ARIZONA DEPARTMENT OF TRANSPORTATION

SOIL EROSION AND DUST CONTROL ON ARIZONA HIGHWAYS

Part I State of the Art Review

Report: ADOT-RS-10-141-I

Prepared by:
Dr. Hassan A. Sultan and Peter Fleming, C.E. Dept.
Arizona Transportation & Traffic Institute
College of Engineering
The University of Arizona
Tucson, Arizona 85721

October 1974

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007

in cooperation with

The U.S. Department of Transportation
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INTERIM FINAL REPORT

SOIL EROSION AND DUST CONTROL ON ARIZONA HIGHWAYS

by

HASSAN A. SULTAN
and
PETER FLEMING

Submitted to

The Arizona Department of Transportation
Highways Division
Phoenix, Arizona 85007

for

Research Project - Arizona HPR-1-10(141)

Sponsored by

The Arizona Department of Transporation

in Cooperation with

The U.S. Department of Transportation

Federal Highway Administration

Arizona Transportation and Traffic Institute
College of Engineering
The University of Arizona
Tucson, Arizona 85721

November, 1974

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-AZ-RD-72-141-I		

4. Title and Subtitle Soil Erosion and Dust Control on Arizona Highways Interim Final Report. Part I State-of-the-Art Review	5. Report Date October, 1974 6. Performing Organization Code
7. Author(s) Hassan A. Sultan, Ph.D.	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Arizona Arizona Transportation and Traffic Institute Tucson, AZ 85721	10. Work Unit No. (TRAIS) 11. Contract or Grant No. HPR-1-10-141 72-29
12. Sponsoring Agency Name and Address Arizona Department of Transportation 206 South 17th Avenue Phoenix, AZ 85007	13. Type of Report and Period Covered Interim Final, Part I December 72 to November 74 14. Sponsoring Agency Code

15. Supplementary Notes

In cooperation with U. S. Department of Transportation, Federal Highway Administration.

16. Abstract

This report represents a comprehensive literature survey illustrating the state-of-the-art regarding soil erosion due to wind, rain, and traffic forces. The report treats each of these factors individually. Each section starts by an understanding of the mechanics of erosion, then proceeds with methods utilized to control erosion with emphasis on chemical stabilization with a detailed review of the available chemical agents and their effectiveness in erosion control. At the conclusion of each section is a summary listing of all the chemical stabilizers that have been reportedly used along with performance ratings given these chemicals in the reviewed references. These ratings were based on observations in both laboratory and field studies. Each section contains a listing of major references consulted.

17. Key Words	18. Distribution Statement
Erosion Control, State-of-the-Art, Chemical Stabilization Rain Erosion, Wind Erosion, Traffic Erosion.	No Restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	132	

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SOIL EROSION AND DUST CONTROL ON ARIZONA HIGHWAYS

PROJECT INTRODUCTION

PROJECT INTRODUCTION

Statement of the Problem

One problem associated with the potential of the arid and semi-arid climate soils to erode is the movement of cohesionless sandy soils due to wind erosion and the development of sand storms and high levels of dust particulates. These dust storms have been the cause of numerous recent chain car accidents on Arizona highways due to the severe reduction in visibility during such storms.

In addition, the unpaved "gravel" secondary road has been a continuous item on the maintenance budget because of the need for periodic grading and replacement of material lost through erosion by traffic. Experience and road studies indicate that annual losses of road material can reach about 200 cubic yards per mile for unpaved roads. In addition to these gravel losses, the loss of air-borne silt and clay size particulates was estimated to the order of 5 to 50 grams per vehicular mile. With a traffic volume of 250 vehicles per day the dust pollution may amount to 0.5 to 5 tons of air-borne particulates per mile per year.

As we are becoming increasingly aware, the above mentioned problems have already posed severe safety, health, and public relations problems and are expected to continue unless positive measures for erosion control are developed and implemented.

Objectives of the Study

The specific aims of the study are to search for, determine, and identify those stabilizing agents that are best capable of controlling soil erosion due to wind and traffic forces and providing positive dust control measures. These selected stabilizers shall be economical, easy to apply in the field, and durable to withstand various environmental conditions.

The ultimate objective of this investigation is the development and implementation of low cost soil stabilization techniques that will provide positive dust control measures and will result in better specifications for the construction of erosion-resistant roads and for the protection and maintenance of existing erodible secondary roads.

REPORT OUTLINE

This project started on December 6, 1972; the currently approved completion date is November 6, 1975. Due to the length of the investigation and the different phases of the work, it has been agreed upon to submit interim final reports covering completed phases of the study.

The results of this study will be presented in the following arrangement as presented hereinafter:

1. Interim Final Report - Part I: This interim final report covers the completed comprehensive literature survey of the state-of-the-art pertaining to the basic parameters affecting soil erosion and the most acceptable soil erosion control and prevention techniques. A detailed review of previous work done on the use of chemical stabilizers for the control of wind erosion, water-rain erosion, and traffic erosion is included.
2. Interim Final Report - Part II: This interim final report presents the results of the completed laboratory testing program. The report covers the criteria for selection of chemical stabilizers, the types of soils used in the laboratory, along with different tests conducted for dust control studies and traffic erosion control studies. The results of the laboratory studies are also presented.
3. Summary Progress Report - Field Tests: Based on the results of the laboratory studies, several chemical stabilizers were selected for application in a full scale field evaluation program. The field tests included dust control studies on non-trafficable areas and traffic erosion studies on an unpaved road. The field program started in May 1974, and the progress report presents a summary of the available data from field monitoring until September 1974.
4. Final Report: At the completion of the project (November 1975), a final report will be presented giving a summary of the interim final reports along with the results of the completed field testing program. This final report completes the project.

INTERIM FINAL REPORT

SOIL EROSION AND DUST CONTROL ON ARIZONA HIGHWAYS

PART I - STATE-OF-THE-ART REVIEW

by

Hassan A. Sultan

and

Peter Fleming

ACKNOWLEDGEMENTS

The writers wish to thank Mr. Gene R. Morris and Mr. Benjamin W. Ong of the Arizona Department of Transportation and Mr. John Porco and Mr. R.E. Mullens of the Federal Highway Administration for their fine cooperation during the conduct of this study.

Sincere appreciation is due to the many authors who forwarded their publications when requested for inclusion in this review.

The excellent work of Mrs. Ellen LaMotte and Mrs. Vicki Gettel in typing the manuscript is apparent and appreciated.

ABSTRACT

This report represents a comprehensive literature survey illustrating the state-of-the-art regarding soil erosion due to wind, rain, and traffic forces. The report treats each of these factors individually. Each section starts by an understanding of the mechanics of erosion, then proceeds with methods utilized to control erosion with emphasis on chemical stabilization with a detailed review of the available chemical agents and their effectiveness in erosion control. At the conclusion of each section is a summary listing of all the chemical stabilizers that have been reportedly used along with performance ratings given these chemicals in the reviewed references. These ratings were based on observations in both laboratory and field studies. Each section contains a listing of major references consulted.

KEY WORDS: Erosion Control, State-of-the-Art, Chemical Stabilization, Rain Erosion, Wind Erosion, Traffic Erosion.

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SECTION A

SOIL EROSION DUE TO WIND

CHAPTER 1

MECHANICS OF WIND EROSION

In arid areas where high winds and fine-grained unconsolidated soils occur together, soil erosion by wind is a major problem. Wherever the soil is bare and finely divided, the surface of the ground is loose and dry and the wind is strong, erosion may be expected. The most dangerous seasons in North America are late winter and early spring, while the wind usually blows the strongest; the land is clothed with the least vegetation and the soil is most susceptible to movement by winds.[7] The usual problems encountered with wind erosion are listed below:

Problems caused by Wind Erosion

1. Serious erosion of fills, necessitating reconstruction.[29]
2. Dust storms pollute the atmosphere - as much as 1,290 tons of per cubic mile have been recorded.[40]
3. Animals suffer from excessive dust and may die from dust suffocation.[40]
4. Damage to highway structures.[29]
5. Damage to signs and vehicles due to sand blasting by strong winds.[18]
6. Safety hazards created by serious reduction of visibility caused by blowing sand and dust.[25]
7. Insects and weed seeds are spread great distances by wind-blown soils.[40]
8. Air transportation is adversely affected.[4]

Since erosion by wind is a natural phenomena and since observations would require too many hours of surveillance, the utilization of laboratory wind tunnels can be used to simulate field conditions. By using this type of simulation in the laboratory, soil erosion equations can be derived.

Soil erosion by wind can be classified as a cycle.[35] This cycle is illustrated in Figure A-1.

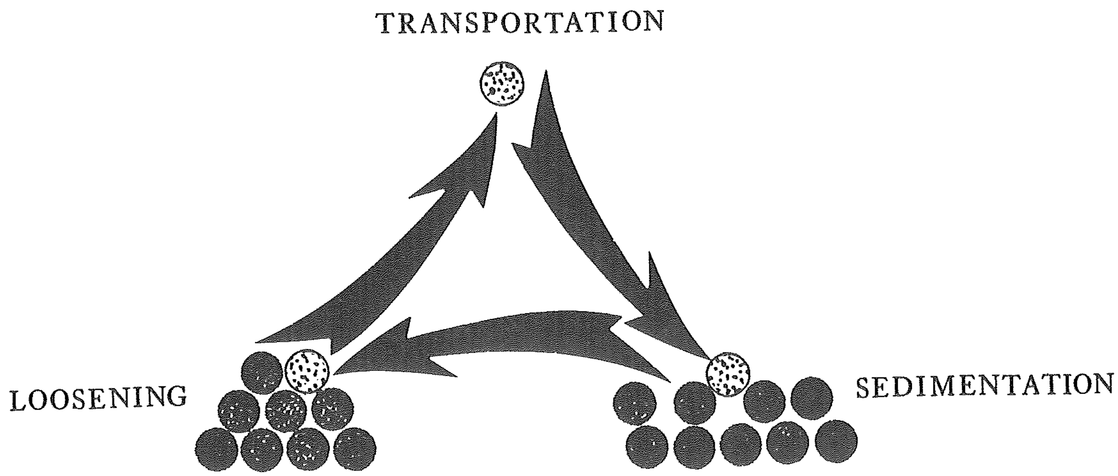

FIGURE A-1: EROSION CYCLE

Detachment Phase

The process of loosening or denudation is attributed to the following: (1) Freezing and thawing, (2) Wetting and drying, (3) Animals and pedestrians, (4) Cultivation, and (5) Beating raindrops.

Once a particle has been loosened, the next phase is to initiate movement. Naturally, movement will begin with the most exposed particle on the surface.[35] These particles fall in the range of 0.1 to 0.5 millimeters in diameter. Since friction slows down the wind near the surface, particles smaller than 0.1 millimeters in diameter do not protrude enough to be moved by the wind, while particles greater than 0.5 millimeters in diameter extend sufficiently above the surface enough to be moved by it; however, since their weight is too great compared to other particles only a small spin occurs. The change between velocity and distance above the surface is illustrated diagramatically in Figure A-2.[12]

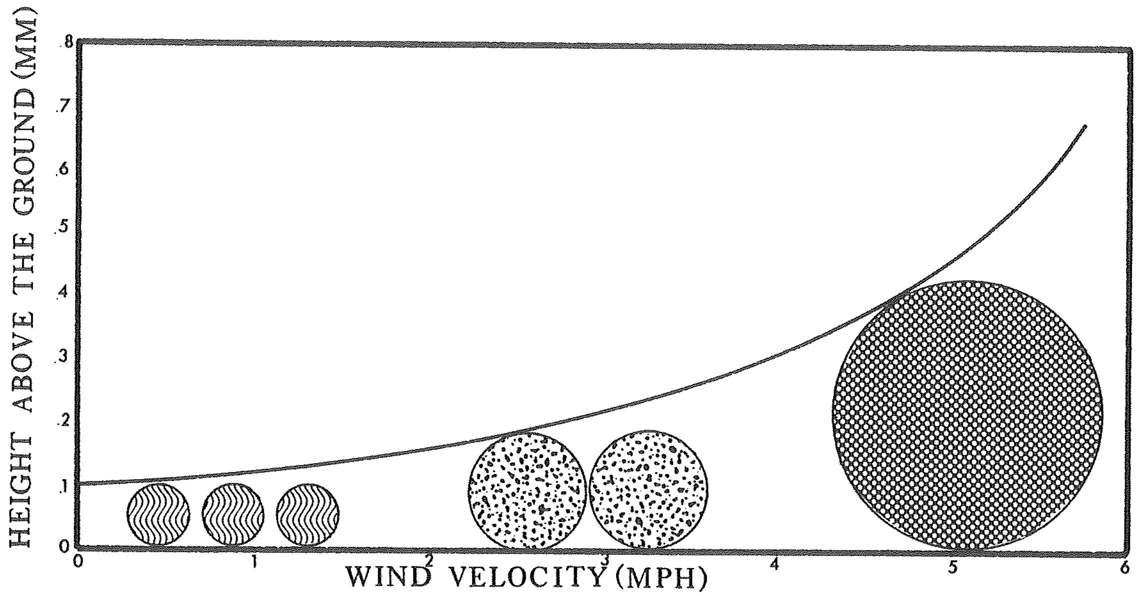

FIGURE A-2: WIND VELOCITY VS. HEIGHT ABOVE THE GROUND

Transportation Phase

Once initiation of movement is completed the next step is the transportation of the particles. Transportation of particles due to wind consists of three types: (1) Saltation, (2) Suspension, and (3) Surface creep.[41]

Saltation

Particles ranging between 0.1 and 0.5 millimeters in diameter are the ones affected by this type of transportation. Saltation constitutes the greatest movement in all cases. If we did not have saltation, very little erosion would take place. As was mentioned previously, the wind velocity at the very surface is practically zero, while at a very small fraction of a millimeter above the ground the wind velocity may be quite considerable. Because of this, the soil receives a much greater impact on the top than on the bottom, consequently a spin is produced. This is illustrated in Figure A-3.[2]

These particles can spin at very large speeds; 200 to 1,000 revolutions per second have been recorded. The top of the particle moves at a greater speed than the wind, so basically there are two components

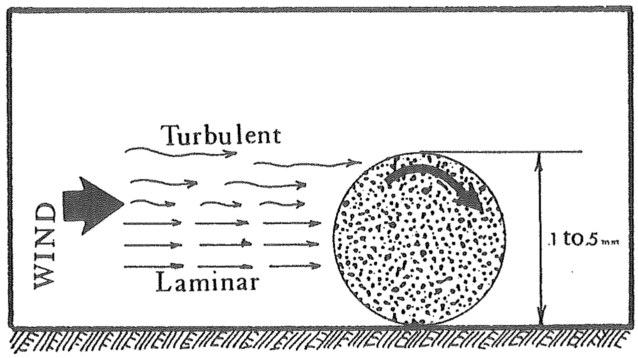

FIGURE A-3: EFFECT OF TURBULENCE ON SALTATING PARTICLES

acting upon the particle: (a) The horizontal force due to the wind and (b) the spining of the particle.

According to Bernoulli's theorem, a partial vacuum is created above the particle, while the air is compressed below it. This difference in pressure causes the particle to shoot straight into the air. The particle rises at an angle between 75° and 90°.[5] The particles usually rise from 6 to 12 inches in height, but depending on the initial velocity of take off the particle may even rise to a few feet. The height of rise is directly related to the horizontal length of grain path. The ratio is about 1:7 for a rise of 2 inches; 1:8 for a rise of 2 to 4 inches; 1:9 for 4 to 6 inches and 1:10 for heights above 6 inches.

Only particles ranging from 0.1 to 0.5 millimeters in diameter can be transported by saltation (jumping). Usually 90 to 98 percent of the particles in saltation are carried below one foot. A microscopic view of a saltating particle is illustrated in Figure A-4.[6]

As the particle is lifted the spinning slows down due to the encounter of substantially faster winds. This encounter causes the particle to gain considerable forward momentum. Since the upward impulse has been reduced, the particle begins to descend due to gravity. The angle at which the particle reaches the ground surface has been measured to be between 6 and 12 degrees. The higher a particle climbs the longer

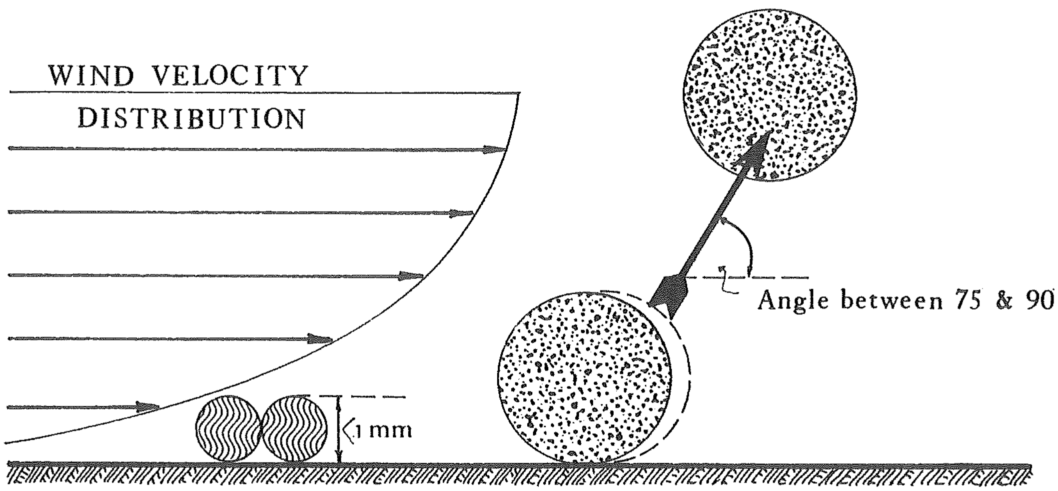

FIGURE A-4: ANGLE OF RISE FOR SALTATING PARTICLE

the average path will be. This was discussed before and is illustrated graphically in Figure A-5.[12]

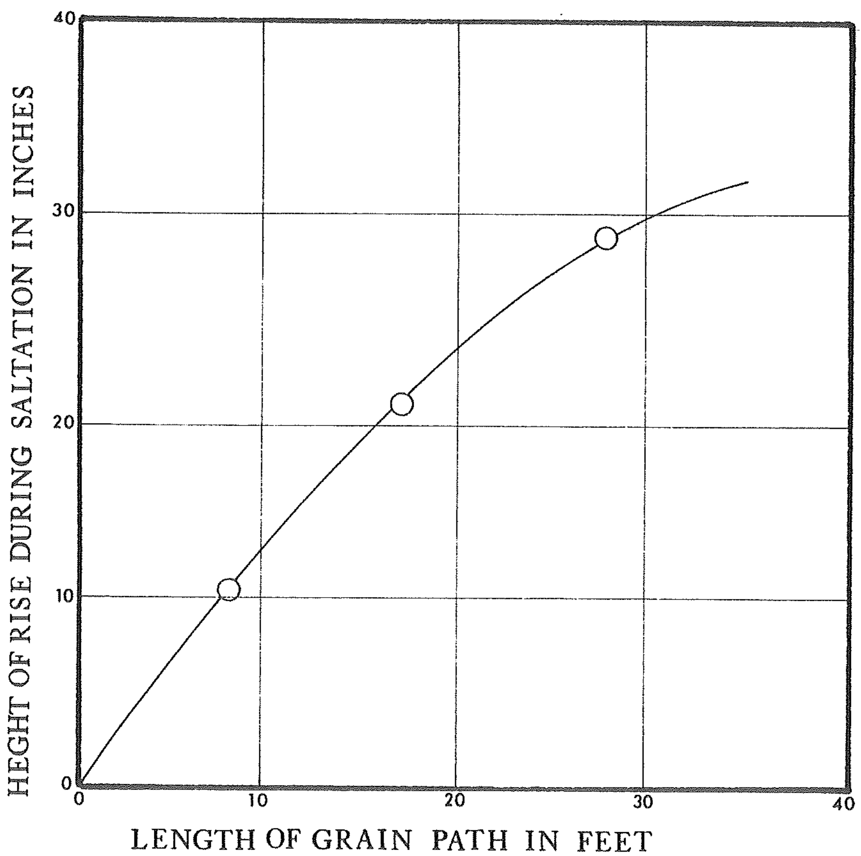

FIGURE A-5: HEIGHT OF RISE VS. LENGTH OF SALTATING GRAIN PATH

Atmospheric Suspension

Soil particles ranging in size from 0.1 millimeters in diameter or smaller are affected by atmospheric suspension movement. Suspension movement or dust clouds could not exist without the existence of saltating particles, except due to disturbance by vehicles, animals, etc. As the saltating particles drop down to the ground they cause the smaller particles to be kicked up, where the stronger winds aloft take over. Since these particles have relatively large surfaces compared to their weights they can stay in suspension. These particles may sometimes travel for several thousand miles before settling down to earth. The high resistance of the fine dust particles to movement by wind is to some degree due to cohesion among the particles. More particularly, their resistance is due to the fact that when the ground surface is thoroughly smoothed, the particles are too small to protrude above the viscous non-turbulent layer of air, known as the Laminar layer. It therefore takes the impact of the descending saltating particles to cause these small grains to enter into suspension.

Surface Creep

Soil particles larger than 0.5 millimeters in diameter are too heavy to be lifted off the ground by common winds.[7] Depending upon the intensity of the wind, these larger particles are pushed along the ground, rolling but not jumping. Saltating particles also contribute to surface creep. Upon descending, the saltating particle may strike a larger particle adding to the rolling motion. It may lose all its kinetic energy or may rebound into the atmosphere again. This situation is very similar to that of the action of billiard balls.

Particles larger than 3 millimeters in diameter cannot be moved by ordinary winds, except for tornadoes, hurricanes etc.

Table 1 shows the three types of transportation and the relative particle sizes affected by them.

The proportion of the three types of movement varies greatly for different soils. Between 50 and 75 percent of the weight of the soil is carried in saltation, 3 to 40 percent in suspension and 5 to 25 percent in surface creep.[2]

TABLE A-1: TYPES OF TRANSPORTATION AND DIAMETER SIZE

TYPE OF TRANSPORTATION	DIAMETER SIZE
ATMOSPHERIC SUSPENSION	Smaller Than 0.1 mm in diameter
SALTATION	0.1mm to 0.5mm
SURFACE CREEP	0.5mm to 3mm

The three mechanisms of transportation are illustrated in Figure A-6.

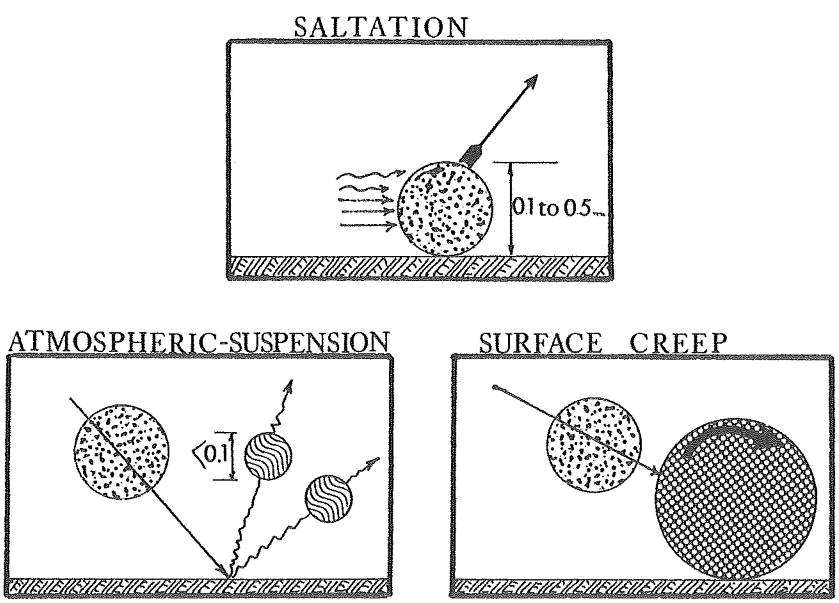

FIGURE A-6: TRANSPORTATION MECHANISMS

Sedimentation Phase

The last phase of the wind erosion cycle is that of sedimentation. Soils eroded by winds travel distances depending upon their weights, sizes and upon the wind intensity. The smallest and lightest particles of dust travel the farthest, usually very far from their original location. These small particles finally settle down when the wind subsides or when it rains. They may also settle if they hit upon some object in their path. Usually in arid and semi-arid regions these dust collectors are small plants which eventually take the form of small mounds or dunes.

CHAPTER 2

METHODS TO CONTROL WIND EROSION

Soil erosion by wind can cause a variety of damages.[40] A few of these have been mentioned in the earlier part of this section. The finest and most valuable part of the soil, such as the silts, clays and organic matter are moved to great distances, leaving the farm land coarse, textured and less fertile.

For many years man has been searching for methods to control erosion. It is a known fact that the reduction of vegetation is a major cause of wind erosion. For this reason man began to control the abrasive action of winds upon the land by planting cover crops. These are crops planted solely to control erosion. Winter and spring wheat, rye, oats, winter peas are a few that have been used successfully.[17] Cover crops are primarily used in areas where water is plentiful[7] and, therefore, it is not a practical solution for arid regions. The planting of large trees to form windbreakers was proven to be more effective. The trees slow down the velocity of the wind and maintain the soil moisture on the leeward side. If the soil is moist, the adhesion between the particles is much greater and, therefore, erosion due to wind is substantially reduced. The use of water is one form of wind erosion control. The sketch in Figure A-7 shows the use of trees for wind erosion control.

This process of planting trees for year-round protection of the soil, and conservation of soil moisture is known as stubble mulching.[40]

Other long term solutions used to control erosion due to winds are stripcropping, crop rotation, deep plowing, sand fencing, gravel blankets, etc., but these are beyond the scope of this report. Construction projects usually are considered short term jobs, so there is no time to start planting crops and consequently other means of control are required.

Since about 10 million acres of land in the United Stated are affected by wind erosion the problem of preventing excessive dust

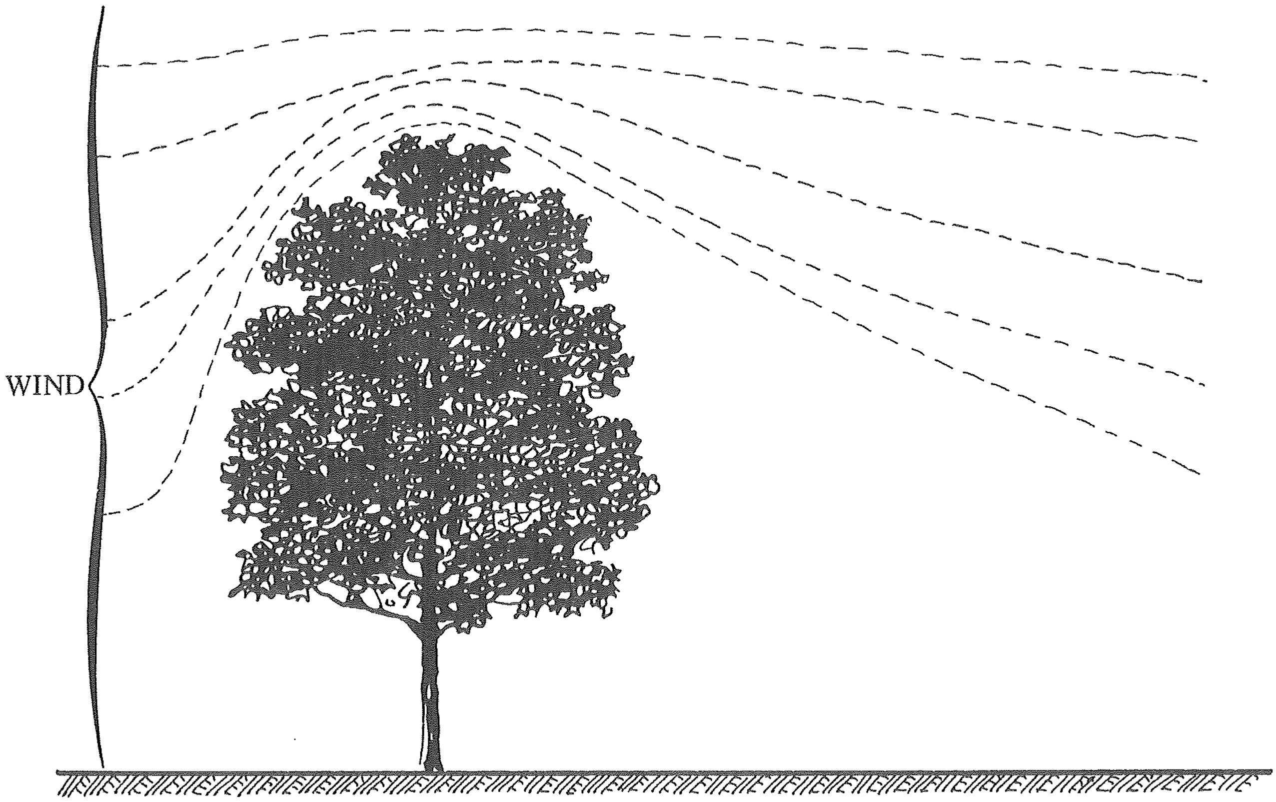

FIGURE A-7: WINDBREAKER

conditions during dry periods has led to the investigation of materials and methods for chemical soil stabilization and dustproofing of soils. The term "chemical soil stabilization" is used to describe any method whereby the engineering properties of natural soils are improved by the chemical, or physico-chemical interaction between the admixture and the soil and includes the use of such general materials as: (a) inorganic salts, (b) inorganic cementing materials, (c) bituminous materials, (d) resinous materials, and (e) polymeric materials. The desired stabilizing effect may be obtained by bonding, dustproofing or otherwise modifying the natural soil in such a manner that the resulting mixture will withstand the detrimental forces of weather, moisture and traffic. Dustproofing primarily deals with maintaining a naturally stable or stabilized soil at its optimum stability conditions. The benefit of additional bonding action and increase in strength would be highly beneficial,but it is not the primary objective. The materials to be used as dustproofing agents must be durable enough to prevent loss of effectiveness under expected traffic and weather exposure conditions. It is of great importance to allow the treated soil to be cured prior to its being subjected to exposure. The usual methods recommended for curing treated soils in the laboratory are: (a) moist curing (b) oven-drying to constant weight at a temperature not exceeding 140°F (c) air-drying to constant weight and (d) partially drying to a predetermined moisture content. All of the above methods have been used at one time or another; however, the best types are moist-curing and air-drying, primarily because these resemble more closely the actual field conditions.

In the following chapter all the encountered major chemical stabilizers and dustproofers are discussed along with their advantages and disadvantages.

Soil Loss Equation

The relationship between annual soil loss by wind erosion from a given field have been tabulated in many references. One such equation which is used by the Soil Conservation Service is given below.[40]

$$E = f(I', K', C', L', V') \text{ where}$$

E = The average annual soil loss in tons per acre.

I' = Is the soil erodibility index, indicated by soil aggregates greater than 0.84 mm in diameter and percentage of land slope.

C' = Is the climatic factor indicated by wind velocity and surface soil moisture.

K' = The soil surface roughness.

L' = Is the unsheltered field width measured along the direction of the prevailing wind.

V' = Is the vegetative cover.

This equation is a highly useful tool in determining potential wind erosion on any field under existing conditions, and determining conditions of surface roughness, soil cloddiness, vegetative cover, sheltering necessary to reduce wind erosion to a tolerable amount.

Many charts and tables are available for solving this equation. The best are found in the Agricultural Handbook No. 346.[1]

CHAPTER 3

CHEMICALS TESTED BY VARIOUS INVESTIGATORS

During the years from 1956[33] to 1959[34] the U.S. Army Corps of Engineers, Waterways Experiment Station at Vicksburg, Mississippi, conducted tests on different materials as dustproofing agents. A major problem that was encountered was the inability to simulate good field conditions in the laboratory for testing the dustproofing materials, and, therefore, most of the tests were conducted in the field.

One of the most common types of dust palliatives used for granular soils is the salt-type additive, such as calcium chloride. Calcium chloride tends to maintain in the soil a moisture content that not only acts as a dust palliative but also tends to have a beneficial effect on the stability of the soil itself.[24] When calcium chloride is added to the soil, a base-exchange occurs, which has the effect of reducing the thickness of water film around the clay particle, thus facilitating compaction. The major disadvantage of calcium chloride is that in areas where frequent wetting and drying occur the calcium chloride is rapidly leached out leaving the soil unprotected. It should be mentioned that the laboratory results with calcium chloride were very poor while the field results were good.[30] The reason for this is attributed to lack of field simulation in the laboratory. Experiments reported in 1956 have shown that calcium chloride is ineffective as a dustproofing agent.[33] Sodium chloride is also used frequently basically because it reacts in the same fashion as the calcium chloride. In arid and semi-arid regions the use of calcium and sodium chlorides are widely used primarily because they are effective and because they are inexpensive.

Other simple salt-type additives such as barium chloride, copper sulfate, barium sulfate, aluminum sulfate, etc. have been evaluated and found to be ineffective.

From experimentation it was found that in arid regions, sodium silicate is a very good dustproofing agent.[33] Sodium silicate is a very good inorganic cementing material and is capable of bonding or hardening the soil. A 1-1/2 inch depth penetration treatment of 3.0 gsy of a 30% solution of sodium silicate satisfactorily dustproofed a fine grained clayey silt soil. After imposing a 2-1/2-ton moving load with 200 coverages, the surface showed no evidence of stress, cracking or abrasion.

Generally, sodium silicate is not a good stabilizing agent for fine grained soils; however, with the combination of strong inorganic salts such as calcium or sodium chlorides successful stabilization can occur. In this method the two chemicals are applied separately (usually by pressure injection) and react within the sand pores to form an impervious gel which upon hardening binds the sand particles into a solid mass. Sodium silicate alone will harden sandy soils only temporarily. For well graded sands, sodium silicate can be used as a dustproofing agent if the sand is compacted prior to application of the sodium silicate. In later years this mixture of sodium silicate and calcium chloride became known commercially as Soil-Lok.

From 1956 to the present day, experimentation with bituminous materials has been undertaken to find a successful dustproofer.[33] It is a well known fact that the primary function of bitumen in soil stabilization is that of imparting water-resistant characteristics to the resultant admixture; however, as a dustproofer, considerably more experimentation is required.

Bituminous substances consist almost entirely of carbon and hydrogen with very little oxygen, nitrogen, and sulphur. The most widely used bituminous materials in this country are the asphaltic bitumens. If these are diluted with solvents such as kerosene, gasoline or naphta then they are referred to as cutback asphalts. If they are emulsified in water, then they are referred to as emulsified asphalts.[20]

Experiments performed by the Corps of Engineers (reports of 1956,[33] 1959,[34] and 1967[28]) have all led to the conclusion that bituminous solvent systems are not very effective as dust palliatives.

Another very effective dustproofing resin experimented with by the Corps of Engineers in the arid regions of the southwestern United States was the Lignin Liquor.[3,18,33] Lignin is a resinous alkali waste liquor of the sulfite process found in the paper industry. Lignin is a bonding agent that showed very good waterproofing and dustproofing characteristics. By the application of hexavalent chromium compound the lignin liquor is changed into a gel which displays good bonding strength and good dustproofing abilities. Experiments with well graded sands and mixtures of 5% lignin to depth of 2 inches appeared to form a tough surface after curing. This surface was able to withstand traffic loads as well as weather conditions. The major problem with this material is that by the application of the chromium compound the resulting chrome-lignin is considered toxic and proper precautions must be exercised in order to eliminate this hazard.

There are many other resins available for soil stabilization and waterproofing, but not too many of them have proven to be very effective as dustproofers. Many of these resins are only presently being tested for their dustproofing abilities. Some of the more important resins are:[23] Amberlite PR-115 (Resorcinol-Formaldehyde Resin), Lauxite RF-901, Resinox L-9673 (Phenol-Formaldehyde Resin), Uformite CB-552, CB-553 (Urea-Formaldehyde Resin), Urac 185, Lauxite UF-77 and UF-101, Furfural Alcohol plus Sulfuric Acid, Calcium Acrylate Resin, Melamine-Formaldehyde, Resimene M75, Stymer Solution, Goodrite Resin 50 (Styrene Resin), among others. The effectiveness of these chemicals are given at the end of this section.

Polymeric materials have been used successfully as waterproofing agents, but experimentation is still continuing to determine their dustproofing abilities. Polymerization is defined as an intermolecular combination functionally capable of proceeding indefinitely. These materials will not be discussed in this section because their major success has been in waterproofing so they are considered in the second section of this report entitled, "Erosion Due to Rain".

The U.S. Army Engineers, Waterways Experiment Station along with the Western Company of North America at Vicksburg, Mississippi (1967)[18] have realized that customary construction materials such as concrete, asphalt, macadam, are not always available for dust control and soil stabilization, and are restricted due to specialized equipment, time, manpower availability, and type of soil. They decided to search for a simple process involving an additive that can be used on native soils, possibly diluted with indigenous water and applied with the available equipment. This new material had to pass the following requirements.[18]

1. Effective when applied at a rate of not more than three pounds per square yard.
2. Available in quantities sufficient to treat 500,000 square yards at a cost less than $2.00 per square yard, including cost of materials and placement.
3. Effective and operationally acceptable not more than four hours after placement.
4. Capable of being placed under temperatures ranging from 40° to 120°F and maximum humidity of 100%.
5. Capable to be effective when applied to all major soil types (sands, silts, clays) without extensive prior surface grading and/or other preconditioning.
6. Effective with only minor hand maintenance, for a minimum of six months.
7. Capable to withstand occasional traffic.

The Western Company had such a material which met most of the above requirements. This material was a special plasticized blend of polyvinyl resin. This material can be sprayed on the surface of the soil, cured within the required time and then form a tough resilient membrane which would be a good dustproofer.

The properties of the vinyl system appeared to fit most of the desired requirements before modification. Modification consisted of mixing many of the base materials together; addition of different additives, such as Portland Cement, silica flour, ethylene glycol, debutyl, etc. and varying the percentages of each.

Both laboratory and field experiments on this and other similar polyvinyl resins from other manufacturers were tested. The major products supplied by the Western Company were: Base 792-A, Base 792-B, Base 792-C, Base 792-D, Base 792-L, Base DPE, and Base 792-E. Other products tested which were supplied by other companies, such as UCAR 131 by Union Carbide Company,will be discussed in the latter part of this section.

In the laboratory, different types of soils were compacted into molds measuring 6-in. by 6-in by 3-in deep. After compaction of the samples, the dust-control-additives were applied to the soil. The sprayer used was a small aerating paint sprayer. The requirements mentioned were strictly adhered to while conducting the experiment. Upon the completion of the four hour curing phase, the samples were immediately put under the test of a power blower, which simulated wind velocities of 50 mph, 100 mph, and 150 mph, respectively.

In the field, soil samples were placed in one square yard wooden frames and sprayed with the chemicals. At the end of the field test, the best materials were tested on a large test plot. These new plots at the termination of the curing phase were subjected to some traffic.

From both the laboratory and field tests, the results had shown that of all the materials tested the best were Base 972-D and Base 972-L. These products performed best without the use of additives. Very good results occurred with a 50-50 mixture of Base 972-D and Base 972-L. This combination had been designated as HK-1. Another combination known as HK-2 is a 75-25 mixture. The properties of HK-2 are described below.[18]

HK-2 is an emulsified water phase, terpolymer blend of polyvinyl acetate, polyvinyl acrylates and internal plasticizers. This system is then further plasticized with an external plasticizer. HK-2 dries and cures to form a tough resilient film, whose curing time is dependent upon the temperature and humidity. The additives can be applied to soils without prior treatments. If the film is broken or ruptured under stress, it can easily be repaired by spraying more additives. Spraying of the additives can be accomplished with pressures of 80-120 psi. The surface film had been successfully subjected to wind velocities of 50, 100, and 150 mph before and after one hour of rainfall; also 20 hours later after drying at 120°F for one hour.

The only disadvantage of HK-2 is that with loose sands the required curing time may exceed seven hours and when humidity is high, curing time exceeds the allowable four hours; however, all in all it was judged a good dustproofing agent.

The other successful material tested, which was mentioned before was UCAR 131 manufacutred by Union Carbide. UCAR 131 became known in

1969 as DCA-70 when the U.S. Army Engineers Waterways Experiment Station at Vicksburg had retested this product.[4]

DCA-70 is a water emulsion of a polyvinyl acetate containing chemical modifiers. It is milky white in color with a slight odor similar to that of latex paint. The material cures within 2 to 4 hours and forms a clear flexible plastic film upon drying. In order to give more strength to this material, in 1969, addition of chopped fiberglass filaments as reinforcement were used with results indicating that after curing it formed a significantly stronger and tear-resistant membrane.

One of the major disadvantages of using the DCA-70 with fiberglass is that it is harmful if blown into the eyes or if it is inhaled, and may even cause skin irritation; however, with a few precautions this product can serve as a very good dustproofing agent for a vast variety of soils.

The price of DCA-70 is $2,816 per acre and $387.00 extra if the chopped fiberglass filaments are used. The DCA-70 with the fiberglass has an approximate life of 10 months while the DCA-70 alone, has an approximate life of one month. From experience it has been found that the DCA-70 plus fiberglass is the more economical choice between the two.

The need for a dustproofer which would be effective and operational within four hours after application on all soil types, was under investigation by the Ashland Chemical Company Research Department. The work was sponsored by the U.S. Army Corps of Engineers (1968) at Vicksburg, Mississippi.[19] The product would have to be able to withstand wind velocities of over 100 mph as well as would require very little maintenance. The need for dust control has become of greater importance, especially in air field areas. It has been observed that under normal weather conditions where dust is controlled, a helicopter rotor blade would have to be replaced after 1100 hours of operation; however, in areas where dust has not been controlled the rotor blade had to be replaced every 200 to 300 hours of operation.

In these experiments[19] three types of soils were used, sand, silt, and clay along with sixteen different resins. Samples, six inches by six inches in diameter were subjected to wind velocities of 150 mph for one minute. The materials which survived this test, without showing any signs of cracks were tested under wetting tests. The wetting test included a freeze-thaw test, a wet-dry test and a special 2-hour duration test. These tests will be discussed in detail in the water erosion section. The materials that had survived both tests were once again subjected to wind velocities of 150 mph. The resins used are listed below, along with their findings:

1. Epon 828: It is an epoxy resin produced by the Shell Chemical Company and has good penetration with sands and clays. The curing time is very slow (12-40 hours); however, the treated sand and silt specimens had good wind and water erosion resistance. The Epon 828 also withstood freeze-thaw and wet-dry cycling tests, without any noticeable changes. Upon curing Epon 828 formed a hard crust.
2. Coherex: It is an emulsified petroleum resin which had been used as a dust palliative for many years. Good penetration is obtained in clays. Coherex withstood only wind velocities of 60 mph and shrinkage cracks were formed on the surface. Coherex did not pass the water erosion test. Cost has been estimated approximately at $0.10 per square yard.
3. 15XPF Gelatin: When used with a formaldehyde catalyst it penetrated the sand and formed a hard flexible, but brittle layer. It passed a 60 mph wind test and water erosion test; however, the flexible layer was easily broken after the water test.
4. AM-9: It is a blend of water-soluble acrylamide and diacrylamide which polymerizes when properly catalized to give a void filling substance. AM-9 rapidly cures to a crumbly soft gel that continues to cure for a period of several days. Upon curing it forms a hard, strong composite.
5. Chem-Rez 200: This is a furfural based, rapid-setting resin which gives significantly higher strength than the aniline-furfural. This material performed very well with both wet and dry clays and sands. The material had passed the load test as well as the water test; however, when this resin was applied to sands and cured with phosphoric acid, the curing is extremely slow. The Chem-Rez 200 is not recommended as a waterproofer.

6. Aniline-Furfural: This material has been found to be an excellent dustproofer and waterproofer. This material is discussed in detail later on.
7. Emlon E-200: This is a water soluble resin, which cures in two hours or less with diethylene triamine which is also water soluble. Emlon E-200 has been found to perform well with sands and clays. It has passed the wind test, but eroded a little during the water test.
8. Sodium Silicate "N": The material was found to be very good with sands, especially because of its rapid curing. Curing time was less than one hour. Sodium Silicate "N" has passed all three tests in good to excellent condition. Upon curing it formed a hard composite.
9. Unsaturated Polyester Resin (Aropol 7510 N, Aropol 7720 N): Because of the very low cost of polyester (less than 25¢/lb. in bulk) and the ability to use low-cost reactive solvents such as (styrene - about 10¢/lb. in bulk) prompted extensive investigation of this material. It had penetrated all three types of soils (sand, silts, and clays) when the viscosity was reduced to essentially the same consistency as that of water. Its resistance to the wind test and water tests were excellent.
10. Water-Soluble Alkyds (Arlon 110, Arlon 310, Arlon 363, Arlon 580): These are resins with the unique advantage of reacting with oxygen in the air to produce a surface which becomes a dustproofer. The resin below the surface should remain in an uncured state to provide selfhealing properties if the skin is broken. Further experimentation is needed for these materials because as yet no definite conclusions are available.
11. Polyurethane Elastomer (Arothane 170, Arothane 160): The Arothane 160 performed very well with clays. It had also passed both the 150 mph wind test and water test.

The other six materials tested are only listed at the end of this section because at the present time no definite conclusive results are available, and further investigations were deemed warranted.

Bituminous materials with certain additives were tested by the U.S. Army Waterways Experiment Station in Vicksburg (1969)[4] with relatively good results. Some of these materials are listed below along with their descriptions.

1. APSB (Asphaltic Penetrative Soil Binder) or (Peneprime): This material is a special cutback asphalt composed of low penetration grade asphalt and a solvent blend of kerosene and naphta. It is produced by the Empire Petroleum Company in Denver. APSB is very similar in character to a standard low viscosity, MC asphalt. APSB is a soil penetrant which cures within 6 to 12 hours depending upon the temperature and weather conditions.

   When cured it forms a tough asphaltic film on the surface. It is especially suited for impervious or tight soils. The major problem with APSB is that it is flammable and may cause skin irritation due primarily to the solvent portion used. If JP-4 fuel or gasoline are used as diluting agents, special care must be utilized because of the explosive property of the material. The equipment necessary for applying the APSB are the same as those used for applying cutback and emulsion asphalts. Application of APSB for attaining the best results should be at an ambient temperature of 130° to 140°F and a surrounding temperature of 80°F or greater. APSB has been found to have an expected life range from 1 to 8 months depending upon the amount of traffic and upon the weather conditions. The average life has been estimated at 3-1/2 months. The cost of this material is $1,200 per acre per year, making this material the cheapest of the 1969 observations.

   In arid regions where soils are dry and usually have a very light coating of surface dust, the surface must be sprinkled lightly with water so that the APSB could penetrate the soil.

2. Polypropylene with Asphalt Emulsion: This is a prefabricated cotton-reinforced polypropylene fabric impregnated at the work site with an asphaltic emulsion. The rapid setting asphalt emulsions such as RS-2K, RS-1 and the slow setting

asphalt emulsions such as SS-K and SS-KH have worked successfully. The emulsions break on contact with the soil and then the polypropylene is unrolled on the asphalt to absorb it. Then a second application of the asphalt emulsion is applied to the polypropylene to form an asphalt impregnated membrane. Curing takes several days; however, curing time can be reduced with the application of a thin sand blanket. The surrounding temperatures should be above 80°F in order to attain the best results. The price of this material is $3,090 per acre per year, with an average expected service life of 10 months. Depending upon the traffic conditions and weather conditions, the service life may vary anywhere from 5 months to 25 months. Polypropylene with asphalt has been applied to a variety of soils with very good results.

Other asphalts have been tried, such as powdered asphalt. This is a dry finely pulverized asphalt with a kerosene solvent. After the 10 day curing period this material was found to be useless as a dustproofing agent.

Many other materials have been used for dust control. Some of these are road oils which include any type of petroleum derived substance such as a crankcase waste, bunker oil, crude oil, marine oil, motor oil, etc.[23] One medium grade oil called Dustrol is a liquid product, consisting of a blend of a distillate of medium volatility and a viscous, non-volatile, non-asphaltic petroleum base. Dustrol was tested by the Corps of Engineers as early as 1956 with successful results.[33] Most oils are absorbed by the soil to form a shallow treated layer. Oils do not cure but form a dense crust after repeated applications over a period of time. Oils are flammable and should be handled with extreme caution. If the oils are diluted with JP-4 fuel or gasoline extreme caution should be employed because of their explosive properties.[4]

The average price of oils is approximately $2,350 per acre per year. Oils have a very low expected service life, they range anywhere from a few days to 25 days depending on surface loading and weather conditions. The use of oils is only a little better than the use of water for control of wind erosion but are much more expensive.

The other types of materials used for dustproofing which received a great amount of research time and money are the resinous materials. Resinous materials are primarily used as bonding and/or waterproofing agents. However, it has been determined that the real good waterproofers are also good dustproofers.[22] One of the most prospective dustproofers is the resin formed by the reaction of aniline and furfural.[33,23,22] Since aniline and furfural begin the bonding reaction upon contact is is necessary to add the chemicals separately. Best results are attained when either of the following methods of application are employed: (a) The two chemicals added separately to the soil after the required mix water had been incorporated and (b) the two chemicals mixed with the dry soil first, and then the required mix-water added.

It has been determined that in order to achieve greatest resinification of aniline-furfural, samples should be air or oven dried rather than moist cured. The component aniline is considered toxic, thus breathing of the material and contact with it must be avoided. However, large quantities can be handled safely if certain precautions are adhered to. It has been found that a ratio of aniline to furfural of 70:30 applied in quantities of at least 2% by soil weight was particularly effective as a dustproofer with fine-grained, clay or silt soils. Several additives applied in quantities of 10% by weight of resin were also effective; some of these additives are (1) Potassium Dichromate (2) Ammonium Chloride (3) Copper Sulfate (4) Santo Resin (5) CRD 155 (resin emulsion) etc; however, out of all the additives tested during the experiments from 1956[33] to 1963[22] the 70:30 ratio of aniline to furfural was still the most effective.

In 1971 the State of California, Department of Public Works had tested sixteen different spray-on materials for controlling wind erosion.[29] The test area was in the community of Indio, where high wind velocities have been recorded and excessive amounts of dust had caused major problems to the local population.

The test plots to which the products were applied were on a slope of 2:1 (i.e. 26°), each test plot being 25 feet high and 15 feet wide and completely surrounded by a gravel blanket to prevent undercutting of the edges of the test plot by wind erosion. A total of 32 test plots were tested (two test plots for each material). The fill on which the test plots were located was a fine-grained rounded wind blown sand.

These sixteen spray-on materials had come on the market recently and were represented as being capable of controlling erosion. The test was conducted on the field for a 6-month period, and was compared to a non-treated identical plot. The sixteen spray-on materials along with their results are discussed below.

1. Aerospray 52: Aerospray is a white, viscous alkyd resin dispersed in water. It has no strong odors and is easy to handle and clean up. After treatment Aerospray 52 left a colorless thin hard crust. Performance of Aerospray 52 was not too satisfactory because the blowing sand had severely scoured the surface of the test plots and had locally cut through the crust. The cost of this material per acre is $819.00. This cost does not include shipping cost.
2. Aquatain: It is a liquid concentrate of water soluble chemicals and pectin. It is very easy to handle; however, because aquatain contains a green dye which facilitates the spraying; clean up operations become very difficult primarily because this dye stains skin, clothing and equipment. Aquatain has no strong odor and upon drying forms a thin fragile crust. Since blowing sand had completely abraided the crust and the wind had stripped most of the fine material, aquatain was judged as unsatisfactory as a wind erosion control agent. The price of aquatain is $550.00/acre.
3. Coherex: It is a brown stable, non-volatile emulsion of semi-liquid natural petroleum resin. It is very easy to use, but because of the oil base, clean up is slightly harder than with other products. It has no strong odor and instead of drying into a crust, it forms a flexible bond between the sand grains. Since the blowing sand had penetrated the surface, Coherex is not too good an agent. Coherex seems to weaken with time, therefore, for short jobs it may be suitable. The price is $287.28 per acre.

4. Conwed Fibers: This material has no odor and is easy to use and clean up. The initial mixing is rather time consuming because the wood fibers which are manufactured from white ash have to be added to the mixer gradually to assure proper mixing and prevent plugging of the pump. The fibers have a light green color which fades very slowly when exposed to sunlight. Upon drying, the conwed fibers developed a continuous flexible surface over the entire test area. This material was judged to be very good because it showed absolutely no sign of distress. The price per acre is $390.00.
5. Curasol AE: It is a while viscous polymer dispersion. It has a strong odor and forms a hard crust when dried. Material adheres to everything it comes in contact with, so unless everything is washed off immediately, clean up becomes difficult. Since the winds did not penetrate the surface, Curasol AE is judged as being a good agent for controlling wind erosion. Price per acre is $390.00.
6. Curasol AH: Curasol AH is also a viscous white polymer dispersion. It is very similar to Curasol AE; however, the major difference is that upon drying it forms a flexible surface. This flexible surface may be desirable on soft uncompacted embankment slopes. As with Curasol AE it was judged to be an effective agent. The price per acre is $401.28.
7. Ecology Control: Ecology control is a brown powder which forms a colorless thin hard surface when drying. It has no strong odor and is very easy to use and clean up. The blowing sand had severely scoured the surface and had penetrated the surface proving this material to be ineffective. The price per acre is $208.00.
8. Erode-X: It is a white viscous concentrate of a plastic material which must be diluted with water before application. It has no strong odor and upon drying forms a colorless hard thin surface. It is very easy to use and clean up. Erode-X is not too effective and is very expensive. The price per acre is $2,378.75.

9. Glenkote: It is a plastic chemical material; it has no strong odors and forms a colorless thin hard surface upon drying. Glenkote is very easy to use and to clean up. This like Erode-X is not a very good dustproofing agent. The price per acre is $871.50.
10. Orzan: It is a dark brown viscous solution of chemicals and lignin sulfonate. This material exhibits remarkable penetration which results in a 3-inch hard crust. It has a strong odor, but it is easy to use and clean up. Upon drying, shrinkage cracks appeared which were unsightly; however, as an erosion controlling agent, it is very good. The price is $670.48 per acre.
11. Soilmaster: It is a water dispersion of epoxies and silicones. It is a little more difficult to use than the others because it comes as two components which are added to the mixing water separately and require certain waiting periods after the addition of each component. Soilmaster has no strong odor and upon drying forms a thin fragile crust. It is very easy to use and clean up. Winds had penetrated through the surface making this agent just marginal. The price per acre is $3,960.00
12. Soil Seal: It is an emulsion of copolymer materials which can be diluted with water. Upon drying it forms a thin hard surface which the wind did not penetrate. Soil Seal has no strong odor and is easy to use and clean up. As a dustproofing agent, Soil Seal has been rated as good. The price is $837.50 per acre.
13. Soil-Lok: It is a sodium silicate that is hardened with an application of calcium chloride. This type of chemical formed a very hard layer on the surface which would probably prevent the development of vegetation. As a dustproofing agent Soil-Lok has been found to be very good. The price per acre is $3,200.00.
14. Surfaseal. It is a white viscous plastic with no strong odors. It is more difficult to use than any of the other spray-ons because the recommended method of application requires three passes with intervening time to permit drying of the previous pass. Surfaseal was found to be a good dustproofing agent. The price per acre is $252.00.

15. Terra-krete: It is a green viscous solution of chemicals in a latex base. When it dries it forms a colorless thin hard surface. It has no strong odors and is easy to use and clean up. It has been judged as a good dustproofing agent. The price is $1,270.00 per acre.
16. Verdyol: It is a brown granular material that is not entirely water soluble and, therefore, requires agitation during application. It has a slight odor, very similar to that of fertilizer because Verdyol is an organic material. It is very easy to use and to clean up. It dries to a colorless thin hard surface; however, since the wind destroyed most of the fine material on the surface it was rated unsatisfactory as a dustproofing agent.

It must be kept in mind that these sixteen spray-on materials were only tested on this one location, so the results obtained by the California Department of Public Works are not 100% conclusive and consequently further studies are warranted.

Peters (1973)[25] tested a few commercially available products, produced by Phillips Petroleum Company, in emulsion form which are available under the following designations (1) Petroset SB, (2) Petroset AX, (3) Petroset RB, and (4) Petroset AT. Each of these products is best suited for a particular soil type or soil condition (these will be discussed later) however, all four types are physically and chemically compatible. The products can be applied to surfaces individually, consecutively, in blends and in dilution with water in all proportions. This mutual compatibility offers the engineer great flexibility and freedom in design. The four products are listed below along with their respective suitabilities:

1. Petroset SB: It has a high wetting and bonding power for soil particles below gravel size. It deposits an elastic bonding agent on the individual particles.
2. Petroset AX: It contains a high strength polymer and also a certain amount of asphaltenes. These asphalt components provide increased hardness and bearing strength for the treated soil.
3. Petroset RB: This material contains bonding agents for large particle aggregates ranging from gravel to rock. It converts loose rock structures into a continuum which is shock absorbent.

4. Petroset AT: It is a rubberizing agent for asphalt surfacing. It is a spary-on which penetrates asphalt pavements, reinforcing the bonds and increasing the durability of asphalt coments.

As was mentioned before, these materials can be mixed together to acquire a better agent, for example, by mixing Petroset SB with Petroset AX, an increase in bearing strength for sands could be attained. Any combination of chemicals in any proportion can be used to satisfy a particular situation.

Work by Peters (1973)[25] included both laboratory and field testing of these materials. The laboratory test consisted of determining the physical and chemical properties of the materials, the storage abilities, the amount of penetration, reaction to wind velocities of 150 mph, simulated rainfall, running water, abrasion tests and repeated loadings.

Since the primary objective of Part A of this report is to compile information on Dust Control; therefore, results pertaining to other aspects of soil erosion control (such as rainfall results and running water results) will be given in Part B of the report. The composition of the four materials is given below in Table 2.

TABLE A-2: COMPOSITION OF INDIVIDUAL EMULSIONS

	Petroset RB	Petroset SB	Petroset AX	Petroset AT
Elastomer	22%	9%	4%	18%
Resins	11%	9%	-	-
Asphalt	-	-	46%	-
Oils	-	27%	-	42%
Volatile Solvents	42%	25%	14%	-
Water & Surfactants	25%	30%	36%	40%

From laboratory tests it was found that Petroset SB had the greatest penetration abilities and both Petroset SB and Petroset AX had passed a 150 mph wind test after having passed a 1-hour rain test. These materials had been approved in the laboratory as successful dust controlling agents.

The second phase of the experiment consisted of a field test, which was conducted at the U.S. Atomic Energy Reservation in Richland, Washington.

A large excavation measuring 80 feet in depth by 360 feet in diameter caused frequent work stoppages because of the excessive dust storms. By using Petroset SB this excavation was successfully dustproofed. At Edwards Air Force Base, a similar problem situation occurred, but here the combination of Petroset SB and Petroset AX were used indicating that the laboratory results had simulated accurately the field results.

These products are relatively new and are still under investigation, but have shown to be very promising dustproofers, especially because of their compatibility. With these materials it is possible to dustproof a soil as well as add considerable strength to it at the same time.

Within the last few years the emphasis on environmental problems has focused attention on the massive nationwide accumulations of mine, mill, and smelter wastes that represent a potential air and water pollution hazard.[8] About 1.7 billion tons of mineral wastes are discarded annually in the United States.[27] The total accumulated mineral solid wastes amount to about 25 billion tons, covering an area of over two million acres of land.[27] A substantial amount of the mineral discard is in fine size material which requires stabilization in order to prevent air and water pollution.[26]

It has been estimated that the waste byproducts from foundries melting automobile scrap metal, is producing 25 tons of dust per day, which when extrapolated to a national basis for the major foundries, indicates a production of 500 tons daily.[8] As can be seen, this is a very important problem that needs to be alleviated.

The United States Department of the Interior, Bureau of Mines, had conducted an extensive amount of experimentation to reduce the large quantity of dust.[8] Methods devised for achieving this stabilization included physical, chemical and vegetative procedures.

Physical stabilization includes the following: The use of soil as covering of wastes; the use of water for sprinkling; the use of bark covering; the harrowing of straw in the top few inches of tailings and the use of windbreakers, etc.[8] Another method is vegetative stabilization which primarily consists of planting alfalfa, rye, barley, etc. to reduce the erosion due to winds. This has one great advantage and that is its long life. As long as there is vegetation the erosion will be controlled.

The Bureau of Mines had tested seventy chemicals in the laboratory and a selected few in the field. The materials were tested by the following procedure:

Samples of the tailings were put into 1-pint paper containers and compacted slightly.[10] Half of the samples were kept dry, the other half were saturated and both allowed to stand for 24 hours. The chemicals were applied to both the wet and dry samples. Twice weekly they were subjected to simulated rain equalling about 2 inches. After several months of alternate wetting and drying, the samples were tested by a water jet. Samples that had survived this test were then subjected to wind velocities ranging between 1 to 80 mph. The amount of surface disruption was measured by weighing the samples before and after exposure to the wind.

Out of the seventy chemicals tested the most promising chemicals are listed below:

1. Aerospray Binder 52: It is a synthetic resin which was not very effective under the last tests. (Results of the 1971 test in California with this product rendered it not too satisfactory).
2. Peneprime: It is a bituminous base product which had produced good wind and water resistant surfaces at a cost of $0.10 per square yard.
3. A cationic Neoprene Emulsion and Rezosol: It is an organic polymer which effectively stabilized the surface at a cost of $0.08 per square yard.
4. Potassium Silicates: A 2.5 ratio of SiO_2 to K_2O proved to be an effective stabilizer at a cost of $0.07 per square yard.
5. Paracol S 1461: It is a blend of wax and resin which produced a good surface at a price ranging from $0.04 to $0.10 per square yard.
6. Paracol TC 1842: It is a resin emulsion which also produced good surface stabilization with a variety of tailings at a price of $0.04 per square yard.
7. Calcium, ammonium, and sodium ligninsulfonates: As well as redwood bark extracts, produced a good stabilized surface at a low cost of $0.02 per square yard.

The other chemicals tested did not produce good and consistent results and therefore, they are not mentioned here. Everyday more and more experiments are performed in search of that one product that will be usable in all soils and under all conditions, at a reasonable price.

CHAPTER 4

PERFORMANCE RATINGS

Rating Format

The major stabilizers on the market today for erosion control due to winds are listed on the following pages along with their ratings. The ratings are as follows:

1. EXCELLENT: This signifies a chemical that endured both qualitative and quantitative tests in the laboratory as well as in the field for a specified length of time.
2. VERY GOOD: Same as "excellent" with the difference that additional investigation is required.
3. GOOD: This rating signifies that a chemical had controlled erosion; however, these chemicals had some form of complications such as: long curing times, very strong odors, toxic nature, very hard to clean, extremely short life etc.
4. MARGINAL: These are chemicals that possess some degree of dustproofing; however, many contradictions exist between investigators and consequently much more research is warranted.
5. UNSATISFACTORY: This signifies that the chemical did not add any benefit to the soil and the majority of investigators recommended not to use the product.

CHEMICAL RATINGS

MATERIAL	RATING	COMMENTS	REF.
Aerospray 52	Marginal	Wind scoured surface, but didn't penetrate	29
Acrylic Emulsion	Marginal	Suited only for clays	19
Admex 710	Good	Formed good surface	19
Aggrecote 600	Good	Need more testing	23
Aluminum Sulfate	Unsatisfactory	Surface was penetrated	33
AM-9	Good	Good surface, long curing time	19
Amberlite PR-115	Marginal	Is very expensive as primary treatment	23
Ammonium Chloride	Marginal	Surface scoured	23
Ammonium Resin	Marginal	Need further study	23
Aniline Furfural	Excellent	Very tough surface for dry fine grained clays and silts, toxic	34 33 22
APSB	Good	For a variety of soils	4
Aquatain	Unsatisfactory	Surface eroded	29
Arlon 110	Marginal	Further tests required	19
Arlon 310	Marginal	Further tests required	19
Arlon 363	Marginal	Further tests required	19
Arlon 580	Marginal	Further tests required	19
Armid O	Unsatisfactory	Weak surface	31
Aroflint 505	Unsatisfactory	Did not cure	19
Aroplaz 832	Marginal	Slow curing, surface broken	19
Aroplax 6008	Marginal	Slow curing, surface broken	19
Aroplaz 6065	Marginal	Slow curing, surface broken	19
Aropol 7110N	Very good	Very good with sand, silt and clay	19
Aropol 7720N	Very good	Very good with sand, silt and clay	19
Arquad	Marginal	Needs further testing	18

MATERIAL	RATING	COMMENTS	REF.
Arquad T-50	Unsatisfactory	Weak surface	31
Arothane 160	Good	Primarily good with clays	19
Arothane 170	Good	Primarily good with clays	19
Base 972-A	Unsatisfactory	Very long curing time	18
Base 972-B	Marginal	Produce good surface, but long curing time	18
Base 972-D	Good	Produced good, strong surface for a variety of soils	18
Base 972-L	Good	Produced good, strong surface for a variety of soils only with the mixture of Base 972-D	18
Base DPE	Unsatisfactory	Slight H_2O destroys surface	18
Base 792-E	Unsatisfactory	Long curing time required	18
Barium Chloride	Unsatisfactory	Leaches out of soil	33
Barium Sulfate	Unsatisfactory	Leaches out of soil	33
Bisphenol A	Good	Produced good surface on sand and clay (slow cure)	19
Calcium Chloride	Unsatisfactory	Good in the field, failed in the lab	24 33
Calcium Acrylate	Marginal	Needs further testing	34
Chem-Rez 200	Good	Slow curing	19
Chrome-Lignin	Marginal	Toxic effects	33, 34
Coherex	Marginal	Does not penetrate deep enough	29
Conwed Fibers	Excellent	No signs of distress in sands	29
Copper Sulfate	Unsatisfactory	Leaches out of soil	33
Coumarone-indene	Marginal	More testing required	23
Curasol AE	Good	Hard to clean, has odor	29
Curasol AH	Good	Hard to clean, has odor	29
Cutback Asphalt	Marginal	Hard to clean, has odor	4
DCA-70	Very good	Produced strong surface	4

MATERIAL	RATING	COMMENTS	REF.
DCA-70 and Fiberglass	Excellent	Produced strong surface	4
DDC	Marginal	Best with clays	22
Dustrol	Good	Forms dense crust	33
Ecology Control	Unsatisfactory	Wind penetrated surface	29
ELO	Good	Formed good surface	19
Emlon E-200	Good	Fast curing, water soluble (good with sands and clays)	19
Epon 828	Good	Formed hard crust	19
Erode X	Unsatisfactory	Wind penetrated surface	29
Everflex G	Unsatisfactory	Weak surface, slow curing	18
Everflex GT	Unsatisfacotry	Weak surface, slow curing	16
Everflex ER-61-L	Unsatisfactory	Brittle surface	18
Everflex ER-E	Unsatisfactory	Soft film	18
Everflex EF-MF	Unsatisfactory	Soft film	18
Furfural Alcohol and Sulfuric Acid	Marginal	Very expensive compared to aniline-furfural	23
Gelatin 15 XPF	Marginal	Formed hard, brittle surface	19
Glenkote	Marginal	Scoured surface by wind	29
Goodrite Resin 50	Marginal	Used with aniline-furfural treated soils	23
Goodyear X335	Good	Withstood winds of 130 mph	28
HK-1	Very good	It's a 50-50 mixture of Base 972D and 972L	18
KH-2	Excellent	75-25 mixture of Base 972D and 972L	18
IGER	Marginal	Further testing required	33
K-ATON 101	Good	Withstood wind velocities of 100-150 mph	28
Landlock	Good	Strong surface	14
Lauxite RF-901	Marginal	Further testing required	23
Lauxite UF-77	Marginal	Further testing required	23
Lemac 40	Good	Good only when used with acetate solvent	18

MATERIAL	RATING	COMMENTS	REF.
Lemac 40	Unsatisfactory	When used with an alcohol solvent	18
Lignin Liquor	Good	Strong surface	18
Ligno Sulfonates	Good	Good stabilized surface	9
Lino-Cure A	Unsatisfactory	Did not cure	19
Lino-Cure C	Unsatisfactory	Did not cure	19
Lino-Cure 2125	Unsatisfactory	Did not cure	19
Magnesium Sulfate	Unsatisfactory	Weak surface	33
Melamine-formaldehyde	Marginal	Needs more testing	23
Neoprene 750	Good	Flexible strong film	16
Orzan	Very good	Forms a 3" thick hard crust	29
Oils	Marginal to Good	Form dense crust after repeated application	4 22
Pacific N-748-N	Good	Forms rigid surface	16
Paper Binder 40	Unsatisfactory	Formed a tacky film	18
Paracol TC 1842	Good	Produces good stabilized surface	10
Paracol S1461	Good	Produces good stabilized surface	10
Peneprime	Good	Produces strong surface	4
Petroset RB	Excellent	For large particles	25
Petroset SB	Excellent	For soil below gravel size	25
Petroset AX	Excellent	For increased strength	25
Petroset AT	Excellent	For asphalts	25
Pliolite 5352	Unsatisfactory	Needs more testing	28
Pliolite 5352 and heating	Good	Withstood winds of 120-160 mph	28
Phosphoric Acid	Marginal	Rigid non-porous surface	16
Polyco 505	Unsatisfactory	Weak surface	18
Polyco 2415	Unsatisfactory	Brittle surface	18
Polyco 1361-4B	Unsatisfactory	Brittle surface	18
Polyco 446-1	Unsatisfactory	Brittle surface	18

MATERIAL	RATING	COMMENTS	REF.
Polyco 561	Unsatisfactory	Brittle surface	18
Polyco 678W	Unsatisfactory	Brittle surface	18
Polyco 8040L	Unsatisfactory	Brittle surface	18
Polyco 577G	Unsatisfactory	Brittle surface no strength	18
Polyco 1404-30	Unsatisfactory	No strength in film	18
Polypropylene and Asphalt	Good	For a variety of soils, tough membrane	4
Portland Cement	Unsatisfactory	Good stabilizer; however, not good as a dustproofer	33
Potassium Silicates	Good	Needs further testing	10
Powdered Asphalt	Unsatisfactory	Absolutely no dust-proofing ability	33
Resinox L-9673	Marginal	Very erratic results	23
Resimene M75	Unsatisfactory	No added benesite to the soil	23
Resin 321	Unsatisfactory	Used as a waterproofer	33
Siroc #1	Unsatisfactory	Did not cure	19
Soil Bond			
Soilmaster	Marginal	Scoured surface by wind	29
Soil Seal	Good	For fine grained sands	15
Soil Lok	Good	No damage after six mos.	29
Sodium Chloride	Unsatisfactory	Good in lab, not good in field	30 33
Sodium Silicate	Good	Tough surface, good bonding action, low cost	10 33
Sodium Silicate N	Good	Very fast cure, good surface	19
Stabilizer "U"	Unsatisfactory	No benefit to soil	13
Stabinol	Unsatisfactory	Good waterproofer, not as good dustproofer	33
Sulfuric Acid	Marginal	Needs more testing	23
Surfaseal	Good	Surface not penetrated	29
Tar	Unsatisfactory	Mainly waterproofer	33
Terra-Krete	Good	Wind didn't penetrate	29
Ucar 130	Good	Strong surface	18

MATERIAL	RATING	COMMENTS	REF.
Ucar 131	Very good	Became known in 1969 as DCA 70	4 18
Ucar 360	Marginal	Brittle film	18
Ucar 684	Unsatisfactory	Cracked surface	18
Ucar 680	Unsatisfactory	No benefit to soil	18
Uformite CB-552 & 513	Marginal	Improvement with addition of zinc stearate	23
Urac 185	Unsatisfactory	No added benefit to the soil	23
Verdyol	Unsatisfactory	Wind penetrated surface	29
Vinsol	Unsatisfactory	As dustproofer	33, 36
Vultex 1-V-10	Excellent	Good, strong surface	16
Wood resin	Unsatisfactory	As dustproofer	33, 36
Water	Marginal	Good for a few hours or less	4

CHAPTER 5

CONCLUSIONS

The dustproofers mentioned in this section are the major stabilizers used for soil erosion control. There are many other stabilizers which were not mentioned, because no conclusive results have been obtained to their effectiveness to this date. Some of these other dustproofers have been lised in Chapter 4.

Out of the materials mentioned in this section it was found that the most promising one was the 70:30 mixture of Aniline-Furfural resin. It was found through experimentation that soils stabilized with Aniline-Furfural showed a certain increase in strength with time even under the severe abrasive action of traffic and weather. Aniline-Furfural was found to be especially effective with fine grained clay and silt soils when dry-cured.

Another excellent dustproofer is the Polyvinyl resin HK-2 combination with the 75:25 percent mixture of Base 972-D and 972-L. Even under simulated wind loads of 50 mph, 100 mph and 150 mph the surface remained intact. This material has been found to be ideal when quick results are needed with many different types of soils.

Another very promising dustproofer is the DCA-70 with the chopped fiberglass filaments. The strong tear resistant membrane formed upon curing was very reliable for 10 months. This too is good for a variety of soils when quick results are required.

Out of the sixteen spray-on materials tested in 1971 the most promising were the Conwed Fiber and Surfaseal especially. The former developed a flexible surface which was not penetrated by the wind. The dark brown viscous solution of Orzan had produced a 3-inch thick hard crust that was not penetrated at all. For long term control where vegetation growth is not required Orzan is the best choice. This material is best suited for fine-grained rounded sands.

The use of the APSB and road oils have shown to be promising but more testing is needed.

Very promising results have been obtained from Petroset SB, AX, RB and AT, especially because of their compatibility with each other. It appears that these emulsions will gain great popularity within the next few years. The ability of gaining strength while gaining a good dustproofer is very appealing to the engineers.

Materials such as EPON 828, 15 XPF Gelatin, AM-9 and Chem-Rez 200 also indicated to be very promising. In late 1972, the California Highway Department tested a few chemicals with good results. These chemicals were Landlock,[14] Soil-Lok[15] and Soil-Bond.[13] Results are not conclusive and no further discussion is given.

To this date the search for that ideal chemical that would dustproof all types of soils is still under investigation.

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SECTION B

SOIL EROSION DUE TO RAIN

The chemical control of soil erosion due to rainfall was not a primary subject of this research project. However, in his state-of-the-art review of wind and traffic erosion control, the principal researcher inevitably encountered considerable information on the related matter of rainfall erosion. This information is presented herein for the interest of the reader.

CHAPTER 1

MECHANICS OF WATER EROSION

Erosion due to water is a major problem of global concern, but arid and semi-arid regions are especially confronted with this problem where desiccation of the soil due to dryness and heat and due to low organic content make the soil extremely susceptible to water erosion. A heavy rain can carry an appreciable amount of the surface to other areas, leaving the ground rough, textured, and bare. Water erosion carries a large amount of the fine particles with it, causing silting of reservoirs, filling highway and railway ditches, plugging culverts, bridge collapse due to scouring plus many other damages. These indirect damages caused by water erosion can affect every person, especially because of the large yearly expenses they cause in reconstruction and repair.

As was discussed in Section A of this report entitled "Mechanics of Wind Erosion", soil erosion once again is defined as the process of detachment and transportation of soil particles due to the abrasive action of either wind, rain or traffic. This section deals only with soil erosion caused by rainfall.

Soil erosion due to rain can once again be considered as a cycle;[5] the cycle being made up as follows: (a) Detachment, (b) Transportation, and (c) Sedimentation.

Erosion by water occurs in five different ways; these are listed and described below.

Sheet Erosion

Sheet erosion is usually associated with the removal of uniform soil layers through the detaching force of raindrops hitting the surface. Sheet erosion is the most insidious and perhaps the most extensive type of water erosion.

Erosion due to rain is a mechanical process that requires energy to put it into action. The diagram in Figure B-1 given by Wischmeir and

Smith (1958) illustrates the relationship between rainfall intensity and raindrop diameter size.[44]

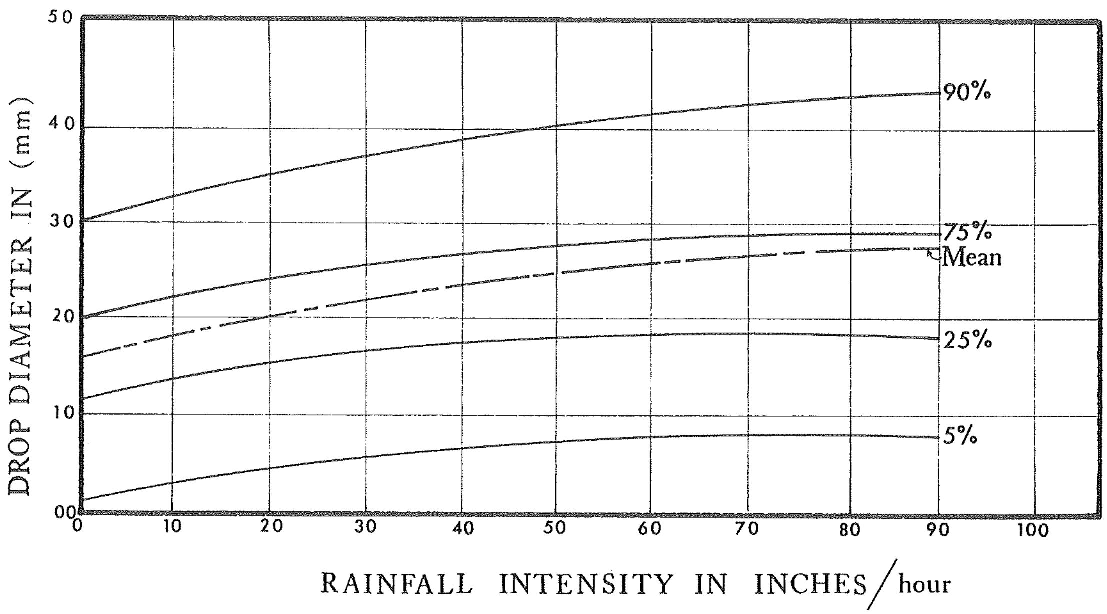

FIGURE B-1: RAINFALL INTENSITY VS. DROP DIAMETER

Most of the energy is in kinetic energy form (K.E. = $1/2mv^2$) and it is influenced by the raindrop size (weight or mass) and by the rate of descent (velocity). The larger the particle size and the faster the rate of descent the larger will be the kinetic energy and therefore the greater the detaching force. During severe rains, the added influence of the wind will increase the velocity of the raindrop, thereby increasing the kinetic energy upon impact.

The diagrams given in Figure B-2 show the relation of diameter size to terminal velocity (i.e. velocity upon impact with the ground).

The principal factors affecting the susceptibility of land to sheet erosion are based on the following parameters: intensity and duration of rainfall, soil texture, soil structure, overland slope, density and condition of vegetative cover, among others. Sheet erosion is generally inconspicuous being only marked by increasing lightness in the color of the surface. Sheet erosion is very common in areas where loose, shallow layers of surface soils overlie a dense impermeable subsoil. Sheet erosion also prevails on soils of high silt content, fragile sandy soils, unstable clays and many soils deficient in organic matter. The immediate effect of sheet erosion is to fill the voids with fine material which in turn reduces soil infiltration capacities and consequently increases surface runoff and thus increases erosion.

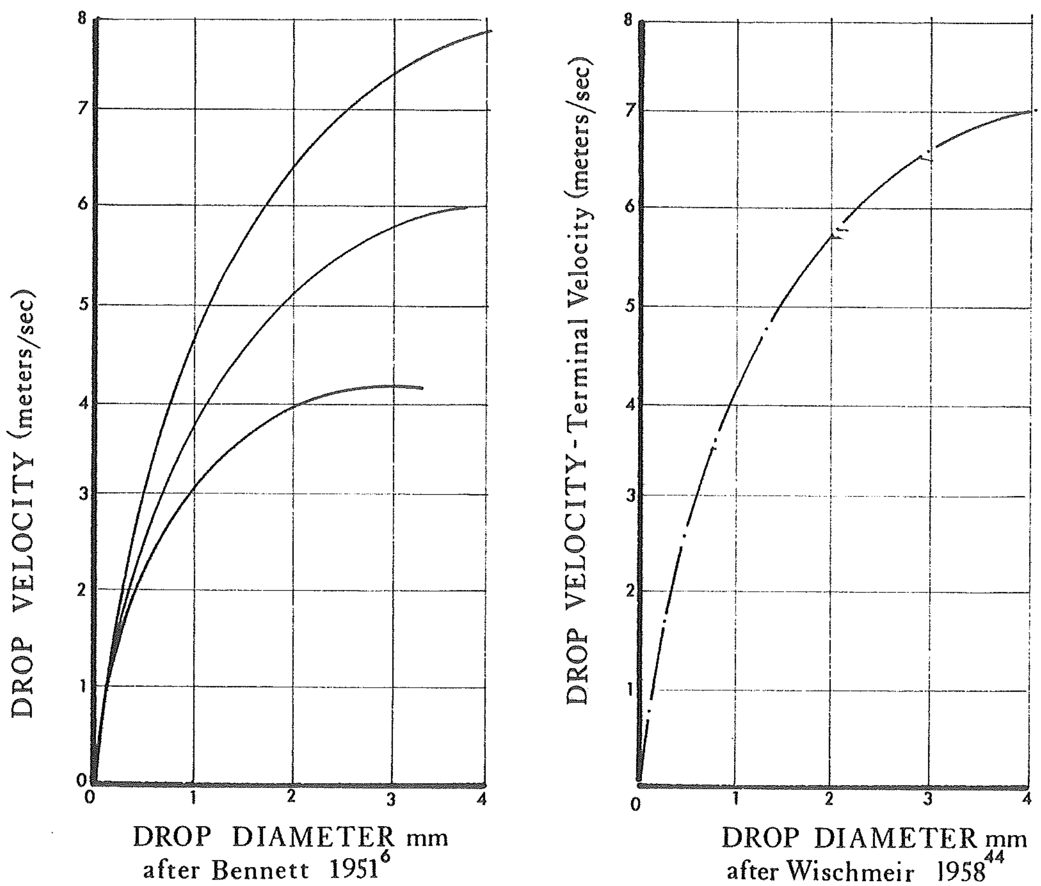

FIGURE B-2: RAIN DROP VELOCITY VS. DROP DIAMETER

Soil losses due to sheet erosion have been correlated statistically with soil erodibility, surface cover, degree and length of overland slope and rainfall intensity.[43] These will be discussed elsewhere in the report. The erodibility of cohesive soils subjected to sheet erosion are determined by soil texture, grain size, nature of the clay mineral, depth of infiltration of the soil profile, organic concentration, moisture content, mean particle size, void ratio, plasticity index, and dispersion ratio, among others.[43]

Through experimentation by Ellison (1947)[9] raindrop velocities have been measured to read 30 feet/second or even greater. It has been estimated that the dead weight of 1.0-inch of water on an acre is more than 110 tons. This weight, falling as countless drops in a hard rain and often driven by violent winds, strikes with a terrific force. This impact furnishes the major part of the energy that causes erosion. The total energy of raindrops has been calculated by Osborn, and reported in 1955,[33] as being equal to roughly 100 horsepower on an acre, during a rainfall of 0.1 inch per hour and 250 horsepower at 2 inches per hour.[33] This latter is sufficient force to lift a 7-inch topsoil layer to a height of 3 feet, 86 times during an hour's rain; it is equivalent to 518 million foot pounds of work.

From experiments by Wischmeir and Smith (1958)[44] equations have been derived to find the kinetic energy of the drop when the intensity of the rain is known. This equation along with its graph is given below in Figure B-3.

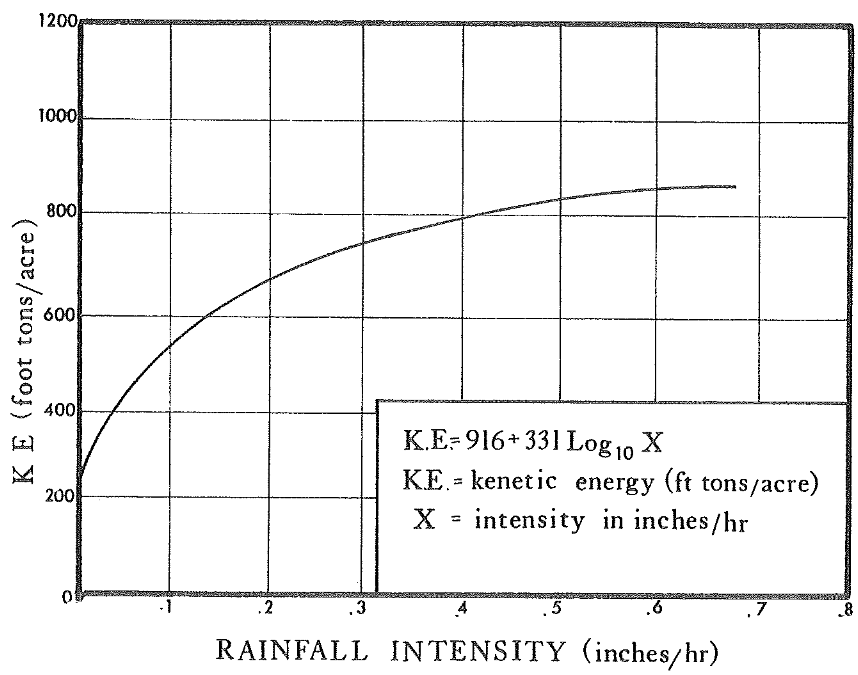

FIGURE B-3: KINETIC ENERGY VS. RAINFALL INTENSITY

Rill Erosion

Rill erosion is the erosion of soil by running water in the form of streamlets.[4] Accelerated erosion of rills and other depressions of the land which tend to concentrate upon surface runoff develop into channel or gully erosion. Rill erosion is most common in regions of intense rainfall and low infiltration capacities.[6] Soils with high silt content are vulnerable to rill erosion.

Channel Erosion

Channel erosion or gully erosion develops from the accelerated erosion of rills or other surface depressions caused by vehicles or animals which tend to concentrate surface runoff in channel-like formations.[43] The degree of channel erosion is dependent upon the hydraulic characteristics of the flow (i.e. local depth and velocity) and upon the cohesiveness of the soil. Gullies may be defined as eroded V-shaped or U-shaped channels having depth up to 100 feet, width greater than 18 inches and length ranging up to several miles. In regions of heavy rainfalls, gully erosion can be observed. Gullies are known in different sections of the United States by different names. In North Central U.S. they are known as "ditches", in the Southwest as "arroyos", in the High Plains as "washes", in the Pacific Northeast as "coulees" and in the Pacific Southwest as "barrancas".

Streambank Erosion

Streambank erosion is primarily due to loss of vegetative cover and toe support. These streambanks become highly susceptible to scour and undercutting by turbulent flows.[43] As with gully erosions the degree of erosion is dependent on the hydraulic characteristics of streamflow and the erodibility of the channel material.

Shore Line Erosion

Shore line erosion is induced by the uncontrolled action of waves and winds on essentially cohesionless shore materials. The erosive energy of the wave is primarily dependent upon the wave amplitude, period, and direction.[43] As this form of erosion is not pertaining to erosion by rain, it will not be discussed here any further.

As was mentioned earlier, water erosion forms a cycle consisting of the detachment, transportation, and deposition phases. The impact of the raindrops upon unprotected land is one of the main sources of particle detachment.[10] Puddling and sealing of the land surface is another effect of the impact of raindrops on bare soils. The force of the drops break down the loose crumbs at the surface. As moisture penetrates the soil, the cementing materials are softened and the lumps desintegrate by slaking.[6] Slaking has been defined as trapped air inside the clods and aggregates and as pressure is building up within, small types of explosions occur, breaking down the clumps into individual fine particles.[39] These fine particles in turn are filling up the larger voids and a sealing process develops which prevents further infiltration of water and consequently runoff begins.

The transportation phase is very similar to that which was discussed under the Wind Erosion Section. Much of the runoff from land slopes are laminar flows. Laminar flows are practically non-erosive, but during intense rainfall they are changed to turbulent flows and then they are able to transport large quantities of soils.

As with erosion due to winds the velocity of the water near the surface and sides of channel are practically zero, consequently only the particles which protrude enough above the surface are moved by the force of the water.

Some larger particles are just rolled by the force of the turbulent water, while others are in suspension or saltation. The mechanics of each are very similar to those mentioned in the Wind Erosion Section and they will not be repeated here. As runoff continues, the larger particles will settle down first, while the smaller particles in suspension are carried for long distances. As these particles settle down we have the final phase of the cycle, the sedimentation part.

Numerous equations have been derived for measuring the amount of sedimentation to be expected when runoff velocities are known. Equations derived by Wischmeier, Smith and Laursen are very popular ones;[19] however, illustrations and discussions of these equations are beyond the scope of this report.

One of the most extensive works on the independent variables affecting the magnitude of soil erosion due to rain, has been presented by A. El-Russtom in his Ph.D Dissertation (1973)[15] at the University of Arizona. He has examined ten variables which were studied by fixing nine variables and varying the remaining one. Three soil types were used, a silty clay, a sandy clay, and a clayey sand, all of which were compacted by static and impact methods of compaction to a maximum dry density and optimum moisture content, using both the standard and modified AASHO compactive efforts. Two types of soil samples were examined, one being 18-inches long, 3-inches wide and 1-inch high and the other was a cylindrical sample with a 4-inch diameter and 1-inch height.

All the samples tested were placed under a rain simulator for a period of 90 minutes (a detailed description of the rain simulator is given later on). In the test, four identically prepared samples were tested under the rain machine, one was removed after five minutes, the second after 30 minutes, the third after 60 minutes and the fourth after 90 minutes. When erosion was plotted in relation to time, it was observed that beyond the 90 minute duration, there was only a slight increase in erosion with time, because of this observation the remaining samples were tested only for 90 minutes under the rain simulator.

The ten independent variables studied by El-Rousstom[15] along with their findings are given below:

Slope Inclination

For many years it was believed that under a constant rain intensity, the greater slopes will cause greater runoff and consequently greater erosion. Musgrave (1947)[30] claimed that the amount of erosion per unit area is directly proportional to the degree of slope raised to the power 1.35 or $E \propto S^{1.35}$ where E is the amount of erosion in tons per acre, and S is the slope in percent.

Wischmeier and Smith (1958)[45] formulated the following equation: $A = 0.43 + 0.30S + 0.04S^2$ where A is the soil loss in tons per acre, and S is the slope in percent. According to this equation, the erosion is a function of the slope only, which is not the case in practice.

From the investigation performed by El-Rousstom three different slopes were used, 4.5° (mild), 14° (intermediate) and 26.1° (steep), it was determined that maximum erosion occurred at the intermediate slope of 14°. Slopes flatter or steeper showed to have lower amounts of erosion. The reason for this has been given as follows: A steep slope has a small projection area, which causes less rain to hit the sample than in the case with a milder slope having a greater projection area. A particle on a mild slope has less gravitational force assisting particle momentum downhill than that available for a steep slope. Therefore, erosion on a steep slope is lower because there is less rain hitting it, and erosion on a mild slope is lower because of the smaller gravity force. On an intermediate slope, a sample has the combined effects of an intermediate gravity force and an intermediate projection area receiving an intermediate amount of rain, which causes the sample to experience the most erosion. (This justification is illustrated diagrammatically by an example in Figure B-4).

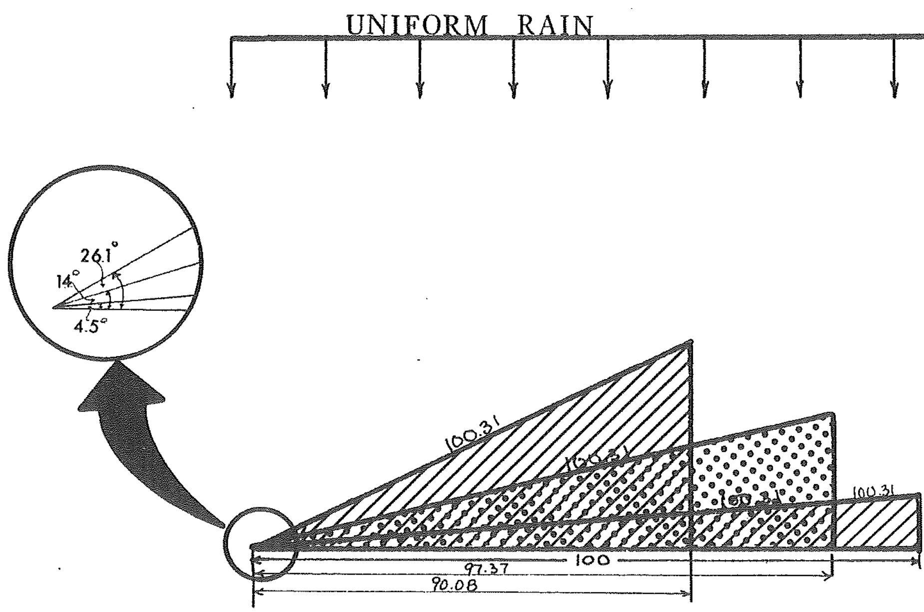

FIGURE B-4: EFFECT OF SLOPE INCLINATION ON EROSION

Rain Intensity

As was mentioned earlier in the report, Wischmeier and Smith (1958)[44] derived equations which showed that as rain intensity increased the kinetic energy had increased and consequently more erosion occurred. In this investigation, El-Rousstom (1973), three different rain intensities were used on all three soil types. The intensities were 1.3 inches per hour (moderate), 1.98 inches per hour (hard) and 2.65 inches per hour (very hard). From the experiments it was concluded that for all soil types, as the intensity increased the amount of erosion increased.

Effect of Grain Size Distribution

The ease of detachment and difficulty of transportation of sands and the difficulty in detachment and ease of transportation in clays has been observed by many investigators. In this investigation samples from all three soil types were compacted at different dry densities and water contents and then the samples were cured. The samples were then subjected to rain intensities of 1.98 inches per hour at the 14° slope. The results had indicated for all cases that the higher the percent clay the lower the erosion; the higher the percent sand, the lower the erosion; the higher the percent silt, the higher the erosion. This is primarily due to the silt being the intermediate of both sands and clays. Silt has more ease of detachment and more ease of transportation than the clay and sand, respectively.

Curing Conditions

Three different curing conditions were used in this research: (a) samples tested immediately after compaction (as molded), (b) samples wrapped and cured in a 70° room for 28 days at constant water content, and (c) samples cured for 28 days in a 70° room at 50% humidity. It was concluded that the lower the relative humidity at which the samples are cured, the higher the erosion. This is probably due to a loss in moisture which may have led to shrinkage and consequently to more erosion.

Water Content and Dry Density

The samples for this phase of the experiment were tested under the 14° slope and 1.98 inch per hour rain intensity. It was observed that samples which were compacted at optimum eroded the most, while samples on each side of the optimum eroded according to their density at the time of the test. It was also concluded that (a) erosion decreased with increasing molding water content and (b) the silty clay eroded more than the sandy clay at the dry of optimum side, while on the wet of optimum side the reverse was true. It was determined that for field curing conditions (50% humidity) the higher the dry density, the higher the erosion, therefore it is unwise to compact at optimum in a dry climate.

Compactive Effort

Both the standard AASHO (12,375 lb-in/cu ft) and the modified AASHO (56,250-in/cu ft) methods of compaction were used. It was concluded from the experiments that at the same water content, the higher the compactive effort, the lower the amount of erosion.

Method of Compaction

In this investigation both the static and impact method of compaction were used. Samples compacted by the impact method are expected to have a more oriented fabric than those compacted statically at identical water contents and dry densities. The ease of detachment of soil particles can be related to their structure and fabric orientation. Samples having the same water content and compacted at the same compactive effort, but using two different methods, could have a difference in the structure and orientation of the compacted soil. It appears that the soil having a more oriented fabric can resist erosion better than that with a randomly oriented fabric, since the soil particles in the former are, in a way, perpendicular to the falling rain, and parallel to the flowing runoff water. The falling rain would tend to compact the soil, and the flowing water would exert only a drag force on the flatly oriented soil particles. This drag force at the surface of contact with the soil will approach zero because the velocity of the runoff water at the surface of the soil is zero. Samples compacted by the impact method eroded less than those by static methods.

Temperature Effect

Soil samples were cured at 50% humidity and then tested under two different temperatures. One at 95° F. and the other at 55° F. Samples tested in the warmer temperatures eroded more than those tested in the cooler weather.

Plasticity

In the study, clayey soils were treated with lime to reduce the plasticity index and bentonite was used to increase the plasticity index. It was concluded that the more plastic the soil or the higher the plasticity index, the harder it is to detach, and if the soil will not detach, it simply will not erode.

Sample Length

Two size samples were used, one measuring 18 inches long, by 3 inches wide by 1 inch thick and the other a cylindrical specimen with 4-inch diameter and 1-inch thick. The larger samples had the effect of the splashing raindrops as the smaller samples with the addition of greater runoff. It was reported that since the runoff was reduced on the smaller sample, less erosion took place.

This investigation has helped the engineer to control and reduce the amount of erosion on any compacted soil structure. For example, it is advisable to compact an embankment with a sheeps foot roller rather than a static compactor. The sheeps foot roller, with its kneading action, produces a more oriented fabric which is less likely to erode than if the embankment was statically compacted.

CHAPTER 2

CHEMICALS TESTED BY VARIOUS INVESTIGATORS

All the major chemicals that are mentioned hereinafter pertain primarily to erosion control due to rains even though these chemicals may also be applicable for other forms of erosion control.

Experiments reported in 1946 by the U.S. Corps of Engineers with resinous water-repellents have led to some conclusive results.[41] One of the resins tested was product 321 supplied by the Hercules Powder Company. This material is a finely powdered, white resinous substance weighing approximately 16 pcf. It is insoluble in water and very resistant to oxidation. It can be stored for long periods of time without deterioration or loss of effectiveness, because it is not hygroscopic. Product 321 is claimed to be effective when applied to the soil in quantities as low as 0.2 to 0.5% by dry weight of the treated soil.

Laboratory capillary rise tests and water absorption tests were conducted as well as wet-dry; freeze-thaw and slow-freeze tests. The capillary rise test will be described later in the report. The other tests are described below. In the absorption test after curing, the specimen is totally submerged in water for a period of 24 hours at which time the percent of moisture pick-up in terms of total percent of optimum moisture is determined; then an unconfined compression test is performed. The criterion for satisfactory water-repellency in this case was considered to be that treatment which controls the water content pick-up to 90% of optimum water content after 24 hours of submergence.

A series of wet-dry tests were conducted according to ASTM Designation D559-40T[43], except that the test specimens were not brushed with the wire brush, and modifications were made in the length of wetting and drying periods. Specimens were approximately 4 inches in diameter and 4 1/2 inches in height. Samples were compacted under the standard AASHO compactive effort and then were dried back to 55% of the molding water content prior to soaking. The specimens were then wrapped in paper towels and allowed to soak in saturated sawdust for approximately 24 hours, at which time they were removed, weighed and oven-dried at 70° C. for about 24 hours. The samples were then re-weighed, measured and resubmerged to start another cycle. Specimens were subjected to a total of 13 cycles.

The freeze-thaw tests were also conducted according to the ASTM specifications.[43] Once again the brushing was eliminated, however, the specimens were prepared in the same manner as those for the wet-dry tests. After soaking initially for 24 hours the specimens for the freeze-thaw tests were placed in a freezing cabinet and subjected to -10° F. temperatures for a period of 24 hours. After this period the specimens were allowed to thaw at room temperature on top of a saturated sand bed. Necessary measurements and weights were taken after removal from the freezing cabinet. After thawing, the specimens were placed in the freezing cabinet again to start a new cycle. A total of 12 cycles were made.

A final test performed on product 321 was a slow-freeze test. The specimens once again were compacted under a standard AASHO compactive effort at the optimum water content; then the specimens were dried back to 55% of the molding moisture content; wrapped in paper towels and submerged in saturated sawdust for approximately 24 hours. After soaking, the specimens were removed, weighed and placed in a special freezing cabinet. The tops of the specimens were exposed to the effect of a gradually decreasing temperature and the bottoms of the specimens were placed in an insulated water bath which was maintained at 40° F. The sides of the specimens were protected by paraffined cardboard containers and were packed in a sand bed above the water bath. The temperature in the freezing cabinet was lowered from 29° F. to -10° F. over a period of 23 days.

Based on these tests, product 321 was found to be an effective water-proofer with silty clays and clayey silts that were on the acidic side (i.e. pH values below 7). It was found that this product could only perform satisfactorily with acidic soils. Product 321 used by itself was unable to properly water-proof sandy silts; however, with the mixture of 1% of 321 and 20% ferrous sulphate or 40% aluminum sulphate, sandy silts were waterproofed.

Another product tested and reported by the U.S. Army Corps of Engineers (1946)[41] and (1956)[42] and also by the Civil Aeronautics Administration Technical Development and Evaluation Center in Indianapolis (1951)[27] was Vinsol. Vinsol resin is a powdered, brown resinous substance obtained from pine stumps in addition to other materials through an extraction process. Vinsol is obtained as an end product in an established commercial process and is not manufactured separately. A slurry of Vinsol and water, with a small amount of sodium hydroxide as a dispersing agent is mixed with the soil to be treated in quantities less than 2% by soil weight, satisfactorily waterproofed the following soils: a sandy silt, silty sand, clayey silt and clayey sand.

It has been surmised that the waterproofing action was due to the resin combining mechanically with water to form a Vinsol-water film around each soil grain, thus reducing the capillary forces that cause absorption of water.[42]

One of the disadvantages of Vinsol is that it is susceptible to microbial attack; however, this can be remedied by the addition of certain antiseptics and bacteria destroying additives.

Lignin liquor which proved to be a very successful soil stabilizer from experiments reported in 1955[3] by the U.S. Corps of Engineers, also proved to be a successful waterproofer from tests reported in 1956 by the Corps of Engineers.[42] Lignin is a resinous alkali waste liquor of the sulfite process found in the paper industry. Lignin, when mixed with a certain hexavalent chromium compound, changes into a gel which displays both excellent waterproofing ability and very good bonding strength. Lignin, with addition of the hexavalent chromium compound is considered toxic and great care must be employed, in order to reduce the danger.

The U.S. Army Corps of Engineers have contributed a wealth of information regarding the waterproofing ability of different materials. They conducted tests (1956)[42] in search of an ideal material that would be a single additive which, when applied in quantities of 5% or less by weight of soil would impart a high degree of water repellency and in addition, develop some degree of bonding action. Although this additional bonding action of the waterproofing material would be desirable, it was not the primary objective. The major objective of a waterproofing material was that of maintaining a naturally stable or stabilized soil at its optimum stability condition.[42] During the investigation many different materials have been tested and some of those along with their findings are given.

One of the very popular inorganic salts tested was calcium chloride which, as was mentioned previously in the Wind Erosion Section of this report, provides very little waterproofing ability, especially in areas of frequent wetting and drying because the material is rapidly leached out by water; therefore, this material is not acceptable as a waterproofer.

Portland cement has been used for many years as an excellent bonding agent when applied in quantities of 10% or more; however, it does not possess water repellent characteristics and in regions of great temperature variations, where freezing and thawing are to be expected, it proved to be a non-durable admixture.[27,42] A major reason for the lack of waterproofing qualities of cements is attributed to the fact that during curing there is a tendency for the soil cement to crack which detracts from its waterproofing ability. Cement alone has proved to be ineffective as a waterproofer.

It would be ideal to find an admixture, that would maintain the excellent bonding action of the cement and add waterproofing characteristics to it. There are a few additives that are able to do just that. One of these is Stabinol. Stabinol has been tested by the Waterways Experiment Station (1946)[41] and (1956)[42] and also tested by the Civil Aeronautics Administration Technical Development and Evaluation Center (1951).[27]

Stabinol consists of three parts portland cement and one part of either product 321 or a complex salt consisting of unneutralized abietic acid, sodium resinate and calcium resinate. Stabinol is a fine gray powdery material which weighs about 50 pcf and can be handled like portland cement. Based on results from the capillary rise test and water absorption tests, as described previously, conducted on eleven different soil types ranging from sandy silts to medium clays to granular bare coarse material, it was found that Stabinol in quantities not exceeding 3% of the soil weight successfully waterproofed all of the eleven soils.[41] The conclusions based on subsequent field tests were the same; Stabinol successfully waterproofed the soils. From the tests conducted by the Civil Aeronautics Evaluation Center [27], however, it was found that Stabinol was not effective under severe laboratory or field exposure tests, unless applied in sufficient quantities to enable the cement fraction to become active as a bonding material. It was also noted that Stabinol deteriorated after long periods of storage.

One of the chemicals tested in the laboratory by the Corps of Engineers (1956)[42] and then re-tested in the field (1957)[4] was Calcium Acrylate. The results of the field tests showed Calcium Acrylate as being capable of forming a strong bond in a wet, fine grained soil by ion exchange reaction and subsequent polymerization. It also demonstrated that besides giving strength to the soil it allowed very little rain to penetrate the treated layer. Polymerization has been defined as an intermolecular combination functionally capable of proceeding indefinitely. A simple molecule of the monomer, usually of low molecular weight, will chemically combine with another similar molecule, forming a molecule consisting of two structural monomeric units firmly attached by chemical bond, and by the same process a third monomeric molecule will be chemically bonded to another and so on indefinitely until the reaction is somehow blocked, or until all the available monomers are used up.

Calcium Acrylate is an organic salt formed by combining calcium carbonate with acrylic acid. The results obtained from tests with this material were by no means conclusive and further testing was considered necessary.

Another salt tested[42] was Quaternay Ammonium Chloride which indicated a potential for being a good waterproofing agent. It had successfully waterproofed a silt soil with quantities less than 1% by soil weight. This material was also recommended to be re-tested in order to get a better idea of its effectiveness.

Many oils have been tested for their waterproofing abilities. One such road oil was Dustrol, which proved to be the most effective waterproofer within the oil group. Two theories are usually considered regarding the action of oils in waterproofing soils. One, the "plug" theory, considers that moisture is prevented from entering by a plugging of the capillaries by bodies of oil.[42] The other is the "intimate mix" theory which assumes that the individual soil particles are coated with oil. Dustrol is a liquid product, consisting of a blend of distillate of medium volatility and a viscous, non-volatile, non-asphaltic petroleum base. Dustrol waterproofed soils relatively well even under traffic loads.

The U.S. Army Corps of Engineers Waterways Experiment Station (1963)[25] had tested a few materials for their waterproofing ability. The water resistance characteristic of compacted treated specimens were examined by means of a capillary rise, wetting test conducted through four cycles of alternate wetting and drying. Previous studies have shown that the results of a capillary rise type wetting test done in the laboratory, correlates reasonably well with actual field behavior. For initial evaluation purposes, the test is normally carried through only one cycle of wetting and drying; however, for this particular study[25] since many different soils were used, the test continued for four cycles.

The capillary-rise test consists of initially recording the weights and volumes of all the air-dried samples, after a four day drying period. Each sample is then put into a loose-fitted membrane that is open at both ends and placed in an upright position on a 3/8-inch thick porous stone in a flat-bottom evaporating dish. Water is placed in the bottom of the dish, the level of the water being maintained approximately 1/8-inch below the bottom of the specimen for a period of four days. The specimens are then removed from the porous plate, and their weights and volumes determined once again. Next the rubber membrane is rolled up to the top of the specimen, to expose the specimen for the second drying cycle. After the second air-drying cycle the weights and volumes are recorded again, and the membrane rolled down once again. This alternate wetting and drying is continued for four cycles or until the specimen had achieved a condition of complete disintergration or deterioration such that further testing was impossible.

The criterion used for determining whether a treatment is satisfactory was that after the soil dried back from an optimum compacted condition, the moisture absorbed by the treated soil upon exposure to water did not exceed 50% of the total volatiles lost during the drying period.

In this experiment two separate laboratory investigations were conducted on five different soil types. The first investigation was examining the capabilities of certain selected soil additives which had previously indicated to have special potential as successful waterproofers. The second investigation consisted of testing the waterproofing potential of previously untested materials. The results of the first investigation are tabulated in Table 1.

TABLE B-1: EFFECTIVENESS FOR INDICATED ADDITIVES

Soil	MC-0 Asphalt	Modified MC-0 Asphalt	SMEPS*	Aniline Furfural	DDC**	Road Oil
Lean clay	1(V)	3(V)	6(M)	2(V)	5(M)	4(V)
Heavy clay	4(P)	3(P)	5(P)	1(V)	2(M)	6(N)
Boston blue clay	5(N)	2(M)	3(M)	1(V)	4(P)	6(N)
New Hampshire silt	6(N)	2(V)	3(M)	1(V)	5(N)	4(P)
Massachusetts Clayey silt	3(M)	1(V)	4(P)	2(V)	5(P)	6(N)

* Sodium Methyl Ethyl Propyl-Siliconate

** Diakyl Dimethylammonium Chloride

Numbers indicate the relative ranking in order of decreasing effectiveness from 1 to 6. Letters in parenthesis indicate the adjudged degree of waterproofing effectiveness as follows: V = Very Good, M = Moderate, P = Poor, N = None.

Of the materials examined, aniline-furfural (a resinous material) proved to be significantly superior to the other additives as a waterproofer of fine grained soils. It was uniquely effective in that it generally showed a continual improvement in its waterproofing ability as the test progressed. It has been found that a ratio of aniline to furfural of 70:30 applied in quantities of at least 2% by soil weight was particularly effective as a waterproofer in a wide range of fine grained soils. In addition to being a very good waterproofing material, aniline furfural also imparted very good bonding properties nearly comparable to soil cements. The methods of application will not be discussed here, as they were mentioned in the first section of wind erosion. Since the component of aniline is considered toxic, special handling must be employed. It should be pointed out however, that moist-curing conditions for aniline-furfural treated specimens, do not give successful results as the dry-curing conditions.

It is recognized by most investigators that the primary function of bitumen in soil stabilization is that of imparting water resistant characteristics to the resulting admixture. Bituminous materials have been used successfully as waterproofers for many years. The bulk of the asphalts used presently comes from the petroleum refining processes.

Asphalt-cements have semi-solid to solid consistencies and therefore must be treated to high temperatures for use. They could also be diluted with either water or other solvents such as gasoline, naptha, or kerosene. If the asphalt is diluted with water, the mixture is referred to as emulsified asphalt. If diluted with gasoline, kerosene, or naptha the mixture is referred to as cutback asphalt.[22] The designations RC, MC, SC refer to rapid curing, medium curing, and slow curing, respectively. The rate of curing is primarily dependent upon the type of solvent used. If a high volatile solvent such as gasoline or naptha is used, then curing will be rapid. If a low volatile solvent were to be used, such as kerosene or oils then a medium to slow cure would result. Rapid curing cutbacks are normally used for sandy soils containing a minimum amount of silt and clay. The medium curing and slow curing cutbacks are normally used for soils containing a considerable amount of silt and clay.

The designation of RC, MC, and SC are usually followed by a number ranging from 0 to 5. This number is an indication of the hardness of the mixture. For example, a rapid curing asphalt designated as RC-5 has the lowest amount of solvent and therefore it is the hardest of all. RC-5 would be the best suited in hot climates. Within the last few years these designations have been changed as follows: The RC, MC, and SC abbreviations remained the same, but the numbers 0, 1, 2, 3, 4, 5 were replaced by 70, 250, 800, and 3000, respectively. These too are indications of hardness but they are a measure of the viscosity of the mixture as measured in centistokes. For example, a rapid curing asphalt RC-3000 has a viscosity of 3000 to 6000 centistokes and it is the hardest of all. It is therefore best suited in hot climates just as the RC-5.

Emulsions as described previously contain asphalt dispersed as small droplets in a water medium. This sytem of water and dispersed asphalt as produced, is thermodynamically unstable. An emulsifying agent is required, in order to prevent the asphalt from coalescing. The emulsifying agent must be compatible with the water and the asphalt (i.e. it has to be both polar and non-polar to mix with the polar water molecules and the non-polar asphalt molecules). There are two types of emulsifying agents, anionic and cationic. To make cationic emulsions a suitable acid is added to the water phase. To make anionic emulsions a base is added to the water phase. Therefore, the cationic emulsion is positively charged and acidic, while the anionic emulsion is negatively charged and basic.

McKesson[42] in studying the phenomena involving bituminous emulsions stated the following "the minute asphalt particles dispersed in the emulsion were intermingled with the soil colloids during the mixing process, and when the water evaporated, these particles were pulled out into thin asphaltic films which by coating the soil grain surface, caused them to become water repellent. It should be noted, that with the gasoline shortage and strict environmental regulations, availability of asphalt cutbacks may be greatly reduced, or completely eliminated in the coming years leaving only the asphalt emulsions as the primary bituminous products.

On the basis of test results[37] it was found that the MC-0 asphalt modified with phosphorous pentoxide and Lauryl amine was second to aniline furfural in overall effectiveness. The modified asphalt was highly beneficial as a treatment for both the less and more plastic soils than the unmodified asphalt. Both the DDC (Deakyl Dimethyl Ammonium Chloride) and the SMEPS (Sodium Methyl-Ethyl Propyl Siliconate) imparted a certain degree of waterproofing, but these were not sufficiently versatile and therefore are considered unsuitable as waterproofers.

In part two of the Corps of Engineers tests,[25] only the lean clay and the heavy clay were used with 23 different additives. The criterion of effectiveness was the same as the one used in part one of the test. Of the several organic, surface-active compounds (such as Amine D acetate, Lauryl amine, N-octylamine) tested, none were effective as waterproofers of lean and heavy clay soil when employed as the primary treatment. A 40-50 penetration asphalt-gasoline cutback (2 to 1 ratio of asphalt to gasoline) in combination with phosphorous pentoxide and octadecyl amine acetate showed to be a promising waterproofer, possibly much better than the MC cutback mentioned in part one of the study.[25]

The lean clay was successfully waterproofed by a formulation of liquid phosphoric acid combined with sodium fluosilicate and noctylamine.[25] Also a combination of quicklime and cutback asphalt proved to be an effective waterproofer; however, considerably more testing was recommended before any conclusive results could be attained. The rest of the 23 materials are not mentioned here because no definite results are known. These remaining additives are listed, however, at the end of this section.

As was mentioned previously in the Wind Erosion Section, the Ashland Chemical Company had tested several chemicals (1968) that showed great promise as possessing good dustproofing and waterproofing abilities.[32] In the Wind Erosion Section these materials were discussed as to their dustproofing ability, here, they are examined only as to their waterproofing effectiveness. The samples were initially subjected to wind velocities exceeding 150 mph. The samples that had survived the test (i.e. showed no signs of broken surface) were then tested for their water erosion resistance. The test specimens were mounted below a spray nozzle calibrated to give 65^{o} solid water cone at a rate of 1.1 gallons per minute at a water pressure of 40 psi. The water erosion test lasted for two hours. Weights immediately after testing were recorded and compared to weights before testing, to determine if any water had been absorbed through the resin surface. These samples were also run on freeze-thaw and wet-dry tests. Some of the more promising chemicals are listed below along with their findings:

1. Sodium Silicate N: It forms a hard crust in sands, after one hour of curing. The water-resistant characteristics have been noted to be very good. This product has good chances for becoming a successful waterproofer.
2. Aroflint 505: It is a specially epoxidized oil resin that forms a hard, ceramic-like crust. The product is unable to cure and its water-resistant characteristics have been rated as poor (i.e. the water had soaked through the surface within one minute).
3. Lino-Cure A, Lino-Cure C, and Lino-Cure 2125: These were newly developed foundry resins. Of the above three, only the Lino-Cure C formed a hard surface which demonstrated very good waterproofing ability when applied with ethylene glycol.
4. Arothane 170: This material cured rapidly and passed the freeze-thaw and wet-dry tests without any indication of failure. Other products such as Arothane 160, Arothane 156 were under investigation with basically similar findings as the Arothane 170.
5. Siroc #1: It is an inorganic siliceous grout which had penetrated both the sand and clay; however, upon the completion of the water erosion test it showed signs of failure. It was rated, therefore as very poor.

6. Epon 828: It is produced by the Shell Chemical Company. It had produced good penetration with both sands and clays. Epon 828 formed a hard crust upon curing, even though curing time was very slow. Aside from the slow curing process, soil specimens treated with Epon 828 withstood freeze-thaw and wet-dry cycling tests without any noticeable changes.
7. Gelatin 15XPF: It gave very good penetration in sands and upon curing it formed a hard but easily breakable surface. The Gelatin 15XPF had passed the water erosion test; however, after the water test, the sample was broken easily.
8. AM-9: It is a rapid curing product (about one hour) which cures to form a crumbly soft gel, that was unable to successfully waterproof any of the soil types.
9. Chem-Rez 200: It is a furfural based, rapid setting resin which aside from its strength characteristics, offered no beneficial waterproofing characteristics with either sands or clays.
10. Emlon E 200: This was a new epoxy resin which cured rapidly (less than two hours). Results of freeze-thaw and wet-dry tests indicated this product to be very good for both sands and clays.

One of the best methods to control long range erosion is by having a vegetative cover over the land. The vegetation slows down the velocity of water, therefore surface erosion is decreased, runoff is diminished considerably, more water gets absorbed by the ground, while the roots of plants hold the soil together and protect it. The California Division of Highways currently uses seeding with rye or barley applied with either straw or sometimes wood fibers as its principal method of erosion control.[21] In most construction projects there is a certain elapsed time between construction and seeding of a vegetative cover to resist erosion. Within this certain elapsed time, rain could significantly destroy the construction site and could erode the entire fine material from the soil surface. For this reason there is a necessity to use other means of control. In 1972 the California Division of Highways had tested some commercially available spray-on products which were represented as being capable of controlling erosion for the elapsed time between rough grading of a site and the growth of vegetative cover over the finished slopes.[21]

The test was conducted on a realigned road between San Ardo and San Lucas, where the average annual rainfall had been measured to be over 10 1/2-inches. The soil was an unconsolidated fine grained sand and silt which was highly erodible. Test plots 15-feet wide and 40-feet high on a 2:1 slope were used. The test plots were seeded and then the waterproofer applied. Below is a listing of each of the materials applied along with their results:

1. Aerospray 52: A white colorless viscous alkyd resin which is water dispersible. It has no strong odor and is easy to handle and clean up. Upon drying, Aerospray 52 formed a colorless hard crust approximately 1/4-inch thick. After four months of exposure the surface cracked and a little vegetation was observed. It was rated as marginal. The price per acre is $1,092.00.
2. Aquatain: It is a water soluble liquid concentrate of chemicals and pectin. It has no strong odor and is easy to use but because of the green dye (which is used to facilitate application) it is very hard to clean up. Upon curing the Aquatain forms a thin fragile crust on the surface and therefore it was rated unsatisfactory. A major problem with Aquatain was its ability to stain skin, clothing, and equipment.
3. Conwed Fibers: They are wood fibers made of white ash. The material is light green with no odor and is easy to apply and clean up. Upon curing it forms a continuous flexible surface. The tests have shown that this material will resist erosion better than any of the other materials tested. Conwed Fibers developed a good amount of vegetative cover after four months.
4. Curasol AE: It is a white viscous polymer dispersion. It has a strong odor and although very easy to use, it was difficult to clean up. The reason being that this material is very sticky and forms a stain almost upon contact. Upon drying, it formed a brittle and very thin crust. Four months of weathering caused the Curasol AE crust to soften even more. This material was rated marginal. No vegetation was present.
5. Curasol AH: Basically the same as Curasol AE in both looks and ease of application. The basic difference is that this product forms a flexible surface. It too was rated only as marginal.

6. Ecology Control: It is a brown powder with no strong odor and very easy to use and clean up. Upon curing it formed a hard colorless surface which weakened after four months of weathering. For this reason it was rated as marginal. There was no sign of vegetation on the test plot.
7. Erode X: It is an odorless white viscous plastic material. It has no strong odor and is easy to use and clean up. When dried it formed a hard colorless surface. After the action of weather on it, the surface weakened. The rating was also marginal and there appeared to be no vegetation at all.
8. Orzan: This is a dark black, extremely viscous solution of chemicals and lignin sulfonate that was capable of forming a hard, 3-inch thick layer. It has a strong odor which disappears after application. It is easy to use and clean up. Shrinkage cracks are formed and disappear upon wetting and drying. The material was rated as very good; however, no vegetation had resulted. Orzan is relatively inexpensive and it has a lot of hope as becoming a very good erosion controller. The price per acre is $328.50. In more recent experiments, Orzan has been found to be leached out by water; however, more testing is required.
9. Surfaseal: It is a white viscous, odorless plastic that is easy to clean up and apply. Upon drying it forms a hard crust which under the abrasive action of weather had weakened. Surfaseal produced no vegetation and was rated only marginal.
10. Surftite: It is a golden brown powder composed of lignin sulfonate. It has a very strong odor, similar to that of Orzan. It is easy to use and clean up. Even though this material is very similar to Orzan, it did not react in the same way and after four months of weathering the crust had softened; therefore, it was only rated as marginal. The major problem with it was, that it leached out with the continuous wetting and drying cycles. The price is $584.00 per acre.
11. Terra-Krete: It is a light green viscous solution of chemicals in a latex base. It has no strong odors and is easy to use and clean up. Upon curing it dried to a hard colorless surface. Terra-Krete was rated marginal especially since after the four

month testing period the crust became soft. This material had exhibited some vegetation.

12. Verdyol: It is a brown granular powder with an odor similar to that of a fertilizer. Verdyol is very easy to use and clean up. Upon curing, it leaves a colorless crust on the surface. After the four months of weathering it showed a weak crust with no vegetation and it was rated as marginal. The price per acre of this material is $348.00.

In 1972 at the University of Arizona, nine waterproofers were examined by Liu.[26] In this investigation two major types of soils were used, a desert rose clay and a riverbed sand. The soil to be used was dried in an oven and then cooled down to room temperature for about eight hours, after which the soil and chemical were mixed for ten minutes by a Blakeslee mixer. The treated soil was then statically compacted to a maximum dry density at optimum moisture content as determined by the standard AASHO compactive effort. The compacted samples were then cured under three different curing periods of 1, 3, and 7 days in a curing room at 70° F. and approximately 30% relative humidity. At the end of the appropriate curing period, the samples were placed under the rainfall simulator for a period of two hours and then they were oven dried for 24 hours. The rainfall simulator is described later in Part II of this Interim Final Report. The nine waterproofers examined in this investigation are listed and described below:

1. Aerospray 52: From the laboratory tests it was concluded that Aerospray 52 generally is not a good waterproofer; however, it behaved better with the sand than with the clay and better results were obtained if curing temperatures were 110° F. The maximum erosion reduction for the sand at 70° F. curing temperature was 50% while for the 110° F. curing temperature it was 81% which was still considered not too good.
2. Aerospray 70: This chemical was found to behave very well with the sand. It produced a 93% erosion reduction after 7-day curing at 70° F. When the treated samples were cured at higher temperatures (110° F.) an erosion reduction of 97% was attained which was very good. The results on the clay indicate that Aerospray 70 was better after 1-day curing at 70° F.; however, it is not recommended to be used with clays. Aerospray 70 was superior to Aerospray 52

under all conditions.

3. Coherex: The chemical reacted very well with the sand, producing a 97% erosion reduction at 70° F. curing temperature. When cured under higher temperatures a reduction in effectiveness was observed. Coherex after 1-day curing at 70° F. reacted well with the clay (68% erosion reduction); however, after the 7-day curing period the treated clay specimens eroded more than the untreated samples. Coherex was not recommended to be used with clays.
4. Enzymatic SS: It is a dark biological material which by catalytic action on the organic content of the soil brings about soil compaction, stabilization, and waterproofing at a dilution ratio of 1:499. Enzymatic SS costs approximately 0.6¢ per square yard. From the laboratory tests it was concluded that this chemical is not suited for either sands or clays because the maximum erosion control was 15%. This product has been rated as unsatisfactory as a waterproofer.
5. Cement: Arizona portland cement which is a grey fine powder was used at an application rate of 5% (of oven dried weight of soil to be stabilized). In this investigation, cement was found to be one of the cheapest and most effective additives for rainfall erosion control. The only drawback was that the quantity required was more than for the other stabilizers. Best results were attained for the sand at 70° F. curing temperatures where 100% erosion reduction was attained. For the clays, best results were after the 1-day curing, where a 99% erosion reduction was attained. From this experiment the cement is rated excellent for all types of soils.
6. Petroset SB: It is a light tan butadiene-styrene rubber and resin tacifier, producted by the Phillips Petroleum Company. Laboratory tests indicated that this chemical was best suited for sands where a 99% erosion reduction was attained after 7-day curing at 70° F. When cured at the higher temperature of 110° F., 100% erosion reduction was achieved. With clays the maximum erosion reduction was 77% which was not considered adequate; however, this is a very good waterproofer for sands.

7. Petroset RB: It is a creamy yellow free flowing oid in water emulsion, produced by the Phillips Petroleum Company. Petroset RB is one of the most effective stabilizers tested in this study. The best results were obtained for the sand at 70° F. curing temperatures where a 98% erosion reduction was achieved. It is important to note that results were the same after 1-day or 7-day curing period. With the clay, the best results were found to be after the 1-day curing period which produced a 97% erosion reduction. The biggest drawback of this chemical is its cost, when applied at the suggested rate and concentration, the cost of material is 47.2¢ per square yard, making it the most expensive among all the stabilizers investigated.
8. Soiloc: It is a brown lignin sulfonate based chemical and co-product of the sulphite pulping industry. Soiloc was found to be ineffective for the clays as a waterproofer (erosion reduction = 15%). For the sands better results were obtained (69% erosion reduction) thereby making it only marginally applicable to sands. Best results were obtained at the 70° F. curing temperature.
9. Formula 125: This waterproofer is one of the best evaluated in this study. In all cases investigated, practically complete erosion control has been achieved. Because of its high dilution ratio of 1:44 by volume, cost of application is moderate and quantity of concentrate involved is extremely small. It was observed that the 3-day curing at 70° F. appears to be the most beneficial. Erosion reduction of 99% and 96% were attained for the sand and clay, respectively. This chemical was rated excellent as a waterproofer for both clays and sands.

Since this investigation was basically a laboratory study, correlations and verification from field investigations are needed for better evaluation of the chemical's performance.

Formula 125 developed during 1971-1972 proved to be an extremely successful waterproofer.[16] This chemical has been used successfully in sealing lakes, ponds and pits, as well as for stabilizing of unpaved roads. The chemical was tested extensively by Fatani (1973)[16] at the University of Arizona.

Formula 125 is a colorless, slightly viscous stabilizer that is claimed to waterseal a wide range of soils from gravels to clays. The exact formulation of the chemical is not avilable, since the manufacturer is protecting proprietary information. However, Formula 125 is generally composed of an ionized polysoloxine base (sodium methyl siliconate) which is a water repellent chemical and cementing agent of an organic nature. In its concentrated form, the chemical is highly caustic and should be handled carefully; however, when diluted no special handling is required, except it should not come in contact with the eyes or taken internally. Usually dilution rates with water are at a ratio of 30:1 (water to chemical). The cost of Formula 125 in its concentrated form was approximately $6.00 per gallon.

Fatani's work (1973)[16] at the University of Arizona consisted primarily of a laboratory investigation. The major conclusions derived from the experiments were as follows:

1. There was no major change in the optimum dry density nor in the optimum molding moisture content for the treated soil, but a wider molding moisture content range was obtained at both sides of the optimum.
2. An increase in the unconfined compressive strength was obtained for the treated soil, with no change in the stress-strain characteristics.
3. An effective treatment for freezing and thawing was obtained due to the sealing effect and the prevention of the formation of ice crystals. The unconfined compressive strength after freezing and thawing was lower than those for specimens not subjected to such conditions.
4. The treatment had sealed most of the soil voids and made it almost impermeable. As a result very little water was allowed to infiltrate into the soil.

Before this chemical can be judged as to its effectiveness further laboratory as well as field testing is required. Of the recent chemicals on the market today, Formula 125 has the best outlook for being an extremely reliable waterproofer.

In late 1973 twenty-one chemical stabilizers for rain erosion control have been investigated in the laboratory at the University of Arizona by

Qaqish.[38] The samples were investigated under both mixing and spraying methods at curing temperatures of 40^o and 110^o F.

It is pointed out that the investigation,[38] was conducted under the direction of the principal investigator during the laboratory phase of this project, and thus the chemicals used are common in the two studies.

For the mixing method the soil (a silty sand) was mixed with water and the chemical (diluted or undiluted as the case may be) such that the total liquid content equalled the optimum moisture content. After mixing, the soil was compacted statically into specimens 18-inches long, 3-inches wide, and 1-inch thick. The specimens were then cured for 3 days at temperatures of 40^o F. or 110^o F. After curing, specimens were tested for rain erosion.

Few specimens (mixed method) were cured for 3-days in a 70^o F. curing room, then subjected to three cycles of freezing and thawing. Each cycle consisted of 6-hours in a 10^o F. freezing room and 18 hours at 70^o F. They were cured again for 3 days at 70^o F. and then tested for rain erosion.

For the spraying method, the soil was mixed with water at optimum moisture content and specimens were prepared by compaction as in the mixing method. After compaction, specimens were cured for 7 days at 70^o F. The stabilizer was then sprayed with a spray gun at the recommended rate of application. Each specimen was then cured for 3 days at 40^o F. or 110^o F., after which the specimens were ready for rain erosion testing.

All rain erosion tests were conducted for one hour at an intensity of 2.38 inches per hour. The rain test was performed using the "Rotadisk Rainulator" which is discussed in detail in Interim Final Report - Part II.

The twenty-one chemicals used are listed and discussed below. These chemicals are non-toxic, non-flammable, non-corrosive, easily soluble in water and unharmful to plant or animal life. The cost was set not to exceed 15.0¢ per square yard. Ratings of effectiveness were based on the percent reduction in erosion relative to untreated samples. The following rating format was given:

Excellent ---------------------------------- 90% erosion reduction
Good-------------------------------------70 - 90% erosion reduction
Fair-------------------------------------50 - 70% erosion reduction
Poor-------------------------------------30 - 50% erosion reduction
Very poor---------------------------less than 30% erosion reduction

1. Compound Sp-301: It is a white latex copolymer emulsion manufactured by the Johnson-March Corporation, and costs $1.30 per gallon. It was used without dilution at a cost of 10.5¢ per square yard. The chemical is easily soluble in water and has a slight odor. From the laboratory tests it was concluded that Compound Sp-301 is best suited for the spraying method at a curing temperature of 110^{0} F. It received a rating of good.
2. White Soil Stabilizer: It is a white latex polymer manufactured by Western Farm Sevices and costs $4.31 per gallon. It was diluted at a ratio of 20:1 (water:chemical) and applied at a cost of 10.8¢ per square yard. This chemical is soluble in water and is easy to work with. From the laboratory tests this chemical performed better for the mixing method at curing temperatures of 40^{0} F., however, it still only received a rating of fair.
3. Aerospray 70: It is a white viscous polyvinyl acetate emulsion resin manufactured by American Cyanamid Company and costs $2.50 per gallon. It was diluted at a ratio of 10:1 (water:chemical) and applied at a cost of 11.8¢ per square yard. It is easily soluble in water, easy to spray and handle. Laboratory results had indicated that this material is suited for spraying at both curing temperatures, and suited for mixing at the 110^{0} F. curing temperature. The chemical received a rating of good.
4. Aerospray 52: It is a white viscous alkyd emulsion resin manufactured by American Cyanamid company and cost $2.85 per gallon. It was diluted at a ratio of 10:1 (water:chemical) and applied at a cost of 13¢ per square yard. The chemical is very soluble in water, and easy to handle. The investigation indicated that this chemical was excellent for spraying at both curing temperatures, as well as being good for mixing at 40^{0} F. curing.
5. Curasol AE: It is a white polymer plastic dispersion manufactured by American Hoechst Corporation and costs $2.60 per gallon. It was diluted at a ratio of 20:1 (water:chemical) and applied at a cost of 12¢ per square yard. It is soluble in water and has a slight paint odor; however, it is very easy to handle. The laboratory tests indicated that this chemical was good for both the mixing and spraying methods at both curing temperatures.

6. Polyco 2460: It is a white styrene/butadiene latex manufactured by Borden Chemical Company and costs \$0.87 per gallon. It was diluted at a ratio of 5:1 (water:chemical) and applied at a cost of 14.5¢ per square yard. It has a strong paint odor, and forms a thin film upon curing. From the laboratory tests it had been rated as excellent for the spraying method at the 40^{0} F. curing temperature and rated good for the 110^{0} F. curing temperature. It is not recommended for the mixing method.
7. Orzan Gl-50: It is a dark brown cementing material manufactured by Crown Zellerbach and costs \$0.30 per gallon. It was diluted at a ratio of 2:1 (water:chemical) and applied at a cost of 10¢ per square yard. The chemical is very soluble in water, and possesses a pungent odor. It was determined that this chemical is good for the spraying method and for the mixing methods at the low temperatures.
8. Surfaseal: It is a white chemical manufactured by Groutech Services and costs \$4.40 per gallon. It was diluted at a ratio of 9:1 (water:chemical) and applied at a cost of 15¢ per square yard. The chemical is easy to handle. From the laboratory experiments Surfaseal was rated excellent for the spraying method at high curing temperatures.
9. Formula 125: It is a colorless ionized polysoloxine base[16] manufactured by Transcontinental Research and Development Corporation and costs \$10 per gallon. It was diluted at a ratio of 40:1 (water:chemical) and applied at a cost of 12¢ per square yard. It has no odor and is highly soluble in water. It is very easy to spray and well absorbed by the soil. The chemical is highly caustic in its concentrated form and should be handled carefully. It was found to be most suitable for use by spraying at high and low temperatures. It was not as effective for mixing methods. It received a rating of excellent for the spraying method and a rating of poor for the mixing method.
10. Dust Bond 100: It is a light brown chemical manufactured by Dust Bond and costs \$0.36 per gallon. It was used without dilution at a cost of 12¢ per square yard. It has a lignin odor and is soluble in water. It was found suitable for both the spraying and

and mixing methods at the 40° F. curing temperature.

11. Sodium Silicate #9: It is a colorless chemical manufactured by E. I. DuPont DeNemours and Company and costs $0.60 per gallon. It was diluted at a ratio of 4:1 (water:chemical) and applied at a cost of 12¢ per square yard. It has a slight odor and is very easy to handle. In this investigation Sodium Silicate #9 was rated as excellent for the spraying method at both curing temperatures and was rated poor for the mixing method.
12. Petroset SB: It is a light tan butadiene styrene rubber and resin tacifier manufactured by Phillips Petroleum Company and costs $1.61 per gallon. It was diluted at a ratio of 12:1 (water: chemical) and applied at a cost of 12.4¢ per square yard. It is easy to handle and is soluble in water. Petroset SB was rated excellent for the spraying method and good for the mixing method.
13. Bio-Binder: It is a dark brown chemical costing $2.57 per gallon. It was diluted at a ratio of 14:1 (water:chemical) and applied at a cost of 12¢ per square yard. It has a slight odor and was rated good for the spraying method at low temperatures.
14. Dresinate DS-60W-80F: It is a dark brown thermoplastic resin, manufactured by Hercules Incorporated and costs $0.06 per pound. It was diluted at a ratio of 3:1 (water:chemical) and applied at a cost of 13.5¢ per square yard. It was rated excellent for the spraying method at the 40° F. curing temperature.
15. Terra-Krete #2: It is a light blue chemical composed of inorganic and organic materials with a synthetic binder, manufactured by Terra-Krete and costs $2.50 per gallon. It was used as a 6% solution in water and applied at a cost of 14¢ per square yard. It has a strong odor, and is easy to work with. It was found to be good at the high curing temperatures for both the mixing and spraying methods.
16. Soiltex: It is a brown lignin sulfonate manufactured by Protex Industries and costs $0.5 per gallon. It was diluted at a ratio of 3:1 (water:chemical) and applied at a cost of 12.5¢ per square yard. It was determined that Soiltex is best suited for the mixing method and the spraying method at 40° F. It received a rating of good.

17. Coherex: It is a light yellow water emulsion of petrochemicals manufactured by Witco Chemical and costs \$0.30 per gallon. It was diluted at a ratio of 4:1 (water:chemical) and applied at a cost of 9¢ per square yard. It was rated good for both the mixing and spraying methods at 40° F. curing.
18. Norlig 41: It is a dark brown lignin sulfonate manufactured by American Can Company and costs \$0.27 per gallon. It was diluted at a ratio of 1:1 (water:chemical) and applied at a cost of 13.5¢ per square yard. Best results were attained when Norlig 41 was mixed with aluminum sulfate or Formula 125. Both mixtures produced an excellent rating for the mixing method at both curing temperatures.

It should be emphasized that these chemicals have been rated based on laboratory results only and field experimentation is necessary prior to making final conclusions regarding their effectiveness.

All the chemicals described in the previous pages were applied to either completely dry soils or to moist soils that were dried back during curing in order to waterproof the soil through stopping the ingress of water into the soil system. Situations do arise, however, where the soil is completely saturated and there is a need to stop the ingress of water; the chemicals described previously did not work effectively with saturated soils.

Soil Loss Equations

As early as 1934, investigators had searched for a reliable equation which would determine the amount of soil-loss that could be anticipated due to rains. Soil loss equations include parameters representing both the internal properties of soils and the external influence of rainfall, overland slope, land management practice, and surface cover conditions. An extensive amount of research work was done by the Agricultural Research Service (1961)[1] which had developed the famous Universal Soil-Loss Equation. It is an empirical relationship between soil-loss per unit area and all the major factors known to influence rainfall erosion. The equation is given below:

$$A = RKLSCP$$

Where A is the computed soil loss in tons per acre; R is the rainfall erodibility index for a given storm period in units of foot-ton inches per acre hour. $R = \frac{EI}{100}$ where E is the total kinetic energy of a given storm and I is the maximum 30-minute rainfall intensity; $E = 916 + \log_{10}X$ and X is the rainfall intensity in inches per hour.[44,46] K is the soil erodibility factor defined as the erosion rate in tons per acre per unit of R. LS is the ratio of soil loss per unit area from a given field to that from the unit plot having a 9-percent slope and 72.6 feet length. The combined LS factor can be computed from the following empirical equation:

$$LS = X^{0.5}\ (0.0076 + .0053S + .0076S^2)$$

Where X is the field length in feet, and S is the dominant field slope in percent. The factor C reflects the combined influence of crop type and crop rotation pattern, and P is the erosion control practice factor which is a parameter representing the reduction in soil loss resulting from soil conservation measures such as contour tillage, contour strip cropping, terracing, etc. The application of the Universal Soil Loss Equation has been fully described in the Agriculture Handbook No. 282.[2] The Soil Loss Equation attempts to quantify many factors associated with the rainfall-erosion process; however, it remains a completely empirical device requiring subjective interpretation by the user.

There are many other very popular equations which are used to determine soil-loss. Musgrave in 1947 after observing 40,000 storms in the United States developed the following formula:[30]

$$E = IRS^{1.35}\ L^{0.35}\ P_{30}^{1.75}$$

Where E is the soil-loss in acre inches. I is the inherent erodibility of soil in inches, R is a cover factor, S is the slope degree in percent, L is the slope length in feet and P_{30} is the maximum 30 minute rainfall depth in inches occurring with a two year frequency. This equation is especially applicable for long term losses occurring on very large areas.

With each year, new soil-loss equations are derived; however, as yet none are 100% accurate or even reliable.

CHAPTER 3

PERFORMANCE RATINGS

Rating Format

The major stabilizers on the market today for erosion control due to rain are listed in the following pages along with their ratings. The ratings are as follows:

1. Excellent: This signifies a chemical that endured both qualitative and quantitative tests in the laboratory as well as in the field for a specified length of time.
2. Very Good: Same as "excellent" with the difference that additional investigation is required.
3. Good: This rating signifies that a chemical had controlled erosion; however, these chemicals had some form of complications such as long curing times, very strong odor, toxic nature, very hard to clean, extremely short life, etc.
4. Marginal: These are chemicals that possess some degree of waterproofing; however, many contradictions exist between investigators and consequently much more research is warranted.
5. Unsatisfactory: This signifies that the chemical did not add any benefit to the soil and the majority of investigators recommend not using the product.

CHEMICAL RATINGS

MATERIAL	RATING	COMMENTS	REF.
Acrylic Emulsion	Unsatisfactory	Cured very slowly	32
Aerospray 52	Good	Discrepancy between investigators	21, 38
Aerospray 70	Good	Good in laboratory tests	26, 38
Aluminum Sulfate	Unsatisfactory	Leaches out with water	42
AM-9	Marginal	Soft, crumbly crust	32
Amberlite PR-115	Marginal	Both in the lab and field	27
Amine D acetate	Unsatisfactory	More testing required	25
Aniline Furfural	Very good	For a variety of soils	25, 42
Aquatain	Unsatisfactory	Thin crust	21
Aroflint 505	Marginal	Forms hard crust, didn't cure	32
Aroplaz 6065	Very good	Good water repellent for sand and clay	32
Arothane 160	Good	No failure indicated by laboratory tests	32
Arothane 156	Good	No failure indicated by laboratory tests	32
Arothane 170	Good	No failure indicated by laboratory tests	32
Barium Chloride	Unsatisfactory	Leaches out with water	42
Barium Sulfate	Unsatisfactory	Leaches out with water	42
Bio-Binder	Good	For spraying method	38
Calcium Acrylate	Good	Strong bonding agent, more research needed	4
Calcium Carbonate	Unsatisfactory	Not enough information	42
Calcium Chloride	Unsatisfactory	Leaches out with water	42
Calcium Sulfonate	Good	Not enough information	42
Castor Oil	Marginal	Not enough information	27
Chem-Rez 200	Marginal	Very slow curing	32
Compound SP 301	Good	Good in the laboratory	38
Coherex	Unsatisfactory	Eroded more than untreated sample	26
Conwed Fibers	Very good	Strong flexible crust	21

MATERIAL	RATING	COMMENTS	REF.
Copper Sulfate	Unsatisfactory	Leaches out with water	42
Cottonseed Oil	Marginal	No conclusive results	27
Curasol AE	Marginal	Soft crust	21
Curasol AH	Marginal	Soft crust	21
Cutback Asphalts	Good	Good for sandy and heavy clays	42
DDC	Marginal	Were not versatile	25
Dresinate DS-60W-80F	Very good	For the spraying method	38
Dust Bond 100	Good	For mixing and spraying	38
Dustrol	Good	Needs more testing	42
Ecology Control	Marginal	Weak crust	21
Enzymatic SS	Unsatisfactory	Did not control erosion	26
Enlom E-200	Good	Cures rapidly, good with sand clays	32
Epon 828	Good	Slow curing but strong crust	32
Erode X	Marginal	Slow curing but strong crust	21
Ferrous Sulfate	Unsatisfactory	No conclusive results	42
Formula 125	Excellent	More testing required (especially in field)	16, 38
Furfural Alcohol and Sulfuric Acid	Marginal	It's very promising, more testing needed, expensive	27
Gelatin 15XPF	Good	With sands	32
Lauxite UF-77	Unsatisfactory	No benefit to treated soil	27
Lauryl Amine	Unsatisfactory	More testing required	25
Lauxite RF-901	Marginal	Good lab results, more field tests needed	27
Lime (hydrated)	Unsatisfactory	Good bonding strength, not water resistant	27, 42
Lignin Liquor	Very good	Toxic material	42
Lino-Cure A	Unsatisfactory	Did not cure	32
Lino-Cure C	Very good	When applied with Ethylene Glycol (slow cure)	32
Linseed Oil	Marginal	No conclusive results attained	27

MATERIAL	RATING	COMMENTS	REF.
Magnesium Sulfate	Unsatisfactory	Leached out by water	42
MC-0 Asphalt	Very good	Suited for lean clays	25
Mineral Oil	Marginal	No conclusive results	27
N-octylamine	Unsatisfactory	No conclusive results	25
Norlig 41	Excellent	In laboratory tests, for mixing	38
Orzan	Good	Formed strong 3" crust	21
Orzan GL-50	Good	Both for spraying and mixing	38
Petroset SB	Good	Suited for particles below gravel size	36, 38
Petroset AX	Good	Suited for strength increase	36, 38
Petroset RB	Good	Suited for large particles gravel, rock	36, 26
Petroset AT	Good	For asphalt-patching	36
Phenol Furfural Resin	Marginal	More testing needed	27
Phosphoric Acid	Marginal	Strong bonding and good waterproofer when mixed with sodium fluosilicate	25
Piccaumaron XX-100	Marginal	More testing needed when used with cement	27
Plasticized Sulfur	Marginal	No conclusive results obtained	27
Polyco 2460	Very good	For spraying method	38
Polyvinyl Acetate	Unsatisfactory	No water proofing ability	27
Polyvinyl Alcohol	Unsatisfactory	More testing required	27
Portland Cement	Unsatisfactory	Very good bonding and strengthening, but no waterproofing ability	26, 42
Powdered Asphalt	Unsatisfactory	Very good bonding and strengthening, but no waterproofing ability	42
Powdered Clay	Unsatisfactory	Bonding, but no water resistance	27
Quaternay Ammonium Chloride	Good	For silt soils	42
Resinox 9673	Good	Good under laboratory testing, needs field tests	27

MATERIAL	RATING	COMMENTS	REF.
Resinox 9671	Unsatisfactory	No benefit to soil	27
Resin 321	Good	Mostly in laboratory testing	41, 42
Road oils	Marginal	Most promising with lean clay	42
Rubber latex	Marginal	More testing needed	27
Siroc #1	Unsatisfactory	Did not cure	32
Silicone Oil	Marginal	More tests required	27
SMEPS	Marginal	For clays	26, 37
Sodium Chloride	Unsatisfactory	Leaches out by water	42
Sodium Fluosilicate	Marginal	Marginal when used in conjunction with phosphoric acid	25
Sodium Silicate N	Very good	Very fast curing time	32
Sodium Silicate #9	Excellent	For spraying method	32
Soiloc	Marginal	Promising for sands	26
Soiltex	Marginal	Suited for mixing and spraying methods	38
Styrene Resin	Unsatisfactory	No conclusive results	27
Stabinol	Good	Under laboratory tests	27, 41, 42
Surfaseal	Marginal	Weakened under the abrasive action of weather (Discrepency among investigators)	21, 38
Surftite	Marginal	Soft crust	
Tall Oil	Unsatisfactory	No benefit to soil	27
Tar	Marginal	More testing required	42
Terra-Krete #1	Marginal	Soft crust	21
Terra-Krete #2	Good	From laboratory tests (mixing and spraying)	21, 38
Tung Oil	Good	Performed on limited areas	27
Ufomite CB552	Marginal	No testing required	27
Urac 185 and Hardener	Unsatisfactory		27
Verydyol	Marginal	Weak crust	21
Vinsol	Good	More testing needed	27
White Soil Stabilizer	Good	For mixing method	38

CHAPTER 4

CONCLUSIONS

The problem of erosion due to rain is a very serious one, for it affects almost every type of construction project. Experiments have been conducted for finding a single product that would satisfactorily waterproof every type of soil; however, to this date none were found that would meet such criteria.

The chemicals mentioned in this section are the most popular types of waterproofers available. Even though some of the chemicals showed great promise as satisfactory waterproofing agents, further testing is important under different climatic conditions, different rainfall intensities, different soil conditions, etc. Some of the products mentioned in this report, have shown excellent waterproofing capabilities in the laboratory. These chemicals should be tested in the field and compared to the laboratory results. Rigorous experimentation such as the one reported in 1963 by the U.S. Army Corps of Engineers have shown that the most promising waterproofer is the aniline-furfural resin in the ratio of 70% aniline to 30% furfural.[25] Its ability to waterproof a vast number of soils as well as adding considerable strength to the soil, proves this product to be a very good waterproofer.

The use of MC-0 asphalt also showed great potential for being a successful waterproofer, but here further experimentation is required. Products such as 321, Vinsol resin, lignin have proved to be very good waterproofers, but with only certain types of soils. Of the twelve spray-on chemicals tested in San Lucas, California in 1972, the most promising were: Conwed Fibers, because of the good flexible crust it formed, and Orzan, because of the thick hard crust it formed.[21] Major disadvantages of Orzan were its inability to allow vegetative growth along with its leaching potential under water; however, for fine grained soils Orzan performed very well as a waterproofer.

From the experiments performed at the University of Arizona in 1972 by Liu[26], a few chemicals were found to possess excellent waterproofing qualities under laboratory tests, Aerospray 70, cement, Petroset SB, Petroset

RB, and Formula 125 are among the successful chemicals tested. Formula 125 has been re-tested in 1973 by Fatani[16], with results indicating that this chemical is an excellent waterproofer. In late 1973[38] more chemicals were tested at the University of Arizona. Some of the more reliable chemicals were Surfaseal, Formula 125, Sodium Silicate #9, Petroset SB, Dresinate DS-60W-80F, and Norlig 41.

In 1973, Peters[36] tested four chemicals both in the laboratory and in the field with very good results. These chemicals were Petroset SB, Petroset AX, Petroset, RB, and Petroset AT. The chemicals were discussed previously in the Wind Erosion Section. These chemicals not only waterproofed the soil, but also added bond-strength to it. These products are physically and chemically compatible and they may be very popular within the next few years.

There are a great number of chemicals that were not mentioned in this report, primarily because no conclusive results of their effectiveness have been attained to this date. Experimentation is continuing in search for the ideal product that would waterproof all different soil types.

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SECTION C

SOIL EROSION DUE TO TRAFFIC

CHAPTER 1

INTRODUCTION

In this third section of the report, the major emphasis is given to control of erosion due to traffic. Here all the major available chemicals as well as other methods of control are discussed along with their advantages and disadvantages. This section is concluded as in the previous two sections with a summary and a short listing of all the chemicals along with their effectiveness ratings. A comprehensive reference list is also included.

In the state of Arizona, a large percentage of roadways are secondary roads which are unpaved and consequently a substantial amount of money is spent yearly for their basic maintenance. Aside from this continuous yearly expense, the roads continue to rut, washboard, ravel, pothole and become a source for billowing clouds of dust.[12]

It is important at this point to distinguish between wind erosion and traffic erosion. In wind erosion, the initiation of movement is attributed to the protruding particles which are moved by the wind. The particles begin to move and spin at large speeds and then shoot into the atmosphere.

The dust clouds are caused by the action of the descending saltating particles on the smaller-size, non-protruding particles which get kicked into the atmosphere, and because of their large surface area as compared to their weights, they stay in atmospheric suspension. As was mentioned in the Wind Erosion Section, if the saltating particles were eliminated, then the smaller particles which do not protrude above the ground and are not affected by the wind would not go into suspension and consequently there would be no dust pollution. In traffic erosion, on the other hand, the action of the tires on the soil kick up these small particles into suspension. Logically much more erosion can be expected due to traffic than due to wind alone. The moving vehicles are able to pick up the larger particles that were subjected to surface creep under the wind forces. This will be discussed in more detail later in this section.

Experiments and road studies indicate that annual losses of road material can reach about 200 cubic yards per mile for unpaved roads.[24] In addition to these gravel losses, the loose aggregates make driving hazardous and result in many cases of vehicle damage including cracked windshields, chipped paint and dents as well as numerous chain accidents. It has been observed that 230% more people get killed per vehicle-mile of travel on unpaved roads than on paved roads, especially because of lack of visibility and skidding.[31]

During the spring thaw and subsequent rains, many of these unpaved roads become extremely soft, slippery and heavily rutted. The dust created by the traffic also increases the safety hazard to both passing and oncoming traffic. It is also a definite household nuisance in rural areas and especially in heavily populated areas. The excessive amount of dust causes damage to crops, such as lettuce and cotton; it causes animals to suffocate and causes laundry to get dirty before it dries. The loss of air-borne silt and clay size particulates was estimated in the order of 5 to 50 grams per vehicular mile. With a traffic volume of 250 vehicles per day the dust pollution may vary from 0.5 to 5 tons of air-borne particulates per mile per year. The dust produced 100 feet behind a car traveling at 35 mph on a moderately dusty crushed stone road was reported as equal to the pollution created by a large industrial city.[31]

As we are becoming increasingly aware of the above mentioned problems, the need for finding some products that will adequately control this erosion process is of utmost importance.

CHAPTER 2

MECHANICS OF TRAFFIC EROSION

Once again, erosion is defined as the detachment and relocation of soil particles through the abrasive action of either wind, rain or traffic. Here the primary objective is erosion due to the action of traffic. Soil erosion due to traffic can be also classified as a cycle consisting of the loosening, transportation, and sedimentation phases.

Traffic tends to reduce both the clay content (which aids in binding together the larger particles) and the moisture content of the road surface leaving it drier and more friable. With traffic, the erosive agent (or the loosening agent) is not the wind forces but the forces of the tires upon the soil grains.[22]

The mechanics of traffic erosion can be considered to occur in three phases. These are listed and shown diagrammatically in Figure C-1: As the wheel approaches, the particle is forced forward and out (Phase 1); when the wheel is directly overhead, the particle is forced downward (Phase 2); and when the wheel leaves, the particle is forced backward and out (Phase 3).

The resistance of a soil to this type of wearing action depends upon the bond between the soil particles. If the bond is broken, but sufficient moisture is present, it will re-establish as the wheel moves away; however, as the soil moisture content decreases, a point is reached where the bond remains broken.[22]

Figure C-2 illustrates microscopically the initial detachment phase of the erosion cycle. As a tire passes over a soil particle, the effect of the pressure and rotational movement picks up the particle and throws it into the atmosphere at a variety of angles depending upon the input torque of the tire.[38] The range of angles has been measured to be between 0^o and 60^o.[38]

The force T, the traction acting between the tire and the soil, can be calculated with simple statics: $T = \frac{w - v}{\sin \eta} = \frac{M + Hy - Vx}{r_e}$

There are several factors which greatly affect the rate at which wearing will take place. Some of these factors are listed below:[24] a) the traffic conditions, b) the roadway geometrics, c) the climatic conditions, and d) the characteristics of the soil aggregate mixtures.

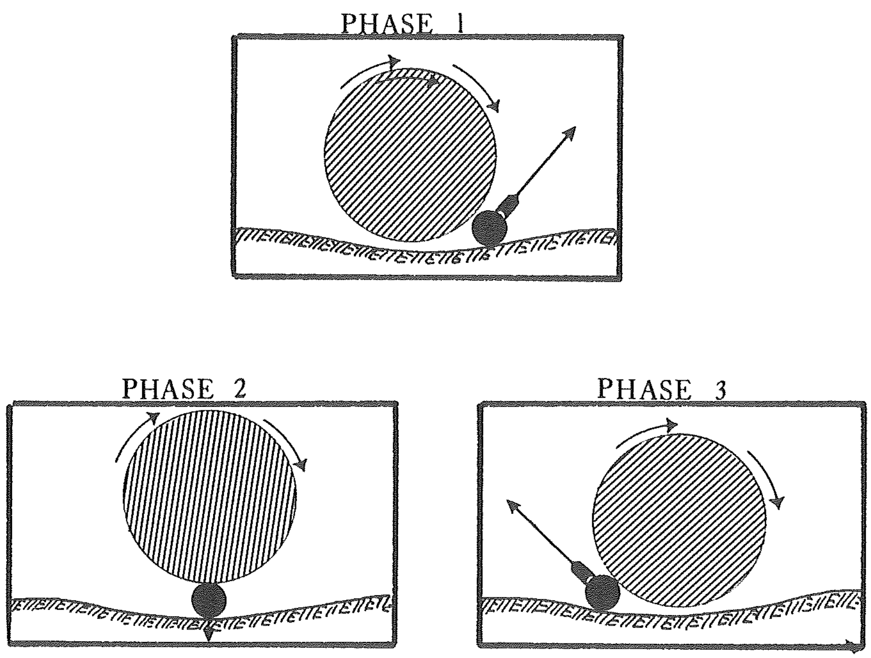

FIGURE C-1: ACTION OF TIRES ON SOIL PARTICLE

Traffic action is the worst offender, it is obvious that as traffic volume increases the wear will increase. The type of vehicle, speed of travel, wheel load, acceleration and deceleration and impact are all known to have some effect. Studies performed by Ekse (1965)[3] concluded that dual tires have much higher loosening effect on straight roadways than do wide single tires under the same loading. On the other hand, Ekse observed that wide single tires may do more damage to curved road sections.[3] Roadway geometrics such as variations in horizontal and vertical alignment, cause acceleration and deceleration which impose larger forces at the surface than are encountered on straight level roads. The centrifugal forces encountered in horizontal curves also can cause large erosion.

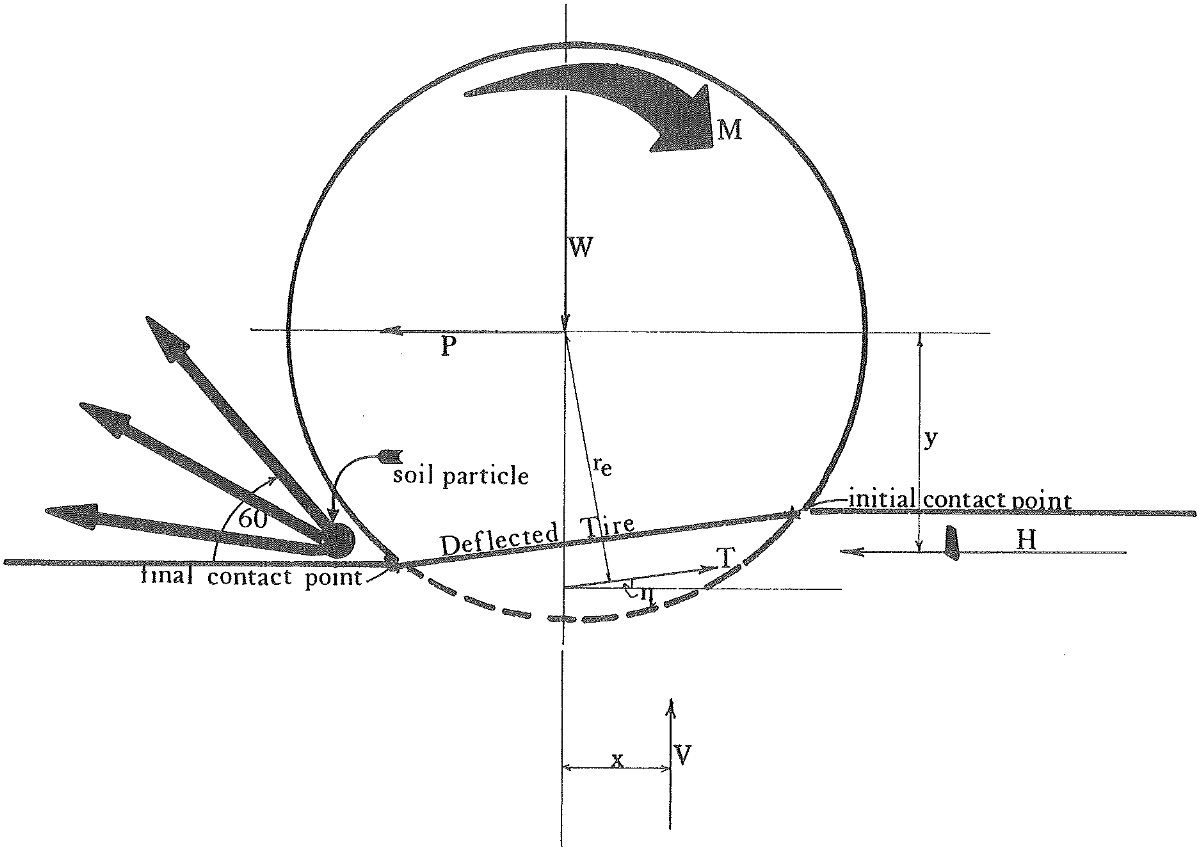

FIGURE C-2: MICROSCOPIC VIEW OF TIRE ON SOIL GRAIN

Because soil moisture has such an important influence on soil strength, the soil characteristics that affect moisture retention qualities are particularly important. Usually a well graded soil composed of larger particles that resist abrasion along with smaller particles to bind them together, offers the best wear resistance; wear resistance increases with increased plasticity index.

Once the particle has been airborn the process of transportation and sedimentation follows the same pattern as was described in the Wind Erosion Section. In wind erosion it was determined that the majority of movement was attributed to the process of saltation. This is the process whereby the particles of 0.1 to 0.5 millimeter in diameter tend to jump into the air. Particles larger than these were said to be moved by surface creep, but do not get thrown into the atmosphere. Because of larger forces produced by the vehicles, even particles as large as 2 inches in diameter have been recorded to get airborne. The damage caused by a descending 0.1 to 0.5 millimeter particle is negligible compared to the one caused by a 2 inch particle.

The process of atmospheric suspension has been described previously; however, it should be noted that under wind forces, it is necessary to have saltating particles in order to have atmospheric suspension while under traffic loads this is not necessary. As the tires roll over the soil, they kick up small particles into the air. For this reason, traffic erosion causes greater dust clouds, primarily due to having two mechanisms working; the wind and the rotational torque of the wheels. The process of sedimentation depends primarily on the size of the airborne particle. The larger the particles, the faster they will fall to the ground. The smallest particles travel the farthest, usually great distances from their original locations.

As it can be seen, the problem of traffic erosion is a major financial and health problem in great need of a solution. There are many alternatives available for controlling traffic erosion.

CHAPTER 3

CHEMICALS TESTED BY VARIOUS INVESTIGATORS

The U.S. Army Waterways Experiment Station has performed many tests for controlling erosion due to traffic. Many of the chemicals which are listed below have also been used for other purposes; however, they are discussed hereinafter as pertaining to traffic erosion only.

As mentioned earlier with decrease in soil moisture content, the tendency to re-establish the bonds between the particles decreases until the point is reached where the bond remains broken, and the soil becomes susceptible to traffic erosion. For this reason it is understandable that the introduction of an additive, which would maintain soil moisture for a considerable time, would help to re-establish the bonds and consequently to reduce the detachment process.

The use of water as a stabilizing agent has been used for many years with good results. For example, a clean beach sand that, when dry, will rut severely under a wheel load might become hard and perfectly capable of bearing the load when dampened.[25] The major disadvantage of water is that it is only a temporary means of stabilization.

Additives used for many years, especially because of their deliquescent nature have been sodium and calcium chloride.[21] These salts tend to pull water from the atmosphere, which helps to maintain the moisture film that binds the soil particles together.[29] The deliquescent effect is much greater for calcium chloride than for sodium chloride because the critical relative humidity of $CaCl_2$ is 29%, while for the $NaCl_2$ it is 80%. This means that any humidity in excess of 29% in the atmosphere will be pulled in by the calcium chloride.[5,31]

Investigations made with calcium and sodium chlorides are innumerous and at times contradictory. Some of the tests, such as the tumbling test conducted by the U.S. Army Corps of Engineers prior to 1959, found calcium chloride to be very reliable in the laboratory, while it failed in the field.

Experiments performed at Iowa State University[12] found calcium chloride to fail in the laboratory, but perform well in the field. At the present time, a majority of the investigators report that calcium chloride and sodium chloride perform better in the field than in the laboratory. One major reason for this has been attributed to not incorporating all the elements available in the field into the laboratory tests. Some of these elements are the effect of ultraviolet light, infra-red radiation and ozone resistance. It is obvious that further testing is required.

One of the more promising soil stabilization materials studied in early research at the Massachusetts Institute of Technology has been calcium acrylate. This material has been retested by the U.S. Army Corps of Engineers in the period between 1955 and 1957. The material was to render naturally unstable soils sufficiently stable to support trucks and airplanes for emergency operations.[4] Calcium acrylate is capable of forming a stable bond between particles of wet, fine-grained soils by means of ion exchange reaction and subsequent polymerization. Tests conducted by the Corps of Engineers, showed that wet, cohesive soils treated in-situ with calcium acrylate in quantities of 10% by soil weight could support wheel loads up to 26,000 lbs. The test consisted of stabilizing two test lanes with calcium acrylate and testing them under a variety of traffic. The treated soil was an inorganic lean clay. The chemical was dumped on the surface and spread by hand to a uniform thickness over the entire width and length of the test strip. Then a pulvimixer traveling at its lowest speed (132 feet per minute) made four passes so as to blend the chemical with the soil to a thickness of 4-6 inches. This mixture was then compacted by a steel wheel tandem roller. After compaction the treated surface was tested under a 10,000-lb. load and a 26,000-lb. load. The results indicated that no severe cracking occurred, and the dust problem was eliminated.

Increasing the calcium acrylate content generally increases the strength of the soil.[37] It has been observed that 10% of calcium acrylate was the optimum amount required to carry the loads as well as to dustproof.

The major disadvantage of calcium acrylate is its cost. The cost varies from $0.50 to $1.00 per pound, depending on the amount produced.

At a cost of $0.50/lb. and a 10% treatment to a depth of 6 inches, stabilizing of one mile long road, 16 feet in width would require about 211 tons of calcium acrylate and the cost of the material alone would be in the order of $211,000. Because of its larger expense, calcium acrylate is suited for only urgent jobs.[4] It has the ability to cure (or be ready) in 4 to 6 hours.

In emergencies, when dealing with wet soils, calcium acrylate could supply both the required strength as well as a good degree of dustproofing.

The most extensive amount of research work on traffic erosion control has been done by the U.S. Army Corps of Engineers. In 1959 thirteen materials were tested for their abrasive resistance,[5] where both laboratory and field testing were conducted. The field investigation consisted of the construction and testing of panels which were surfaced with a three inch thick layer of soil mixed with one of the selected materials. Traffic was applied to the test section by a military M-51, five-ton dump truck loaded to achieve a gross weight of 40,000 lbs., and tire inflation pressure of 50 psi. The total gross weight of the vehicle was distributed approximately equally to each wheel, resulting in about 4,000 lbs. single-wheel load or about 16,000 lbs. on the rear axles. After each application of traffic, all abraded material was collected from a 10 square foot area on each panel by a conventional household vacuum cleaner. Visual observations as well as photographs were taken of the gradual changes apparent in the test lane surface to aid in the evaluation of the various treatments. The test panels were exposed to weather conditions for a period of 13 months.

The vehicles travelled the test lane in such a way that all panels were travelled on each pass. The forward speed of the vehicle was maintained between 5 and 7 mph. The low speed was primarily to preclude excessive blowing away of the abraded material.

The following 13 materials were tested: quaternary ammonium chloride, a commercial road oil, calcium acrylate, aniline furfural, MC-0 asphalt, sodium methyl-ethyl propyl siliconate (SMEPS), chrome lignin, portland cement, sodium silicate, calcium chloride, an emulsified asphalt, an isomerized glyceryl ether of resin (IGER), and DDC (diakyl dimethyl ammonium chloride).

Each traffic test consisted of 40 passes of the vehicle; thus the panels were subjected to a total of 280 passes during the test period. After the first 40 tests all the treated panels had a slight surface deflection except for the modified MC-0 asphalt which had great deflections and showed rutting of the surface. After the second 40 passes the only panel which showed signs of distress was the one surface with calcium chloride, which formed severe cracks. During the five subsequent traffic tests of 40 passes each (making a total of 280 passes over the 13 panels) no additional failure or difficulty was encountered in any of the remaining panels.

Observations of the test panels immediately after periods of rainfall and during prolonged dry periods showed noticeable differences in their appearance and characteristics. In general, the DDC, aniline-furfural, MC-0 asphalt, and SMEPS panels retained a dry appearance following a heavy rainfall, with little or no apparent swelling or reduction in strength of the surface. Panels treated with the road oils also looked dry after rains; however, the surface was easily broken into fragments that crumbled readily when crushed between the fingers. The other panels such as the calcium acrylate, chrome-lignin, sodium silicate, and IGER had a wet appearance and evidenced swelling. The amount of abraded material increased with increasing rains.

The following is a list of the chemicals in order of their decreasing effectiveness from 1 to 13.

Chemicals	Resistance to Abrasion
Aniline-Furfural	1
MC-0 Asphalt	2
SMEPS (Sodium Methyl Ethyl Propyl Siliconate)	3
DDC (Diakyl Dimethyl Ammonium Chloride)	4
Road Oil	5
Quaternary Ammonium Chloride	6
Chrome Lignin	7
IGER (Isomerized Glyceryl Ether of Resin)	8
Portland Cement	9
Sodium Silicate	10

Chemicals	Resistance to Abrasion
Emulsified Asphalt	11
Calcium Acrylate	12
Calcium Chloride	13

The least effective treatment, calcium chloride, appeared to be holding up better during the first traffic tests than during the remaining ones. Near the last tests the calcium chloride showed an abraded condition, worse than that of untreated soils. The best treatment, aniline-furfural, seemed to increase in effectiveness with time, compared to the other chemicals.

A laboratory program involving attempts to develop a suitable abrasion test that would produce results correlative with those obtained in the field was also performed during this investigation.[5] Several different abrasion techniques were tried in an effort to develop a good laboratory method, some of these are given below.

The first trial was a rolling abrasion test with sand in varying quantities as the abrasive agent. The rolling test had failed to abrade a significant quantity of soil, even from untreated specimens in a reasonable length of time. After a few preliminary tests, experiments utilizing the rolling abrasion technique were discontinued. The second test was a tumbling test, with steel balls supplying additional impact and abrasion. This test was more effective than the rolling abrasion test in producing abrasion of the test specimens; however, it did not correlate with the field results. As part of the test, calcium chloride (least effective treatment in the field) and aniline-furfural (most effective treatment in the field) were subjected under the tumbling test. The results had found that calcium chloride was far superior to aniline-furfural, which is not the true field condition.

The final attempt to develop a satisfactory laboratory abrasion test was the sliding test in which sand is used, as an abrasive material, in a machine where the specimen is held stationary in a vertical position, while the sand rotates at varying speeds. This test was the best of the three; however, it also did not correlate with field results.

As mentioned earlier, the paving of roads is relatively expensive and, therefore, chemical stabilization would be the next best solution. It is important to find a stabilizer that is not too expensive; easy to apply, cures rapidly, easily accessible, and requires very little maintenance for a long period of time.

The Soviet Union in 1967 had tested a few products which are reported as being suitable as road stabilizers.[20] One such material meeting the above requirements is a product of the processing of oil shale--liquid shale tar (Shale Oil). The Soviet Union recovers most of their shale oil from the Baltic Shale Basin. Baltic shale is a hard rock consisting of a complex organic and mineral compacted mixture. The mineral component of Baltic shale consists of carbonate rocks (chiefly limestone) and also quartz and clay. As a result of thermal degradation with gradual temperature rise, different substances are obtained, including shale tar. The greatest part of the tar is used to obtain motor and boiler fuels, while the residue of the tar, mainly the heavy fractions are oxidized by sweeping hot air through them to form a road asphalt.

Accelerators have been found that when added to the liquid shale would reduce curing time as well as act as a hardener. Experiments have concluded that liquid shale tar readily penetrates cohesionless soils of a wide range of moisture contents. Shale oils with the accelerators worked very well on cohesive soils.

Another product tested to meet the previously mentioned requirements was the aniline-furfural. This product was discussed in great detail in both the Wind Erosion Section and in the Rain Erosion Section; however, as was mentioned previously the basic disadvantage of aniline-furfural has been its toxic effect, requiring special handling. Soviet researchers attempted[20] to replace liquid aniline in furfural-aniline resin with an equal amount of non-toxic powdered aniline hydrochloride. Furfural forms a resin with neutralized powdered aniline hydrochloride that is analogous to aniline-furfural resin. Aniline hydrochloride ($C_6H_5H_2HCL$) is a gray crystalline odorless powder, readily soluble in water and alcohol, and is non-toxic. It has been found that soils treated with non-toxic aniline hydrochloride exhibit adequate strength and waterproofing and dustproofing qualities. This chemical is primarily suited for highly acidic or neutral soils having a plasticity index (PI) of 3 to 20. If the PI is greater, it may be necessary to use lime prior to using the furfural resin. As with the aniline-furfural, this product is ineffective with wet soils, therefore, the combination of aniline hydrochloride and lime were found to be successful.

The third chemical tested in the Soviet Union[16] was the Sulfite liquor, which is a waste product of the cellulose-paper industry, exhibiting strong bonding properties when it reacts with hexavalent chromium compound. It forms a gel capable of dustproofing, waterproofing, and possesses good bonding strength. As mentioned in Section B of the report, the hexavalent chromium compound is toxic and causes problems during handling. During the above experiment the calcium ions in the complex were replaced with aluminum ions and a hardening accelerator-urotropine was added. In preparing this agent, the chromium consumption was reduced in half and better bonding strength was attained. A variety of soils, such as sandy silts and clays were successfully stabilized with this product.

As the search continues for an ideal product which would satisfactorily dustproof the soil as well as add a certain degree of strength to it, in order to tolerate the action of traffic without cracking, many companies were influenced to experiment with a variety of chemicals. The Dynateck Corporation was one such company.[7] They tested a few chemicals aiming for a treatment level of three pounds or less per square yard and that would be effective with a variety of soils for dust control and added bearing capacity. The materials were designed to be sprayed as liquids on the soil surface and to produce coherent, highly flexible, and extensible surface layers which effectively seal off the surface preventing the generation of dust. The flexible layer formed could withstand considerable deformations without failure. The chemicals were required to impart sufficient strength to prevent failure of the dust cover or membrane under the action of traffic. The advantage of a flexible film is that upon the application of the loads the membrane elongates and conforms to the new terrain surface. Elongation of several hundred percent may be necessary without reducing the capability of withstanding the traffic loads. Strength of over two pounds per linear inch of membrane appeared to be adequate to withstand traffic.[7]

Soil samples of sand, silts, and clays were tested both in the laboratory and in the field. Since the sand was the most difficult to stabilize most of the experiment was devoted to sands. The laboratory samples were tested under simulated wind velocities, rains, drying tests, infrared heating, ozone resistance and ultraviolet lights. In the field, the treated soil plots were allowed to cure for four hours after which they were subjected to pedestrian and vehicular traffic for a qualitative analysis. The first product tested was a plasticized urea-resin system (a mixture of an acid cured urea-resin with an emulsion of polyvinyl acetate). This material cured very rapidly but formed a film of very limited flexibility, which was unable to resist the traffic loads. Since the urea-resins were unable to control the surface from cracking under the wheel loads, this material was rated unsatisfactory. Next, instead of the urea-resins, polymers were used. The polymers cured very rapidly and were capable of much greater elongations.

One chemical tested with good results was Vultex I-V-10, which is prevulcanized rubber latex (60% solids) and was used with a phosphoric coagulator.[7] Phosphoric acid is an excellent bonding agent, similar to that of portland cement. The use of phosphoric acid is gaining popularity because it mixes easily with the soil, and requires the addition of only a very small amount to give a high degree of bonding strength to the soil. The combination of Vultex-V-10 and phosphoric acid formed an excellent, tack free coating with very good rubber properties.

It has been observed that the best results against traffic erosion are attained if after the first application of the chemical and coagulants, the surface is re-sprayed for a second time with more coagulants. A slight spray of the coagulant on top of the emulsion layer was found to set the film immediately, making the surface trafficable within a matter of minutes.

The above experiment consisted of mixing a variety of chemicals with different coagulants, such as aluminum sulfate, zinc chloride, phosphoric acid, calcium chloride, calcium nitrate, and zinc nitrate. Two coagulating agents which proved to be superior to phosphoric acid (less toxic and easier to handle) were zinc chloride and aluminum sulfate. From the chemicals tested the two most promising were Vultex 3-N-10V (a polychloroprene emulsion) and Hereatex P-1397 (a prevulcanized rubber latex), they were good dust-proofers and capable of surviving the traffic test. The other chemicals used,[7] along with their ratings are given at the conclusion of the report.

From May 1966 to December 1968, the Armour Industrial Chemical Company conducted a research program on bituminous and resinous materials for the U.S. Army Waterways Experiment Station, for the development of a new or improved dust palliative that would satisfy the following criteria:[34]

1. Be spray-applicable with currently available equipment
2. Cure fully within four hours
3. Be able to withstand random traffic over selected soil conditions
4. Possesses good stability

The primary materials tested were bitumen and resin in combination with various elastomers. These were formulated into emulsions of cationic and anionic types. The difference between the two emulsions is that in the anionic a basic type emulsifier is used which produces a negative charge on surface of the asphalt globules and thereby attracts positive surfaces, such as limestones.[31] In the cationic emulsions an acidic emulsifier is used which produces a positive charge on the surface of the asphalt globules and thereby will attract negative surfaces, such as quartz.[31]

In this experiment three different soils types were used; a sand, a silt and a clay. The treated samples were tested for their wind resistance, waterproofing abilities and their load bearing pressures. Some of the successful chemicals[34] are listed and described below:

1. Cationic Asphalt Emulsion (Identification number 803-90-66): It was found to be effective for silts and clays. Curing time was less than four hours, and upon curing it formed a strong film on the surface.
2. Cationic Petroleum Emulsion (Identification number 803-89-66): The soil was pre-wetted with water prior to the application of the chemical. This system worked only for the sandy soil, with curing time of four hours. The chemical had penetrated the soil to a depth of 1/4 inch.
3. Cationic Vinyl Asphalt Emulsion (Identification number 936-38A): Here again the surface had to be pre-wetted with water prior to the application of the chemical. This material cured in four hours; however, it did not penetrate the soil at all. This material was rated unsatisfactory for all three soil types.
4. Alkyd Resin (Identification number 936-10): This chemical worked well with all three soil types. The product cured within

four hours to form a good surface. The Alkyd Resin had penetrated the sand to 1/2 inch and penetrated both the clay and silt to 3/8 inch. This product was rated satisfactory.

5. Arquad T-50: The soil was pre-wetted with water, then the chemical was applied. Arquad had penetrated the sand to 1/4 inch and the silt and clay to 3/10 of an inch. The basic disadvantage of this product was its inability to cure rapidly. It did not cure even after 24 hours.

The other chemicals tested[34] are only mentioned at the end of the report, because no conclusive results have been obtained as to their effectiveness.

Another company searching for a successful product to control traffic erosion was the Ashland Chemical Company.[15] In their study (1968) the soil samples were tested in the laboratory under wind velocities, rain tests, freeze-thaw and wet-dry as well as unconfined compression tests.[15] These products were discussed previously both in the Wind Erosion Section and in the Rain Erosion Section. The only results obtained from the experiments which were not discussed previously were the unconfined compression tests. The chemicals listed below are the ones possessing good strength qualities .

1. Emlon E-200: This is an epoxy resin soluble in water and capable of curing within two hours or less. The unconfined compressive strength was very good (approximately 1388 psi). This specimen reacted very well under the freeze-thaw test.
2. Arothane 170: It is a polyurethane resin which cures by reaction with moisture in the air in about one hour. The results of the unconfined compression test indicate good results (700 psi).
3. Aropol 7110: An unsaturated polyester resin producing strength from 1173 psi to 2300 psi. This material appears good for traffic erosion control.

It has been observed that of all the chemicals tested by the Ashland Chemical Company, unconfined compression strength values greater than 1000 psi on treated soils were obtained with epoxy resins and unsaturated polyester resins. Aniline-furfural produced strengths ranging from 200 psi to 1000 psi, and was rated satisfactory.

During 1968-1969 the Pulp and Paper Research Institute of Canada had sent out questionnaires to several companies who had used successful stabilizers for secondary roads, to determine all the quantitative and qualitative information regarding the stabilizers.[25] The brochure included questions such as cost per mile, amount of treatment required, type of soil used, and beneficial effects.

The primary objective of all the chemicals used was to maintain adequate strength so as to hold the traffic loads without cracking, and to be able to control or eliminate the dust pollution problem. The majority of the chemicals reported were: Calcium chloride, sodium chloride, hydrated lime, prime oil, and sulphite liquors.

Response to the questionnaire regarding the use of $CaCl_2$ included a report that 95 miles of road had been tested with this chloride on gravel roads. The quantity varied from four to six tons per mile at a cost ranging from $481 to $771 per mile. The beneficial effects noted (i.e. in comparison to a similar untreated road) are listed below:

1. Dust control was achieved.
2. A hard running surface was formed, thereby substantially reducing the normal maintenance cost.
3. The surface became smoother.

The use of sodium chloride was also used for its dustproofing ability. A sand and gravel road approximately twenty-five miles in length was treated with sodium chloride. The quantity of treatment varied from 4.4 tons per mile to 16.5 tons per mile, at an average cost of $396.00 per mile. The benefits derived from the sodium chloride have been very similar to that obtained from the calcium chloride.

Since calcium chloride has a critical relative humidity of 29% while sodium chloride has a relative humidity of 80% the deliquescent nature of $CaCl_2$ is greater than that of NaCl.[31] As mentioned earlier in this part of the report, the major disadvantage of both $CaCl_2$ and NaCl is their leaching effect when water is introduced into the system.

The use of oils (such as liquid asphalt, coal tar, ET-2) for dust control on roads have been reported as being satisfactory with gravels. These oils are sprayed on the surface and then immediately covered with sand or stone chips. The oils have been used for short distances especially because of their cost of $1,600 per mile. After treatment, the dust problem has been alleviated and it was observed that vehicle velocities had increased over five miles per hour. These oils required individual patching operations at a cost of up to $127 per mile, per year.

Another chemical which was recorded as being very good with sands and gravels is sulphite liquor. Treatment with this chemical was performed on a 20-mile road at a very low cost of $150 to $500 per mile.[25] The sulphite liquor is sprayed on to the road under high pressures. After short curing time, the dust problem was controlled and a smooth, hard, well compacted surface was formed. The sulphite liquor coated the gravel particles, but repair jobs were difficult and potholes occurred under heavy loads. In one instance the whole road was in poorer condition than before treatment. Basically this product needs much more investigation.

The U.S. Department of the Army had conducted extensive research for finding a successful chemical which would dustproof the soil as well as be capable of maintaining sustained traffic loads.[1] In Part A of this report under Wind Erosion, these products were discussed as to their wind erosion resistance. In this section, the products are discussed as to their resistance to traffic erosion. Several sections were treated with chemicals to withstand regular channelized traffic by vehicles, aircraft or personnel for a limited time period. Traffic consisted of several thousand passes by rubber tire vehicles. Out of the chemicals tested, the most promising was the polypropylene and asphalt emulsion combination, which was extremely good with firm, slightly damp clays, silts and sands. This is a combination of prefabricated, cotton reinforced polypropylene fabric impregnated at the work site with an asphalt emulsion. The emulsion breaks on contact with the soil and the polypropylene is unrolled on the asphalt to absorb it. A second application of asphalt emulsion (either cationic or anionic) is then applied to the polypropylene to form an asphalt-impregnated membrane. Curing takes several days, and blotting with a thin coating of sand may be required where traffic may be applied immediately. The price of polypropylene is $0.38 per square yard and the asphalt emulsion is $0.19 per gallon, or the total application cost per acre year is $3,090.00. The useful life of a road, tested with this product under traffic conditions was estimated to be approximately 8-12 months.

Another product which reacted favorably under traffic conditions has been the DCA-70 with fiberglass. DCA-70 plus fiberglass is a polyvinyl acetate emulsion with chopped fiberglass roving used as reinforcement. Fiberglass roving contains a large number of untwisted fiberglass strands gathered in parallel and wound into the form of a cylindrical spool type package. DCA-70 plus fiberglass successfully dustproofed and sustained the wheel loads for a firm-slightly damp clay, silt, and sand. The life expectancy is not as good as that of the polypropylene and asphalt; the average life was estimated at seven months. The cost of application per acre per year is $3,943.00 which is slightly more expensive than the polypropylene and asphalt.

The third runner up in effectiveness was the DCA-70 without the fiberglass. The life expectancy was only about two months; therefore, not as good as the previously mentioned materials.

Sultan et. al. (1971)[32] conducted a laboratory investigation on the utilization of resins for rapid soil stabilization of roads and military airfields. Fifty-seven resin-formulations were investigated for their stabilization potential of sandy and clayey soils at a high moisture content. Tests included penetration resistance, compressive strength, flexural strength, double shear strength and environmental testing including freeze-thaw cycles, variable temperatures during curing and after curing along with prolonged submergence during curing and after curing.

Compressive strength values in excess of 2300 psi within curing periods not exceeding 24 hours were obtained. Flexure strength and shear strength values in excess of 290 psi and 390 psi, respectively, were attained for similar curing periods. The following is a brief description of the 18 resins that were judged to give the best performance. The additional 39 resins are listed at the end of this section of the report.

1. Amoco A: This resin formulation consisted of: unsaturated polyester resin, 100 pbw; triethanol amine, 10 pbw; ammonium persulphate (accelerator), 2.5 pbw. Amoco A is a water soluble resin which is highly compatible with water (requires the presence of moisture to cure). It cured and formed a gel within 10 to 15 minutes. Amoco A was rated better with the sand than with the clay. The sand-resin mixes hardened and continued to cure under water. At 40^{o} F. atmosphere, the sand-resin did not cure.

2. Amoco B: This resin formulation consisted of:

Unsaturated polyester	100 pbw
Triethanol amine	7 pbw
Dimethyl aniline	0.2 pbw
Benzoyl peroxide	0.5 pbw

Amoco B is a water soluble resin which cured and formed a gel in about 20 minutes. It generally rated better with sand than with clay. The sand resin mixes hardened and continued to cure under water, however, the clay resin mixes did not.

3. Ashland CR-726: This resin formulation consisted of:

Resin CR-726 (Resorcinol)	100 pbw
Accelerator 30	20 pbw

Ashland CR-726 is very water soluble and it took about five hours before it gained enough strength to be removed from the molds. Generally, better strength was achieved with clay mixes. The sand resin mixes hardened and continued to cure under water, however, the clay resin mixes did not. At low temperatures (both 10^{o} F. and 40^{o} F.) the sand resin mixes did not completely cure.

4. Celanese 510 + 872: This resin formulation consisted of:

Epi Rez (epoxy resin)	100 pbw
Epi Cure 872	35 pbw

Celanese 510 + 872, when mixed with water the resin formed an emulsion. When 3% bentonite was used the resin resulted in the greatest increase in strength. The sand resin mixes hardened and continued to cure under water, however the corresponding curing rates for the clay resin mixes were very slow. At 40^{o} F. the sand resin mixes did not appear to cure completely after 24 hours. Compressive strengths of sand resin mixes continued to increase with increasing number of freezing and thawing cycles, however, the clay resin mixes deteriorated after six cycles.

5. Celanese 16-78-16: This resin formulation consisted of:

Epi Rez 510 (Epoxy resin)	85 pbw
Epi Rez 5044 (Epoxy resin)	15 pbw
Epi Cure 8701	55 pbw

Celanese 16-78-16 was found to be highly compatible with water (requires the presence of moisture to cure). This resin was the most outstanding among all the celanese resins tested. It rated better with sand than with clay. Excellent strength performance was achieved with sand mixes in all tests. Sand and clay resin mixes hardened and continued to cure under water. The sand resin mixes cured at all temperatures ranging between 10^{o} F. and 100^{o} F. Compressive strengths of the sand resin specimens continued to increase with increasing number of feezing and thawing cycles, however, the clay resin specimens continued to deteriorate.

6. <u>Celanese 16-78-1</u>: This formulation consisted of:

Epi Rez 510 (Epoxy resin)	100 pbw
Epi Rez 856	45 pbw
Epi Cure 87	8 pbw

The addition of 2% and 3% bentonite significantly increased the penetration resistance of the sand resin mix. This resin was rated better with clay than with sand. Good strength performance was achieved with clay mixes in all tests. Sand resin mixes hardened and continued to cure under water, however,the corresponding curing rates for the clay resin mixes were relatively slower. Sand resin mixes cured at all temperatures ranging between 10^{o} F. and 100^{o} F.

7. <u>Celanese 16-78-7</u>: This resin formulation consisted of:

Epi Rez 510 (Epoxy resin)	100 pbw
Epi Cure 856	50 pbw
Accelerator MAP	15 pbw

The addition of 2% and 3% bentonite significantly increased the penetration resistance of the sand resin mix. Best strength performance by this resin was achieved for clay mixes at 10% moisture content. Sand resin mixes hardened and continued to cure under water, however the corresponding curing rates for the clay resin mixes were relatively slower. At low temperatures (both 10^{o} F. and 40^{o} F.) the sand resin mixes did not appear to cure completely.

8. <u>Jones-Dabney #6</u>: This resin formulation consisted of:

Epi Rez 5159 (Epoxy resin)	80 pbw
Epi Rez 5044 (Epoxy resin)	20 pbw
Epi Cure 874	25 pbw

The mixture of the components formed a very fluid mix which was highly compatible with water (requires the presence of moisture to cure). Better strength performance was achieved with clay than with sand mixes. Sand and clay resin mixes hardened and continued to cure under water. It appeared that the sand resin mixes did not completely cure in 10^{o} F. or in 100^{o} F. atmosphere.

9. CIBA 509 + X8157/136: This resin formulation consisted of:

Resin: Araldite 509 (Epoxy)	100 pbw
Hardner: Araldite X8157/136	75 pbw

The addition of 2% and 3% bentonite to the sand resin mix significantly increased the penetration resistance. Excellent strength performance by the resin was shown in all tests with clay mixes. Its performance with sand mixes was very poor, and it appeared that the sand resin mixes did not completely cure in 10^{o} F. or in 100^{o} F. atmosphere.

10. CIBA 6010 + X8157/136: This resin formulation consisted of:

Resin: Araldite 6010 (Epoxy)	100 pbw
Hardener: Araldite X-8157/136:	75 pbw

The addition of 2% and 3% bentonite significantly increased the penetration resistance of the sand resin mix. Outstanding performance by the resin was shown in all tests with the clay mixes at both low and high moisture contents. The sand resin mixes hardened and continued to cure under water,however the corresponding curing rates for clay resin mixes were relatively slower. Sand resin mixes appeared to cure at all temperatures ranging between 10^{o} F. and 100^{o} F.

11. Dow CX-7: This resin formulation consisted of:

Resin: CX-7056-45 (Vinyl ester)	100 pbw
Benzoyl peroxide	1.0 pbw
N.N. Dimethylanitine	0.3 pbw

Dow CX-7 is water soluble and cures rapidly in about 10 minutes. It rated better with sand than with clay. The resin showed the most outstanding performance among all the selected resins with sand mixes at all moisture contents. Excellent strength values were obtained in all tests after 3, 6, and 24 hours of curing. Sand resin mixes hardened and continued to cure underwater, however, clay resin mixes had very low penetration resistance values whether cured in air or under water. Under prolonged submergence conditions, compressive strengths of cured sand resin specimens were exceptionally high, however, the cured clay resin specimens disintegrated rapidly upon submergence. Sand resin mixes cured completely at all temperatures ranging from 10^{o} F. to 100^{o} F.

12. Dow Derakane 114: This resin formulation consisted of:

Resin: Derakane 114 (Vinyl ester)	100 pbw
Benzoyl peroxide	1.0 pbw
N. N-Dimethylaniline	0.5 pbw

It is a water soluble resin being highly compatible with water (requires presence of moisture to cure) and cured rapidly in about 10 minutes. This resin was rated slightly better with sand than with clay. Compressive strength of sand resin mixes at 3 and 24 hours of curing were very high, however, strengths of clay resin mixes hardened and continued to cure under water, however clay resin mixes had very low penetration resistance values whether cured in air or under water. Sand resin mixes cured completely at all temperatures ranging from 10^{o} F. to 100^{o} F.

13. Edoco X-2111-1: The formulation of this resin was not revealed by the formulator. The mixture is a very viscous clear material which is partially water soluble. A fairly good strength rating was achieved with both sand and clay mixes. Sand resin mixes continued to cure under water, however the corresponding curing rates for the clay resin mixes were relatively slower. Under prolonged submergence conditions, compressive strengths of cured sand resin specimens were exceptionally high, however, the cured clay resin specimens lost considerable amounts of their strengths. Sand resin mixes cured at all temperatures ranging between 10^{o} F. and 100^{o} F.

14. General Latex-Vultex: This resin formulation consisted of:

Resin: Vultapox 20-5501 (Epoxy)	140 pbw
Catalyst: 20-5501-B	40 pbw

This resin is classified as an emulsified epoxy which forms an emulsion when mixed with water. The addition of 2% and 3% bentonite increased the penetration resistance of the sand resin mix. This resin was relatively at the low end of the strength rating scale. The sand-resin mixes cured at all temperatures ranging from 10° F. to 100° F.

15. General Mills TSX-429 + TSX-428: This resin formulation consisted of:

Resin: TSX-428	191 pbw
Co-Reactive Resin TSX-429	270 pbw

This resin is classified as an emulsified epoxy which forms an emulsion when mixed with water. The addition of 2% and 3% bentonite significantly increased the penetration resistance of the sand resin mix. Its performance was at the low end of the strength rating scale. The sand resin mixes appeared to cure at all temperatures ranging between 10° F. and 100° F.

16. Shell Epon 828 + V40: This resin formulation consisted of:

Shell Epon 828	100 pbw
Epon V-40	100 pbw

When mixed, a very viscous fluid mixture which is not water soluble results. This resin is classified as an epoxy. The addition of 3% bentonite significantly increased the penetration resistance of the sand resin mix. This resin showed an excellent strength performance with both sand and clay mixes in all the conducted tests. Sand resin mixes hardened and continued to cure under water, however the corresponding curing rates of the clay resin mixes were slower. Under prolonged submergence conditions, compressive strengths of both sand and clay resin mixes were exceptionally high. Sand resin mixes completely cured at all temperatures ranging between 10° F. and 100° F.

17. Vistron Silmar S-384 D: This resin formulation consisted of:

Resin S-3840	100 pbw
Styrene Monomer	10 pbw
Dimethylaniline	15 pbw
Benzoyl Peroxide	1.5 pbw

The mixture is very fluid and is classified as a modified polyester resin. This resin is water soluble and cured very rapidly in about 10 minutes. The resin was found to be highly compatible with water (required the presence of moisture to cure). Its general performance was at the low end of the strength rating scale, with best performance for flexural and shear strengths of clay mixes at 20% moisture content.

18. Whitesides 69-Y-1: The formulation of this resin was not revealed by the formulator. The resin was a very viscous white paste material which is not water soluble. It is classified as an emulsified epoxy resin. The resin had better strength performance with sand than with clay mixes, since a uniform mixture was not possible with the latter. Sand resin mixes hardened and continued to cure under water, however the corresponding curing rates for the clay resin mixes were slower. Under prolonged submergence conditions, the cured sand resin specimens retained a considerable amount of their strengths, however the clay resin specimens deteriorated after four weeks of submergence. Sand resin mixes hardened at all temperatures ranging between 10^{o} F. and 100^{o} F.

At Iowa State University (1973), asphalt products were tested to determine their suitability for road stabilization in order to control erosion by traffic.[12] As part of the research, a traffic simulator apparatus was developed. The traffic simulator consists of a main frame about 11-feet long, 3-feet wide, and 2-feet high supported by legs bolted to a concrete slab. The frame supports a traveling carriage and specimen-retainer box. The carriage operates in an oscillating to and fro motion with an 8-inch diamter, 1 1/4-inch wide, solid rubber tire imposing the load and driving the carriage during its forward motion. This machine is also equipped with a water sprayer that simulates rain conditions. The speed was about four miles per hour, making about 1,000 passes per hour. The wheel loads which were regulated by air pressure provide a contact pressure of about 85 psi.

In that project six materials were tested in the laboratory and then the most promising materials were tested again in the field. The six materials are listed below:

1. Redicote E-36, cationic asphalt emulsion
2. MC-800, cutback asphalt
3. Peneprime, a specially processed cutback
4. Semi-Pave, a specially processed cutback
5. Petroset SB, cationic latex emulsion
6. Petroset RB, cationic latex emulsion

All these were relatively new products with the exception of the MC-800 cutback asphalt. From the unconfined compression tests the latex emulsions (Petroset SB and RB) were found to have the greatest strength compared to the others. This is probably due to the high tensile strength developed by the latex. Petroset SB and Petroset RB were also tested by Peters (1973)[28] with very promising results, and are discussed later in the report.

Several trial runs using various values of load, duration and sequence of rain, and number of passes were performed on the treated materials. Rutting, quantity of dust, and visual observations were made. The MC-800 specimen had the lowest initial rutting value while the Petroset SB exhibited the highest initial rutting value during the first 1,000 passes.

The first rain period did not exhibit any deterioration of the surfaces. Usually short duration light rains or even short duration heavy rains (if the road is well crowned) do not cause severe surface deterioration in the form of rutting. It is the long drizzling type of rain in which moisture is constantly available for absorption, aided by traffic action, that is conducive to rut formation. The second rain test proved this point in the laboratory.

Basically, the results indicated that Redicote E-36 cationic asphalt emulsion, and Petroset SB cationic latex emulsion were superior in ability to prevent rutting. MC-800 was ranked third.

These three materials seemed to be the most promising. A comparison of the cost of each of these materials is given below:

Petroset SB @ $1.50/gallon

Redicote E-36 @ 0.18/gallon

MC-800 cutback @ 0.19/gallon

Because of the very high cost of Petroset SB it was advised to neglect it as an erosion controller. In the 1973 test,[12] a road was constructed where these chemicals were tried under field conditions. This test road was subjected to heavy traffic yielding about 180 vehicles per day. The field results did not correlate very well with the laboratory test. Even with these chemicals about 100 tons of solid material in the form of dust have been removed per year under a 100 vehicle per day traffic.

As was mentioned previously, these materials are relatively new and further testing is required before any real conclusive results can be drawn.

As was mentioned in the Wind Erosion Section of the report, products under the designations of Petroset SB; Petroset AX, Petroset RB and Petroset AT have been found to be very promising materials for wind erosion control as well as for both water and traffic erosion control. These products were tested by Peters at the U.S. Andrews Air Force Base (1973).[28] As was mentioned earlier, these four products are physically and chemically compatible with each other, therefore, the chemicals can be applied alone or in any combination. Petroset SB was found to possess a high bonding power for soil particles smaller than gravel size, while Petroset RB was found to be best suited for soil particles larger than gravel size, such as boulders or rocks. Each of these four products produces a specific benefit to the soil which the soil engineer may utilize for the particular job at hand. During these tests, the four products were tested both in the laboratory and in the field, and all illustrated very good erosion protection.

In 1973, the Highway Research Board Committee on chemical stabilization had contacted numerous agencies for the purpose of determining the types of stabilizers currently being used along with their results and recommendations.[33] The most common chemicals used with the exception of lime, cement and asphalt are discussed below:

1. SA-1:[18] This chemical was produced by the Central Chemical Company, Fresno, California, as a soil stabilizing agent to be used in reconstruction of old roadway base courses. SA-1 is a liquid chemical and it has been claimed by the manufacturer that, when diluted with water to soil, produces better compaction properties through the removal of various chemical compounds which inhibit compaction and limit stability. Also claimed, is that when SA-1 solution is added to an old asphalt pavement it would result in the temporary emulsification of the existing asphalt, enabling the existing asphalt and aggregates to be mixed and recompacted in place for use as a bituminous stabilized base. The chemical was compared both in the field and in the laboratory to untreated soil sections.

   The Louisiana Department of Highways[18] had concluded that SA-1 (1966) did not increase the strength considerably. It did not aid in facilitating compaction, or show a decrease in compactive effort requirements when compared to the untreated section in order to obtain the desired base densities. Louisiana Department of Highways recommended further testing.

Experiments performed by the New Mexico State Highway Department[33] found SA-1 to provide a stronger roadbed, and reduced the amount of base course needed to obtain the desired stability. The New Mexico Highway Department does not recommend using this chemical with sand materials that lack fines.

Required treatment consists of one gallon of SA-1 to 1,000 gallons of water. SA-1 costs $25.00 per gallon and the recommended treatment costs about $0.43 per square yard, or $600.00 per mile of 24-foot wide roadway. The Illinois Department of Transportation[13] had also tested this product; however, they would not recommend it, for SA-1 failed to produce the claimed results of dispersing bituminous materials.

2. <u>Paczyme</u>: A chemical which has been tested for its benefical effect on unpaved secondary roads by a number of Highway Departments around the country is Paczyme[17] which is manufactured and marketed by the Larutan Corporation of Anaheim, California. Paczyme is 96% "ferment" which is derived from yeast and sulphate of magnesium. The "ferment" is 92% water, and it contains 2% Polyoxyethylene ester and 2% Alkyd Aryl Polyxethylene Glycol. Paczyme is claimed to aid compaction of soils by an enzymatic process of lubricating soil particles to attain higher densities. It is also claimed that Paczyme will react with organic components if present in the soils to produce increased stability of increasing cohesion and cementing soil particles together. North Carolina Department of Transportation[33] (1971) tested this chemical on four problem roads that warranted stabilization because of the physical characteristics or the effect of adverse weather conditions. The roads included both silty soils and clayey soils. The stabilization treatment was conducted on a 500 to 1000-foot section of the two lane, secondary soil-roads. A liquid solution of Paczyme, of appropriate concentration, was sprayed over scarified, in-place road material to a depth of 3 to 4 inches. The resulting material was then thoroughly blade

mixed and compacted. The stabilized area was then sealed with an asphalt emulsion. The treated sections were observed and evaluated periodically over the next seven to nine months. The sections were compared to an adjacent untreated area. At the conclusion of the test period, Paczyme was judged unsatisfactory.

Paczyme had also been tested by the Federal Highway Administration laboratories, the U.S. Army Corps of Engineers Waterways Experiment Station, the Georgia Highway Department, as well as the States of Colorado, Oregon, Alabama, and Illinois. Illinois had found that density had increased slightly; however, stability had decreased considerably. Therefore, they, along with the other agencies, had found Paczyme as unsatisfactory.

3. Lignosulfonate: Another chemical tested by various agencies has been Lignosulfonate. The Pennsylvania and Montana Highway Departments found that this product is not too effective as a dust palliative or as a soil stabilizer; however, the Iowa Highway Department found this chemical to control dust as well as provide a smooth riding surface.

CHAPTER 4

PERFORMANCE RATINGS

Rating Format

The major stabilizers on the market today for erosion control due to traffic are listed on the following pages along with their ratings. The ratings are as follows:

1. Excellent: This signifies a chemical that endured both qualitative and quantitative tests in the laboratory as well as in the field for a specified length of time.
2. Very Good: Same as "excellent" with the difference that additional investigation is required.
3. Good: This rating signifies that the chemical had controlled erosion; however, these chemicals had some form of complications such as, long curing times, very strong odors, toxic nature, very hard to clean, extremely short life, etc.
4. Marginal: These are chemicals that possess some degree of traffic erosion control power, however, many contradictions exist between investigators and consequently more research is warranted.
5. Unsatisfactory: This signifies that the chemical did not add any benefit to the soil and the majority of investigators recommend not to use the product.

MATERIAL	RATING	COMMENTS	REF.
Aerospray 52	Unsatisfactory	Did not hold up under traffic	30
Alkyd-Resin (936-10)	Marginal	Is expensive	34
Aniline Furfural	Excellent	Strong surface formed	5
Aniline Hydrochloride Furfural	Very good	As good as the aniline, non-toxic	20
AM-9	Good	Formed flexible surface	15
Amoco A	Very good	Better with sands (cures in 10 - 15 minutes)	32
Amoco B	Very good	Better with sands	32
Amercoat FV-30	Unsatisfactory	Did not set	32
Amercoat, 1987	Marginal	Low compressive strength	32
Amercoat, 1988	Unsatisfactory	Very low compressive strength	32
Arlon 110	Marginal	Needs more testing	15
Arlon 310	Marginal	Crumbly surface	15
Arlon 363	Marginal	Slow cure	15
Armid O	Unsatisfactory	Weak surface	34
Aroplaz 832	Marginal	Medium hard surface	15
Aroplaz 6008	Unsatisfactory	Did not harden	15
Aropol 7110	Good	Needs more testing	15
Arothane 170	Good	Cures by reaction with moisture in air	15
Arothane 160	Good	Hard crust with sands, slow cure	15
Arquad T-50	Marginal	Very slow curing	34
Ashland CR 726	Good	Better strength with clays	32
Ashland CR 851	Unsatisfactory	Very low strength	32
Ashland CR 866	Unsatisfactory	Did not set	32
Ashland CR 896	Unsatisfactory	Very low strength	32
Asphalt Emulsion (no. 803-90-66)	Very good	Formed strength surface	34
Atlas Korez	Unsatisfactory	Very low strength	32
Atlas #267	Marginal	Low compressive strength	32
Butapreme XR 3138	Unsatisfactory	Did not set	32
Calcium Acrylate	Very good	Good with wet soils, is expensive	4, 5, 37

MATERIAL	RATING	COMMENTS	REF.
Calcium Chloride	Unsatisfactory	Weak film, did not hold loads	5
Celanese JDK #1	Unsatisfactory	Very low strength	32
Celanese JDK #2	Unsatisfactory	Very low strength	32
Celanese 13-67-5	Good	Good compressive strength	32
Celanese 16-78-6	Marginal	Low strength	32
Celanese 510 + 872	Very good	High compressive strength, with sand resin mix	32
Celanese 16-78-16	Excellent	High strength with sand mixes	32
Celanese 16-78-1	Very good	Better with clays	32
Celanese 16-77-1	Very good	Best strength with clay mixes	32
Chem Rez 200	Marginal	Too soft, slow curing	15
Chrome Lignin	Marginal	Did not hold up loads	5
CIBA 509+830+850	Marginal	Low strength	32
CIBA 509 + 955	Unsatisfactory	Very low strength	32
CIBA 509 + 956	Marginal	Low strength	32
CIBA 509 + X8157/136	Excellent	Best results with clays	32
CIBA 6010 + X8157/136	Very good	Very good strength with sand	32
CIBA 6010 + X8157/156	Good	Good compressive strength	32
CIBA 6010 + 830 + 850	Marginal	Low strength	32
CIBA 6010 + 955	Marginal	Low compressive strength	32
CIBA 6010 + 956	Marginal	Low compressive strength	32
Coherex	Unsatisfactory	Did not harden - could not support load	15
DCA-70	Very good	Formed strong surface	1
DCA-70 and Fiberglass	Excellent	Stronger than DCA-70	1
DDC	Good	Is dispersible in water	5
Dow	Very good	Best suited for sand	32
Dow CX-7B	Good	High strength	32
Dow Derak 321+ CX	Marginal	Low compressive strength	32
Dow Derak 321 + 732 + CX	Marginal	Low compressive strength	32
Dow Derakane 114	Very good	High compressive strength with sand	32
Dupont Elvax	Unsatisfactory	Very low strength	32

MATERIAL	RATING	COMMENTS	REF.
Dupont Evanal	Unsatisfactory	Did not set	32
Edoco X-2111-1	Good	Both with sands and clays	32
Emlon E 100	Good	Formed strong surface	15
Epon 828	Unsatisfactory	Crumbly crust	15
Everflex G7	Marginal	Formed flexible surface	7
Exon 450	Marginal	Low strength	32
Exon 470	Marginal	Low strength	32
Exon 7351	Unsatisfactory	Did not set	32
Gelatine 15VPF	Marginal	Forms brittle surface	15
General latex vultex	Good	Better with sands	32
General Mills TSX-429 + TSX-428	Good	Better suited with sands	32
Geon latex 31X	Unsatisfactory	Unable to support loads	11
Goodrite Resin 50	Marginal	Brittle surface formed	19
Heavetex P1396	Good	Strong rubber surface	7
Heavetex P1397	Good	Strong rubber surface	7
Hercules	Marginal	Low strength	32
HK-1	Marginal	Forms strong surface	11
HK-2	Good	Better surface than HK-1	11
Hysol	Good	Good compressive strength	32
IGER	Marginal	Wet surface, more testing needed	5
Jones-Dabney #6	Very good	Best with clays	32
Jones-Dabney #7	Good	High compressive strength	32
Lauxite	Unsatisfactory	Did not hold up under traffic	19
Lignosulfonates	Good	Held up under traffic loads	21
Liquid Shale Tar	Good	Held up under traffic loads	20
MC-0 Asphalt	Very good	Held up under traffic loads	5
MC-800	Very good	Held up under traffic loads	12
Neoprene 750	Good	Flexible surface	7
Orzan	Good	Strong 3" crust	30

MATERIAL	RATING	COMMENTS	REF.
Pacific N748-N	Good	Strong surface	7
Paczyme	Unsatisfactory	Added no benefit to the soil	17
Peneprime	Marginal	Needs more testing	12
Petroleum Resin Emulsion #803-89-66)	Good	Strong surface, only with sands	34
Phillips BE-6	Marginal	Low strength	32
Phillips PR	Marginal	Low strength	32
Polyco 505	Unsatisfactory	Formed a weak surface	11
Portland cement	Very good	Formed very good stabilized soil with good strength	35, 24
Petroset SB	Excellent	Strong surface, suited for small size particles, expensive	28, 12
Petroset RB	Excellent	For large particles	28
Petroset AX	Excellent	Suited for extra strength	28
Petroset AT	Excellent	For asphalts	28
Phosphoric Acid	Very good	Formed strong surface	5
Emulsion Polypropylene and Asphalt	Very good	Forms a strong surface	1
Prime oil	Marginal	More testing needed	25
Q.A.C.	Unsatisfactory	Unable to carry the traffic loads	5
R + H Acrysol	Unsatisfactory	Did not set	32
Redicote E-36	Good	Held up under traffic	12
Resin 321	Marginal	Weak, unable to hold traffic loads	28
Road oil	Marginal	No conclusive results	5
SA-1	Unsatisfactory	No added strength to the soil	18, 13, 33
Shell Epon 828 + V40	Excellent	Both with clays and sands	32
Siroc #1	Unsatisfactory	Did not carry traffic loads	15
SMEPS	Good	Held up under traffic	5
Semi-Pave	Marginal	Firm surface, unable to hold traffic loads	12
Sodium Chloride	Unsatisfactory	Contradictory results obtained from laboratory and field testing	31

MATERIAL	RATING	COMMENTS	REF.
Sodium Silicate N	Marginal	Needs more testing	15
Soil Seal	Unsatisfactory	Very low strength	32
Stabinol	Marginal	Good in laboratory, needs more field testing	19
Sulphite liquor	Good	Inexpensive, needs more testing, strong bonding	16, 25
Synoset LNP	Marginal	Low strength	32
Thermoset 605 #8	Unsatisfactory	Very low strength	32
Tung oil	Marginal	Did not hold up under traffic	19
Urea Resin	Unsatisfactory	Weak limited flexible surface	20
(USS) Test #176	Unsatisfactory	Very low strength	32
Vinsol	Unsatisfactory	Did not carry traffic loads	19
Vinyl Asphalt Emulsion (936-38A)	Unsatisfactory	Did not carry traffic loads	34
Vistron Silmar S-3840	Good	Low strength, good performance for flexure and shear strength of clays	32
Vultex I-V-10	Marginal	Tack free surface	7
Vultex 2-V-109A	Unsatisfactory	Weak coating	7
Vultex 3-N-10	Marginal	A good rubber surface	7
Witco/Coherex	Marginal	Low strength	32
Whitesides 69-Y-1	Very good	Best with sands	32

CHAPTER 5

CONCLUSION

From this section of the report, it is clearly seen that traffic erosion is a serious problem that can affect every member of the community. Traffic erosion is a great financial burden on the State, which consequently affects every citizen. Aside from the large yearly maintenance expenses, there are numerous other undesirable side effects of this problem; like dust affecting the growth and quality of crops and creating health hazards for the population.

Most of the chemicals discussed in this third section of the report are in need of further experimentation; however, out of all the chemicals tested, aniline-furfural is one which for many years has proved to be effective. A major disadvantage of aniline being a toxic was alleviated by the experiments conducted in the Soviet Union, where they replaced the liquid toxic aniline in Aniline-Furfural with an aniline hydrochloride which was non-toxic. Although strength characteristics were reduced slightly, it still remains a good stabilizer for traffic erosion.

The use of calcium and sodium chlorides are still in a controversial state. Some investigators reported excellent results while others reported complete failures. Some found that the samples treated with calcium chloride decreased in strength, while others reported an increase in strength of 600 percent.[25] So, even though calcium and sodium chloride have been used for many years as successful dustproofers, their ability to control traffic erosion is not yet known.

A chemical possessing good qualities as a traffic erosion controller has been the polypropylene and asphalt emulsion tested by the U.S. Department of the Army.[3] This product had the advantage of having a service life of 8 to 12 months. Products such as DCA-70 plus the fiberglass also demonstrated good results with slightly lower service lives. As was also mentioned in the Wind Erosion Section, products such as Petroset SB, Petroset AX, Petroset RB and Petroset AT have all been found to be good stabilizers for traffic erosion especially because they are chemically and physically compatible with each other.

New chemicals are emerging in the market continuously, all represented as being good stabilizers for traffic erosion. The ideal product which would stabilize all soil types at a very economical price is still being sought.

There have been many chemicals which were not discussed in detail in this report, primarily because no conclusive results of their usefulness have been drawn. However, the summary given in Chapter 4 is a listing of the major products investigated and reported in the literature.

REPORT CONCLUSIONS

CONCLUSION

As can be concluded from the three sections of the report, to this date, no one chemical has been found which is capable of controlling erosion due to wind, rain or traffic on all major soil types. Numerous chemicals have been tested; some proved to be very effective while others showed no benefits at all to the treated section. It has been observed that good waterproofers also made good dustproofers.

A chemical that proved to be excellent for wind, rain and traffic erosion was aniline furfural resin. During the 1950's this chemical was one of the most popular ones available; however, because of its toxic nature, the chemical had lost much of its popularity in the 1960's and 1970's. Another reason for the loss of popularity is attributed to the fact that aniline-furfural only reacts well with dry soils, and any moisture or dampness in the soil reduces the strength considerably.

Salts such as sodium and calcium chlorides have been used as successful dustproofers for many years; however, to this date most laboratory results do not correlate well with the field results. Usually tests with chlorides in the laboratory fail, while they do work relatively well in the field. This leads to the obvious fact that better laboratory techniques are required.

Chemicals such as Petroset AX, Petroset RB, Petroset SB and Petroset AT, have demonstrated to be very reliable for erosion control, primarily because of their intercompatible nature which allows the engineer to utilize any or all of the individual products to suit the particular job at hand.

It has been observed that Formula 125 has an excellent prospect of becoming one of the most successful waterproofers available, yet it still is in great need for further demonstrations.

Asphalt paving has been used successfully for many years to control erosion; however, with the exponential increase in cost of all petroleum products within the last few years, the need for chemical stabilization is becoming quite obvious.

From this report it is clearly seen that more extensive research is needed in the laboratory as well as in the field to find the "ideal" erosion control agent.

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