COST, EFFECTIVENESS AND UTILITY OF POLYMER SOIL STABILIZERS

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CHAPTER I

INTRODUCTION

Terrain surfaces made up of cohesionless soil material are subjected to severe wind and water erosion. Erosion involves disintegration of the soil mass and then the transportation of soil particles from one place to another. This causes damage at both places--where the erosion or degradation occurs and where the deposition or aggradation takes place. Accelerated soil erosion depletes agricultural lands and removes large quantities of topsoil. The product of erosion is sediment. This can fill ditches, cover road surfaces, pollute and fill rivers, streams and lakes, increase construction costs due to the damage to sites, and adversely affect the aesthetics of an area.

Soils which are most susceptible to erosion are sands and silts. In many circumstances, it is difficult to grow the right kind or any kind of vegetation on such soils. Severe erosion also occurs on newly built projects or during the course of construction where sufficient time has not passed to grow vegetation or use other preventive measures.

Among the many factors that contribute to soil loss at a particular site, soil erodibility is only one, but a major one. Soil erodibility is defined as the inherent susceptibility of soil particles to detachment and transport by rainfall drops, running water, or wind.

This is due to the lack of cohesion among individual particles of the soil. Shear stress, at the boundary of contact between flowing fluid (wind or water) and the surface of the soil grains, causes the particles to be carried away or knocked from their position of rest. The restoring force consists of cohesion and the weight of the particle. Thus, a soil which has high cohesion or which consists of heavy particles is comparatively less erosion prone than other soils.

In order to keep the particles of the erosive soil in their place, it is necessary either to reduce the external force which causes the stress, or to increase the resistance of the soil to withstand this stress. Applying vegetative cover serves more or less both purposes, but to a limited degree. The upper part of the cover acts as an energy dissipator and reduces a major amount of the force of the eroding medium. The roots provide a certain degree of cohesion among the particles of the soil. But unfortunately, growing the right kind of vegetation on some highly erosive soils is neither easy nor economical. For example, in wind-blown sands, lack of nutrients and poor water-holding capacity prevent the proper growth of any kind of vegetation. All other techniques center mainly around reducing the force of the eroding medium by some means or other.

The other aspect of erosion control could be to increase the resistance of erosive soil by some artificial means. There are a number of materials which have been used for this purpose. The most common materials that have been tried so far are asphalt cutbacks, road oil, asphalt emulsion, Portland cement, and various kinds of chemicals. In most of these cases, only a limited degree of erosion control has been achieved. All of the above mentioned materials, except some chemicals, have one or more drawbacks, which limit their use considerably. For example, Portland cement when added in small quantities does not reduce erosion significantly, and in certain cases it may increase erosion susceptibility. But when added in somewhat larger quantities, it causes cracking of the soil and also reduces permeability considerably. Asphaltic materials have their own problem. They lack either cohesive strength or adhesion, depending upon the amount and grade of asphalt used. Road oil provides protection only by surface tension and some water-proofing action. As time passes, the oil either evaporates or becomes oxidized to solid material, providing no protection to the soil.

Erosion control by means of chemicals offers considerable promise for significant accomplishment. Various kinds of materials developed by the chemical industry have provided great opportunity for the soil engineer to utilize them as successful soil stabilizers. Among the large number of chemicals made by the industry, polymers have drawn considerable attention. Although polymers are new for this area of application, they have shown enough success both economically and in performance to warrant extensive evaluation studies. This may encourage the chemical industry to develop different kinds of polymers having more desirable properties with respect to soil stabilization in general and soil-erosion control in particular.

The principal object of this study is to evaluate some of the more promising polymers available in the market for stabilizing soil to control erosion. In addition to that, a significant part of the study has been devoted to a determination of some of the physical and/or chemical properties of the polymers which are most helpful in achieving the object of erosion control.

CHAPTER II

LITERATURE SURVEY

Soil Erosion

Wind Erosion

Erosion of soil material by wind and its redistribution on the earth's surface is one of the important geological processes of soil formation operating over long time periods. Accelerated wind erosion is a problem associated with land use which occurs when equilibrium between vegetation, soil, and the climatic environment has been disturbed by the growing of cultivated crops or overgrazing of the land or building new projects.

The most serious damage is the change in soil texture, physical condition and fertility, and the atmospheric pollution caused by wind erosion. The finer soil particles and organic matter are carried away, leaving coarse, sandy and less productive soil surfaces. These soils then become more susceptible to both wind and water erosion. The sand may begin to drift and form unstable dunes which encroach on productive lands. Large areas of productive land have been ruined in this way. Dust storms caused by wind erosion are not only a great health hazard, but also do harm to plants and vegetation, factories and buildings. The problem of erosion by wind is more serious in arid and semi-arid regions where soil remains fairly dry for a long period of the year and the prevailing winds are strong.

Mechanism of Wind Erosion. The process of erosion consists of three distinct phases:

detachment or loosening of soil particles

transportation

deposition or sedimentation

Detachment: This is a process by which individual soil grains are loosened from the clods or surface. Unless soil grains are loose enough, they cannot be picked up by the wind. The factors that contribute in loosening the soil particles are a) freezing-thawing; b) wetting-drying; c) beating by rain drops, and d) movement or disturbance caused by livestock and machinery. In addition, some soils are inherently noncohesive and loose, and thus highly susceptible to wind erosion. Once the soil becomes loose, due to either its inherent characteristics or some other physical phenomenon, it is ready to be picked up by the winds and carried away.

Transportation: The loosened soil grains are carried away by the wind in three distinct ways: a) saltation; b) suspension, and (c) surface creep.

a) Saltation. The greatest portion of soil is transported by saltation. In this process, individual grains jump from the initial position of rest and then fall slowly at a very flat angle and in doing so, cover a considerable horizontal distance.

Mechanism of Saltation: Wind velocity varies with the height above the ground surface. Below a height of 0.1 mm, it is practically zero, and increases very rapidly (exponentially with height), as shown in Figure 1. Thus, particles which are smaller than 0.1 mm in size are subjected to very little wind pressure. Particles larger than 0.1 mm in diameter are subjected to an uneven pressure distribution, as shown in Figure 2. Due to this uneven pressure distribution, a torque is developed on individual particles. This causes particles to spin, sometimes as rapidly as 1000 revolutions per second (40). Thus, the top surface of the particle moves faster than the wind velocity. This creates a partial vacuum above the particle and the air is compressed below it, producing a "lift" on the particle. Due to this "lift," the particles shoot into the air at a very steep angle, ranging from 75° to 90°, as shown in Figure 3. The height to which a particle rises into the air depends upon size of grain and wind velocity.

Using boundary layer theory in conjunction with the laws of aerodynamics, the critical threshold force and critical velocity were calculated by Woodruff and Chepil (46) by the formulas given below. Units were not reported in the formulas.

$$F_c = \left[0.52\, d_s^{\,3}\, (P_s - P_w) - L_c\right] \tan \phi$$

$$V_c = A\left(\frac{P_s - P_w}{P_w}\right)^{0.5} \cdot g \cdot d_s$$

where

F_c = critical force

V_c = critical wind velocity

d_s = diameter of soil grain

L_c = lift

P_s = mass density of soil grain

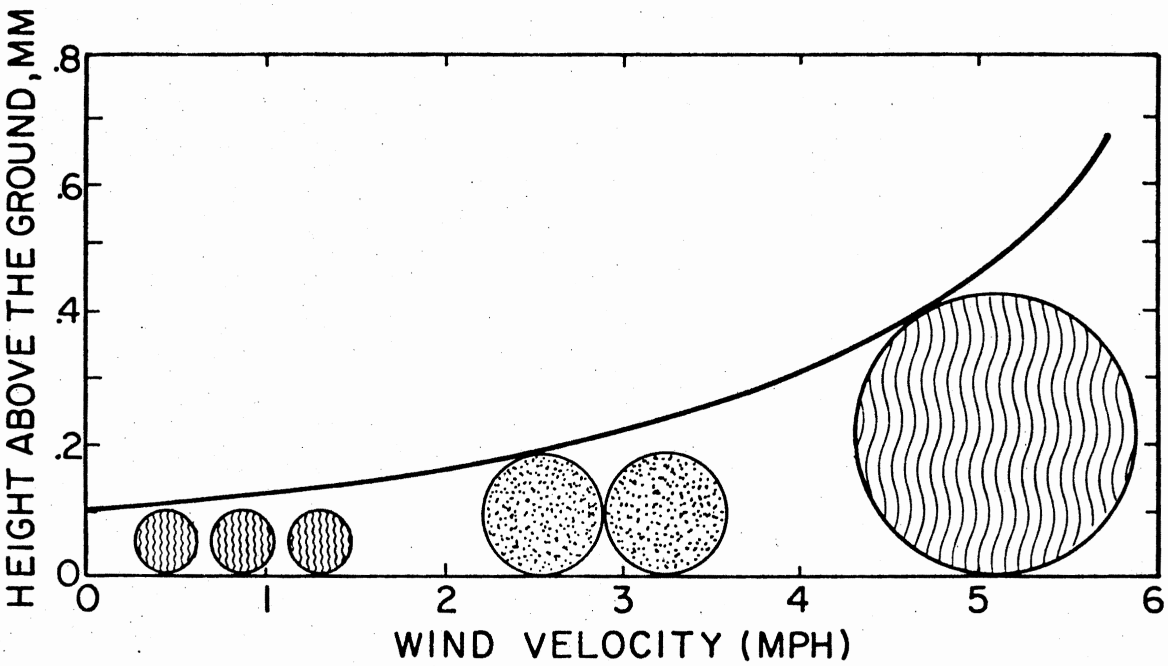


Figure 1. Distribution of Wind Velocity Above the Ground and its Effect on Soil Particles of Different Sizes (5)

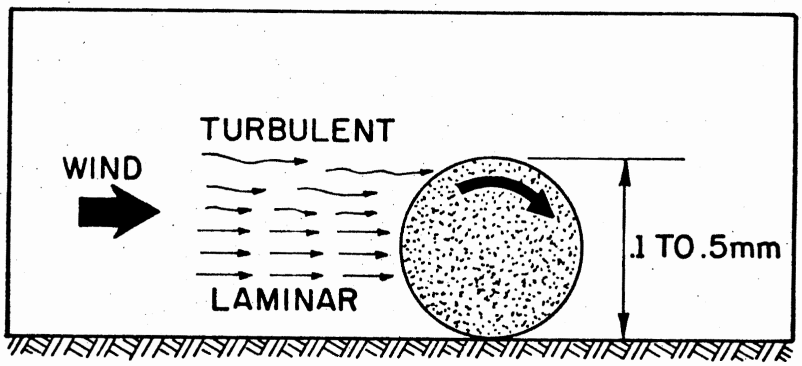


Figure 2. Impact on the top Portion of the Saltating Particles due to Turbulence

P_w = mass density of air

A = constant = 0.1

ϕ = angle of repose

Once the wind velocity exceeds the threshold velocity, the particle is lifted and carried away as described. As soon as it is picked up, the forces acting on the particle suddenly change. Force of "lift" is suddenly reduced and "drag" takes over because of direct wind pressure. The force diagram is shown in Figure 4.

Once the particle reaches its maximum height, it starts falling under gravity. During the process of falling, the drag force continues to exist. This causes the particle to fall at a very flat angle--around 6^o to 12^o. Thus, the horizontal distance is related directly to the vertical height the particle attains during the lift. It has been found that the ratio of height to horizontal path varies from 1:7 to 1:15, as shown in Figure 5.

b) Suspension. Soil particles smaller than 0.1 mm are carried by what is called suspension. Suspension movement cannot exist without saltating particles, unless there is extraneous disturbance such as that caused by vehicle traffic or livestock. The cause of initiation of movement on these particles is the impact of large-size particles which move by saltation. As the saltating particles drop down or shoot up from the ground, they cause smaller particles to be kicked up where the strong winds aloft take over. Since these particles have a large surface area compared to their weight, they stay in suspension for relatively longer periods. Once picked up by winds, these particles can travel hundreds of miles without settling down to earth. Particles normally settle when it rains. As the cause of this kind of

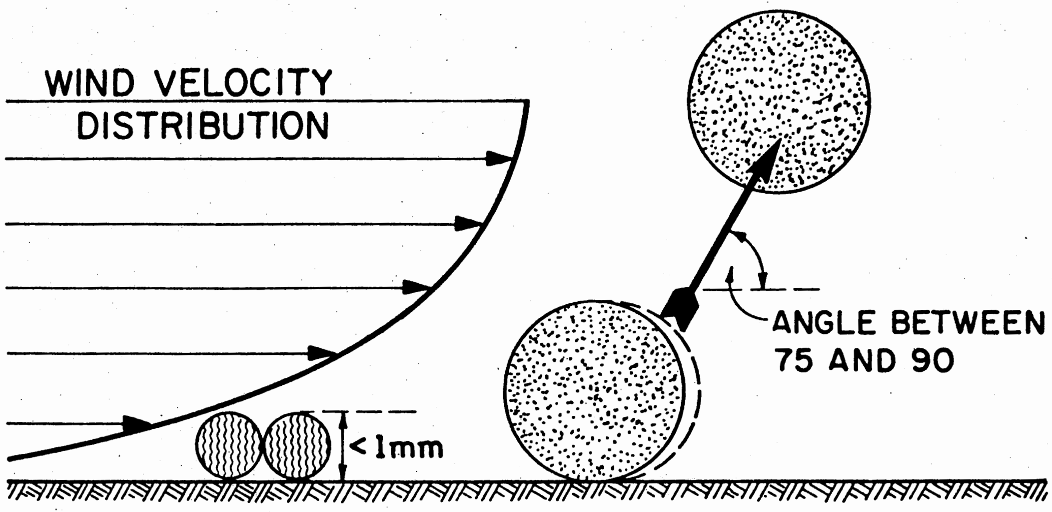


Figure 3. Mechanism by Which the Particles are Picked up by the Wind and the Angle of Rise of Saltating Particles (5)

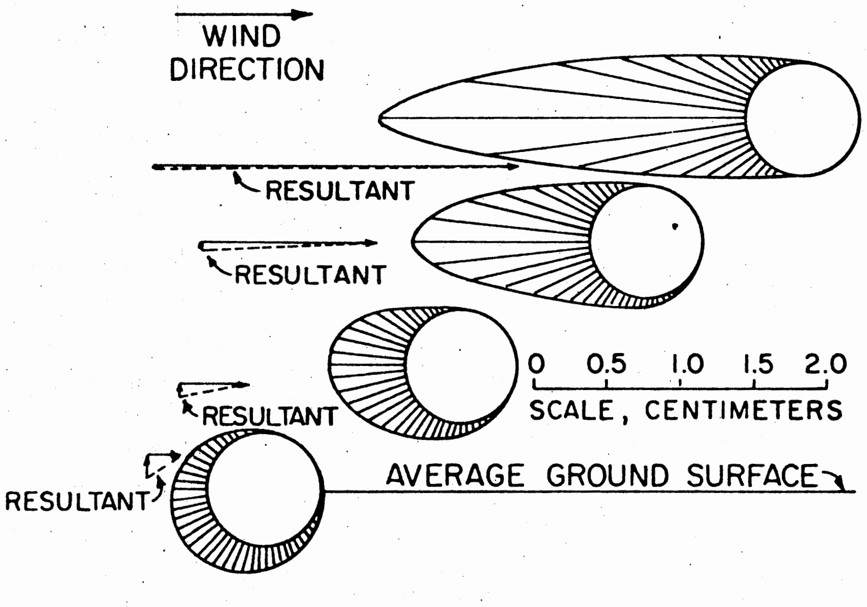


Figure 4. Pattern of Approximate Pressure Differences Between Position 1 on Top of Sphere and Other Positions on Sphere at Various Heights in a Windstream (43)

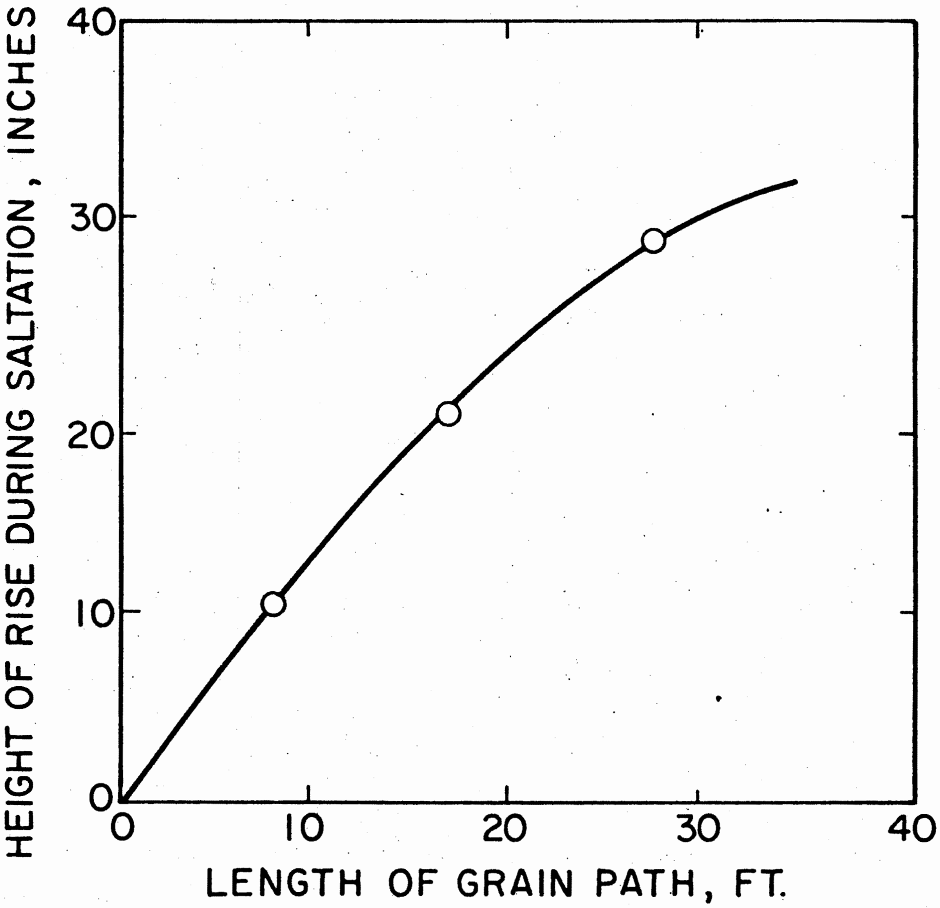


Figure 5. Variation of Distance of Travel of Saltating Particles With Respect to Height of Rise During Saltation

movement is initiated mainly by saltation, elimination of saltation will automatically eliminate suspension. Thus, soils which contain particles that are mostly smaller than 0.1 mm in diameter are less susceptible to both saltation and suspension. Secondly, soils having a large percentage of particles smaller than 0.1 mm in size possess some amount of cohesion, and hence are less erosive in nature.

c) Surface Creep. Soil particles larger than 0.5 mm in diameter are too heavy to be lifted off the ground by common winds (6). As the spin velocity of the particles is not enough to cause lift, these particles simply roll on the ground and are pushed by the wind. Surface creep consists of both rolling and sliding on the surface. Saltating particles may have a great rolling velocity when they fall back to the ground.

Deposition: Sedimentation of the particles takes place when the wind subsides. The first to be deposited are large particles rolling on the ground followed by these moving in saltation. Finally, fine grains settle after a long time.

Austin (48) observed that in heterogeneous soil materials there is no meaningful threshold velocity or shear at which soil movement is initiated and sustained. From a practical viewpoint, movement on bare and erodible field surfaces occurs normally when the atmospheric wind velocity two feet above the surface is 16-24 km/hr.

In a wind tunnel experiment (45) where approximately uniform cohesionless beds of sand ranging from 0.2 to 0.7 mm in particle diameter were studied, a saltation threshold has been found to be

$$Ts = .007d$$

where

Ts = apparent shear by wind, psf

d = diameter, mm

It was further found that the minimum shear force required to initiate soil movement occurs where the diameter of the particles is somewhere in the range of 0.10 to 0.15 mm. Thus, soil grains of this size are most susceptible to wind erosion. Relation between threshold shear velocity of the wind and the maximum equivalent diameter of the particle that can be carried by it is shown in Figure 6.

Water Erosion

Soil erosion by water is a complex process that involves the interrelation of many factors. Some of these influence the capability of the erosive agents--rainfall and runoff--to detach and transport soil material. Others influence the ability of the soil surface to resist the forces of these erosive agents. Fundamentally, the process of erosion consists of three phases (as noted on page 5):

detachment of individual soil grains
transportation
deposition or sedimentation

Mechanism of Water Erosion. There are two ways in which water erosion occurs: 1) splash by raindrops, and 2) scour by runoff. In both cases the soil particles are detached, transported, and finally deposited elsewhere, leaving the area of erosion depleted of topsoil. Each year during storms, this process is repeated and more and more soil is lost from the places where it is most needed and is deposited

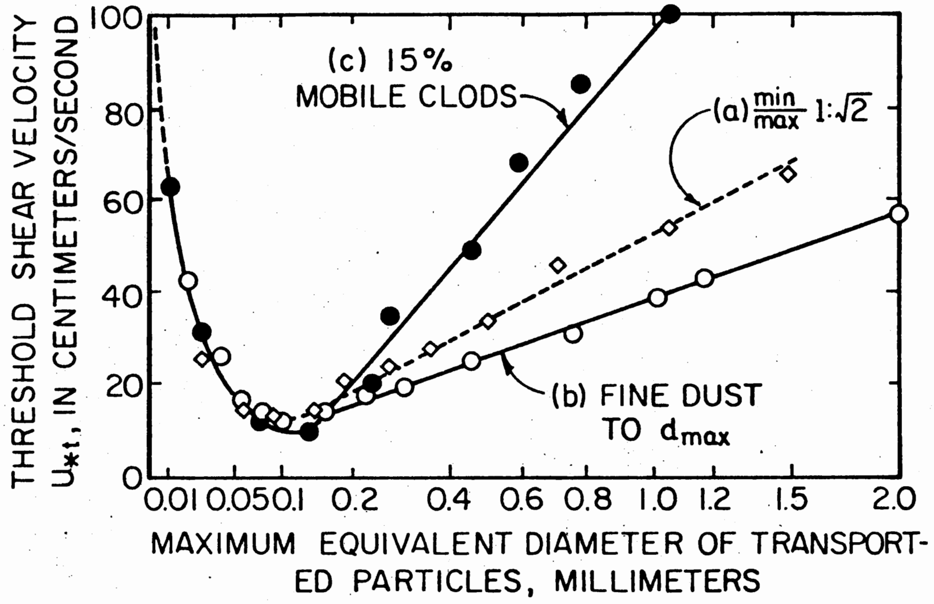


Figure 6. Relation of the Fluid Threshold Shear Velocity of the Wind to the Maximum Equivalent Diameter of the Transported Soil Particles (43)

in the places where it is least required.

Splash by Raindrops (9)(10)(11)(12): Damage caused by raindrops hitting the soil surface at a high velocity is the first step in the erosion process. Falling raindrops, when they strike the ground surface or a thin film covering it, splash small bits of soil into the air. The total kinetic energy, about 0.18 joules/cm^2/hr, is suddenly transmitted to the soil particles. The total energy of raindrops has been calculated by Osborn (32) and reported as being equal to roughly 100 horsepower per acre during a rainfall of one inch per hour, and 250 horsepower when it rains at the rate of two inches per hour.

Wischmeir and Smith (45) developed an experimental equation relating the kinetic energy and intensity of rainfall (Figure 7). It is given as follows:

$$KE = 916 + 331 \log x$$

where

KE = kinetic energy (ft lbs/hr), and

x = intensity of rainfall in inches/hr

Ellison (10) measured the velocity of raindrops and reported that in general the velocity is about 30 ft/sec and that drop diameter is about 2 to 4 mm, depending upon the intensity of rainfall. The total energy of each raindrop is suddenly transmitted to the soil particles, and moves them upward and outward from the point of impact. Because of their different trajectories, the particles are scattered in all directions from the point of impact. If the ground surface is absolutely horizontal, the net movement resulting from splash will be zero because the number of soil particles moving out from a point is

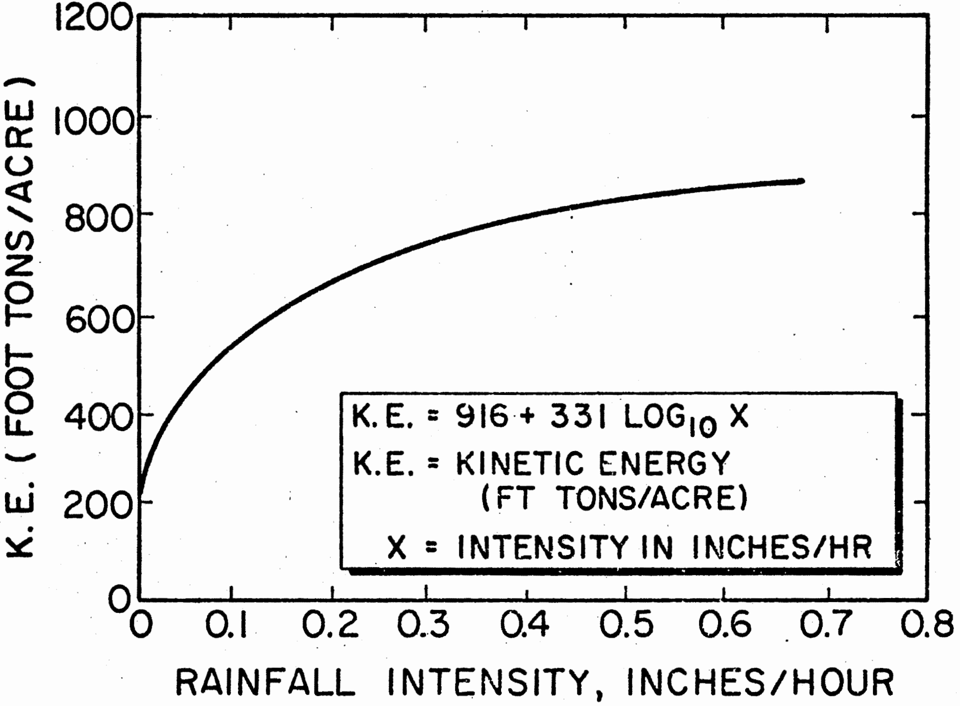


Figure 7. Relationship Between Kinetic Energy and Intensity of Rainfall During a One-hour Storm (42)

equal to the number of particles moving in from other locations. But if the ground surface has slope, this movement of soil grains is not uniform in all directions. Larger numbers of particles are splashed in the downhill direction than in the uphill direction. Secondly, distance covered by splashed grains is greater in the downward direction. Due to this, more and more soil moves in the downhill direction, and erosion occurs. On steeper slopes, this phenomenon is more severe and, consequently, more erosion takes place. But there is a critical value of slope at which the erosion is maximum. The reason is that slopes above the critical value have lesser projected area subjected to raindrops which fall vertically. In other words, the steeper the slope, the less the number of raindrops per unit of slope area. This is illustrated in Figure 8.

A ground surface with a 45^0 slope will get only 70.7 percent; a 26^0 slope will get 89.8 percent, and a 14^0 slope will get 97 percent of rainfall per unit area as compared to horizontal surface (shown in Figure 8). Thus, on steeper slopes, the force of gravitation is more, but the intensity of rainfall is less, and on milder slopes, intensity of rainfall is greater but the effect of gravity is less. El-Roussten (18) found that the critical slope is around 14^0, at which splash erosion is a maximum.

Scour Erosion

Soil movement by surface runoff is called scour erosion. As the surface water accumulates, it moves down the slope. This water rarely moves as a uniform sheet over the surface of land. It would move in this manner if the surface were smooth and uniformly inclined, which

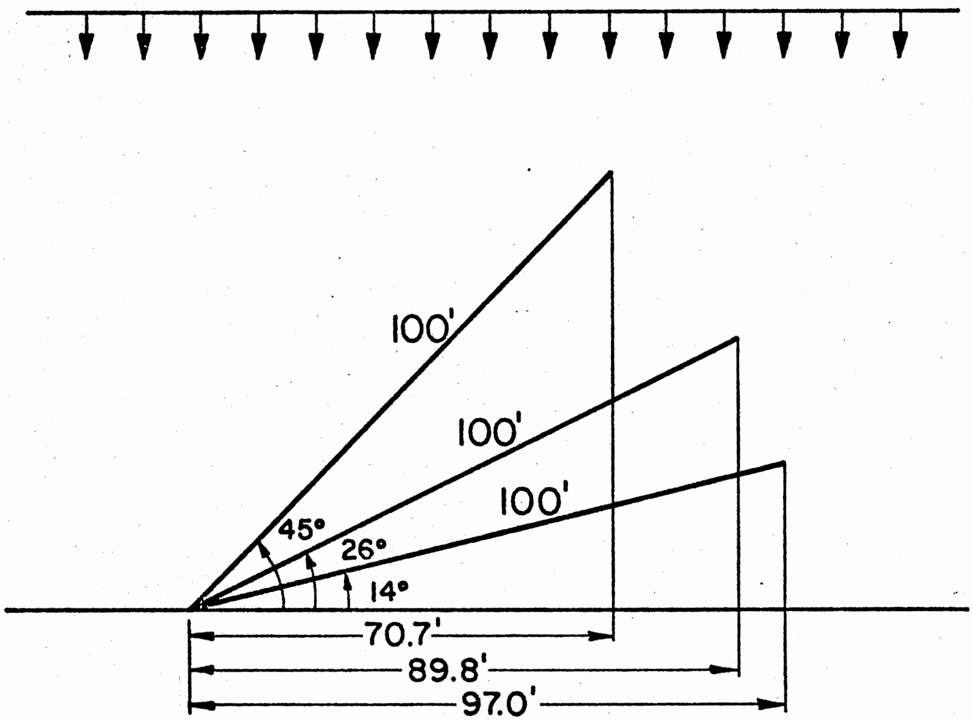


Figure 8. Effect of Slope Inclination on the Distribution of Rainfall in the Catchment Area (18)

is seldom the case. The surface is almost always irregular. Surface areas a few feet square generally exhibit in miniature the drainage pattern of a major watershed. Each small portion of the runoff water takes the path of least resistance, concentrating in depressions and gaining in velocity as the depth of water and slope of land increases. Due to this irregular behavior of the flow, the erosion pattern becomes the same as that for a similar large area. Rills, gullies, and channels are formed. Water then tends to accumulate in these places and causes further erosion at a faster rate. The eroded material resulting from raindrop splash tends to be moved as a uniform sheet, but the erosion caused by surface runoff is associated mainly with rills, gullies, and channels.

Mechanism of Scour Erosion. Scour erosion consists of detachment and transportation of soil particles. Detachment results from several mechansims or a combination of them which include the following:

Rolling: When surface flow moves across a relatively smooth surface, there are forces at work that tend to roll or drag the soil particles along with the flow. These forces are developed mainly from the viscous resistance offered by the soil grain surfaces. This force is directly proportional to the velocity of flow. When the velocity of flow reaches some magnitude, the viscous forces can drag the particles. They become dislodged from their original position and start rolling and creeping along with the flow. Rolling generally occurs when the soil grains are relatively large in size and cannot be lifted by the flowing water. In the process of detachment, slope plays a very significant role. The steeper the slope, the more unstable are the surface particles and, hence, the more easily they can be dislodged and detached by the flowing water.

Lifting: This normally occurs on rough surfaces. When the water flows over a rough surface having small depressions, the water retained in the depressions has no horizontal velocity while the water just above it and below it will be flowing. This velocity difference sets up a differential pressure between the moving and still layers of water. This pressure difference causes vertical currents and eddies to be set up. Upward flowing water may lift particles of soil materials and set them in motion in the flowing water.

Abrasion: Soil particles in transit dislodge other particles from the surface by a process called abrasion. Due to the impact of the particles in suspension or in a rolling state, particles attached to the surface are knocked loose and set in motion. This process cannot start by itself unless there is already soil material suspended in the flowing water.

The detached particles may be transported by a combination of three different processes, defined as follows:

Surface Creep: The horizontal forces of the water flowing over the surface not only dislodge particles, but also transport them downstream by rolling and sliding. As these particles remain on the ground during their transport, the slope of the surface influences the transportation. Steeper slopes give rise to faster transportation and, therefore, more erosion. Most commonly, sand-size particles are carried by surface creep.

Suspension: Particles which are very small in size (clay or silt) are carried in suspension. Once these small-size particles are picked up by the flowing water, they do not settle down for a fairly long period. The water can carry them great distances. This is the reason that most eroded terrains do not have fines at the surface. The fines have been carried away by the water to streams and lakes.

Saltation: This is an intermediate phenomenon between surface creep and suspension. When the turbulence in the flowing water is fairly high, larger particles are also lifted by the water and carried along before they settle out. In this way even sand-size particles are continually picked up and carried short distances downstream. Particles move by a series of jumps or skips. A very large quantity of soil material is carried in this manner. The higher the velocity of flow, the longer is the length of jump. Thus, on steep slopes which generate high velocities, saltation is at a maximum.

The flow through channels and other drainage devices is fairly uniform and hence it can be analyzed mathematically. Extensive work has been done to analyze the characteristics of the flowing water with respect to erosion and sedimentation. All of these mathematical treatments are based on fundamental principles of "drag" and "lift" on immersed bodies. All of the equations relating the various forces and their effect on soil particles on the surface or in suspension make use of physical constants which vary considerably according to shape, size of soil particles, and flow characteristics of water.

According to Chezy's formula, the velocity of flow can be determined by the formula (53)

$$V = C(MS)^{\frac{1}{2}}$$

where

M = A/P

A = cross-sectional area of flow (units of length^2)

P = wetted perimeter (units of length)

S = slope (dimensionless)

V = velocity (units of length/time)

C = constant (units of length$^{\frac{1}{2}}$/time)

Some relationships between the velocity of flow and the maximum size of soil grain that can remain in suspension were determined as follows (53): (No specifics for various parameters were provided.)

$$V_c = 0.2 \left(S_c - 1\right)^{0.5} d^{0.3}$$

$$V_c = 0.17 \left(S_c - 1\right)^{0.5} d^{0.24}$$

where

V_c = critical or miniumum velocity of flow for particles to remain in suspension

d = maximum diameter of the soil in suspension

S_c = specific weight of the soil particle

Factors that affect scour erosion are soil, rainfall, and slope.

Soil: The soil characteristics important to the erosion problem are permeability or infiltration rate, detachibility, and transportability. These are described as follows:

Permeability: When the rate of rainfall exceeds the rate of infiltration, the depressions on the surface are filled and overflow causes runoff. Soils which are highly permeable, such as sand dunes, are not affected by scour erosion because there is little or no runoff--all of the storm water simply percolates into the ground. These soils are normally eroded by wind and splash erosion. In other kinds of soils, where the infiltration rate is less than the usual intensity of storm, surface flow occurs and scour erosion does occur.

Detachability: Soil erosion is a combination of detachment and transportation of soil particles. If individual soil particles are detachable but cannot be transported by flowing runoff water, no scour erosion will occur. Similarly, if the soil resists detachment, no transportation will take place and, therefore, there will be no scour erosion. Thus, soils which are either not detachable or not transportable are less prone to scour erosion. Soils having large amounts of clay are normally resistant to detachment and therefore erosion-resistant in nature. Shear strength, plasticity, and type of clay fraction influence the detachability of the soil. Clays with high shear strength, high plasticity, and low-swelling characteristics normally resist detachment. Swelling clays generally give rise to higher detachability compared to non-swelling clays because of the increase in void ratio during swelling, which leads to reduction of interparticle attraction.

Transportability: As mentioned previously, no erosion will occur unless soil particles are transported from their original position. Transportability depends upon the size of individual particles; finer particles can be easily transported a long distance by suspension. Larger particles, however, are transported by creep, rolling, or saltation. Thus, sandy soils are less prone to scour erosion because of their poor transportability.

Detachment of soil grains from the surface and their subsequent transportation depend mainly on the velocity of flow over the surface.

A higher rate of rainfall gives rise to a greater velocity of runoff flow and, hence, greater scour erosion. Furthermore, raindrops cause turbulence in the surface flow. This generates eddies which can pick up more soil particles from the surface, and also help to keep them in suspension for a longer period. This increases scour erosion.

Both the angle of the slope and its length affect scour erosion. While the energy of splashing drops tends to be uniform on each part of the slope from top to bottom, the energy of surface flow tends to concentrate and be greatest at the bottom portion of a long slope. This increases with each increment of slope length that is added. Increase in the length of slope tends to increase the quantity as well as the velocity of the flowing water near the bottom of the slope. Thus, the energy of the rainfall that will run off the slope is a function of the length of the slope, measured from the top. This is the reason the scour erosion is greatest near the bottom of a slope. Steeper slopes increase the velocity of flow, and consequently increase erosion. Thus, on steeper or longer slopes, the scour erosion is more severe than on short and mild slopes.

Several empirical relationships relating soil erosion and slope are (48)

$$X = CS^{m}L^{m}$$

$$X = C(0.52 + 0.363S + 0.52S^{2})^{m}L^{n}$$

$$A = 0.43 + 0.30S + 0.04S^{2}, \text{ and}$$

$$E = CS^{1.35}$$

where

X = total soil loss, weight units, tons per acre

S = land slope, percent

L = horizontal length of slope, ft

m = constant

n = constant

A = soil loss, tons per acre

C = constant

E = soil loss per unit area, tons per acre

Polymers

A polymer may be defined as a large molecule comprised of repeating structural units joined by covalent bonds. Commonly, a large molecule is regarded arbitrarily as one having a molecular weight of at least 1000 or one containing 100 structural units or more (35). By structural unit is meant a relatively simple group of atoms joined by covalent bonds in a specific spatial arrangement. Since covalent bonds also connect the structural units to one another, polymers are distinguished from those liquids and solids wherein repeating units (ions, atoms, or molecules) are held together by ionic, metallic, or hydrogen bonds, dipole interaction, or van der Waals' forces. The term "resin" is often used to refer to any material whose molecules are polymers. Some applications of polymers are shown in Figure 9.

Most of the synthetic polymers are prepared from simple starting materials called monomers. These monomers are made to react and link themselves to form a large polymeric molecule. Thus, there is a repeating monomer unit in each polymer molecule. The larger the number of repeating units present, the greater is the molecular weight of the polymer and the higher is the degree of polymerization. Structural formulas of some of the common polymers are given in Figure 10.

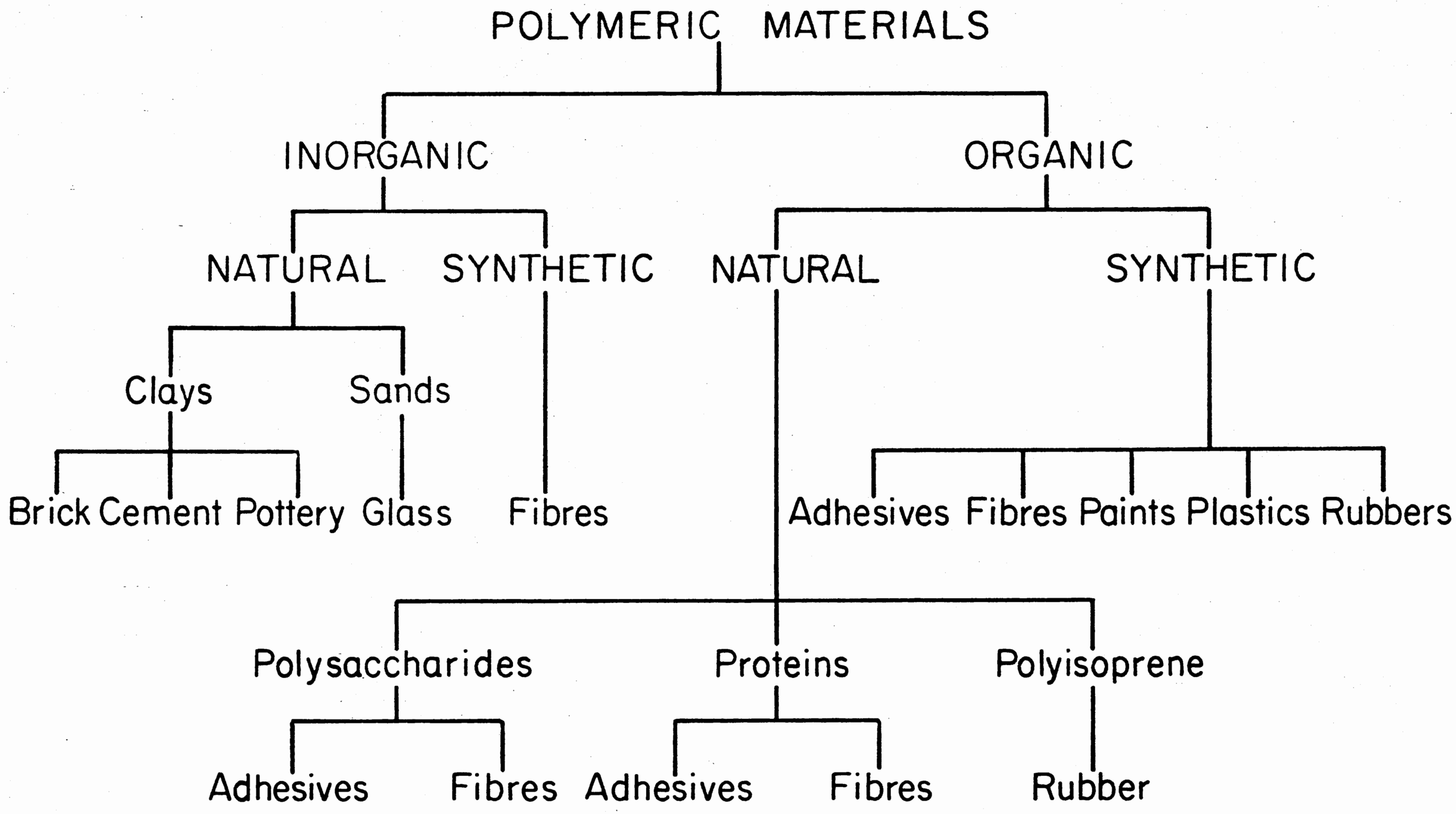
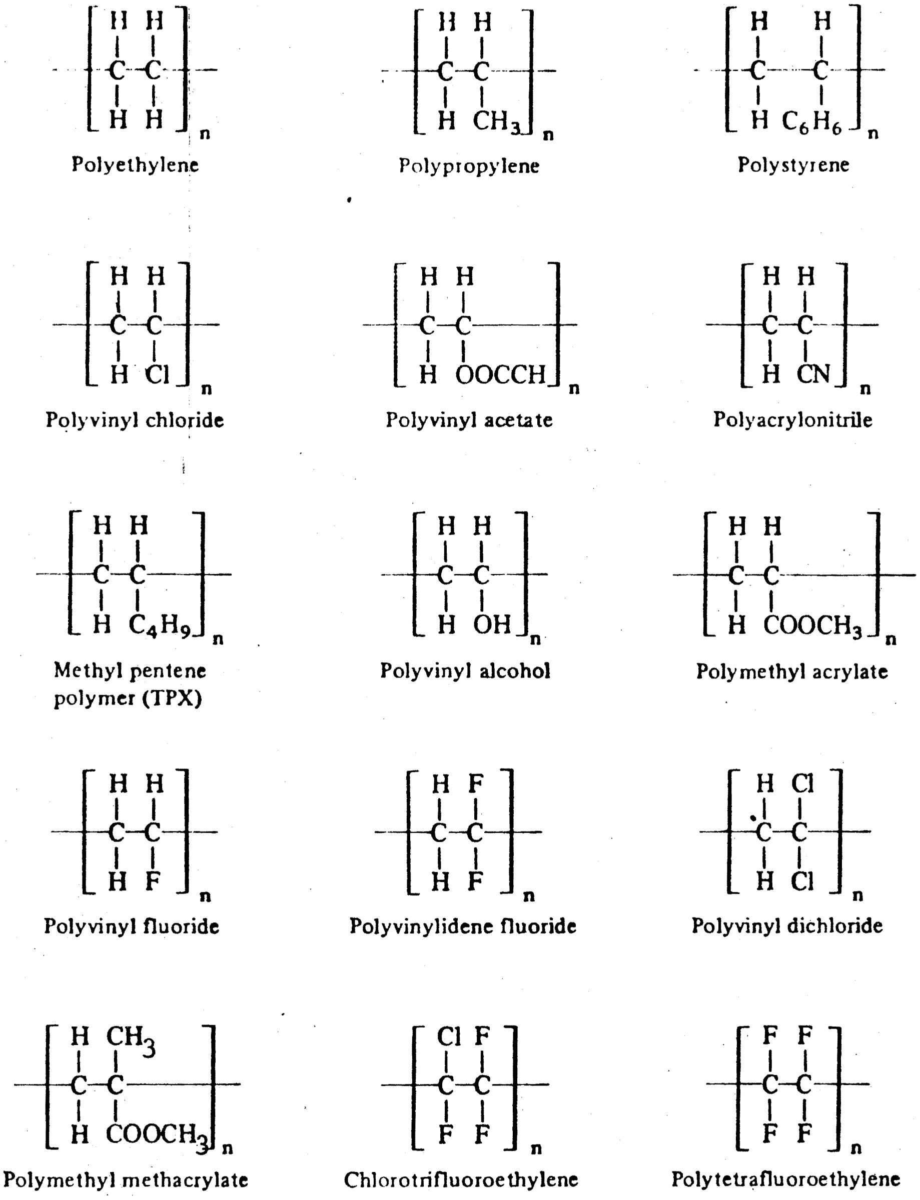


Figure 9. Some General Applications of Polymeric Materials (32)



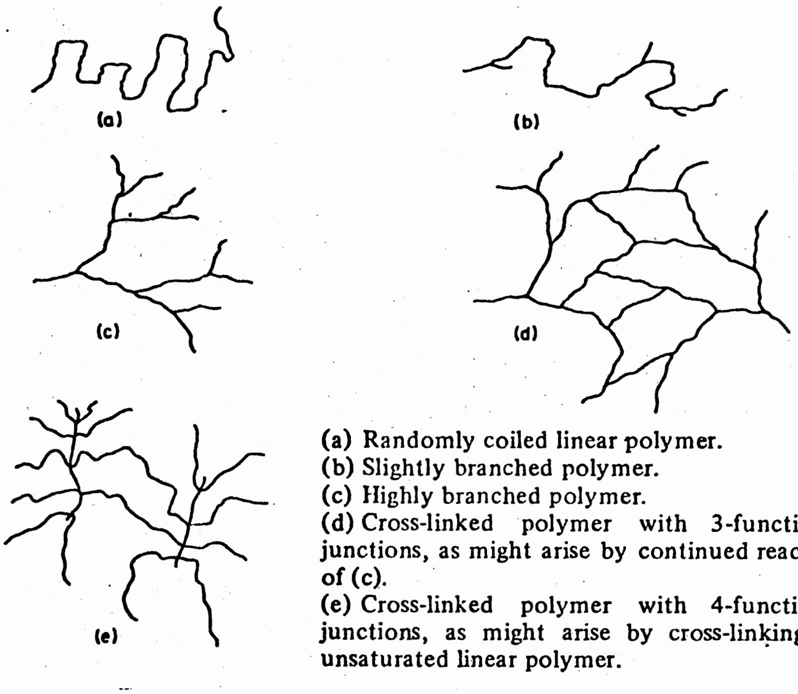
Polyethylene
Polypropylene
Polystyrene
Polyvinyl chloride
Polyvinyl acetate
Polyacrylonitrile
Methyl pentene polymer (TPX)
Polyvinyl alcohol
Polymethyl acrylate
Polyvinyl fluoride
Polyvinylidene fluoride
Polyvinyl dichloride
Polymethyl methacrylate
Chlorotrifluoroethylene
Polytetrafluoroethylene

Figure 10. Structural Formulas of Some Common Polymers (52)

(The unit within brackets is the repeating monomor and n is the degree of polymerization.)

In order to be useful as a solid material of construction, a polymer must be capable of being manipulated to some desired shape, be it cement concrete, soil cement, asphaltic materials, or plastic film and fiber. A material may undergo liquid flow either as a melt (at a temperature high enough to give sufficiently low viscosity), or as a solution, latex, paste, or emulsion. In the latter cases, either a chemical reaction or removal of solvent is necessary to solidify the material in the required shape or at the required place. In the former case, cooling down to the ambient temperature is sufficient.

Polymers like polyethylene, polystyrene, polyvinyl chloride, etc. are composed of long chain molecules which are not linked together by covalent bonds. Most of these are prepared (polymerized) in the form of either an emulsion or suspension in water. Later, the water is removed and the solid polymer is obtained. Before water is removed, the polymer is in liquid form and can be used as such for surface coating, adhesive, or any related purpose, including soil stabilization. After removal of water, these polymers can be manipulated later by heat or by solution. Polymers of this kind are sometimes called thermoplastic polymers. The other kind of polymers are cross-linked polymers. In this case, a different situation exists. Here the polymer chains are linked together by covalent bonds, as illustrated in Figure 11. Thus, when the polyer is formed, it must be used immediately, like Portland cement, which must be placed before it starts to set. In certain cases, cross-linking of the polymer can be delayed by withholding a cross-linking agent. In that case, polymers can be kept in liquid form for fairly long periods. Polymers of this kind are viscous liquids, chemically reactive and toxic to a certain degree, before the



(a) Randomly coiled linear polymer.
(b) Slightly branched polymer.
(c) Highly branched polymer.
(d) Cross-linked polymer with 3-functional junctions, as might arise by continued reaction of (c).
(e) Cross-linked polymer with 4-functional junctions, as might arise by cross-linking an unsaturated linear polymer.

Figure 11. Schematic Diagram of Different Kinds of Polymers (35)

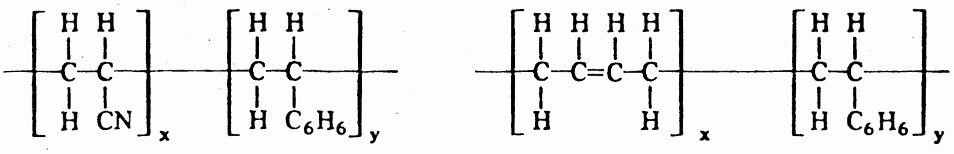
cross-linking occurs. These polymers can be diluted only by chemical solvents, which pose some additional problems regarding environment, safety, and cost. Cross-linked polymers are also called thermoset polymers. For soil stabilization purposes and especially for erosion control, these polymers have a limited usefulness. On the other hand, water-base thermoplastic polymers have great potential to become excellent soil stabilizers.

The big advantage in using polymers for soil stabilization lies in the ease with which these materials can be handled and in the properties which they incorporate in the soil. Some of these properties are difficult to achieve by other means or materials at a reasonable cost. Furthermore, a number of desirable properties can be developed in a polymer through what is known as copolymerization. In this process, two or more monomers are polymerized together. The polymer thus obtained is called a copolymer and has properties in certain respects different from either homopolymer. By adjusting the ratio of each monomer, the properties of the copolymer can be varied according to need. Structural formulas of some common monomers are shown in Figure 12. Not all monomers can be copolymerized. There must be a compatibility among the monomers to form a copolymer.

There is a simple mathematical relationship by which the amount of each monomer can be determined to obtain a certain copolymer having the desired amount of each monomer (38).

$$\frac{m_1}{m_2} = \frac{M_1}{M_2}\,\frac{r_1M_1 + M_2}{r_2M_2 + M_1}$$

where

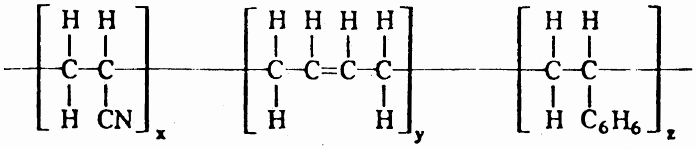


$$-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{CN}{|}}{C}}-\right]_x-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{C_6H_6}{|}}{C}}-\right]_y-$$

$$-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{C}=\overset{\overset{H}{|}}{C}-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\right]_x-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{C_6H_6}{|}}{C}}-\right]_y-$$

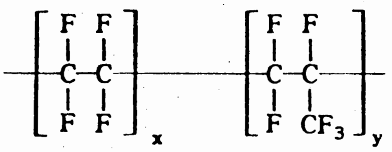
Acrylonitrile-styrene copolymer

Butadiene-styrene copolymer



$$-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{CN}{|}}{C}}-\right]_x-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{C}=\overset{\overset{H}{|}}{C}-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\right]_y-\left[-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{C_6H_6}{|}}{C}}-\right]_z-$$

Acrylonitrile-butadiene-styrene copolymer



$$-\left[-\overset{\overset{F}{|}}{\underset{\underset{F}{|}}{C}}-\overset{\overset{F}{|}}{\underset{\underset{F}{|}}{C}}-\right]_x-\left[-\overset{\overset{F}{|}}{\underset{\underset{F}{|}}{C}}-\overset{\overset{F}{|}}{\underset{\underset{CF_3}{|}}{C}}-\right]_y-$$

Tetrafluoroethylene (TFE)–Hexafluoropropylene (HFP) copolymer

Figure 12. Structural Formulas of Some Copolymers (52)

(The unit within each bracket is the repeating monomer; x and y are the degrees of polymerization of each monomer in the copolymer.)

m_1 and m_2 = ratios of each monomer in the copolymer

M_1 and M_2 = concentration of each monomer

r_1 and r_2 = reactive ratios of each monomer

There is a large amount of literature available dealing with various properties of polymers alone or with small amounts (usually less than 25 percent) of mineral filler (20)(37)(39)(42). Mathematical expressions to characterize these systems have been developed from the classical derivation of Einstein (15) and subsequent modifications (16). These are based on energy required for the displacement of a fluid around rigid dispersed mineral particles.

Apparently no similar analysis has been made of systems in which the mineral phase dominates--that is, where there are intergranular contacts and where voids are not completely filled with polymer, which is usually the case in polymer treatment of soils. In order to study such a system with the present state of knowledge, one has to depend on the basic properties of polymers in relation to the silicious surface of soil particles. For example, one has to find out how polymers form films which can coat and adhere to surfaces, what factors affect the adhesion of the polymer to the substrate, how polymer degradation occurs, and what causes certain polymers to be stronger than others. Once these factors are clearly understood, a better picture of soil polymer interaction can be drawn.

The basic properties which make a polymer a successful soil stabilizer can be summarized as follows:

high adhesive strength with soil surface
high cohesive strength
low shrinkage during setting

low water-susceptibility after cure

resistance to elements of nature, sugh as sunlight, atmospheric oxygen, and biological degradation

minimal reduction in permeability of soil after treatment

nontoxic

nonpolluting

inexpensive

It is obviously difficult to achieve all of these properties in one polymer for all kinds of soils, but not all of these properties are required in all situations regarding soil type, location of treatment, and purpose of treatment. For example, in erosion protection of steep highway slopes, the polymer need not produce a very high compressive strength. Similarly, for places where only temporary erosion control is needed, such as construction sites, the polymer need not be highly resistant to biological degradation. In the case of lining drainage channels, it may be beneficial if the polymer makes the soil impermeable.

Water-base Polymers (38)

Water-base polymers have definite advantage over non-aqueous solvent base polymers for numerous reasons. Use of organic solvents or diluents with a polymer solution or dispersion to obtain acceptable properties for soil stabilization presents certain problems. The volatile organic solvents are a fire hazard, they are toxic, they contribute to atmospheric pollution, and they increase the cost of the polymer system yet they do not form part of the final cured polymer. All of these problems can be overcome by using water-base polymers in which water can be used as a diluent. Furthermore, in many situations soil is in a wet or moist condition at the time of treatment. Non-aqueous-base polymers are adversely affected if water is present in the soil, because if a film of water is present on particle surfaces, the intimate contact between soil-grain surface and polymer is not attained. The solvent evaporates more readily than water, leaving a cured polymer film without any adhesion of the film to the soil grains. Also, the free pore water in the soil becomes mixed with the polymer and, thus, impairs the ability of molecules to come close to each other and form a uniform film. A polymer film formed in the presence of water has a honeycomb structure with voids which reduce its strength considerably.

There is no such problem associated with water-base polymers. In addition to this, water systems offer the possibility of cleaning the equipment easily, conveniently, and cheaply. However, water-base polymers are also not completely free from problems. Because of its high latent heat of vaporization, water takes relatively more time and slightly higher temperatures to evaporate and give a final cured product. Also, water causes swelling in some fine-grained soils, and this might cause some problems in proper film formation of the polymers. However, interaction between clay minerals and polymers is much more complex than simple film formation. In this situation, the role of water is much more than that of a diluent. It provides a medium in which clay and polymer react chemically to form a clay-polymer complex. This aspect is presented later in this chapter in more detail. Most of the erosive soils, such as sands and silts, do not swell significantly when wetted, so the swelling problem is of very little significance.

A water-base polymer can be water soluble or it can be prepared in the form of a latex or emulsion. In the former case, only a small amount of polymer can be dissolved. Also, only a few kinds of polymer can be prepared in the form of a solution. In the latter case, large quantities of solid polymer can be maintained in the form of a liquid. The advantage is that this concentrated liquid polymer can be diluted at the site and hence the cost of transportation of water from the factory to the site is eliminated. A large number of polymers can be prepared in the form of an emulsion or latex. Some of the most important are

polystyrene
most acrylic polymers
most vinyl polymers
many polyesters
a few polyurethanes
copolymers of the above
elastomers, such as butadiene and its copolymers

These polymers are quite stable in the form of emulsion and stay emulsified for a fairly long period of time.

Film Formation

Film formation from a dispersion is comparatively a more complex phenomenon than the film formation from a solution. A dispersed polymer or polymeric emulsion consists of a separate polymer phase in the form of individual spheres dispersed in a liquid medium (water). Such a system is not homogenous on a molecular basis. As the water evaporates, the spherical polymer particles come closer and closer together and finally touch. Thus, in order to obtain a continuous polymer film free from voids, deformation of these polymeric spheres is necessary. This requires the existence of some driving force of sufficient magnitude to overcome the resistance of the polymeric spheres to this change in shape. Hard polymers will resist deformation very strongly under imposed stresses, whereas rubbery polymers will deform more readily. The potential for film formation of a dispersed polymer is related to this deformability. If the polymer is very rigid, deformation does not occur, and the film formation will not be accomplished; a spongy or powdery structure remains after evaporation. The capillary pressure of water exerts forces which pull the dispersed particles together. As the water evaporates and the spheres come closer together, the pressure increases. When the spheres touch, further evaporation of water exerts additional pressure, deforming the spheres to form a continuous film, as shown in Figure 13.

Factors Affecting Film Formation

All of those factors which influence film formation will also affect the performance of the soil-polymer mixture, since poorly formed films will cause a weak linkage between soil particles which will soon break apart. The factors that affect film formation are time, temperature, size and shape of polymer molecules, and physical influence.

Time: An adequate amount of time is required to allow the film to form properly. Slow or controlled evaporation of water will delay film formation. More rapid film formation will take place when the rate of evaporation is high.

Temperature: Temperature governs the film formation in two ways.

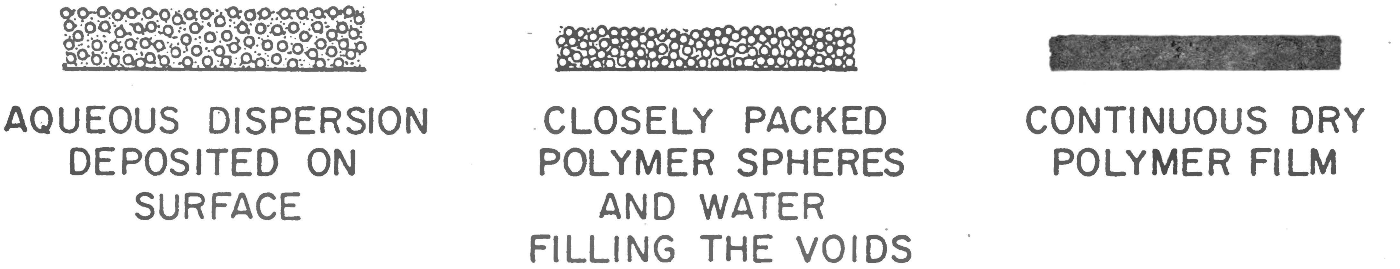


Figure 13. Development of Polymer Film From Aqueous Dispersion

First, higher temperature leads to a faster rate of evaporation and hence quicker film formation. Second, the rigidity of the polymer spheres also depends on temperature. At higher temperatures, the spheres are softer or less rigid, and hence more intimate contact between adjacent spheres is obtained. This gives rise to a denser and stronger film. Thus, those polymers whose molecules deform easily (even at low temperatures), like elastomers, form dense and strong films.

Size and Shape of Polymer Molecules: The particle size has a definite effect on the formation and performance of the film. Smaller particle sizes give rise to larger surface area of content between individual polymer spheres, and hence stronger film. Similarly, a film consisting of finer polymer particles shows better adhesion to the substrate. Highly branched polymer molecules keep the chains farther apart, reducing density, rigidity, and tensile strength, as shown in Figure 14.

Physical Influence: Physical state of the emulsion has an important influence on film formation. Normally, in an emulsion which has fine particles dispersed uniformly, it is easier to develop a good film. If the emulsion is in a partially flocculated state, it may trap water or air bubbles leaving voids and a discontinuous film.

Strength of Polymer Films

Cohesive strength of a polymer is defined as the force by which individual molecules (or chains) of the polymer are held together. The higher the force, the stronger will be the polymer and greater will be the shear strength of the material. Individual chains of most of

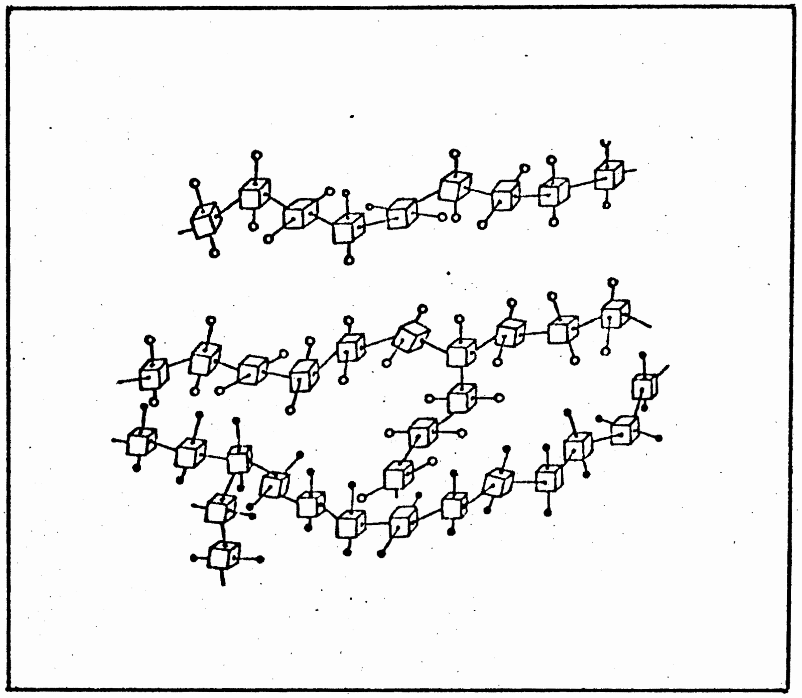


Figure 14. Molecular Structure of Linear Polyethylene (top) and Branched Polyethylene (bottom). (Branching keeps the chains farther apart, reducing density, rigidity and tensile strength.)(52)

the thermoplastic polymers are held together by secondary forces (hydrogen bond, van der Waals' and polar interaction). These forces are relatively much weaker than the covalent bonds by which the individual units of the polymer are linked. Thus, the mechanical strength of the polymer depends on these secondary forces. Additional strength is also achieved through entanglement of the individual chains. Closeness of packing of the polymer molecules, molecular weight, and degree of cross-linking also affect the strength of the polymer. Crystalline polymers are stronger than their amorphous counterparts. In crystalline polymers, the molecules are very closely packed. This gives rise to both high density and strong intermolecular forces which, in turn, increase the strength of the polymer.

In polymers of high molecular weight there are stronger secondary forces. This gives rise to stronger polymer film. Degree of cross-linking and molecular chain entanglement also increase the cohesive strength of the polymer. On any shear plane, there are both covalent bonds and secondary bonds which ultimately take up the shear stress. The strength of the polymer is derived from the combined effect of covalent bonds (bond energy 50-200 Kcal/mole) and secondary bonds (bond energy 2-10 Kcal/mole).

Cohesive energy density (CED) is generally used as a measure of total internal forces of a polymer. The higher the CED, the stronger will be the polymer. Crystalline polymers have relatively higher CEDs than do the amorphous polymers. However, polymers which have high CEDs are poor adhesives. Due to the stronger internal forces, the molecules of the polymer do not have the opportunity to develop intimate contact with the substrate, which is essential for good adhesion. There is no direct way to measure the CED of a polymer. It is calculated with the help of a solubility parameter, δ. It is observed that stronger polymers, or polymers with higher CEDs, possess higher solubility parameters as well. A direct relationship is found to exist between CED and δ (44).

$$\text{CED} = (\delta)^2$$

Since the solubility parameters of most polymers and copolymers are known, the above relationship helps to ascertain the cohesive strength of a polymer.

Viscosity of a polymer affects its adhesive as well as its cohesive strength. An increase in viscosity increases the cohesive strength but decreases adhesion, and vice versa. This is the reason that asphaltic materials need to be heated for better coating of an aggregate surface. Crystalline polymers have high melting points as well as high glass transition temperatures because of their high cohesive energies. Glass transition temperature (Tg) of a polymer is defined as a temperature above which the polymer is soft and possesses rubber-like properties. Polymers which have a glass transition temperature close to the ambient temperature provide better adhesion. This is true because at a temperature above the glass transition temperature (Tg), the rate of increase of volume with respect to temperature is greater. Due to the increase in volume, the secondary forces are reduced considerably. This gives rise to a higher degree of freedom of movement of individual molecules within a mass of polymer which, in turn, makes the polymer soft and rubbery. Due to this freedom, the molecules of the polymer achieve better and more intimate contact with the substrate and form a stronger bond with it.

For soil stabilization and especially for erosion control without reducing soil permeability significantly, the choice narrows down to those polymers which have excellent adhesion along with some cohesive strength at ordinary temperatures. There are a few polymers and copolymers which satisfy these requirements fairly well. In addition, polymer additives can also help to achieve the optimum condition in a polymer to suit it for soil stabilization in erosion control.

Polymer Degradation and Additives (33)(36)

The exposure of a polymer to the influence of environmental factors over a period of time generally leads to deterioration in physical properties. The degradation reactions under various environmental conditions are often complex. Broadly, degradation of polymers may be considered as any type of modification of a polymer chain involving the main-chain backbone, side groups, or both. These modifications are often of a chemical nature, i.e., requiring the breaking of primary valence bonds (33). This can lead to lower molecular weights, cross-linking, and cyclization. The molecular weight of the polymer is lowered because of breakdown of the chain. Cross-linking occurs because of a chemical reaction between the broken chains of different molecules. Cyclization (reorganization of molecules into a ring structure) occurs when the combination of some of the chains at various points forms a closed structure like that of benzene. Main-chain scission or breaking may occur in either or both of two ways, corresponding approximately to the reverse of the two types of polymerization processes. Thus, scission may occur randomly (random degradation) where chain breaking occurs at random points, or at the end of the polymer chain where monomer units are released successively (unzipping). In the former case, the molecular weight decreases continuously with the extent of reaction, and the fragments formed, which are large relative to the monomer unit, are mixtures having molecular weights of up to several hundred. In the latter case of depolymerization, the production of monomer is appreciable. Random degradation may be regarded roughly as the reverse of condensation polymerization, whereas chain depolymerization (unzipping) is the reverse of the propagation step (33).

In addition, breaking of secondary valence bonds within a chain may also occur, but this kind of degradation does not lead to much change in the basic properties of the polymer. Thus, it is of relatively less significance.

Degradation symptoms may be described as hardening, embrittlement, softening, cracking, discoloration, or alteration of certain properties, e.g., adhesion and dielectric constant. As these alterations are undesirable, various additives are incorporated into most commercial polymeric products which prevent, minimize, or postpone the onset of degradation. The efficiency of these stabilizers depends on concentration, combination with other compounds, and type. Effective stabilizers against thermal, oxidative, and ultraviolet attack have been used widely. There are also other kinds of additives which are incorporated in the polymer to improve certain properties such as elasticity, adhesion, and flexibility. These are known as plasticizers.

Oxidative Degradation and Anti-oxidants (36)

Most of the polymers are fairly stable at or near room temperature and therefore are not affected by atmospheric oxygen. However, certain polymers like polyisoprene may absorb as much as 15 percent oxygen at ordinary temperatures. As little as one percent oxygen will destroy the elastic properties. This is the reason that most of the synthetic rubbers and elastomers need anti-oxidants.

The role of oxidation is related to polymer structure. Linear saturated hydrocarbons such as high density polyethylene are notably resistant to oxidation. The crystalline areas are much more resistant than amorphous regions. Unsaturated polymers such as natural rubber are readily oxidized. Pendant groups are susceptible to oxidation.

In the absence of an anti-oxidant when the chain breaks, the active centers immediately react with the atmospheric oxygen and the polymer chain remains broken permanently. On the contrary, in the presence of anti-oxidants, the active centers of the broken chain combine with an anti-oxidant molecule to re-link the polymer chain. In this way only chain transfer takes place and no breakdown occurs. Thus, the free radical of an anti-oxidant works as a coupling to join the broken chains. The common anti-oxidants are acetaldehyde, aniline, and adol-a-naphthylamine. Other anti-oxidants are various amines, phenols, sulfur compounds, and phosphorous derivatives.

Ultraviolet Degradation and Stabilizers (33)

Most of the radiation from outer space is absorbed by the atmosphere before it reaches the surface of the earth, but that which does reach the earth damages some polymers very significantly. Essentially, all radiation shorter than 10^4Å in wavelength affects the polymer chains. Degradation of polymers by radiant energy is conveniently subdivided into two types, depending on the mode of action, which in turn is dictated by the wavelength of the radiant energy involved.

Photolysis (photochemical radiation): Ultraviolet light having a wavelength, λ, in the range of 10^4 to 10^2Å and imparting energy in the range of 10^2 to 10^3 Kcal/mole.

Radiolysis (ionized radiation): The wavelength, λ, is in the range of 10^2 to 10^{-3}Å and imparts energy in the range of 10^5 to 10^7 Kcal/mole.

In the context of soil stabilization, only photolysis or photochemical radiation is encountered. Degradation of a polymer by ultraviolet light (UV) is caused by the absorption of energy in discrete units by specific functional groups that may be present in the chain. The receipt of UV radiation excites an electron within the specific functional group to a higher energy state.

Photochemical radiation is capable of cleaving the C-C bond (carbon to carbon bond). For example, light with a wavelength of 2800 Å having an energy of 100 Kcal/mole may in principle break the C-C bond whose energy is about 80 Kcal/mole. Generally during photodegradation chain scission, cross-linking and monomer production including production of other small molecular weight fractions, can occur. Chain scission is generally of the random type. Trace impurities present in commercial polymers may catalyze this degradation.

The rate of degradation may be retarded by the addition of stabilizers which absorb energy in the region of the spectrum at which the polymer is photosensitive. Pigments have been used as ultraviolet absorbents in coatings, films, and articles made from polymers. Carbon black is particularly useful because in addition to absorbing the radiation, it also supplies free radicals which form stable products by coupling with compounds produced in the process of degradation. There are other organic polymer stabilizers which react in the same way as carbon black or anti-oxidants. Some of the common polymer stabilizers are phyenyl salicylate, 2,4-dihydroxy-β-benzophenon and resorcinol monobenzoate. The concentration of ultraviolet light stabilizers in stabilized polymer formulations ranges from 0.2 to 1.5 percent.

Plasticizers (33)

A large number of polymers are too rigid to be useful. In order to make them flexible, two methods are generally used. One is copolymerization with a flexible polymer. The other involves the incorporation of plasticizers. In the former case, not all monomers can be copolymerized and, further, a copolymer may not have some desirable properties that were offered by the original polymer. A copolymer may be weaker or it may be susceptible to oxidative or UV degradation.

A plasticizer is a solid with a high boiling or low melting temperature which imparts flexibility to an amorphous polymer. The gel and lubricity theories have been advanced to explain the effect of plasticizers. According to the gel theory, the plasticization process is somewhat similar to the solution process. Thus, when a plasticizer or solvent of similar cohesive energy or solubility parameter is added to the polymer, it reduces secondary forces including van der Waals' forces. This makes the polymer molecules relatively more free and relaxed. Thus, the rigidity of the polymer is reduced. The lubricity theory suggests that plasticizers reduce the internal resistance to deformation by acting as a lubricant to promote relative internal molecular mobility.

Ferry (33) suggested that each plasticizer molecule contributes a certain increment of free volume. When sufficient plasticizer is added, the percent free volume characteristic of glass transition temperature, Tg, for all polymers is reached. Therefore, the polymer film becomes flexible. In other words, a plasticizer lowers the glass transition temperature of the polymer.

There are various kinds of plasticizers available on the market, including some oils. Oil-extended elastomers are quite common for many applications. For soil stabilization, it seems that oil-extended elastomers will be uniquely effective. This is because the oil also has the property to make the polymer film water-repellant. Thus, the polymer film will be less affected by the presence of water in the soil, and the soil polymer mixture will remain relatively less water susceptible.

Soil Treatment With Polymers

A number of investigators have tried to make use of various polymeric materials for stabilizing soil in general and for erosion control in particular. In most of the publications, only the effectiveness of various kinds of polymeric products in terms of strength, erosion control aggradation of soil particles, reduction in plasticity, and variation in permeability has been reported. No serious effort has been made to explain the mechanism of soil-polymer interaction. One of the reasons for this ambiguity is that there are so many kinds of polymers available and there are so many kinds of soils that it is very difficult to arrive at a particular theory of reaction that can be applied to most of the situations. However, there are some publications in which the authors have tried to explain the results either in terms of reaction between soil and polymers (8)(27) or in terms of mechanical behavior of soil treated with polymeric compounds (23)(42). Most of the authors who dealt with the chemistry of soil polymer reaction worked with the clayey soils.

In the following section the published works are discussed in two groups--one dealing with the interaction of polymers and fine-grained soils, and the other dealing with coarse-grained soils. In the latter part of the section, the possibility of various kinds of chemical and physico-chemical reactions between soil and polymer has been explored.

Treatment of Fine-grained Soils

Lambe (23) used polycalcium acrylate to stabilize silty and clayey soils. He used the monomer of calcium acrylate and polymerized it in situ with the help of a redox catalyst. According to the author, this reaction gave a product consisting of soil particles interwoven in and attached to the strong and flexible chains of polycalcium acrylate, as shown in Figure 15. Effectiveness of the polymer treatment was measured in terms of reduction in liquid limit and gain in tensile strength. Maximum reduction in liquid limit was observed in soils that had high clay contents. For example, in Buckshot clay from Vicksburg, Mississippi, the liquid limit was reduced from 67 to 46.3 by adding 10 percent calcium acrylate. On the other hand, for sandy-silt, the liquid limit was reduced only from 21.7 to 18.4 with the same amount of polymer.

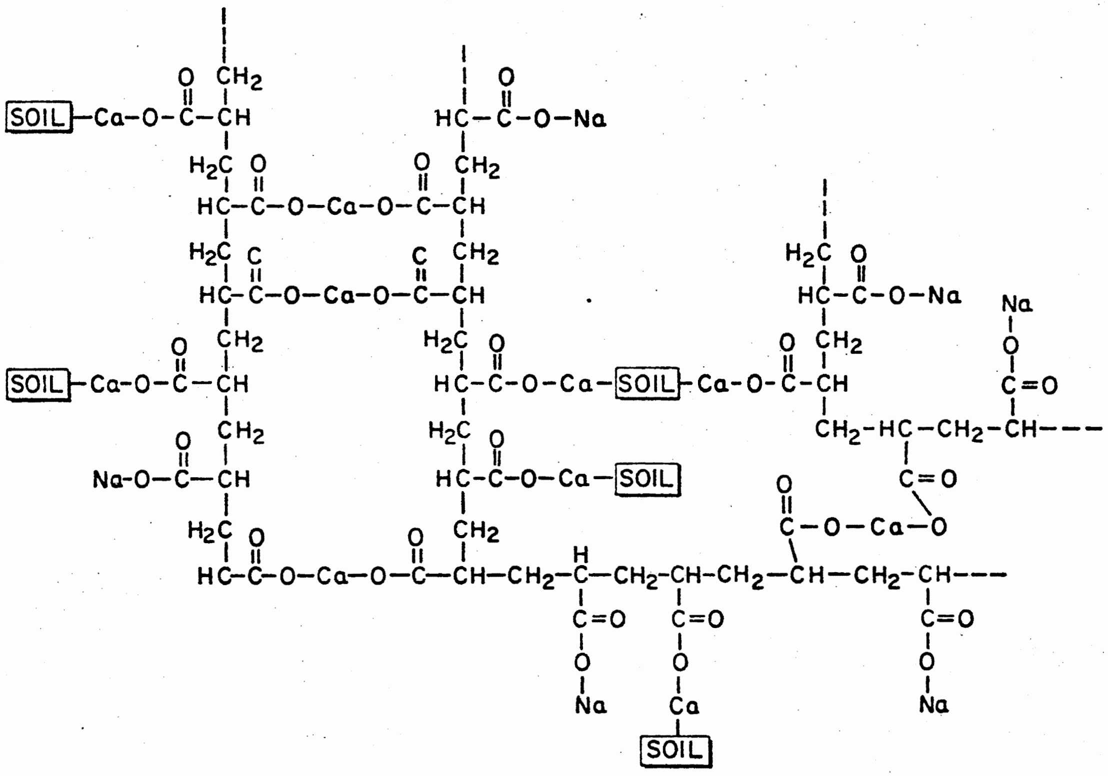


Figure 15. Interaction Between Clay Particles and Calcium Acrylate When the Latter is Polymerized in situ

Similarly, the tensile strength of the treated silty-clay was observed to be 43 psi, but for silty sand it was only 17 psi. Both of these soils had zero tensile strength before treatment. These results lead one to believe that clayey soils perform significantly better than do sandy soils. This is due to calcium ion bridging. Calcium ions are held by the surface charge of clay minerals and are also a part of the structure of the polycalcium acrylate film. In this way, individual clay mineral particles are attached strongly to one another, causing reduction of plasticity and increased strength. But silty and sandy soils do not have a high cation exchange capacity, and therefore show poor performance when treated with polycalcium acrylate.

In the same study, a copolymer of calcium acrylate/N-metholola-crylamide was used to impermeate cohesionless sand. It was found that 2 percent of this compound made the soil impermeable, and a compressive strength of 588 psi was obtained. The reason that this material was so effective was that the polymer swells when wetted. In this case, the polymer swelled to six times its original volume when soaked in water, and hence completely blocked the pores of the sand to make it impermeable.

A similar study was carried out by Davidson et al. (30). They used large organic cations, polyacids, and lignins, separately as well as in combination, to stabilize Iowa silty loam. Large organic cations have been found to waterproof the soil considerably, probably because of the carbon groups attached to these ions. The effect was to reduce the dry strength of treated soil below that of untreated soil. However, treated soil was considerably stronger than untreated after immersion in water. Both the immersed strength and the air-dry strength were increased by the addition of polyacids. A soaked strength of up to 550 psi was obtained by treating the soil first with 0.2 percent of an organic cation (2 HT di-hydrogenated tallow dimethyl-ammonium chloride) and then by 0.6 percent of polyacrylic acid. The role of the organic cation was basically to modify the clay minerals. The cations were absorbed on the negatively charged surface of the clay mineral and modified its electro-chemical properties. Due to their greater van der Waals' attractive forces, large cations are difficult to replace by smaller inorganic cations. When polyacid was added to the soil after the treatment or modification of clay minerals, the strength was further increased by the provision of bonds between various particles. Thus, the strength of the treated soil became a function of not only the bond between cation and polyacid, but also of the strength of polyacid chains. Thus, when polyacrylic acid ionized with NaOH is added to the soil organic cation system, the polymer changes into an elongated configuration, orients itself between the cation-coated mineral surfaces, and forms an ionic bonding between them. The reaction can be represented as in Figure 16. Additional strength was also achieved by adding metallic ions such as iron or copper to the polymer-soil mixture. These ions played a dual role. First, they contracted the polymer chains to develop a prestress in it so that the ultimate strength of the chains was increased. Second, they made the chains hydrophobic due to chelation with carboxyl groups in polyacids.

In another study, Emerson (8) used a number of polymers to stabilize two different kinds of clayey soils. The Hosfield soil was acidic (pH 5.3) containing 29 percent clay whereas the Barnfield soil was calcareous (pH 7.2) containing 15 percent clay. The clay separates gave

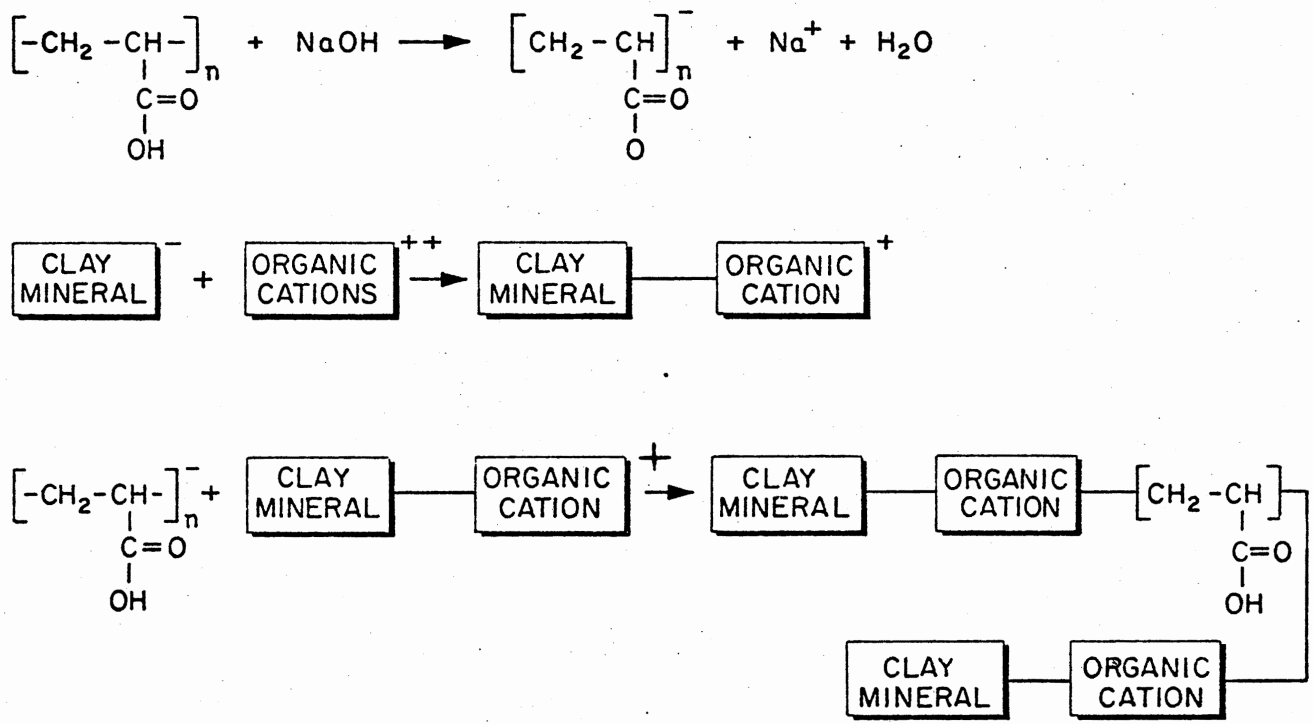


Figure 16. Mechanism by Which Individual Clay Mineral Particles are held Together With the Help of Organic Cation and Ionic Polymer

identical X-ray patterns, indicating about 60 percent kaolinite and 40 percent mica-type minerals. The polymers used were CRD 186 (a copolymer of vinyl acetate and mono-ester of maleic acid), polyvinyl alcohol, sodium alignate, polyacrylic acid, and dextran. It was necessary to add 0.2-0.5 percent of the polymer to the calcareous soil to produce crumbs of maximum stability. The alignate, however, was effective only if the crumbs were first sodium-saturated. The acidic soil required only one-tenth the concentration of maleic acid copolymer required by the basic soil. According to the author's explanation, nonionic polymers like polyvinyl alcohol and dextran form interlamellar complexes, whereas carboxylated polymers are joined to the edge faces of the crystals. The presence of divalent cations was unnecessary for this linkage, as the polymers were equally effective when only sodium ions were present. The author hypothesized that carboxylated polymers form a series of hydrogen bonds with exposed oxygen and hydroxyl atoms of the octahedral layer. Since those atoms have greater tendency to coordinate at a lower pH, the carboxylated polymers would be expected to be more efficient on acid soils. This was further supported by infrared measurements in a separate study (57), which indicated an increase in hydrogen-bonded OH^- with the addition of CRD186 to montmorillonite.

In a study conducted in the Soviet Union (34) a number of polymeric materials were used as structure-forming agents suitable for creating highly water resistant and mechanically strong soil structures. The polymers included were polyacrylamides, copolymer VIII (60 percent methacrylic acid + 40 percent methacrylamide), and hydrolyzed polyacrylonitrile. The purpose of the study was to find a way to control erosion by wind and water on farm lands which were under cultivation.

The permeability of a humus podzol soil increased 15-20 times when treated with 0.05 percent polyacrylamide. Due to the increased permeability, no runoff took place and erosion was reduced considerably. Similarly, calcareous heavy clay behaved the same way when treated with only 0.03 percent polyacrylamide. In addition, butadienestyrene and polyvinyl acetate were also used and were found quite promising for controlling either wind or water erosion. According to the author of the paper, polystyrene and polyvinyl acetate emulsion penetrated into the soil aggregates and formed a film after water was evaporated. The film was at the point of contact between the soil particles and cemented them together, preventing them from being carried away.

In other studies conducted in the Soviet Union (31), optimum value of a number of polymers was determined on the basis of compressive strength, surface area, and permeability. The polymers used were sodium polyacrylonitrile acrylate, calcium polyacrylamide acrylate, and a copolymer of sodium polyacrylonitrile nitromethylacrylate and polyethylene aminocarbonyl. It was found that 0.1 percent of these polymers provided best aggregation of agricultural soils without affecting the permeability. Strengths up to 2 kg/cm^2 were observed in certain cases. Best results were obtained when the soil was treated with a polymer solution having a different pH value than the soil

In a study conducted by Voronkerich (42), polyvinyl alcohol (PVAL) was used to reinforce clayey soils. It was found that a pure polyvinyl alcohol film was quite water-soluble; therefore modified polyvinyl alcohol was used. A number of modifying agents like substituted methylphosphonic acid (SMPA), substituted hydroxymethylphosphoric acid (SHMPA), triethanolamine titanate (TEAT) and triaminoethyl borate (TEAB) were used. These compounds are capable of reacting with hydroxyl groups of a polymer without a catalyst at normal temperature, dissolve readily in water, and react readily with polyvinyl alcohol. The studies were carried out on loess, loess-type kaolinite and montmorillonite clay of broken and unbroken texture. Effectiveness of the treatment was measured in terms of change in grain size analysis. In all soil types where modifiers were used, the fine fraction of the treated soil (mainly the clay fraction) was considerably reduced. For example, when montmorillonite was treated with 2.0 percent (PVAL) and 2.0 percent TEAB, the fraction smaller than 0.001 mm was reduced from 79.8 percent to 8.1 percent. In the case of loess, the change was much less significant. Aggregates formed by modified PVAL were characterized by high water resistance and were not softened by one to two hours of boiling in water. They were also resistant to long-term soaking and cyclic wetting and drying.

Blavia et al. (2) tried thirteen chemicals to stabilize surface clods of three different kinds of soils with varying amounts of clay. Clarion loam had 19.1 percent clay, whereas Webster loam and Luton silty clay had 26.1 and 51 percent clay, respectively. The most effective chemicals were found to be superflocs, polyvinyl alcohol (PVAL), and vinyl acetate-maleic acid copolymer (VAMA). Except for VAMA, the chemicals were more effective on Clarion loam (19 percent clay) than on the other two soils. All of the chemicals were least effective on Luton silty clay (51 percent clay). According to the author, super flocs formed an interlamellar complex like that formed by PVAL but unlike VAMA and polyacrylic acid (PAA) which link to the edge faces of the clay minerals.

Hagin and Bodman (21) studied the influence of the calcium salt of polyvinyl acetate-maleic acid copolymer (CRD 186) on aggregations of different kinds of soils. The soils used were sand, sandy clay, and clay. The treatment resulted in an appreciable increase in the size and percentage of water-stable aggregates. According to the authors, the reaction between CRD 186 and clay minerals was only a surface phenomenon. No change in interplanar spacing of clay minerals was observed. The amount of polymer needed was proportional to the surface area of the soil. As clayey soils have a large surface area, they needed more polymer. Similarly, fine clay minerals (bentonite) need more polymer than large clay minerals (kaolinite).

Hedrick and Mowry (22) used the sodium salt of hydrolyzed polyacrylonitrile (CRD 189), the calcium salt of polyvinyl acetate-maleic acid copolymer (CRD 186) to stabilize silt loam and alluvial sandy loam. By treating with 0.1 percent polymer, water-stable aggregates of sand size were formed. Treatment increased the infiltration rate of the soil; increased growth of carrots was also observed. The treatment was still effective when last observed after two and a half years.

Davis (7) developed a polymeric compound of polycalcium acrylate to stabilize and impermeate the soil. In order to stabilize the soil, polyvalent cations were first introduced and then polyacrylic acid was added. Cross-linking occurs in situ due to the polyvalent cations. The polyacrylic acid solution should have a viscosity in the range of 10-200 centiposes/sec (cps) for best results. According to the authors, presence of polyvalent cations is extremely important for gel formation. If monovalent cation salts are present either in the soil or in the polymer, they will hamper the proper gel formation. Thus it is necessary that an exchange of polyvalent cations take place first. Monovalent cations in the soil may react with the polymeric acid and render it relatively ineffective for cross-linkage by the polyvalent cations. This is particularly true if the polyacrylic acid solution is introduced first in the soil. Thus, for better results, polyvalent cations must be introduced first and then polyacrylic acid. The gel which would hold the particles together will then be formed and make the soil impermeable.

Treatment of Coarse-grained Soils

Other studies have been directed toward treating noncohesive silty and sandy materials with various polymers to control wind and water erosion. These have included some attempts to use soil-polymer grouting. In most of the papers dealing with coarse-grained soil polymer stabilization, the authors have not tried to explain the results either in terms of polymer chemistry or the type of soil.

Ambrust (1) used some thirty-four chemical products, including a number of commercial polymers, to stabilize highly erosive sandy materials. The most successful materials were found to be those containing styrene-butadiene copolymer, polyvinyl acetate, or vinyl chloride-vinylidene chloride copolymer. The materials which did not do the job well consisted of polyvinyl, various kinds of cellulose, protein colloids, and asphalt emulsions. All of those materials found successful did not affect the growth of vegetation, including tomatoes and beans. The cost of this temporary erosion control was found to vary from $14.00 to $50.00 per acre, but this cost was less than one-fourth of that recommended by manufacturers because of the lower rate of application of polymers used by the investigator.

Fungalori (48) used an acylic polymer for stabilizing soil classified as A-4 in the AASHTO system. A compressive strength of 445 psi was achieved by adding 2 percent of the polymer. The cost of polymer was $.1475 per pound. The author concluded that it is more economical to stabilize the soil with polymer than with Portland cement. This paper did not give any information regarding the immersed or water-soaked strength of the samples. According to the experience of the writer, immersed strength of most of the acrylic polymers is fairly low unless polymers are added in such quantity that they block the movement of water into the soil sample so that high dry strength is maintained.

In an extensive series of studies to evaluate soil stabilizing materials, a number of petrochemicals and polymers were tested by Morrison et al. (22)(23)(24)(25) at Denver, Colorado. Both premixed and sprayed samples were tested for erosion and compressive strength. Outdoor testing was also carried out in which samples were kept outdoors for a period ranging from a few weeks to 18 months. In the first study (22), polyvinyl acetate was evaluated in the stabilizing of two different kinds of noncohesive sandy soils. According to the results reported, polymer applied in the form of dilute solution in water (1:9) --one part of polymer to nine parts of water--at the rate of one gal/sq yd provides excellent resistance against erosion. The depth of penetration was found to be 0.3 in. to 0.7 in. The material cost of treatment was found to be $.25/sq yd or $1210.00/acre. In a field experiment where the material was used on a slope of 1½:1 at the rate of 3 gal/sq yd with 1:10 dilution, the cost of the project was found to be $5500.00 ($4000 material + $1500 labor) for an area of 170 sq yd. This comes to \$1.29/sq yd (1973 price). The depth of penetration was found to be six inches. It is the opinion of the writer that the amount of treatment was much greater than needed. Moreover, on a slope of this nature, this kind of treatment which impermeates the soil completely may cause problems.

In the next part of the same study program (23), polyvinyl acetate (Aerospray 70) and Curosal AH (an unknown polymer) were used to stabilize clean sand. Polyvinyl acetate gave an excellent nonerosive surface when sprayed at the rate of 1 gal/sq yd with a dilution of 1:10 at a cost of \$871/acre. Curosal AH also provided good erosion resistance at the cost of \$1287/acre (1973 price).

In the third phase of this study (24), a polyurethane latex, XB-2391, was evaluated for stabilization of sandy material. The material was sprayed at the rate of 1.5 gal/sq yd. This polymer reacted with moisture in the soil and cured. Visual observation was made, and it was found that excellent erosion resistance was achieved. The cost of the treatment was extremely high and prohibitive for normal usage. Compressive strength results were 2214 psi, dry, and 527 psi in the soaked condition. It is the opinion of the writer that this material seems to be more suitable for grouting sand at depths and lining channels rather than for the general purpose of erosion control.

In the last phase of the study (25), five materials including latex XB-2391 were evaluated in the laboratory. Enviro, a polyvinyl copolymer emulsion, provided erosion control at the cost of \$.20/sq yd.

A mulch binder, which is a copolymer of butadiene-styrene called XFS-4163-L developed by Dow Chemical Company (29), has been found to be quite effective in controlling erosion when sprayed at the rate of

40 gal/acre with 400 gallons of water. It forms a water resistant surface without affecting vegetative growth.

In another extensive study carried out by Sultan et al. (40) at the University of Arizona, 46 chemicals including a number of polymeric materials were evaluated for erosion control on Arizona highways. A number of those materials had been tested previously by other investigators, and some of them are also included in the present study by the writer. Most of the materials evaluated in this study were reported to accomplish the job, provided they had been applied in the right amounts. The cost of treatment varied from material to material. As testing was limited mainly to that simulating wind and traffic erosion, some of the water-soluble materials have also been reported to work successfully. The most successful and promising materials reported in this study were those containing polyvinyl acetate, polystyrene-butadiene copolymer, and some acrylic polymers. The soils consisted mostly of sands.

Various kinds of polymers have also been used as grout materials to stabilize the soil in situ. The main purpose in most of the grouting projects was to enhance the strength of the existing soil (43) or to impermeate it to stop seepage loss (17). The difference between the polymers used for grouting and for surface treatment is that in grouting there is very little opportunity for the water or solution to evaporate, as in the case of surface treatment where the polymer film is formed by the removal of the diluent by evaporation. In grouting, solidification or film formation of the polymer has to be accomplished by chemical reaction. This is known as cross-linking the polymer. Most of the thermoset polymers can be cross-linked in situ by chemicals called cross-linking agents. When the polymer solution and cross-linking agent are mixed together, a quick reaction takes place and the polymer solidifies into a hard and rigid material. Polymers which can be easily cross-linked in situ are polyesters, polyurethanes, and epoxies. Polyesters have been found to be ideal for this purpose. These are manufactured in the form of viscous liquid which can be further diluted with styrene. Cross-linking is accomplished by adding ethylmethyl-ketone peroxide. This does not affect the properties of the cured polymer. Moreover, polyesters are relatively inexpensive. Epoxies have also been found very successful, but their cost is quite high.

Polymer-Soil Interaction

Soils can be broadly classified into two main categories: noncohesive granular soils such as sand and coarse silt, and fine-grained soils having a large percentage of clay fraction. Coarse-grained soils are chemically inert materials and do not play a significant role in chemical reactions. On the other hand, fine-grained soils are often involved in chemical reactions. For example, clays react with Portland cement, many fertilizers, chemicals, and organic compounds. These reactions are due chiefly to electrical charges on the surface of the clay particles.

When a polymer is mixed or sprayed on a soil, it behaves quite differently, depending on the type of soil. In order to understand soil-polymer interaction, it is necessary to divide the whole into two major groups: coarse-grained soil-polymer interaction, and fine-grained soil-polymer interaction. In both cases, the ultimate goal is to provide a strong bond between individual soil grains.

Coarse-grained Soil-Polymer Interaction

Success of any polymer as a soil stabilizer and especially for erosion control depends mainly upon the quality of the bond that is developed between the soil particles and the polymer. The importance of the quality of the adhesive bond lies in the considerations that the quantity of polymer to be added to the soil has to be very small and that the voids are not to be filled with the polymeric material so that the soil is made impermeable. An ideal situation would be that the particles of the soil are joined together at the point of contact by the polymer film and the voids are left empty, as before. An advantage in this kind of treatment is that the quantity of polymer needed is very small and, therefore, the cost of treatment will be less. Also, the permeability is not greatly affected. The latter aspect is quite important in certain locations for slope stability reasons, and also for the growth of vegetation.

The strength and durability of the bond between the soil grains and the polymer film depend upon a number of factors related to the properties of the polymer and the surface characteristics of the soil grains. The adhesive bond is attained primarily through secondary or van der Waals' forces, polar interaction, and chemical reaction.

The most important of the adhesive bonds are the secondary or van der Waals' forces that give rise to attraction between molecules. Most significant of these are the London or dispersion forces, which are responsible for virtually all molecular cohesion of the non-polar polymers, such as polyethylene, natural rubber, SBR, and butyl rubber. These forces act at a distance of approximately 4 Å and diminish rapidly with the sixth power of the distance between atoms. Consequently, molecules must be in close proximity for London forces to be effective. This is the reason that natural rubber with flexible molecules is a better adhesive than styrene-butadiene rubber (SBR) with only moderately flexible molecules, and far better than polystyrene, which has relatively stiff molecules. Low modulus of elasticity, indicating freedom of rotation on a molecular scale, permits the adhesive polymer to conform to the substrate and develop strong bonds. On the contrary, crystalline polymers such as linear polyethylene, Nylon 66 and Saran, are generally deficient in adhesive bond strength. Similarly, Portland cement, which is an inorganic polymer, does not do a good job in erosion control where it is added in amounts too small to form a close matrix around individual soil grains.

As the bond strength depends directly upon the distance between the polymer molecules and the substrate, all those factors which give rise to a more intimate contact between the two will yield a stronger and more durable bond. Those factors can be summarized as being

surface texture of the soil grains
porosity of the soil particles
adsorption of the polymer onto the substrate

The first two factors are related to the soil, whereas the third is related to the polymer.

Rough-textured and comparatively more porous surfaces have greater specific area, help to spread the polymer more intimately and, therefore, provide a stronger and more durable bond. On the other hand, nonporous and highly polished surfaces yield poor spreading and hence weaker bonds.

Adsorption of a polymer onto the substrate is a function of many polymeric and environmental conditions (24). Important ones are

viscosity of the polymer solution
temperature
molecular weight of the polymer
nature of the substrate or adsorbent surface
type of diluent or thinner
type of polymer

Some of these factors are interdependent--for example, viscosity of the polymer and its molecular weight are directly related.

Viscosity of a Polymer Solution: This plays a very significant role in the adsorption of the polymer onto the substrate and hence in adhesion. The lower the viscosity, the greater will be the adsorption. On the other hand, lowering the viscosity affects the cohesive strength of the polymer. This is because the viscosity can be lowered either by using larger amounts of thinner or by reducing the degree of polymerization (molecular weight). In the latter case, due to smaller size molecules, the attractive force between them will also be less and hence cohesive strength will be reduced. This is the reason monomers of the same compound do not form a film unless they are polymerized. In the former case, the molecules of the thinner compete for the same spaces on the substrate and hence reduce the chances of the polymer molecules coming in contact with the substrate and forming a strong bond with it.

Temperature: Increase in temperature generally reduces the viscosity and leads to better adsorption. But if there is no appreciable change in viscosity due to temperature variation, adsorption will not be affected.

Molecular Weight: Rate of adsorption of smaller molecules is higher than the rate of larger molecules due to diffusion. Therefore, smaller molecules are adsorbed from polymer solution in the initial stages of curing. They are then replaced by large molecules corresponding to thermodynamic equilibrium. However, if the adsorption bond is very strong, such a displacement may not occur and smaller molecules will be adsorbed preferentially. In most cases it has been observed that the increase in molecular weight of the polymer molecules increases the total adsorption. Both styrene butadiene and polyvinyl acetate show increased adsorption with increased molecular weight. Similarly, adsorption of polymethyl methacrylate increases with increased molecular weight from 440,000 to 1,500,000 on quartz surfaces (24).

Type of Polymer: Some polymers are preferentially adsorbed in comparison with others. It has been found that polymethyl methacrylate is adsorbed onto a silica surface in preference to polystyrene. Though these two polymers are not compatible, polymethyl methacrylate can rapidly and completely replace polystyrene on a silica surface. This phenomenon can be explained in terms of polarity of the two polymers. This will be discussed later in this chapter. It has been observed that an order of affinity of polymer to silica (24) is

polyvinyl alcohol > ethyl celluose > polymethyl methacrylate
> polyethylenevinyl acetate > polystyrene

There is also a preferential adsorption of polar polymer to polar surfaces and non-polar polymers to non-polar surfaces. Thus, if a mixture of two polymers--one polar and the other non-polar--is allowed to be adsorbed on a polar substrate, the polar polymer will be adsorbed preferentially. Thus, there is a polar compatibility between the polymer and substrate for better adsorption.

Type of Diluent: When a polymer solution is allowed to adsorb onto a substrate, both thinner and polymer molecules compete for the same spaces. If the diluent or thinner has better affinity for the substrate, it will be adsorbed first and then it will be replaced slowly as the concentration of diluent is reduced by evaporation. But if the polymer itself has higher affinity for the substrate, the adsorption will start from the beginning and will further increase as diluent evaporates.

In the present situation, the thinner in most cases is taken as water and the substrate as a silica surface. Water and the silica surface are both polar in nature and hence the surface has more affinity for water than for most non-polar polymers. Thus, when a mixture of a polymer and water is applied to a silica surface, water spreads quickly and preferentially. Later on when water is evaporated, polymer molecules substitute for the water molecules. Therefore, the strength of bond is not fully attained until all of the water evaporates. It is also found that the adsorption is inversely proportional to the solvent power of the diluent. Solvents of high power do not release the polymer molecules easily and, therefore, adsorption of polymer onto the substrate is lowered considerably. As most of the polymers are in the form of an emulsion in water and not as solutes, they will be readily released for adsorption.

Polar Interaction

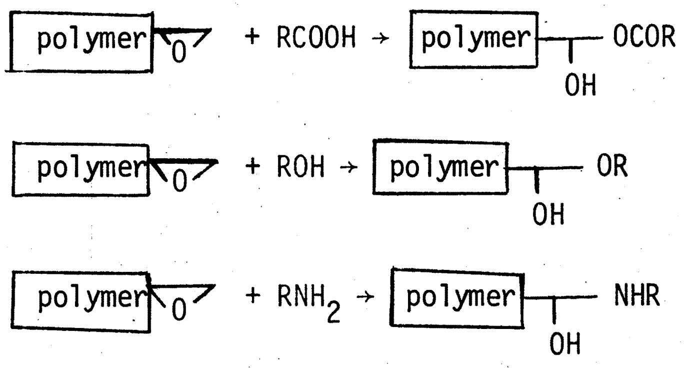
The second important force that is responsible for the bond between a polymer and a substrate is polar interaction. The strength and durability of this kind of bond depends upon the physico-chemical (electrical) nature of both polymer and substrate. In order to understand the mechanism of the polar bond, it is necessary to know the mineral structure of the soil and the electro-chemical properties of the polymer.

Most silts and sands are made up of quartz, which is silicon dioxide, with the chemical formula SiO_2. The basic structural unit consists of four oxygen atoms and one silicon atom, arranged in the form of a tetrahedron. The tetrahedra are linked together by sharing divalent oxygen atoms and thus form a three-dimensional structure of quartz. All of the important soil-making minerals are silicates, and tetrahedral structures are their fundamental units. The mineral feldspar has a three-dimensional structure similar to that of quartz in which at least a quarter of the silicon atoms are replaced by aluminum. The presence of trivalent aluminum in place of tetravalent silicon requires an additional metallic atom or ion to balance the overall charge. In most cases, this additional atom is potassium to give a fundamental chemical formula of $KAlSiO_3$.

Most of these silicates and alumino-silicates possess surface energy on exposed faces. The nature of this energy is complex, but it is due mainly to a) broken bonds of the crystal lattice, b) electronic or ionic forces, c) electrical charges, d) polar nature of mineral molecules, and f) adsorbed ions. The total quantum of this free energy depends upon all of the above factors. For example, soils which are relatively fine-grained have a larger surface area and consequently possess more energy per unit weight. Similarly, polarity of the miner- also gives rise to higher free energy. A polar molecule is one in which the electrical centers of positive and negative charges do not coincide. For example, water molecules are polar in nature and have fairly high polarity. Similarly, most quartz surfaces are polar in nature and give rise to higher free energy. The substances that are most readily attracted by free surface energy of a particle are those which exhibit high polarity. Thus, water, which is polar, spreads and wets a silica surface immediately, whereas mercury does not. Most of the fine-grained siliceous soils retain a considerable amount of adsorbed water which is held primarily by polar interaction. Even coarse-grained sands retain a very thin film of water in the same manner.

If a liquid polymer which is polar in its characteristics is either mixed or sprayed on a soil consisting of quartz mineral, it will develop a strong bond with it. The bond strength will depend, among other things, upon the polarity of the polymer. The higher this polarity, the stronger will be the bond and water will not be able to break this bond and replace it. Hence the soil will remain strong under soaked conditions also. Thus, polar polymers seem to be more promising for both fine-grained and coarse-grained soils. The performance of a polymer will not be affected by the presence of fines in the soil except that slightly more polymer will be required because of the greater surface area.

The functional groups which can be easily incorporated in the polymer to increase the polarity of the polymer and hence its adhesion are carboxyl, hydroxyl, and amino groups (38). In order to incorporate these groups in acrylic polymers, various monomers can be added during polymerization. These functional groups can be incorporated even after polymerization by treating the polymer with carboxylic acid, alcohol, or amines.



Chemical Reaction

According to Rice (50), when a solid is wetted by a liquid, adsorption occurs at the surface followed by a chemical reaction between the adsorbed material and the constituents of the solid phase. Therefore, for many soils which are acidic due to the presence of quartz, polymers which are alkaline in nature (pH >7) would provide a better reaction. As this theory is not well accepted and because contrary results have been observed, it should not be given undue influence in forming concepts.

Fine-grained Soil-Polymer Interaction

Reaction between fine-grained soils and polymer molecules is more complex and less understood than that associated with coarse soils. The clay fraction present in fine-grained soils plays the key role. There is no agreed theory pertaining to the reaction of polymers with various kinds of clay minerals to stabilize them. Explanations of the clay-polymer reaction have been advanced on the basis of two different theories, without strong evidence to support either of them. One of the theories can be called the "Cation Bridge Theory," and the other the "Hydrogen Bond and Chemical Theory."

Cation Bridge Theory

According to this theory, various kinds of polyvalent cations, especially of calcium contained in organic compounds, are strongly held by the negative charges on the surface of clay mineral particles. When a polymer is mixed with a particular clay mineral, ionic and electrostatic forces are developed between the adsorbed cations and the polymer molecules. These forces hold the polymer molecules to the clay minerals. In many situations, the cations also become part of the polymer film. For example, when calcium acrylate is polymerized in situ to polycalcium acrylate, the calcium ions become a part of the polymer chain and are also held by the clay minerals. Because the cations act as a bridge between the clay minerals and polymer chains, this theory has been called the "Cation Bridge Theory." It is illustrated in Figure 16 on page 51.

Hydrogen Bond and Chemical Reaction Theory

According to this theory, there are two kinds of polymers, ionic and nonionic. Nonionic polymers, such as polyvinyl alcohol and dextran, form an interlamellar complex when mixed with clay minerals. X-ray studies have shown that these polymers increase the c-axis spacing of the clay mineral (8). These interlamellar complexes hold the clay minerals together. No subsequent swelling of the clay minerals was observed when treated clays were soaked in water. On the other hand, when ionic or carboxylated polymers containing carboxyl groups as the only charged groups were mixed with the clay minerals, no increase in c-axis spacing was observed. The same situation is observed when sodium polymethacrylate or carboxylated polycalcium acrylate is added to the clay minerals. Furthermore, swelling due to soaking in water continues to exist. This indicates that these polymers do not form interlamellar compounds; instead, polymer chains are linked directly to the edge vaces of the clay minerals, as shown in Figure 17. The presence of divalent or polyvalent cations is unnecessary for this linkage, as polymers have been found to be equally effective when only sodium ions are present. The linkage between polymer and clay minerals is due to a series of hydrogen bonds with the exposed oxygen and hydroxyl atoms of the octahedral layer. Since these atoms have a greater tendency to coordinate a hydrogen ion as the pH is lowered, the carboxylated polymers are found to be more efficient with acid soils. Furthermore, the amount of polymer needed is directly proportional to the surface area of the clay minerals. For example, bentonite requires more polymer than does kaolinte because bentonite is more finely divided.

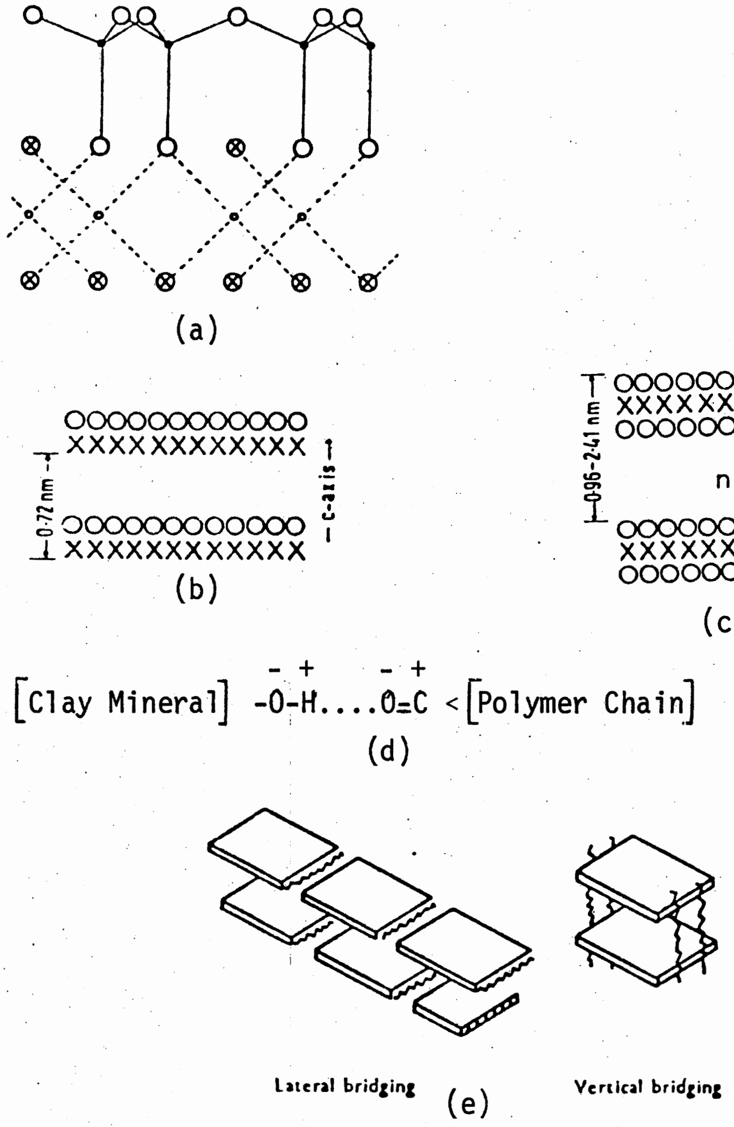


Figure 17. Structure of Clay Minerals and Mechanism of Cementation With Carboxylate or Acetate Polymers (8)(49)(51)

a) Structure of kaolinite, schematic drawing (49)
   O = oxygen; ● = silicon; ⊗ = hydroxy; o = aluminum
b) and c) Simplified representation of kaolinite and montmorillonite (49)
   O = $(Si_2O_5)_n$ layer or silica layer
   X = $(Al_2(OH)_4)_n$ layer or alumina layer
d) Bond between clay mineral and polymer chain due to polar interaction and hydrogen bonding (51)
e) Mechanism through which individual clay particles are bonded by polymer chains (8)
   ∼∼ = polymer chains

CHAPTER III

MATERIALS

Four different soils and ten different polymers were used in the studies covered by this report. All of these are described in considerable detail in the following sections.

Soils

Four sites were selected in the State of Oklahoma where unconsolidated non-cohesive materials were available. Soils were brought from these places and testing was carried out in the laboratory. All of these sites present erosion problems of some kind or another. Soils from the first three sites are of sandy texture; the fourth site presents metamorphosed shale, which is quite similar to slate and can scarcely be classified as soil. Not all of the tests were possible on the fourth soil.

Soil I

This soil was obtained from the north side of State Highway 51 in Section 24, T19N, R7E IM, Creek County. The area is one of windlaid sand dunes with a natural cover of post oak. Steep slopes along the highway have very little vegetation on them. The natural surface on the top of the slope does have some vegetation consisting mainly of isolated trees. The soil is mapped as the Eufaula series (54).

Grain-size analysis of the soil is shown in Figure 18. It is a poorly graded sand with only 2.5 percent of the material passing the #200 sieve. Due to the complete absence of clay, it is highly non-cohesive. Poor gradation has made it highly susceptible to wind erosion when it is dry. Due to its very high permeability and high percolation rate, water erosion is unlikely to present a problem. Figure 19 is a photograph of the site. Specific soil properties are

percent fines (passing #200 sieve) - 2.5 percent
permeability, 3.7 x 10^{-3} cm/sec
percolation rate, 5.4 in/hr
maximum dry density, 105.5 lbs/ft^3
specific gravity, 2.64

Soil II

This material is from a location on the east side of U. S. Highway 81 in Section 11, T17N, R7W IM, Kingfisher County; this place is also one of wind-deposited dunes. Scrubby forest vegetation is present in some areas; soil series present are Eufaula and Lincoln. Some areas are simply mapped as sand dunes; the sampling site is mapped as the Lincoln Series (56).

Grain-size distribution is shown in Figure 18. This soil has relatively more fines than does Soil I; about 8 percent of the material passes the #200 sieve. The soil is completely non-cohesive sand and is highly susceptible to both wind and water erosion. Specific soil properties are

fines (passing #200 sieve), 8 percent
permeability, 2.0 x 10^{-3} cm/sec

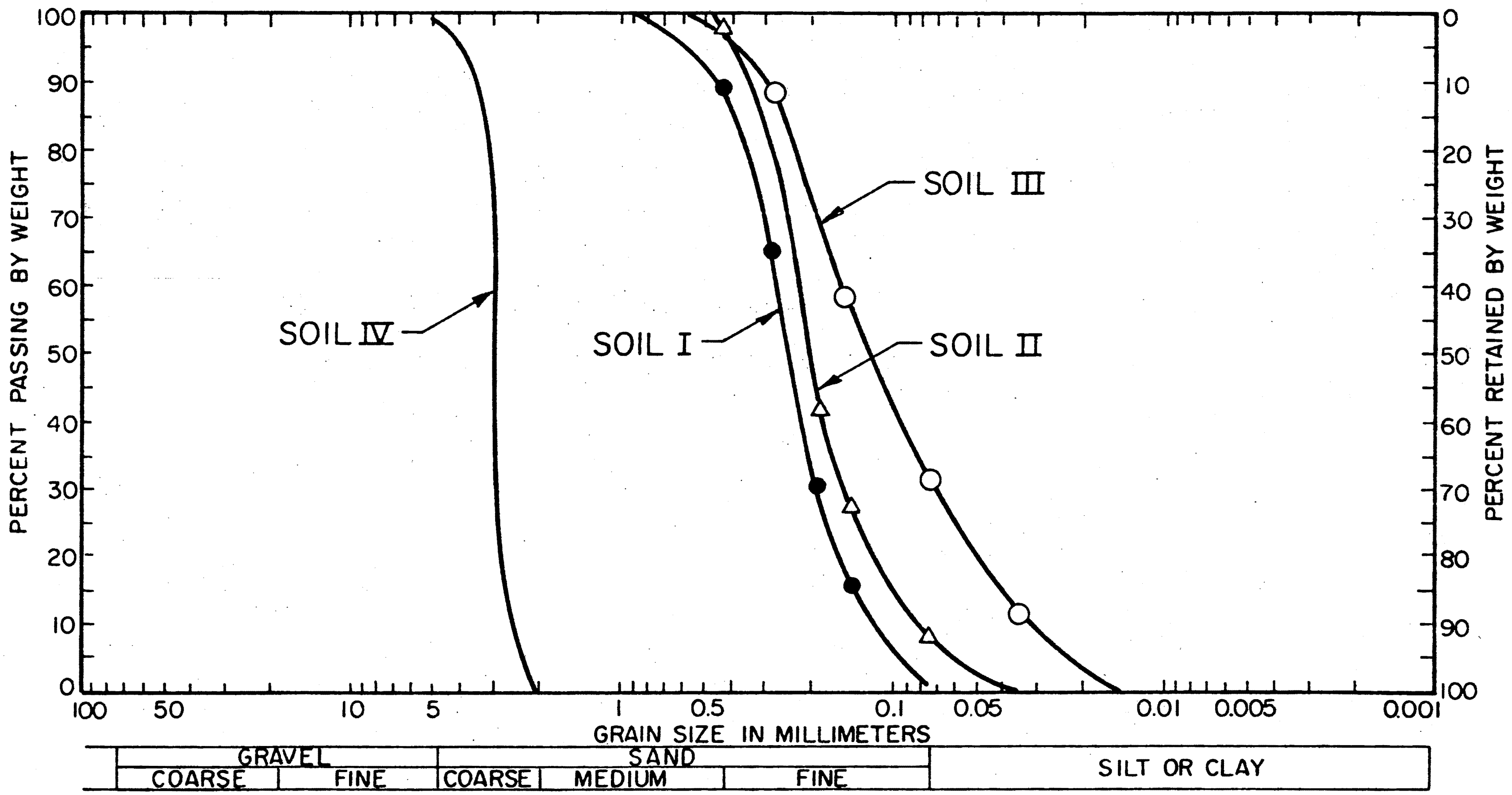


Figure 18. Mechanical Analysis of the Soils

Figure 19. Site Location of Soil I

percolation rate, 2.9 in/hr
maximum dry density, 108 lbs/ft^3
specific gravity, 2.63

Soil III

This soil was sampled from a site along State Highway 32 in Section 36, T6S, R3E IM, Love County. It is a residual sandy material weathered from Cretaceous sandstone. Surface material is mapped as the Stephenville Series in more level areas and as Sandy Broken Land where it is strongly sloping and eroded (56). The soil contains a higher percentage of fines than do Soils I and II, but is non-cohesive under soaked conditions. As the permeability is relatively low and the percolation rate is also low, the soil is highly susceptible to water as well as wind erosion. Specific soil properties are

percent fines (passing #200 sieve), 33 percent
percent fines (passing #325 sieve), 12 percent
permeability, 1.1×10^{-3} cm/sec
percolation rate, 1.6 in/hr

Soil IV

This material can scarcely be classified as a soil. It was obtained from a site near State Highway 10 in Cherokee County. The material consists of metamorphosed shale of dark black color; it is very similar to slate, but is relatively weak and soft. It is found in the form of laminated fragments of various sizes ranging from less than an inch (2 cms) to five or six inches (12-15 cms in length). The thickness varies from very thin liminations to two or three inches (few to 8 cms). The surface of individual pieces is smooth and shining. Soaking in water does not affect the surface characteristics or any other property of the individual pieces.

As this material can be easily crushed to any desired gradation, it was decided to reduce it to the size of the finer material at the site. The material was crushed and sieved. Material passing the #4 sieve and retained on the #10 sieve was used for study. Specific gravity was found to 2.41. A photograph of the site is shown in Figure 20.

Polymers

Under various commercial names, a large number of polymeric materials are available on the market for different uses. In most cases, the general chemical name of the product is known but actual chemical composition and structure is not revealed by the manufacturers. The complete list of compounds that have been tested in this study is at the end of this section. The products have been selected on the basis of their chemical and physical properties as supplied by the manufacturers. In addition, some products have been tested by other investigators and have shown sufficient promise to be included in this study. Care has been taken to include most of the general polymeric groups which are inexpensive and have potential for soil stabilization. However, there are certain kinds of polymers which have potential for soil stabilization but could not be studied because of their non-availability in a form adaptable to soil stabilization at the present time.

Liquid polymers which are dilutable in water and also can form water-resistant films at ambient temperature have the potential to

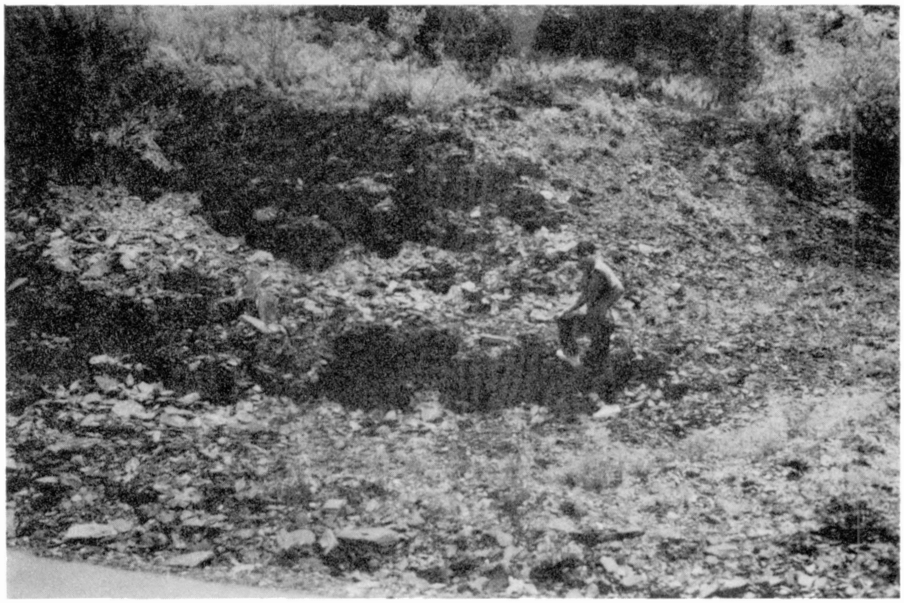


Figure 20. Site Location of Soil IV

become good soil stabilizers. Most of the polymers selected in this study met the foregoing criteria. However, some of the polymers which do not satisfy both of these conditions were included in the study for comparison purposes. A brief description of the polymers follows.

NeoCryl 601A (Polyvinyl Chemical Industries)

This is an acrylic emulsion with 32 percent solids in water. According to the manufacturer's claim, an air-dried film of this compound is clear, tough, and glossy, and shows superior adhesion to many substances such as wood, concrete, steel, and aluminum. The film exhibits excellent resistance to abrasion, water, sunlight, and weathering. The other properties are

appearance - milky white liquid
non-volatile content (solids) - 32% ± 1
pH - 7.5 - 8.0
viscosity at 25°C - 100 centipoises/sec (cps)
density at 25°C - 8.4 lbs/gal
storage problems - must not be allowed to freeze
ultraviolet resistance - 200 hrs Fadeometer, no discoloration
cost - $2.00/gal (1977)

Rhoplex H-8 (Rohm and Haas Company)

This is another acrylic polymer latex emulsion which can be diluted with water. According to suppliers, this material has excellent resistance to ultraviolet light and aging, excellent pigment binding properties, and durability to washing. No cross-linking agent is required for film formation. The other properties are

appearance - milky white liquid
film characteristics - soft and tacky
solid content - 45.5 percent
emulsifying system - non-ionic
viscosity - 550 centipoises/sec (cps)
pH - 3.0
density - 8.7 lbs/gal
storage - above freezing point
cost - $2.04/gal (1977)

Petroset SB (Phillips Chemical Company

This is a copolymer of butadiene and styrene in the form of an emulsion which can be diluted with water to any desired concentration. It does not need a cross-linking agent and is resistant to ultraviolet sunlight. The other properties are

appearance - light tan liquid
viscosity - 80-200 centipoises/sec (cps)
solid content - 48 percent
particle charge - positive
pH - 6.0 ± 0.5
storage - above freezing point
density - 8.6 lbs/gal
cost - $2.40/gal (1977)

Aerospray 70 (American Cynamide Company

This is a polyvinyl acetate emulsion with 60 percent solids in water. According to the manufacturer's claim, this compound was developed especially for stabilizing soil and for dust control. It can be diluted with water to any desired concentration. The other properties are

appearance - milky white liquid
film - colorless and transparent
solids - 60 ± 1 percent
pH - 4-6
density - 9.25 lbs/gal
viscosity - 1800-3800 centipoises/sec (cps)
storage - above freezing point
cost - $2.50/gal (1977)

<u>Terra Krete</u> (Kingman Chemical Company)

This is fermented extract of malt and vanilla (wort) in combination with magnesium sulphate, aluminum sulphate, and citric acid. According to the manufacturers of this compound, it can be used as a building material for different kinds of roads, parking lots, and shoulders. It can also be used for lining channels and for erosion control. The other properties of this compound are

appearance - light green liquid
solids - 48 percent
viscosity - 66 centipoises/sec (cps)
pH - 3.2
density - 8.8 lbs/gal
storage - above freezing point
cost - $8.00/gal (1977)

Latex XP-4026-128 (Hooker-Ruco Division)

This is a polyurethane latex based on aliphatic isocyanate. It can be diluted with water as desired. According to the manufacturer's claim, it is a self-curing polymer which can form a film at temperatures above 40°F. Other properties are

appearance - milky white liquid
viscosity - 3000 centipoises/sec (cps)
solids - 57 percent
cost - $15.00/gal (1977)

Corexit 7730 (Exxon Chemical Company)

This is a partially neutralized polyamide which can be diluted with water as desired. Not much information is available. The cost was $3.50/gal in 1977.

Norlig 41 (American Can Company)

The main constituents of this compound is calcium lignosulfonate, which is a spent sulfite liquor containing non-cellulose material recovered from the pulping of wood. The other properties are

appearance - dark brown liquid
solid content - 50-58 percent
viscosity - 60-450 centipoises/sec (cps)
pH - 3-3.5
metal oxides - 5-10 percent
cost - $.05/gal (1977)

Orzon GL-50 (Crown Zellerbach Corporation)

This is an ammonium lignin sulfonate. It is used as a binder, dispersant, emulsifier, and sequestering agent. Properties are

appearance - dark brown liquid
solid content - 50-60 percent
cost - not available

Altak 59-50 (Alpha Chemical Corporation)

This is a polyester in a styrene monomer and is the only polymer in the study which is not water-based. It is a viscous liquid which can be diluted with styrene and requires a curing agent, methyl-ethyl ketone peroxide (MEK) for cross-linking. It has a slightly pungent odor and the rate of film formation varies with the amount of styrene and quantity of MEK peroxide. Special equipment is required for spraying, as this material sticks to equipment and is difficult to remove. MEK peroxide is added just before spraying. Delay in spraying results in clogged nozzles and fouled tanks.

CHAPTER IV

EQUIPMENT

No standard testing procedure has received general acceptance for laboratory investigation of erosion resistance. Procedures and equipment were conceived which simulated severe field conditions. Equipment was fabricated in the Civil Engineering laboratory of Oklahoma State University.

Water Erosion Equipment

The equipment consisted of two sprayers mounted on a stand; the angle and intensity of flow could be varied. The sprinklers supplied a continuous flow of water in the form of jets 0.024 inches (0.06 cm) in diameter spaced 0.24 inches (0.6 cm) center-to-center. The velocity of water could be increased up to 15 ft/sec (4.6 m/s), but throughout the testing program the velocity of flow was maintained at 10 ft/sec (3.1 m/sec). The energy supplied by this apparatus with a water velocity of 10 ft/sec was calculated to be 41.6 ft lbs force/in^2/hr (0.96 joules/cm^2/hr). The energy of an ordinary rainstorm has been reported to be 7.8 ft lbs force/in^2/hr (0.18 joules/cm^2/hr) (2). The equipment is shown in Figure 21.

Wind Erosion Equipment

This consisted of a wind blower attached to a flume-shaped air

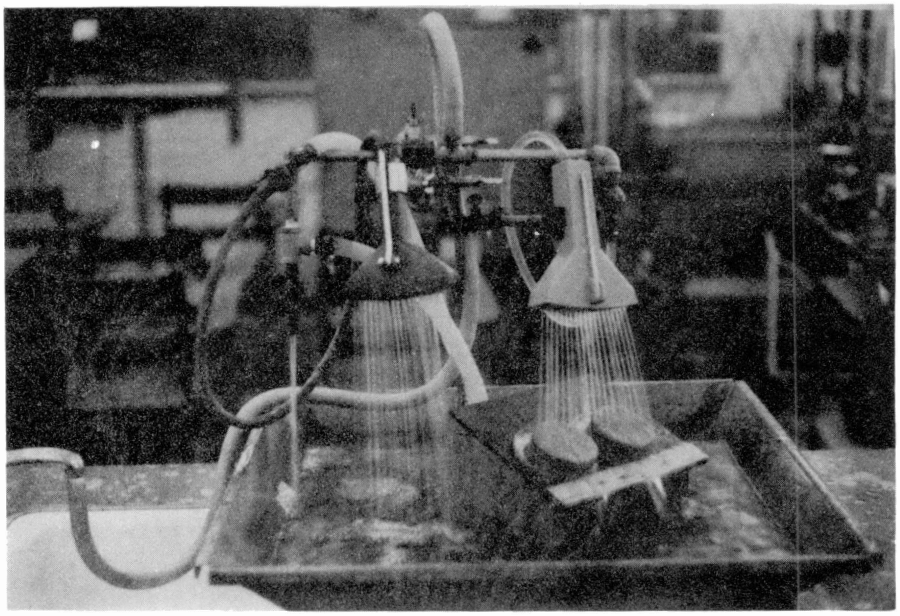


Figure 21. Water Erosion Testing Equipment

exhaust system. It provided a continuous flow of air at a constant velocity of 45 mph at a distance of two inches from its mouth. The specimen could be placed at any desired angle to the direction of air flow; all of the specimens were kept at an angle of 45°. The equipment is shown in Figure 22.

Preparation of Samples and Testing Procedure

Sample Preparation

Four different kinds of samples were prepared--two for erosion testing, one for unconfined compressive strength measurements, and one for permeability determination. Of the two erosion samples, polymer was applied to the soil of one by spraying and to the other by mechanical mixing. Premixed samples were used for compressive strength tests and sprayed samples were used for permeability studies.

Preparation of Compressive Strength Samples

Samples for unconfined compressive strength tests were prepared in Harvard Miniature molds. The compaction was carried out by applying Standard Proctor compaction effort (12,300 ft lbs energy/ft^3 of compacted material) through a falling hammer.

Soil and polymer were first mixed and then compacted in four layers. As different polymers had different viscosities and different solid contents, it was essential to add water to achieve a uniform distribution of polymer in the soil and better compaction. For each soil an "optimum fluid content" was determined before the actual specimens were prepared. This "fluid" consists of polymer and water mixed

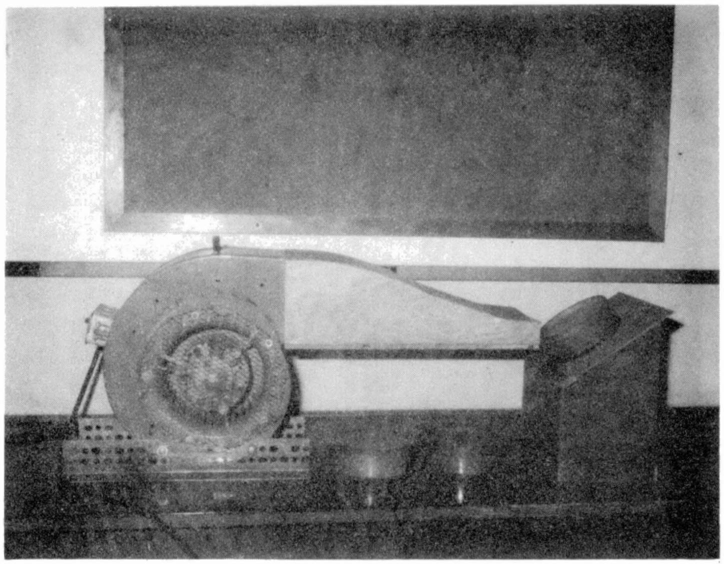


Figure 22. Wind Erosion Testing Equipment

together. All specimens of the same soil were prepared at "optimum fluid content" (OFC). In this way, better control of density was maintained. Extruding the sample immediately after compaction was not possible because of the noncohesive nature of the soil. The samples after compaction were left in the molds and kept in the oven for curing at $35^{0}C \pm 1$ for 24 hours. During this period, samples developed sufficient strength so that they could be handled outside the molds. After extrusion, the compacted samples were kept for an additional six days in the same oven for final curing. Thus, after a total of seven days of curing, samples were taken out and subjected to testing.

Preparation of Erosion Test Samples

Two kinds of erosion test samples were prepared--premixed samples and sprayed samples.

Preparation of Premixed Samples for Erosion. These samples were prepared in steel rings 2.8 inches in diameter and 1.0 inch in height. The density of sample and optimum fluid content were kept the same as in the premixed compressive strength samples. Compaction was carried out by hand-tamping with a steel rod 0.5 inch in diameter. After compaction, the surface was smoothed with a knife edge and the steel ring was removed without disturbing the samples. Samples were then placed in an oven for seven days of curing at the temperature previously noted.

Preparation of Sprayed Samples for Erosion Test. Two sizes of molds were used to prepare sprayed samples. Large molds were 5.3 inches in diameter and 2.0 inches in height, with an open top and a fixed perforated bottom through which water could drain freely. The smaller molds were 4.0 inches in diameter and 2.0 inches in height with a detachable perforated bottom plate. These molds were machined from plastic (lucite) tubes of the respective diameters. Detachable-bottom molds were used only to determine the depth of penetration of polymer solution into the soil. Erosion and permeability tests were carried out only on samples prepared in the large fixed-bottom molds.

The molds were filled with dry soil at a density of 90 percent of maximum dry density (r_{max}) by shaking and tapping. Then the water-polymer solution was prepared in the required dilution and sprayed with the help of a sprayer (Spray-All Electric Spray Gun manufactured by Kastar Inc., Bellport, New York). It provided a uniform spray and had a capacity of 26 fluid ounces. The amount of solution delivered to the specimen was found by weighing the specimen frequently during spraying. After spraying, the samples were kept in an oven for seven days of curing.

Sample Preparation for Permeability Test

These samples were prepared in 5.3 inch-diameter molds. The procedure followed in preparing the samples was the same as for the sprayed samples for erosion tests described earlier, with one difference. The molds were not completely filled with soil; instead, the depth of soil in the 2.0 inch high molds was kept at 1.6 inches. It was determined earlier that the treatment depth was always around 1.5 inches. A depth of 1.6 inches of soil in the molds for permeability determination provided almost fully treated soil samples instead of partially treated and partially untreated soil. The permeability thus determined was primarily that of treated soil, and any discrepancy due to untreated soil beneath it was very minimal. In the percolation test, water was placed in the top 0.40 inches of the mold above the soil surface and allowed to infiltrate.

Curing

All of the samples were cured at $95^{O}F$ ($35^{O}C \pm 1$) for seven days before testing. The reason this slightly elevated temperature was chosen for curing was that in Oklahoma, ground surface temperature in the summer is often this high or higher during the daytime. Thus, this temperature was thought to be more analogous to field conditions than the 70^{O} often used in cement-concrete and soil-lime curing. The other advantage in choosing this temperature for curing was that curing and durability cycles could be carried out in the same oven without temperature adjustments. During wet-dry cycles, the samples became partially dry on the surface when kept at this temperature for 18 hours. At $70^{O}F$, little drying actually took place.

Most of the environmental characteristics which affect polymer properties adversely do so at an accelerated rate of higher temperatures. Thus, a polymer tested only at or around $70^{O}F$ may not show as much deterioration during weathering cycles as would actually occur in the field where the temperature is relatively high. Thus, using $35^{O}C$ as a temperature for curing and weathering provided the opportunity to test the polymer performance under the most severe conditions which are likely to occur in the field.

The period of seven days of curing was chosen primarily to maintain uniformity with soil-lime and soil-cement stabilization where curing periods of 7, 14, or 28 days are customary. In addition to that, this seven-day period has some relevance in soil-polymer stabilization. It was observed that adhesive and cohesive strength become fully developed with the formation of a polymer film which occurs with the completion of drying. It was further observed that the weight loss of treated specimens which accompanies evaporation of water ceases in around five days at 95°F (35°C). An additional two days were included to attain both stable conditions and uniformity.

Testing

Samples were tested under two conditions--without weathering cycles and after weathering cycles.

Testing Without Weathering Cycles

All samples after curing for seven days were taken out of the oven and kept at room temperature for three to four hours before testing to attain ambient temperature (22 to 25°C). Thereafter, samples were tested for unconfined compressive strength and erosion resistance.

Unconfined Compressive Strength

Unconfined compressive strength tests were carried out on soaked as well as dry samples. For soaked strength, the samples were immersed in water for 24 hours before testing. Dry samples were tested just after the cooling period. A compression testing machine (Karol Warner Inc., N. J., Model 550) was used. Rate of loading was kept at 0.04 in/min (0.1 cms/min). Both failure load and deformation were recorded.

Erosion Resistance Tests

All samples were tested first for wind erosion resistance, and then the same samples were tested for water erosion resistance. It was found that in all of the samples much less polymer was needed to achieve no-erosion conditions with wind erosion than with water erosion.

Wind Erosion Tests

After seven days of curing, the specimens were weighed to ± 0.01 gram. Then the samples were subjected to wind erosion for four hours, as shown in Figure 22. After each four hours, the samples were weighed. In this way, total loss in weight in eight hours of erosion was measured. In the final testing, no loss in weight was achieved.

Water Erosion Tests

All water erosion tests were conducted on samples immersed in water for 24 hours. After immersion, samples were subjected to water erosion for four hours. Premixed samples were weighed before and after erosion, and in this way the amount of soil loss through erosion was determined. Sprayed samples, however, were too large to be weighed precisely. Also, the amount of water within the samples could change during testing, making the results erroneous. In order to find the amount of soil loss during the erosion test, the eroding water was allowed to flow through a #200 sieve after passing over the samples. In this way the eroded soil was collected, dried, and weighed. Though this procedure may not be applicable for precise measurements with relatively fine-grained soils, it worked well in this situation for several reasons. First of all, both Soil I and Soil II had a very small fraction passing the #200 sieve; secondly, the emphasis was on finding polymer treatments which resulted in little or no erosion occurring during the test. In preliminary studies, it was observed that treatments with unsuitable polymers or insufficient amounts of polymer resulted in specimens which eroded away completely in a short time while a suitable treatment produced materials that appeared to be almost completely unerodible. Thus, the purpose of testing became one of determining which polymers were suitable for erosion control and what quantity is needed to provide complete erosion resistance. Often, this quantity was only a little more than one which provided no protection at all.

Permeability Determination

It was not possible to determine permeability of sprayed samples 5.3 inches in diameter by regular procedures. It was decided to determine the percolation rate of treated samples and from that calculate permeability.

Samples were first saturated by immersing them in water for 24 hours. These samples were then placed in a large tray so that the bottom portion of the samples was touching the water in the tray. Then 142.0 ml of water was poured on top of the sample; the time for all of the water to percolate down through the sample was recorded. The test was repeated several times until a constant time was achieved. This was recorded as percolation time. The depth of water was about 1.0 cm before the percolation started. The time in which this amount of water can percolate through treated soil can be compared with the amount of rainfall descending in a brief intense storm.

Permeability was calculated by the formula

$$K = \frac{qi}{At}$$

where

K = permeability, cms/sec

A = cross-sectional area of flow of water = 142 cm^2

i = hydraulic gradient

t = time of flow, sec

q = quantity of water = 142 ml

$$i = \frac{h}{L} = \frac{4.06 + .5}{4.06} = 1.1, \text{ taken as } 1.0$$

This gives the final formula as

$$K = \frac{1}{t}$$

Testing After Durability Cycles

Three kinds of durability tests were carried out: wet-dry cycles, freeze-thaw cycles, and ultraviolet exposure tests.

Wet-Dry Cycles

After curing, the samples were carefully weighed. Each wet-dry cycle consisted of eight hours of immersion in water at room temperature and sixteen hours of drying in an oven at 95^oF (35^oC). Ten such cycles were performed, and then the samples were tested as previously described. The only difference was in the sequence of testing. In this case, samples were first tested for water erosion and later for wind erosion after drying in the oven at 35^{o}C.

Freeze-Thaw Cycles

After the required curing, the samples were weighed carefully. Each freeze-thaw cycle consisted of 16 hours of freezing at -10^{o}C and eight hours of thawing at 25^{o}C in an ambient humidity of 100 percent. Before the freeze-thaw cycles were started, samples were immersed in water for 24 hours. In this way, samples remained more or less saturated with water throughout the freeze-thaw cycles. After then such cycles, samples were tested as before.

Ultraviolet Exposure Test

Ultraviolet exposure tests were carried out on the sprayed samples prepared for erosion resistance testing. The purpose of this test was to find if there was any deteriorating effect of ultraviolet light on treated samples. In order to find the effect of ultraviolet light, the treated sample was first half-covered with a 2 mm-thick aluminum plate; the remaining half was left uncovered. The sample was then exposed to ultraviolet light. The ultraviolet light was produced by a 275 Watt General Electric sunlamp. These lamps are used primarily for suntanning. Distance between the lamp and samples was kept at 1.0 ft. According to the manufacturer's recommendations, the bulb should be kept at least two feet from the human body. Thirty minutes of exposure is more than two days of sun exposure. Samples were first exposed for eight hours in dry conditions and then soaked in water for 24 hours; then again exposed for another eight hours. After these two cycles, the samples were further soaked in water for 24 hours and subjected to water erosion testing. Comparison was made between the two halves--the one which was exposed and the one which was not.

Determination of Polymer Film Properties

In order to determine the film properties of the polymers alone, Pyrex glass dishes 3.5 inches (8.9 cms) in diameter and 0.5 inch (1.3 cms) deep were used. As glass has a close resemblance to the silicious materials of sandy soil, it was assumed that results thus obtained would be reasonably indicative of those that would be present in sand. Furthermore, Pyrex glass has relatively more silica (SiO_2) and alumina (Al_2O_3) than regular glass, which contains a large amount of soda (Na_2O). This makes Pyrex glass chemically closer to the alumino-silicate minerals of the sandy soils than regular glass. In addition to that, Pyrex glass and quartz minerals have a very low (but almost the same) coefficient of thermal expansion of the order of (10 to 30) x 10^{-7} in/^{o}C. Ordinary glass has a coefficient of (90 to 120) x 10^{-7} in/^{o}C. Thus, physically and chemically, Pyrex glass seems to be reasonably representative of the silicious materials of a sandy soil.

A 1:1 polymer solution in water was prepared. Twenty ml of this solution was placed in each dish and was allowed to dry in an oven at 95^{o}F for three days (72 hours). Three such samples were prepared for each polymer. After three days of curing, two of the three dishes were filled with water and allowed to soak for 24 hours, and some up to three days. One of the soaked specimens was then redried.

Peeling Test

A peeling test was carried out on all three kinds of samples prepared by curing polymer in Pyrex glass dishes. It was determined whether the cured film could be peeled from the dish by using the fingernails or the edge of a knife. In situations where it was possible to peel the film fully intact or in fairly large pieces, the film was further tested for brittleness at room temperature as well as after freezing. The peeled films were redried at room temperature and were bent and twisted to evaluate the brittleness of the polymers. In situations where it was not possible to peel the film in fairly large pieces, no brittleness test was made.

Two layers of the same polymer as well as of different polymers were also prepared to determine the adhesive properties of one polymer with respect to itself as well as with respect to other polymer film substrates. The first layer of the polymer was prepared as usual and then an additional 20 ml of the polymer solution was poured over it and allowed to cure. In this way two layers of the same as well as different polymers were achieved and adhesion between them was observed.

CHAPTER V

RESULTS

Laboratory tests included those of soil-polymer mixtures to evaluate such characteristics as erosion resistance, permeability, and compressive strength along with a determination of the best or optimum polymer treatment to obtain desired results in these areas. Other tests included those of the film properties of the polymers themselves under various conditions. In this section, results of tests on soil-polymer mixtures will be discussed. This will be followed by a discussion of the tests of the polymer film properties.

Detailed results of laboratory tests of soil-polymer mixtures are presented for polymer materials which proved useful in providing erosion resistance--Petroset SB, Aerospray 70, Terra Krete, Rhoplex H-8, NeoCryl A-601, Altak 59-50, and two combinations of the foregoing. Other polymers which were investigated were Norlig 41, Corexit 7730, Orzan-GL-50, and Latex XP-4026-128. These were found to be unsuitable because they simply did not make the soil resistant to erosion in the first place, or because any benefits evolving were lost if the soil became wet after treatment and curing. Film characteristics of the polymers which proved unsuitable are presented in the latter part of this section along with those polymers which proved beneficial. General observations of the characteristics of all polymers investigated are stated in the Discussion section.

The samples treated with Norlig 41 and Orzan GL-50 showed very poor resistance to water and fell apart when immersed in water. The film of these compounds also dissolved when kept in water for a few minutes. Corexit 7730 did not form dry film either separately or with the soil. The sample treated with it could not resist water erosion. Latex XP-4026-128 formed water-resistant film, yet failed to provide adequate erosion protection with a reasonable rate of application. The soil particles continued to erode, leaving a fine matrix of polymer film.

It has been noted that tests of erosion resistance and permeability were conducted on soil polymer-mixtures at an "optimum fluid content" of polymer solution or emulsion which was the minimum treatment required to make the soil non-erodible. This treatment was found by a trial-and-error approach for each soil and each polymer, and included both an optimum dilution of polymer in water or solvent as well as the optimum amount of diluted polymer that should be applied to the soil to provide protection. An ideal dilution ratio for the polymers can be expressed in several ways, including percentage of solid polymer in water or solvent or as a dilution ratio for the product already in water or solvent suspension, as supplied by the manufacturer. In Tables I through VIII, optimum treatment to provide erosion resistance to soils I, II, and III are listed for each polymer. For the sprayed samples used in erosion and permeability studies, optimum dilution is expressed as a dilution ratio for the liquid product supplied by the manufacturer. The optimum amount of diluted product is stated in gallons per square yared (gal/sq yd) of surface to be treated. It will be seen that in most cases this is the application which will result in a treatment depth of 1.5 inches.

Samples for compressive strength testing were prepared by mechanically premixing the soil and polymer suspension for each soil and polymer. Samples were prepared through a considerable range of polymer content. The minimum treatment required to provide non-erodible surface when premixing was done is noted for each soil and polymer in Tables I through VI. In this case, treatment is expressed as percentage of liquid polymer suspension as supplied by manufacturers which was mixed with the soil. The percentage of dry or solid polymer which this treatment incorporated into the soil is also noted. It may be seen that the amount of treatment required to provide an erosion-resistant surface using the soil and polymer may differ, depending on whether the polymer is mixed with the soil mechanically or diluted and applied by spraying. The cost of polymer for erosion-resistant treatment of a square yard of surface to a depth of 1.5 inches by spraying and mechanical premixing is shown in Tables I through V. It may be seen that providing erosion resistance by mixing generally required two to three times as much solid polymer as spraying, and hence the material cost for mixing is considerably greater.

Permeability testing of sprayed samples has been described. Results reported in the tables include both the steady-state percolation or infiltration rate for water under a static head of 0.4 in (1.0 cm) above a freely draining sample 1.6 in (4.0 cms) thick and the computed coefficient of permeability. Results are given for untreated soil and for soil treated by spraying to provide erosion resistance. It may be seen that the polymer treatment necessary to provide erosion resistance reduces the permeability of the soil to some extent, and that in some cases the reduction is considerable. Various polymers are seen to differ considerably in this respect. Petroset SB (Table I) is seen to perform best where it is desired to control erosion with minimal loss of permeability. However, in all cases, soils may still be regarded as "permeable" after treatment.

The compressive strength of soil-polymer mixtures prepared at polymer content required to provide erosion resistance through mechanical premixing is reported for both dry and soaked conditions in Tables I through VI. It may be seen that there is considerable variation among various polymers in this respect. Both dry and soaked strength resulting from treatment with Petroset SB (Table I) is noticeably low. Rhoplex H-8 (Table IV) imparts considerable dry strength which is almost completely lost with soaking. The others also exhibit considerably more dry strength than they do soaked strength, but even the low soaked strength (on the order of 10 to 25 psi) of soils treated with water-based Aerospray 70, Terra Krete, and NeoCryl A-601 (Tables II, III, and V) are useful in many applications.

Table VI presents the results of tests on the only non-aqueous polymer investigated--Altak 59-50--diluted in styrene and cured with MEK peroxide. In this case, spray treatment was tried unsuccessfully and the results reported are for treatment by mechanical premixing only. While no formal permeability test was made, it was observed that the soils appeared to be quite impermeable to water when treated to provide erosion resistance. The compressive strength of the treated material is seen to be quite high after soaking.

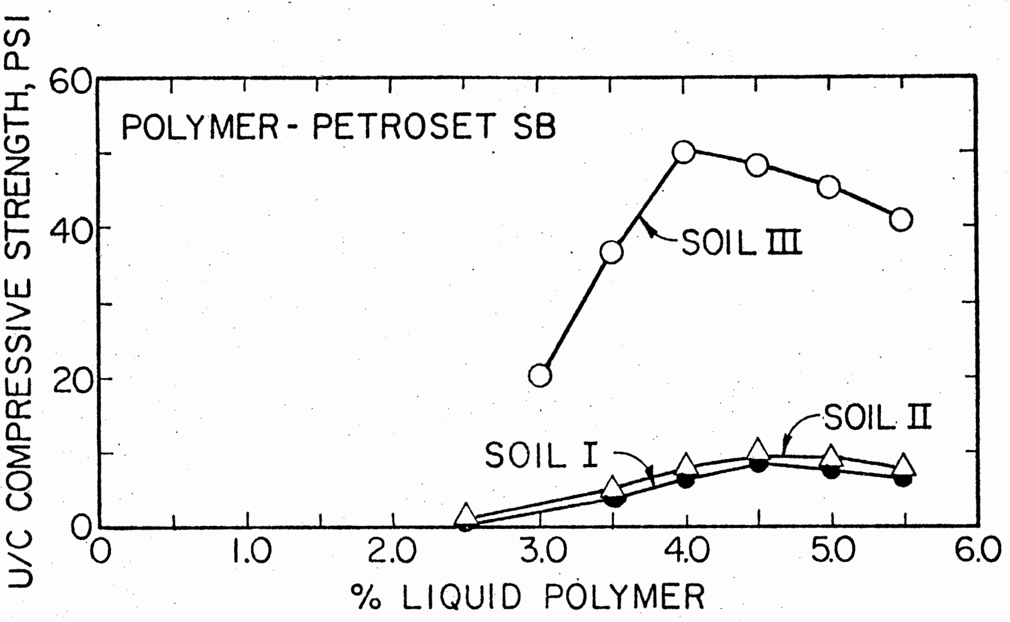
Tables VII and VIII report the results of tests with combinations of polymers-- NeoCryl A-601 with Aerospray 70, and Terra Krete with

Aerospray 70, respectively. Several other combinations of polymers were tried including NeoCryl A-601 with Terra Krete, Rhoplex H-8 with NeoCryl A-601, and Petroset SB with NeoCryl A-601, with Rhoplex H-8, with Terra Krete, and with Aerospray 70. However, in these cases, the polymers proved incompatible and curdled or set on mixing. In these tests of polymer mixtures, only sprayed samples were prepared to determine the optimum treatment for erosion protection and the permeability of soil polymer-mixtures.

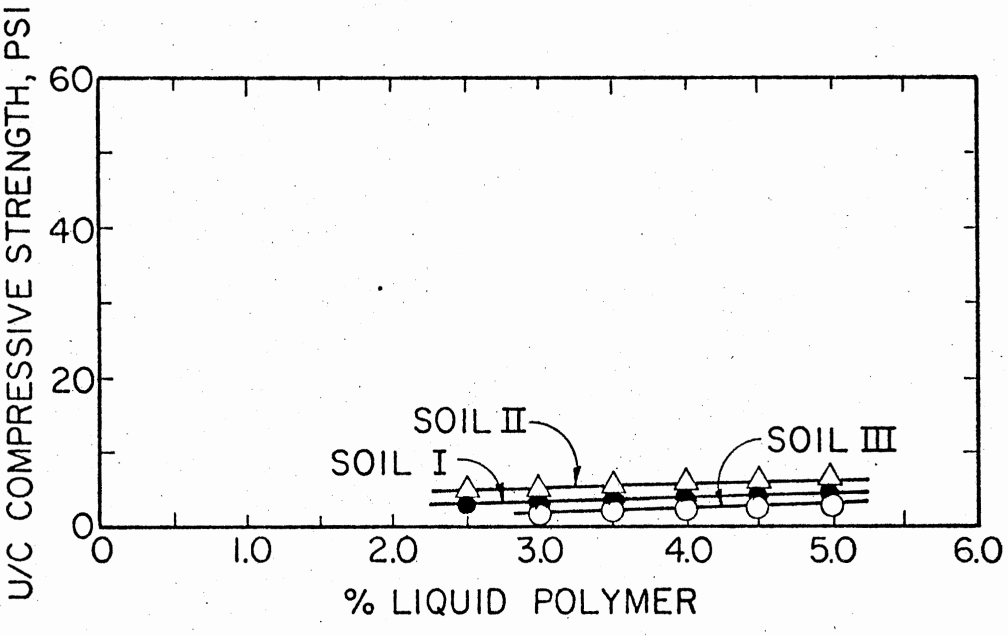
It has been noted that the mechanically premixed samples for compressive strength testing were prepared at a number of polymer contents. The compressive strengths reported in Tables I through VI are for the content which proved optimum in providing erosion resistance. Compressive strength tests were made, however, on the samples prepared at the other polymer contents. The results are reported graphically in Figures 23 through 28. Results include those for both dry and soaked materials. It may be seen that if the object of polymer treatment is to increase compressive strength, considerable success is possible. With the exception of Petroset SB, even the soaked strength of the order of several hundred psi can be obtained with water-base polymers. To obtain such strengths it may be seen that heavier treatment of polymer than that required to provide erosion resistance is needed. The graphs of Figures 23 through 28 relate compressive strength to percent liquid polymer suspension as supplied by the manufacturers. In terms of dry or solid polymer, it may be seen that the treatment required to provide soaked compressive strength of the order of 100 psi or so ranges from about 1.5 percent for Terra Krete, 2.0 percent for Aerospray 70, 2.5 percent for NeoCryl A-601, and 3.6 percent for Rhoplex H-8. It was observed that treatments sufficient to provide considerable soaked compressive strength make the soil impermeable or nearly so to the extent that the interior of compacted samples appeared dry during testing even after soaking. It may be recalled that Soils I, II, and III presented increasingly greater fines contents in that order. It may be seen from Figures 23 through 28 that the least polymer is needed to provide a given compressive strength for Soil II and maximum for soil III.

All samples were subjected to wet-dry and freeze-thaw cycles before testing. It was found that in all cases wet-dry cycles were more severe than were freeze-thaw cycles. It required slightly higher concentration of polymer in the solution to provide erosion resistance after wet-dry cycles than after freeze-thaw cycles. For Petroset SB, it required only 1:11 dilution to achieve no-erosion conditions after freeze-thaw cycles compared to the dilution of 1:9 which was required to achieve the same conditions after wet-dry cycles for Soil I. Similarly, for Aerospray 70, Terra Krete, NeoCryl 601 and Rhoplex H-8, it required one to two percent less polymer in the solution to achieve stable conditions after only freeze-thaw cycles compared to wet-dry cycles. The recommended dilution given in Tables I to VIII is the one which provided protection after more severe conditions, i.e., after wet-dry cycles. No harmful results in terms of accelerated erosion on polymer-sprayed samples could be detected due to ultraviolet light exposure.

Soils I, II, and III were similar in that they were all essentially sands. Soil IV, it may be recalled, consisted of flaky fragments of metamorphsed shale, or slate. All particles of the material were as large or larger than the spaces of the #10 sieve and samples of the material resisted erosion well in testing without polymer treatment.

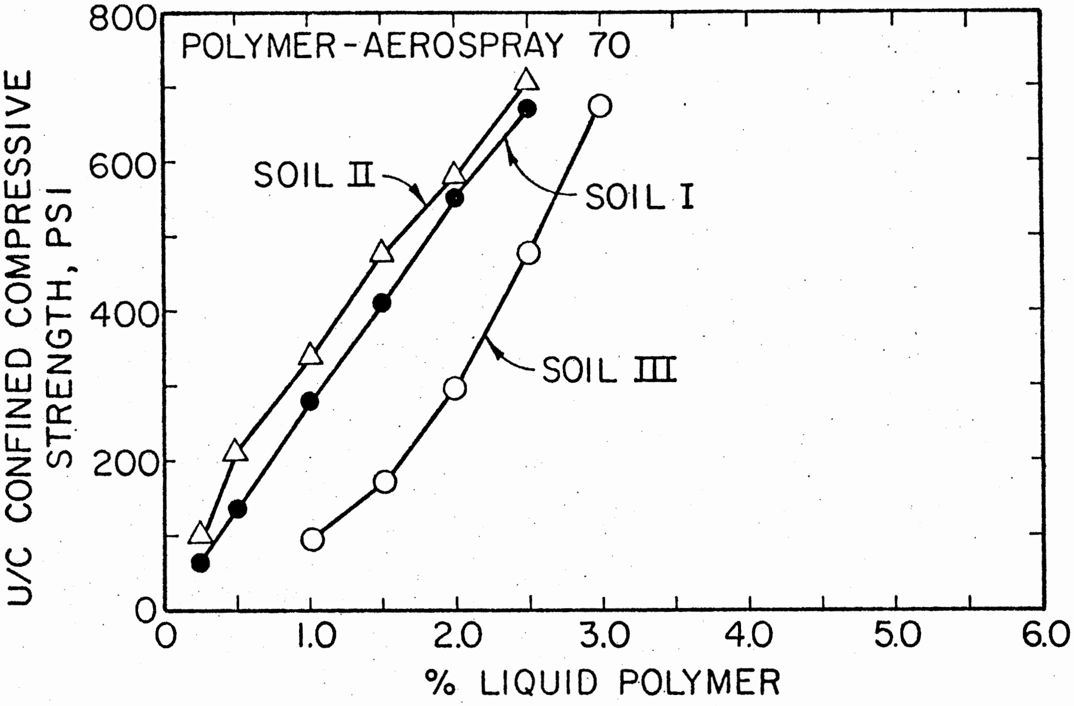


(a) DRY STRENGTH

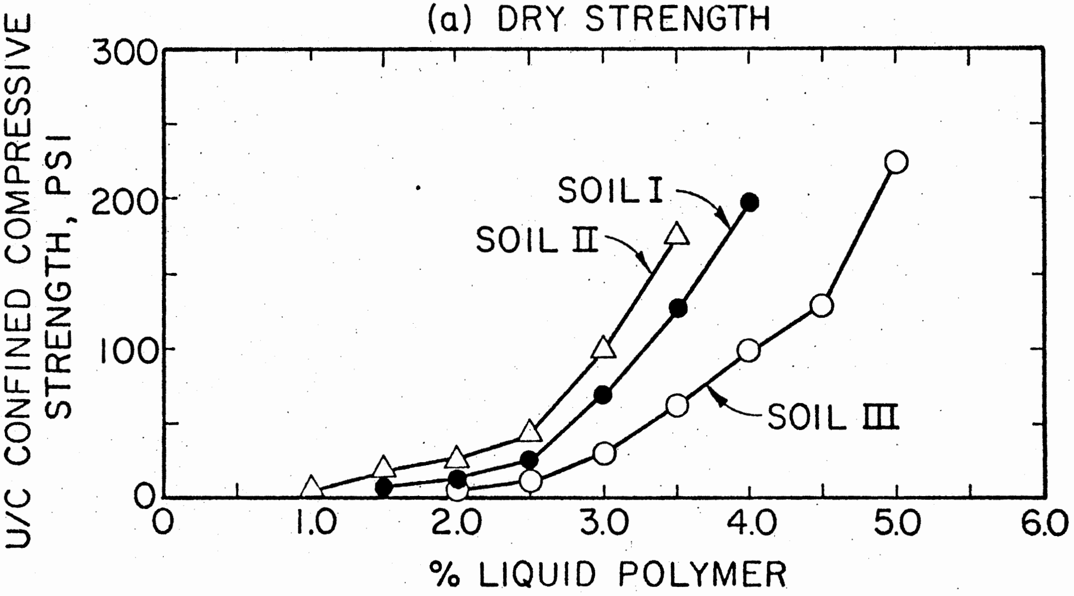


(b) SOAKED STRENGTH

Figure 23. Effect of Polymer (Petroset AB) on Unconfined Compressive Strength of Soil in Dry and Soaked Conditions

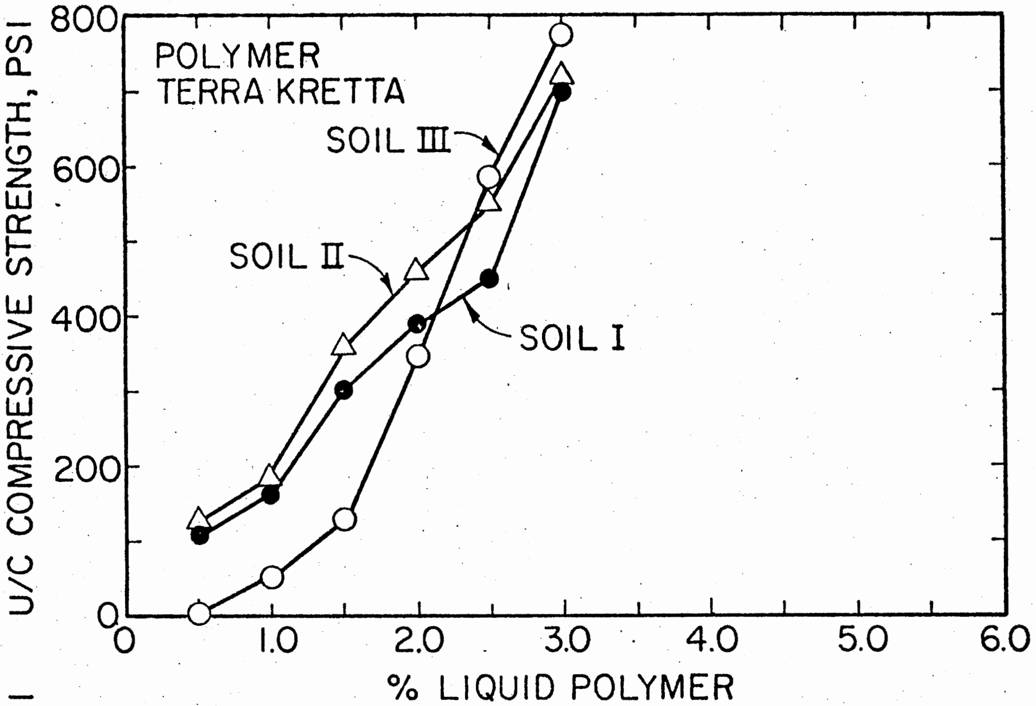


(a) DRY STRENGTH

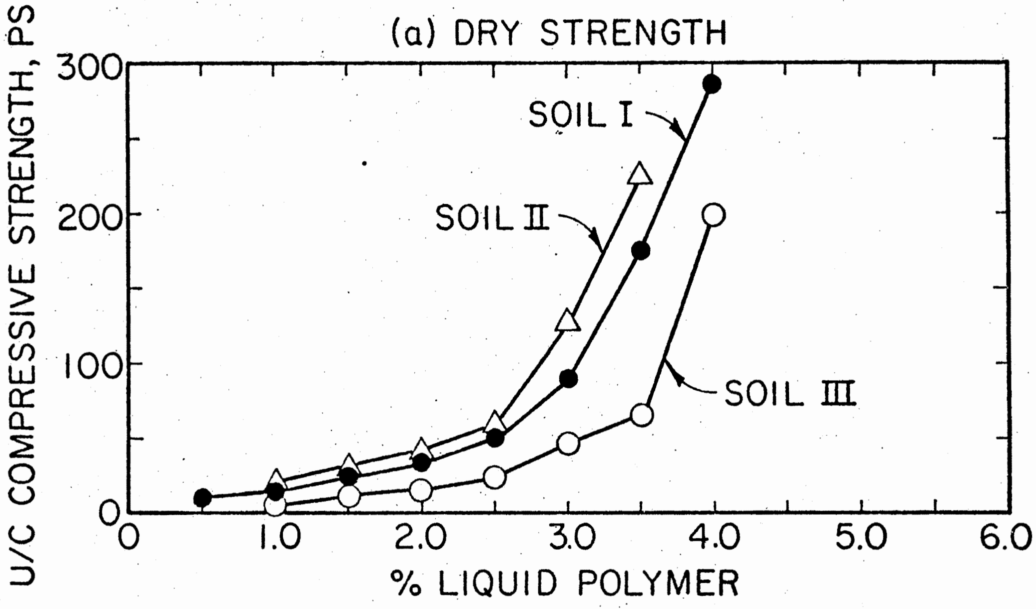


(b) SOAKED STRENGTH

Figure 24. Effect of Polymer (Aerospray 70) on Unconfined Compressive Strength of Soil in Dry and Soaked Conditions

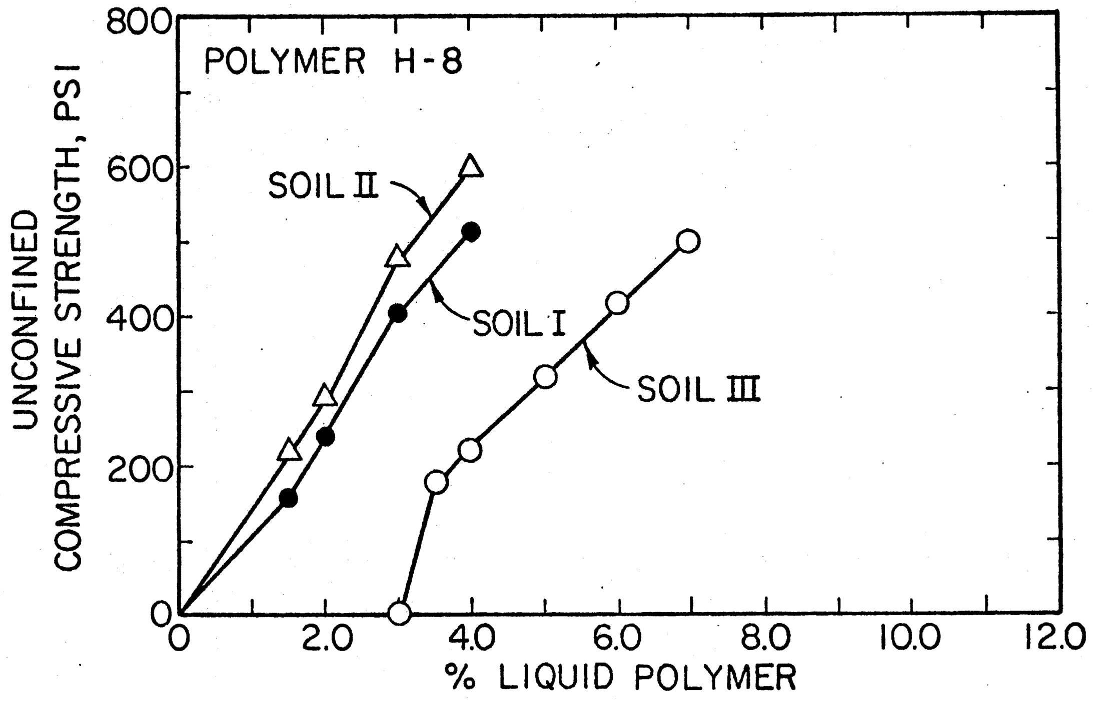


(a) DRY STRENGTH

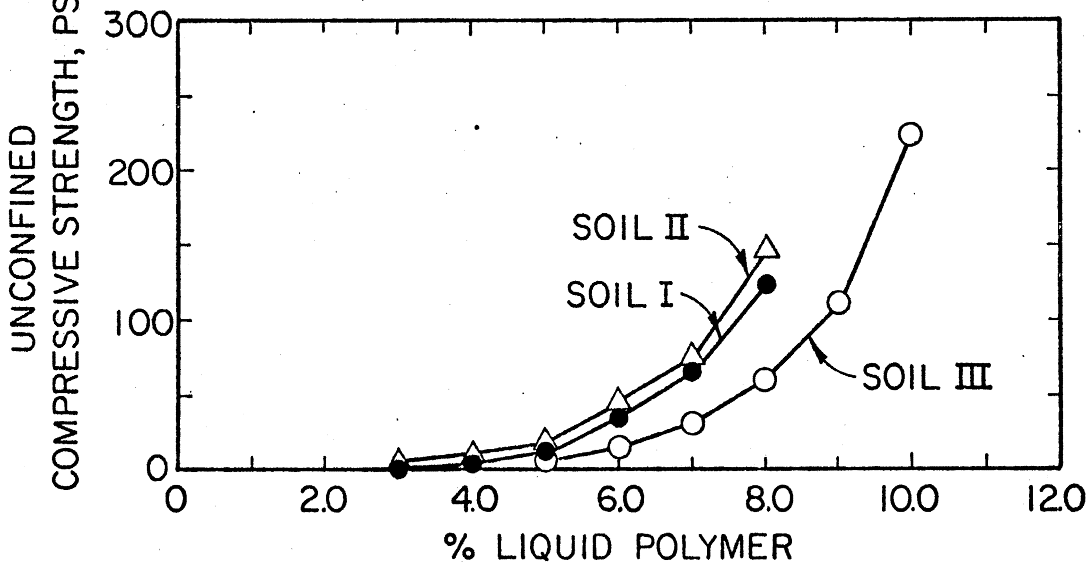


(b) SOAKED STRENGTH

Figure 25. Effect of Polymer (Terra Krete) on Unconfined Compressive Strength of Soil in Dry and Soaked Conditions

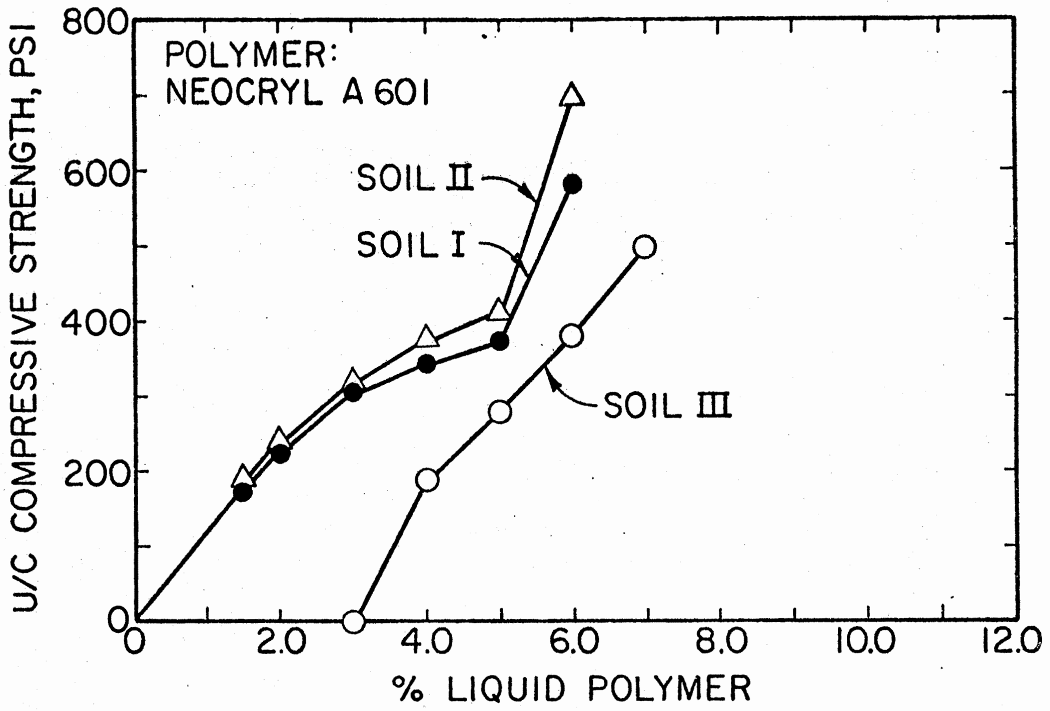


(a) DRY STRENGTH

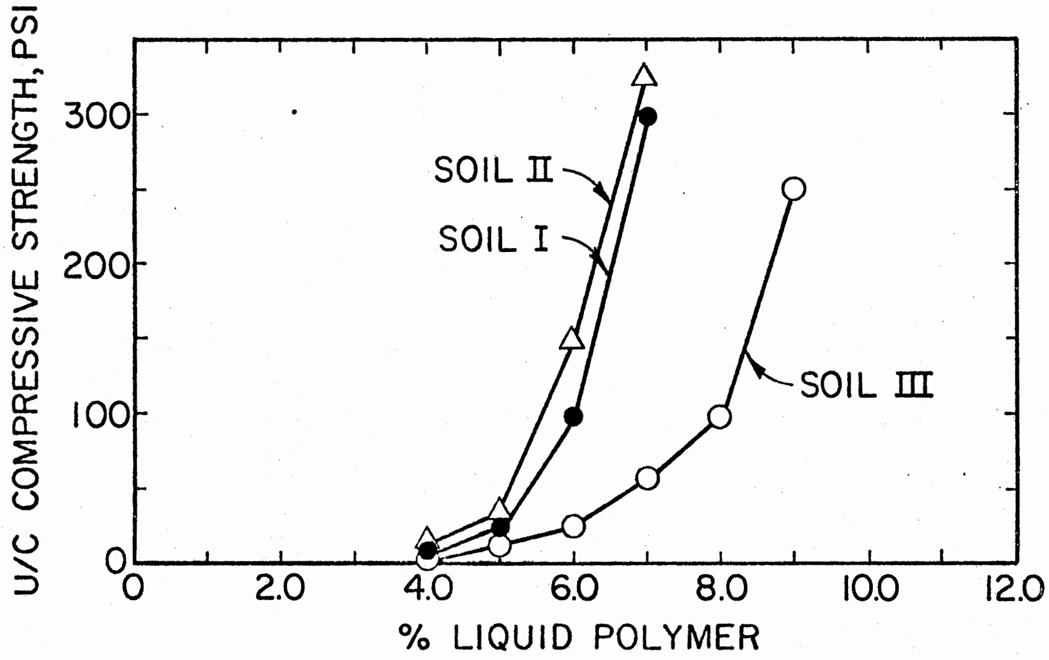


(b) SOAKED STRENGTH

Figure 26. Effect of Polymer (4-8) on Unconfined Compressive Strength of Soil in Dry and Soaked Conditions

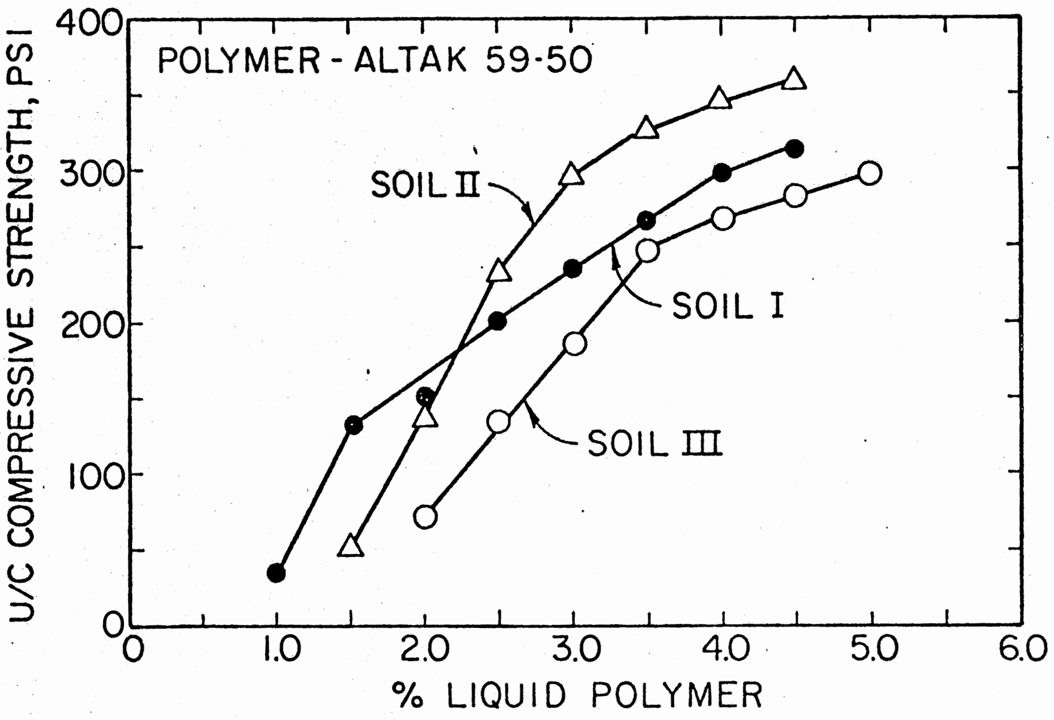


(a) DRY STRENGTH

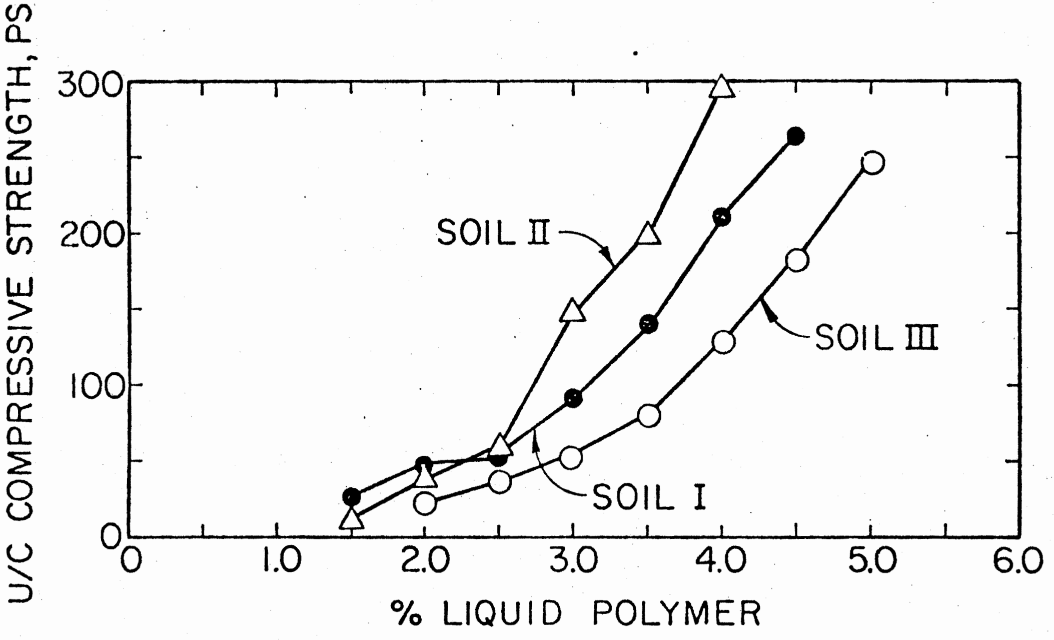


(b) SOAKED STRENGTH

Figure 27. Effect of Polymer (NeoCryl 601) on Unconfined Compressive Strength of Soil in Dry and Soaked Conditions



(a) DRY STRENGTH



(b) SOAKED STRENGTH

Figure 28. Effect of Polymer (Altak 59-50) on Unconfined Compressive Strength of Soil in Dry and Soaked Conditions

TABLE I

TEST RESULTS ON SOIL-POLYMER MIX. POLYMER-PETROSET SB

Percent solids: 48
Cost (1977): $2.40/gal
Density: 8.6 lbs/gal

Test	Results Soil I	 Soil II	 Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:9	1:1	1:12
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.5
water percolation rate, in/hr			
untreated	5.4	2.9	1.6
treated	2.2	1.9	0.9
permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	1.6×10^{-3}	1.3×10^{-3}	6.6×10^{-4}
polymer cost, $/sq yd	0.48	0.44	0.37
Premixed			
percent polymer to give non-erosive surface whole liquid polymer/actual dry polymer	4/1.92	4/1.92	4/1.92
compressive strength at above % polymer			
dry strength, psi	6	9	50
soaked strength, psi	4	4	3
water absorption, %	15	15	19.5
polymer cost of 1½ in. thick non-erosive surface, $/sq yd	1.32	1.32	1.32

TABLE II

TEST RESULTS ON SOIL-POLYMER MIX. POLYMER-AEROSPRAY 70

Percent solids: 60
Cost (1977): $2.50/gal
Density: 8.6 lbs/gal

Test	Results Soil I	 Soil II	 Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:12	1:12	1:14
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.5
water percolation rate, in/hr			
untreated	5.4	2.9	1.6
treated	0.6	0.4	0.2
permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	4.4×10^{-4}	3.1×10^{-4}	1.6×10^{-4}
polymer cost, $/sq yd	0.39	0.39	0.39
Premixed			
percent polymer to give non-erosive surface			
whole liquid polymer/actual dry polymer	2.0/1.2	2.0/1.2	2.5/1.5
compressive strength at above % polymer			
dry strength, psi	550	580	460
soaked strength, psi	15	24	10
water absorption, %	12.5	13.2	8.9
polymer cost of 1½ in. thick non-erosive surface, $/sq yd	0.64	0.64	0.64

TABLE III

TEST RESULTS ON SOIL-POLYMER MIX. POLYER-TERRA KRETE

Percent solids: 48
Cost (1977): $8.00/gal
Density: 8.6 lbs/gal

Test	Results Soil I	 Soil II	 Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:19	1:19	1:19
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.4
water percolation rate, in/hr			
untreated	5.4	2.9	1.6
treated	1.1	0.8	0.4
permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	7.0×10^{-4}	5.5×10^{-4}	2.9×10^{-4}
polymer cost, $/sq yd	0.80	0.80	0.80
Premixed			
percent polymer to give non-erosive surface			
whole liquid polymer/actual dry polymer	1.5/0.72	1.5/0.72	2.0/0.96
compressive strength at above % polymer			
dry strength, psi	300	355	350
soaked strength, psi	25	25	12
water absorption, %	12.5	12.8	10.4
polymer cost of 1½ in. thick non-erosive surface, $/sq yd	1.60	1.60	2.14

TABLE IV

TEST RESULTS ON SOIL-POLYMER MIX. POLYMER-RHOPLEX H-8

Percent Solids: 45
Cost (1977): $2.04/gal
Density: 8.7 lbs/gal

Test	Results Soil I	Soil II	Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:7	1:7	1:9
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.3
water percolation rate, in/hr			
untreated	5.4	2.9	1.6
treated	0.80	0.70	0.20
permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	5.5×10^{-4}	4.8×10^{-4}	1.7×10^{-4}
polymer cost, $/sq yd	0.51	0.51	0.41
Premixed			
percent polymer to give non-erosive surface			
whole liquid polymer/actual dry polymer	3.5/1.57	3.5/1.57	4.5/2.02
compressive strength at above % polymer			
dry strength, psi	400	480	210
soaked strength, psi	4	4	2
water absorption, %	14	15	10
polymer cost of 1½ in. thick non-erosive surface, $/sq yd	0.97	0.97	1.24

TABLE V

TEST RESULTS ON SOIL-POLYMER MIX. POLYMER-NeoCRYL 601A

Percent solids: 32
Cost (1977): $2.00/gal
Density: 8.4 lbs/gal

Test	Results		
	Soil I		Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:5	1:5	1:6
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.3
water percolation rate, in/hr			
untreated	5.4	2.9	1.6
treated	0.70	0.45	0.17
permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	4.8×10^{-4}	3.2×10^{-4}	7.5×10^{-5}
polymer cost, $/sq yd	0.66	0.66	0.59
Premixed			
percent polymer to give non-erosive surface			
whole liquid polymer/actual dry polymer	4.5/1.44	4.5/1.44	7.0/2.24
compressive strength at above % polymer			
dry strength, psi	380	400	500
soaked strength, psi	20	25	55
water absorption, %	18	18	12
polymer cost of 1½ in. thick non-erosive surface, $/sq yd	1.27	1.27	1.97

TABLE VI

TEST RESULTS ON SOIL-POLYMER MIX. POLYMER-ALTAK 59-50

Diluent: Styrene
Curing Agent: MEK Peroxide
Cost (1977): $2.50/gal
Density: 9.2 lbs/gal

Test	Results Soil I	 Soil II	 Soil III
Premixed Samples			
dilution ratio (polymer:styrene)	2:1	2:1	2:1
% MEK peroxide required	0.5	0.5	0.5
% polymer to give nonerosive surface	3	3	3
Compressive Strength at the Above % Polymer			
dry strength, psi	260	300	190
soaked strength, psi	95	155	50
polymer cost of 1½ in. thick non-erosive surface, $/sq yd	1.00	1.00	1.00

TABLE VII

TEST RESULTS ON SOIL WITH MIXTURE OF NeoCRYL 601A AND AEROSPRAY 70

Percent solids: 46
Cost (1977): \$2.25/gal
Ratio of NeoCryl A-601 to
Aerospray 70: 1:1 by volume

Test	Soil I	Results Soil II	Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:12	1:12	1:12
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.5
Water Percolation Rate, in/hr			
untreated	5.4	2.9	1.6
treated	0.8	0.6	0.3
Permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	5.5×10^{-4}	4.1×10^{-4}	2.1×10^{-4}
polymer cost, \$/sq yd	0.35	0.35	0.35

TABLE VIII

TEST RESULTS ON SOIL WITH MIXTURE OF TERRA KRETE AND AEROSPRAY 70

Percent solids: 52
Cost (1977): $6.08
Ratio of Terra Krete to
Aerospray 70: 2:1 by volume

Test	Results Soil I	 Soil II	 Soil III
Sprayed Samples			
polymer dilution (polymer:water)	1:19	1:19	1:19
rate of application, gal/sq yd	2.0	2.0	2.0
penetration, inches	1.5	1.5	1.4
Water Percolation Rate, in/hr			
untreated	5.4	2.9	1.6
treated	1.1	0.8	.40
Permeability, cm/sec			
untreated	3.7×10^{-3}	2.0×10^{-3}	1.1×10^{-3}
treated	7.0×10^{-4}	5.5×10^{-5}	2.9×10^{-4}
polymer cost, $/sq yd	0.62	0.62	0.62

The only investigation that was made using this material was one to determine if polymers could be used to cement particles so that a mass of material would not slake when soaked, since an outstanding field difficulty with the material has been its tendency to spall or flake from exposed slopes and fall by gravity to accumulate on road surfaces and in ditches. It was found that some of the polymers could be used to provide stability against slaking. Required treatments are stated in Table IX.

TABLE IX

MINIMUM POLYMER CONTENT REQUIRED TO PROVIDE "ADQUATE" CEMENTATION OF SOIL IV PARTICLES*

Polymer	% Liquid Polymer
Aerospray 70	2.0
Terra Krete	2.0
NeoCryl 601A	3.5
Rhoplex H-8	3.0
Altak 59-50	2.0
Petroset SB	does not work
Norlig 41	does not work
Corexit 7730	does not work
Orzan-GL-50	does not work
Latex XP-4026-128	does not work

*"Adequate" is referred to as the degree of cementation which can maintain sufficient strength so that the specimens do not slake or disintegrate after soaking in water for three days or more.

The way in which peeling qualities and other film properties of polymers was investigated was described in the preceding section. It will be recalled that the polymer solutions were first diluted with water or styrene monomer and then allowed to cure in Pyrex glass dishes for three days. The films thus formed were peeled in dry and soaked conditions. The results of these tests are given as film properties under the following conditions:

S_1 - dry film after curing; no further treatment

S_2 - film soaked in water for 24 hours

S_3 - film soaked in water for 24 hours and then redried

Petroset SB

S_1 - dark brown, strongly held to substrate and cannot be peeled by fingernails. Using knife edge, the film can be stretched considerably (four to five times the initial length) before it breaks. Failure of the film is purely cohesive.

S_2 - same as S_1.

S_3 - same as S_1.

Aerospray 70

S_1 - colorless, transparent, strongly held to substrate and cannot be peeled by fingernails or knife edge. No shrinkage cracks.

S_2 - milky white film and swells considerably. Difficult to peel by fingernails but easy with knife edge. The film breaks into pieces during peeling, indicating relatively superior adhesion but poor cohesive strength. Dry film is flexible.

S_3 - same as S_1.

Terra Krete

S_1 - colorless, transparent, strongly held to substrate and cannot be peeled either by fingernails or knife edge. No shrinkage cracks.

S_2 - after three days (72 hours) of soaking, the film changes color slightly to milky white but cannot be peeled.

S_3 - same as S_1.

Rhoplex H-8

S_1 - colorless, transparent, strongly held to substrate and cannot be peeled by fingernails or edge of knife. No shrinkage cracks; film is flexible.

S_2 - slightly milky and tranlucent and easily peeled from the substrate. Film is very flexible and stretchable in both dry and soaked conditions. In soaked condition, it breaks relatively easily. In dry condition, it elongates more than 100 percent before breaking.

S_3 - same as S_1.

NeoCryl 601A

S_1 - colorless, transparent, strongly held to substrate and cannot be peeled by fingernails or knife. No shrinkage cracks observed.

S_2 - slightly milky and translucent and easily peeled from the surface intact. Film is flexible and can be bent or twisted when soaked. After redrying, the film turns brittle and breaks when bent or twisted.

S_3 - colorless and transparent and can be chipped off with the help of knife edge, indicating some reduction in adhesion on redrying.

Altak 59-50

S_1 - light brown film, strongly held to substrate and cannot be peeled by fingernails or knife edge. No shrinkage cracks.

S_2 - same as S_1.

S_3 - same as S_1.

NeoCryl 601A and Aerospray 70 - in ratio of 1:1 by volume

S_1 - colorless, transparent, strongly held to substrate and cannot be peeled by fingernails or knife edge. No shrinkage cracks.

S_2 - slightly milky and translucent, adheres well to the substrate. Can be peeled with edge of knife; film is flexible in both dry and soaked conditions.

S_3 - same as S_1.

Aerospray and Terra Krete - in ratio of 1:2 by volume

S_1 - same as S_1 of Terra Krete alone.

S_2 - same as S_2 of Terra Krete alone.

S_3 - same as S_3 of Terra Krete alone.

Norlig 41 and Orzan GL-50

S_1 - dark brown film with shrinkage cracks on the surfaces. It cannot be peeled by fingernails but can be scrubbed and removed with knife edge. Powdery substance is obtained instead of film; no film formation took place.

S_2 - immediately dissolved into water, and dark solution is obtained. The substance does not adhere to the substrate.

S_3 - same as S_1.

Corexit 7730

S_1 - no film formation. Thick viscous liquid remains which can be easily removed with the help of a knife or fingernail.

S_2 - dilute solution with water. No film remains.

S_3 - same as S_1.

Latex XP-4026-128

S_1 - slightly whitish film with no adhesion to substrate. Film shrinks considerably during film formation. It is easily peeled by fingernails. It is flexible, having very poor adhesion, but is fairly good in cohesive strength.

S_2 - slight swelling in the film, but film was found strong in cohesive strength. No damage to the film due to soaking, but no adhesion.

S_3 - no adhesive affinity for substrate; other properties as in S_1.

In addition to the foregoing tests, the adhesion of polymer films formed at different times and between different polymers was also investigated by placing polymer solution in a Pyrex dish, allowing it to dry and form a film and then placing more solution of the same polymer as well as of different polymer in the dish without removing the first film. It was generally found that when the second film dried, if it was of a different polymer, it could be easily separated from the first after soaking in water, and especially if one of the films was of Petroset SB. But in case of the same polymers, the two films formed a strong bond and could not be separated. Thus, it could be concluded that polymer films formed by treating material at different times by different polymers will exhibit poor adhesion (or that the entire film will have poor cohesion), but if the same polymer is sprayed again it will form a good bond and the entire mix will remain strong. In other words, when the treated surface starts showing signs of deterioration due to aging, a new treatment over the existing one will be equally effective to control further erosion.

CHAPTER VI

DISCUSSION

In this chapter, the significant findings of the investigation are reviewed briefly, and consideration is given to how these findings can be used to evaluate other polymeric compounds for potential use in soil stabilization for erosion control.

There are numerous polymeric products available on the market in different forms and for different purposes, but most of these compounds are not in a form in which they can be used for soil stabilization. The present set of results and subsequent discussion, based on the experimental findings and literature survey, will enable an engineer to not only select a suitable polymer from those available but also will help him to specify the chemical composition of a polymer to satisfy his needs. Fundamentally, a most promising polymer for erosion control is one which when added to the soil binds the soil particles without changing their properties significantly. The polymer should be durable and water resistant. Reduction in the permeability of the treated surface material on steep slopes can cause serious stability problems due to hydrostatic pressure buildup behind it. Also, reduction in the percolation rate of surface material will ultimately lead to higher surface runoff. This may create new and more severe erosion problems at other places where such problems did not previously exist. For good vegetation growth, the soil should have enough continuous pores for the movement of air and water (aerable soil). Materials which can block moisture movement through the soil will inhibit very seriously the use of the soil surface for propagation and growth of vegetation. Another important consideration is the water resistance of the cured soil-polymer mixture. A polymer film which is affected adversely by prolonged soaking will not be able to resist erosion effectively.

Judging from the criteria mentioned above, the most successful polymer was found to be Petroset SB, followed by Terra Krete and Aerospray 70. The other polymeric compounds tested protect the soil from erosion, but fail to meet other stated criteria. They either reduce the permeability considerably or are water susceptible, or both.

Petroset SB

This is a styrene-butadiene copolymer. The material provides excellent erosion resistance from both wind and water under the most severe conditions. The cost of the material for treatment is \$0.48 sq yd (1977). Permeability of the treated soil was found to be only slightly reduced in this treatment (Table I). The film of this material is highly elastic, stretchable, and rubbery in nature. It remains well adhered to a siliceous substrate and does not swell when soaked in water for several days. For this reason, soil treated with Petroset SB resists erosion even after prolonged periods of soaking.

The success of this material lies in the fact that it is an elastomer. Most of the elastomers are excellent adhesives and are water resistant. As mentioned earlier, adhesive properties of a polymer depend to a great extent on the flexibility of the molecules. Rigid polymers have poor adhesive qualities. Elastomers are very flexible materials, depending upon the diene (-CH_2-CH=CH-CH_2-) group in the copolymer, and thus they adhere to the substrate very strongly. This makes the treated soil sufficiently strong to resist erosion under severe conditions of prolonged soaking in water. Elastomers having large amounts of butadiene lack flexural rigidity or stiffness. This is the reason that soils treated with this material do not show any appreciable compressive strength (Figure 23). On the other hand, they can undergo 20 percent deformation (strain) without developing cracks. For soil erosion protection, this property is of great significance. A rigid material like soil-cement fails to provide adequate erosion protection because of its inability to adjust to minor differential settlements or to shrinkage which results in cracking. But soil treated with this kind of polymeric material or elastomer can adjust to such changes easily, remain intact, and continue to protect the soil from erosion.

Most of the elastomers have a low glass transition temperature. This gives an added advantage. In the range of the glass transition temperature, adhesion of the polymer is increased considerably. Thus, on hot summer days when the soil is likely to be dry and susceptible to wind erosion, increased adhesion is provided. Another advantage of this kind of polymer is that it does not become hard and brittle at or below the freezing point of water. This makes it quite suitable for all weather conditions.

A number of factors influence the properties of elastomers. The properties which are most pertinent in the context of soil stabilization are adhesion, cohesion, and water resistance. Adhesion of an elastomer, such as styrene-butadiene copolymer, depends upon the ratio of its constituent monomers. By adjusting the ratio of styrene and butadiene, certain properties can be varied. For example, by increasing the styrene content, the polymer becomes more rigid and stronger in cohesive strength, but its adhesive strength is reduced, and vice versa.

In the case of carboxylated elastomers, the carboxylic group (COOH) governs most of the properties. The practical advantages of carboxyl incorporation are increased hardness and crumb strength, resistance to hydrocarbon solvent, and easier film formation (49). The main disadvantage is increased tendency to oxidative disintegration. As the carboxyl level is increased in a polymer, the polymer becomes tougher and less elastic. For example, in butadiene-methacrylic acid copolymers, all of the elastic properties are lost if the incorporation of acid or carboxylic group reaches 45-50 percent of the total polymer. On the other hand, tensile strength increases considerably. This is shown in Figure 29.

The effect of carboxyl group content on adhesion is somewhat different. As the carboxyl content (percent acid) is increased or as the degree of neutralization with amine is increased, the bond strength increases to a maximum and then decreases. Concurrently, if the polymer yields to breaking or rupture, the character of the break changes from that of a cohesive failure to a mixed cohesive/adhesive failure and then to an increased proportion of adhesive failure. This behavior agrees with the theory that with a low concentration of salt, crosslinking molecules readily diffuse into a carboxylated rubber phase to give adhesive forces greater than the cohesive forces derived from the

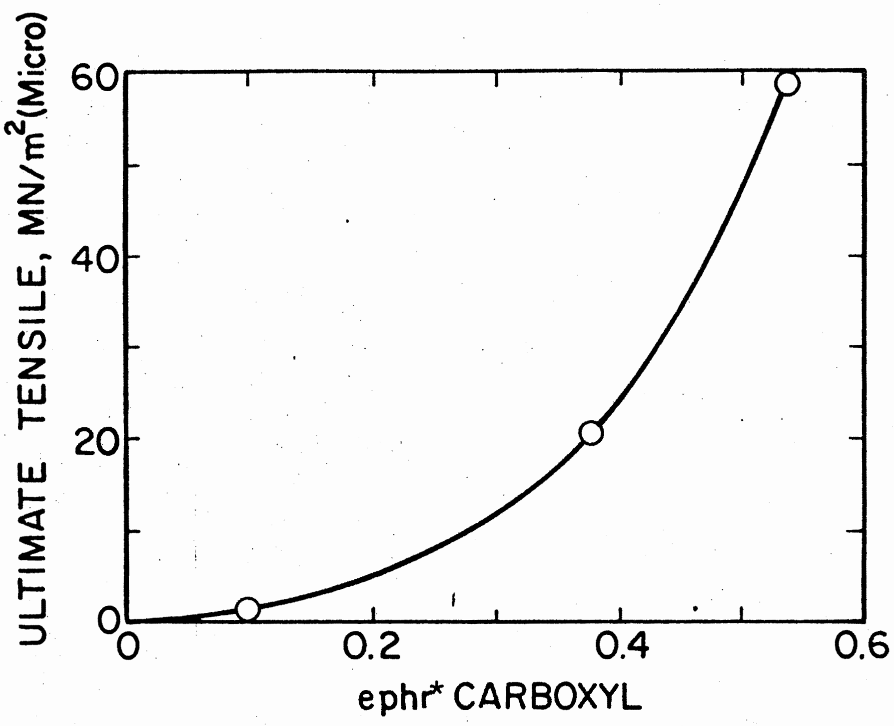


Figure 29. Ultimate Tensile Strength of Raw Copolymers of Butadiene With Methacrylic Acid (49)

*ephr is defined as equivalent per hundred parts of rubber.

cross-linking. At higher cross-link densities, the ionic bonding gives increased cohesion but decreases compatibility due to the rigidity of the molecules and hence a lower degree of diffusion or adsorption results, which reduces the adhesive force. Effect of carboxyl or acid content is shown in Figure 30. It is evident from the figure that the polymer having acid content of around 20 percent provides maximum adhesion. Polymers or carboxylated elastomers having 20 percent acid content possess the highest adhesion, but the ultimate tensile strength is not a maximum. For erosion protection purposes, however, it is more than sufficient.

The most common elastomers available on the market are styrene-butadiene rubber (SBR), polyacrylates (ABR), neophrene (CR), and polyurethane elastomers (AU). But these polymers are available in the form of sheets and rolls or in solution with some organic solvents which cannot be used for soil stabilization. In order to use these materials, it is necessary to procure the product before it is dried and turned into a solid state, or turned into a solution with some organic solvent.

Aerospray 70

This is a polyvinyl acetate polymer. It provides erosion protection to all soils tested when applied at the rate of 2 gal/sq yd at a dilution ratio of 1:12. The cost of treatment comes out to be $0.38/sq yd (1977). Dry compressive strength is quite high, as shown in Figure 24, depending upon the amount of polymer added; the soaked strength is low. Strength is regained almost entirely in subsequent redrying. As it is difficult to compare any two polymers in terms of strength gain for each

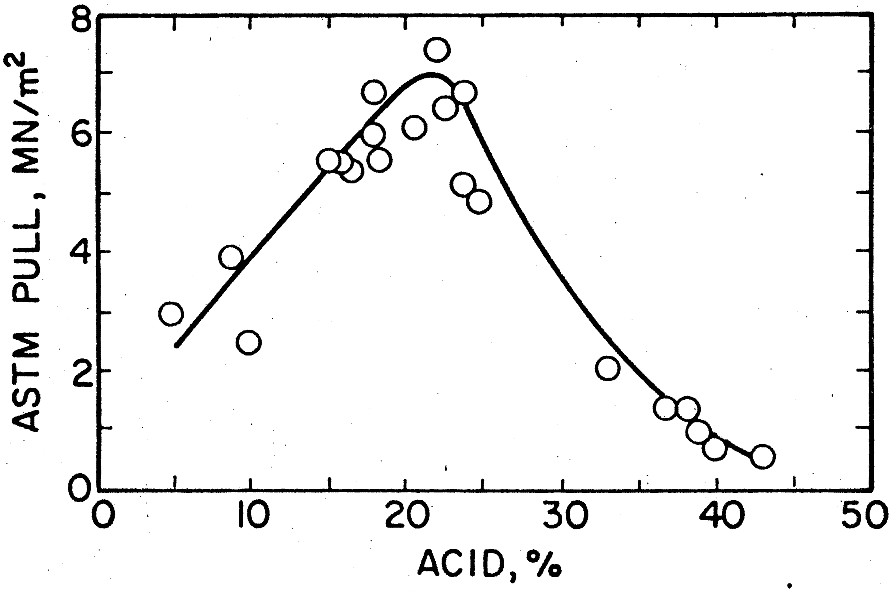


Figure 30. Effect of Acid Content on Adhesion (Butadiene-Methacrylic Acid Polymer) (49)

increment of polymer content, it is more logical to compare gain in strength for each dollar spent. From this standard, Aerospray 70 seems to be most economical. The same strength can be achieved at almost one-third of the cost of Terra Krete, its closest competitor.

Aerospray 70 film is relatively water susceptible. It swells when immersed in water for more than 24 hours. Due to the swelling, the film becomes weaker and breaks apart when peeled. The failure is mainly cohesive, indicating that the film maintains adhesion better than cohesion, but redrying the film restores both adhesion and cohesion completely. This is the reason that no strength is lost after wet-dry cycles. Adhesion in polyvinyl acetate is due mainly to the acetate group on the polymer. Due to the presence of acetate ($COO\text{-}CH_3$) group, the polymer becomes more polar and consequently its affinity for polar compounds like siliceous soil materials is increased. Thus, acetate polymers form strong bonds with siliceous soils. As water is also a highly polar material, its affinity for polar polymers is also high. This makes the acetate polymers more water susceptible. Thus, the properties of the polymer depend very much on the amount of acetate group present. Again, for soil stabilization, an optimum amount of acetate group is needed.

Pure polyvinyl acetate is too brittle at room temperature and therefore needs some kind of plasticizer or copolymerization to make the polymer film flexible. The most common plasticizer is dibutyl phthalate (about 10-15 percent). A limitation of external plasticizers of this kind is that they may eventually be lost by evaporation, leaving an imperfect or brittle film, as explained previously. This limitation may be overcome by the use of copolymers. Co-monomers which may be employed for this purpose include alkyl (2-ethylhexyl) acrylates, fumarates, and maleates. Typically, the copolymer contains 15-20 percent by weight of such co-monomer.

Aerospray 70 when sprayed in the amount mentioned previously reduces the permeability considerably. Reduction in permeability is due mainly to the larger quantity of solid polymer between the voids which is needed to keep the soil particles cemented together. As the film is harder than that of Petroset SB, the soil particles are pulled and brought closer as the film forms. This again reduces the void space, which leads to reduction in permeability. Also, the film swells significantly when soaked in water. This blocks the flow of water through the pores, leading to reduction in permeability.

In order to use this material for soil stabilization in places where strength is needed, it is essential to use it in such an amount that the flow of water through the soil is blocked. For example, when this polymer is used in amounts greater than 4 percent for soils I and II and 3 percent with soil III, it impermeates the soil completely and the soaked strength is increased considerably.

Terra Krete

Chemistry of this polymer is not known. It is some kind of polymeric mixture; it contains various sulfates of aluminum, magnesium and iron, along with citric acid and fermented wort. This material provides excellent erosion protection when sprayed at the rate of 2 gal/sq yd with a dilution of 1:19. As this material provides erosion protection at the lowest solid content, reduction in permeability of sprayed surface is also relatively less, but greater than that resulting from treatment with Petroset SB. About two percent of this material gives the soil a compressive strength of more than 400 psi (Figure 25). As the compound is quite expensive, the cost of treatment is higher than for all other polymers considered. It provides protection at a cost of about $0.80 sq yd, which is almost double that of Aerospray 70 and 180 percent of the cost of Petroset SB treatment.

The film of this material resists water well. It is not affected by soaking in water for four days. For this reason it can protect the soil at a low polymer content. Prolonged soaking does affect properties to some extent, but it is safer and stronger than Aerospray 70 under soaked conditions. Full strength is regained with drying after soaking. As the chemistry of this polymer is not well known and also because the cost is high, the writer would rank it third in potential for soil stabilization among the polymers studied.

NeoCryl 601A

This is an acrylic polymer. The exact nature of the polymer is not known. It provides good erosion protection when sprayed at the rate of 2 gal/sq yd at the dilution ratio of 1:5. Like all other polymers, it also reduces permeability. Reduction in permeability is greater than for the three polymers described previously. The cost of treatment is around $0.66 sq yd (1977).

The film of this material is quite water resistant with respect to cohesive strength. It does not swell much when immersed in water for 24 hours; it also remains fairly strong. However, adhesion becomes very poor, and the film can be peeled easily. After redrying, the film does not adhere well to the substrate. For this reason there is considerable loss of strength if treated soil is tested after wet-dry cycles or in a soaked condition, as shown in Figure 27. It takes more solid polymer to stabilize the soil. The reason, perhaps, is that the polymers which are poor adhesives need to make a close matrix of polymer film around each particle, while good adhesive polymers do not need a close matrix; spot jointing is enough to keep the particles in place. This polymer is suitable for stabilizing the soil where high strength is required. If high soaked strength is desired, more polymers can be added to the soil. This will impermeate the soil and maintain high strength. The cost and need to impermeate the soil to maintain adhesion make this polymer unsuitable for erosion control.

Rhoplex H-8

This is also an acrylic polymer, but of slightly different nature than NeoCryl 601A. It provides erosion protection when sprayed at the rate of 2 gal/sq yd at the dilution of 1:9. The surface of the treated soil is not hard and brittle as is the case with NeoCryl 601A or even Aerospray 70. Permeability of the soil is greater than with NeoCryl 601A. The cost of treatment is about $0.40 sq yd (1977).

The film of this material is very flexible and quite stretchable. Though it has poor adhesion after 24 hours of soaking, it has very good readhesion properties. Upon redrying, the film adheres to the substrate very well. For this reason there is very little loss of strength after wet-dry cycles. Another property which is unique to this polymer is that it continues to gain strength even after seven days of curing. Thouth this aspect has not been fully evaluated, it has been found that treated specimens show significantly more strength if they are tested after one month of curing than after seven days. Other polymers did not have this property.

Latex XP-4026-128

This is a polyurethanic latex which can be diluted with water. This material did not provide adequate erosion protection within a reasonable price range. The cost of treatment is about $5.00/sq yd (1977). The film of this material does not adhere to a glass substrate; it simply peels off after drying. Though the film is quite flexible and water resistant, it did not provide erosion protection because of the very poor adhesive properties. Due to both high cost and poor performance, this material is not suitable for soil stabilization for any purpose.

Corexit 7730

This is a partially neutralized polyamide. It failed to protect the soil from erosion, no matter how much was added. The reason is that this material does not form a dry water resistant film. Instead, it remains in a fairly viscous form after all of the water is evaporated. As it remains in liquid form, it does not provide the needed shear resistance which can resist water erosion effectively. Also, it remains a water dilutable material and leaches out quickly, leaving the upper soil material deficient in polymer. As this material is fairly inexpensive, it can be used for temporary wind erosion control, especially for construction sites.

Norlig 41 and Orzon GL-50

These two products are almost identical in nature. Both are lignin sulphonates. When mixed with the soil, they provide very high strength, but when soaked in water, the samples slake immediately and fall apart. The reason is the water susceptibility of these compounds. When the film is immersed in water it dissolves immediately. These materials are obviously quite unsuitable for water erosion control. Once it rains, all of the polymer will be leached away. These materials can be used for temporary protection against wind erosion in places such as construction sites.

Altak 59-50

This is a polyester in styrene solution. This is the only non-water base polymer evaluated in the study. It provides excellent erosion resistance under all conditions. This product does not form a film by evaporation, but by cross-linking. The most common cross-linking agent is methylethyl ketone peroxide. The polymer which is in the form of a viscous liquid can be diluted with styrene solution. The big advantage with this polymer is that it impermeates the soil completely and the film of this compound is strong and water resistant. It is not affected by prolonged immersion in water, and relatively less loss in strength was observed when the samples were soaked, as shown in Figure 28. As mentioned previously, this polymer has all of those disadvantages which a non-aqueous solution-base polymer can have. It is difficult to apply; it pollutes the atmosphere, and cleaning of equipment is difficult. Most of the styrene was evaporated before the polymer was fully cured.

This material seems to be more suitable for grouting purposes where water-base polymers do not work well because of lack of evaporation of water. It can also be useful as a surfacing material or base course treatment for low cost roads, where Portland cement may not be very effective. As the film of this compound is relatively stretchable, shrinkage cracks are unlikely to develop in treated soil materials.

Combinations of Polymers

Polymers which are unlike in their film properties and are compatible produce a film when mixed together that is different from that of either constituent polymer. This means that the properties of a polymer can be altered significantly by incorporating another polymer in the right amount. In this way, improvement in certain properties of the polymers can be achieved and, in some cases, the cost of treatment can be reduced significantly. With these two goals in mind, combinations of compatible polymers were tried. Two combinations, one of NeoCryl 601A and Aerospray 70, and the other of Terra Krete and Aerospray 70, were found worthy of consideration. In the former case, improvement in the properties of Aerospray 70 was the goal, whereas in the latter case, the aim was to reduce the cost of treatment. Significant success was achieved in both cases.

Aerospray 70 and NeoCryl 601A

As mentioned earlier, Aerospray 70 provides excellent erosion protection but the film of this polymer is quite water susceptible. It swells and consequently loses quite a bit of its cohesive strength. Loss in adhesion also occurs with water absorption. On the other hand, NeoCryl 601A film has little water susceptibility, although it has poor adhesive properties. In other words, when soaked, Neocryl 601A maintains high cohesive strength but fails in adhesion.

If Aerospray 70 can be made so that it will not absorb water, its adhesive and cohesive properties can be enhanced significantly. With this in mind, NeoCryl 601A was incorporated with Aerospray 70 on a 1:1 volumetric basis. The results were found to be extremely good. The film of the mixed polymer did not swell much with soaking, and consequently both adhesion and cohesion were maintained.

When this combination was tried as a spray or premixed, it worked significantly better than either individual polymer. The quantity of treatment was measured in terms of increased permeability and lower solid polymer. In the case of premixed samples, much less solid polymer was required to provide erosion protection.

Terra Krete and Aerospray 70

This combination was tried to reduce the cost of treatment without sacrificing the quality. Terra Krete is an expensive material and the cost of treatment is also high ($.80/sq yd 1977). But this material provides excellent erosion protection. On the other hand, Aerospray 70 is a relatively inexpensive material and also provides good erosion protection though it is more water susceptible. By trial, it was found that a combination of two parts of Terra Krete and one part Aerospray 70 works almost as well as pure Terra Krete. The film of this combination behaves almost exactly the same way as that of Terra

Krete alone. It does not swell or break under prolonged soaking.

When the combination of these two compounds was sprayed in the same amount as pure Terra Krete, it provided the same erosion protection. Permeability of the treated material also remains the same as that of pure Terra Krete. The cost of treatment is reduced from $0.80 to $0.62 sq yd. A reduction of 23 percent in cost can be achieved by using the combination of these two polymers without sacrificing the quality of treatment.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In summary, it can be stated that polymers which possess good adhesion and form a water resistant film are most successful for erosion control, no matter what their constituents are. The materials which can provide this kind of film are copolymers such as butadiene-styrene, butadiene-methacrylic acid, butadiene-acrylonile, and some other vinyl and acrylic polymers. The properties of the film such as adhesion, cohesive strength, and water susceptibility can be adjusted by manipulating various monomers in the copolymer. In addition, polymers and copolymers can also be modified to suit special conditions by incorporating plasticizers and polar groups like carboxylic and acetate groups. As most of the properties are interdependent, a change in one affects the others. For example, when adhesion of a polymer film is increased, it either becomes weak in cohesive strength or becomes water susceptible. Similarly, cohesive strength is generally increased at the cost of adhesion.

In the copolymers of butadiene, flexibility and adhesion are contributed by butadiene, and the other monomer provides cohesive strength. An optimum combination of cohesion and adhesion can be achieved by adjusting the ratio of the two monomers. For example, in the copolymer of butadiene-styrene (Petroset SB), butadiene provides flexibility and adhesion, and styrene provides the cohesive strength. The higher the styrene content in the copolymer, the more rigid and strong will be the film. Most copolymer formulations have a butadiene to styrene ratio of 3:1. These copolymers are very flexible and rubbery in nature. Though they provide very good adhesion, they lack cohesive strength, which makes them inferior for many uses including soil stabilization. By increasing the styrene content, cohesive strength can be increased significantly. This, of course, might reduce adhesion somewhat.

The other way to increase both cohesion and adhesion is by incorporating carboxylic or acetate groups in the polymers or copolymer. Due to the presence of these groups, the polymer molecules become more polar in nature, and consequently their affinity for polar substrates like siliceous soils is increased considerably. Cohesive strength also increases because of the increased molar cohesion due to polar groups. But incorporation of more than an optimum amount of these groups reduces adhesion because of excessive intermolar forces within the polymer. This leads to poor adsorption of polymer onto the substrate. Increased amount of polar groups in the polymer also make it water susceptible. This is because water is also a highly polar material and is strongly attracted by other polar materials.

The right combination of monomers along with an optimum amount of polar groups can provide an excellent polymer for soil stabilization and erosion control. The polymer Petroset SB provides excellent erosion protection because of its good adhesive properties, but it fails to provide adequate cohesive strength in the case of a very coarse-grained soil. Increasing the styrene content and incorporating some carboxylic group could make it acceptable for all kinds of soils.

The other vinyl or acrylic polymers seem to be less effective for soil erosion control. These polymers, in general, either lack adhesive or cohesive strength, or are water susceptible. It is very difficult to achieve the most favorable combination of all three properties in a single material. In most cases, these polymers are very strong in cohesive strength but lack adhesion. When adhesion is induced, the polymers become water susceptible. This occurs because adhesion is generally induced by incorporating some plasticizers and polar groups. Both of these make the polymers water susceptible. Vinyl and acrylic polymers seem to be more effective for premixed soil stabilization where high strength is an important requirement and reduction in permeability of the treated material is of no significance. In such cases, incorporating two to three percent of these polymers into the soil can provide fairly high strength of the order of 400 to 500 psi. Shrinkage cracks, which are often a problem in soil-cement treatment, usually do not develop in polymer-treated soil. This is because the polymers can stretch much more without cracking than can Portland cement. Thus, the polymers can replace Portland cement in many situations and especially in treatment of soils having large amounts of fines and organic matter.

Conclusions

1. All polymers which form a water resistant film protect the soil from wind and water erosion to a certain extent.

2. Among other properties, flexibiity and adhesion of the film play a significant role.

3. Most of the polymers which are highly flexible and rubbery in nature are also good adhesives.

4. Elastomers, such as butadiene-styrene copolymer, work significantly better than do other polymers.

5. High strength of soil-polymer mixture is not essential for erosion control. A minimum of 5 to 10 lbs/sq in. in the soaked condition is sufficient.

6. Rigid polymer films show poor adhesion and also perform in a significantly inferior way.

7. Water susceptibility of a polymer film is the main cause of failure of treatment; polymer films which are most water resistant are also most successful for erosion control.

8. For wind erosion control, much less polymer is required than for control of water erosion. This means that if the treatment is successful for water erosion control, it certainly will be successful for wind erosion control.

9. All polymers perform better dry than in a soaked condition. Also, if a polymer-treated soil sample is subjected to an erosion test after only a few hours of soaking, it will perform better than when it is tested after several days of soaking.

10. All polymers reduce the permeability of the soil; however, with some polymers it is possible to achieve desired properties of strength and erosion resistance without greatly reducing soil permeability.

11. A minimum of 2 gal/sq yd of polymer solution is needed for best results. An amount of polymer solution less than this amount causes "blanket" or "crust" formation which ultimately leads to poor percolation rate and quick failure.

12. Concentration of polymer becomes less with depth in a spray

treated surface. Concentration is maximum in the top 1/4 to 1/2 inch, depending upon the soil type. Pre-wetting the top surface sometimes helps to minimize this concentration of polymer in the top portion but, in most cases, if the polymer is sprayed in the right dilution, the concentration of polymer on the top layer is reduced.

13. In addition to the quantity of polymer, rates of dilution of polymer in water are important in performance. Dilution rates greater or less than optimum lead to poor results. A dilution with less concentration of polymer leads to weaker surface material, while a high concentration leads to poor penetration, crust formation, uneven distribution of polymer, and significant reduction in permeability.

14. Each polymer has its own unique optimum dilution ratio.

15. Higher ambient temperature leads to quick evaporation of water and to early film formation.

16. Effect of freeze-thaw cycles is significantly less damaging than wet-dry cycles.

17. Compressive strength varies significantly with temperature at the time of testing. Samples tested at 25°C were found to have higher strength than those tested at 35°C; on the other hand, more strain was tolerated at 35°C.

18. Nonaqueous solution-base polymers are less affected by the presence of water after curing and consequently perform better in the soaked condition; but they have other deficiencies, such as polluting the atmosphere, difficulty in application, toxicity, and water susceptibility before cure.

19. For soils made up of coarse sand or gravel, the polymer

should have sufficient cohesive strength along with good adhesion. Elastomers of low cohesive strength do not cement the particles of these soils effectively, and consequently fail to provide adequate protection.

Recommendations

Petroset SB, which is an elastomer based on butadiene-styrene copolymer, has been found to be the most effective material for erosion control without seriously affecting the other properties of the soil such as permeability. This material is effective only for soils finer than coarse sand. It should be applied at the rate of 2 gal/sq yd at the dilution ratio of 1:9. For soils which contain large quantities of coarse material like gravel and coarse sand, a polymer which has higher cohesive strength is required. Another formulation of butadiene-styrene copolymer having a higher percentage of styrene would be more suitable. Incorporation of carboxylic (COOH) group up to 20 percent with the copolymer would also help to increase its cohesive and adhesive strengths.

Properly diluted polymer can be sprayed on either wet or dry soil. It is necessary, however, that the treated surface dry and the polymer cure before rain occurs. For this reason, clear, warm and sunny days should be chosen for field application. As butadiene-styrene does not reduce the permeability of the treated surface significantly, it can safely be applied on steep slopes without endangering the stability through increased pore pressure in material behind the slope. This polymer is not suitable, unless modified, for highway surfacing or base course.

Polymer and copolymers of butadiene origin are nonpolluting, nontoxic, and have proven noncarcinogenic characteristics. Their use on a large scale will neither hurt the environment nor hamper the growth of vegetation. Vinyl chloride and some other vinyl-base polymers are questionable with regard to health safety. Their use on a large scale may be hazardous.

Aerospray 70 is another good choice for erosion control and can also be used in highway base course and subgrade stabilization. It can be used for fine-grained soil as well as sands. For base course construction, two to three percent of solid polymer will provide adequate strength. As this polymer reduces permeability considerably, its application on steep slopes should be made with caution regarding the stability of the slope.

In general, concentration of solid polymer in water for spray application varies from two to five percent for best results. Soils which contain a higher percentage of fines need a lower concentration of polymer in solution for better penetration and more uniform distribution. An average of 2 gal/sq yd is quite effective to stabilize the surface material to a depth of 1.5 inches. If the percolation rate of the soil is very low, plowing or loosening the surface material may be needed to obtain uniform and rapid penetration. Plowing before spraying will also help to maintain a high percolation rate of the treated surface after the polymer is cured. This will help to reduce the runoff and lessen erosion.

Dilute polymer emulsion should be sprayed at a low enough rate so that no runoff occurs during application. This calls for precise control on speed and discharge rate of the spraying equipment. Each area should be covered in only one run. Respraying due to an insufficient amount of the material sprayed in the previous run will result in poor penetration and concentration of polymer on the surface with reduction in soil permeability. Most of the general types of sprayers can be used for this purpose, but calibration of the equipment is essential.

BIBLIOGRAPHY

1. Armbrust, D. V. and J. D. Dickenson. "Temporary Wind Control: Cost and Effectiveness of 34 Commercial Materials." Journal of Soil and Water Conservation, Vol. 26, 1971.
2. Blavia, F. J. and D. E. Law. "Materials for Stabilizing the Surface Clods of Cropped Soil." Proceedings Soil Science Society of America, Vol. 35, 1971.
3. Chepil, W. S. "Clod Structure and Erodibility of Soil." The Journal of Soil Science, Vol. 76, 475:479, 1953.
4. Chepil, W. S. "Dynamics of Wind Erosion, Part II." The Journal of Soil Science, Vol. 60, 1945.
5. Chepil, W. S. "Dynamics of Wind Erosion, Part III." The Journal of Soil Science, Vol. 60, 1945.
6. Chepil, W. S. "Erosion of Soil by Wind." Yearbook of Agriculture, 1957.
7. Davis, R. W. and J. L. Lummus. "Compositon and Method for Plugging and Consolidating." United States Patent Office, Patent No. 2,842,338. July 8, 1958.
8. Emerson, W. W. "Synthetic Soil Conditioners." Journal of Agricultural Science, Vol. 47, 1956.
9. Ellison, W. D. "Soil Detachment by Surface Flow." Agricultural Engineering, October, 1947.
10. Ellison, W. D. "Soil Erosion Studies, Part I." Agricultural Engineering, Vol. 28, April, 1947.
11. Ellison, W. D. "Soil Detachment Hazard by Raindrop Splash. Soil Erosion Studies, Part II." Agricultural Engineering, May, 1947.
12. Ellison, W. D. "Soil Transportation in the Splash Process. Soil Erosion Studies, Part IV." Agricultural Engineering, August, 1947.
13. Ellison, W. D. and O. T. Ellison. "Soil Detachment by Surface Flow. Soil Erosion Studies." Agricultural Engineering, September, 1947.

14. Ellison, W. D. "Soil Detachment and Transporation." Journal of Soil Conservation, 1949.

15. Einstein, A. Annalen der Physik. 19:289, 1906.

16. Einstein, A. Annalen der Physik, 34:591, 1911.

17. Einstein, H. H. and M. Schnitter. "Selection of Chemical Grout for Mattmark Dam." Proceedings ASCE Soil Mechanics and Foundation Division, SM 6, November, 1970.

18. El Rousstom, A. K. "Rain Erodibility of Compacted Soils." PhD Dissertation, University of Arizona, 1973.

19. Fungaroli, A. A. and S. R. Pranger. "Evaluation of Some Acrylic Polymers as Soil Stabilizers." Industrial Engineering Chemistry, Vol. 8, No. 4, 1969.

20. Guth, E. "Theory of Filler Reinforcement." Journal of Applied Physics, Vol. 16: 20-25, 1945.

21. Hagin, J. and G. B. Bodman. "Influence of Polyelectrolyte CRD-186 on Aggregation and Other Physical Properties of Soils." Journal of Soil Science, Vol. 78: 367-371, 1954.

22. Hedrick, R. M. and D. T. Mowry. "Effect of Synthetic Electrolytes on Aggregation and Water Relationships of Soil." Journal of Soil Science, Vol. 73: 427-430, 1951.

23. Lambe, T. W. "The Effect of Polymers on Soil Properties." Proceedings of Third International Conference on Soil Mechanics and Foundation Engineering, Vol. I: 253-255, 1953

24. Lipalov, Y. S. and L. M. Sergeeva. Adsorption of Polymers. John Wiley and Sons, New York, 1976.

25. Morrison, W. R. "Chemical Stabilization of Wellton-Mohawk Soil." Memorandum, United States Government, Denver, Colorado, March 20, 1973.

26. Morrison, W. R. and V. L. Kuehn. "Laboratory Evaluation of Petrochemicals for Erosion Control." Memorandum, United States Government, Denver, Colorado, June 12, 1973.

27. Morrison, W. R. and V. L. Kuehn. "Chemical Stabilization of Gravel Lining, McClusky Canal - FY74 OCCS Program." Memorandum, United States Government, Denver, Colorado, April 9, 1976.

28. Morrison, W. R. and V. L. Kuehn. "Laboratory Evaluation of Petrochemicals for Erosion Control - FY74." Memorandum, U. S. Government, Denver, Colorado, May 31, 1974.

29. Nelson, K. E. and E. M. Jankowiok. "A Mulch Binder for Soil Erosion Control." The Dow Chemical Company, Function Products and System Department, January, 1976.

30. Nicholls, R. L. and D. T. Davidson. "Polyacids and Lignin Used With Large Organic Cations for Soil Stabilization." Proceedings Highway Research Board, Vol. 37: 517-537, 1958.

31. Otis, J. L. "Recent Studies in Raindrops and Erosion." Agricultural Engineering, Vol. 21, November, 1940.

32. Osborn, B. "How Rainfall and Runoff Erode Soil." Yearbook of Agriculture, 1955.

33. Reich, L. and S. S. Salvatore. Elements of Polymer Degradation. McGraw-Hill Book Company, 1971.

34. Revut, I. B. "Increasing the Fertility and Resistance to Erosion of Soils." Soviet Plastics, No. 10, 1972.

35. Saunders, K. J. Organic Polymer Chemistry. Chapman and Hall, London, 1973.

36. Seymour, R. B. Introduction to Polymer Chemistry. McGraw-Hill, Inc., New York, 1971.

37. Smallwood, H. M. "Limiting Law of the Reinforcement of Rubber." Journal of Applied Physics, 15: 758-766, 1944.

38. Solomon, D. H. The Chemistry of Organic Film Formers. John Wiley and Sons, Inc., New York, 1967.

39. Stearn, R. S. and B. L. Johnson. "Interaction Between Carbon Black and Polymer in Cured Elastomers." Industrial Engineering Chemistry, 43:146-154.

40. Sultan, H. A. Soil Erosion and Dust Control on Arizona Highways, Part II. Arizona Department of Transportation, Report ADOT-RS-141-II.

41. Szwark, M. "The Action of Carbon Black in Stabilizing Polymeric Materials." Journal of Polymer Science, 19: 589-590, 1956.

42. Voronkevich, S. D. "Use of Modified Polyvinyl Alcohol for Reinforcement of Clayey Soils." Soviet Plastics, No. 7, 1973.

43. Vinson, T. S. and J. K. Mitchell. "Polyurethane Formed Plastics in Soil Grouting." Proceedings ASCE, Soil Mechanics and Foundation Division, SM6, June, 1972.

44. Williams, D. J. Polymeric Science and Engineering. Prentice-Hall, Inc., New Jersey, 1971.

45. Wischmeir, W. H. and D. D. Smith. "Rainfall Energy and Its Relationship to Soil Loss." Transactions Americal Geophysical Union, Vol. 39, No. 2, 1958.

46. Woodruff, N. P. and W. S. Chepil. "Wind Erosion and Transportation." ASCE, Journal of Hydraulics Division, March, 1965.

47. U. S. Department of Agriculture. Soil Conditions That Influence Wind Erosion. Technical Bull. 1185, 1947.

48. Agricultural Engineering Handbook, Wind Erosion and Its Control.

49. Holliday, L., Ionic Polymers. John Wiley and Sons, New York, 1975.

50. Rice, James A. "Relationship of Aggregate Characteristics to the Effect of Water on Bituminous Paving Mixtures." ASTM, STP, 240, 17, 1958.

51. Handbook of Adhesives. Reinhold Publishing Corp., Chapman & Hall, Ltd., London, 1965.

52. Plastic Engineering Handbook. Van Nostrand Reinhold Company, New York, 1976.

53. Rouse, Hunter. Engineering Hydraulics, John Wiley and Sons, New York, 1961.

54. U. S. Dept. of Agriculture Soil Conservation Service, Oklahoma Agriculture Experiment Station, Soil Survey of Creek County, Oklahoma, 1959.

55. ———, Soil Survey of Kingfisher County, Oklahoma, 1962

56. ———, Soil Survey of Love County, Oklahoma, 1966.

57. Wadsworth, M. E. and R. O. French. Journal of Physical Chemistry, 58: 805 (1954).

APPENDIX A

POLYMER MANUFACTURERS AND SUPPLIERS

Product	Company
Terra Krete	Kingman Chemical Company 1310 West Collins Orange, California 92667
Latex XP-4026-128	Hooker-Ruco Division New South Road Hicksville, New York 11802
Altek 59-50	Alpha Chemical Corporation P. O. Box Drawer A Collierville, Tenn. 38017
Rhoplex H-8	Rohm and Haas Philadelphia, Pa. 19105
NeoCryl A-601	Polyvinyl Chemical Industries 730 Main Street Wilmington, Mass. 01887
Corexit 7730	Exxon Chemical Company 2000 Classen Center East Oklahoma City, Oklahoma 73106
Norlig 41	American Can Company Suite 400, Antares Building 730 N. Post Oak Road Houston, Texas 77024
Orzan-GL-50	Crown Zellerbach Corporation Chemical Product Division Camas, Wa. 98607
Aerospray 70	American Cyanamide Company Industrial Chemical Division Wayne, New Jersey 07470
Petroset SB	Phillips Chemical Company Bartlesville, Oklahoma 76004

APPENDIX B

ADDITIONAL TECHNICAL DATA ON SOME OF THE POLYMERS USED IN THE STUDY

Petroset SB

Petroset SB is supplied as a concentrate and should be diluted with water before use. Most soil types can be treated with it. Petroset SB normally darkens the soil slightly. Application equipment should be cleaned with water following use. Any residual deposits may be cleaned with hydrocarbon solvents, such as Stoddard Solvent, Kerosene or diesel oil. Petroset may be diluted with most of available water including sea water.

DESCRIPTION The following typical data can be used to characterize the emulsion:

Physical State	Free flowing, oil in water emulsion containing hydrocarbon solvents	**Storage Stability**	Excellent at normal warehouse temperatures of 50 F to 110 F
Color	Light tan	**Heat Stability**	Minimum 24 hours at 140 F
Sieve Test, No. 100, percent retained	Maximum 0.1	**Cold Stability**	Stabilized to resist damage from freezing**
Specific Gravity	1.04 ± 0.03	**Miscibility with Water**	Unlimited
Brookfield Viscosity*, CP	80 200	**Miscibility with Salt Water**	Stable for 24 hours after dilution with four volumes of 5% NaCl solution
Solids Content, percent	48 ± 2		
Particle Charge	Positive		
pH	6.0 ± 0.5		

*2:1 dilution, LVT model, No. 1 spindle, 12 RPM, 75 F

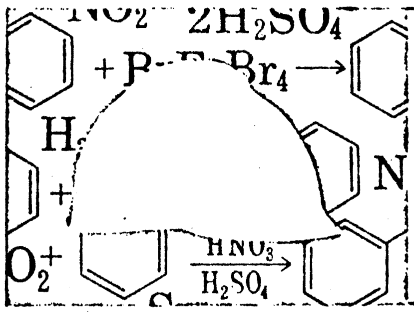
**Do not expose to repeated freeze-thaw cycles

TABLE I Suggested Spread Rates (gsy) of Dilute Petroset SB Emulsion To Attain Desired Depth of Soil Penetration.

Size of Particles Mesh Size	Depth of Penetration — Inches ¼"	 ½"	 1"	 2"
Dust <No. 200	.50	1.0	2.0	3.0
Fine 60- 200	.35	.75	1.35	2.0
Intermediate 30- 60	.25	.50	1.00	1.5
Coarse 30- 10	.20	.40	.75	1.25
Small Clods 10- 4	.15	.30	.50	1.00
Large Clods >No. 4	.10	.20	.35	.75

TABLE II Suggested Ratios of Dilution of Petroset SB Emulsion For Different Types of Service and Particle Size Soils.

	Abrasive Force			
Soil Classification By Particle Size	**Wind Erosion <90 mph**	**Rainwater Erosion**	**High Velocity Wind >90 mph**	**Flowing Water Erosion**
Dust Grains <No. 200	1:19	1:14	1:9	1:7
Fine Grains <No. 60 >No. 200	1:14	1:9	1:7	1:5
Intermediate Grains <No. 30 >No. 60	1:9	1:7	1:5	1:4
Coarse Grains <No. 10 >No. 30	1:7	1:5	1:4	1:3
Small Clods & Rocks <No. 4 >No. 10	1:5	1:4	1:3	1:2
Large Clods & Rocks >No. 4	—	—	1:2	1:1



AEROSPRAY® 70
binder

PRODUCT BULLETIN EN 100B

AEROSPRAY® 70 binder is the latest development in polymeric soil stabilizers and dust control agents. It functions to reduce and eliminate surface erosion caused by wind and rain. At low treatment levels, AEROSPRAY 70 binder works as an effective binding agent which also forms a surface film coating when used in higher concentrations.

Advantages

- **EXCELLENT RESULTS –**
  Stabilizes surface soil and prevents erosion by wind and rain while leaving the esthetic appearance of the treated area unaffected.
- **ECONOMICAL –**
  AEROSPRAY 70 binder controls dust in areas of light traffic without the need for costly surface treatments.
- **STABLE –**
  Extremely resistant to sunlight and completely safe for both germinating and growing plants.
- **EASY TO USE & SAFE TO HANDLE –**
  AEROSPRAY 70 presents no fire or explosion hazards either in storage or during application.

Principal Uses

AEROSPRAY 70 binder has been proved effective in a wide range of stabilization problems on several types of soils and mine tailings under varying environmental conditions. Some areas where AEROSPRAY 70 binder might be used effectively include:

Agriculture

- As a binder to prevent erosion during seed germination in establishment of vegetative cover.
- To prevent damage to seedlings by dust blown from adjacent locations.

Aviation

- The suppression of dust on the perimeter areas of runways and taxiways.
- Used in conjunction with the construction of runways, taxiways, and hanger ramps at secondary airports.

CYANAMID

ENGINEERING CHEMICALS, AMERICAN CYANAMID COMPANY, WAYNE, NEW JERSEY 07470

Conservation

- Sand dune stabilization.
- Dust suppression.
- Erosion control.

Construction

- Dust suppression on job sites.
- To complement road construction.
- As a binder for both seeds and hay mulch on newly graded slopes and roadway embankments.

The Home

- As an aid in establishing lawns by preventing seed bed erosion during germination, expecially in high slope areas.
- The construction of walkways.

Mining

- The stabilization of tailings piles to control environmental pollution.
- To minimize the losses incurred in transporting crushed coal, or ore in open vehicles; such as, railroad cars, trucks, and ships, etc., by binding the exposed surface.

Water Management

- Water catchments.
- Pond liners.
- Irrigation ditch liners.

Typical Properties

AEROSPRAY 70 binder is supplied in concentrated form, and requires only dilution with water in the field to the desired level for application. Typical properties of AEROSPRAY 70 binder as supplied are:

Appearance	Milky-white, viscous liquid
Film	Colorless, transparent, non-reemulsifiable
Total Solids	60 ± 1% by weight
Average Weight per Gallon at 20°C.	9.25 lb.
pH at 25°C.	4 to 6
Viscosity, Brookfield No. 4 spindle at 60 rpm.	1,800 to 3,800 cps.
Storage Stability	Excellent; avoid prolonged storage temperatures above 110°F. or exposure to freezing (32°F.)
Dilution Stability	Excellent

Continuous Films

Very concentrated mixtures, containing more than 2 parts of AEROSPRAY 70 binder per part of water, form a continuous film when applied to substrates that are highly compacted, contain a high percentage of fine particles, or both. An example of this type of substrate is compacted clay. Application of concentrated AEROSPRAY 70 binder mixtures on clay will produce a tough, continuous film, impermeable to water when applied at a rate of 1 to 3 gallons per square yard. This is suitable for surfaces subjected to intermittent light vehicular traffic, such as highway shoulders, airport ramps and taxiways, and temporary road surfaces.

Application Techniques

AEROSPRAY 70 binder requires only dilution with water to prepare it for use. Although exceptionally stable to dilution with hard water, it is good practice to use the cleanest water available for dilution and equipment clean-up.

Dilution of two parts AEROSPRAY 70 binder with 1 part of water, by volume, results in a fluid consistency suitable for spray or spreader application. However, the excellent dilution stability of the material permits further reduction to meet specific application demands. Experience has shown that simple mixing ratios in the following range will cover most requirements:

Part of Volume AEROSPRAY 70 binder	:	Water	Approximate Solids, Per Cent by Weight
2	:	1	41.1
1	:	1	31.5
1	:	10	5.8
1	:	20	2.9
1	:	50	1.2

AEROSPRAY 70 can be used to line farm ponds and irrigation canals to reduce the loss of water by penetration into the surrounding soil. If the film liner is damaged by livestock, etc., it can easily be repaired by simply pouring some fresh AEROSPRAY 70 binder over the tear. The new material will bond securely to the old to form a seal. For applications with less severe service requirements than those described above, the quantity of AEROSPRAY 70 binder can be sharply reduced. The optimum dilution ratio and application rate are dictated by the characteristics of the substrate and the desired results of the treatment.

As a general rule, the best practice is to add the water to the material rather than the reverse. Use a recirculating pump for mixing if the application tank is not equipped with a stirrer. Manual mixing of drum quantities will suffice to produce a homogeneous dispersion.

When 10 per cent water is added to AEROSPRAY 70 binder, the viscosity of the mixture is reduced considerably. When 20 per cent or more water is added to AEROSPRAY 70 binder, the viscosity approaches that of water. This coupled with the excellent mechanical stability of AEROSPRAY 70 allows a wide latitude in the selection of methods of application of AEROSPRAY 70. In general, any method that will cause the mixture to strike the surface in a low speed spray with uniform coverage is acceptable.

Application Equipment

The specific design of application equipment will be determined by the typography of the job site. In general, much of the equipment that is available for application of liquid fertilizers and insecticides, and for spreading asphalt emulsions can be used to apply AEROSPRAY 70 with little or no modification. Such equipment can be purchased with oversize tires to permit its use on unstable surfaces, like sand dunes. Hand-held pressure sprayers, commonly used for applying insecticides can be used for small jobs or for patching. A gravity feed water sprinkler truck can be used for applying the material to roadways, shoulders, parking lots, and other similar surfaces. The environment of each specific job will guide the selection of the proper application equipment.

In any case, the application system should consist of a tank for mixing and storing AEROSPRAY 70 binder and water, and one or more spray nozzles. The energy necessary for spraying the material can be supplied by pumping, or by pressurizing the hold tank. Suitable pumps include the Series 151 "Viking" pump, the "Blackmer" type GL sliding vane pump, and the "Waukesha Dualobe" pump. Centrifugal pumps can be used for handling diluted AEROSPRAY 70 binder and water mixtures. The concentrate is much to viscous for efficient use of centrifugals. A "Moyno" pump, fitted with a stainless shaft and rotor, also provides excellent service.

In all cases, pump shafts and bearings should be provided with a water-proof lubricant sealed off from the circulating AEROSPRAY 70. Since it is a water based material, AEROSPRAY 70 is not self lubricating. If it is allowed to leak into the pump bearings, rubbing friction may cause it to coalesce on bearing surfaces and may cause the pump to bind.

Spray nozzles should be selected to give a coarse droplet spray at the desired delivery rate. High shear forces in the nozzle, caused by improper nozzle configuration, or excessive spraying pressure are to be avoided, as they will cause the product to atomize and, in effect, spray dry on its way to the target substrate. A Model ¼ T9520 nozzle, supplied by Spraying Systems, Inc. has been used effectively to produce a flat fan spray pattern with low atomization at approximately 20 gallons per minute with 40 psi. nozzle pressure. Application rates can be increased by selecting a larger nozzle of a similar configuration or by teaming several nozzles on a spray bar. It is best to position the nozzle between 6 and 12 inches above the target to minimize material losses.

Equipment clean-up is simple and easy, but must be done before the coating dries out. Equipment should also be clean *BEFORE* use. Tanks and lines need only be washed with water containing a small quantity of detergent. In general, it is desirable to start with a minimum of added water under recirculation, and then gradually increase the dilution while draining the equipment. Flush with fresh water until it runs clear.

As with all aqueous systems, AEROSPRAY 70 will promote rusting of plain steel. Corrosion resistant materials are desirable for permanent installations. Galvanized iron, brass, or other zinc containing mixtures should not be used.

The binding and film forming properties of AEROSPRAY 70 binder result from the coalescing of the polymer particles as the water is lost by evaporation into the air, or by absorption into the surrounding substrate matrix. Drying time is dependent upon several factors, including the dilution ratio, application rate, and environmental conditions such as wind velocity, temperature and relative humidity. It can range from twenty minutes to several hours. To achieve optimum results, AEROSPRAY 70 should not be applied when the soil temperature is lower than about 45°F.

AEROSPRAY 70 will provide a coating that can be made to vary from a tough continuous surface film of polymer to an almost imperceptible web of microscopic threads which fill the interstitial voids in the soil matrix, literally tying the particles together. The characteristics of the coating are dependent upon several things; primarily the dilution ratio and application rate of AEROSPRAY 70 binder and the degree of compaction and particle size distribution of the substrate.

Binding

When AEROSPRAY 70 binder is mixed with 1 part or more of water and applied to non-compacted substrates similar to sand, no surface film will be formed. Instead, the mixture will penetrate into the matrix and bind the individual particles. Experience has shown that the depth of penetration is more dependent upon the quantity of solution applied rather than its concentration. Figure 1 illustrates this for solutions of AEROSPRAY 70 binder and water ranging from 1 part AEROSPRAY 70 binder in 1 part water to 1 part AEROSPRAY 70 binder in 20 parts water. The mixtures in the example were applied to a sandy silt extracted from lower New York Bay.

FIGURE 1

PENETRATION OF AEROSPRAY 70 BINDER IN PORT ELIZABETH, N.J., SOIL

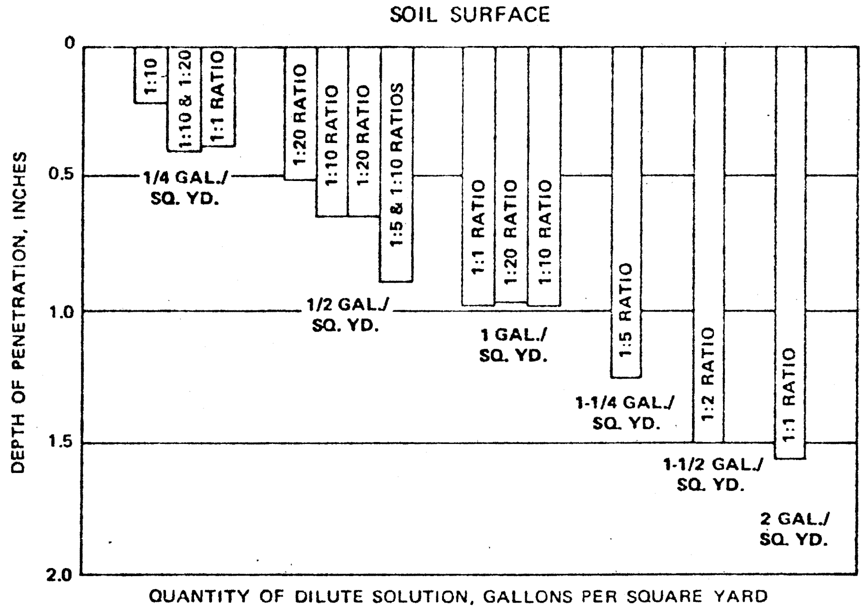
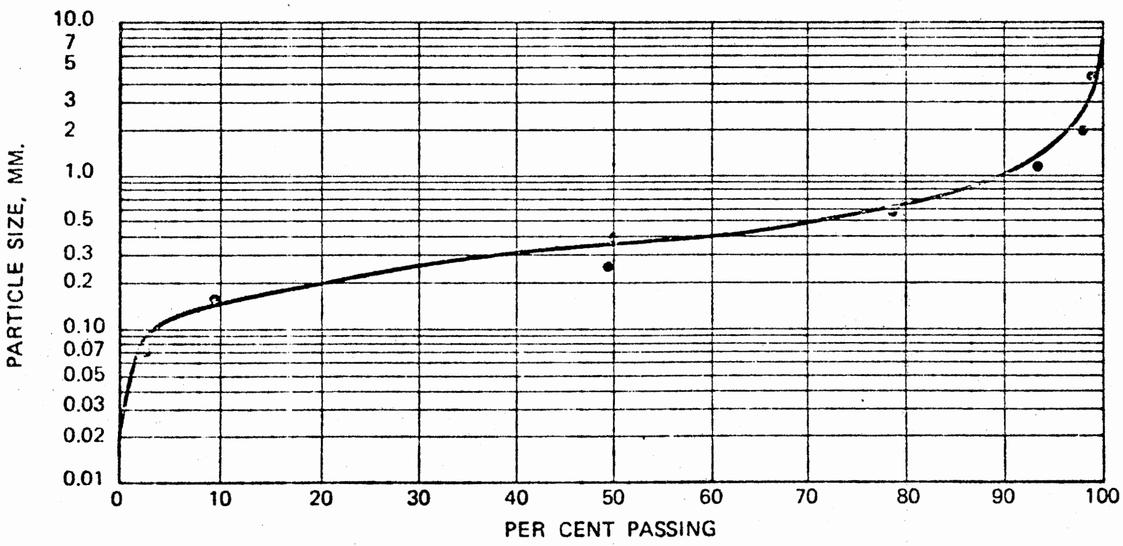


Figure 2 shows the distribution of particle sizes in the test soil. Information about the structure of the substrate to which the AEROSPRAY 70 will be applied is helpful in determining optimum application rates, because results are heavily dependent on the substrate characteristics. An increase in the proportion of larger particles, as for example, in coarse sand, would result in greater penetration for a given quantity of AEROSPRAY 70 binder. Where there are greater percentages of fine particles, as in soils rich in clay, penetration is reduced. Under these conditions, AEROSPRAY 70 binder will form a surface film with very little penetration when applied in a solution of 1, 2, or more parts AEROSPRAY 70 binder to 1 part water, as described above.

The strength of the layer of bound soil will increase with increasing AEROSPRAY 70 binder concentration for a fixed application rate. The permeability of the treated soil will decrease. This is because of the manner in which AEROSPRAY 70 binder performs its function in dilute mixtures. The individual soil particles are laced together by a web of polymeric bridges. As the quantity of AEROSPRAY 70 binder is increased, the network of bridges becomes more intricate, until all the voids in the soil matrix are filled with the polymer. The desirability or undesirability of completely filling all of the void space in a given substrate layer will, of course, depend upon the cost-performance objectives of the particular application. In the stabilization of walkways, parking lots, and other light-trafficked surfaces, a strong impermeable surface is desired, and a relatively heavy application of AEROSPRAY 70 binder, perhaps in a mixture of 1 part AEROSPRAY 70 binder to 1 part water, and applied at the rate of 0.5 or more gallons per square yard would be required. The optimum rate of application and dilution ratio should be determined by preliminary examination on a sample of the material to be treated, followed by a small field test.

FIGURE 2

PORT ELIZABETH SAND: PARTICLE SIZE VS. PER CENT PASSING

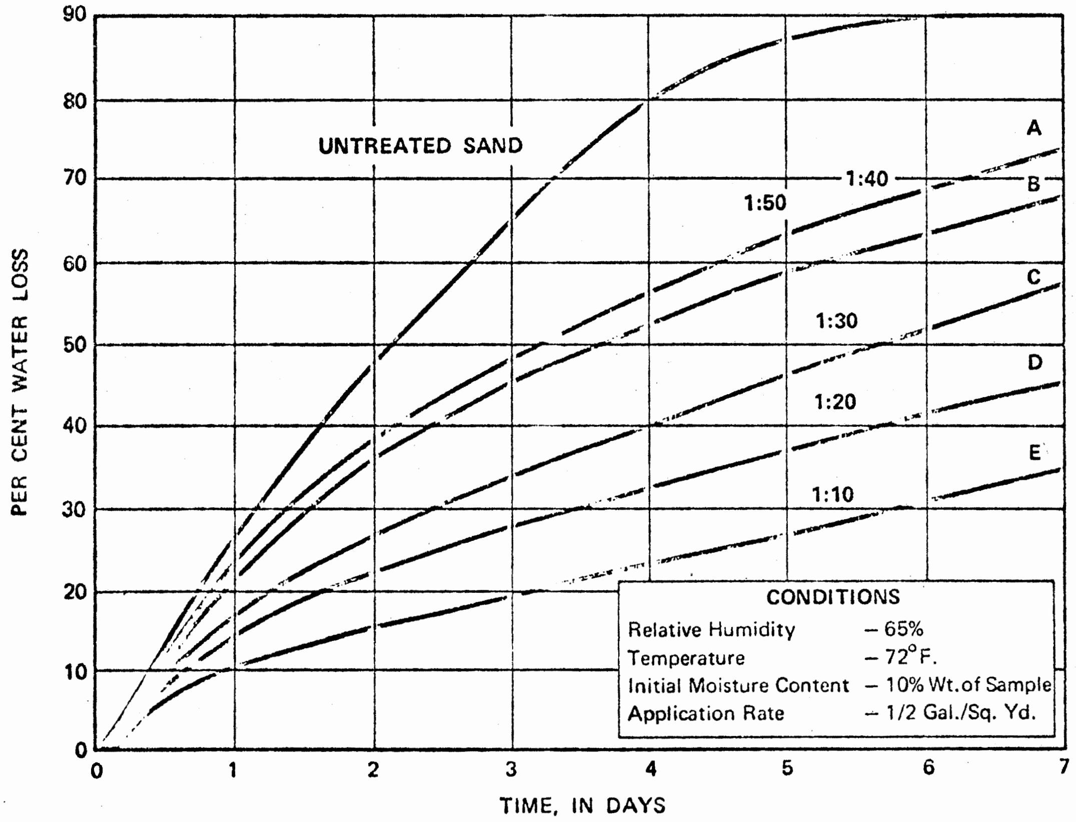


If AEROSPRAY 70 binder is applied lightly, in dilutions of 1 part to 20 or more parts of water, at ½ gallons per square yard; a high degree of binding can be expected, but the surface will remain permeable to water to the extent that seeds will germinate through the bound layer. This feature is invaluable in situations where the desired objective is long-term erosion control. The seeds will be held in place by the polymeric web until they have a chance to germinate. Upon germination, the plant cover will break up the bound layer, and establish itself as the first line of defense against erosion.

Treatment with AEROSPRAY 70 will substantially reduce evaporation losses. This is particularly important in areas where farming is conducted under conditions where water is scarce or where water must be brought in by irrigation.

Figure 3 illustrates moisture loss for samples of sand treated with various concentrations of AEROSPRAY 70 binder ranging from one part AEROSPRAY 70 binder in ten parts water to one part AEROSPRAY 70 binder in fifty parts of water. At the beginning of the experiment half of the samples contain 10 per cent by weight of water. Note that the untreated sand lost nearly three times as much water in one week as did sample E. Note that even a treatment with a very dilute solution of AEROSPRAY 70 binder (sample A) was of significant benefit.

FIGURE 3
MOISTURE LOSS THROUGH PORT ELIZABETH SAND
TREATED WITH AEROSPRAY 70 BINDER



Terra-Krete CEM

EROSION CONTROL

PREVENT WIND AND RAIN EROSION

PERMANENTLY

APPLY ONE GALLON TO 70 - 100 SQUARE FEET FOR BARREN SLOPES.

TEMPORARILY

APPLY ONE GALLON TO 250-500 SQUARE FEET TO HOLD SOIL UNTIL PLANT ROOT DEVELOPMENT ALLOWS NATURAL EROSION CONTROL.

DUST CONTROL

PILES of SOIL, SAND, TAILINGS, CHEMICALS, etc.

FRESH EXCAVATIONS

APPLY ONE GALLON TO 350–650 SQUARE FEET.

FOR EROSION CONTROL PURPOSES, TERRA-KRETE CEM MAY BE APPLIED BY SIMPLY SPRAYING IT ON THE SURFACE TO BE PROTECTED. RIPPING OF THE SOIL AND COMPACTION ARE NOT REQUIRED. TERRA-KRETE CEM MAY BE USED OVER FRESHLY SEEDED SOIL AS IT DOES NOT INHIBIT GERMINATION.

TERRA-KRETE CEM IS NON-TOXIC AND NON-FLAMMABLE, AND IT IS EASY TO CLEAN UP. TERRA-KRETE CEM IS PACKAGED IN STANDARD 55 GALLON DRUMS.

Terra-Krete ATC

SOIL COMPACTION

AIDS WATER PENETRATION

LUBRICATES SOIL PARTICLES

SOIL COMPACTION IS SPEEDED BY ADDING ONE-FOUR GALLONS OF TERRA-KRETE ATC PER 1000 GALLONS OF WATER IN THE NORMAL WATERING PROCEDURE. THE EXACT AMOUNT TO BE USED DEPENDS ON THE EXACT NATURE OF THE SOIL.

PROCTOR COMPACTION READINGS CAN BE RAISED TO THE REQUIRED LEVEL ON FINISHED SUB-GRADES BY ADDITION OF TERRA-KRETE ATC TO THE SURFACE FROM A WATER TRUCK AND REROLLING. REWORKING THE SOIL IS NOT NECESSARY.

TERRA-KRETE ATC IS NON-TOXIC AND NON-FLAMMABLE AND IT IS EASY TO CLEAN UP. TERRA-KRETE ATC IS PACKAGED IN STANDARD 55 GALLON STEEL DRUMS.

TERRA-KRETE ATC & TERRA-KRETE CEM ARE MANUFACTURED UNDER ONE OR MORE CLAIMS OF US PATENT #3,943,078, AND ADDITIONAL US AND INTERNATIONAL PATENTS PENDING.

For further information regarding test data, costs, and application information, without obligation, contact:

KINGMAN CHEMICAL COMPANY
TERRA-KRETE DIVISION
1310 W. COLLINS, ORANGE, CALIFORNIA 92667
(714) 639 9904

Terra-Krete CEM

SOIL CEMENTATION

MAKE

ROADS

PARKING LOTS

RUNWAYS

PONDS

FROM NATIVE SOIL

APPLY ONE GALLON TO 20 - 50 SQUARE FEET.

FOR SOIL CEMENTATION APPLICATIONS, THE SOIL IS FIRST SCARIFIED AND BROUGHT TO BELOW OPTIMUM WATER LEVEL BY EVAPORATION. THE REQUIRED AMOUNT OF TERRA KRETE CEM IS APPLIED FROM THE WATER TRUCK WITH SUFFICIENT WATER TO BRING UP THE SOIL TO OPTIMUM FOR COMPACTION. AFTER DRYING, THE SURFACE MAY BE COATED WITH A SEALER OR IT MAY BE PAVED WITH ASPHALT FOR HEAVIER TRAFFIC.

TO PREVENT WATER PERCOLATION, PONDS MUST BE SEALED WITH EITHER A BLACK ASPHALT EMULSION OR TRANSPARENT TERRA KRETE NPS FOR NATURAL LOOKING DECORATIVE PONDS.

FOR SPECIFIC APPLICATION INSTRUCTIONS, PLEASE SEE OUR DETAILED LITERATURE.

KINGMAN CHEMICAL COMPANY
TERRA-KRETE DIVISI
1310 W. COLLINS, ORANGE, CALIFORNIA 92667
(714) 639 9

PHYSICAL PROPERTIES OF TERRA-KRETE CEM

PH	3.2
SOLIDS	48 %
WEIGHT PER GALLON	8.8 lbs.
VISCOSITY (Krepp Units)	66
TOXICITY	NON-TOXIC
COLOR	LIGHT GREEN
ODOR	ODORLESS
COMBUSTION	NON FLAMMABL

TERRA KRETE IS NOT AN OIL DERIVATIVE. IT CONTAINS NO OIL/ PETROCHEMICALS.

For more information please call Kingman Chemical Co., or your local dealer.

Specialists in high polymers
POLYVINYL CHEMICAL INDUSTRIES
730 Main Street, Wilmington, Mass. 01887   Europe: Polyvinyl Chemie Holland, N. V., Waalwijk, Netherlands

BULLETIN 601A

PHYSICAL PROPERTIES

TYPICAL EMULSION PROPERTIES

Appearance	Milky white
Non-volatile content	32% ± 1
pH	7.5-8.0
Viscosity, 25°C., cps	100
Freeze-Thaw stability	Keep from freezing
Density, 25°C., lbs./gal.	8.4

TYPICAL FILM PROPERTIES

Hardness, Sward, air dry, 24 hrs.	18
" , 15 min./140°F.	34
Hardness, Pencil, air dry, 24 hrs.	4B
" , 15 min./140°F.	HB
60° gloss	
clear	91
6% PVC	75
12% PVC	60
20% PVC	40
35% PVC	25
Impact resistance, in.-lb.	
direct, (pass/fail)	12/16
reverse, (pass/fail)	0/4
Flexibility, 1/8" cylindrical mandrel	no cracking
U.V. Resistance	
200 hr. Fadeometer	no discoloration

CROSSLINKING

Certain applications may require an increase in the resistance of A-601 coatings to solvent, plasticizer migration, or other chemicals. Wood finishes requiring maximum alcohol resistance, paper coatings needing higher paint solvent resistance, vinyl coatings requiring washability and resistance to migrating plasticizer, and concrete sealers specifying high oil and gasoline resistance are illustrative cases.

Addition of an amino resin to Neocryl A-601 based coatings will produce a stable one-part system which will crosslink on heating to provide increased toughness and solvent resistance. The following starting point formulation will cure in five minutes at 150°C. Variation in the curing agent and/or catalyst level may optimize film properties and/or curing rate.

technical information

Specialists in high polymers

POLYVINYL CHEMICAL INDUSTRIES

730 Main Street, Wilmington, Mass. 01887 · Europe: Polyvinyl Chemie Holland, N. V., Waalwijk, Netherlands

BULLETIN 601A

NEOCRYL A-601

WATER-BASED POLYMER FOR INDUSTRIAL FINISHES

Neocryl A-601 is an acrylic emulsion with exceptional leveling, fast drying, and rapid film hardness development. These are characteristics not normally found in products of this type. Air dried films are clear, tough, glossy, and show superior adhesion to many substrates such as wood, plastics, paper, concrete, steel, anodized or chromate treated aluminum. Films exhibit excellent abrasion, water, sunlight and weathering resistance. Clear films of Neocryl A-601 coated on aluminum and bonderized steel show excellent retention of gloss, adhesion and integrity after more than 12 months outdoor exposure. Neocryl A-601 shows unusual resistance to discoloration at higher temperatures and can be pigmented, thickened, or flattened to meet your specific application requirements. Neocryl A-601 can be formulated into primers or rich high-gloss coatings. These coatings can be applied by spray, dip, roller coat or flow coat using existing equipment. The emulsion is designed to be used in most applications without crosslinking. However, to enhance chemical resistance and toughness, it may be heat crosslinked with amino resins or for air dry or low tempearture cure applications with experimental crosslinker CX-100. Laboratory tests indicate that coatings formulated with Neocryl A-601 offer the following properties and advantages:

- extremely fast development of hardness and toughness with only air drying or force drying at low temperature. (similar to solvent based air dry lacquers)
- exceptional water and detergent resistance
- excellent adhesion to wood, metal, paper and a wide variety of plastics
- good compatatibility and formulating latitude with a wide variety of pigments
- ease of application with existing spray, dip, roll or flow coat equipment
- excellent mechanical stability
- non-polluting and eliminates use of expensive and hazardous solvents

textile
chemicals
technical
bulletin

Textile and Paper Chemicals Department
Rohm and Haas Company

RHOPLEX® HA-8 • RHOPLEX HA-12 RHOPLEX HA-16

Rhoplex HA-8, Rhoplex HA-12, and Rhoplex HA-16 emulsions are a series of nonionic, self-crosslinking acrylic polymers. These water-based products vary in the hardness of the films they form, and can be used in a wide variety of applications. By being mutually compatible, they can be blended to achieve any intermediate effect or property desired.

Characterized by ease of formulation, resistance to discoloration on exposure to ultraviolet light and ageing, excellent pigment binding properties, and durability to washing and drycleaning, Rhoplex HA-8, Rhoplex HA-12, and Rhoplex HA-16 are recommended for fabric finishing, bonding nonwovens, fabric backcoating, and as adhesives for lamination and fiber flocking. As self-crosslinking polymers, they do not require the addition of a nitrogenous or other external crosslinking agent. Their rate of crosslinking can be increased by the addition of an acid or latent acid catalyst.

TYPICAL PROPERTIES

	Rhoplex HA-8	Rhoplex HA-12	Rhoplex HA-16
Appearance	Milky-white liquid	Milky-white liquid	Milky-white liquid
Film characteristics	Soft, tacky	Firm, tack free	Hard
Solids content	45.5%	45%	45.5%
Emulsifying system	Nonionic	Nonionic	Nonionic
pH (as packed)	3.0	3.0	2.9
Density at 25°C.	8.7 lb./gal.	8.8 lb./gal.	8.8 lb./gal.
Specific gravity at 25°C.	1.05	1.06	1.06
T_{300}*	−14°C.	+17°C.	+33°C.
Minimum film formation temperature	<0°C.	+5°C.	+22°C.
Brookfield Viscosity at 25°C. (as packed)	550[a]	550[a]	600[b]
Storage	Protect from freezing	Protect from freezing	Protect from freezing

*T_{300} – Temperature at which the torsional modulus of an air-dried film is 300 kg/cm.^{2}; a relative parameter of film stiffness.

[a] #3 spindle, 60 rpm. [b] #3 spindle, 30 rpm.

CATALYSIS

Since Rhoplex HA-8, Rhoplex HA-12, and Rhoplex HA-16 emulsions are self-crosslinking, a catalyst is not needed to achieve durability to washing and drycleaning. Self-reactive sites are built into these resins which will crosslink with time and heat. However, to increase this rate of crosslinking and to obtain maximum durability under less than optimal conditions, an acid or latent acid catalyst is recommended. Table I lists the catalysts and concentrations recommended with these Rhoplex emulsions.

TABLE I — CATALYST CONCENTRATIONS

Catalyst	Concentration (solid product on total weight of formulation)
Oxalic acid	0.1%
Diammonium hydrogen phosphate	1.0%
Ammonium nitrate[1]	0.5%

When Rhoplex HA-16 is used in the spray bonding of polyester fiberfill, 0.1 percent (instead of 0.5 percent) ammonium nitrate is recommended.

The amount of time and temperature needed to dry and cure a fabric finished with Rhoplex HA-8, Rhoplex HA-12, or Rhoplex HA-16 is dependent on a large number of factors such as fabric, fabric structure, and specific formulation as well as the type of equipment used, and is best determined under actual operating conditions. In some cases, equal durability can be achieved at slightly shorter times and/or lower temperatures using ammonium nitrate instead of diammonium hydrogen phosphate (DAP) as a catalyst. With oxalic acid, temperature can be lowered (compared to that needed with DAP) about 20 degrees and, in some instances, time also reduced. Without a catalyst, an additional 20 degrees, over that required with DAP, is needed.

Oxalic Acid—This catalyst is the strongest of those listed in Table I, and is especially recommended for use with the Rhoplex emulsions when curing conditions are marginal. At the specified concentration, oxalic acid provides excellent catalysis without injury to the fabric. This catalyst should be added from a 10 percent aqueous solution and used with a neutral thickener such as Methocel MC Standard 4000 cps. or Methocel J 12-HS.[2] The pot life of oxalic acid catalyzed mixes is usually 3 to 5 days.

Diammonium Hydrogen Phosphate—Diammonium hydrogen phosphate is a latent acid catalyst that can effectively be used to crosslink the Rhoplex emulsions. It is especially recommended when Acrysol® ASE-60 and Acrysol ASE-95[3] thickeners are used, because it buffers these products at pH 6.5 and thus raises the viscosity. The DAP should be added very slowly to the formulation after the Acrysol products, from a 25 percent aqueous solution. Most formulations containing DAP as a catalyst have a pot life that exceeds 90 days.

Ammonium Nitrate — Ammonium nitrate, like DAP, is a latent acid catalyst. When this catalyst is used with the Acrysol thickeners, ammonium hydroxide is needed to raise the pH of the mix. Ammonium nitrate should be added from a 25 percent aqueous solution. The pot life of mixes with ammonium nitrate is usually over 30 days.

Thermosetting Resins

Although a thermosetting resin is not needed with Rhoplex HA-8, Rhoplex HA-12, or Rhoplex HA-16 because they are self-crosslinking, its addition to a formulation (with or without catalyst) will reduce the minimum curing temperature about 25 F. This reduction is especially helpful when curing conditions are minimal.

Recommended additives are Uformite® MM-83[4] resin, Aerotex Resin M-3[5], Valmel 40[6] and Perma Set 1300[7]. Approximately 5 percent resin solids on Rhoplex emulsion solids should be used; higher concentrations will not further depress the curing temperature and can stiffen the adhesive.

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[1] Rohm and Haas Company, Philadelphia, Pa.

[2] The Dow Chemical Company, Midland, Michigan.

[3] Rohm and Haas Company, Philadelphia, Pa.

[4] Rohm and Haas Company, Philadelphia, Pa.

[5] American Cyanamid Company, New York, New York

[6] Valchem, Chemical Division of United Merchants & Manufacturers, Inc., New York, New York.

[7] Refined Onyx Division, Millmaster Onyx Corporation, Lyndhurst, New Jersey.

VITA

Razi Ahmad Siddiqi

Candidate for the Degree of

Doctor of Philosophy

Thesis: COST, EFFECTIVENESS AND UTILITY OF POLYMER SOIL STABILIZERS

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Lucknow, India, August 15, 1947, the son of Mr. and Mrs. Mohammed Sami Siddiqi.

Education: Graduated from Aligarh Muslim University, Aligarh, India, with the degree of Bachelor of Science in Civil Engineering in August 1968; attended graduate school at the University of Roorkee, Roorkee, India, between 1969 and 1971 and received the Degree of Master of Engineering in Highways; attended Polytechnic Institute of New York, New York, between 1973 and 1974 and received the Master of Science degree in Transportation Engineering and Planning; enrolled in the doctoral program in the School of Civil Engineering, Oklahoma State University in 1974; completed requirements for the degree of Doctor of Philosophy in July, 1978.

Professional Experience: Worked as Apprentice Engineer for the R. K. Mission Constructions, Lucknow, from September, 1968, to July, 1969; as Associate Lecturer at Mulana Azad College of Technology, Bhopal, India, in 1971-1972; and as Teaching and Research Associate at Oklahoma State University, 1974 to 1978.

Professional Organizations: Associate Member of the American Society of Civil Engineers; Associate Member of the American Society of University Professors; Member of Chi Epsilon.