

STABILIZATION OF CLAY SOILS AGAINST EROSION LOSS

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Abstract—Accelerated soil erosion from construction sites and the resulting increase in downstream sediment load constitute a significant environmental problem. Laboratory studies indicate that small percentages of hydrated lime or of Portland cement will stabilize clay soils against rainstorm erosion by preventing particle detachment. Coordinated measurements of the size distribution of water-stable aggregates, of pore size distribution by mercury porosimetry and of microstructure by scanning electron microscopy and energy dispersive X-ray spectrometry were used to clarify aspects of the mechanisms responsible for the development of erosion resistance. Attainment of such resistance was marked by aggregation of a significant part of the clay into water stable aggregations of the order of several mm in size and of minimal change in porosity and pore size distribution on exposure to the test rainstorms. At least some of the clay particles in the aggregations appeared to be partly converted to calcium-bearing reaction products and formation of the "reticulated network" variety of calcium silicate hydrate gel linking adjacent particles was demonstrated.

INTRODUCTION

Accelerated soil erosion from construction sites during the period that such areas are denuded of their natural vegetative cover before permanent pavements, water-channeling structures and grass or other plantings are provided, represents a serious environmental problem in many localities (Younkin, 1973; Thronson, 1971; Thronson, 1973; Roberts, 1974, etc.). The present paper represents work done in a project aimed at developing an expedient and relatively inexpensive means of preventing such accelerated erosion. The methods explored involve incorporation of small amounts of known soil stabilizers such as calcium hydroxide or Portland cement. In order to evaluate the effectiveness of such treatments, rainfall simulation equipment was designed with the specific capability of testing resistance to erosion of a large number of specimens of soil stabilized in various ways. Full details of the design, construction and operating characteristics of this equipment were provided by Diamond and Kawamura (1974). This equipment was used to evaluate the resistance of test stabilized soils to erosion arising from the impact of raindrops delivered in a standard test rainstorm sequence. The present paper reports the results of some of these tests, together with the results of investigations aimed at clarifying the mechanism by which the erosion resistance is conferred.

It should be noted that the results obtained do not necessarily reflect the ability of the stabilized soils to resist erosion caused by running water over steep slopes, a situation in which channeling and rill forma-

tion often occur. However, it has been established by Young and Wiersma (1973) that soil detachment due to raindrop impact is the major cause of erosive loss in sheet erosion.

MEASUREMENT OF EROSION RESISTANCE

The simulated rainfall equipment was designed to deliver a rainstorm of controlled intensity ($3\frac{1}{4}$ in/hr) to a group of three replicate soil specimens. These were compacted in 4 in dia. molds and mounted in specially designed holders maintained at an angle of 5° to the horizontal to permit free runoff of water. A rainfall applicator provided with more than 400 individual drop formers spaced 1.2 in apart in a triangular array produced drops averaging 0.012 in (0.3 mm) in diameter delivered uniformly over the soil specimens. Calculations indicated that the energy delivered was more than 80% of that delivered by a natural storm of the same $3\frac{1}{4}$ in/hr intensity. The standard erosion test sequence adopted consisted of the application of $3\frac{1}{4}$ in of simulated rainfall in one hour, a delay of 23 hr, and then a second $3\frac{1}{4}$ in application in one hr. The amount of rainfall actually delivered was checked each time by rain gauges positioned among the soil containers.

Provision was made to collect all of the runoff from each specimen, and the soil removed was recovered, dried and weighed to provide a direct assessment of erosion loss. The losses for the three replicate specimens were averaged, and expressed as weight of soil removed/cm² of specimen surface. In practical terms

a 1 g/cm^2 loss corresponds to about 45 tons of soil lost/acre.

In general it was found that reproducibility of results between individual replicate specimens was satisfactory and that erosion loss was reasonably consistent from test to test. The overall coefficient of variation measured in a special test series was less than 7%.

MATERIALS AND SPECIMEN PREPARATION

The results reported here were derived using two different soils, three different stabilizing materials, several levels of stabilizer addition and curing periods ranging from 1 day to 28 days prior to exposure to the test rainstorm sequence. One of the soils was a B-horizon material derived from a member of the Crosby series, a till-derived soil with a clay fraction containing montmorillonite, some mixed-layer clay and kaolinite; this material has a clay content of about 20%. The other soil was the well-known "grundite" illite-bearing commercial clay* commonly employed as an experimental material in many laboratory studies. The stabilizers included two varieties of calcium hydroxide: an analytical reagent grade† and a rather unsatisfactory commercial hydrated lime which was found to be partly dolomitic and somewhat carbonated; and a conventional Type I Portland cement of normal composition.

The specimen preparation procedure involved blending air-dried soil and stabilizer for 15 min in the dry state, followed by addition of water in the form of a fine spray, both processes being carried out in a Patterson-Kelley twin-shell solid-liquid blender. The amount of water added was that previously determined to yield the Standard Proctor optimum moisture content for the specific soil, 19% by weight for the Crosby and 20% by weight for the grundite. The moist soil-stabilizer-water mixes were then compacted using the standard Proctor hammer in specially fabricated split molds 4 in dia. and 1 in high. The number of blows applied was that calculated to deliver the same applied energy/unit vol as is delivered in the standard Proctor compaction method (ASTM Designation: D 698-70, Method A). The compacted specimens were then sealed in plastic sacks and cured in a fog room at 74°F for the desired period prior to commencement of the erosion test sequence. The surface exposed to the test rainstorm was the original bottom surface of the specimen, not the surface formed by trimming the directly impacted layer.

RESULTS

Erosion loss of unstabilized soils

It was found that compacted but otherwise unstabilized Crosby soil lost 2.1 g/cm^2 of exposed soil in the standard rainstorm test sequence, while the corresponding grundite specimens lost an average of

1.7 g/cm^2 . These losses, corresponding to the order of 90 tons/acre, indicate the intensity of the test rainstorm sequence.

The appearance of the residual surface of the Crosby soil is indicated in Figure 1(a). The soil particles are clearly dispersed, little residual aggregation being apparent. Individual sand and gravel sized grains are visible and are free of adhering clay particles, the latter having been washed away. In the grundite soil the surface after rainstorm exposure appears somewhat different and was characterized by residual small scale aggregations of clay particles and greater topographic relief.

Effectiveness of Portland cement in reducing soil erosion

Figure 2 shows the effectiveness of Portland cement treatment in reducing erosion with Crosby soil, in which soil lost in the standard rainstorm test sequence is plotted against curing time, for specimens treated with 2.5% and with 1% cement by weight of soil. It is apparent that the 2.5% treatment effectively and rapidly stabilizes Crosby soil, a 1-day curing period being sufficient to achieve almost zero soil loss. Treatment with 1% cement is effective, but only after a somewhat prolonged curing period of 28 days. After 7 days of curing the soil loss recorded was still about half that of the additive-free control specimens.

The appearance of the specimens treated with 2.5% cement and cured for 1 day after rainfall exposure is indicated in Fig. 1(b). Most of the original exposed surface of the specimens has been retained, soil loss being confined to a few patches and parts of the rim area. It should be understood that these specimens, despite the shiny surface appearance, were in no sense converted to a solid pavement; they remain highly permeable and have only modest strength.

The appearance of the residual surface of specimens that were inadequately stabilized (i.e. those receiving

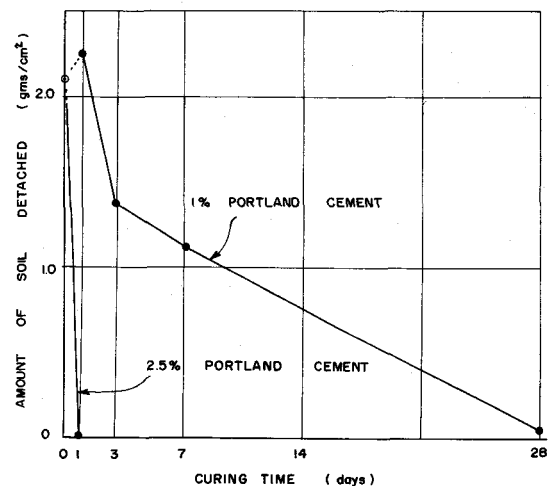


Fig. 2. Erosion losses of Portland cement treated Crosby soil specimens as functions of cement level and curing time.

* Illinois Clay Products Co., Lansing, IL.

† Mallinckrodt AR grade.

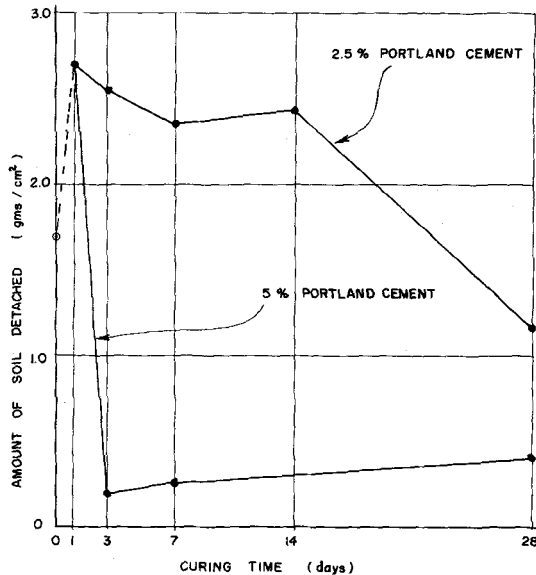


Fig. 3. Erosion losses of Portland cement treated grundite clay specimens as functions of cement level and curing time.

too little stabilizing agent or insufficient curing time) is represented by Fig. 1(c). All of the original surface of the specimen has been eroded away. The appearance of the residual surface exposed at the conclusion of the test rainfall sequence suggests that while some dispersion of the particles had taken place, dispersion was incomplete and the exposed sand and gravel particles remain coated with a layer of partly cemented clay.

The results of the attempt to stabilize the grundite clay with 2½% Portland cement were less than satisfactory, as indicated in Fig. 3. It appears that, at least at first, the effect of the "stabilizer" was to increase, rather than reduce, the amount of soil lost in the test rainstorm sequence. Additional curing brought only modest improvement and even after 28 days the treated clay lost almost as much material eroded away as the untreated control specimens.

Clearly 2½% cement was inadequate to stabilize grundite, and a second test series incorporating 5% cement was initiated. Here again, the effect after 1 day of curing was that the erosion loss was worse than the control; but by 3 days of curing the effect was reversed and reasonably successful stabilization was attained, as is indicated in Fig. 3. As will be discussed subsequently, the relatively high percentage of cement required to properly stabilize grundite is matched by a similar high requirement of this soil for hydrated lime. This requirement seems not to be a reflection of the high surface area (around 85 m²/g) or of the high clay content (around 60% by weight), but rather of the extremely acidic character of this clay, which is treated with strong acid in the commercial processing of the material. The measured pH of 1:1 clay-deionized water slurries was in the range 2.7 to 2.9.

Effectiveness of hydrated lime in reducing soil erosion

The effectiveness of hydrated lime in reducing the erosion loss of Crosby soil in the test rainstorm sequence is indicated in Fig. 4.

Treatment at the 1% level resulted in a decrease of erosion by more than a factor of 3 after one week of curing. Subsequent curing improved the erosion resistance, but only marginally. At the 2½% treatment level the effectiveness was considerably improved, the soil loss after 21 days being an insignificant 0.07 g/cm² of exposed surface. It is clear that hydrated lime, while not as rapid in its action as Portland cement, still is a potentially valuable stabilizer against rainstorm erosion.

An indication of the surface appearance of the Crosby soil stabilized with lime is given in Fig. 1(d), the specimen pictured being one of those treated with 2½% lime and cured for 7 days prior to exposure to the test rainstorm sequence. While only part of the original specimen surface was retained, it appears that the soil is hardly dispersed, and again large sand and gravel grains are not washed free of the stabilized clay particles. The permeability of lime-stabilized specimens resembles that of the corresponding cement-treated soils and the stabilized material again has only modest mechanical strength.

The results of attempts to stabilize the highly acidic grundite clay with hydrated lime were less successful. It was expected that a relatively high lime concentration would be required to overcome the acidity of the clay and it was found that reagent grade calcium hydroxide added at the 5% level was quite satisfactory, reducing the erosion loss to about 0.2 g/cm² of exposed surface after 7 days of curing. However, with the impure partly dolomitic carbonated lime, success was not attained even at the 5% treatment level. In fact, the erosion losses of the treated samples were greater than that of the original clay, rising to 2.2 g/cm² after 1 week of curing and to almost complete loss of the clay (2.7 g/cm²) after two weeks of

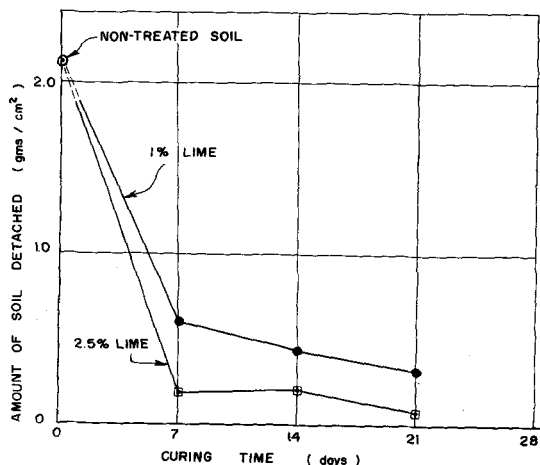


Fig. 4. Erosion losses of hydrated lime treated Crosby soil as functions of lime level and curing time.

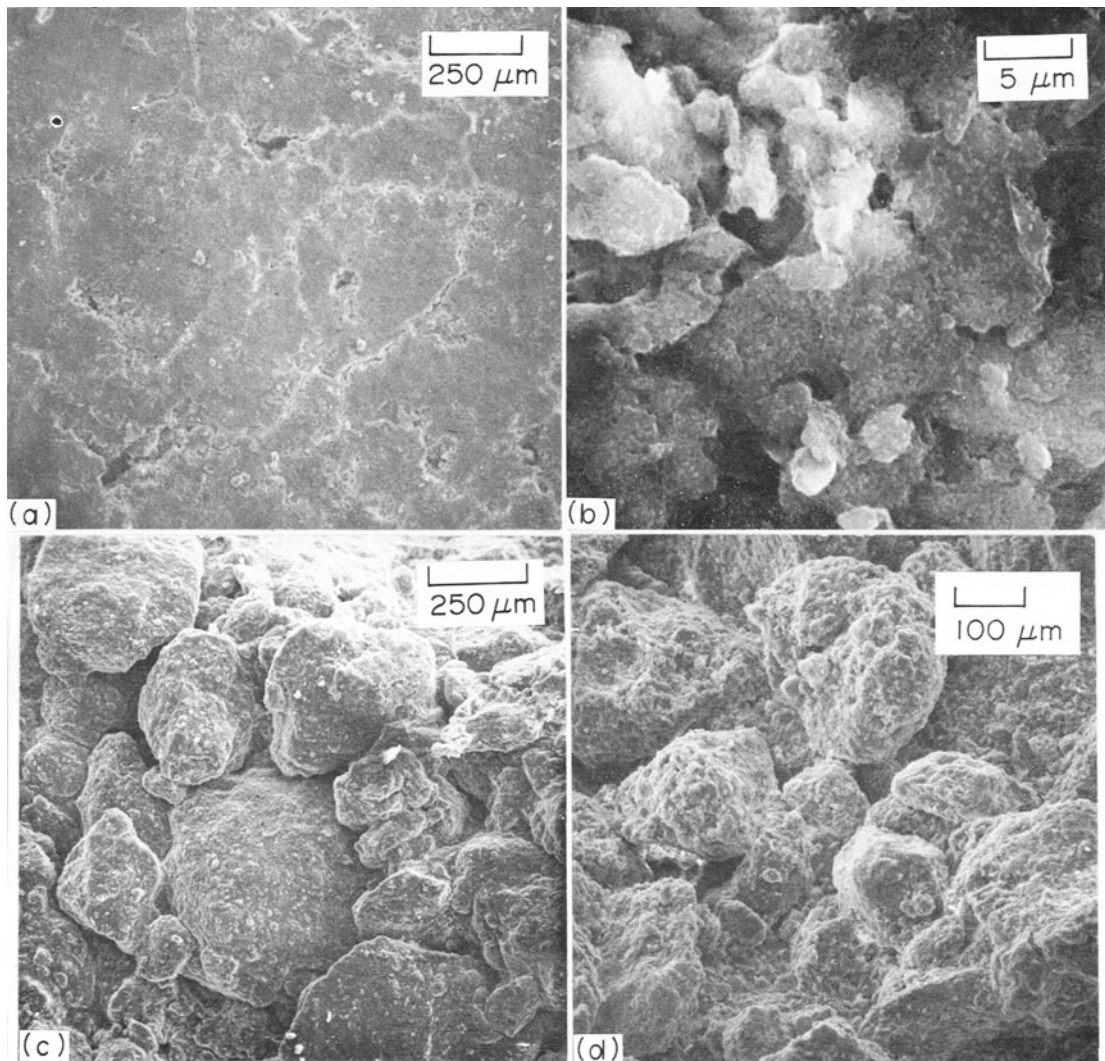


Fig. 1. Appearance of the surface of various Crosby soil specimens after exposure to the test rainstorm sequence: (all figures are at approximately full scale) (a) Unstabilized soil. (b) Stabilized with 2½% Portland cement and cured for 1 day prior to exposure. (c) Inadequately stabilized: treated with 1% Portland cement and cured for 7 days prior to exposure. (d) Stabilized with 2½% hydrated lime and cured for 7 days prior to exposure.

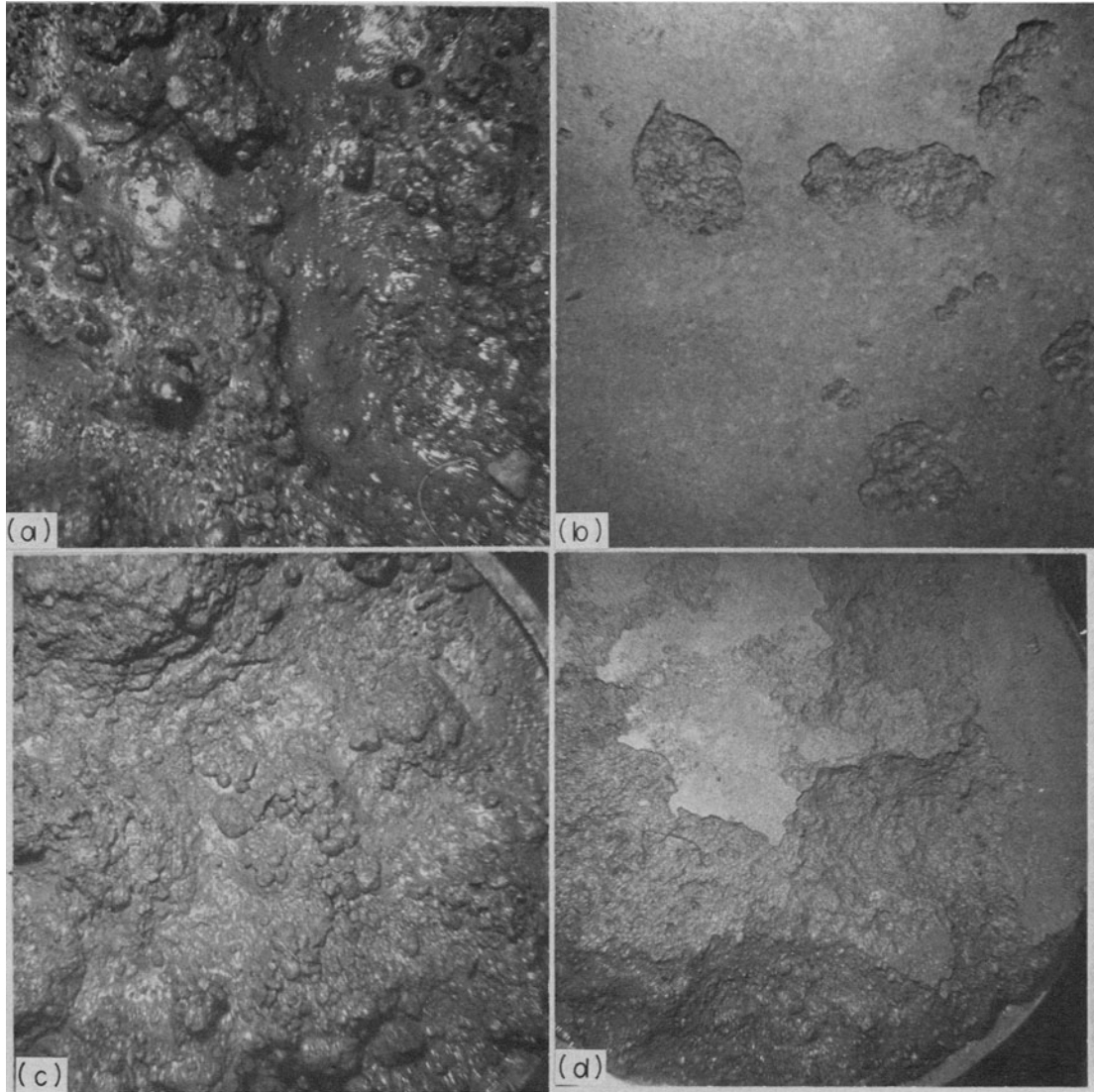


Fig. 10. Scanning electron micrographs of grundite specimens. (a) Surface of untreated specimen before rainfall exposure, at low magnification. (b) High magnification micrograph of a portion of the above showing detail of the oriented clay layer and a region (upper right) of an open area. (c) Eroded surface remaining after exposure of the specimen to the rainstorm sequence, showing underlying dispersion-resistant aggregations. (d) Residual eroded surface of grundite specimen inadequately treated with 5% of impure commercial hydrated lime and cured for 6 days prior to exposure showing partial breakdown of aggregations under raindrop action.

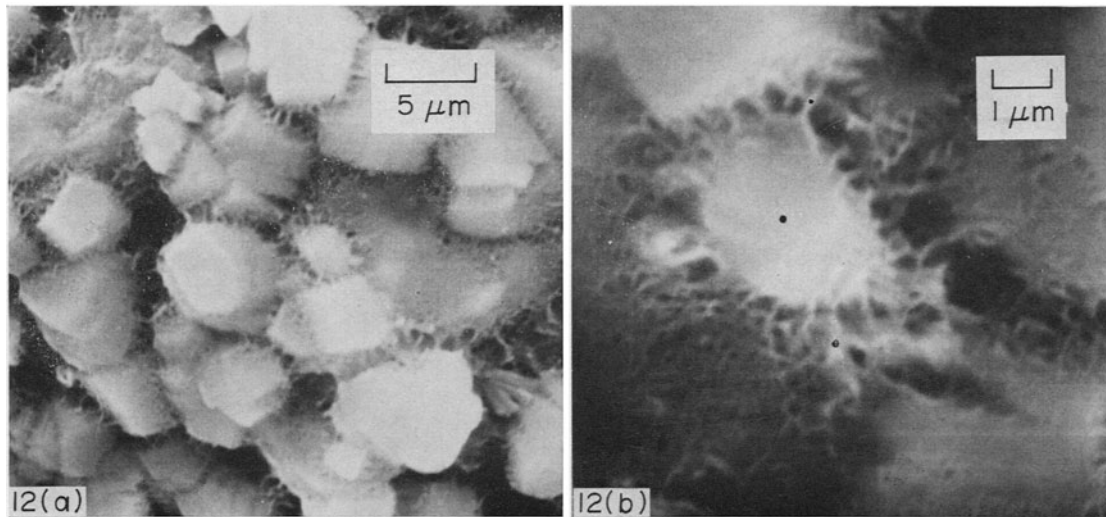
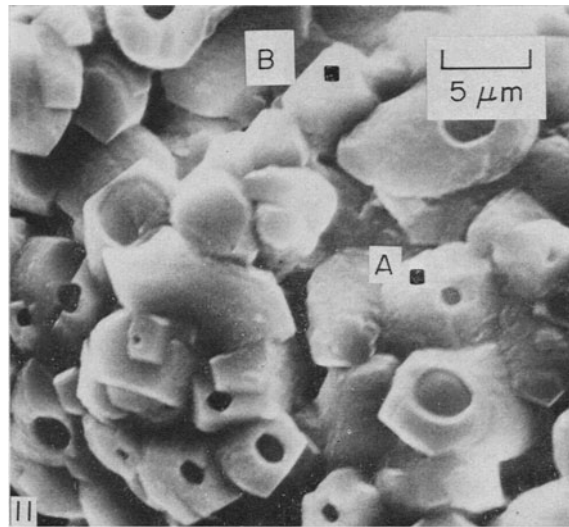


Fig. 11. Scanning electron micrograph on residual surface of grundite clay stabilized with 5% Portland cement and cured for 14 days before exposure, examined at high magnifications.

Fig. 12. (a) Scanning electron micrograph of residual surface of grundite clay stabilized with 5% Portland cement and cured for 13 days before exposure, showing formation of calcium silicate hydrate gel linking adjacent grains. (b) Higher magnification view of a portion of the above showing the reticulated network structure of the calcium silicate hydrate gel surrounding a clay particle.

curing. It was obvious that these treated clay specimens were completely dispersed under the beating action of the test rainstorm sequence.

Influence of pH on stabilization

The influence of hydroxyl ion concentration (pH) of the pore fluid on soil stabilization processes has been appreciated for some time, particularly with respect to lime stabilization. Eades and Grim (1966) developed a quick test to determine the level of lime treatment necessary to mechanically stabilize a particular soil. This consisted of measuring the pH of a series of soil-lime-water slurries to determine the minimum lime content necessary to generate a pH of 12.4 (i.e. that of saturated lime solution). Evaluation of the test in terms of the unconfined compressive strength of stabilized soils produced by mixtures generating various pH levels was carried out by Thompson and Eades (1970). They concluded that the test conservatively indicates the lime required to produce effective stabilization in terms of the development of mechanical strength.

Stabilizing soil for the purpose of resisting erosion by raindrop impact presumably does not set as stringent a requirement as stabilization to develop mechanical strength for use in a highway subgrade; thus the pH 12.4 requirement is undoubtedly more conservative than necessary for present purposes. In the writers' experience, pH values of the order of 11.5 appear to indicate that sufficient lime or cement has been used for resistance to raindrop impact erosion to develop.

As mentioned earlier, the pH of a grundite slurry was only about 2.7, far lower than the normal range for natural soils. A 1:1 slurry of Crosby soil and water produced a measured pH of 5.6. It was found that pH values measured with slurries of both soils with 5% of reagent grade calcium hydroxide by weight of soil added was of the order of 11.5 and increased slightly with aging. An explanation for the failure of the impure commercial lime to stabilize the grundite soil became apparent when it was found that a corresponding slurry generated an initial pH of only 8.0. Even after 24 hr, the pH had increased to only 10.4. On the other hand, with the more nearly normal Crosby soil, slurries made with this lime reached a pH of 11.5 after 1½ hr of standing.

While the failure of the commercial lime to stabilize the grundite clay can be understood in terms of the insufficient pH attained, additional insight is required to explain the fact that when treated with this lime the clay was actually de-stabilized, i.e. significantly more soil was lost than was lost by the untreated clay. It is believed that this too is a pH-dependent response. The untreated acid clay is in fact strongly acid flocculated and the dried flocs possess some resistance to dispersion and removal under the raindrop impact. Increasing the pH to the 8–10 range undoubtedly disaggregated these flocs, while at the same time it did not permit sufficient chemical reaction between

clay particles and calcium hydroxide to generate effective lime stabilization.

In Fig. 3 a similar effect seems to be observed with the inadequate level (2½%) of Portland cement. Here too, it appears that the pH of the clay stabilizer mixture is high enough to lose what benefit the dried acid flocs can provide without at the same time providing sufficient cementation to offset the loss.

Effect of stabilizers on water-stable aggregate size distributions

Measurement of the size distribution of water stable aggregates was carried out by wet sieving (Yoder, 1960; Kemper and Chepil, 1965). It was found that successful stabilization as indicated by the measured resistance of the standard rainfall sequence was correlateable with large increases in the content of water stable aggregations in the size ranges above 0.5 mm. Examples of such increases are shown in Fig. 5, for Crosby soil treated with 2½% lime and cured for various periods and Fig. 6 for grundite stabilized with 5% Portland cement and cured for up to 7 days. In contrast, Fig. 7 indicates that grundite treated with 2½% cement, but not successfully stabilized (as indicated in Fig. 3), did not form significant volumes of water stable aggregations. Attempts to correlate the "aggregation index" (Kemper and Chepil, 1965) with resistance to erosion did not lead to any consistent pattern or relationship, although some weak association between the two variables undoubtedly existed.

Pore size distributions

Determination of the pore size distribution of a number of specimens was carried out using a conventional mercury intrusion technique (Diamond, 1970A). Specimens were dewatered by oven drying at 105°C prior to mercury intrusion and the results

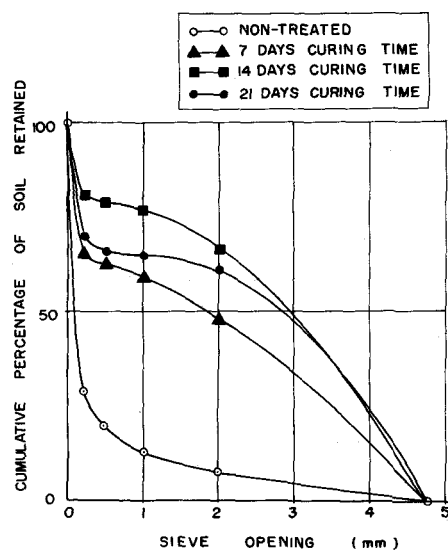


Fig. 5. Water-stable aggregate size distributions for Crosby soil treated with 2½% hydrated lime and cured for various periods.

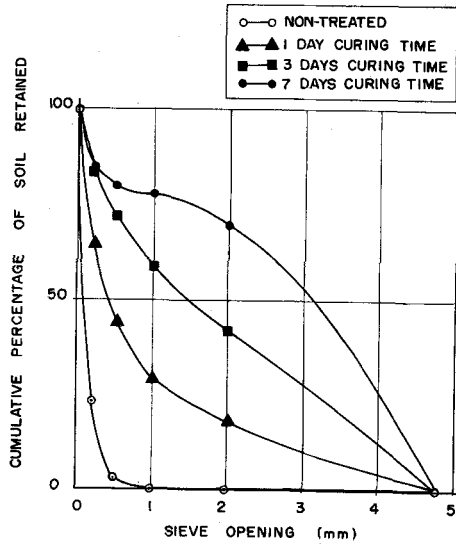


Fig. 6. Water-stable aggregate size distributions for grun-dite clay treated with 5% Portland cement and cured for various periods.

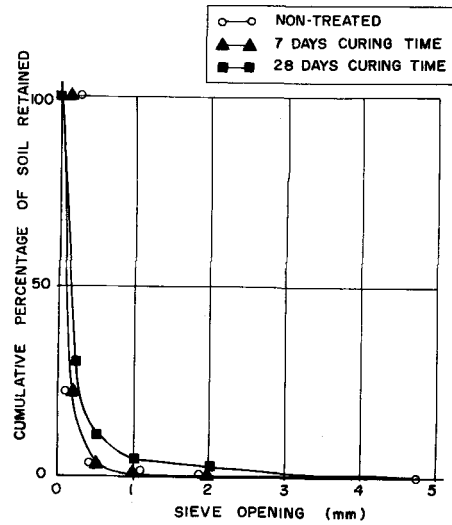


Fig. 7. Water-stable aggregate size distributions for grun-dite clay inadequately treated with 2½% Portland cement and cured for various periods.

reflect any changes in pore structure taking place during this drying process. In general it was found that only minor differences were exhibited between soils compacted without stabilizers and the same soils compacted with the modest stabilizer contents employed.

However, it is instructive to compare these pore size distributions with those of small specimens recovered from the residual surface regions of the samples that had undergone exposure to the test rainstorm sequence. An illustration of such a comparison is provided in Fig. 8. Additive-free Crosby soil, after compaction and oven drying, showed a total porosity

available to mercury (at pressures up to 15000 psi) of about 0.18 cm³/soil. Most of this space was indicated as being in pores of dia. about 10-0.3 μm. Specimens prepared from the exposed surface region of the same untreated soil after rainstorm exposure and partial erosion showed a similar distribution, but with an increase in total pore space intruded from 0.18 to 0.22 cm³/soil. Most of the increase was in pores larger than 5 μm. This may represent pore space created by washing out some of the less stable naturally-occurring aggregations at the surface, or it may be an effect of whatever swelling might have taken place. Fig. 8 also shows a distribution curve for the

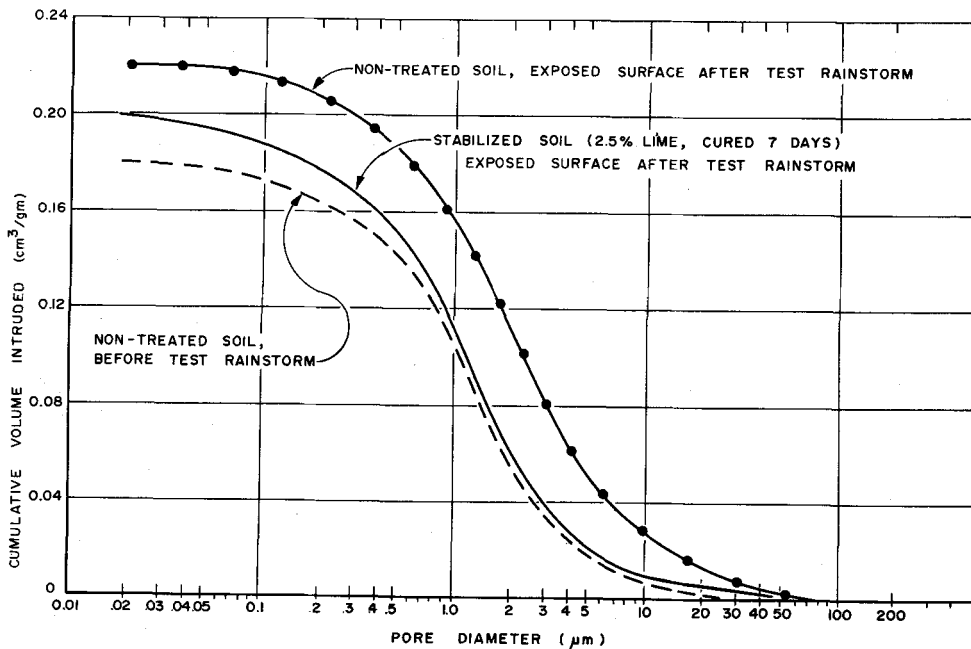


Fig. 8. Mercury intrusion pore size distributions for Crosby soil specimens.

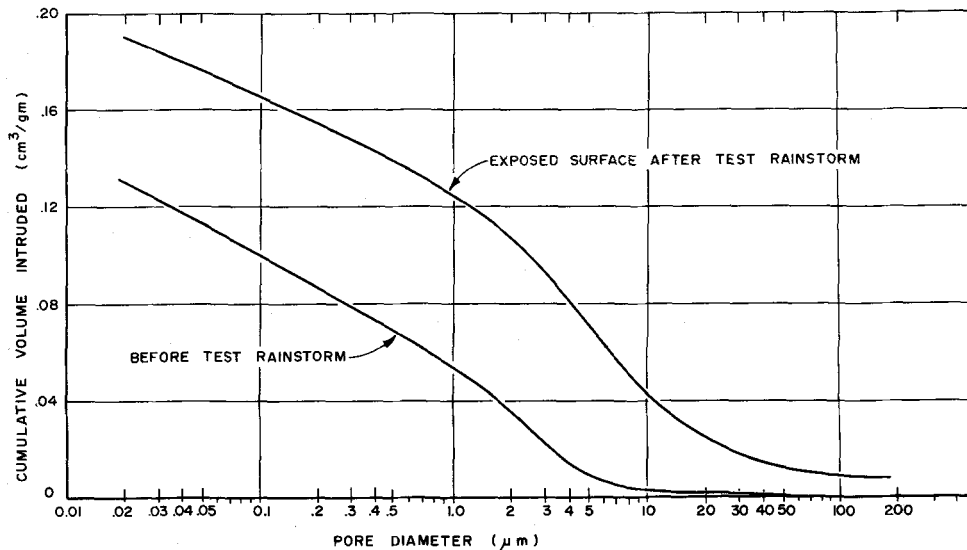


Fig. 9. Mercury intrusion pore size distributions for grundite soil inadequately treated with 2½% Portland cement and cured for 14 days.

residual surface zone of a stabilized Crosby soil (2½% lime, 7 days of curing) after exposure to rainfall. It is apparent that this distribution is essentially the same as that of the “before exposure” specimen of untreated soil, except for a modest increase in the content of fine pores that is presumably associated with the reaction product formed between lime and the soil. The important feature of the distribution curve is the lack of significant alteration traceable to the rainfall exposure itself. Apparently properly stabilized soils, although they may erode slightly, do not undergo significant microstructural change under the beating action of the raindrop impact.

Porosimetry measurements provided some additional insight into the “destabilization effect” exhibited by grundite soils treated with inadequate amounts of quality of stabilizer. It was found that additive-free grundite soil exhibited virtually the same pore size distribution before exposure to rainfall that the residual surface zone exhibited after such exposure, indicating that there was comparatively little breakdown of the acid-stabilized aggregation units. However, as indicated in Fig. 9, the same was not true for grundite “destabilized” by treatment with 2½% Portland cement and cured for 14 days. Here the surface zone left after rainfall exposure showed a large increase in pore space intruded (0.19 as compared with 0.13 cm³/g soil), and a clear indication that this increased pore space is in large pores—tens of μm dia. Apparently the breakdown of the pre-existing aggregates associated with the change from an acid to a moderately alkaline pH permitted the “destabilized” soil to swell under the action of the rainfall, creating the large pores.

The untreated Crosby soil, being far less acid than the grundite undergoes some microstructural breakdown on exposure to the rainstorm sequence, as indi-

cated earlier. Presumably this represents the more nearly normal state of affairs with most soils and the response of the grundite is to be considered unusual.

Scanning electron microscope observations

A series of investigations was carried out using a Jeol SMU-3 scanning electron microscope (SEM) equipped with an EDAX International energy-dispersive X-ray analyzer (EDXA) to attempt to document morphological detail of the grundite and stabilized grundite materials in various conditions. As indicated in Fig. 10(a) and (b), the surfaces of additive-free grundite specimens at the start of the rainstorm had a relatively smooth partial “skin” of oriented clay particles. The skin was incomplete and there are open areas, as indicated in Fig. 10(b), with a loose collection of individual unoriented clay particles and some small aggregations. There is an underlying structure of coarse aggregations that makes up the bulk of the specimens, which is not visible at the uneroded surface. However, when the surface is exposed to rainfall, the skin is rapidly eroded away and the underlying structure of the aggregations is exposed (Fig. 10c). In the process of erosion of additive-free grundite these tend to be broken down only slightly to smaller sizes, and removed without dispersion. However, when the clay is inadequately treated with a stabilizing agent and “destabilized”, there is a continuing breakdown of these aggregations into smaller clusters and ultimately individual particles. A micrograph of a portion of the residual eroded surface of a grundite specimen inadequately stabilized with 5% of the impure commercial lime and cured for 6 days, as shown in Fig. 10(d), yields some indication of this breakdown especially in the lower portion of the figure.

Grundite specimens stabilized with Portland cement apparently retain the smooth but incomplete

surface skin characteristics of additive-free grundle specimens, at least before exposure to rainfall. Well stabilized specimens properly cured before exposure show only small areas on the surface from which material is removed but the skin undergoes a dramatic change of morphology. Fig. 11 shows the surface of a residual flat area of a specimen of grundle stabilized with 5% Portland cement, cured for 7 days and examined after exposure to the test rainstorm sequence. The surface now has an incomplete layer of angular, blocky particles several μm in size, and some rounded particles of similar size. Some of the particles show distinct holes of unknown origin. EDXA examination of two typical grains, marked "a" and "b" in the micrograph, reveals that the former, rounded grain has prominent peaks for silicon at 1.71 keV, aluminum at 1.45 keV; and smaller ones for potassium at 3.3 keV, calcium at 3.7 keV and iron at 6.4 keV. The chemical composition is clearly compatible with that expected for a partly reacted illite clay particle or aggregation of particles and that is what must be present here. In contrast, the blocky grain at "b" shows only calcium peaks, and is almost certainly a crystal of calcite (calcium carbonate) formed from reaction with calcium hydroxide deposited in the cement hydration reaction. Indications that this is so were obtained from X-ray powder diffraction patterns secured from powder scraped from the surface layer of this specimen. Calcium carbonate was found to be absent from the X-ray pattern of a companion specimen not exposed to the rainstorm, but calcium hydroxide peaks were detected. Presumably the wet condition obtained during and subsequent to the test rainstorm sequence facilitates the conversion.

While blocky calcite crystals have been found in eroded portions of similar specimens and, after some period, even on fracture surfaces not directly exposed to the rainfall, it is thought that these do not contribute significantly to the stabilization process. Of far greater consequence is the generation of calcium silicate hydrate gel (C-S-H gel) both by direct cement hydration and by secondary reaction of some of the calcium hydroxide generated by cement hydration with the silica-bearing clay particles. It appears, as indicated in Fig. 12(a), that such gel acts to bind together individual clay particles and aggregations into a reasonably well knit framework which should resist dispersion on raindrop impact. As indicated in Fig. 12(b), at least some of the C-S-H gel is the "reticulated network" variety (Diamond, 1970b), found in cement hydration products.

DISCUSSION AND CONCLUSIONS

The results of the erosion tests suggest clearly that lime or cement treatment (involving mechanical mixing, addition of water to near the standard Proctor optimum moisture content and compaction approaching that of the standard Proctor method) can effectively reduce or eliminate raindrop-asso-

ciated erosion loss under severe rainstorm conditions.

The erosion-resistant stabilized soils described in this work had only minimal amounts of stabilizer added to obtain the erosion resistance. They are not rendered impermeable, nor do they develop very high mechanical strength.

Highly acidic soils will require relatively large amounts of added stabilizers to overcome the effect of the acidity.

Hydrated lime can be as effective, in practical terms, as Portland cement, provided that a period of several weeks of curing is allowed between the stabilization and the rainfall. It appears that in difficult situations hydrated lime of a reasonably high quality may be required.

Both hydrated lime and Portland cement applied in inadequate amounts to highly acid soils may act to promote, rather than reduce erosion loss, by raising the pH level sufficiently to destabilize previously existing acid flocculation-bound aggregates, while not providing the minimum pH level (around 11.5) that seems to be necessary for reaction with the soil particles.

The achievement of erosion resistance is correlatable with development of relatively large water-stable aggregations and conversely treated specimens that fail to develop such aggregations undergo erosion loss. It appears that properly stabilized specimens do not undergo significant changes in pore size distribution under the action of the rainfall, even though some material may be eroded away.

The primary stabilizing effect seems to be associated with the development of calcium silicate hydrate gel binding together individual clay particles. Although partial breakdown of some of the clay particles may occur, it is highly unlikely that the extensive decomposition of the clay observed by Mitchell and El Jack (1966) and to some extent by Kawamura *et al.* (1970) would occur with the limited levels of cement or lime addition considered here.

The formation of blocky crystals of calcium carbonate seems to occur on exposed surfaces of stabilized soils during the test rainstorm but it is thought that such crystals do not contribute significantly to the development of erosion resistance.

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