper maintenance is periodic fertilization for improving vegetative cover quality and function. Field observations indicate that a rate similar to that used for the establishment of vegetation can be applied once every 2 or 3 years. There is also evidence to indicate that a slow-release source of nitrogen fertilizer is more advantageous than rapid and highly soluble sources.

The importance of establishing and maintaining high-quality vegetation is reflected in vigorous plants, continuous development of extensive root systems, sustained functional qualities, and an overall gain in aesthetic properties.

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J. D. PETERS, U.S. Air Force
F. S. ROSTLER and B. A. VALLERGA,
Materials Research and
Development, Inc.

PROMISING MATERIALS AND METHODS FOR EROSION CONTROL

Laboratory studies and field tests initiated by the U.S. Air Force resulted in the selection of a family of products and a method of application for combating surface erosion. The main objectives of the investigation were to devise a system of methodical erosion control on Air Force installations and to formulate acceptance specifications based on standardized testing procedures for materials to be used with the system. Although many attempts have been made to find products to correct wind and water damage to natural soils, the present study was directed toward forestalling damage to all types of ground surfaces existing on Air Force installations. Erosion on and around air fields is created not only by wind and water but also by many other forces such as downdraft from aircraft (which is considerably more severe than natural winds), vehicular traffic, fuel spillage, and other man-made causes. The main emphasis of this study was on prevention of erosion rather than a cosmetic treatment of damage caused. In realization of the fact that no single product or treatment can serve all purposes of erosion control but that, on the other hand, logistics requires a simple procedure and a minimum of different materials, an effort was made to find products that, even if used for different effects, could be applied in the same manner, either by themselves or in combination. Another objective was to treat the existing soils as integral parts of the erosion-resistant surface rather than to cover the soils by a protective coating. In other words, soil modification was the objective rather than a "Band-Aid" approach to damaged soils. The products found to satisfy these requirements are emulsions that have characteristics such as a similarity of emulsification systems and common ingredients that make them mutually compatible. The main difference between the products is that they were developed to be combined with specific forms of soils, i.e., rock, gravel, sand or fine particles in loose form or embedded in artificial surfaces such as pavements. The paper describes properties, applications, field experience, and tentative specifications and testing procedures devised for Air Force use. Data, photographs, and case histories are presented to illustrate that the products selected constitute very promising materials for fortifying earth surfaces against the widest variety of forms of erosion.

Erosion control is a branch of geotechnics, the science dealing with enhancing the utility of the earth's surface. Geotechnics is defined in Webster's Dictionary as the applied science of making the earth more habitable. In its broadest

definition, erosion control encompasses all measures employed to combat the effects of wind, water, and mechanical forces of traffic on natural and man-made surfaces. Environmental conditions such as temperature fluctuations and exposure to sunlight affect the severity of attack by wind, water, and traffic. The type of erosion control is dictated by purpose, e.g., military, agricultural, or industrial, and severity of forces causing erosion. The erosion forces to be controlled are more severe on and around airfields than for instance in agricultural areas because, besides wind and rain, there are additional man-made forces such as downdrafts from helicopters and direct air blasts from aircraft, fuel spillage, and vehicular traffic by a diversity of equipment.

In an academic sense, the surfaces to be protected from erosion range from open fields and painted surfaces, e.g., traffic signs, to various engineering structures such as pavements and bridges. The area of this study was limited to soil erosion; however, the study was broadened to deal with all soils including rock, gravel, sand, and fine particles such as silt and clay, in loose form or embedded in artificial surfaces such as pavements.

Natural forces are the main powers of erosion. All surfaces of the earth are attacked and shaped by these forces. Examples of erosion on natural surfaces by natural forces are shifting of sand dunes and erosion of shore lines that should be contained by man for benefit to man. Man is concerned with controlling these natural phenomena to enlarge areas of habitation.

Dust, the result of wind erosion, is an ecological problem and at times and in some areas is the largest pollutant of our air. Dust resulting from faulty agricultural practices and inconsiderate construction practices must be held to a minimum for general ecological reasons. For military purposes dust must be controlled because of interference with visibility and damage to aircraft and airfield installations as well as its adverse effect on health. As pointed out, the work reported here was initiated by the Air Force for Air Force purposes, but the facts developed are of utility for all interested in methodical and standardized methods of erosion control.

TECHNOLOGICAL BACKGROUND OF STUDY

Available information on erosion control is voluminous but scattered through various disciplines. No single textbook is available that contains all the essential information an engineer responsible for erosion control would like to have, but there are some outstanding basic textbooks. Bagnold (1) is the most comprehensive book dealing with the action of wind on soils, particularly sand; Winterkorn (2) presents a concise discussion of soil stabilization as it pertains to civil engineering and improvement of soils as foundation and construction material; Stallings (3) deals primarily with agricultural questions, but his book contains a wealth of general information and references to work by Chepil, Woodruff, Zingg, and many other workers in this field. Sherard et al. (4) deal with engineering problems in design and construction of safe and economical structures built from natural soils and rocks. Lambe (5) presents in laboratory manual form a description of basic soil testing procedures and explains the significance of the tests. Hottenstein (6) in a paper describing current practices in erosion control along highways discusses extensively the use of turf for soil protection. In reference to emulsions, he made the statement that they are too new to permit a complete evaluation at this time. Publications originating from the U.S. Army Engineers Waterways Experiment Station are another source of information on testing methods and use of various products. The periodical Soil Conservation published by the U.S. Department of Agriculture is most informative on current problems and new developments.

The purpose of this study was to explore available concepts and to recommend materials that can be used routinely and methodically for control of all types of erosion on Air Force installations.

A previous study performed for the Corps of Engineers had established that emulsion products are most convenient to use in all types of applications and that a spray-on application is adaptable to use in nearly all cases (7). Large-scale use of an emulsion product in conjunction with planting of vegetation was performed in

1959 at Vandenberg Air Force Base (8, 9). The results achieved are described and shown later in the presentation of case histories. Based on this experience, rational considerations, and logistics, the following guidelines were established from the outset of the study, stipulating that the material to be used should be

1. A liquid that combines with the surfaces to be treated forming erosion-resistant surface layers to the depth likely to be disturbed,
2. Usable in spray-on applications,
3. Noncombustible,
4. Capable of being combined or fortified with other liquids to satisfy the widest possible requirements,
5. Commercially available at reasonable cost, and
6. Defined by characteristics determinable in standardized testing procedure suitable for acceptance and purchasing specifications.

Work performed in the laboratory and in the field has established that the listed requirements can be met.

RESULTS OF PREVIOUS WORK

It would be outside of the scope of this summary report to describe in detail the work done preceding this study and the reasoning behind it. Most of the details are given in previous publications (7, 10, 11). It will suffice to report the latest laboratory tests and to give a few case histories of field applications.

The principal earlier findings can be summarized as follows: One multipurpose product, i.e., one effective with all soil surfaces under all conditions of erosion by wind, water, and traffic, is an unrealistic goal, but a family of products, each with different capabilities for reinforcement of soil surfaces, can be used to control various conditions of erosion and can provide a practical means for methodical erosion control, provided the products can be used in conjunction.

Four commercially available products that can be used to demonstrate the feasibility of the approach are produced by Phillips Petroleum Company in emulsion form and are available under the designations Petroset SB, Petroset AX, Petroset RB and Petroset AT (12). Products can be added to this family of materials to satisfy other requirements of performance not considered in the present study, if they are made to be physically and chemically compatible with the other products.

FUNCTIONAL DESCRIPTION OF PRODUCTS TESTED

All four products had the following characteristics:

1. A nearly equal emulsification system, cationic in nature, and very high stability,
2. A high-strength thermoplastic elastomer in a solvent, which is a good solvent for all ingredients contained in the oil phases of the four emulsions,
3. High mutual compatibility of all ingredients,
4. A distinguishing and identifying color for each of the emulsions,
5. Miscibility of the emulsions with each other and with water in all proportions, and
6. Ease of penetration into surfaces having measurable porosity to liquids.

These common characteristics are believed to be important in that these products can be used for various purposes either by themselves or in combination with each other.

Petroset SB has high wetting and bonding power for soil particles below the size of gravel and deposits an elastic bonding agent on the individual particles. The product can be used with fertilizer in mulching operations or with sterilant without breaking the emulsion. Petroset AX contains, in addition to the high-strength polymer, a certain amount of asphaltenes, the asphalt component that provides increased hardness and bearing strength for this cementing agent. Petroset RB contains

a bonding agent for large aggregates ranging from gravel to rock, converting loose rock structures into a shock-absorbent and vibration-damping continuum. Petroset AT is a rubberizing agent for asphalt surfacings that, in a spray-on application, penetrates asphalt pavements, reinforces the bonds, and increases the durability of asphalt cements.

The products not only are mutually compatible but are synergistic when used in proper combinations. They can be applied to surfaces individually, consecutively, in blends, and in dilution with water in all proportions. This mutual compatibility offers engineers great flexibility and freedom of design. Petroset SB can, for instance, be reinforced in bearing strength and hardness by blending with Petroset AX; addition of Petroset AT to SB or AX increases elasticity and extensibility.

DEMONSTRATING THE CAPABILITIES OF THE EMULSIONS

The apparatus and procedures used for evaluating the products in the laboratory have been described in previous publications (7, 10, 13, 14, 15). The materials examined were soils ranging in size from fine-grained silt and clay to large rocks and asphalts representative of all ranges of durability. The asphalts and method of rating have been described earlier (15).

The soils were tested in loose form and in form of briquettes of prespecified densities; the asphalts were tested in mixtures with aggregates, in form of briquettes, and in other preformed specimens.

LABORATORY TESTS

Most of the laboratory tests performed consisted of the following steps:

1. Determining physical and chemical properties of the products including storage stability, performance during handling (e.g., frictional stability during pumping), and stability on dilution with water of various hardnesses;
2. Measuring penetration of the emulsions into loose and slightly compacted soils and into briquettes made from standardized test soils; and
3. Comparing erosion resistance of specimens treated with various amounts of the emulsions and blends of the emulsions on exposure to air blasts (defined by wind velocities), simulated rainfall, running water, abrasion, aging, applied loads, and repeated loading.

Some typical tests performed and results obtained are presented later. Descriptions of the test procedures and apparatus used are available from Materials Research and Development, Inc.

Physical and Chemical Properties of Materials Tested

Table 1 gives the compositions of the four products examined. The performance of the individual products and blends made from them is governed by the amounts and proportions of the effective ingredients.

Effect of Blending Products AX and SB on Bearing Strength

Figure 1 shows that, by blending SB with increasing amounts of AX, load bearing capacity is increased proportionately. Figure 2 shows photographs of soil test briquettes that were split after application of the treating agents. Material 104 is AX, material 105 is SB, and 104/105 is a 50-50 blend of SB and AX. Also shown are two split briquettes treated consecutively with 104 and 105. Materials 101, 102, and 103 are solutions of three asphalts in a petroleum solvent. Material 103 contains the same asphalt as emulsion 104. It is significant that the emulsions penetrated uniformly without separation, whereas in the case of the asphalt solutions the asphalt was filtered out on the surface of the specimen.

The composition of the synthetic test soil by weight was graded Ottawa sand (ASTM C 109), 85 percent; ground sand (No. 1 D.M. silica), 10 percent; and Dixie clay, 5 percent.

Figure 1. Load bearing capacity of soil treated with Petroset SB and Petroset AX.

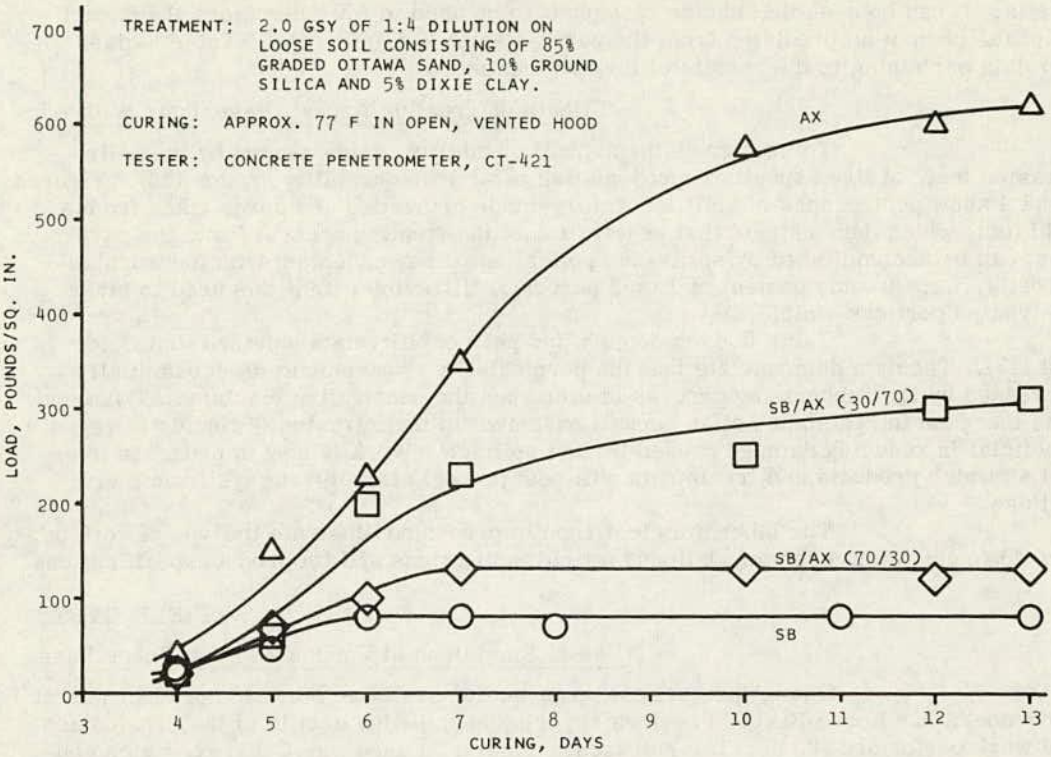


Table 1. Composition of emulsions.

Ingredient	Emulsion RB	SB	AX	AT
Elastomer	22	9	4	18
Resins	11	9	—	—
Asphalt	—	—	46	—
Oils (nonvolatile solvents)	—	27	—	42
Volatile solvents	42	25	14	—
Water and surfactants	25	30	36	40

Figure 2. Split soil briquettes.

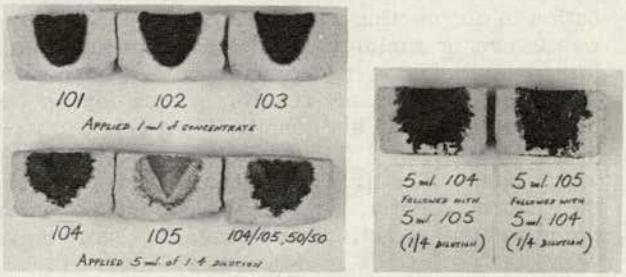


Table 2. Physical properties of materials tested.

Material	Viscosity at 77 F (millipoise) 0.05 sec^{-1}	0.001 sec^{-1}	Shear Susceptibility	Penetration[a] Measured	Calculated[b]	Elastic Recovery (percentage of strain) 1 min	1 hour	Durability Parameter[c]	Abrasion Loss of Aged Ottawa Sand[d] (mg/rev)
101	41.5	61	0.20	17	16	1.5	2.2	1.11	147.8
102	2.09	2.09	0.00	65	62	1.0	4.6	0.905	4.8
103	3.48	4.20	0.05	58	55	3.0	6.3	0.885	1.3
104	3.48	4.20	0.05	58	55	3.0	6.3	0.885	1.3

[a]ASTM D 5-65.
[b]From Saal, Baas, and Heukelom (22).
[c]From Halstead, Rostler, and White (15): $\frac{N + A_1}{P + A_2}$.
[d]Pellet abrasion test (15).

Data given in Table 2 identify the solids in four of the treating materials. It can be seen that choice of asphalt to be used in AX determines the durability of the cement as predicted from the parameter $(N + A_1)/(P + A_2)$. Table 3 gives test data pertaining to the results of the two treatments.

Effects of Treating Asphalt Pavements With AT

Table 4 gives the asphalt durability, as measured by the pellet abrasion test, of five asphalts representative of various durability groups (16). Figures 3 and 4 show photographs of split laboratory-made briquettes and cores taken from a field test, which demonstrate that penetration of the treating agent AT into the pavement can be accomplished by spray-on application on any pavement with measurable porosity, i.e., a voids content of 1 or 2 percent. Ultraviolet light was used to make the treated portions visible.

Table 5 gives density and permeability data obtained in a field test (17). The data demonstrate that the permeability of pavements is substantially decreased by the rubberizing process in situ when the penetrating emulsion AT is used. This increase in resistance of an asphalt pavement to the intrusion of liquids is very beneficial in reducing damage caused by fuel spillage. Work is now in progress to establish which products and treatments will best protect airfield runways from fuel spillage.

The laboratory test results presented illustrate the type of work performed to establish recommendations for field applications and for product specifications.

FIELD TESTS

Use of Emulsions at Vandenberg Air Force Base

One of the earliest large-scale uses of an emulsion product was at Vandenberg Air Force Base. Previous reports describe the details of the erosion control work performed (8, 9). The soil treating material used was Coherex, which contains resinous petroleum fractions that have a great affinity to soils. It contains different ingredients and has a different emulsification system from the Petroset emulsions but is, like Petroset, an oil-in-water emulsion. Because Coherex has only limited resistance to water and moderate resistance to strong winds, it was used in this application in conjunction with snow fences and planting. The purpose of the snow fences was to create miniature sand dunes that function as traps for blowing sand. It was later established that forming 1- to 2-ft berms treated with a soil-stabilizing agent accomplishes the same results as snow fences. Berms have the advantages of not being unsightly and not constituting a general barrier to emergency traffic.

Figure 5 shows photographs of an area before stabilization and 12 years later. The first photograph was taken shortly after stabilization of the area and the second recently. Stabilization succeeded in stopping in a matter of a few months the movement of active sand dunes that shifted around at Vandenberg for thousands of years.

There is much discussion about defacing the earth's surface by man. The work performed at Vandenberg and other air bases shows that man can reclaim and in many cases has reclaimed areas subjected to natural erosion for human habitation.

Stabilization of U.S. Atomic Energy Reservation

The Bechtel Corporation successfully stabilized an excavation approximately 80 ft deep and 360 ft in diameter by means of Petroset SB. Previous to the stabilization, work stoppages were frequent due to dust storms. Figure 6 shows the excavation and the application, which was by water truck and fire hoses. This work was not done by the U.S. Air Force but is reported here because it is evidence that an emulsion belonging to the family of products described can serve a variety of objectives.

Soil Stabilization Tests at Edwards Air Force Base

The purpose of the field tests at Edwards Air Force Base was to repeat on a large scale tests performed in the laboratory on the effect of blending

Table 3. Results of two treatments on soil briquettes.

Sample	Brookfield Viscosity at 77 F, as Applied (cps)	Penetration Into Soil Briquettes			Wind and Water Erosion[a]		Load Bearing Capacity After 1 Week (psi)	Solids (percentage by weight)
		Amount Applied	Time (sec)	Depth (in.)	Amount Applied	Test Results		
101	60	0.17 gsy, concentrated	60-120	0.30	0.40 gsy, concentrated	Fails 150-mph wind after passing 1 hour of rain	3	50
102	39	0.17 gsy, concentrated	60-120	0.25	0.40 gsy, concentrated	Passes	4	50
103	70	0.17 gsy, concentrated	60-120	0.25	0.40 gsy, concentrated	Passes	3	50
104	3.6	0.85 gsy, 1:4 dilution	30	0.40	2.0 gsy, 1:4 dilution	Passes	>63	51
105	4.0	0.85 gsy, 1:4 dilution	36	0.35	2.0 gsy, 1:4 dilution	Passes	43	45

[a]Specimens cured 72 hours before testing; test methods 1-4, Contract Report 3-165 (7).

Table 4. Effect of Petroset AT treatment on asphalt quality.

Asphalt Composite	Average Abrasion Loss at 50 F (mg/rev)			
	Control	0.75 Percent Polymer	1.0 Percent Polymer	1.5 Percent Polymer
I	3.532	2.837	1.832	
II	6.892	3.644	2.689	
III	8.132		4.391	2.370
IV	14.04		5.814	4.390
V	15.30		7.047	4.018

Figure 3. Effect of voids content and application rate on penetration of briquettes.

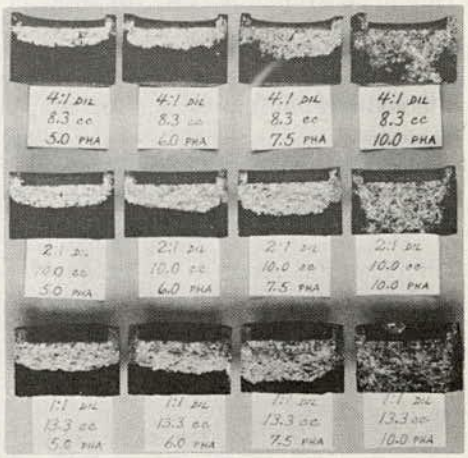


Figure 4. Cores from field test viewed under ultraviolet light.

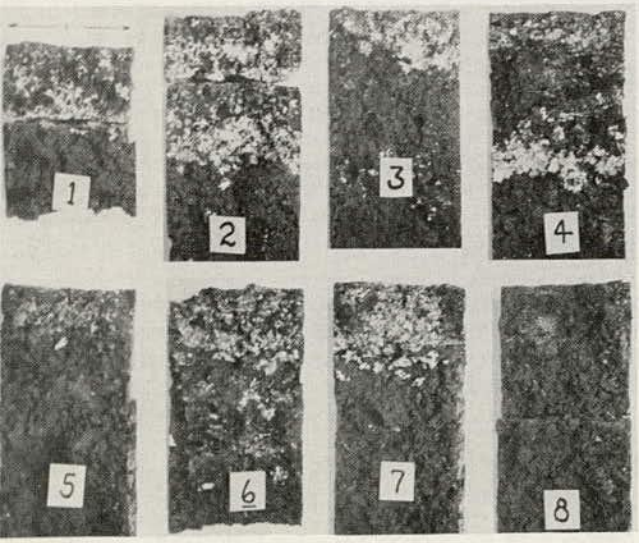


Table 5. Air permeability and density measurements of cores taken 7 months after application of Petroset AT.

Core	Application (gal/yd^2)	Permeability ($ml/min/in.^2$)[a]	Density (lb/ft^3)
Level course[b]	None	2.1	148.0
	0.32	1.4	147.8
Surface course[c]	None	15.7	147.2
	0.32	1.0	148.6

[a]From Kari and Santucci (23).
[b]Asphalt content, 6.2 percent.
[c]Asphalt content, 5.9 percent.

Petroset AX and Petroset SB. As discussed earlier, the two products are compatible and have complementary capabilities. The laboratory tests were performed by treating a synthetic soil. In the Edwards Air Force Base tests, a factorial experiment design provided a number of test sections to explore the behavior of the products in the field individually and in combinations. Figure 7 shows the method of application. Figure 8 shows a closeup of the depth of penetration obtained. The tests were highly successful in that they demonstrated that laboratory results can be duplicated on a large scale, that the treatment with the emulsions resulted in formation of a thick mat of erosion-resistant soil, and that the natural soil responded the same way as the synthetic soil. Recent inspection of the area showed that, during the 3 years since application, wind and rain have not disturbed the treated areas.

Use of Petroset RB to Bind Ballast Rock

Petroset RB was primarily designed to stabilize ballast rock to form a shock-absorbing continuous structure under railroad ties. The effectiveness of the emulsion to stabilize railroad ballast to accommodate high-speed trains was tested by the U.S. Department of Transportation. Because the emulsion is very stable and slow breaking, the ballast rock was pretreated with a dilute ammonia solution. This pretreatment effects breaking of the emulsion and depositing of the cementing agent as shock-absorbing miniature vibration pads at the points of rock contact. The pretreatment of a stratum to accomplish controlled breaking of an emulsion when desired is believed to be superior to using quick breaking, unstable emulsions. This is of considerable importance for purposes of logistics. The treatment with emulsion RB converted the contiguous but loose ballast rock into a continuous structure "welded" together by means of a cementing agent, which constitutes the oil phase of the emulsion. Figure 9 shows the adhesion attained. The rock pile retained its shape in tilting, whereas untreated rock just rolled off.

The process was tested on actual scale by the Association of American Railroads at the research center in Chicago (Fig. 10). The details of the work have been reported elsewhere (18, 19). It will suffice to show the beneficial effects of the treatment on settling. Figure 11 is reproduced here from the AAR report. The abstract of the technical report submitted by the AAR to the U.S. Department of Transportation reads as follows:

> The purpose of the investigation was to evaluate the ability of a compound developed under the sponsorship of FRA to enhance the load-resistant characteristics of conventional stone ballast. This compound, an emulsion based on a new butadiene-styrene block copolymer, was sprayed on the stone ballast of a short section of railroad track. A second section of track, similar but untreated, provided the sample of conventional construction.
>
> In the conduct of this investigation pulsating, single point, vertical loads varying from 5,000 lb to 50,000 lb (and to 75,000 lb in some cases) were applied to, first, the untreated track and, then, the treated specimen in a uniform manner for 4,000,000 cycles. The treated ballast was finally subjected to 11,000,000 vertical stress cycles. Static lateral stress was also applied to each section. At 2,500 lb the untreated section was in constant motion. At 11,500 lb the treated section had deflected 0.113 in. Upon release of load, approximately 50 percent of this strain was self-recovered.
>
> Comparisons established through this study are, conservatively stated, that the permanent settlement of ties supported on the untreated ballast was 10 times that recorded for the ties of the treated ballast test phase. Resistance to lateral displacement was at least five times greater for the treated specimen than for its companion.

Large-scale tests treating ballast rock have since been performed by the U.S. Department of Transportation and have confirmed the findings. It is self-evident that treatment of large rock has beneficial effects on a variety of structures such as rock placed on embankments and facings of earth dams.

Figure 5. Crest and slip face of active dune area before and after stabilization.

Figure 6. Treatment of excavation with Petroset SB.

Figure 7. Application equipment and procedures: (a) 800-gal capacity distributor truck; (b) 8-ft spreader bar; and (c) hand spraying of slope.

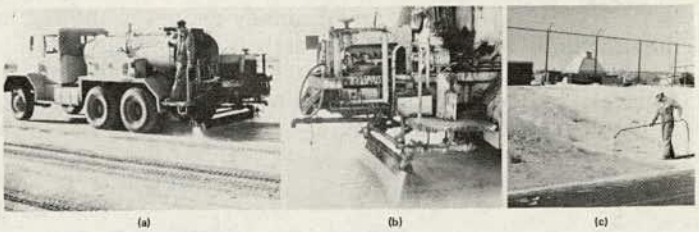


Figure 8. Depth of penetration in field test.

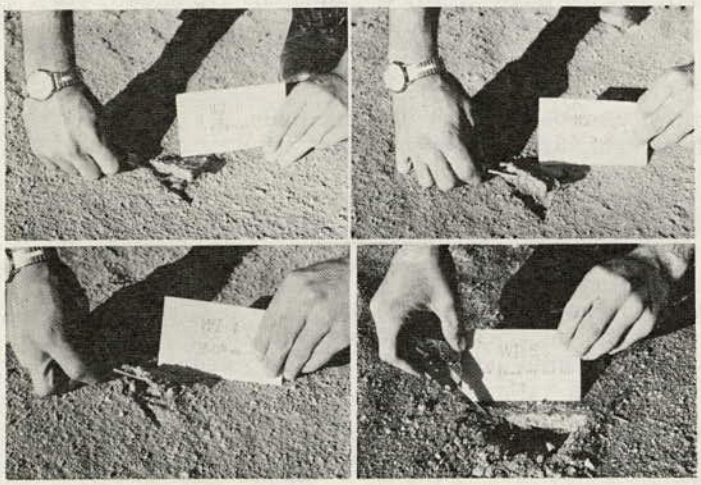
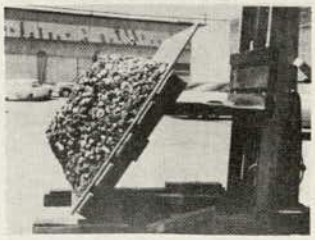


Figure 9. Tilted treated rock pile, demonstrating cohesion of "welded" ballast rock.



Erosion of Asphalt Concrete

Asphalt concrete is basically graded soil of particle sizes ranging from fine grains to rock cemented together by asphalt. It is this graded soil or aggregate that gives the asphalt concrete its strength and traffic-bearing capacity. The asphalt cement serves to keep this soil structure in place and makes it resistant to displacement, oxidation, and the abrasive action of traffic and water intrusion.

Emulsion AT has been used for treatment of highways, county and city roads, parking lots, airport runways, and gasoline stations. Some of the results have been reported extensively (16, 17, 20). One of the most recent uses of AT was an application in North Dakota to test reduction in reflection cracking. The application was made in the fall of 1971. After a severe winter with excessive snowfall and prolonged exposure of the pavement to studded tires, the advantages of the treatment were evident. The photographs shown in Figure 12 document the results obtained. Figure 12A shows that treatment with AT made the pavement highly resistant to cracking. An existing crack in the untreated passing lane had enlarged and continued the spalling process, whereas the crack in the treated traffic lane has healed. Figure 12B shows the difference between the treated and untreated pavements after exposure to the cutting action of studded tires. The photographs are typical of the results obtained over the entire test stretch.

In a preliminary report to the North Dakota State Highway Department, James A. Glick (21) described the results obtained with Petroset AT as follows: "After several days of traffic, the surface of the pavement looked tightly knit and effectively sealed as opposed to untreated sections which were rather porous looking due to the coarseness of the mix."

PROPOSED TENTATIVE SPECIFICATIONS FOR EROSION CONTROL MATERIALS

Based on results obtained to date by the U.S. Air Force, Materials Research and Development, Inc., and other organizations the following tentative specifications have been designed to cover materials to be used in erosion control. In general, the products should be oil-in-water emulsions that can be used individually or in form of blends and in various dilutions with water. More specifically, specification limits encompassing the properties of the whole family of emulsions are shown below as examples of the properties specified (narrower limits are specified for the individual products):

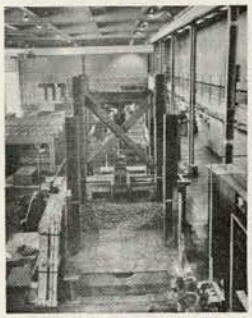
1. Specific gravity, 0.97 to 1.08;
2. Sieve test, retained on No. 100, maximum 0.1 percent;
3. Solids content, 32 to 64 percent;
4. Elastomer content, 4 to 25 percent;
5. Water content, maximum 40 percent;
6. Brookfield viscosity (2:1 dilution, LVT model, No. 1 spindle, 12 RPM, 75 F), 20 to 200 cP;
7. pH, less than 6.5;
8. Particle charge, positive;
9. Heat stability, minimum 24 hours at 140 F;
10. Cold stability, minimum 24 hours at 40 F; and
11. Miscibility with water, unlimited.

The special provision is that performance tests should be made on soils to be treated to ensure adequate penetration into the soil and specified resistance to air blast and exposure to simulated rain.

SUMMARY AND CONCLUSIONS

Cationic oil-in-water emulsions containing a high-strength elastomer or resins or both constitute a family of products most promising for use in

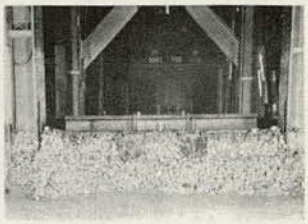
Figure 10. Equipment used in tests performed by Association of American Railroads.



loading frame and test track

tie and rail assembly equipped with deflection roads

spraying operation used for ammonia solution and Petroset RB



cross section through test track after completion of tests

Figure 11. Effect of repeated loads on permanent settlement of cross ties.

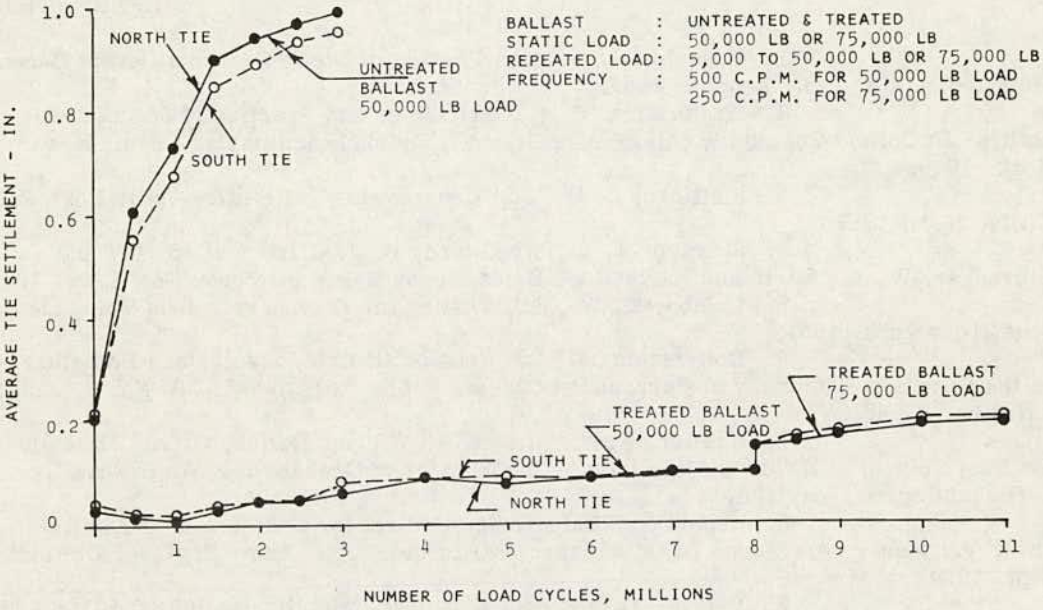
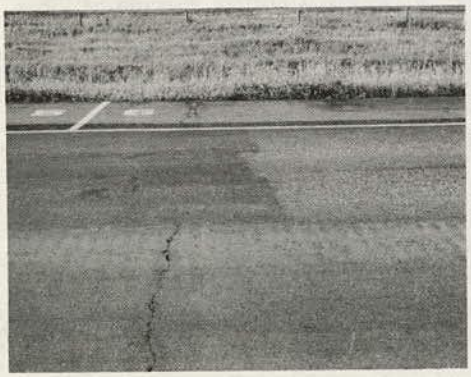
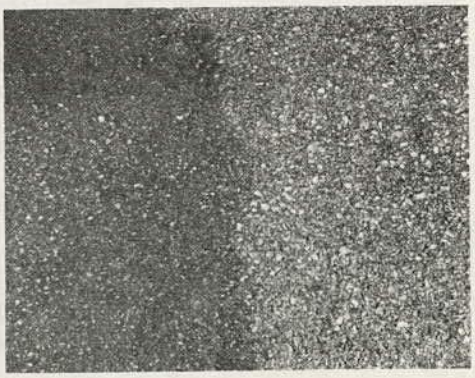


Figure 12. Highway in North Dakota treated with Petroset AT.





methodical erosion control. Tests performed in the laboratory and in the field have been presented that support this conclusion. Tentative specifications for the products that can be used for acceptance and purchasing specifications have been formulated.

ACKNOWLEDGMENT

The work reported in this paper is the result of cooperative efforts of many individuals and organizations. Special mention is gratefully made to the following: Air Force Special Weapons Center, Kirtland Air Force Base; Vandenberg Air Force Base; Edwards Air Force Base; Air Force Systems Command, Andrews Air Force Base; U.S. Army Corps of Engineers; and U.S. Army Corps of Engineers Waterways Experiment Station.

The opinions expressed in this paper are those of the authors and do not necessarily represent the views of the U.S. Air Force. Naming of products does not imply endorsement by any of the agencies concerned. The tentative specifications presented do not constitute specifications in force; they are presented only to demonstrate the type of specifications under consideration.

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WILLIAM T. PLASS, Northeastern Forest Experiment Station,
Princeton, West Virginia

CHEMICAL SOIL STABILIZERS FOR SURFACE MINE RECLAMATION

Successful stabilization of surface mine spoils and other drastically disturbed areas depends on the establishment of a grass and legume cover. Mulches and soil stabilizers may be used on these sites to help establish vegetation and reduce erosion. The selection of an appropriate mulch or soil stabilizer is complicated by the number of products that are commercially available and by the scarcity of information on their effectiveness. Two cooperative demonstrations compared vegetation establishment and erosion loss following 30 treatments with six mulches and 12 soil stabilizers. There is no evidence that these materials are necessary for vegetation establishment; they are used primarily to control erosion. Mulch, soil stabilizer, and soil stabilizer-mulch treatments were effective.

Successful stabilization of surface mine spoils and other drastically disturbed areas requires establishment of a grass and legume cover. A high degree of skill is needed to select and apply treatments appropriate for the varied conditions that occur on these areas. The selection of plant species adapted to the site and the application of adequate amounts of a suitable fertilizer are fundamental treatments. Complementing these basic requirements are a variety of materials and treatments that may aid vegetation establishment and growth.

Among the options are various materials for mulching and soil stabilization. This facet of revegetation technology has experienced rapid growth during the past few years. Much of the interest in these new products may be related to our growing concern about the environment. Interest also comes from the belief that mulches are the solution to our revegetation problems and that they will eliminate the frustrations and hard work often experienced today. Evidence indicates that mulches and soil stabilizers are useful for erosion control, but neither is considered necessary for vegetation establishment in the eastern United States.

There is little well-documented information on appropriate rates of application. The effects of a mulch or soil stabilizer on erosion losses and the factors affecting the site protection provided by various treatments have not been clearly established.

The problems that may occur in prescribing and using mulches are illustrated by the West Virginia statute regulating surface mining. One section in this law states that all slopes of 20 deg or more created by surface mining will be mulched. Acceptable materials and rates of application were not specified; it was left to the designated regulatory agency to develop and enforce technical requirements. A wide variety of products would satisfy the intent of the law, but the scarcity of well-documented information about product acceptance, rates of application, methods of application, and limitations on use made it difficult to prepare specific regulations.

Recognizing the need for more specific information, the West Virginia Department of Natural Resources asked the U.S. Forest Service to initiate a cooperative project to evaluate mulches and soil stabilizers for areas disturbed by surface

mining. This paper describes the results of two demonstrations conducted during a 2-year period.

DEMONSTRATION NO. 1

An exploratory study was initiated in June 1971 to compare various commercial products by measuring vegetation establishment and growth on sample plots. Mulches and soil stabilizers were evaluated (Table 1). These were applied to plots established along a steep fill slope composed of uncompacted, gray to black shale. The pH of the spoil ranged from 2.5 to 5.8. However, most of the site would support vegetation when the appropriate kinds and amounts of seed and fertilizer are applied. Twenty-two of the plots were a quarter acre each, and six were 1,000 sq ft each. Half of the quarter-acre plots had a western exposure; the remainder and the 1,000-sq ft plots had a northern exposure. All plots were seeded with a mixture of Kentucky 31 fescue, sericea lespedeza, Korean lespedeza, and sudum, a hybrid of sudan grass and sorghum. Ammonium nitrate and diammonium phosphate were applied at rates sufficient to provide 85 lb of nitrogen and 50 lb of P_2O_5 per acre.

Each product was assigned to one plot with a western exposure and one plot with a northern exposure, except the Genequa products, which were applied to six 1,000-sq ft plots. All treatments were selected by the manufacturers' representatives. In most cases, the same treatments were applied on the western and northern exposures. A few manufacturers applied a different treatment to each of their assigned plots. The mixing and application were supervised by the manufacturers' representatives.

Normal seasonal weather occurred during the study period. Conditions were favorable for germination, and adequate precipitation maintained vegetation growth.

It was apparent that all these materials can be classified under two broad categories: mulches and soil stabilizers. A mulch can be described as any organic or inorganic material applied to the soil surface to protect the seed, maintain more uniform soil temperatures, reduce evaporation, enrich the soil, or reduce erosion by absorbing raindrop impact and intercepting surface runoff. A soil stabilizer is any organic or inorganic material applied in an aqueous solution that will penetrate the soil surface and reduce erosion by physically binding the soil particles together. These materials can also reduce evaporation and protect the seed.

Mulches appeared to be more effective than soil stabilizers in aiding the establishment of the sudum hybrid. The wide range in mean height at the end of the first growing season indicates that some treatments improved the growth and vigor of the sudum hybrid.

The excellent growth of the sudum hybrid on the untreated check plots indicates that a mulch or soil stabilizer is not necessary to establish a vegetative cover.

DEMONSTRATION NO. 2

The results of the first demonstration indicated that mulches may be superior to soil stabilizers for establishing vegetation and that treatments affected vegetation growth. A second demonstration was established in May 1972 to verify these results and to compare sediment loss among several treatments.

Nineteen treatments using 15 products were applied to a slope with a southern aspect. The slope varied from 16 to 25 deg. No mulch or soil stabilizer was applied to one plot; erosion was controlled on this plot by the grass and legume cover. The spoil was a mixture of light-colored brown sandstone and gray shale that had been partially compacted as it was regraded. Spoil pH ranged from 5.2 to 6.5.

Runoff subplots were established on each plot. Each subplot was 15 ft wide along the contour and 74.5 ft long at right angles to the contour. At the lower end, two strips of 30-in. belting were fitted into a trench to form a V-shaped

runoff trough. The trough emptied into a piece of gutter that drained into a 34.9-cu ft wooden box (Figs. 1 and 2). These boxes were designed to release the runoff slowly while retaining the sediment.

Representatives of the participating companies selected and applied treatments to assigned plots (Table 2). It is interesting to note that many of the soil stabilizer manufacturers recognized the value of wood fiber as a mulch and included it as part of their treatment. This contrasted with the practice in the previous year, when all soil stabilizers were applied with little or no mulch.

The grass-legume mixture included Kentucky 31 fescue, perennial ryegrass, sericea lespedeza, weeping love grass, and Japanese millet. Ammonium nitrate and diammonium phosphate were applied at rates to provide 85 lb of nitrogen and 50 lb of P_2O_5 per acre, as in the previous demonstration.

Because of frequent rain showers, the soil was at or above field capacity the week before the treatments were applied. During the week of treatment, rain kept the soil moist, and air temperatures remained unseasonably cool. These conditions emphasized differences among the soil stabilizers. One product required a 2- to 3-hour warm, dry curing period after application. A rain shower after this product was applied caused concern, and the manufacturer's representative had the plot re-treated during a period of dry weather. Other soil stabilizer treatments may have been affected to a lesser extent by the high moisture content of the soil. These products depend on infiltration to carry the binder into the soil. The depth of penetration and the effectiveness of the treatment depend on the soil moisture at the time of treatment. On a few plots the surface soil became saturated during the treatment, causing some of the solution to run off. This loss may have reduced the effectiveness of the treatment. On other plots the solution puddled in small depressions and remained on the surface for several hours. It was assumed that the rate of infiltration was slow and the zone of treatment shallow. Therefore, the layer of treated soil may have been thin and easily destroyed by rainfall and erosion. Runoff and puddling can be controlled to some extent by reducing the amount of water used to mix the solution.

Vegetation germinated and grew much more rapidly on plots treated with a mulch or a combination of soil stabilizer and wood fiber. Straw tacked with Curasol AH, hardwood bark, Curasol AH with wood fiber, Aerospray 70 with wood fiber, and Aquatain resulted in an acceptable, uniform cover 8 weeks after treatment. The Japanese millet on the plots treated with Aerospray 70 had a healthy green color. Some yellowing of the millet foliage occurred on the plots treated with straw tacked with Curasol AH, Curasol AH with wood fiber, and Aquatain. Hardwood bark caused extreme yellowing of the foliage. The yellowing occurred along the leaf margins near the tip of the leaf blade and resembled the symptoms of nitrogen deficiency.

Plots treated with soil stabilizers without wood fiber did not have so dense a cover, nor was the vegetation so tall as on the plots treated with mulch or a soil stabilizer with wood fiber. This is consistent with results obtained the year before.

The treatments were expected to have their greatest effect on sediment loss during the time from application until a vegetative cover was established. On many spoils, a protective ground cover can be established in 8 to 10 weeks with a suitable seed mixture and adequate fertilization. The vegetation becomes more effective for erosion control as the plants grow and the ground cover density increases. At the same time, the effectiveness of the mulch or soil stabilizer may decrease as it deteriorates by weathering.

The straw tacked with Curasol AH was considered one of the most effective erosion control treatments. It was used as a standard with which to compare sediment loss on the other plots. This proved to be a valid basis for comparison, inasmuch as sediment loss from this plot was the lowest of all treatments. Sediment loss was very low on plots treated with hardwood bark, Curasol AH with wood fiber, experimental wood fiber No. 2, and Aquatain. At the end of 8 weeks, four mulches, three soil stabilizers, and three soil stabilizers with wood fiber had produced low sediment losses.

Table 1. Treatments tested in demonstration No. 1.

Treatment	Rate per Acre	Northern Exposure		Western Exposure	
		Est. Mean Height[a] (ft)	Plant Vigor	Est. Mean Height (ft)	Plant Vigor
Control					
No mulch or soil stabilizer	–	5 to 6	Good	5 to 6	Good
Mulches					
Hardwood bark	27 cu yd	5 to 6	Good	–	–
Straw tacked with asphalt	1½ to 2 tons with 80 gal	5 to 6	Good	–	–
Hay tacked with Curasol AH	1½ to 2 tons with 40 gal	6 to 7	Good	–	–
Hay tacked with Aerospray 52	1½ to 2 tons with 20 gal	–	–	5 to 6	Good
Wood fiber	1,200 lb	5 to 6	Good	5 to 6	Good
Erocom	2 tons	1 to 2	Poor	1 to 2	Poor
Soil stabilizers					
Aquatain	5 lb	3 to 4	Good	2 to 3	Fair
Terra-Tack	40 lb	4 to 5	Good	3 to 4	Fair
Curasol AH with wood fiber	60 gal with 200 lb	–	–	3 to 4	Fair
Curasol AE with wood fiber	22 gal with 200 lb	4 to 5	Fair	–	–
Aerospray 70	30 gal	3 to 4	Poor	–	–
Aerospray 70 with wood fiber	20 gal with 200 lb	–	–	3 to 4	Poor
Genequa 743	100 gal	3 to 4	Fair	–	–
Genequa 743	50 gal	4 to 5	Good	–	–
Genequa 743 with Genequa 8	50 gal with 50 lb	3 to 4	Fair	–	–
Genequa 169	50 gal	4 to 5	Good	–	–
Genequa 555	50 gal	3 to 4	Fair	–	–

[a]Height was estimated at several points where plant density was the highest; estimates were checked occasionally by measuring the height of several plants.

Figure 1. In demonstration No. 2, runoff from 1,000-sq ft subplot is channeled into the collection box to measure sediment yield.

Figure 2. In demonstration No. 2, a trough of belting channels the runoff into a gutter; gutter empties into a 34.9-cu ft box.

Table 2. Treatments tested in demonstration No. 2.

Treatment	Rate per Acre	Average Height of Japanese Millet[a] (ft)	Foliage Color[b]	Ground Cover Density[c]	Sediment Loss per Acre (cu ft)
Control					
No mulch or soil stabilizer	–	1.6	G	L	309.5[d]
Mulches					
Straw with Curasol AH	1¼ tons with 40 gal	2.6	F	H	10.5
Hardwood bark	27 cu yd	2.1	P	M	52.3
Erocom	2 tons	1.4	G	M	183.0
Erocom	½ ton	1.7	F	M	172.6[d]
Conwed No. 1	1,000 lb	1.6	F	H	52.3[d]
Conwed No. 2	1,000 lb	1.5	P	H	94.2
PFM	500 lb	1.8	F	M	313.8
Soil stabilizers					
Aquatain	10 lb	2.7	F	M	52.3
Terra-Tack	20 lb	1.6	F	L	204.0
Terra-Tack with wood fiber	20 lb with 400 lb	1.5	F	M	962.2[d]
Curasol AH with wood fiber	40 gal with 800 lb	2.2	F	H	15.7
Aerospray 70 with wood fiber	80 gal with 800 lb	2.6	G	H	88.9
Aerospray 70 with wood fiber	40 gal with 400 lb	1.0	G	L	287.7[d]
M-145	72 gal	1.8	G	M	83.7
M-145	18 gal	1.8	F	M	209.2[d]
Genequa 743	55 gal	2.8	G	L	73.3
Genequa 169 with wood fiber	40 gal with 1,000 lb	1.9	F	L	109.8
XB-2386	114 gal	2.7	G	L	172.6
XB-2386 with wood fiber	75 gal with 600 lb	1.0	G	L	407.9[d]

[a]Measured at 10 randomly selected points on each plot.
[b]Subjective evaluation of the vegetation on the entire plot: G = no yellowing; F = slight yellowing; P = pronounced yellowing.
[c]Estimated on each plot: H = 75 to 100 percent; M = 50 to 74 percent; L = <50 percent.
[d]Subplots with a slope of 20 deg or more.

CONCLUSIONS

There is no evidence that mulches or soil stabilizers are necessary for vegetation establishment, but some of these treatments affected the rate of germination and the growth of sudum hybrid and Japanese millet. This may or may not affect total sediment loss.

Sediment loss was reduced by several of the treatments evaluated in these demonstrations. This is the most important reason for recommending mulches or soil stabilizers. No one group of products had any apparent advantage over another. Mulches, soil stabilizers, and soil stabilizers with wood fiber were all effective; however, some treatments within each category were more effective than others.

All of the products tested can be mixed easily without danger to personnel involved. All can be applied with a conventional hydroseeder. Seed, fertilizer, and other additives may be included in the mix.

There is a growing trend toward including a mulching material such as wood fiber with a soil stabilizer. This combination may hasten the germination of the vegetative cover on some sites. A dye in the wood fiber colors the slurry and provides a means of determining what areas have been completely and uniformly treated.

High soil moisture and cool weather may limit the use of some soil stabilizers. The depth of penetration depends on infiltration, so treatments may be more effective on soils with a moisture content below field capacity. The bond between the soil particles determines their resistance to erosion. The strength of this bond can depend on the proper curing of the soil stabilizer. It is believed that warm, dry weather after the application will encourage rapid and complete curing of these stabilizers.

Much research with soil stabilizers is needed to determine how to use them most effectively. There is a need to document differences in sediment loss from plots treated with several rates of application at different soil moisture levels, to evaluate soil stabilizers combined with other mulching materials, and to compare sediment losses for soils with specific chemical and physical properties. It may also be advisable to establish standard methods of evaluating the new products that enter the market each year.

HAROLD H. HUBER, Pennsylvania Department of Transportation

PENNDOT'S RESPONSE TO EROSION CONTROL

PennDOT has been engaged in post-construction erosion control activities for many years through the use of seeding, mulching and plantings, proper landscape management, and ditch paving. Mention was made of erosion control during actual earth-moving activities in the PennDOT construction specifications; however, this was not enforced, except possibly when the project was in close proximity to a public water supply. In early 1970 the Federal Highway Administration issued a memorandum requiring that all federal and federal-aid contracts be strengthened to include specific temporary pollution control provisions in contract documents and to provide for direct payment for this work. From this memorandum, Pennsylvania adopted a provision for temporary project water pollution control (soil erosion) for projects let since October 1, 1970. The Pennsylvania Department of Environmental Resources prepared a draft of proposed erosion control regulations printed on February 26, 1972, and public hearings were scheduled in May 1972. The Pennsylvania Environmental Quality Board adopted the regulations in September 1972. This regulation requires that a permit be secured from PennDER for any earth-moving activity in excess of 25 acres with the exclusion of farming activities. In Cumberland County, a research project on erosion control is being conducted jointly by PennDOT, the Pennsylvania Department of Agriculture, and the U. S. Geological Survey before, during, and after the construction of Interstate 81. The erosion control methods used on highway construction projects in Pennsylvania are outlined. Other research projects and studies currently under way are also discussed. Aside from water pollution, the PennDOT pollution control program involves other forms of pollution, e.g., air, land, aesthetic, and social.

PennDOT has been engaged in post-construction erosion control activities for many years through the use of seeding, mulching and planting, proper landscape management, and ditch paving. Prior to 1969, temporary erosion control during actual earth-moving activities was very limited; however, it was considered and provided for in the construction specifications for many years. In the fall of 1928 the Pennsylvania Department of Highways officially established the Forestry and Landscape Unit to monitor roadside development and erosion control aspects of highway development. Between 1947 and 1952, the Pennsylvania State University Agricultural Experiment Station conducted research on grass and legume slope plantings. The techniques established by this research served to guide state programs in erosion control throughout most of the Interstate Highway construction program.

Many other agencies, such as the Soil Conservation Service, U. S. Department of Agriculture; the state soil and water conservation commissions; state fish commissions; and state and local water quality agencies, have worked diligently in the past to develop effective erosion control methods and to try to educate a reluctant public in the proper use of these methods.

The present environmental trend has made all of us aware of the need for an intense effort to curb soil erosion problems that are so prevalent every-

where. Soil erosion can effect serious pollution of rivers, streams, and lakes; it can destroy agricultural lands; it can increase maintenance costs for transportation facilities; and it can create hazardous conditions to homes and other structures. If soil erosion can be kept to an acceptable minimum, we can preserve our national resources, reduce maintenance, reduce damage claims, and create better public relations.

CONSTRUCTION SPECIFICATIONS AND GUIDELINES

When the Federal Highway Administration issued a memorandum entitled, Prevention, Control, and Abatement of Water Pollution Resulting From Soil Erosion in April 1970, it became mandatory that all federal and federal-aid highway contracts include specific temporary pollution control provisions in the contract documents and provide for direct payment for this work. PennDOT adopted Section 212, Temporary Project Water Pollution Control (Soil Erosion), which is now a part of construction specifications. This specification has been in effect for projects (including 100 percent state-funded projects) let in Pennsylvania since October 1970.

Section 212 concerns itself with temporary erosion control measures required during the life of the contract to control water pollution. Temporary measures must be coordinated with any permanent erosion control features specified elsewhere in the contract. Our highway designers are encouraged to incorporate more erosion control features into the actual project plans, where they will become biddable items. The highway contractors find this approach to be much more acceptable during the course of bidding on a construction project.

Erosion control measures include utilization of dikes along the top edge of new fill slopes, dams placed downstream from a project to catch construction debris, sedimentation basins in water courses to allow sediment to settle (must be cleaned periodically), slope drains, diversion ditches along the top of cut slopes, interceptor ditches located perpendicular to slopes, jute matting or soil retention blankets in swales, early seeding and mulching, stage or sequential seeding and mulching on cut-and-fill slopes, and causeways constructed across streams to eliminate stream fording (Fig. 1).

One of the major requirements of Section 212 is that, prior to the start of construction, the contractor submit to PennDOT for acceptance a plan showing anticipated erosion control schedules and methods of operation. This requirement is very important and must be emphasized because it is also a requirement of PennDER in the newly adopted erosion control regulations, which include all earth-moving activities. Earth-moving activities involving developments in excess of 25 acres must apply to PennDER for a permit and must be accompanied by a satisfactory erosion and sedimentation control plan. PennDOT has requested exemption from the permit requirement for earth-moving activities on the basis of the 750,000-sq ft (18 acres) limit on exposed area at any one time and also, because highway construction is performed under bond, on the basis of contract and specifications that substantially provide for and require erosion control during construction activities.

EXAMPLES OF EROSION CONTROL

Throughout the 1970, 1971, and 1972 construction seasons, the use of erosion control measures during highway construction continually increased. Increased use of these measures has resulted in improvements in the design of these features and has created a greater understanding of their function. There are many excellent examples on past highway projects where concern was given to protecting watersheds of public water supplies and where special consideration was made during the early design phase of highway development. In some cases, water treatment plants were built prior to construction of the highway where water quality might be jeopardized. In other cases, sedimentation basins and sod-lined roadside ditches were specified on the plans and constructed prior to the start of earth-moving activities to protect the water quality in a stream. Early and many times multiple seeding and mulching were also specified to provide continuous protection to newly graded sections.

It has become common practice during the dewatering of footer excavations for stream overpasses to pump the water into siltation basins for filtering purposes, prior to returning the water to the stream. This procedure (Fig. 2) is now the accepted standard of PennDOT and has the blessing of the Pennsylvania Fish Commission and the Pennsylvania Soil and Water Conservation Commission.

At the present time the PennDOT Bureau of Design is developing a series of standard drawings covering the design of erosion control devices. This series will become a part of the manual containing standard construction drawings that will be made available to all highway designers and consultants for use during design and construction activities.

PRESENT RESEARCH IN EROSION CONTROL

A research project on erosion control measures currently under way (1) is being sponsored by PennDER, the U.S. Geological Survey, and PennDOT. The purpose of this study is to determine the effectiveness of different types of erosion control measures in reducing stream sedimentation during and after construction.

The study area is located in Cumberland County (Fig. 3), west of Harrisburg, and comprises five adjacent drainage basins of compatible size and drainage characteristics. Four of the basins are to be crossed by Interstate 81 and the fifth basin (basin 1) will serve as a control.

The basins vary in size from 0.38 to 0.76 sq mile and are drained by streams with headwaters near the base of Blue Mountain. Each stream is monitored near the point where it crosses Valley Street, located downstream from the project. The portion of highway to be constructed in each of the four monitored basins is to be subjected to different methods of erosion and sediment control.

The portion of I-81 that crosses basin 2 will be constructed using methods of erosion and sediment control practiced prior to the issuance of erosion control guidelines. A rockfill desilting basin will be provided on the stream below the gauging station to trap excessive sediment. This basin will have to be cleaned periodically during construction and may be removed following completion of the highway. In basin 3, the roadway will be constructed using the current Section 212 of the construction specifications to control erosion and sediment.

The roadway in the remaining two basins, 2A and 2B, will be constructed using modified construction practices in addition to those prescribed by Section 212. For basin 2A, these additional sediment control measures will include providing culverts for the existing streams and separate culverts or drainage ditches or both for the runoff from the construction area and roadway surface. The separate drainage will be directed through off-stream desilting basins or spread over nonconstruction areas before entering the stream. We are also considering using only a sheepsfoot roller on this section of roadway to provide some on-site storm-water storage, thereby reducing the quantity of runoff water during each storm.

For basin 2B, the additional sediment control measure planned is the installation of two more elaborate on-stream desilting basins than those used with Section 212. The desilting basins in 2A and 2B will be installed prior to the start of the clearing and grubbing operations and will have to be cleaned during construction. Table 1 gives the basins and the type of erosion control measures to be implemented in each.

The collection of rainfall, streamflow, sediment, and turbidity data is in progress at all five sites. The data collection activities consist of continuous monitoring of rainfall, stream stage, and turbidity. Suspended-sediment samples are collected by automatic sampling equipment at selected intervals. Data will be collected to document the phase of roadway construction and the relative cost of implementing the erosion control features incorporated in each basin. The data will be analyzed to evaluate the effectiveness of the various erosion control measures in minimizing sediment concentrations, sediment discharges, and turbidities.

Figure 1. Causeway constructed across stream eliminates need for fording of stream.

Figure 2. Water being pumped from footer excavation and discharged into sedimentation basin.

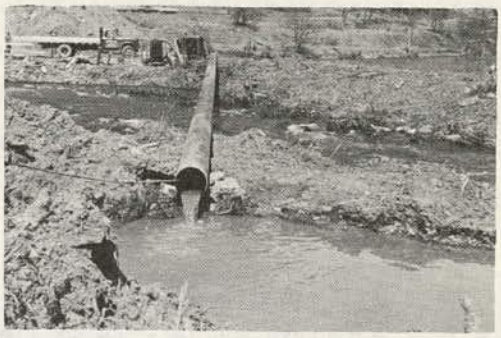

Figure 3. Study area in Cumberland County.

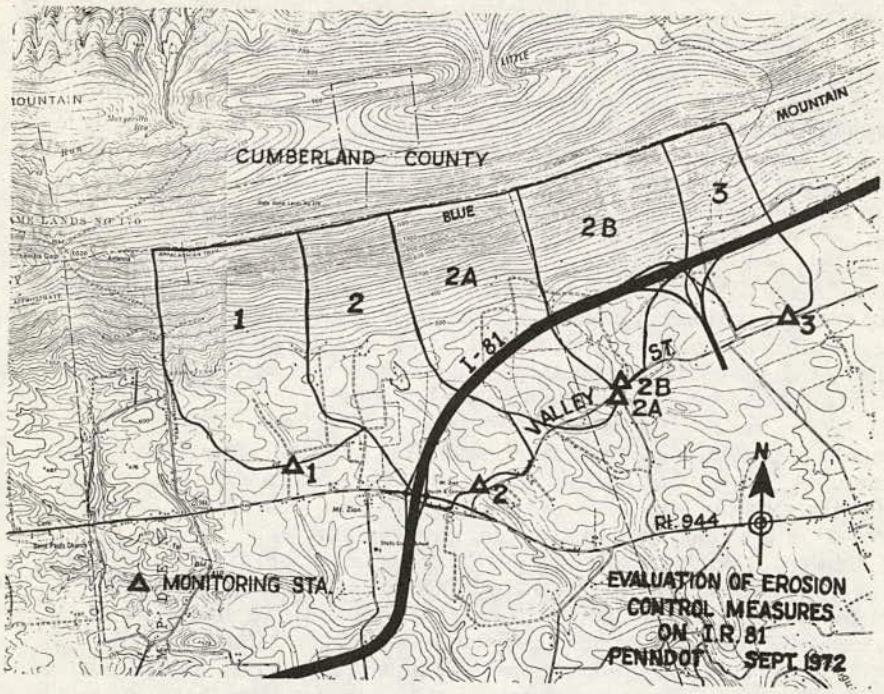

Table 1. Types of erosion control measures to be used on Cumberland County project.

Basin	Main-Line Stationing	Erosion Control Measures
1	Control area	None
2	475 to 516 SB 480 to 522 NB	Practices used prior to Section 212 guidelines
2A	516 to 542 SB 522 to 549 NB	Section 212 plus separate drainage, off-stream desilting, and sheepsfoot roller
2B	542 to 576 SB 549 to 568 NB	Section 212 and on-stream desilting basins
3	586 to 616 SB 589 to 613 NB	Section 212 guidelines

OTHER RESEARCH PROJECTS

Another erosion control study is being conducted by the Department of Civil Engineering of Bucknell University, sponsored by the U.S. Department of Transportation and PennDOT. The study area involves Interstate 80 in the White Deer Creek drainage basin approximately 12 miles south of Williamsport.

The Division of Roadside Development in PennDOT's Bureau of Maintenance conducted an experiment in 1971 to evaluate chemical mulch as an interim means of controlling erosion when multiple or sequential seeding is required during construction or maintenance activities. Four experimental plots were established to compare and evaluate several chemical mulches available at the time.

The bureau is also attempting to consolidate the approximately 1,200 chemical stockpile areas and to eliminate those located close to streams. At many of these areas, asphalt pads and sediment basins have been built to eliminate the leaching problems associated with chemical stockpiling. A study of damage from a model salt storage facility is being conducted near the intersection of I-80 and I-81 in Luzerne County. Continuing studies are being made on the proper use and application of salt for de-icing purposes.

A research project involving stream relocation during highway construction is being jointly sponsored by the Pennsylvania Fish Commission, the U.S. Geological Survey, and PennDOT. During the construction of Penn-15 north of Williamsport, a 2,700-ft relocation of Blockhouse Creek, a fishing stream, is required. Water quality samples and fish and insect data have been collected from the stream prior to highway construction and stream relocation activities. Sampling will continue throughout the construction phase to determine the effects of the relocation on the stream life. Sampling will also take place after construction to determine the length of time required for the stream to return to normal. Past studies of this type have indicated that, with the use of proper planning procedures, effects on the stream life can be minimal.

A research project to investigate the build-up of sodium and chlorine ions in roadside soils has been submitted to the Federal Highway Administration for approval. An excess accumulation of sodium ions in a clay soil has deleterious effects on the soil structure through deflocculation of the clay particles and subsequent disruption of drainage. It is not known how fast these ions may accumulate under various conditions of climate, soil type, and rates of application. In all probability, modifications of design will be required with emphasis on the prevention of salt-laden water coming in contact with clay-containing subgrade soils. This might be done by the use of an impervious surface or by the use of porous granular materials to intercept this water before it penetrates the subgrade. There is also the possibility of the use of additives that will counteract the deflocculation action of the sodium.

ADDITIONAL ENVIRONMENTAL STUDIES

Since the National Environmental Policy Act of 1969 came into being, PennDOT has experienced a tremendous change in its environmental philosophy. PennDOT highway district personnel are actively engaged in the preparation of environmental impact statements, necessitating in-depth analysis of environmental effects along all proposed highway corridors. Other state agencies are required to review and comment on the environmental impacts for all highway proposals within the commonwealth. The Soil and Water Conservation Commission of PennDER is responsible for providing the expertise and performing the necessary study of erosion control for all proposed highways.

Water quality sampling before, during, and after construction of highway projects to evaluate sediment loads in adjacent streams has become a normal procedure in PennDOT. Many of the 11 highway district offices are now equipped with portable water testing equipment and perform their own analyses. Testing equipment is also available in the central laboratory of the Bureau of Materials, Testing, and Research for those district offices that are not fully equipped or where more in-depth analysis is required.

A more comprehensive research project is being proposed to evaluate several existing or recently developed chemical soil stabilizing agents and to determine the relative effectiveness of these materials as compared with the hay and straw mulch currently in use (2). In addition, the length of effectiveness, cost, ease of application, and other factors will be investigated. These chemicals have shown promise of temporarily reducing soil erosion when sprayed on slopes. They form a surface layer of aggregated particles that readily permit penetration of water and air, allow the emergence of germinating seeds, and are relatively stable under rainfall.

The control of erosion and the resulting sediment is a concern that deserves the full attention of everyone involved with disturbance to large quantities of earth. The response to this need by highway design and construction engineers, and especially by contractors, has been gratifying, as evidenced by the growing use of erosion control measures on construction projects today. It is necessary, however, that proper evaluation be made of those erosion control methods and procedures currently in use to determine their effectiveness under varying conditions. It is also important that a continuing search be made for new and improved methods for controlling erosion. Finally, for use to benefit fully from any new developments on the state of the art, it is necessary to find means of effectively disseminating this information.

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DUDLEY B. CHITTENDEN, Pennsylvania
Department of Transportation

PREVENTION AND CONTROL OF SOIL EROSION: THE STATE OF THE ART

The basic fundamentals contributing to soil erosion are temperature, wind, and water. Weather disrupts rock surfaces through alternate heating and cooling, and ice wedges in the interstices and joints of rock. This prepares the material for transport by wind and water. Water that freezes in surface soil causes heaving and loosens the soil; these processes also prepare it for transport. It is imperative that control measures be devised and implemented that will prevent dislodgment of soil particles and reduce runoff velocities to prevent accelerated soil erosion. Several states have surveyed the soil erosion problem; the survey results should be disseminated to officials responsible for construction and maintenance of roads and to citizens interested in conservation and development of a quality environment. The control of accelerated soil erosion is everybody's job.

"Since the first crude plow uprooted the first square foot of sod, and since man's axe first bit into virgin forest, erosion of the soil has been a problem. It is as old as history. Down through the ages it has influenced the lives of men and the destinies of civilizations. In the United States today, no problem is more urgent." This quotation, from the preface of Hugh Hammond Bennett's book (3) written in 1939, is still applicable. It points out the basic problem in the control of soil erosion by noting the removal of the vegetative cover and exposure of raw soil to the action of the elements. Soil erosion, in itself, is not necessarily destructive. Through the action of temperature, rain, and wind, parent materials are broken down to form soils, and these, by continuing processes, shape the landscape. However, through the removal of the protective cover and the shaping of steep slopes, the natural processes are speeded up and we have accelerated soil erosion, which is the destructive phase.

Accelerated soil erosion depletes agricultural lands and removes large quantities of subsoils and parent materials and deposits these to the detriment of man and his creations. Not only does the loss of topsoil from a field or subsoil from a highway grade result in a direct loss from the affected area, but also it may have a greater economic impact at the place of deposition. Who can accurately calculate the cost of removing the accumulated sediment from homes and industries annually deposited there by floods? Many acres of fertile river bottom lands are lost each year through the deposition of infertile overwash. Streams may have their total ecology changed by the deposition of sediment or the scouring of new channels. What is the economic loss and the suffering for humans, domestic animals, and wildlife in a major dust storm? What percentage of the highway maintenance cost goes into the removal of sediment from structures or the filling of eroded ditches and slopes? Eroding soil is responsible for much of the water pollution that plagues the world and, to a degree, air pollution, all of this in addition to the economic loss of the soil.

FUNDAMENTALS OF EROSION

In addressing ourselves to the problems of soil erosion and its control, we should review a few of the basic fundamentals contributing to it. These are principally temperature, wind, and water. Temperature influences erosion in two ways. It is active in disrupting rock surfaces through alternate heating and cooling and through the wedge action of ice formed in the interstices and joints of the rock. This weathering prepares the material for transportation by wind and water. Also, with the freezing of water in surface soil, frost heaving occurs and loosens the soil so that it may be easily carried away by wind and water or transported downslope through mass movement.

Wind erosion, a problem found principally in the more arid, sparsely vegetated regions, is also of local importance along the edges of highway pavements where the turbulence of passing traffic removes significant quantities of unprotected soil. Chepil (6) observed: "The wind erosion process has several major phases: initiation of movement of the soil and its transportation, sorting, abrasion, and deposition. Each phase is influenced by the condition of the air, the ground surface, and the soil." It is, however, turbulence that causes erosion.

Buckman and Brady (5) consider water erosion to be one of the most common geological phenomena. "It accounts in a large part for the leveling of our mountains and the development of plains, plateaus, valleys, river flats and deltas. The vast deposits that now appear as sedimentary rocks originated in this way. This is normal erosion. It operates slowly, yet inexorably. When erosion exceeds this normal rate and becomes unusually destructive, it is spoken of as accelerated.... Two steps are recognized in accelerated erosion—the detachment or loosening influence, which is a preparatory action, and transportation by floating, rolling, dragging, and splashing."

These authors also note that raindrop impact exerts three important influences: It detaches soil; its beating tends to destroy granulation; and its splash, under certain conditions, effects an appreciable transportation of soil.

Total rainfall and its intensity are both important factors, intensity usually being the most important. However, the slope also influences to a great degree the amount of soil loss. According to Buckman and Brady (5), "Theoretically, a doubling of the velocity enables water to move particles 64 times larger, allows it to carry 32 times more material in suspension and makes its erosive power in total 4 times greater." Bennett (3) feels that this figure is too high and states, "This principle, or law, is based on idealized conditions which never occur in nature. The corresponding law applicable to natural conditions varies more nearly as the fifth power of the velocity, or possibly slightly less. In other words, if the velocity is doubled, the weight (or volume) of the particle that can be moved is multiplied by 32 or a number slightly less." On the question of volume of material that can be transported he states, "Scientific and engineering literature throws even less light, but it may be reasonably safe to state that, by analogy, the quantity of material that can be moved by flowing water under natural conditions would vary as the fourth power; or if the velocity is doubled, the quantity will be multiplied by 16."

In view of the tremendous capacity for flowing water to dislodge and transport not only soil particles but also sand, boulders, trees, other vegetation, and man-made structures, it is imperative that control measures be devised that will first of all prevent the dislodgment of soil particles and also reduce and maintain runoff velocities at or near levels that will prevent accelerated soil erosion.

The National Environmental Policy Act of 1969 and the subsequent issuance of PPM 90-1 by FHWA focused the attention of highway officials on the magnitude of the effects of highway construction on the environment. Those problems that had been regarded as more or less a specialty for the agronomist, horticulturist, or landscape architect suddenly became the prime concern of highway management. These problems are complex in that they involve several diciplines and require cooperative efforts for their solution.

INVENTORY OF ROADSIDE EROSION

In-depth study is the first step in the solution of a problem. In 1969 Wisconsin issued to its citizens a report (4) that was a survey of accelerated soil erosion on state, county, and town roads and that had recorded all areas of 100 sq ft or more where there was a soil erosion problem. Briggs (4) stated that an average of one site for every 4 miles of roadside was found to need erosion control of some kind. There were 21,000 silt-producing sites found on 87,000 miles of roadway.

Statewide cooperation by a number of agencies was required for this effort. Data compiled from the field investigations revealed that 73 percent of the problem was on town roads, 24 percent on county roads, and 3 percent on state roads. This in itself is a reflection of the relative standard to which these various roads are constructed. Generally, town roads are on narrow rights-of-way with comparatively steep profile grades and steep slopes, and little consideration is given to vegetative erosion control practices. County roads are characterized by somewhat lower profile grades and flatter sideslopes. State roads are usually constructed on wider rights-of-way with easy profile grades and moderate sideslopes protected by adequate vegetative cover. These conditions are more or less proportional to the amount of traffic carried by the various classes of roads and the funds available for construction and are not peculiar to Wisconsin.

After this determination of the type and extent of the problem, responsible officials established policies and procedures for vegetating new highways and maintaining established roadsides. This program has also resulted in an action program, particularly on the town and county road systems, whereby equipment has been acquired for efficient seeding and mulching of newly constructed highways, and, above all, there has been public awareness of the problem and its solution.

EROSION CONTROL STRUCTURES

To be efficient and economical, erosion control must be designed into a project and not added cosmetically after construction. This involves a careful analysis of the many factors involved with rainfall, soil, and slope that have an effect on soil erosion. Barnes (2) points out that this must be brought to the attention of those responsible for project planning, design, and construction. "It must also be recognized that needed erosion control measures may significantly increase project costs."

Two of the principal factors that should be considered in corridor location are the soil characteristics and groundwater problems that may be encountered. A most helpful device that may be employed in this study is a county soil map compiled by the Soil Conservation Service. Thus, through the avoidance of highly erosive or otherwise undesirable soils that could adversely affect the proposed highway or by modification of the design to include necessary structures or other controls, soil losses may be held to a minimum during the construction phase of the work and until vegetative cover can be established.

There are a wide variety of structures that can be used to control surface runoff. Among these are diversions that are designed, graded channels constructed across a slope to intercept the water and lead it to an outlet where it can be safely discharged. Diversions may be placed above cut slopes to intercept overburden water, or they may be placed across a slope to reduce its length to nonerosive segments. Berms or benches may also be used on slopes in the same manner as diversions to reduce slope length and divide the runoff into easily handled volumes.

Waterways, either constructed or natural, are used for the disposal of water collected in diversions or berms. They should be lined with vegetation or paved and designed for flow velocities that the lining can safely carry. Pipe outlets may be required to remove water from diversions or berms. They should be designed for a 10-year, 24-hour storm, as a minimum.

Peak runoff may be temporarily stored by a retarding structure and released at a slow rate. Through the use of these structures, consisting of an

earth embankment and spillways, runoff is released over a longer period of time and requires smaller waterways or culverts downstream.

Mechanical structures to retain, regulate, or control the flow of water may be required where grade, volume of water, or other factors preclude the use of more simple means. These may be drop spillways, drop inlet spillways, or chute spillways and are usually constructed of concrete, rock masonry, prefabricated metal, or wood. They may be designed for 10- or 25-year frequency storms, although more complex structures may be designed for greater frequencies. Where the flow in these structures is intermittent and the velocity can be kept below the critical level, sod chute spillways are useful for small drainage areas.

Debris basins are structures used to temporarily detain water carrying heavy silt, sand, or gravel. Reducing the velocity allows the load to be deposited in the basin and permits the water to flow away slowly. Debris basins may consist of an earth embankment with perforated pipe spillways, rock dams, or brush dams.

USE OF HERBACEOUS PLANTS FOR EROSION CONTROL ON ROADWAYS

In conjunction with the use of structures for the control of accelerated soil erosion, the importance of a good vegetative cover must not be minimized. Numerous references (3, 5, 6, 12, 15) emphasize the great importance of this cover as a controlling factor. In the nearly 40 years since its inception, the Soil Conservation Service (originally the Soil Erosion Service) has been involved in a national program of research and development of methods and practices for the protection and conservation of soil resources, including the establishment and maintenance of vegetative cover.

Turelle (17) has pointed out a number of legal subdivisions of government that work through the Soil Conservation Service to render assistance to numerous agencies, including highway departments, in the development of plans and procedures for the solution of erosion problems. In addition, its plant material centers and cooperating state experiment stations have developed and improved many plants for use as a more effective vegetative cover for the soil.

Highway designers may use the universal soil loss equation for predicting the magnitude of the erosion problem. This equation is based on rainfall intensity, erodibility of the soil, length and steepness of the slope, supporting conservation practices, and vegetative ground cover. Although originally developed for agricultural use, it has been modified for construction use by development of erodibility factors for subsoils and used to predict soil losses from a given site. Such predictions may influence the design of the facility or the treatment required for stabilization.

Important principles and criteria for establishing vegetation involve correction of soil deficiencies, if they exist; selection of an appropriate species for climate, site conditions, and purpose of planting; preparation of a stable seedbed; and proper seeding and mulching practices where required.

Although use of topsoil is expensive, it should be used when required and when the topsoil is readily available. The additional cost may be justified where highly adverse soil conditions are encountered.

Among the specific characteristics that should be considered in selecting plants for use as vegetative cover are areas of adaptation, growth habits, hardiness, tolerance to adverse conditions, seed properties, required maintenance, and aesthetic qualities. The use of native grasses for roadside stabilization is preferred because of their lower maintenance requirements, low fertilizer needs, competitive nature, and long life.

Numerous techniques are employed in the establishment of vegetative cover along roads. Among these are the use of seeds, planting stock, springs, and sod. Seed is the most widely used because of its low cost. The use of crowns or

plugs is expensive but may be feasible for difficult sites. Sprigging is suitable for those grasses that produce stolons and is more prevalent in the establishment of warm-season grasses. Sod is used for either spot, strip, or solid sodding. Where it is necessary to have rapid establishment of cover, sodding is the best method to use, but it is also the most expensive. It is well adapted for use in waterways where erosion may damage unprotected soil.

Mulching is necessary to protect soil, seed, and fertilizer from erosion by wind and water. It stabilizes the microclimate and promotes seed germination and establishment by conserving soil moisture. To be effective, mulch should be anchored in place.

Once a vegetative cover is established on the highway, it must be maintained. This involves mowing, liming, fertilizing, weed and pest control, and repairs as necessary. It is usually less costly to carry on a maintenance program than to make repairs after neglect. Well-maintained plants usually have enough reserve to carry them through emergencies.

CHEMICAL SOIL STABILIZERS

The search for more and better soil stabilizing agents has been enhanced by the recent emphasis on environmental quality as it relates to air and water pollution. This is particularly true in the case of "in-construction" soil stabilization where the use of hay or straw mulch creates as many problems as it solves. Whereas numerous studies have reported the use of chemical soil stabilizers, one of the most comprehensive was conducted by Armbrust and Dickerson (1), who studied 34 materials from the chemical, animal, and petroleum industries for the control of wind erosion in Kansas. Six of the materials met the following criteria: cost less than $50 per acre, prevented erosion initially and reduced it for at least 2 months, did not reduce plant germination and growth, and could be applied easily. Additional studies are under way or have recently been completed by several state agricultural experiment stations and highway departments.

Plass's report (15) covers two series of studies on highly acid, steep slopes of infertile subsoil and parent material that is typical residue of surface mining operations. In the first series of plots a seed mixture of Kentucky 31 fescue, sericea lespedeza, Korean lespedeza, and sudum, a hybrid of sudan grass and sorghum, was applied to all plots along with ammonium nitrate and diammonium phosphate at rates of 85 lb of nitrogen and 50 lb of P_2O_5 per acre. There were 22 plots ¼ acre in size with a northern or western exposure; six plots were 1,000 sq ft in size with a western exposure.

Two mulches alone, three mulches in combination with chemicals, and nine chemical stabilizers were tested in 1971, and the report concludes with the following observations: "Mulches appeared to be more effective than soil stabilizers in aiding the establishment of the sudum hybrid.... some treatments improved the growth and vigor of the sudum hybrid. The excellent growth of the sudum hybrid on the untreated check plots indicates that a mulch or soil stabilizer is not necessary to establish a vegetative cover."

The 1972 series consisted of 19 treatments using 15 materials applied to a moderate slope having a southern exposure. Runoff sub-plots were superimposed on each plot and soil losses were collected. Interestingly, the author states that "many of the soil stabilizer manufacturers recognized the value of wood fiber as a mulch and included it as a part of their treatment."

He concludes that "Vegetation germinated and grew much more rapidly on plots treated with a mulch or a combination of soil stabilizer and wood fiber."

Also "Plots treated with soil stabilizers without wood fiber did not have so dense a cover, nor was the vegetation so tall as on the plots treated with mulch or a soil stabilizer with wood fiber."

Vegetative mulches, principally hay and straw, have been useful for many years for erosion control purposes, and, through experience, methods and procedures have been developed for their use. Such is not the case with these new

chemical stabilizers, and much is yet to be learned about their use. Factors such as soil type and texture, soil moisture content, and rainfall following application appear to be significant factors as is the proper curing of the material to ensure proper aggregation of the soil particles. With the emphasis that is being placed on environmental quality and pollution control there can be no question that current materials will be adequately researched and development by industry will be producing newer and better materials for this purpose.

PROMISING MATERIALS AND METHODS FOR EROSION CONTROL

Another approach to the erosion control problem is presented by Peters, Rostler, and Vallerga (14), who describe laboratory and field work undertaken by the U.S. Air Force to prevent the types of erosion common on their worldwide installations. They observe that erosion forces are more severe on and around airfields than, for instance, in agricultural areas because, besides wind and rain, there are additional man-made forces such as downdrafts from helicopters, direct blasts from aircraft, fuel spillage, and vehicular traffic by a diversity of equipment.

The authors' purpose was to explore the available concepts and to recommend materials that can be used routinely and methodically for control of all types of erosion on Air Force installations. In addition, it was stipulated that the material to be used should be a liquid that combines with the surfaces to be treated, forming erosion-resistant surface layers to the depth likely to be disturbed; usable in spray applications; noncombustible; capable of being combined or fortified with other liquids to satisfy the widest possible requirements; commercially available at reasonable cost; and defined by characteristics determinable in standardized testing procedures suitable for acceptance and purchasing specifications.

Four commercially available products were used in this study. All four products, according to the authors, had the following characteristics:

1. A nearly equal emulsification system, cationic in nature, and very high stability,
2. A high-strength thermoplastic elastomer in a solvent, which is a good solvent for all ingredients contained in the oil phases of the four emulsions,
3. High mutual compatibility of all ingredients,
4. A distinguishing and identifying color for each of the emulsions,
5. Miscibility of the emulsions with each other and with water in all proportions, and
6. Ease of penetration into surfaces having measurable porosity to liquids.

These products can be used either by themselves or in combination and are also synergistic in action when used in the proper combinations. These materials may be used individually, consecutively, in blends, and in dilution with water in all proportions depending on the requirements of the problem.

One of the products was used successfully to stabilize soil on an atomic energy reservation at Richland, Washington, where work stoppages had been frequent due to dust storms. A blend of two of the products was applied to natural soil at Edwards Air Force Base, California, and after 3 years' exposure wind and rain have not disturbed the treated areas.

One of these products, which acts as a cementing agent, was applied to railroad ballast as a stabilizer. This treatment bound the loose ballast into a continuous structure that withstood tilting to approximately 45 deg without loss of material while the untreated ballast rolled off. A material having these cementing properties has a valuable place in the treatment of rock riprap on the facings of earth dams or in other areas where a coarse rock mulch is desirable but loose rocks might not be.

Another of the products is a rubberizing agent and has been used for sealing the surface of asphalt pavements.

Their report notes that one of the products is compatible with fertilizer and soil sterilants, but the authors do not clarify the effects, if any, on germination of seeds and establishment of plants. Research by Armbrust and Dickerson (1) reported that this material effected no significant reduction in germination and yield for both tomatoes and beans, but there still remain unanswered questions regarding grasses and legumes.

PENNDOT'S APPROACH TO EROSION CONTROL

Up to this point, this state-of-the-art review has been concerned with a look at the problem of accelerated soil erosion with a casual glance at peripheral areas of concern. Along with a determination of the problem, we have looked at methods and materials by which erosion may be held within tolerable limits. It is also common knowledge that highway departments have been engaged in erosion control work on new construction projects for many years. In past years this work was usually the last item to be performed on the new highway. Moreover, because of seasonal requirements, many highways have become seriously eroded before vegetative cover was ever planted, much less established. This situation can no longer be tolerated, and FHWA has issued an instructional memorandum to ensure prevention, control, and abatement of water pollution that results from soil erosion.

Huber (10) in his report on the current erosion control practices on Pennsylvania's highways lightly passes over the post-construction methods used in that state but emphasizes the steps being taken to reduce soil erosion and the consequent pollution of adjacent waters during the construction phase of highway operations. This problem, though serious in extent, has been passed off as just another one of the multitude of problems involved with grading work. It is difficult, if not impossible, to apply a monetary value to the losses to the state and the contractor or to assess the damage to adjacent lands due to the deposition of this material lost during the construction period. This is probably one of the principal reasons that so little attention has been paid to it. Huber sums up the benefits by stating, "If soil erosion can be kept to an acceptable minimum, it is possible to preserve our natural resources, reduce maintenance, reduce damage claims, and create better public relations."

With the advent of FHWA's memorandum, PennDOT adopted Section 212, on temporary control procedures, that is now a part of the construction specifications and is applicable to all projects let since October 1970, including those using 100 percent state funds.

Among the principal features of Section 212 are the following:

1. It requires coordination of temporary and permanent erosion control features;
2. It encourages designers to incorporate more erosion control items in the plans, thereby making these items biddable;
3. It includes the use of dikes along the top edge of fill slopes, dams placed downstream from the work to catch debris, sedimentation basins, slope drains, diversion and interceptor ditches, ditch lining materials such as sod or jute matting, early seeding and mulching, stage seeding and mulching on long cut or fill slopes, and causeways across streams where crossing is necessary; and
4. It requires the contractor to submit, prior to starting the work, a plan showing his proposed schedules and methods of operation.

Many successful examples of these practices now exist on projects built in the last two construction seasons. The PennDOT Bureau of Design is currently developing a series of standard drawings for the various erosion and pollution control devices, and these will become a part of the PennDOT standards used by all highway designers.

Huber also points out that research on pollution problems arising from highway construction is an important part of the program. Research is currently under way on a project that will evaluate various practices used during and after construction to reduce stream sedimentation. Another research project (18) sponsored by

the U.S. Department of Transportation and PennDOT on the sediment load in streams was conducted by Bucknell University. A further project by PennDOT is investigating the effect of relocation on stream life and involves a complete study of the preconstruction ecology of a stream and the period of time required for ecological recovery following relocation.

Other proposed investigations involve the buildup of sodium and chloride ions in roadside soils as a result of de-icing operations and the relative effectiveness of chemical soil stabilizers.

Significantly, the author concludes with the following observation: "It is also important that a continuing search be made for new and improved methods of controlling erosion. Finally, for us to benefit fully from new developments on the state of the art, it is necessary to find means of effectively disseminating this information."

EFFECT OF HIGHWAY CONSTRUCTION ON SEDIMENT LOADS IN STREAMS

Highway construction has long been considered a major contributor to the sediment load of adjacent streams. Younkin (18) reports that few data are available that can establish the exclusive contributor of an area undergoing highway construction. The author points out the salient values of this study when he states that a method of predicting erosion "could be employed simply to determine whether highway construction would be a significant pollution source at a particular site, and, as such, it could be one of the criteria considered by an engineer during location studies. It would define the variation of sediment yield with the construction process, which would allow necessary abatement works to be phased with the construction rather than requiring completion of controls before construction could begin. Thus construction would not be delayed, and the result would be savings of time and money for the public. The predicted values would be useful as the required capacity in the design of desilting basins or sediment traps. It could also be employed as the basis for comparison to determine the effectiveness of attempts to control sediment yield from construction areas."

The research plan recognized three phases in the determination of suspended sediment yield of a stream due to rainfall:

1. The first phase involves detachment of the soil particles and their movement from the construction area. The ease of detachment is a function of the soil and its erodibility and the condition of the soil surface as related to its compaction, which, in turn, is related to the phase of construction and the intensity of construction activity. The transport of the particles is a function of slope length and gradient. Finally, the total yield is related to the area of soil exposed by construction.
2. The second phase, overland transport of the sediment from the construction area to the stream, is highly dependent on slope length, slope gradient, and natural ground surface between them. Antecedent moisture in the ground will affect the infiltration rate and consequently the quality of the sediment reaching the stream. The density and nature of the vegetation and surface debris are factors that tend to trap sediment before it reaches the stream.
3. The final phase is the stream transport process. This process is concerned with the ability of the stream to carry the sediment load it has received. The size and concentration of suspended material, channel cross section, and boundary roughness as well as channel slope are factors in this process.

The construction process was divided into clearing and grubbing, structures, embankment, drainage, and seeding and mulching phases. Clearing and grubbing began in June 1968, and the seeding and mulching were completed in August 1970.

Those factors the author considered to be significant in the development of the prediction equation are total rainfall energy, area of exposed surfaces, average depth of cuts and fills, and proximity of the area to the stream.

Through observation and study, the following basic equation was developed:

$$Q_s = \frac{K R^a (\log A)^b c^D}{P^d}$$

where Q_s is the suspended sediment yield in tons, a, b, c, and d are empirical constants, and K represents the soil erodibility factor. The factor R is the rainfall intensity, A is the area exposed to erosion, D is the height of cuts and fills, and P is the proximity factor.

A graphical multiple regression analysis was performed on 86 sets of data. The solution was transformed back to the equation, which yielded the following prediction equation:

$$Q_s = \frac{0.034\, R^{1.5} (\log A)^{2.45} (3.0)^D}{P^{0.72}}$$

which was found to have a standard error of estimate of 24 percent.

The author's discussion of the results points out that the maximum rainfall intensity could be expected in approximately 2 years; the range of exposed area from 3.3 to 168.75 acres would appear adequate for most conditions; a height of cut and fill values of 0 to 3.2 yd, although representative of this project, might be exceeded on others; and the low proximity factor is indicative of the close location of the construction to the stream.

Of the four factors studied, rainfall had the greatest effect on the sediment yield. The depth of embankment indicates the potential erodibility available to the rainfall factor. Although the area exposed is most significant, the depth factor tends to modify this. Though these three factors indicate the potential for sediment leaving the construction area, this is reduced by the proximity factor, which has major influence on the quantity of sediment reaching the stream.

To extend this prediction equation to other areas will require that a soil erodibility factor for the particular soil encountered be developed. For this purpose the universal soil loss equation, as modified, offers a possible approach. Data from three other areas, currently under study in Pennsylvania, should permit evaluation of this factor. These data may also be used to evaluate the effect of slope gradient and the nature of the ground cover because these areas have terrain and land uses different from those of the White Deer Creek basin.

In conclusion Younkin (18) states: "An equation has been developed that may be employed to predict the suspended sediment load carried by a stream system during the period of rainfall-induced erosion of disturbed soils common to highway construction." This equation "considers the effect of the erosive power of the rainfall; the effect of the important construction phase parameters, area of exposed soil system, and average depth of embankment; and the effect of the proximity of the construction to the stream system."

IN SUMMARY—THE LOOK AHEAD

In perspective, the problem of accelerated soil erosion has been investigated to determine what the problem is; broad areas of control methods have been discussed; details of the measures employed by one state were enumerated; and an equation was reported by which the potential sediment load of a stream adjacent to a construction area may be predicted. What then are the next steps to be taken?

Several states have, to date, made surveys of the erosion control problem on their highways. This has been either a 100 percent survey as done in Wisconsin (4) or a percentage sample as done in Georgia (19). No matter what the method employed, the results should be as widely disseminated as possible and particularly to two groups, the officials responsible for the construction and maintenance of these roads and citizens interested in conservation and development of a quality

environment. Through these two groups positive action may be introduced that will ensure the establishment and maintenance of the necessary erosion control measures.

The most fundamental erosion control measures on highways take place in the early design stages. On major highways this will be the corridor location phase, whereas on others it will be during the preliminary design phase. At this time there are two principal factors that must be considered. These are the geometric design of the roadway and a consideration of the soils involved.

Good geometric design of a highway dictates that the highway relate the construction elements with each other and with the topography. This requires the application of the principles of curvilinear horizontal alignment together with a gentle but topography-fitting vertical alignment. On multilane highways this may also dictate the use of independent horizontal and vertical alignments for each lane. Through the reduction of cut-and-fill slopes to the minimum commensurate with good design, the problem of slope stabilization is reduced. In addition, adequate right-of-way is necessary to permit the use of flatter slopes, which are easier to stabilize and maintain. Encroachment on the alteration of streams and natural waterways must be avoided if possible or provisions made for protection and restoration where required.

As an aid in corridor location studies, the universal soil loss equation (20), as modified for construction purposes, can be of value in avoiding soils that may be highly erosive and that require extensive erosion control structures or other treatments. If such soils cannot be avoided, the necessary erosion control features can be designed into the project; thereby needless delay and expense may be prevented. Although the Soil Conservation Service has used this equation for some time to predict soil losses on agricultural lands and to determine treatments that will hold these losses within tolerable limits, the modified form has only recently been developed, and its use is not widespread at this time. Additional research directed toward a wider scope and, undoubtedly, modification of the sediment prediction equation as proposed by Younkin (18) should be undertaken so that this additional approach may be used in these preliminary studies. With the current emphasis on environmental quality, the highway designer and builder will need every aid available to reduce and prevent soil losses by erosion and pollution of water by the sediment.

Erosion control is a problem that does not lend itself to one universal treatment. On highways it begins with the design, carries on through construction and post-construction phases, and finally becomes a function of maintenance. Years ago, most of the states adopted vegetative methods for stabilizing the primary highways after they were constructed, but only recently have they done anything about erosion control during actual construction. Here a whole new field opens up because many of the post-construction methods are not adapted to "in-construction" use. Huber (10) pointed out some of the practices now in use in Pennsylvania, and other states are developing methods adapted to their needs. Much stricter control must be exercised over the construction sequence, including limitations on the area that may be exposed to potential erosion at one time, completion of finishing operations, and installation of temporary or permanent erosion control measures.

The limitation on exposed soil may be a variable quantity, becoming smaller in periods when high-intensity rainfall may be expected and greater when normal rainfall is light. Then, too, definite criteria must be established for the use of mulch alone, mulch and temporary seeding, and mulch and permanent seeding. Structures such as diversions, silt or trash basins, paved or sodded waterways, and other erosion control devices should be shown on the construction plans and included in the contract quantities. It is here that the use of chemical soil stabilizers will probably be of greatest value. Materials that aggregate the surface to prevent particle dislodgment, that require no specialized equipment for application, that present no adverse effects on grading and compaction operations, and that are low in cost are needed right now. Along with other "in-construction" problems may be included the disposal of clearing and grubbing waste. One of the methods now in use is the chipping of this material and its use as a mulch. There is no denying the value of this material for mulching purposes, but there are economic and logistics problems that are in need of solution.

Plant materials that provide better vegetative cover are also needed. Here, again, several states (7, 8, 9, 11, 13, 16) have conducted research into both herbaceous and woody materials for this purpose. Many species have been found that offer good protection through better growth or increased survival on the so-called "hostile environment" of the roadsides. In addition, the Soil Conservation Service through its plant material centers has added to the fund of knowledge through the introduction and testing of new materials. There are, however, restrictions on the widespread use of many of these new materials because they thrive best in relatively limited geographical areas. Tree planting studies conducted in Pennsylvania during the past 10 years have shown wide variations in the rate of survival on a statewide basis. When these same data were studied on a major land resource area basis, which considers land use, elevation and topography, climate, soil, and water, an entirely different picture developed. Only three species of trees have had superior survival rates over the state, whereas three other species that have been widely planted in the past should be discontinued on highway planting except where most ideal environmental conditions exist and then only when proper maintenance will be available. Much more work remains to be done on herbaceous and woody plant materials for highway use.

There are also two other limitations that have an effect on the research, development, and use of new methods and materials. Perhaps the greatest of these is an adequate source of supply. Frequently, a promising plant may be difficult to propagate or harvest which makes it economically unattractive to a producer. Some of the native prairie grasses are limited in use for these reasons. Woody plant materials that are used primarily for erosion control usually do not appeal to the nurserymen because of a relatively small and frequently uncertain market. Their production is planned several years in advance of harvest, and they cannot commit the resources of land and funds that are required. Zak et al. (21) have conducted extensive work in Massachusetts over the past 10 years under contractual relations with the Massachusetts Department of Public Works and the FHWA. They have undertaken work in the fields of plant breeding, plant propagation, planting techniques, fertilizer use, and mulching studies. Their work has indicated approaches to supply problems and survival through the use of direct seeding of woody materials, the use of root cuttings, and the planting of container-grown plants.

The development of improved strains of grasses is often based on a selection process rather than breeding. Many plants, including grasses, are heterozygous in nature meaning that they normally develop many differing forms, and, through observation, the more desirable forms are selected and propagated. Merion, delta, and several other improved Kentucky bluegrass selections fall into this category. However, breeding is not overlooked, and many researchers are engaged in this work. Due to the length of time required for investigation and evaluation, most of it is done by university agricultural research stations. Additional funding of this work will be an excellent investment because we need plants with greater tolerance to atmospheric, soil, and water pollutants, a wider adaptability to soil and other environmental conditions, less maintenance, and more effective soil stabilization and that also present a pleasing and attractive appearance.

Therefore, the conclusion may be drawn that the control of accelerated soil erosion is everybody's job. It involves not only the plant and soil scientist but also the engineer, the chemist, the journalist, and, above all, the general public. None of these disciplines can accomplish the task alone, and combined they still need the interest and support of everyone.

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