7. Chemical, Mineralogical, and Engineering Properties of Alabama and Mississippi Black Belt Soils. Alabama and Mississippi Agricultural Experiment Stations and Soil Conservation Service; Southern Cooperative Series No. 130, Auburn Univ., Auburn, Ala., Feb. 1968.
8. Soil Survey of Macon County, Alabama. U.S. Department of Agriculture and Alabama Department of Agriculture and Industries, Series 1937, No. 11, 1944.
9. W. B. Cochran and G. M. Cox. Some Methods for the Study of Response Surfaces. Experimental Designs, Wiley, New York, 2nd Ed., 1957.
10. R. K. Moore, T. W. Kennedy, and J. A. Kozuh. Tensile Properties for the Design of Lime-Treated Mixtures. HRB, Highway Research Record 351, 1971, pp. 112-114.

Publication of this paper sponsored by Committee on Chloride Stabilization.

**Mr. Ozier was at the Department of Civil Engineering, Auburn University, when this research was performed.*

Laboratory Study of the Effectiveness of Cement and of Lime Stabilization for Erosion Control

George Machan,* L. R. Squier, Inc., Lake Grove (Portland), Oregon
Sidney Diamond, School of Civil Engineering, Purdue University
Edmond Leo,* Geo Testing, Inc., San Rafael, California

Soils ranging in texture from sand to heavy clay can be rendered effectively resistant to the soil erosion caused by raindrop impact by treatment with as little as 1 percent portland cement or hydrated lime. Erosion resistance was evaluated in a standard rainstorm sequence in which 8.2 cm (3.25 in) of rain was applied for 1 h on each of two successive days. Compacted but otherwise unstabilized soils lost 1 to 2.5 g/cm² (0.014 to 0.035 lb/in²) of exposed surface, equivalent to 45 to 110 tons/acre, in this standard test. Incorporation of stabilizer and appropriate curing before exposure decreased this erosion loss to about 0.11 g/cm² (0.0016 lb/in²), equivalent to 5 tons/acre, for fully compacted specimens. Cement-treated soils tested after only modest compaction maintained their erosion resistance, but lime-treated soils were adversely affected by reduced levels of compaction. These laboratory test results do not necessarily predict practical field performance, because the effects of running water erosion, of the incomplete mixing characteristic of field incorporation of stabilizers, and of cycles of temperature change, wetting and drying, and freezing and thawing have not been tested.

Accelerated soil erosion at construction sites is a serious environmental problem in many parts of the United States. The present methods of erosion control are not uniformly effective.

For many years, soils have been stabilized for use as highway or airfield subgrade materials by treatment with portland cement or hydrated lime.

The present work is based on the idea that treatment of soils exposed on construction sites with small amounts of cement or lime might be useful in preventing erosion. The use of these stabilizers would be relatively expensive in terms of the usual costs of erosion control, but it might provide effective erosion resistance and be a useful alternative to conventional methods, particularly where erosion may lead to especially harmful or serious consequences.

EVALUATION METHODS

Characterizing the erosion resistance of a particular soil or treated soil is, in the final analysis, a field-scale problem. Nevertheless, laboratory assessment based on measurement of the soil lost in controlled artificial-rainstorm tests should be helpful in screening the effectiveness of various kinds of erosion-control treatments on various soils. The present paper reports the results of tests on a range of Indiana soils treated with small amounts of hydrated lime or portland cement, compacted, and cured to various degrees before exposure to a standardized laboratory rainstorm sequence and discusses the extent to which such laboratory results might reflect field effectiveness.

The apparatus used measured the resistance of 10.2-cm (4-in) diameter test specimens exposed to a standard rainstorm sequence of approximately 7.6 cm (3 in) of rain delivered in 1 h, followed by a 23-h rest period, and then by another rain cycle of the same kind. Equipment quirks prevented the delivery of exactly 7.6 cm (3 in) of rainfall in 1 h, and 8.2 cm (3.25 in) was standardized on. The rainfall device delivered droplets of uniform size and spatial distribution that had a kinetic energy approximating that of the average drop in natural storms of the same intensity.

In the tests, the surfaces of the specimens were maintained at a 5° angle to the horizontal to prevent ponding. Three replicate specimens were exposed simultaneously, and the actual amount of rainfall delivered was monitored by rain gauges between the specimens. The soil removed from each specimen was collected and dried and weighed for the quantitative assessment of the amount of erosion. Erosion was expressed in terms of weight loss per unit area of exposed specimen surface.

The apparatus and test procedures have been described previously (1).

SOILS AND STABILIZERS USED

Four natural Indiana soils were chosen to provide examples of a full range of textural classes from a heavy, montmorillonite-bearing clay soil to a predominantly sandy soil with only about 3 percent clay. They are described in Table 1.

The stabilizers used were a type 1 portland cement of normal chemical and other characteristics and a reagent-grade hydrated lime (calcium hydroxide). While reagent-grade hydrated lime is somewhat more effective than most commercial limes, the differences are not usually of major consequence.

EROSION RESISTANCE OF UNSTABILIZED SOILS

The erosion resistance of the untreated soils used as blanks against which the effects of the stabilizers could be evaluated were measured by using the same procedures of specimen preparation, except that no stabilizers were incorporated and hence no curing was required. The procedure consisted of air drying the soil and then compacting it to the approximate standard Proctor (ASTM designation D 698-method A) unit weight at optimum moisture content. Some deviation of compaction technique was necessary to adapt the method to the specimen size used, which was considerably smaller than the standard Proctor specimen.

The results of the erosion tests on these compacted but otherwise unstabilized soils are given below (1 g/cm^2 = 0.0142 lb/in^2).

Soil	Loss (g/cm^2)
Romney clay	1.08
Blue clay till	1.70
Tan till	2.24
Glacial outwash	2.53

The losses varied from slightly over 1 g/cm^2 (0.014 lb/in^2) for the heavy clay soil (Romney clay) to more than 2.5 g/cm^2 (0.035 lb/in^2) for the sandy soil (glacial outwash). The field equivalents of these losses are about 50 and 110 tons/acre.

The higher erosion of the sandier soils agrees with the expectations developed from long-term field tests (2), which suggests that soils with high contents of fine sand and silt erode most rapidly.

One of the projected uses for these erosion-control treatments would be on highway slopes too steep for effective compaction by heavy equipment. Consequently, one of the objects of the present study was to provide information on the effectiveness of stabilization treatments where the treated soil is compacted only lightly, or perhaps not at all. To provide blanks for such experiments, the effect of the degree of compaction on the erosion loss of unstabilized soils was assessed.

In this assessment, specimens were tested in which the compactive effort was reduced in stages by decreasing both the number of blows and the height of fall of the compaction hammer from that prescribed for the standard Proctor compaction. This produced unit weights down to about 80 percent of the standard Proctor unit weight, which corresponds roughly to the field densities of the undisturbed soils. In all cases, the moisture content was adjusted to be approximately optimal for the compactive effort actually applied. Details of the procedures followed have been described previously (3).

The results of the rainstorm-exposure tests indicated that fully compacted soils suffered more erosion (i.e., were less erosion resistant) than did lightly compacted soils of the same type. Over the range of unit weights explored (from 100 to about 80 percent of the standard Proctor), the loss for the heavy clay soil (Romney clay) decreased from 1.1 to 0.2 g/cm^2 (0.016 to 0.0028 lb/in^2). The effect was generally less pronounced for the other soils; the loss for the blue clay till decreased from 1.7 to 1.0 g/cm^2 (0.024 to 0.014 lb/in^2), that for the tan till decreased from 2.3 to 0.7 g/cm^2 (0.032 to 0.0099 lb/in^2), and that for the sandy glacial outwash decreased from 2.5 to 1.9 g/cm^2 (0.032 to 0.027 lb/in^2) over the same range of decreasing unit weights.

The explanation for this appears to depend on the effect of compaction on the permeability and the swelling behavior of the soil. If sufficient permeability exists after compaction (i.e., for lightly compacted soils of lower unit weight), the soil appears to resist swelling and dispersion of its particles under the impact of the raindrops.

Conversely, clay-bearing soils rendered relatively impermeable by full compaction tend to swell, disperse, and erode under raindrop impact. Predominantly sandy soils are less affected by variations in the degree of compaction because they are highly permeable in any case; however, there is so little interparticle bonding that the impact of the drops causes rapid particle detachment and erosion of the silt and sand grains.

These results are the basis for assessment of the erosion losses of the same soils after treatment with stabilizers. The degree to which the stabilization treatment reduces erosion loss compared to that of the same soil compacted in the same way in the absence of the stabilizer provides a working assessment of the effectiveness of the treatment.

EFFECTIVENESS OF PORTLAND CEMENT TREATMENT

Both hydrated lime and portland cement depend for their stabilizing effect on a chemical reaction with individual soil grains. Such reactions are not instantaneous and require curing at a high relative humidity and a reasonable temperature for some hours or days after mixing and compaction. Curing in laboratory tests is normally carried out in a fog room at a controlled temperature, even though such conditions may not be duplicated in the field.

In the tests with portland cement, the specimens were mixed and compacted at the optimum moisture content and then cured in a fog room at approximately 21°C (70°F) for 3 d or longer before being exposed to the artificial rainstorm.

Preliminary results had indicated that all of the soils might be effectively stabilized against erosion in the standard erosion-test rainstorm sequence by the addition of as little as 1 percent cement by weight of soil. This percentage was used in all cases, with additional tests carried out at higher levels of cement content where indicated.

The erosion-test results for specimens treated with 1 percent portland cement compacted to the full standard Proctor unit weight and cured for various periods are shown in Figure 1. (In this and the succeeding figures, the erosion plotted at zero curing time actually represents the erosion of blank specimens compacted to the same unit weight as the series indicated.)

These results show that the erosion of all four soils tested decreased to the order of 0.1 g/cm^2 (0.0014 lb/in^2) after 3 d of fog-room cure. The particles actually detached at this level of erosion loss come mostly from the edges of the specimens. The bulk of the specimens appear to be essentially undisturbed; thus, this level of treatment effectively stabilizes the soils against erosion.

A number of additional tests were carried out with specimens mixed with 1 percent cement, but compacted under reduced compactive efforts to lower unit weights. These tests did not encompass a full spectrum of reduced compactive efforts, but the following results were obtained.

The blue clay till and glacial outwash soils lightly compacted to unit weights of about 80 percent of the standard Proctor unit weight were effectively stabilized

[their erosion losses were about 0.1 g/cm^2 (0.0014 lb/in^2)] after 7 d of fog-room curing.

The tan till soil compacted to 90 percent of the standard Proctor unit weight (the only level explored) was effectively stabilized after 3 d of fog-room curing.

The Romney clay soil, the heavy montmorillonitic clay material, had a low erosion loss when compacted to 80 percent of the standard Proctor unit weight even without added stabilizer. This loss [0.2 g/cm^2 (0.0028 lb/in^2)] was not improved on by adding 1 percent portland cement and compacting to the same level, regardless of curing time allowed. Apparently heavy clays that are not effectively compacted require more cement for any improvement in erosion resistance to occur. A special test was conducted with 3 percent cement and compaction to 80 percent of the standard Proctor unit weight, and complete stabilization in terms of erosion loss was attained after 7 d fog-room curing.

EFFECTIVENESS OF HYDRATED-LIME TREATMENT

Fog-room curing was even more important for the development of resistance to erosion of lime-treated soils; specimens were cured up to 28 d.

Again based on preliminary results, a treatment level of 1 percent of stabilizer by weight of soil was reasonably effective; this amount was used in all tests except those where it was clear that higher levels were needed.

The results of erosion trials on specimens mixed with 1 percent lime, compacted to standard Proctor unit weight, and cured in a fog room for up to 28 d are shown in Figure 2.

Most of the soils tested showed lower erosion-loss levels after lime treatment, but fully effective stabilization requires more than the 3-d curing period that is sufficient with portland cement. Curing in the fog room for 7 d before exposure yields satisfactory results, however, except for the Romney clay soil.

This soil was not effectively stabilized against erosion loss by a 1 percent lime treatment, regardless of the curing period allowed. Presumably a larger percentage of lime is required for this heavy montmorillonitic soil.

The effect of reduced compaction was more complicated for lime treatment than for cement treatment, and varied somewhat for the different soils tested.

The glacial outwash soil developed adequate resistance to erosion when the compacted density was reduced to 90 percent of the standard Proctor unit weight, but the erosion resistance development required 28 d of fog-room curing. At a lower unit weight (78 percent of the standard Proctor value), complete erosion resistance was not attained even after 28-d curing. These results are shown in Figure 3.

The tan till soil was even more sensitive to the degree of compaction: Specimens compacted to as much as 90 percent of standard Proctor unit weight showed appreciable erosion loss even after 28 d of curing.

As shown in Figure 4, the blue clay till soil was stabilized against erosion loss at a unit weight of 96 percent of the standard Proctor value after 7 d of curing and at a unit weight of 90 percent of the standard Proctor value after 28 d of curing. However, further reduction of unit weight prevented entirely effective erosion resistance even after 28 d of curing.

The Romney clay soil had previously been found to show only a small soil loss when prepared without stabilizer at reduced levels of compactive effort. As shown in Figure 5, the addition of 1 percent of lime generated no improvement in the erosion resistance of lightly compacted specimens, regardless of the curing time allowed. It is clear that a greater amount of stabilizer is required for this heavy clay soil at low unit weights. Specimens mixed with 3 rather than 1 percent of lime were effectively stabilized after only 7-d curing.

Generalizing on the results of the tests with lime-treated soils, it appears that treatment with 1 percent lime is as effective as treatment with 1 percent portland cement, but the curing time required to develop effective erosion resistance is longer, and the sensitivity to reduced compaction is greater. At reduced unit weights comparable to those of the natural soils, effective stabilization by treatment with 1 percent lime seems unattainable.

CHARACTERIZATION OF STABILIZED SOILS

The soils treated with portland cement and with lime were in no sense converted to massive, concrete-like materials. While a modest strength, sufficient to permit careful handling, was produced, the original particulate character of the soils was largely retained, and the compacted and cured specimens were usually porous and permeable.

The erosion resistance developed is apparently due to the formation of a calcium silicate hydrate gel around some of the soil grains and as a mesh linking adjacent grains together (4). This results in the generation of water-stable aggregations of particles that do not break down under the impact of raindrops. These changes are the effect of irreversible chemical reactions and hence would seem permanent.

An earlier report (3) compared these test results with those for specimens of a silty clay soil on which a full stand of Alta fescue grass had been grown to maturity. The erosion loss of such specimens averaged 0.5 g/cm^2 (0.070 lb/in^2) in the standard rainstorm sequence, which is significantly higher than most of the losses reported for properly compacted and cured cement and lime-stabilized soils, even at the 1 percent level of stabilizer. Thus, at least under laboratory conditions, the stabilization treatments tested here are more effective in conferring erosion resistance than is a stand of grass.

Table 1. Characteristics of experimental soils.

Soil	Unified Soil Classification	Percentage Clay (<0.002 mm)	Type of Clay Mineral	Liquid Limit (%)	Plasticity Index (%)	Maximum Unit Weight[a] (kg/m^3)	Field Density (kg/m^3)
Romney clay	CH	48	Montmorillonite	68	39	6.1	4.6
Blue clay till	SC	20	Illite, chlorite, kaolinite, montmorillonite	23	10	7.8	6.0
Tan till	SM	5	Illite, chlorite	19	4	7.8	6.4
Glacial outwash	GM-GC	3	Illite, chlorite, vermiculite, montmorillonite	21	5	7.4	5.8

Note: 1 kg/m^3 = 0.062 lb/ft^3; 0.002 mm = No. 10 Sieve.

[a] ASTM D 698-70 method A.

IMPLICATIONS FOR FIELD USE

Success in stabilizing small soil specimens against erosion loss in a laboratory test rainfall does not necessarily mean that the same methods will be successful in a field-scale treatment. There are a number of differences between the kind of laboratory-scale testing described here and actual field situations. A few of these merit specific discussion.

First, the specimens were tested only against the impact effects of raindrops. Actual soil erosion involves at least two mechanisms, one that is due to raindrop impact and results primarily in sheet erosion, and another that is due to the tractive force of running water, especially on long steep slopes, and results in rill and gully formation. There is evidence, however, that the mechanisms that involve impact effects exert control in the sense that the impact effects are a necessary precurser to rill erosion. For example, Young and Wiersma (5) found that in field-scale experiments where soil loss was primarily by rill erosion, preventing impact effects by placing a screen above, but out of contact with, the soil reduced soil loss by 90 percent or more. They concluded that 80 to 85 percent of the soil lost in the experiments without the screen was first detached by rainfall impact and then transported down the rills by running water effects.

A second difference between these laboratory tests and field-scale use is that of the completeness of mixing attainable in the two situations. Laboratory-scale mixing is more efficient and complete than any feasible field-scale method of incorporation of the stabilizer. In consequence, it is likely that a significantly higher content of stabilizer would be required to ensure the presence of at least the amount needed at all points throughout the material.

Third, the curing procedure used does not have an

Figure 1. Effect of 1 percent portland cement treatment on erosion loss of soils as a function of curing period.

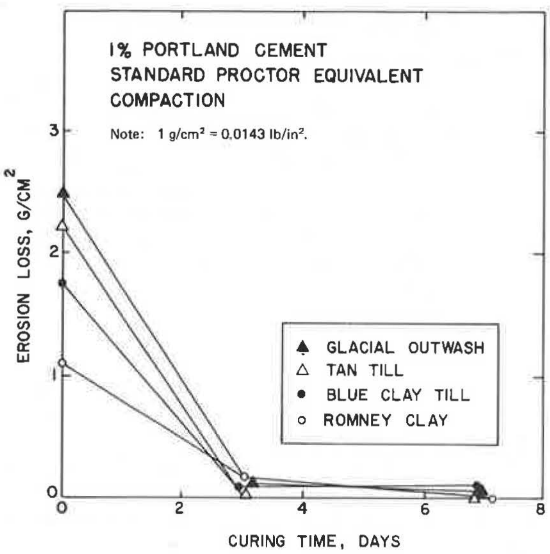


Figure 2. Effect of 1 percent lime treatment on erosion loss of soils as a function of curing period.

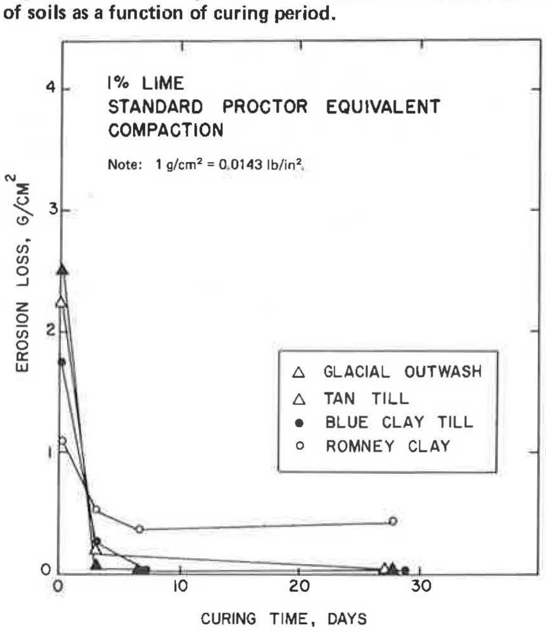


Figure 3. Effect of 1 percent lime treatment on erosion loss of sandy soils compacted at reduced compactive effort as a function of curing period.

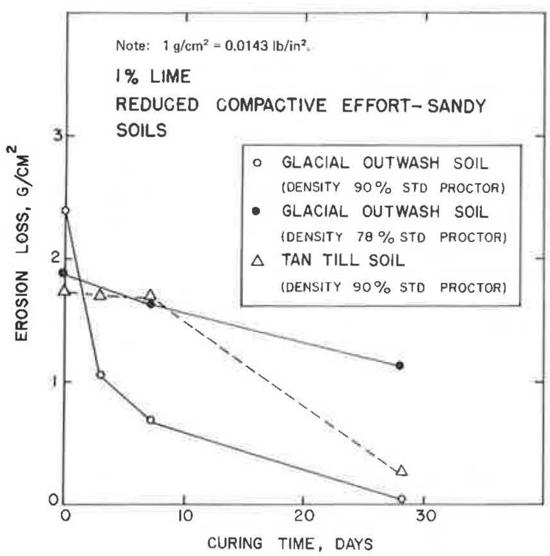


Figure 4. Effect of 1 percent lime treatment on erosion loss of blue clay till soil compacted at reduced compactive efforts as a function of curing period.

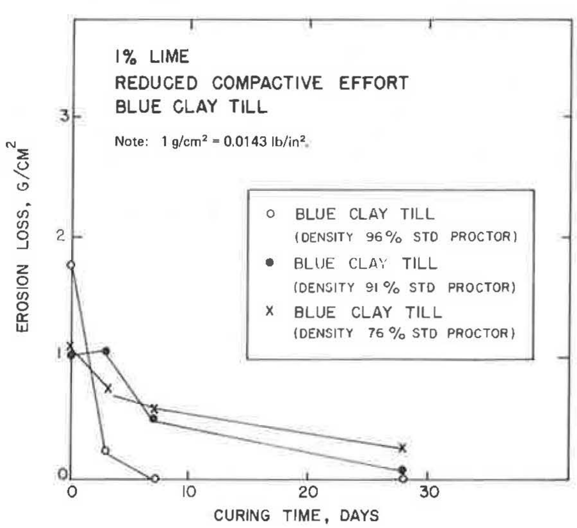
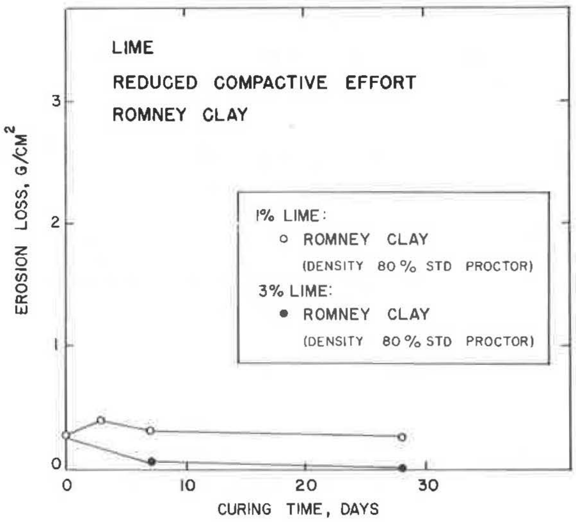


Figure 5. Effect of lime treatment on erosion loss of Romney clay soil compacted at reduced compactive effort as a function of curing period.



exact counterpart in field-scale applications, although expedient means of field curing stabilized soils are widely used in the application of lime and cement to soil stabilization for subgrades.

Finally, the permanence of the treatment in field exposures where temperatures cycle daily, where wetting and drying cycles occur frequently, and most important, where freezing and thawing occur might be questioned. The chemical reactions resulting in the binding together of the particles are irreversible, but whether this binding is sufficiently strong to overcome the environmental forces tending to disruption in practical cases remains to be seen.

CONCLUSIONS

1. Standard, laboratory rainfall tests showed that both type 1 portland cement and reagent-grade hydrated lime used at levels of 1 percent by weight of soil, in specimens that were thoroughly mixed, compacted, and cured before testing, provided effective control against erosion caused by raindrop impact (except in a heavy montmorillonite clay soil that required more stabilizer).
2. The portland cement treatments were effective after only 3 d of room-temperature fog-room curing; hydrated lime seemed to require a week or more of curing for the development of full effectiveness.
3. The reduction in the unit weight of soil specimens produced by reduced compactive efforts in specimen preparation did not seriously interfere with the development of erosion resistance with portland cement, but delayed, and in some cases prevented, the development of full erosion resistance with lime.
4. Soils stabilized by either treatment retained most of their natural soil characteristics and were not rendered impermeable or greatly strengthened.
5. Only the erosion resistance with respect to the impact effects of raindrops was tested. The erosion resistance to the tractive force of running water was not tested. However, there is reason to believe that soils stabilized with respect to falling-drop impact should be at least partly resistant to running-water effects.
6. The erosion resistance developed has been tested only with laboratory-scale specimens not subject to temperature, wetting and drying, or freezing and thawing cycles before exposure to the rainstorm. Whether such resistance is permanent in field-scale exposure is a subject for further testing.

ACKNOWLEDGMENTS

This work was carried out with the support of the Federal Highway Administration and the Indiana State Highway Commission and is a contribution from the Joint Highway Research Project, Purdue University.

The successful prosecution of this research was made possible in large part through the development of the sophisticated and effective test rainstorm installation by Mitsunori Kawamura, whose contribution to this work is gratefully acknowledged.

The assistance of Mark Levy and Janet Lovell in the experimental program is acknowledged with thanks.

The contents of this report reflect our views and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Indiana State Highway Commission or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. S. Diamond and M. Kawamura. Soil Stabilization for Erosion Control. Joint Highway Research Project, Purdue Univ., Rept. JHRP-74-12, 1974.
2. W. H. Wischmeier, C. B. Johnson, and B. V. Cross. A Soil Erodability Nomograph for Farmland and Construction Sites. Journal of Soil and Water Conservation, Sept.-Oct. 1971, pp. 189-192.
3. G. Machan. Stabilization of Soils for Erosion Control on Construction Sites. Joint Highway Research Project, Purdue Univ., Rept. JHRP-75-5, 1975.
4. M. Kawamura and S. Diamond. Stabilization of Clay Soils Against Erosion Loss. Clays and Clay Minerals, Vol. 23, 1975, pp. 444-451.
5. R. A. Young and J. L. Wiersma. The Role of Rainfall Impact on Soil Detachment and Transport. Water Resources Research, Vol. 9, 1973, pp. 1629-1636.

Publication of this paper sponsored by Committee on Soil-Portland Cement Stabilization.

**Mr. Machan and Mr. Leo were at the School of Civil Engineering, Purdue University, when this research was performed.*