

tures of approximately 20°C to 25°C (68°F to 77°F). Higher curing temperatures help accelerate the increase in strength.

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Polymer Stabilization of Sandy Soils for Erosion Control

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The usefulness of a number of polymeric materials in increasing the resistance of cohesionless sandy soils to wind and water erosion was studied. Erosion resistance, compressive strength, and permeability of treated soil samples were measured. Film properties of individual polymers were also studied. These properties were then related to the performance of the polymer in controlling erosion. The optimum dilution of polymer with water and the quantity of polymer required to provide a nonerosive surface were determined for three different soils. A copolymer of butadiene-styrene is suggested as an ideal polymer for controlling erosion without significantly reducing the permeability of the treated soil. Other polymers such as polyvinyl acetate and acrylic polymers were found to be water sensitive in various degrees and consequently did not perform well. From a practical viewpoint, the application of polymers to soils by spraying has an obvious advantage over mechanically mixing polymers and soils. In the study it was found that less polymer is required to provide a nonerosive surface if spraying is used. In addition, aqueous-base polymers have numerous advantages over solution-base polymers.

Various materials and methods have been proposed for controlling erosion of agricultural lands and other terrain surfaces such as highway cut-and-fill slopes. The common methods of erosion control are the application of asphaltic products or portland cement, the establishment of vegetative cover, or the provision of riprap. All these methods and materials have limited usefulness and require frequent maintenance, which increases the total cost of a project. Another possibility is the use of polymeric materials, which have great potential for use as soil stabilizers for erosion control and for other purposes. Some of these polymeric compounds have already been used in the field and have been

found quite successful (1-6). In this study, the usefulness of this versatile group of materials for application in soil stabilization has been evaluated and some of the fundamental properties and characteristics related to their performance have been identified. A full account of the studies reported here has been made by Siddiqi (7).

MATERIALS

Ten different polymeric products were studied by using three different soils. The soils were essentially noncohesive sands of varying fine (< no. 200-sieve) content obtained from different locations in Oklahoma. The pattern of results for the three soils is quite similar; consequently, the results for only one of the soils are presented. Figure 1 shows the grain-size analyses of the soils. Table 1 presents general information about the polymers used in the study. All but one of these polymers were in the form of a liquid that can be diluted with water as desired. Altak 59-50, a solution-base polymer, was included in the study for comparison purposes. This polymer requires MEK peroxide for curing and styrene as thinner.

EXPERIMENTAL PROCEDURE

Some samples for the study of erosion control and permeability were prepared by spraying the diluted

Figure 1. Grain-size analyses of soils.

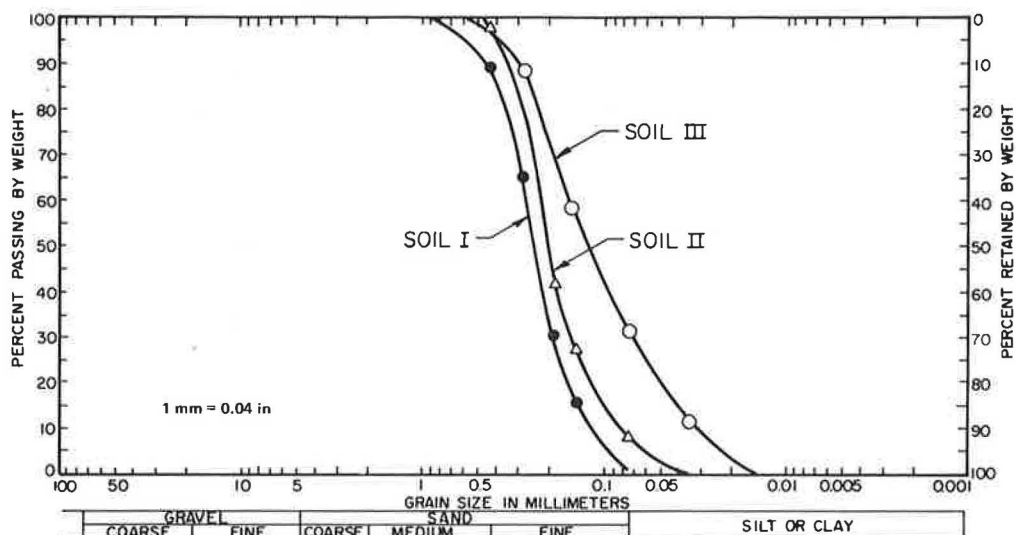


Table 1. General information on polymers used.

Name	Manufacturer	Type of Polymer	1977 Cost (\$/L)
Petroset SB	Phillips Chemical Co.	Butadiene styrene copolymer	0.63
Aerospray 70	American Cyanamide	Polyvinyl acetate	0.63
Terra Krete	Kingman Chemical Co.	Fermented extract of malt and vanilla (wort) and citric acid + metallic sulfates	2.12
NeoCryl 601A	Polyvinyl Chemical Industries	Vinyl polymer	0.53
Rhoplex H-8	Rohm and Has	Acrylic polymer	0.54
Altak 59-50 ^a	Alpha Chemical Corp.	Polyester in styrene	
Corexit 7730	Exxon Chemical Co.	Partially neutralized polyamide	0.93
Norlig 41	American Can Co.	Calcium lignosulfonate	
Orzan GL-50	Crown Zellerbach Corp.	Ammonium lignosulfonate	
Latex XP-4026	Hooker-Ruco Division	Polyurethane latex	3.36

Note: 1 L = 0.264 gal.
^aSolution-base polymer.

polymer solution on the soil surface and others by mechanically mixing the polymer with the soil. The sprayed samples were prepared in molds that had a diameter of 134 mm (5.3 in) and a depth of 50 mm (2.0 in). The molds were open at one end and perforated at the other to permit flow of water through the sample. Mechanically mixed samples were prepared in molds that had a diameter of 71 mm (2.8 in) and a depth of 25 mm (1.0 in) and were open at both ends. Samples were removed from the molds immediately after compaction. Samples for the study of unconfined compressive strength were prepared by mechanically mixing the soil and polymer and compacting the mixture in Harvard miniature molds by using a standard American Association of State Highway and Transportation Officials (AASHTO) compaction effort by means of a drop hammer. All samples were cured at 35°C (95°F) for seven days before being tested.

The effects of 10 freeze-thaw cycles and 10 wet-dry cycles were investigated. In the former, the samples were subjected to alternate freezing at -10°C (14°F) for 16 h and thawing at 25°C (77°F) for 8 h in an ambient relative humidity of 100 percent. Before the first freeze, the samples were immersed in water for 24 h. The wet-dry cycles consisted of 8 h of soaking at room temperature and 16 h of drying at 35°C (95°F).

The effects of exposure to ultraviolet light were also investigated. Samples half-covered with a 2-mm (0.08-in) aluminum plate were placed 254 mm (1 ft) below a 275-W sunlamp. Samples were first exposed for 8 h in a dry condition, soaked in water for 24 h, and then exposed again to the light for 8 h.

Following this, the samples were further soaked for 24 h and then subjected to water-erosion testing. Total exposure was roughly equivalent to two months' exposure to sunlight.

Resistance to wind erosion was evaluated by subjecting dried samples to wind velocities of 72 km/h (45 miles/h) produced 50 mm (2 in) from the discharge snout of a blower. The velocity was measured by a pendulum anemometer that had been calibrated in a wind tunnel. The sample was positioned to simulate a horizontal wind striking a IV:2H slope with a velocity of 72 km/h.

Resistance to water erosion was measured by subjecting the soaked samples to a uniform water spray. The spray applicator produced jets that had a diameter of 0.6 mm (0.02 in) and were spaced 6.0 mm (0.24 in) apart. The jet velocity was maintained at 3.1 m/s (10 ft/s). The energy supplied by the water jets per unit area of sample surface was about four times that of a natural storm (1).

Film properties of the polymer were investigated by using a film formed by drying 20 mL of a 1:1 mixture of polymer and water in Pyrex glass dishes 89 mm (3.5 in) in diameter. Film properties such as cohesion, adhesion to the substrate (Pyrex glass) or to another layer of the same polymer or to a different one, brittleness, and swelling due to soaking in water were observed quantitatively. Some of the polymer films could be peeled from the glass by using a fingernail, whereas others required a knife blade. It was noted whether the film could be peeled intact from the glass or whether it came off in fairly large pieces or small flakes. If pieces were large enough, they were flexed and folded to

Table 2. Quality of spray-treated surface.

Name	Suitability of Polymer for Erosion Control ^a				
	Dilution Ratio	Rate of Application (L/m ²)	Solid Polymer (kg/m ²)	Cost of Treatment (1977 \$/m ²)	Quality of Treatment
Petroset SB	1:9	9.00	0.35	0.52	Excellent
Aerospray 70	1:12	9.00	0.34	0.47	Good
Terra Krete	1:19	9.0	0.37	0.95	Good
NeoCryl 601A	1:5	9.0	0.40	0.79	Fair
Rhoplex H-8	1:7	9.0	0.42	1.16	Fair
Altak 59-50	1:4	4.5	0.36	0.60	Fair
NeoCryl 601A and Aerospray 70	1:12	9.0	0.26	0.42	Good
Terra Krete and Aerospray ^b	1:19	9.0	0.20	0.74	Good

Notes: 1 L/m² = 0.264 gal/yd²; 1 kg/m² = 2.2 lb/yd²; 1 m² = 10 ft².

Excellent = no surface or internal erosion, flexible surface; very small reduction in permeability.

Good = no surface erosion, hard surface, significant reduction in permeability.

Fair = no surface erosion and significant reduction in permeability, but internal erosion is possible; or polymer is difficult to apply.

^aSpray treatment for 38-mm (1.5-in) layer of soil.

^b(1:1) by volume.

Table 3. Permeability of spray-treated surface.

Name	Permeability of Soil (cm/s)	
	Before Spray Treatment	After Spray Treatment
Petroset SB	2.0 x 10 ⁻³	1.3 x 10 ⁻³
Aerospray 70	2.0 x 10 ⁻³	3.1 x 10 ⁻⁴
Terra Krete	2.0 x 10 ⁻³	5.5 x 10 ⁻⁴
NeoCryl 601A	2.0 x 10 ⁻³	4.8 x 10 ⁻⁴
Rhoplex H-8	2.0 x 10 ⁻³	3.2 x 10 ⁻⁴

evaluate pliability and brittleness (soaked films were dried before flexure).

The optimum proportion of water to polymer in a solution to be used for spray applications and the minimum amount of solution needed to provide a nonerosive surface were determined by trial and error for each polymer. A fixed quantity of the polymer was mixed with varying amounts of water for the trials, and each batch was sprayed onto a sample of the soil. The samples were allowed to dry and were then cut into a few pieces to permit the depth of penetration to be observed. In early trials, dye was used to facilitate this observation, but since the filtering effect of the fine granular soils permitted the dye to penetrate farther than it did in the polymer, this procedure was abandoned. The effective penetration depth was finally taken as the thickness of the surface layer that remained intact after the samples had been gently tapped. The optimum dilution for the polymer was considered (perhaps somewhat arbitrarily) to be that which provided a 38-mm (1.5-in) effective depth of penetration. If the solution was too dilute, greater penetration was obtained, but the treated layer was too weak to survive the tapping test. If the dilution was less than optimum, the intact layer was less than 38 mm in thickness, although it was stronger than that corresponding to the optimum dilution. The thinner but stronger surface layer was rejected as unacceptable because its permeability was too low and because the risk of internal erosion of the soil below it, with consequent loss of support for the treated layer, was deemed too great.

RESULTS

For the soils and polymers used in this study, the quantity of polymer required to prevent wind erosion was invariably much less than that required to control water erosion. It was also found that 10 cycles of wetting and drying affected erosion resistance more adversely than did 10 freeze-thaw

cycles. Consequently, test results are presented only for those polymeric materials that provided significant resistance to water erosion after 10 wet-dry cycles. Petroset SB, Aerospray 70, Terra Krete, Rhoplex H-8, NeoCryl 601A, Altak 59-50, and two combinations of the foregoing are of that category. The two-polymer combinations were tried with the idea of either suppressing some of the undesirable properties of one polymer with the help of another or reducing the cost of an expensive polymer by incorporating a cheaper one without sacrificing the quality of treatment. The other polymers studied were found to be unsuitable, either because they did not make the soil resistant to erosion or because any benefits gained were lost after the polymers had been soaked in water.

The samples treated with Norlig 41, Orzan GL-50, and Corexit 7730 showed very poor resistance to water erosion and fell apart when immersed in water. Neither Norlig 41 nor Orzan GL-50 formed a film but changed into powder after drying and dissolved immediately when immersed in water. Similarly, Corexit 7730 did not form a dry film after curing but remained in the form of viscous liquid that was easily leached away by water. Only those polymers that formed water-resistant films were found to be suitable for erosion control.

The optimum dilution and minimum quantity of polymer solution required to provide a nonerosive surface for soil II are given in Table 2. It was found that 9 L/m² (2 gal/yd²) is sufficient to provide a treated surface layer 38 mm (1.5 in) thick. The 1977 cost of the material is given in the same table. Although the cheapest treatment is a combination of NeoCryl 601A and Aerospray 70, the quality of treatment is best for Petroset SB, and the reduction in permeability is also the least. Permeability of spray-treated samples is given in Table 3. It may be observed that all the polymers except Petroset SB reduce the permeability quite substantially.

The minimum amount of polymer required to provide a nonerosive surface in premixed samples is given in Table 4. It may be observed that the cost of polymer to provide a nonerosive surface by premixing is two to three times that of spray treatment. Samples for compression tests were prepared through a considerable range of polymer content, and the results of strength tests for soil II are given in Table 4 and in Figure 2. It may be seen that if the object of polymer treatment is to increase compressive strength, considerable success is possible, although heavier treatments of polymer may be required than are necessary for erosion control. Petroset SB, which seems to be ideally suited for erosion control, is not very effective in improving strength.

Thus, polymers that may provide good erosion control do not necessarily provide high strength.

Regarding the water susceptibility of polymer films, it was observed that, with the exception of Petroset SB, Altak 59-50, and (possibly) Terra Krete, the polymer films were adversely affected when soaked in water for 24 h or more (Table 5). Either the film swelled, as in the case of Aerospray 70, or it lost adhesion, as in the case of NeoCryl 601A and Rhoplex H-8. It is concluded that polymers that provide short-term protection from erosion do not necessarily provide long-term protection. Surface characteristics of the spray-treated soil must also be considered. If the surface is very hard and rigid, it would inhibit the growth of vegetation. This could be an undesirable result from an esthetic point of view. For this reason, polymers that form flexible or rubberlike films may be more suitable for erosion control.

The investigation of the effect of environmental factors on these polymers was limited in scope. However, the brief exposure to ultraviolet radiation produced no observed effects on any of the polymers, and those listed in Table 2 were not intolerably damaged by the 10 freeze-thaw cycles or the 10 wet-dry cycles. It is possible—even probable—that more-extensive degradation would occur during extended field conditions. It is believed, however, that the effectiveness of the treatment may be restored from time to time, as may be required, by an additional light application of the polymer. All those in Table 2 exhibited satisfactory adhesion not only to the soil substrate but also to dried films of the same polymer. The susceptibility of these materials to biological degradation was not addressed in this study.

DISCUSSION

There are numerous polymer products available on the market that have the potential to stabilize soils. However, many of these products would be more suitable for use in soil stabilization if the material were modified to some extent. For example, most of the solution-base polymers are initially manufac-

tured by a process called emulsion polymerization. Later, the water is removed from the emulsion and replaced by a solvent. These solution-base polymers are not only less suitable for soil stabilization but are also more expensive. They require special equipment for spraying, pollute the atmosphere, and are a fire hazard in storage. Aqueous-base polymers are less expensive, easier to apply, and generally better soil stabilizers.

Common polymers that are relatively inexpensive and can be manufactured as an emulsion or latex are acrylic polymers, polyurethanes, and copolymers of butadiene-styrene and butadiene-acrylonitrile. Most of the acrylic polymers and their derivatives are water sensitive and consequently have limited use for soil stabilization. Vinyl polymers are less water sensitive but lack adhesion. It has been ob-

Figure 2. Effect of polymer content on unconfined compressive strength of soil in dry and soaked conditions.

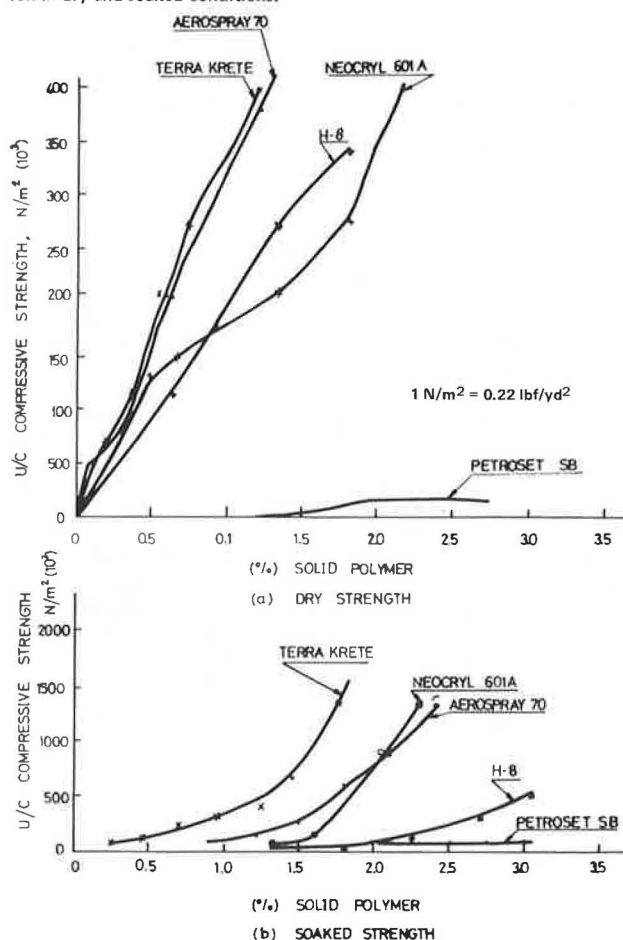


Table 4. Cost of mechanically mixed polymer-treated surface.

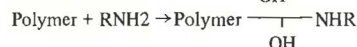
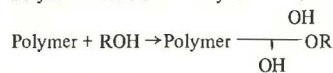
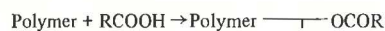
Name	Solid Polymer for Nonerosive Surface (%)	Compressive Strength (N/m ²)		1977 Cost of 38-mm Treated Layer (\$)
		Dry	Soaked	
Petroset SB	1.92	0.062 × 10 ⁶	0.0275 × 10 ⁶	1.32
Aerospray 70	1.20	3.792 × 10 ⁶	0.165 × 10 ⁶	0.64
Terra Krete	0.72	2.447 × 10 ⁶	0.1723 × 10 ⁶	1.60
NeoCryl 601A	1.44	2.758 × 10 ⁶	0.1722 × 10 ⁶	1.27
Rhoplex H-8	1.57	3.310 × 10 ⁶	0.075 × 10 ⁶	0.97

Note: 1 N/m² = 0.224 lbf/yd²; 1 mm = 0.04 in.

Table 5. Adhesive properties of polymer films.

Name	Adhesion to Glass			
	Before Soaking	After 24 h of Soaking	After 36 h of Soaking	After Redrying
Petroset SB	Good	Good adhesion, no swelling	Good adhesion, no swelling	Good
Aerospray 70	Good	Weak adhesion, swelling	No adhesion, slight swelling	Good
Terra Krete	Good	Good adhesion, no swelling	Weak adhesion, no swelling	Good
NeoCryl 601A	Good	Poor adhesion, no swelling	Poor adhesion, slight swelling	Weak
Rhoplex H-8	Good	Weak adhesion, swelling	Poor adhesion, high swelling	Weak
Altak 59-50	Good	Good adhesion, no swelling	Good adhesion, no swelling	Good
NeoCryl 601A and Aerospray 70	Good	Good adhesion, no swelling	Weak adhesion, no swelling	Good
Aerospray 70 and Terra Krete	Good	Poor adhesion, no swelling	Weak adhesion, no swelling	Good
Latex XP-4026	Poor	Poor adhesion, no swelling	Poor adhesion, slight swelling	Poor

served that lack of adhesion is a major deficiency in a polymer that is to be used for soil stabilization. Adhesion between polymer molecules and a polar substrate such as the quartz surfaces of most sandy noncohesive soils depends, among other things, on the flexibility and polarity of the polymer molecules. Water, a polar material, spreads on quartz surfaces very quickly. Similarly, natural rubber, which has very flexible molecules, is a very good adhesive. Thus a polymer that is relatively flexible, like an elastomer, and is also polar has good properties for stabilization for erosion control. Due to the polarity of molecules, there will be a strong electrical force between them and the polar substrate. This will give rise to strong adhesion. In addition, if the molecules are flexible, a large area of contact and better adsorption will result. This will increase the van der Waals forces, which in turn will improve adhesion. Flexibility in a polymer can be increased by incorporating a suitable plasticizer. Similarly, polarity can be induced or increased by combining an acid group in the polymer molecule. These functional groups can be incorporated, even after polymerization, by treating the polymer with carboxylic acid, alcohol, or amine. The resulting modifications are indicated below:



The main disadvantage to adding an acid group is that it makes the polymer more sensitive to the effects of water.

Most of the elastomers, such as butadiene-styrene and butadiene-acrylonitrile, have quite flexible molecules and consequently are good adhesives. These copolymers are also less water sensitive. If such copolymers can be made polar, their adhesive and cohesive strength can be further increased. The most common acid group that can make these elastomers more polar is the carboxylic group (COOH). By incorporating this group into an elastomer, a strong and good adhesive polymer can be produced. The amount of carboxylic group in the elastomer will affect the overall properties of the polymer. It has been reported (8) that the addition of up to 20 percent of an acid group in an elastomer increases both the adhesion and the cohesive strength of the

polymer because of the increased intermolecular and intramolecular forces. When the acid group exceeds 20 percent, the polymer becomes rigid and its adhesive properties decrease. Moreover, it becomes somewhat water sensitive. Thus, for controlling the erosion of noncohesive sandy and silty materials, a carboxylated elastomer of butadiene-styrene or butadiene-acrylonitrile in the form of latex or emulsion, which is dilutable in water, would be a promising polymer.

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Pore-Size Distribution and Its Relation to Durability and Strength of Shales

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Shale durability is measured by resistance to slaking in a standard laboratory test. All slaking mechanisms (namely, air-pressure breakage, differential swelling, and dissolution of cementing agents) require that water penetrate the pore space of the shale pieces. Since it is now possible to measure the magnitude and size distribution of these pores by mercury intrusion, correlation of slaking and pore-size distribution is feasible. Testing of slake durability, pore-

size distribution, and point-load strength was undertaken on eight Indiana shales of varying durability and strength. It is proposed that the shales be classified as to performance in compacted embankments by slake-durability and point-load-strength indices and that either index can be estimated from parameters of the pore-size distribution. Parameters from the pore-size distribution study (namely, cumulative porosity, median diameter, and spread