SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

JHRP-75-20

METHODS OF SOIL STABILIZATION FOR EROSION CONTROL

Sidney Diamond

PURDUE UNIVERSITY
NDIANA STATE HIGHWAY COMMISSION

Final Report

METHODS OF
SOIL STABILIZATION FOR EROSION CONTROL

October 1, 1975

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-50H

File: 6-19-8

The attached Final Report is submitted on the HPR Part II Research Study titled "Soil Stabilization for Erosion Control". The title of the Report is "Methods for Soil Stabilization for Erosion Control". The Report is authored by Professor Sidney Diamond, director of the Study, and Research Associate on our staff.

This Report is a summary of the research conducted and reported in two earlier Interim Reports. Considerable success was found in reducing erosion from rainfall impact through the use of portland cement, hydrated lime and cement plant dust. Field trials are recommended for further evaluation of the treatments and development of procedures for incorporation of the stabilizing materials into the soil. The findings herein reported indicate that practical, economical techniques may soon be available to control soil erosion at construction sites.

The Report is submitted for acceptance as fulfillment of the objectives of this Study. It will be forwarded for review, comment and similar approval by FHWA and ISHC.

Respectfully submitted,

Harold L. Michael

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by

Sidney Diamond
Professor of Engineering Materials
and
Research Associate

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Prepared as Part of an Investigation
Conducted by
Joint Highway Research Project
Engineering Experiment Station
Purdue University
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Indiana State Highway Commission
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U. S. Department of Transportation
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Purdue University
West Lafayette, Indiana
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Executive Summary Report

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16. Abstract

The objective of this study was to investigate the possible application of inexpensive soil stabilization treatments for the purpose of reducing or preventing soil erosion on construction sites and consequent downstream sediment problems. Treatments were evaluated by measuring erosion loss of treated soil specimens exposed to a severe standardized rainfall test sequence. Treatments investigated included modest percentages of portland cement, hydrated lime, or waste cement plant dust incorporated with the soil by mixing and compaction, or by application in slurry form over the surface of previously compacted specimens.

It was found that all of the stabilizers used in reasonable amounts (1 to 2½ percent) would almost completely eliminate erosion in the test rainstorm sequence. Required curing periods were apparently conditioned by the level of compaction exerted; in favorable cases only 1 to 3 days were required, particularly with portland cement treatment. Hydrated lime and cement dust treatments, while eventually equally successful in preventing erosion in the standard test, required longer curing times, especially when the specimens were only lightly compacted. Waste cement dust may be a promising additive, in view of its negligible materials cost.

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EXECUTIVE SUMMARY REPORT

S. Diamond, "Methods of Soil Stabilization for Erosion Control on Construction Sites," Final Report JHRP - 75 - , July 1975

Purpose: The objective of this study was to investigate the possible application of inexpensive soil stabilization treatments for the purpose of reducing or preventing soil erosion on construction sites and consequent downstream sediment problems. Treatments were evaluated by measuring erosion loss of treated soil specimens exposed to a severe standardized rainfall test sequence. Treatments investigated included modest percentages of portland cement, hydrated lime, or waste cement plant dust incorporated with the soil by mixing and compaction, or by application in slurry form over the surface of previously compacted specimens. Soil types ranging from sands to heavy clay were investigated, and the effects of curing time were examined. Levels of compaction ranging downward from full standard Proctor to almost negligible compaction were investigated to see what effect reduced compaction would have on development of erosion resistance. The physicochemical mechanics of the stabilization processes were explored in order to establish whether the effects were liable to be permanent.

Results: It was found that all of the stabilizers used in reasonable amounts (1 to 2½ percent) would almost completely eliminate erosion in the test rainstorm sequence. Required curing periods were apparently conditioned by the level of compaction exerted; in favorable cases only 1 to 3 days were required, particularly with portland cement treatment. Hydrated lime and cement dust treatments, while eventually equally successful in preventing erosion in the standard test, required longer curing times, especially when the specimens were only lightly compacted. Waste cement dust may be a promising additive, in view of its negligible materials cost. Application of hydrated lime or portland cement in slurry form led to the development of a crust which successfully resisted raindrop erosion. It was found that portland cement treatment, either in slurry form or mixed with the soil, is compatible with germination and development of grass, and combined treatments are possible. This is not true with hydrated lime, nor probably with waste cement dust. The mechanism responsible for the stabilizing influence is similar in all cases, and involves permanent chemical reaction leading to the development of hydrated calcium silicates similar to the effective binders in portland cement concrete. However, the stabilized soils retain their individual particle character, permeability, etc. and are not bound into a concrete-like mass. It was found that the resistance to erosion provided by most of the treatments was markedly superior to that provided by a thick stand of Alta fescue grass exposed to the same standard rainstorm test.

Application: The results of these laboratory studies clearly indicate that modest levels of conventional stabilizers (portland cement or hydrated lime) or of waste cement plant dust will serve to virtually eliminate erosion loss due to raindrop impact when suitably incorporated with most soils. The low level of treatment required and the lack of stringency on compaction requirements suggest that such treatments should be inexpensive and easily carried out in practice. The possibilities for slurry application are even more attractive. However, it should be noted that the results are all laboratory scale determinations, and field trials are obviously called for before practical application on job sites is contemplated. Further, the tests measure only resistance to "impact erosion" caused by falling rain; resistance to the tractive effect of flowing water, especially down long steep slopes, may require more intensive and carefully controlled stabilization treatments more nearly like those used for subgrade stabilization under highway pavements.

SUMMARY STATEMENT ON RESEARCH IMPLEMENTATION

The results of this research project can be summarized in over-simplified form as indicating that:

1. Treatment of soils exposed on construction sites with small quantities of conventional soil stabilizing materials (portland cement and hydrated lime) can provide effective resistance against erosion due to rainfall impact.

2. Methods of application of these materials can be tailored to suit particular conditions or needs.

3. Application of portland cement can be combined with or supplemented by the usual procedure of development of a stand of grass or other vegetative cover for additional erosion resistance and esthetic value.

4. The costs associated with the proposed erosion control treatments are not excessive.

Application of these results rests on the success of field tests and development procedures which need to be carried out for two purposes:

a) To generate experience with and solve the small practical problems associated with optimizing the procedures for incorporation of the stabilizers, either by direct mixing and compaction is normally done in stabilizing highway subgrades or modifications of such procedures to suit backslopes and other relatively steep area normally inaccessible to heavy compaction equipment, or by spray application using hydroseeders or other spray equipment, and

b) To evaluate the success of such treatments in resisting erosion caused not by rainfall impact but by rapid water movement down steep slopes. Such resistance was not specifically quantified laboratory research carried out in this project.

Should such field application trials prove successful, it is reasonable to consider that one or more "standard designs" for accomplishing the objectives desired could be formulated by the Indiana State Highway Commission and other operating agencies.

As a results of discussions with ISHC and FHWA operating personnel, plans are being formulated to carry out at least one field trial in the near future. Cooperation of research workers at Utah State University who have developed a complete system for evaluating field erosion losses on construction sites is being solicited so that the field trial can be set up to yield accurate numerical results rather than crude indications of success or lack of success.

Should the field trial (and possibly other field trials carried out independently by other agencies) be favorable, successful application would be then dependent on

a) realistic assessment of the costs of the particular form of application of the stabilizers selected, and

b) proper selection of those situations and circumstances in highway construction activities that could reasonably be considered to require special precautions for erosion control.

As illustrations of b) above, one might consider circumstances where construction activities are taking place in areas upstream of and likely to influence water supply reserviors, heavily used recreation areas, etc.; situations where conventional vegetative treatment carries a significant risk of failure of long delay in reaching effectiveness such as late fall construction, or construction when potential rainy season storms are expected before grass can be established; and situations where construction activities expose large areas of soil which past experience has indicated to be particularly subject to erosion, especially where such exposure is in urban areas.

While it is difficult to put dollar values on the potential benefits that could be derived from applications of these findings, it is clear that judicious and careful application can result in considerable benefit to highway construction and operating agencies in dealing with "sticky" situations of erosion control, and equally important, the benefits to the public at large in terms of decreased sediment load on streams, increased life of reserviors, and reduction in expensive dredging activity in those areas where such activities must be carried out to maintain navigable channels. Of less absolute importance but perhaps also highly useful to operating agencies is the potential benefit in terms of reduction in complaints from members of the public suffering inconvenience from sediment derived from construction site activity.

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1. INTRODUCTION

The present report constitutes the Final Report on a project entitled "Stabilization of Soils for Erosion Control on Construction Sites," conducted by the Joint Highway Research Project, Purdue University, and sponsored by the Indiana State Highway Commission in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

Major portions of the work accomplished under this project have previously been reported in Interim Reports as follows:

1. "Soil Stabilization for Erosion Control," S. Diamond and M. Kawamura, Report JHRP - 74 - 12, 1974 (1)
2. "Stabilization of Soils for Erosion Control on Construction Sites," G. Macha, Report JHRP - 75 - 5 (1975) (2).

The present Final Report summarizes much of the material previously presented. In addition recent experimental results not previously available are given, and an overall interpretation and assessment of the results and of prospective applications are provided. Approximately 500 individual specimens have been tested for erosion resistance in the course of this work.

2. THE PROBLEM OF SOIL EROSION ON CONSTRUCTION SITES

The title of this section is essentially a misnomer. One of the major peculiarities of the difficulties stemming from soil erosion in connection with construction activities is that much of the problem does not involve the construction site or construction activities per se, but rather stems from soil removed off-the-site and carried into the drainage systems, or alternately deposited in various inconvenient places downstream of the construction site itself. Generally, loss of soil from place to place within the construction area usually presents comparatively little difficulty with regard to the progress of construction, except perhaps for occasional regrading of affected areas. To some extent the problem is thus a public relations or social concern problem, rather than an engineering problem per se.

The magnitude of the down-stream sediment difficulty varies with place, time, and degree of construction activity, and also with the existing precautions enforced on the site, if any. In at least some areas of the country it has become apparent that by far the greatest contribution to the sediment load in recent years has been due to accelerated erosion from construction activities. As a result Federal and State agencies monitoring stream pollution, rate of silting behind dams, and other effects of soil erosion have become sensitive to the influence of construction activities, particularly highway construction activities, on these problems. The public is not far behind in this respect.

Technical responses to the problem have varied. Progress has been made in predicting the quantitative effects of construction activities with respect to erosion and sediment yield. The use of the so-called "Universal Soil Loss Equation" derived for agricultural soils, in predicting soil loss from unstabilized construction areas has been discussed by Wischmeier and Meyer (3). Specific measurements of sediment loads in streams induced by highway construction activities in a drainage basin in central Pennsylvania have been reported and analyzed by Younkin (4), who developed a regression equation to predict sediment yield from a given rainstorm in terms of the rainstorm characteristics and such site-related factors as area exposed by clearing and grubbing operations, average depth of embankment work, and proximity of the construction area to the stream system.

Generally speaking, existing procedures for amelioration and control of soil loss on highway and other construction sites are only partially successful. Typically, the provision of water channeling facilities, catchment basins, and similar hydraulic structures at an early stage in construction minimizes the off-site sediment outflow, but does not completely prevent the occurrence of erosion difficulty. Use of vegetation and mulching on slope areas helps to prevent long-term difficulties after the construction stage is completed, but does not prevent the accelerated erosion that is associated with construction activities. Such permanent vegetative treatments are not applied until final grade is established, and typically require several months or longer to establish sufficient vegetative growth to be effective against reasonably severe storms. Occasionally climatic problems, drought, etc. interfere with the establishment of grass or other vegetative cover for prolonged periods after construction has been completed.

The possibility of providing effective erosion prevention treatments for use primarily on construction sites to avoid the accelerated erosion characteristic of construction operations provided the basic impetus for the present project. It was felt that modified soil stabilization treatments, patterned after those used in highway subgrade stabilization but less expensive and less technologically demanding, might be developed.

Such treatments could provide useful tools for construction organizations in cases where erosion problems might be expected to be severe or particularly harmful in terms of stream pollution, premature reservoir siltation, or other such situation.

3. QUANTITATIVE EVALUATION OF PROSPECTIVE SOIL STABILIZING TREATMENTS

One of the first tasks that had to be faced in this project was the development of a means of evaluating efficacy of prospective erosion control treatments.

Soil erosion normally is divided into several distinct types or categories, with, of course, some overlap. On relatively flat areas, "sheet erosion" usually takes place; that is, soil is removed in thin sheetlike layers, without the formation of gullies. On steep slopes, particularly long steep slopes, rills form early in the erosion process, and if not stabilized, are progressively widened and deepened into gullies which may become many feet deep and broad. In addition, special forms of erosion occur along stream banks, and lakes shores, and in limestone "sink" areas.

Somewhat overlapping this classification by macroscopic field pattern is a classification by physical effect. One distinguishes between erosion caused by the impact of the raindrops themselves on the bare or lightly covered soil, and erosion caused by the tractive force of running water, particularly down steep, long slopes.

It appears that the role of rainfall impact predominates, even in the case of erosion where moderate rill formation takes place. In an experimental study reported recently by Young and Wiersma (5) it was found that decreasing the energy of the raindrops (by placing a screen above, but out of contact with the soil) without decreasing the intensity of the rainstorm reduced the soil loss by 90% or more; while transport out of the test plot was primarily by rill flow, 80 to 85 percent of the soil lost was initially detached by rainfall impact and then transported to the rills before leaving the plot.

These considerations strongly influenced the philosophy adopted in this project with respect to measuring the relative efficacies of possible erosion control treatments.

Basically one must choose whether to model a complete erosion control situation, or whether to extract from it the most essential elements, in the interest of providing experimental simplicity and capacity to perform many tests. The first approach would involve measuring soil loss from a scale model of a prototype slope, using a definite gradient, length of slope, profile, etc. under a particular rainfall schedule, and using a single experimental soil or treated soil. The difficulty with this scheme is obvious; each test requires the construction of a whole new system, and only a very few soil and treatment combinations could have been evaluated in the bounds set for this research project.

The second approach would involve extracting the important element from the erosion situation and standardizing on relatively quick tests designed to compare resistances to that element.

For some purpose, for example resistance to streambank erosion or resistance to scour on canal linings, it is clear that the essential element is the tractive force exerted by moving water. Research studies evaluating stabilizer effectiveness in such contexts have been reported by Christiansen and Das (6), by Akky and Shen (7) and by others. However, our judgement, based on the results of Young and Wiersma (5) is that hydraulic erosion was of less consequence on most construction sites than is the impact effect of falling raindrops which seems to be the necessary first step in getting erosion started and providing the disaggregated material for transport. Basically the problem in most circumstances should be prevented if erosion due to the impact of falling drops could be prevented.

We thus decided to evaluate the various possible treatments by developing a system to measure the relative erosion resistance produced by such treatments with respect to rainfall impact. The task then facing us was to develop a relatively simple apparatus and operational scheme that could provide standardized, repeatable, but rapid measurements of the resistance of a given treated (or untreated "blank") soil to a standardized test rainstorm sequence. The development of this apparatus and operational scheme was detailed in the first Interim Report of this project (1), but will be briefly summarized here.

4. APPARATUS FOR TESTING EROSION RESISTANCE

The apparatus developed in this project can be described as a combination of three distinct systems, viz. the test rainstorm application system, the specimen preparation and exposure system, and the erosion loss monitoring system. These will be discussed individually.

4.1 Test Rainstorm Application System.

It was decided that since the rainstorm parameters most strongly influencing soil loss are the product of rainfall intensity (in inches per hour) and the total energy applied by the falling drops (8), these factors were most crucial to control in design of the rainstorm application system. The former is relatively easy to assess; the latter is not. The kinetic energy of a rainstorm is a function of its drop size distribution and of its intensity. In artificial rainfall devices, the energy is a function of the velocity which the drops attain, which in turn depends on height of fall and on drop size. Height of fall was limited to 14 feet in the facilities available to this project; this is insufficient to attain terminal velocity except for very large drops, which are impractical from the point of view of providing good drop coverage over the specimen surface exposed. A design compromise was reached involving drop sizes of slightly in excess of 0.3 cm., produced from drop formers spaced 1.2 inches apart in a triangular array. Under a design rainfall intensity of 3.25 in/hr, it was calculated that the energy delivered to the soil by the rainstorm would be approximately 84 percent of the energy delivered by the statistically "average" natural storm of the same intensity as defined by the regression equation developed by Wischmeier and Smith (8). The design tests and the basis for the calculations were reported in detail previously (1). Detailed operating instructions and characteristics have been provided earlier (1). It was found that the device operated effectively and without major difficulty for hundreds of runs over a three year period in which the research was carried out. The effectiveness of the device reflects in large part the technical ingenuity of its designer and assembler, Dr. M. Kawamura of Kanazawa University, Kanazawa, Japan, who was associated with this project for one year.

4.2 Specimen Preparation and Handling System.

Specimens were prepared by several laboratory procedures, usually but not always involving air drying, disaggregation, addition of the stabilizing agent and an appropriate amount of water, mixing in a twin-shell solids liquids blender, compaction designed to simulate standard Proctor compaction, and trimming so as to present a trimmed face to the rainstorm. The diameter of the mold was 4.0 in, indicating that the area exposed on each specimen was 12.7 square inches. The specimens were normally one inch thick. Specimens were cured in a fog room for various periods before exposure to the test rainstorm sequence.

Among the variations explored in the course of the experimental program were reduction in compaction to approach a simulated field density, application of the stabilizer in slurry form over the surface of previously-compacted soil without incorporated stabilizer previously being introduced, and several special trials in which thickness was varied. Basically, however, the specimen format was unaltered.

The specimens were mounted on specially designed devices that maintained the surfaces at a 5^{o} tilt from the horizontal. This feature was provided to ensure free drainage from the surface of the specimens, so that fresh drops would impact on the soil surface and not on ponded water. In general, the specimens were both permeable and free draining; that is, the interior rapidly approached saturation and in many cases some swelling took place, but it was clear that splash and flow off the surface removed most of the water.

4.3 System for Monitoring Erosion Loss.

Each specimen is supported approximately half-way up a 6 in. diameter, 12.5 in. tall metal cylinder. Run off water carrying the eroded soil particles are swept to the bottom of the cylinder, and there enter a tube which delivers the suspension to a large container positioned underneath the supporting bench. After the conclusion of the rainstorm sequence any loose soil is swept down the tube to join the previously collected suspension. The container is allowed to stand overnight, the particles are flocculated and settle to the bottom, and the clear supernatant water is decanted. The soil is then oven dried and weighed to provide a quantitative evaluation of its mass.

In all of the tests, specimens were run in triplicate, and averages of the results reported. A check was continuously maintained on specimen-to-specimen variation, which was generally found to be within reasonable limits.

Soil erosion in this program is expressed as weight removed (grams) per unit area of exposed surface (square cm). One gram per square cm. is roughly equivalent to a loss of 45 tons of soil per acre.

4.4 Standard Rainstorm Test Sequence.

Following accepted practice in the study of erosion of soils induced by artificial rainstorms, a test sequence consisting of a period of intense exposure to rainfall, a wait of approximately one day, and a second period of intense rainstorm was installed. The initial rainfall was for one hour; the intermediate halt was for 23 hours for experimental convenience; and the final rainfall was again for one hour. Initially an intensity of 3 in./hr. was attempted, but it was found that with the apparatus as constructed an intensity of 3 in/hr. was difficult to control, but that an intensity of 3½ in./hr. could readily be reproduced and this was adopted as the standard intensity throughout the experimental program.

Such a standard rainstorm test sequence constitutes a severe but not unreasonably severe challenge to the ability of a treated soil to resist raindrop erosion. While rain varies in "typical" storm intensities in different regions of the country, rainstorms of this intensity occur reasonably frequently in many places, at least for short periods of time.

5. PRELIMINARY RESULTS

A considerable volume of experimental results were obtained with specimens prepared from two soils available in the requisite large quantities desired for extensive preliminary studies. One of these was a commercial clay consisting mostly of the clay mineral illite, sold under the trade name of "Grundite" by the Illinois Clay Products Co., Lansing, Ill. The other soil, designated as the "Crosby" soil, is a silty clay derived from the B pedologic horizon of the Crosby soil series, a series of widespread occurrence in Indiana and neighboring states. Details of the properties of the two materials and of the experimental results were described *in extenso* in the first Interim Report of this project (1).

5.1 Erosion Characteristics of Unstabilized Soils.

It was found that under the standard rainstorm test sequence, the Crosby soil compacted at optimum moisture content but not otherwise stabilized lost an average of 2.1 grams of soil per cm^2 of exposed surface. One gram per cm^2 reflects an erosion of about 0.22 in of material at reasonable density; the sediment yield corresponding to such a loss is approximately 45 tons per acre. Thus untreated Crosby soil eroded approximately 0.45 in. and the equivalent of approximately 90 tons/acre of sediment in the standard test rainstorm sequence. The soil aggregations were clearly dispersed by the impact of the raindrops; the water stable aggregate content was minimal, and the pore size distribution of the residual surface showed significantly higher pore volume and coarser pore sizes than did the original compacted soil.

The grundite soil was slightly more resistant to the erosion test, losing only 1.7 g/cm^2 of exposed surface. There was considerable residual aggregation after the test rainstorm, due apparently to bonds formed as a result of strong acid treatment given in the commercial preparation of this clay. It was found that the strong residual acidity (slurry pH about 2.7) interfered with attempts at stabilization with lime and to a lesser degree with cement; in fact smaller quantities of these stabilizers actually increased erosion loss, by destroying the acid flocs that gave the compacted clay much of its resistance to dispersion by raindrop impact.

5.2 Effectiveness of Lime Treatments.

It was found that for the Crosby soil as little as 1 percent of hydrated lime (calcium hydroxide) added to the soil in dry form, mixed thoroughly, and after moistening to optimum moisture content and compaction to approximate standard Proctor maximum density reduced erosion loss significantly after as little as one week curing time. Curing for 1 week reduced the loss from 2.1 g/cm^2 for "unstabilized" soil to about 0.6 g/cm^2, with further decreases observed for increased curing times. With 2½ percent lime the loss was reduced to a negligible 0.2 g/cm^2 in a week. Clearly calcium hydroxide properly incorporated is an effective stabilizing agent for this soil.

The characteristics of the stabilized soils were investigated in a number of collateral investigations. It was found that the content of water-stable aggregates in the lime-treated soil was vastly increased by the lime treatment, and that the volume of pores and the pore-size distribution of the residual soil surface after exposure to the test rainstorm were not very different from their original values; in fact, some of the original specimen surface was not eroded during the test.

It was found that the grundite soil was not stabilized by addition of a slightly carbonated commercial lime, due to its inability to raise the pH sufficiently to enable the stabilization reactions to occur. Results with a 5 percent treatment of reagent grade calcium hydroxide were more successful, cutting the erosion loss from 1.7 g/cm^2 for untreated soil to the satisfactory level of approximately 0.2 g/cm^2 after a week of curing. In these tests comparatively little of the stabilized surface was lost, erosion being confined to the rims of the specimens and to isolated patches. While it was not specifically investigated, it was felt that treatment with significantly lower levels of even reagent grade lime would not provide effective stabilization because of the high acidity of the soil. A minimum pH level of roughly 11.4 was indicated to be required for the stabilization reactions to provide even marginal erosion resistance.

5.3 Effectiveness of Portland Cement Treatments.

Treatment of the Crosby soil with 1 percent of Portland cement in the same manner as that for the lime treatments described above resulted in somewhat less effective stabilization for the first week or so than did the lime treatment, but by 28 days erosion loss under the standard rainstorm test sequence was negligible, i.e. less than 0.1 g/cm^2. Treatment with 2.5 percent of portland cement was almost immediately effective, resulting in a barely-measureable loss of only 0.01 g/cm^2 after 1 day. Thus portland cement at a reasonable treatment level was found to be completely effective in stabilizing this soil against the rather severe test rainstorm series.

Due to the residual acidity of the grundite soil material, portland cement in small quantities was not found to be an effective stabilizer for grundite. Addition of 2.5 percent portland cement in fact resulted in increased erosion over the untreated specimens, losses of well over 2 g/cm^2 being found for curing periods up to two weeks. Four weeks curing did produce partial stabilization at this level. Use of portland cement at the 5 percent treatment level did, however, provide effective stabilization (loss 0.2 g/cm^2) after 3 days of curing.

5.4 Basis for the Development of Erosion Resistance.

Soil stabilization attained with calcium hydroxide or with portland cement rests on the ability of these stabilizers to chemically react with at least portions of the soil to generate a) physicochemical responses resulting in rapid formation of permanently bonded aggregations of individual clay particles, and b) transformation of some of the particles to cementing materials, particularly calcium silicate hydrate gel. The latter is the main product of hydration of portland cement in the absence of soil, and is generally considered to be the effective cementing agent in portland cement concrete. Another reaction product produced in normal portland cement hydration is calcium hydroxide; thus portland cement may be doubly effective as a stabilizer, producing both primary cementing material in the form of calcium silicate hydrate gel, and also the secondary lime, itself being able to react with clay and other soil particles.

In general, the quantities of lime or of portland cement used in these experiments were far too small to permit assay of the reaction products by x-ray diffraction, and attempted use of differential thermal analysis for this purpose was also less than successful. However, scanning electron microscopy and energy-dispersive x-ray analysis provided the means to examine eroded surfaces and fracture surfaces of specimens treated with various contents of stabilizers. It was found that in favorable cases particles which had apparently been individual clay particles and were now apparently partly reacted with calcium silicate hydrate and "melded" together could be detected. A considerable content of blocky grains of a calcium bearing compound identified as calcium carbonate was found on eroded surfaces, some of which had peculiar holes present. Apparently the grains are derived from calcium hydroxide carbonating in the humid environment of the erosion test. Most important, it was shown that a network of reticulated calcium silicate hydrate spread among the grains, providing the basis for permanent tying together of the residual soil particles. This form of calcium silicate hydrate is an important feature of the hydrated paste in portland cement concrete.

This is not to suggest that the treated soils became concrete-like in any serious manner. The soils developed only limited mechanical strength and had to be handled very carefully; more important they retained their permeability, and much of the water drained through the one-inch thick specimens, rather than around them. The water content in the lower portions of the specimen rose rapidly from its initial optimum moisture content for compaction to essentially saturated levels. Nevertheless, it is clear that the basis for the development of erosion resistance in successfully-stabilized soils is the formation of permanent hydrated calcium silicate products similiar to those formed in ordinary concrete, and that in consequence the stabilization achieved should be considered as a permanent change in the behavior of the soil.

5.5 Summary of Preliminary Results.

All of the information cited in this section is derived from work reported in the first Interim Report of this project (1). It was found possible to construct an effective, comparatively simple erosion test device in whch a reproducible test rainstorm sequence of moderate intensity was applied to replicate small specimens of treated or untreated soil and the resulting erosion loss measured.

Application of this system to a Crosby B-horizon soil material and to a commercial acid-treated illite clay produced a number of results. Calcium hydroxide was shown to be an effective treatment cutting the erosion loss to a small fraction of that of the untreated specimens, but a week or more of curing was required. Portland cement was highly effective with the Crosby but required relatively large treatment percentages to successfully stabilize the acid-washed grundite clay.

Successful stabilization was correlated with other changes in the soil (development of water-stable aggregations, loss of sensitivity of pore structure to wetting and raindrop impact induced changes) and was shown to be associated with the formation of calcium silicate hydrate gel, suggesting that the effects of the treatments would be permanent.

6. EXPERIMENTAL RESULTS OF EROSION PREVENTION TREATMENTS WITH INDIANA SOILS

6.1 Soils Used for Testing.

After the conclusion of the preliminary work with the Crosby soil and with the grundite clay described previously, a series of four additional soils was collected from the field. These reflect a spectrum in clay content and in classification from a very sandy material with almost no clay ("glacial outwash" soil, a GM-GC soil in the Unified classification), through a low clay content SM soil with a PI of only 4 ("tan till"), through a silty clay soil with a clay content of about 20 percent and SC classification ("blue clay till") to a highly montmorillonitic heavy clay (CL-CH) derived from the Romney soil series and identified herein as "Romney Clay". In the second interim report of this project the tan till was somewhat inappropriately referred to as "tan clay till". Details of the characterization of each of these materials is given in the above mentioned report (2).

6.2 Erosion Loss Characteristics of Untreated Soils.

It was found that the untreated soils, compacted to the approximate standard Proctor maximum density at the optimum moisture content, had erosion losses varying from 1.1 g/cm^2 of exposed surface for the heavy montmorillonite clay Romney soil to over 2.5 g/cm^2 for the sandy glacial outwash soil. The relatively low clay content "tan till" had a higher loss (2.3 g/cm^2) than did the relatively high clay "blue clay till" (1.7 g/cm^2). This suggests a general inverse correlation of erodability with clay content, a fact generally in agreement with long-term experimental results which indicate that silt and fine-sand rich soils tend to erode most readily (9).

6.3 Effect of Lime Treatment With Full Compaction Applied.

Tests were carried out at the single treatment level of 1 percent by weight of soil, with compaction equivalent to full standard proctor compaction applied after mixing the soil and lime in the dry state. The "glacial outwash" soil which is the most erodable in the untreated condition, was effectively stabilized with only 3 days cure, the loss being less than 0.1 g/cm^2. The "tan till" behaved similarly; the "blue clay till" was not quite as well stabilized, losing 0.2 g/cm^2 after 3 days cure. Success for the Romney heavy montmorillonite clay was only partial, loss being cut only to 0.5 g/cm^2, with not much further improvement with time.

These results, and the effects of further curing periods, of up to 28 days are given in Fig. 1.

It is apparent that effective stabilization is attained where the clay content is not too high for reaction with the relatively small amount of added lime stabilizer; presumably raising the amount above 1% would have completely stabilized the Romney clay soil as well. Calcium hydroxide is thus confirmed as an effective soil stabilizing agent for rainstorm erosion control.

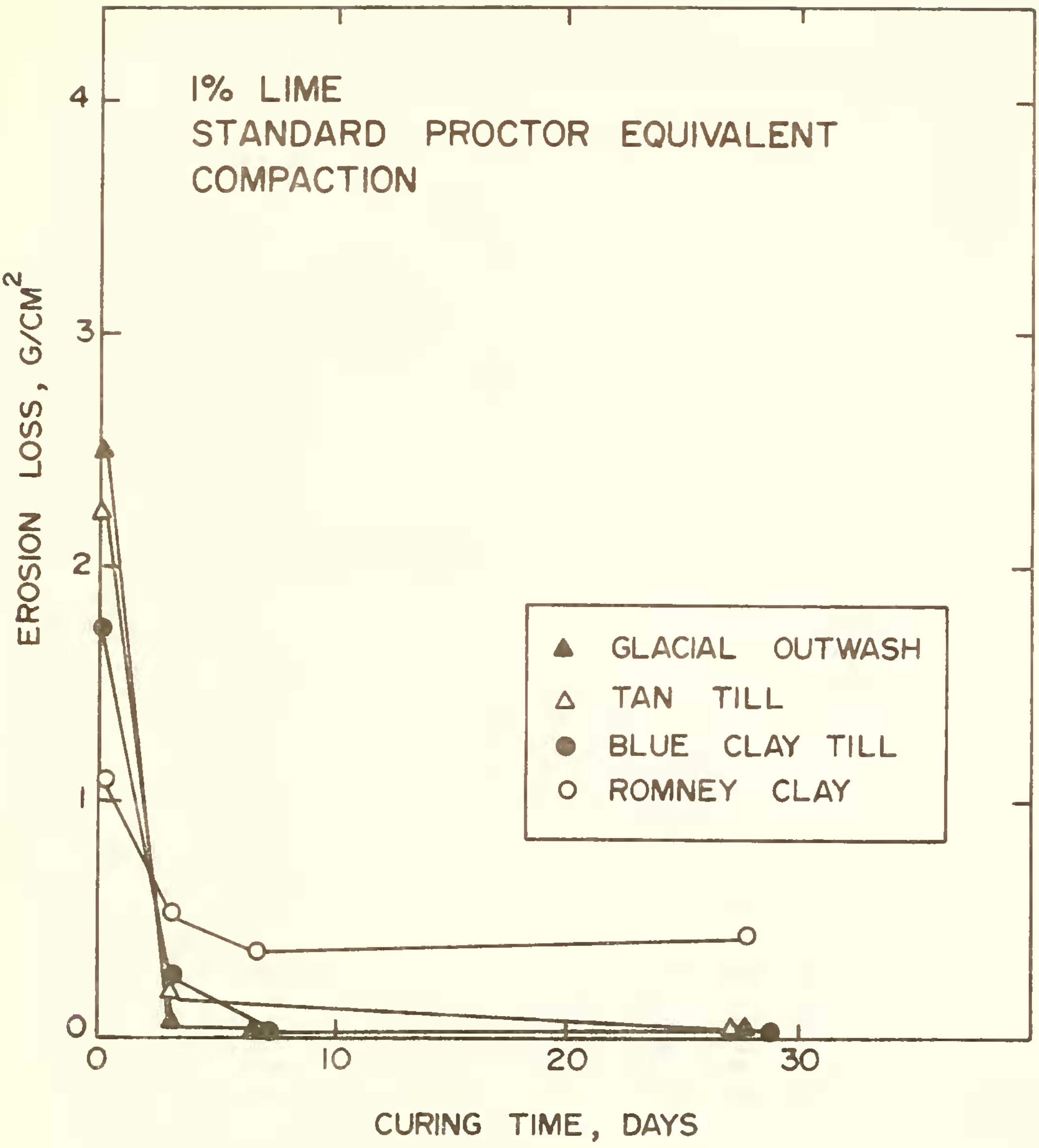

Fig. 1. Effect of 1% Lime Treatment on Erosion Loss of Soils as a Function of Curing Period.

6.4 Effect of Portland Cement Treatment with Full Compaction Applied.

Experimental trials similar to those just described for treatment with lime were carried out also with 1 percent portland cement. Since the response to portland cement treatment is generally considerably faster, curing was only carried out to a maximum of one week.

Portland cement proved to be even better than hydrated lime, successfully stabilizing all of the soils against erosion loss, including the Romney soil. The data are given in Fig. 2. It is thus clear that portland cement is equally, if not more, effective at low concentrations in establishing successful resistance to soil erosion from rainfall impact.

6.5 Effects of Reduced Compactive Effort.

One of the potential difficulties with respect to practical application of the treatments considered here is the application of compaction substantially equivalent to the normal standard Proctor compaction. In many areas for which such stabilization may be considered, the heavy equipment used to effect normal subgrade compaction may not be readily available when such treatment is contemplated, or indeed be suitable for the relatively steep slopes or restricted areas which need stabilization.

Thus an important phase of the present investigation was to determine quantitatively the effect of reducing the compactive effort, in stages, to a level so low as to reasonably simulate field density in the absence of any significant compactive effort at all. Reduced compactive effort was attained by lowering the number of hammer blows and the fall height of the hammer, to produce densities corresponding to anywhere from 95 to as low as 78 percent of the standard Proctor density of each of the

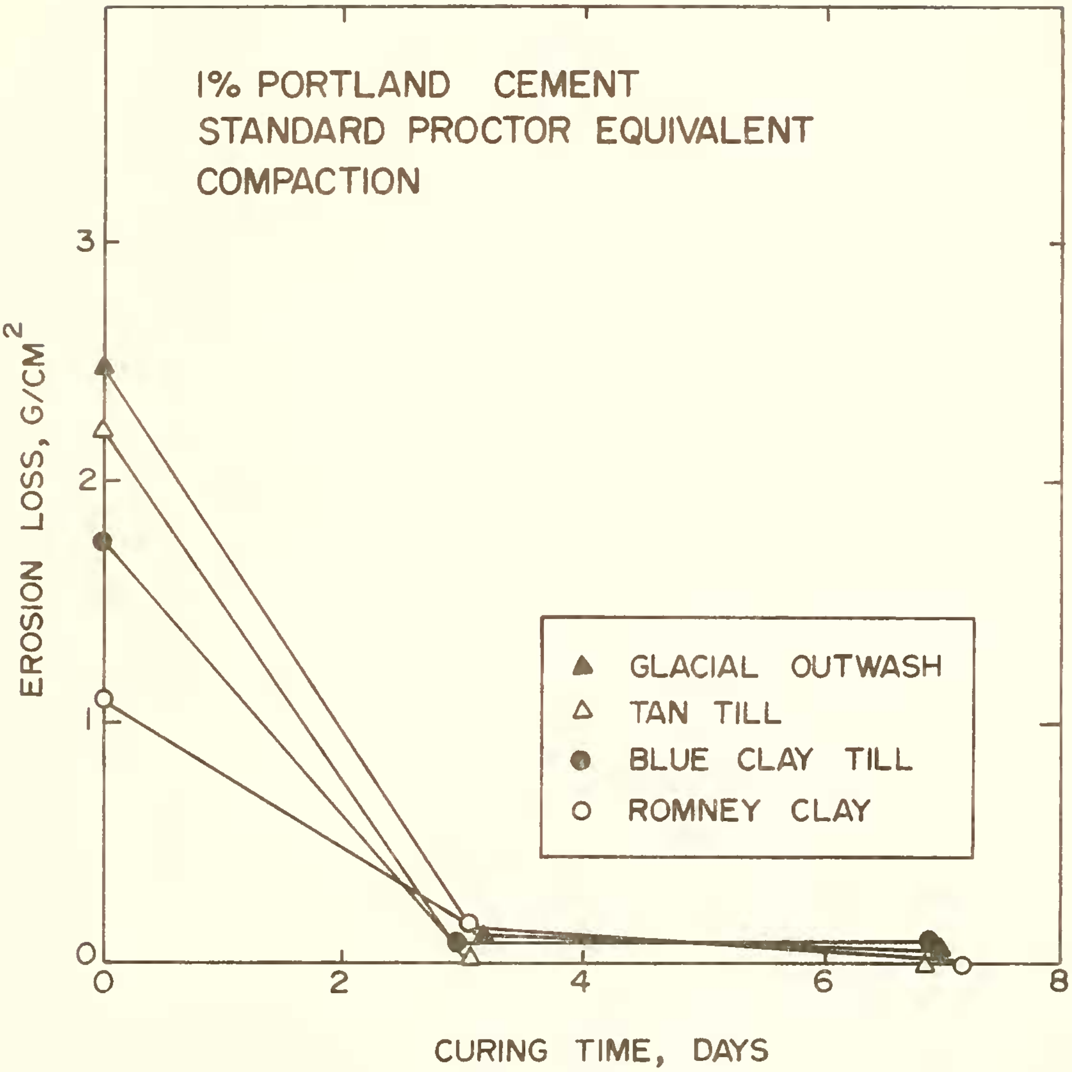

Fig. 2. Effect of 1% Portland Cement Treatment on Erosion Loss of Soils as a Function of Curing Period.

soils, the latter being a reasonable approximation to those of the original undisturbed soils. In each case the moisture contents used were adjusted to be optimal for the compactive effort actually applied.

6.51 Changes in erosion loss of untreated soils with reduced compactive effort.

It was found, somewhat surprisingly, that untreated soils compacted to lower than standard Proctor densities were more resistant to erosion than the same soils in the fully-compacted condition. The effects were rather large for all soils, except for the sandy "glacial outwash" soil. Over the full range of densities explored, the glacial outwash soil erosion dropped from 2.5 to 1.9 g/cm^2; the tan till from 2.3 to less than 0.7 g/cm^2; the blue clay till from 1.7 to an average of 1.0 g/cm^2, and the Romney clay from 1.1 to only 0.2 g/cm^2. These results are apparently explainable on the basis of the increased permeability and reduced swelling associated with the less highly-compacted materials, especially the heavier, clay-rich materials. These seem to have a natural structure that resists dispersion if sufficient permeability exists and little swelling takes place in the rainstorm test. Conversely, if highly compacted they are relatively impermeable, and tend to swell, disperse, and erode. Sandy soils are relatively unaffected by variations in compaction; permeability is high in any case, but there is little interparticle bonding and impact results in rapid detachment of the sand and fine silt grains under any circumstance.

6.52 Effect of reduced compactive effort on erosion resistance of lime stabilized soils.

The results for lime-treated specimens indicate that the degree of compaction strongly influences the rate at which erosion resistance is attained and in some cases, erosion resistance is not secured even after 28 days of curing, the maximum time examined.

The glacial outwash soil responds to a drop in compaction resulting in a dry unit weight of 90 percent of that of Proctor optimum by a delay in attaining effective stabilization, but this does occur by 28 days; reduction in compaction to about 78% of standard Proctor density (approximate field density) drops the erosion loss of the untreated soil, but further benefit from adding the lime is marginal. The tan till responds similarly, at least for the former condition; the extreme reduction treatment was not tested. The data for these soils is given in Fig. 3.

A full spectrum of degrees of compactive efforts was applied to the blue clay till. The less the compaction, the less the improvement in erosion resistance in the early stages (up to 7 days) but by 28 days all specimens, including those compacted to only about the original field density, were satisfactorily stabilized, having erosion losses of 0.2 g/cm^2 or less. These data are shown in Fig. 4.

It was found that for Romney clay, reduction of compaction to yield about 80 percent of normal standard Proctor density resulted in a soil resistant to erosion even in the absence of stabilizer. One percent lime treatment conferred no further erosion resistance; however, a special trial at 3% lime addition effectively eliminated all soil loss and completely stabilized the soil by 28 days. These data are shown in Fig. 5.

Thus it has been shown that moderately decreased compaction results only in slightly delayed development of erosion resistance with

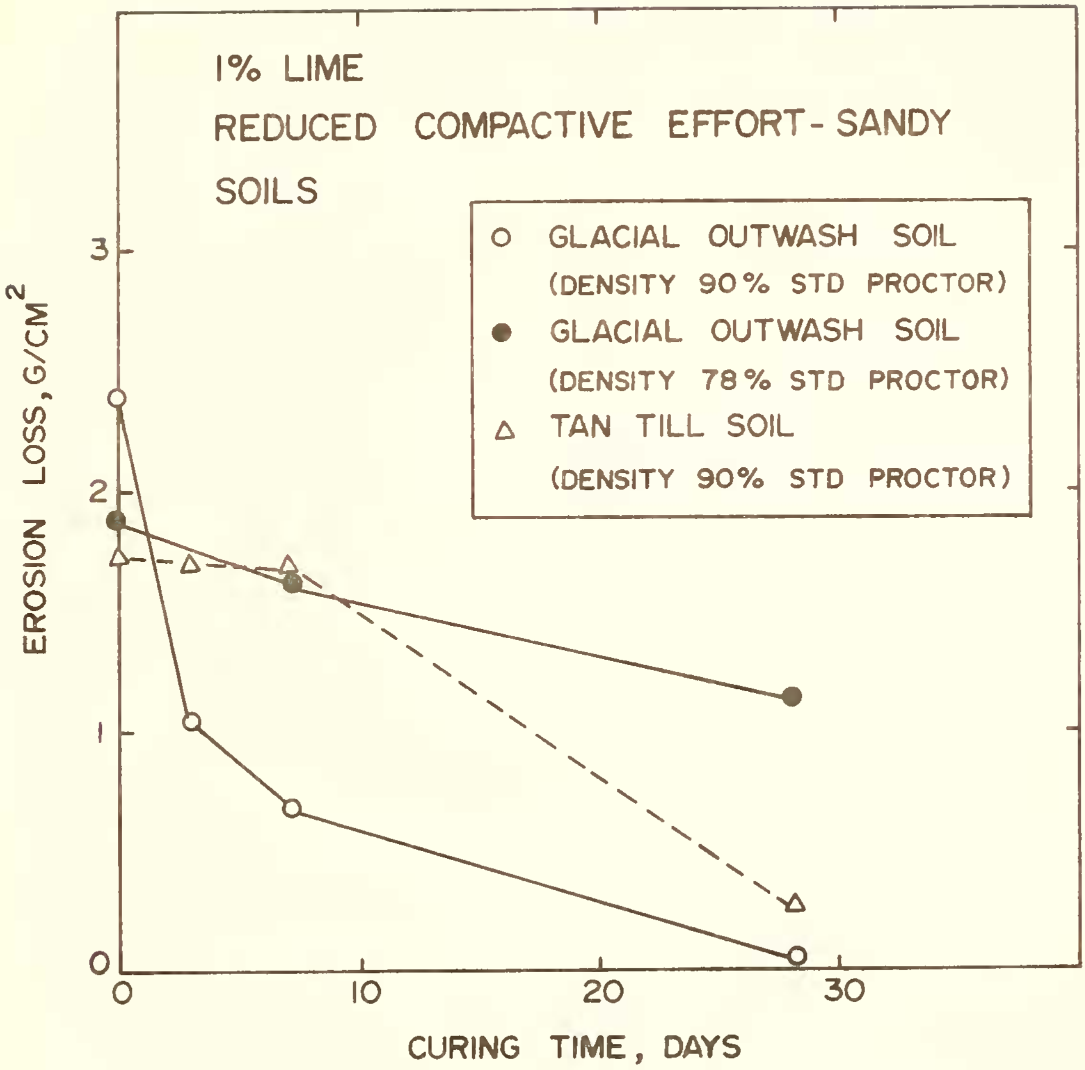

Fig. 3. Effect of 1% Lime on Erosion Loss of Sandy Soils Compacted at Reduced Compactive Effort, as Functions of Curing Period.

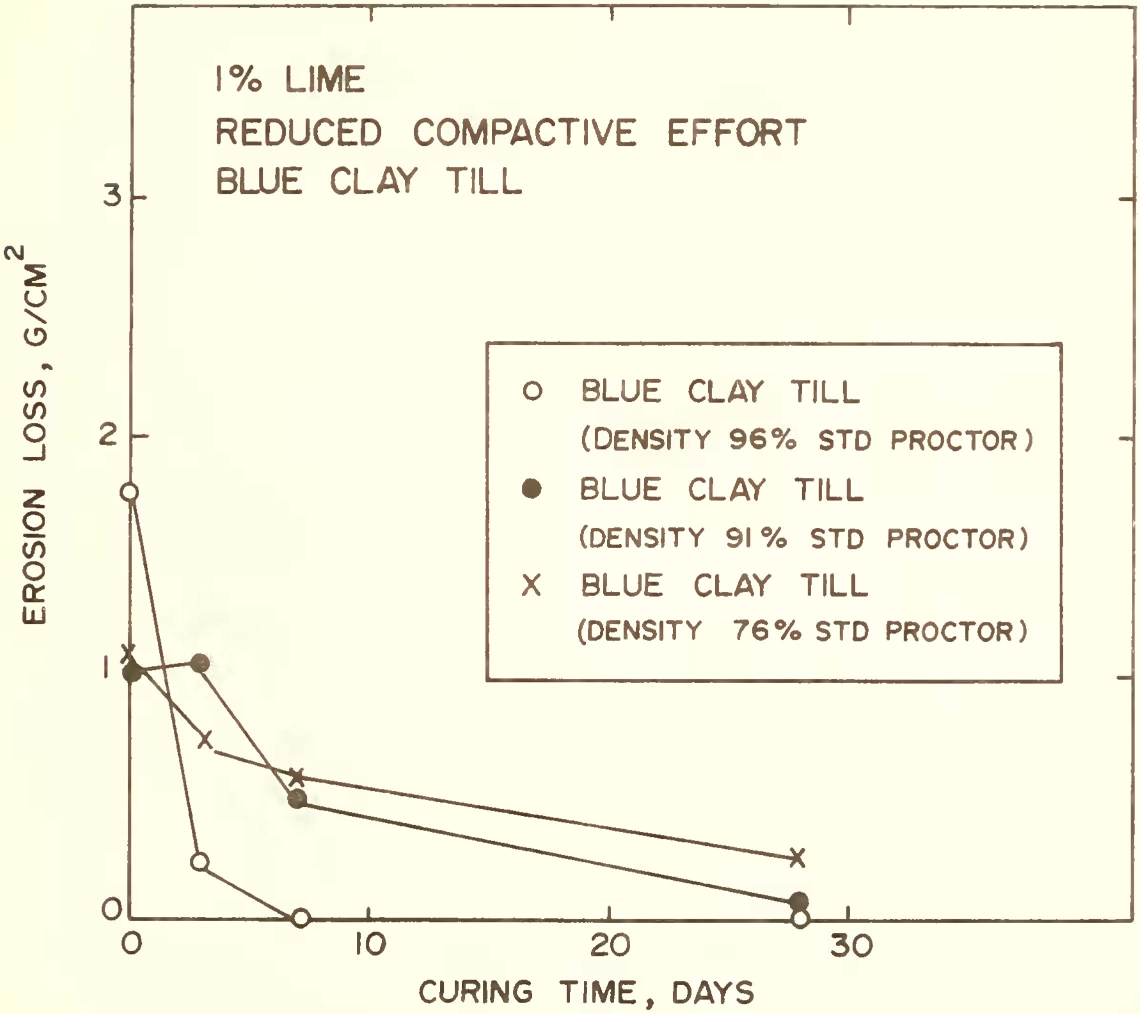

Fig. 4. Effect of 1% Lime on Erosion Loss of Blue Clay Till Soil Compacted at Reduced Compactive Efforts, as Functions of Curing Period.

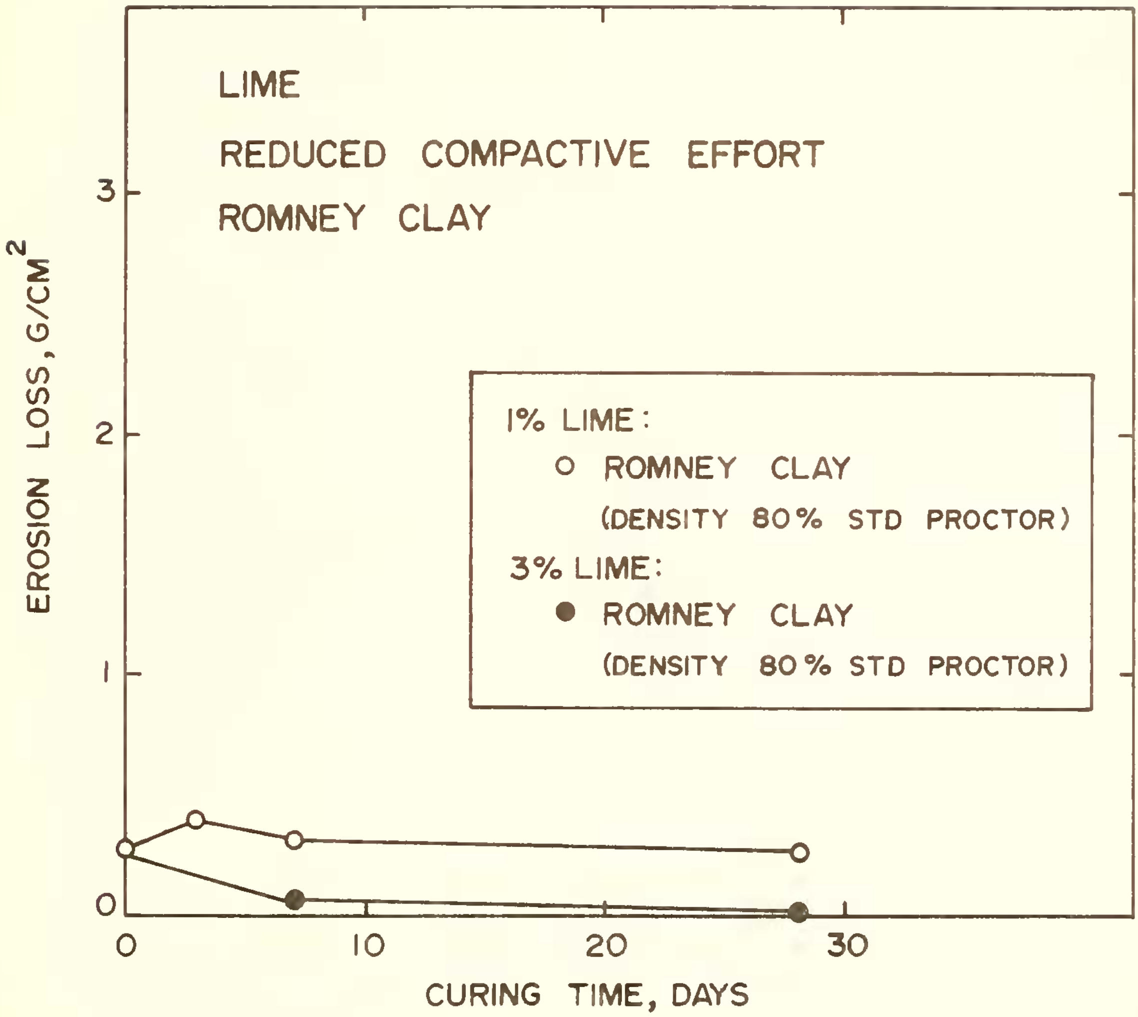

Fig. 5. Effect of Lime on Erosion Loss of Romney Clay Soil Compacted at Reduced Compactive Effort, as a Function of Curing Period.

lime treatment, but that almost completely uncompacted soils may lose much of the benefit of the addition. The situation is complex, however, since untreated, lightly compacted soils are apparently inherently less erosive than fully compacted ones. It appears that if increased amounts of lime were used, such soils may attain a large measure of protection from erosion without significant compactive effort being applied.

6.53 Effect of reduced compactive effort on erosion resistance of portland cement stabilized soils.

Similar experimental trials at reduced compactive efforts showed that the influence of portland cement stabilization is somewhat less dependent on the level of compaction than is the influence of lime stabilization.

For glacial outwash soil, full stabilization was attained by seven days even with the lightest compaction, resulting in only 78 percent of standard Proctor density. Similar results were obtained with the blue clay till soil. With the tan till, at 90% of standard Proctor density (the only reduced effort tried), effectively complete stabilization was attained in 3 days. Thus portland cement treated soils respond quite well to reduced compactive effort.

The results with the Rommey clay were entirely similar to those described above with respect to lime treatment. Again at a density of 80 percent of standard Proctor, there was no improvement over the already excellent resistance of the untreated soil itself by a 1 percent addition; and again, addition of 3 percent of the stabilizer, in this case portland cement, resulted in effectively complete stabilization.

6.54 Summary of the effects of reduced compaction.

Reduced compaction seems to have a number of effects:

a) for untreated soils (except sands) the erosion resistance is considerably better than it is for fully compacted specimens of the same soil.

b) for lime additions at the 1 percent level, the time required to attain effective stabilization is prolonged, and with sufficiently low compaction, some soils may never attain that condition. Heavy clays, on the other hand, are reasonably erosion-resistant at very low compaction efforts, and get no improvement from 1 percent lime treatment. They do respond very successfully to 3 percent lime.

c) for portland cement additions at the 1 percent level, good erosion resistance is conferred in from 3 to 7 days, regardless of the degree of compaction, except that again, heavy clay soils require more stabilizer.

In general it appears that the use of a somewhat larger application of portland cement will make up for the tendency to lose effectiveness in the absence of full stabilization; increases in lime content may also be satisfactory if prolongation of the curing period is not a serious problem.

7. DEVELOPMENT AND TESTING OF SLURRY APPLICATION TREATMENTS

7.1 Introduction.

Under some circumstances it is either impractical or inadvisable to attempt to stabilize soils for erosion control purposes by methods in which the stabilizer is mixed into the soil in the dry state.

Sometimes mixing equipment is unavailable or unsuitable to the terrain; sometimes nearness to occupied urban areas renders the possibility of dust emission into the atmosphere (especially with lime) unacceptable, either legally or from a community relations standpoint.

Under such circumstances a treatment where the lime or cement stabilizing agent is incorporated into the soil in the form of a slurry would be most welcome, if in fact such treatment were effective. Use of lime slurries in soil stabilization for building foundations, and to a lesser extent, for highway subgrade uses has become reasonably routine; for example, the foundations of the terminal structures of the Dallas-Fort Worth airport have been treated in this fashion. To the knowledge of the writer, only lime has been used in this fashipn; cement slurries have not been proposed or used, perhaps because of the potential practical difficulty associated with premature setting of the cement.

It appeared to the writer that such slurry treatment might offer good potential in stabilizing soils against erosion losses on construction sites, from both practical and economic points of view. A series of laboratory investigations of the potential effectiveness of such treatments in producing an erosion-resistant condition in the soil was then carried out.

7.2 Results of Slurry Treatments Using Hydrated Lime.

It is obvious that slurry applications of stabilizers, in order to be effective in this context, must penetrate the soil to a reasonable depth. The penetration is obviously related to three factors: the permeability of the soil, its existing degree of saturation prior to the application of the slurry, and the effective viscosity of the slurry itself. The latter is of course a function of the concentration of suspended solids.

After a series of preliminary trials it was considered that appropriate measurement of the potential of such treatments would be obtained by (1) reducing the level of compaction to that yielding densities in the range of 90 to 95 percent of standard Proctor density (or less), (2) insuring that the moisture content be at approximately the optimum moisture content for compaction at that level prior to application of the slurry, and (3) applying the stabilizer in a slurry of approximately 10 percent solids content. In general, 55 ml. of slurry was added to each specimen; the water percolated entirely through the 1 inch-thick specimen in all cases, and ran out the bottom as a clear fluid. Penetration of the solid stabilizer particles generally was on the order of more than half of the specimen thickness, and after reasonable curing a layer of 3/8 in. to half an inch or more was found to be mechanically knit together. Some lime was always deposited as a surface film on the outer specimen surface.

It is not possible to give a meaningful figure for the "level" of application in the same way that was given for mixed specimens, since the distribution of lime in the solid was non-uniform. The amount applied, however, was of the order of 1.5 percent of the total soil weight of the 1-in. thick specimens.

The treatment was relatively ineffective for the sandy glacial outwash soil, erosion loss being as high as 1.75 g/cm^2 after 7 days of curing. However, given sufficient curing time a reasonable erosion control potential was established even for this soil; after 28 days the loss was only 0.1 g/cm^2.

The other two soils tested, the blue clay till and the Romney Clay, both showed excellent stabilization potential. For the blue clay till it was found that erosion under the test rainstorm was cut to 0.05 g/cm^2 or less by seven days of curing. Two levels of compaction were imposed on the soil before adding the slurry, yielding densities equivalent to 76% and to 93% of standard Proctor density for this material. Erosion resistance was substantially identical for both degrees of compaction, indicating effective penetration in both cases.

Somewhat surprisingly, even the heavy montmorillonite Romney Clay responded very favorably to such treatment; here erosion loss in the standard test sequence was reduced to a negligible 0.03 g/cm^2 by seven days of cure.

In general, it appeared that the use of slurry application of lime had real potential in terms of erosion resistance. The treatment appears to be most efficient in terms of placing the lime where it is most needed, i.e. in a relatively thin layer at the surface of the soil. On the other hand, such a treatment perhaps may be vulnerable to the influence of heavy equipment movement in terms of breaking up the crust that is providing the protection, and this treatment should be considered when evaluating the potential of such treatment for field evaluation.

7.3 Results of Slurry Treatments Using Portland Cement.

In preliminary trials it was found that portland cement slurries responded about as did the lime slurries in terms of applicability. It was decided to use the same slurry concentration (10 percent by weight) and the same application conditions, in preparing such specimens.

With the sandy glacial outwash soil, the use of portland cement slurry was highly successful; losses in the erosion test were cut to the low value of only 0.15 g/cm^2 in three days cure, for specimens pre-compacted to 95% of Proctor optimum; for specimens whose density was similar to the original field density (78 percent of standard Proctor optimum), a similar response was obtained by 7 days. Thus for sandy soils, it appears that portland cement slurries are effective, while lime slurries are effective only after prolonged curing.

For the blue clay till soil, specimens compacted to 93 percent of standard Proctor densities yielded excellent results after 7 days cure, only 0.05 g/cm^2 being lost; similar, but not quite as good results were obtained for specimens compacted to approximate original field density (76% of standard Proctor density). Thus this soil, intermediate in textural gradation, is readily stabilized by either portland cement or lime slurries.

The Romney Clay did not respond well to cement slurry treatment; soil losses of 0.3 g/cm^2 persisted after as much as 7 days cure for specimens compacted only to simulated original field density. Thus this heavy clay is seen to respond very well to lime but poorly to portland cement in this form of application.

7.4 Summary of Erosion Resistance of Soils Treated by Slurry Applications.

It appears that there is considerable potential for slurry treatments in giving rise to effective soil erosion control on construction areas. The present results indicate that applications of reasonable quantities of such slurries to the surfaces of soils either at approximately original field density, or compacted to modest extents can produce essentially complete resistance to erosion loss by raindrop impact. The results suggest that lime applications may be better for heavy clay soils, and that portland cement applications seem to be very satisfactory for sandy soils, where lime is relatively unsuccessful.

8. POSSIBLE USE OF WASTE CEMENT PLANT DUST AS A STABILIZER AGAINST EROSION LOSS ON CONSTRUCTION SITES

8.1 Introduction.

The possible activity of waste cement plant dust (kiln dust) as a stabilizer capable of being used in the same way as hydrated lime or portland cement is of considerable interest. Such material can no longer be vented into the atmosphere except under severely restricted conditions, and in consequence is being collected in large quantities at cement plants all over the country. Disposal of the material presents the cement industry with serious problems, and a potential use such as this one, if practical, would be welcomed. Needless to say the material cost should be significantly less than those for either portland cement or hydrated lime.

Waste cement dust obtained from the Lone Star Industries plant at Greencastle, Indiana, was used in a series of trials not previously reported. The specimens were prepared in the manner previously described, although contents of the prospective stabilizer used were in general higher than the 1 percent level adopted in most other trials.

8.2 Examination of Cement Dust.

The composition of cement dust varies considerably; it may have constituents derived from the kiln feed (i.e. the limestone and clay or other source of silica), but much of the material is at least partially burned. The concentration of alkalies and of sulfate is normally high.

Laboratory determinations indicated that close to 20 percent of the cement dust as supplied is immediately soluble in water (standard 10-min. shaking test). X-ray diffraction analysis of the insoluble portion, roughly 80 percent of the whole, yielded peaks for calcium carbonate and for mixed-layer clay minerals. X-ray diffraction of the original as-supplied dust indicated that a small content of free lime, CaO, is present. The solutions dissolved from the sample in the 10-minute shaking test were recrystallized by evaporation, and found to contain potassium chloride, gypsum (calcium sulfate dihydrate) and several other recrystallized substances not identified.

The important compositional feature insofar as the present experiments are concerned is the content of free calcium oxide, combined with the relatively high content of alkalies. A check on the pH of a 1 part dust to 1 part water slurry yielded a pH value of 12.78. This is approximately the same pH that would be secured by a portland cement slurry, i.e. one reflecting at least a saturated calcium hydroxide solution, augmented in hydroxyl content probably by alkali hydrolysis. Thus the cement dust is a material at least potentially able to react with soil consituents in the same manner as calcium hydroxide or portland cement.

8.3 Erosion Resistance of Cement Dust Treated Soils.

A considerable number of trials were carried out using various percentages of cement dust mixed with the soil and compacted to various degrees. Essentially all of this work was performed on the blue clay till soil.

It was found that excellent stabilization could be attained using 5 percent of the cement dust, and employing compaction equivalent to that required to attain standard Proctor density. This was true provided that the moisture content was slightly on the wet side of the optimum moisture content for the soil itself. The optimum moisture content for blue clay till was approximately 10 percent moisture (for this level of compaction). Specimens mixed at 13 percent moisture were sufficiently stabilized at 1 day to lose only 0.13 g/cm^2 of surface in the standard rainstorm test sequence. By 7 days the loss was completely negligible, being only 0.01 g/cm^2.

On the other hand, specimens with the same cement dust content, and compacted to roughly the same density, but at moisture contents on the dry side of the optimum moisture requirement (around 9 percent moisture) did not perform as well. Such specimens lost 0.6 g/cm^2 after 1 days curing, about the same amount after 3 days, and it was 7 days before effective erosion control (0.1 g/cm^2 of loss) was achieved. Further curing of relatively dry specimens did reduce the erosion loss to essentially nothing, 0.02 g/cm^2 at 14 days. Thus the rate of attainment of erosion resistance with cement dust is sensitive to moisture content, being much slower if the soils are mixed and compacted slightly dry of the effective optimum moisture content; but highly effective stabilization is attained even in such cases after several weeks.

Reducing the content of cement dust to 2.5% resulted in equally good results; with appropriate moisture content (12 - 14 percent) and compaction to standard Proctor density, losses after only 1 days curing again averaged about 0.13 g/cm^2, and by 7 days were down to the very low value of 0.05 g/cm^2. An illustration of the appearance of two of these specimens is provided in Fig. 6. Corresponding photographs for most of the treatments previously discussed have been published earlier (1, 2). Again, compaction on the dry side of optimum moisture content (8.5 -9 percent moisture) delayed the attainment of satisfactory erosion resistance somewhat, but by 7 days the loss was down to 0.22 g/cm^2.

Only a few trials were made at the 1 percent treatment level. These specimens were compacted slightly on the dry side (between 9 and 10 percent moisture), and did not yield satisfactory stabilization, the losses being greater than 1 g/cm^2 even after 7 days of curing. Since the content of active stabilizer in the cement dust itself is not particularly high, it is doubtful that treatment at the 1 percent level would prove to be practical.

The effect of reducing the compactive effort was also explored for cement-dust treated blue clay till specimens treated with 2.5 percent cement dust. In one series of trials the number of compaction blows was cut in half, reducing the density to about 95% of standard Proctor. The effect was to appreciably increase erosion loss at 1 day (0.60 g/cm^2 compared to about 0.13 g/cm^2 at full compactive effort). By 28 days negligible loss of soil was recorded (0.05 g/cm^2). Reducing the compactive effort still further, to densities only about 80-85 percent of standard Proctor, yielded losses of approximately 0.25 at 7 days and again at 28 days, suggesting reduced stabilization effectiveness. Thus it appears that with cement dust at reasonable treatment levels, modest reduction in compactive effort only slightly delays effective stabilization against erosion; major reductions in compaction are tolerable, but yield a

Fig. 6. Appearance of Specimens After Exposure to the Standard Rainstorm Test Sequence:

a. (above): Blue clay till incorporating 2.5% cement dust, compacted to standard Proctor density, and cured for 7 days prior to exposure. Erosion loss averaged 0.04 g/cm^2.

b. (below): Romney clay incorporating 5% cement dust, compacted to standard Proctor density, and cured for 7 days prior to exposure. Erosion loss averaged 0.6 g/cm^2.

measureably less effective, although still somewhat erosion-resistant product.

A single set of trials was carried out to check the effectiveness of cement dust as an additive to the heavy montmorillonite Romney Clay soil. An admixture of 5 percent cement dust was used, and compaction to the equivalent of standard Proctor density was carried out at a moisture content of 20 percent, slightly on the dry side for this soil. The extent of stabilization achieved after 7 days cure was marginal, an erosion loss of 0.6 g/cm^2 being recorded in the standard rainstorm test sequence. The appearance of such specimens is illustrated in Fig. 6. The Romney soil similarly compacted without additive loses about 1.1 g/cm^2.

8.4 Summary of Results and Interpretations Concerning Possible Use of Cement Dust.

It has been definitely established that cement dust may serve as an effective stabilizer of soils from the point of view of conferring resistance against rainfall-induced erosion. The "active agent" in the dust is apparently free CaO, augmented by alkalies present; the major constituents, $CaCO_3$ and some clay, are presumably inert.

With a "medium-textured" soil of reasonable clay content (about 20 percent) treatment at 5 percent cement dust and compaction to yield standard Proctor densities is almost immediately effective, but only if the moisture content is on the wet side. Similar treatment with 2.5 percent cement dust is equally effective, but a level of 1 percent apparently is not sufficient for proper soil reaction.

It is possible to reduce the compactive effort without serious consequence; even a compacted density not much higher than the original field density results in reasonably satisfactory stabilization at the 2.5 percent treatment level.

Possible applicability of cement dust treatment in slurry form was not tested, but there appears to be no reason why such treatment should not be equally effective as with portland cement or hydrated lime.

9. COMPARISON OF THE EFFECTIVENESS OF STABILIZATION EROSION CONTROL TREATMENTS WITH OTHER METHODS

The work reported here has indicated that the various stabilization treatments are effective in reducing and in some cases in virtually eliminating erosion of soil from small specimens exposed to a severe standard test rainstorm sequence.

There are a number of ways in which erosion from construction sites has been controlled in the past, and new methods have been developed and effectively marketed for this purpose in recent years. While a number of alternative methods such as the use of wood chips, stone mulches, etc. simply are not compatible with the small-size specimens used in these experiments, it is possible to get some information on how a few of the alternative treatments might do in a test such as the one used here. This would provide some basis, even though an inadequate one, for comparison of the effectiveness of the different kinds of treatment.

In the present experimental program, compacted but otherwise untreated soils have been found to erode at a rate of between 1.7 and 2.5 g/cm^2 of exposed surface, which is equivalent to roughly 80 to 120 tons of soil per acre, in the standard rainstorm test sequence.

An exception has been noted for the heavy montmorillonitic Romney Clay soil, which is considerably more resistant than the others. It has also been found that untreated soils compacted only lightly do somewhat better in the erosion test.

One direct comparison with what might be effected by "conventional" erosion control was provided in results for a series of specimens of the Crosby soil which was compacted without stabilizer, the top surface loosened, and a planting of Alta fescue grass established from seed. The grass was grown to an initial height of about three inches, then trimmed every few weeks to a 2 inch length. After approximately three months a thick stand of grass completely covered the soil surface. The specimens were than exposed to the standard rainstorm sequence in the same way as the stabilized soil specimens have been. It was found that despite the heavy grass cover, which was substantially matted down from the effects of the rainstorm, the loss of soil averaged 0.5 g/cm^2 of soil surface, the equivalent of about 24 tons/acre. In trials with the same soil, a 2.5% portland cement treatment reduced the soil loss to 0.02 g/cm^2, (less than 1 ton/acre) with only a 1 day cure. It is thus apparent that the kind of stabilization provided by appropriate cement (or lime, or cement dust) application may be much more effective than stabilization by providing a dense grass cover.

Recently a number of firms have marketed various forms of netting or non-woven fabric designed for the purpose of resisting erosion primarily by encouraging the growth of grass. One such material, consisting of rather wide-spaced jute fiber mesh, was tested in the standard rainstorm test sequence, being applied directly over a full-compacted but otherwise untreated blue clay till material. The resulting soil loss was considerably reduced over that of the soil alone, amounting to 0.11 g/cm^2 or roughly 5 tons/acre. The effect is presumably due to reduction of impact of at least some of the drops which do not hit the soil surface directly. An illustration of such specimens is provided in Fig. 7. The erosion resistance tallied is surprisingly good, but not as good as that of 1 percent portland cemet treatment after 3 days or 1 percent hydrated lime after 7 days, both of which yielded results below 0.013 g/cm^2 (about 0.6 tons/acre).

10. PROSPECTIVE FIELD APPLICATIONS

It appears that in the light of the present results it should be possible to stabilize construction sites against erosion either on a temporary basis until permanent construction features are on the ground, or as part of a permanent program for areas that will not be covered by pavement or other structures.

Use of conventional mixing and compaction equipment, where appropriate, should provide efficient and economical mixing and compaction, in much the same way that is normally done for soil stabilization of subgrades. The only differences would involve a significantly decreased content of stabilizer, and a significantly thinner required depth of treatment. The present results suggest that for many soils, treatment as low as 1 percent of portland cement or lime would effectively confer erosion resistance in a brief period. Probably, one should consider 2 or 2½ percent as more nearly appropriate, since mixing is bound to be less than perfect, and since curing in the field will probably be less effective than

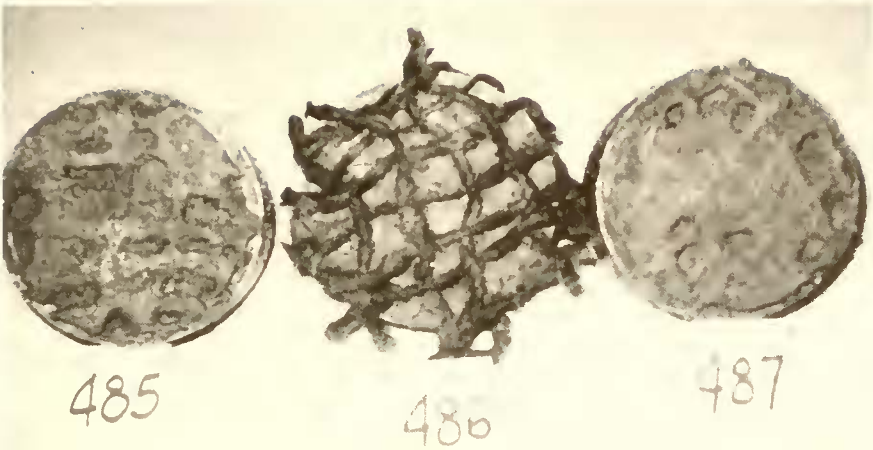

Fig. 7. Specimens of Blue clay till compacted to standard Proctor density and covered with jute netting product prior to exposure to test rainstorm. Specimen in center shown with netting present. Erosion loss averaged 0.11 g/cm^2.

laboratory curing. There seems to be no intrinsic requirement for a minimum depth of material to be treated, but practically speaking, it would seem that a two-inch layer would probably be the minimum that field equipment could effectively mix and compact. Since the requirements are not very stringent with respect to compaction, it may be that mixing with agricultural-type equipment and compaction by truck or other wheeled vehicular traffic may prove sufficient, especially in less critical situations.

The use of light equipment is almost mandatory on side slopes and back slopes where conventional heavy mixing and compaction equipment is not easy to operate.

Alternatively, application of slurry treatments seems to be a viable possibility. There are obvious equipment problems that would have to be met in this context. All of the stabilizer slurries contemplated are highly alkaline, with a pH of 12.5 or higher. Corrosion of equipment may be accelerated under these conditions. Portland cement slurries can "set up" in the equipment, especially if low water contents are inadvertently provided. However this is extremely unlikely for slurries of anywhere near the 10 percent solids content suggested.

One possibility that has been raised is the potential use of conventional hydroseeding equipment to apply the stabilizer in slurry form. This may or may not be practical.

Another related possibility is that of combining portland cement treatment with eventual provision for grass or other vegetative cover, especially for side slopes and other areas that will not be covered by paving or permanent structures. It has been shown experimentally that at least one common variety of grass will germinate readily and grow normally to yield a full stand on soil specimens that have been treated with portland cement, either mixed in or applied by slurry application. The portland cement treatment would provide almost immediate protection against severe storms; after a few months the vegetative cover will mature and supplement the erosion protection, while at the same time providing a more pleasing appearance.

It has been shown that hydrated lime cannot be combined with provision for vegetative cover in this fashion, since grass (and presumably other plants) will not germinate or grow on soil specimens treated with lime. Very likely the same situation would hold for specimens treated with cement dust.

Before serious consideration to full scale use of cement and lime erosion control treatments is attempted, it is wise to consider the limitations of the present study. It has been shown clearly and conclusively that small scale laboratory specimens can be well stabilized against a severe rainstorm test sequence by appropriate addition of small amounts of the agents mentioned. However, no facilities have been available for large scale testing. In particular, the test procedure does not measure the resistance of the stabilized soil to erosion by running water, especially down long, steep slopes. Indications that under "reasonable" conditions, such erosion is dependent on prior particle detachment by impact of individual raindrops (5) are encouraging and suggest that the present treatments will be useful in preventing or resisting such erosion as well. Indeed, several authors have measured resistance to scour of cement stabilized soils in connection with their use in drainage ditch linings, and have found satisfactory results (7). Nevertheless, it is highly appropriate that before practical applications are attempted, a program of field testing of stabilization treatments of the type contemplated here be carried out by some agency or group of agencies.

11. ECONOMIC CONSIDERATIONS

A projection of costs of the prospective treatments contemplated here and a comparison of these with costs of other erosion control measures has been carried out and reported previously (2). In brief, under 1974 economic conditions in Indiana, mixing and compaction treatments using reasonable levels of cement or of hydrated lime were estimated to cost a little less than $4,000 per acre. If application of portland cement slurry by use of hydroseeders proves practical, such applications could be carried out for about one-third of this cost, or about the same as conventional treatment of prospective grassed areas by hydroseeder application of fertilizer, agricultural lime, seed, and mulch. If the portland cement/grass seeding applications could be combined, the combination would cost little more than either treatment alone. Similarly, incorporation of seed and fertilizer in a "mix and compaction" treatment would add little to the cost of such treatment by itself. All of these treatments appear to be only half as costly as the application of sod, which under the conditions evaluated was estimated to cost about $8,000 per acre.

12. CONCLUSIONS

Laboratory scale experimental results have shown that small quantities of portland cement, hydrated lime, or waste cement kiln dust can confer a high order of resistance to soil erosion by raindrop impact. The standard test sequence consisted of intensities of 3¼ in. per hour of rainfall applied for one hour on each of two successive days, involving a total of 6½ in. of rainfall and constituting a severe challenge to any erosion-prone soil.

Soil specimens of a variety of types from sandy to very heavy montmorillonitic clay were examined. It was found that most soils lost the equivalent of 80 to 120 tons per acre when exposed to the test rainstorm after compaction to standard Proctor density. Reduction in compactive effort seemed to decrease the erosion loss somewhat.

Soils containing one to several percent of either hydrated lime or portland cement, when mixed dry, brought to the optimum moisture content, and compacted to standard Proctor density, were found to have developed strong resistance to erosion, the erosion loss typically falling to less than 10 tons per acre, and in some cases to less than 1 ton per acre. In general, specimens treated with lime required a week or more of moist curing to achieve this result; soils treated with portland cement became erosion-resistant within 1 to 3 days.

It was found that waste cement kiln dust is equally effective, but that a slightly higher amount might be required, and care was needed to insure that compaction was carried out on the wet side of the optimum moisture content.

It was found that much if not all of the benefit could be retained with most soils if compaction were reduced, and significant benefit was accrued even in the practical absence of compaction, i.e. when the specimens were prepared at densities approximating those of the original soils in the field.

Slurry applications of both lime and of portland cement were found to also be effective, particularly when made at slurry concentrations of the order of 10 percent by weight, and where the soil was at a reasonable moisture content approximating its optimum, and where it had been compacted only lightly so that penetration of the stabilizer was effective.

The order of erosion resistance conferred by lime, cement, and cement dust treatments was found to be superior to that characteristic of a dense stand of resistant grass, exposed to the same test situation. It appeared to be superior to that potentially conferred by open-textured fabrics whose chief function seems to be promoting grass development.

It was found that portland cement treatments could be combined with grass or other vegetative treatment, the cement addition having no ill effect on the germination and growth of the grass. This is not true of hydrated lime treatments.

The stabilization effected was found to stem from permanent chemical reactions with the soil minerals, involving generation of calcium silicate hydrate gel, and as such, was considered to be essentially irreversible.

The economics of prospective treatments were examined and found to be not unreasonable in view of the benefits conferred, and by comparison with other treatments for the reduction or prevention of soil erosion.

The test sequence involved resistance of the treated soil to erosion produced by raindrop impact. Resistance to rill and gully erosion by running water was not specifically examined, although there is reason to believe that the treatments would be reasonably effective in conferring resistance to such erosion as well. Testing, preferably on a field scale, should be carried out before soil treatments of the kind contemplated here are applied in practice.

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