STUDY NO. F-5; Non-Standard Stabilization

Douglas E Scholen
USDA Forest Service
Southern Regional Office
Engineering Directorate
1720 Peachtree Road
Atlanta, Georgia 30367
(404)347-2349

Abstract

This Study is part of the Coordinated Federal Lands Highways Technology Implementation Program (CTIP). It will serve the immediate needs of those who design and construct Federal Lands Highways, plus it will be helpful to many other agencies, states, counties and private parties .

Traditionally, various native soil and aggregate road bases and surfaces have been improved through inplace treatment by lime, cement or asphalt as appropriate. These improvements have included such benefits as decreased moisture sensitivity, increased supporting strength and increased lateral stability. Treatment is an economic alternative to importing and using larger quantities and higher quality materials. There exists a significant body of knowledge on benefits and limitations of these traditional materials, predictable performance criteria, and design and construction criteria.

A variety of non-traditional inplace treatment materials are presently available on the market. Attractions of these materials include local availability, concentrated forms for minimum shipping cost, or low cost in-place mixing operations not requiring special and extensive equipment spreads. However, the short and long term benefits of these materials are not known or quantified, the various soils and environments under which the various materials would provide the best service is not known, the nature of the materials and the mechanism of their contribution is not clearly understood, and specifications for design and construction are not available. Users have needed a systematic, independent assessment of these "non-standard" stabilization materials.

In response, this study has provided over 160 miles of test and demo sections on more than 60 projects across the U.S. Stabilizer types included three pozzolans, four bioenzymes, two sulfonated oils, an ammonium chloride, two mineral pitches and two clay fillers. All of these stabilizers have performed well when applied to the appropriate soils or aggregates.

Evaluations have been based on field perfomance and reduction of maintenance as related to aggregate gradation and clay content. Standard laboratory tests have not predicted field performance observed to date.

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INTRODUCTION

In recent years, a number of relatively unknown soil and aggregate stabilizers have been made available to road, street and highway engineers. Most of these materials are by-products of unrelated processes, produced or modified specifically for use as stabilizers. Unlike the traditional stabilizers such as hydrated lime, Portland cement and bitumins, these stabilizers have no standard laboratory tests in use to effectively predict their performance in the field. Because their producers are generally unfamiliar with the construction field, effective communication with engineers has been wanting or missing, and their considerable benefits remain undiscovered to large segments of the construction industry, many of whom are seeking effective solutions to long standing problems.

The gap in communication was widened in the late sixties during sporadic attempts to market several nonstandard stabilizers across the US. Two products achieved considerable noteriety in the Pacific Northwest and Rocky Mountain areas where a number of miles of road were constructed at the encouragement of enthusiastic product salesmen. The road surfaces failed completely, understandably resulting in a good deal of bitterness on the part of the project engineers. While it is difficult to pin down the exact reasons for these failures after 20 years, these areas are known for their silty soils of low plasticity which react poorly with chemical stabilizers. The products themselves, produced by fledgling companies and marketed by individuals without any real knowledge of either the stabilizer or the properties of soils, may have lacked adequate control in formulation and quality. In one case it has been reported that the company was a father-son operation in which the father kept the secret of the product formulation. When the father died suddenly, the son attempted to carry on by guessing at the formulation, resulting in project failures, and skeptics in the highway industry.

The purpose of the Study is to attempt to bridge this gap in communication by identifying some of the benefits and limitations of these products, and thereby assist the builder to reap the benefits of the years of research and study that have gone into the development of these materials for use as stabilizers. The Study has concentrated efforts on three types of materials: pozzolans, bioenzymes (biocatalysts), and electrolytes. An acrylic polymer, a pine tar derivitive, and a bentonite additive are also included.

With effective standard laboratory testing lacking, the Study has relied primarily on construction of test and demonstration road sections. During the past few years, well over 160 miles of road surfacing or subgrade have been stabilized with these materials at over 60 sites scattered across the United States. The majority of these sites are on Forest Development Roads (FDR's) on National Forest (NF) land of the United States Department of Agriculture, Forest Service (USFS) Southern Region (R8). The prolonged and often intense rainfall of this area, together with the thousands of miles of highly erosive aggregate surfacing and vast exposures of expansive clay subgrade soils had provoked an early interest in low cost stabilizers among National Forest road managers. Other users of these materials include several state, county, and local government organizations, and private enterprise. (See Table 1).

The USFS Southern Region began trial installations of these materials in 1982. Initial efforts were based upon reports from New Zealand (1) on their experience with modifying soils and aggregates using low percentages of Portland cement or lime. Attention shifted to other stabilizers as they became known. Project specifications have been developed for treatment of subgrades, aggregate bases and aggregate surfacing. This final assessment includes evaluation of all sections currently completed.

CURRENT USAGE

The commercial stabilizers included in this study have been on the market for several years or more, but until recently there has been little effort made at developing a market. The producers strategies have generally centered on corresponding with government agencies responsible for highway and street construction in attempt to get their product included in ongoing work. Since these producers have their backgrounds in other industries and know little of highway construction and maintenance, they have been unable to communicate adequately with highway engineers more often causing resentment and misunderstandings than the desired effect. Standard testing procedures employed by highway materials laboratories frequently produce mixed results that are considered inconclusive. Because the stabilizers provide properties to the soil or aggregate not normally found in these construction materials, the standard tests were not designed to identify these properties and cannot adequately predict actual field performance.

Table 1: CTIP STUDY F-5 Project Listing

Project Name	*Location*	*Stabilizer*	*Miles*	*Width*	*Date*
Rd 3421, GP NF	OR	Condor SS	0.1	16	1988
Mist-Vernonia, DOT	OR	Condor SS	2.0	30	1987
Kerr Parkway, Portland	OR	Condor SS	0.5	30	1982
City Streets, Pocatello	ID	Condor SS	3.0	30	1988
City Street, Pocatello	ID	Condor SS	1.0	30	1985
Gum Springs, Kisatchie	LA	Condor SS	2.0	24	1990
Gum Springs, Kisatchie	LA	Condor SS	2.0	24	1991
FDR 141, Gila NF	NM	Condor SS	2.2	24	1991
FH 131, Uinta NF	UT	Condor SS	2.5	24	1991
Entry Rd Chickasaw NRA	OK	Consolid 444	0.2	30	1991
City Street, Stillwater	OK	Perma-Zyme	1.0	30	1981
FDR 214, Ottowa NF	MI	Bio Cat	1.0	16	1987
FDR 724/749, Oakmulgee	AL	Lime kiln Dust	4.2	16	1983
Flatwoods, Cherokee NF	TN	Lime	4.0	16	1982
		lime kiln dust	4.0	16	1984
		lime kiln dust	4.0	16	1986
Calf Pasteur, GE NF	VA	Lime	1.9	16	1984
	VA	EMC Squared	1.0	16	1991
Tuckaho, GW NF	VA	Lime kiln dust	1.0	18	1984
		EMC Squared	1.0	18	1991
Tank Farm Rd, Converse C	WY	C Flyash	0.2	36	1991
Wyoming HWY, DOT	WY	C Flyash	230	36	1978

Table 1: CTIP STUDY F-5 Project Listing

Project Name	*Location*	*Stabilizer*	*Miles*	*Width*	*Date*
New Blaine, Ozark NF	AR	Bio Cat	0.5	18	1988
		Bio Cat	1.9	18	1990
White Rock, Ozark NF	AR	Bio Cat	0.3	24	1988
		Bio Cat	0.5	24	1990
Rich Mtn, Ozark NF	AR	Bio Cat	3.0	16	1990
Rain Mine	NV	Bio Cat	13	30	1987
FR 185, Allegheny NF	PA	Bio Cat	0.8	18	1988
Rd 21, Gifford P NF	WA	Bio Cat	1.0	18	1988
Rd 30, Pifford P NF	WA	Bio Cat	1.0	18	1988
Rd 1802, Willamette NF	OR	Bio Cat	0.4	18	1989
Rd 310, Carson NF	NM	Bio Cat	0.1	16	1988
Yellow Gap, Pisgah NF	NC	Bio Cat	0.5	16	1987
FDR 204, Sam Houston NF	TX	Bio Cat	2.5	20	1989
Burrel's Fd Andrew P NF	SC	Bio Cat/EMC	2.7	20	1990
FDR 309, Appalach. NF	FL	Bio Cat	1.8	24	1989
FDR 643, Ouachita NF	AR	Bio Cat	0.1	18	1988
Spring Creek, L&C NF	MT	Bio Cat	2.5	16	1989
Lick Creek, L&C NF	MT	EMC Squared	2.3	16	1989
FR 51 spurs, Siuslaw NF	OR	Cement kiln d	2.0	14	1980
FR 53, Siuslaw NF	OR	Cement kiln d	1.0	16	1974
FR 4811, Siusslaw NF	OR	Cement kiln d	2.0	16	1975
Five Mile Bell, Sius.NF	OR	Cement kiln d	2.5	16	1978

Table 1: CTIP STUDY F-5 Project Listing

Project Name	*Location*	*Stabilizer*	*Miles*	*Width*	*Date*
Davidson Riv, Pisgah NF	NC	Lime kiln dust	2.0	16	1985
		Lime kiln dust	1.7	16	1987
Yellow Gap, Pisgah NF	NC	Lime kiln dust	3.5	16	1987
Cathy's Crk, Pisgah NF	NC	Lime kiln dust	1.4	16	1987
Headwaters Crk,Pisg.NF	NC	Lime kiln dust	6.4	16	1987
FDR 202, Desoto NF	MS	Lime kiln dust	1.0	18	1986
		lime kiln dust	11.0	18	1987
FDR 319, Desoto NF	MS	LKD/HL-FA	8.3	18	1989
FDR 235, Oceola NF	FL	Lime kiln dust	5.0	24	1988
Sorghum Hollow,Ozark NF	AR	Cl "C" flyash	0.2	18	1984
FDR 1614, Ozark NF	AR	Cl "C" flyash	1.5	18	1988
New Blaine, Ozark NF	AR	Cl "C" flyash	2.0	18	1988
Shores Lake, Ozark NF	AR	Cl "C" flyash	5.0	18	1988
White Rock, Ozark NF	AR	Cl "C" flyash	5.0	18	1988
Harkey Valley, Ozark NF	AR	Cl "C" flyash	2.0	18	1990
FDR 508, Desto NF	MS	Cl "C" flyash	14.8	18	1989
FDR 513, Desoto NF	MS	Cl "C" flyash	2.5	18	1989
FDR 570, Kisatchie NF	LA	Cl "C" flyash	4.7	22	1988
Ground Hog, DeChutes NF	OR	Bentonite	6.0	30	1988
Benham Falls,DeChtes NF	OR	Bentonite	3.5	30	1990
FDR 1178, Chatta. NF	GA	Acrylic Poly	0.1	bank	1990
FDR 573, Ocala NF	FL	Acrylic Poly	0.2	16	1991

An example of this is the tensile strength provided by the binding properties of the stabilizers. None of the standard tests, including Proctor, CBR, unconfined compression test for this property. Thus materials engineers are unable to verify the effectiveness of the products and are unwilling to certify them. Project engineers are usually not authorized to do experimental work with public funds except in rare cases, and department managers often do not understand the technical processes. The exceptions are found in the smaller governmental organizations, counties and smaller cities with limited budgets, lighter traffic loadings, and desperate for cost reducing methods. Other successful marketing areas have included mining access roads, oil well access roads, private industrial and railroad loading areas and access roads, shopping center parking areas. Because of the limited traffic and specialized vehicles involved, this work has not caught the attention of the larger public agencies.

Unable to develop a market in the US, producers have gone overseas to developing nations, particularly in the tropical and subtropical areas with high mileage in poor subgrade soils and substandard aggregate. These relatively lucrative overseas markets have enabled some producers to survive in spite of the lack of interest at home.

Inspired by successes overseas, producers have been willing to invest more time and effort on sales in the US. This new effort, combined with failures or high costs of traditional stabilizers, and aided by this CTIP study, has resulted in some recent increase in use here, particularly in areas with extensive poor subgrade soils and substandard aggregates. In those areas traditionally rich in construction materials, new concerns.over environmental impacts are limiting development of new sources, focusing interest on conserving existing supplies. With governments at every level strapped for funds, cost saving methods are receiving renewed attention.

CERTIFICATION OF CHEMICAL STABILIZERS

The proprietary nature of the chemical stabilizers creates problems in providing chemical analyses by independant laboratories to certify the quality of a product delivered to the job site. While advanced research laboratories have this capability, the average chemical laboratory does not and will not until the producers go to the considerable expense of developing product specifications. In the absence of this information, the producers ensure quality by shipping directly from the factory to the project, avoiding and middleman contact with the stabilizer that could result in dilution of the concentrate or damage due to improper storage or handling.

Stabilizers are delivered in sealed drums carefully labeled. Seals should be inspected for tampering, and damaged drums rejected. Bioenzyme stabilizers are particulary sensitive to freezing and exposure to air, and a pinhole leak in a drum caused by a forklift can result in renewal of fermentation, ruining the stabilizer.

SOIL CHEMISTRY

TECTONIC CYCLES

While highway engineers tend to think of their natural materials as inert rock and soil with varying physical properties, these materials are in fact chemical substances that will react with other chemicals if the required conditions are present. The silicate, aluminate, magnesia, calcate and ferrate compounds comprising the earths crust change form in cycles that are functions of temperature and pressure deep in the earth's crust(2). Varying conditions of temperature and pressure are provided in the crust by the tectonic activity which forms the ocean basins and the continents. In the zones where crustal plates meet, the rocks melt into pools of liquid from which mineral crystals form and precipitate in a sequence determined by their physical properties. In cooler zones, oxide forms are altered in response to changes in temperature and pressure. At the surface alteration is caused by exposure to air and water. All of these processes are reversible under the required conditions, resulting in a cyclic chain of events through which materials experience changes in form from one mineral to another.

WEATHERING

Combinations of tectonic activity and weathering expose these rocks at the surface. The basic rocks, containing the darker minerals such as horneblend and mica are rich in compounds of aluminum, iron and magnesia. These compounds now become a part of the adjacent soil. The acid rocks have fewer dark minerals and are higher in silica, producing a sandier soil. Both basic and acid rocks may contain feldspar depending on their history. The primary weathering process in moist climates is that of hydrolysis, a chemical process in which the rock minerals, primarily the feldspars, break down to clay minerals while under the influence of acid or alkaline aqueous solutions circulating through the rock joints(3). With soil and aggregate formation, chemical processes are further affected by growth of vegetation and associated soil bacteria which incorporate nitrogen and carbon dioxide into the soil moisture, along with the various salts, acids and bases developed from the rock minerals.

In moist humid climates, where adequate water is available for hydrolysis, feldspars from acid rocks gradually convert over to platy clay minerals which provide ample percentages of plastic clay with high ion exchange capacity in the soil horizon. Feldspars from the basic rocks are less susceptible to hydrolysis and tend to form silty soils with limited ion exchange capacity. Quartz silt particles have no ion exchange capacity. In the drier climates, hydrolysis cannot take place, and feldspar rich sands are common. Under these conditions, the residual soils from feldspar rich acid or basic rocks form silt and sand of low plasticity and little to no ion exchange capacity.

ELECTROLYTE SYSTEMS

Cation Exchange

When comprised of the ion exchanging minerals, a variety of native soils are known to behave as electrolyte systems, including many subgrade soils, pit run aggregates, crushed rock from the weathered horizons, and mixtures of soils and crushed rock. The subject is discussed extensively in the literature(4). The multiple layered lattice structure of clay minerals in flat molecular sheets, and the concepts of osmotic gradient and colloid transport are fundamental to the behavior of these soil electrolytes. The unique molecular structure provides most clays with a net negative charge. To preserve electrical neutrality, positively charged cations are attracted to and held on the surfaces and edges of clay particles, and in some clay structures between the layers. These cations are termed "exchangeable cations" because in most instances cations of one type may be exchanged with cations of another type(5). When the cation charge is relatively weak, the remaining negative charge attracts polarized water molecules, filling the interlayer spaces of the clays with partially ionized water.

Osmotic Pressure Gradients

When during the weathering processes a concentration of a particular cation passes through a clay mass, the individual cations are unable to disperse freely because of the attractions of the negatively charged surfaces of the clay particles. This inability to disperse evenly throughout the solution creates an osmotic pressure gradient which tends to equalize the cation concentration throughout, and results in movement of moisture from areas of low cation concentraton to areas of high cation concentration to achieve the equilization. An example of osmotic gradient can be provided by two columns of liquid, one of sea water and the other of fresh water, connected at the base by a tube containing a flexible membrane that prevents the liquids from merging. Since the sea water has a higher unit weight, the fresh water column must rise proportionally higher to balance the pressures. This rise is the osmotic gradient(4).

Colloid Activity

Colloids are amorphous macro molecules without crystalline structure, usually one micron or less in size. Particles of this size are more strongly influenced by Brownian motion than by gravitational forces. Brownian motion is caused by bombardment by the fluid molecules or random thermal motion. Colloids are found in all natural waters, and in high concentrations when clay soils are present. Colloids have a net negative charge that enables them to attract and transport free cations in an electrolyte solution, subsequently losing the cation when contacting a more strongly charged clay particle, leaving the colloid free to seek other free cations. This activity is influenced by both physical and electrochemical effects(6). The physical phenomena are related to media pore size distribution, laminar velocity shear, and Brownian motion. Media pore size distribution determines both the laminar velocity and the proximity of the clay lattice to the passing colloids and cations. The laminar velocity shear influences the rate of cation exchange with the clay lattice. Brownian motion overcomes the effects of gravity and prevents deposition of the colloids.

Electrochemical phenomena are related to the attraction forces between positive cations and negative anions, known as Van der Waals forces, and to the repulsion forces between ions of the same charge. When a concentration of cations is introduced into a clay soil media, a micro environment is created in which the cations are prevented from dispersing by their attraction to the adjacent clay lattice. If the media is not completely saturated, capillary forces will carry the liquid phase through the soil pores in laminar flow, leaving the higher concentration of cations near the source. This creates an osmotic gradient which draws colloidal solution from zones of lower cation concentration. The colloids pick up some of the free cations, reducing the ion concentration and the osmotic gradient. This reduction in the osmotic gradient results in a hydraulic gradient in the opposite directions which carries the cation transporting colloids outward from the original zone of cation concentration where the cations are released in the presence of other clay lattice and resulting in new zone of cation concentration and osmotic gradient.

Influence of Cations

This ebb and flow of cationic solution through clay deposits has sometimes drastic effects on the behavior of the soils, resulting in natural soils in the alternating shrinking and swelling through the changing seasons of each year. When a stabilizer solution is introduced, the magnitude of the effect depends to a great deal on the nature of the particular cation. In general, the number of positive charges, or valence of the cation, and its size are the important factors. The size of the cation determines its mobility; the smaller cations travel the greater distances, and the hydrogen ion is by far the smallest. There is an exception in the case of valence: again the hydrogen ion is doubly effective in affecting the clay lattice. Although having only a single charge, the hydrogen cation produces an affect of valence of two, similar to that of Ca or Mg because of its high ionization energy. These higher valence cations exert a stronger pull on the clay layers, pulling them together and exuding the trapped moisture permitted by the single valence Na and K cations. This loss of absorbed moisture often results in a strengthening of the molecular structure of the clay with a corresponding loss of plasticity and a reduction in particle size(4). Volume is reduced, sometimes substantially, and the capacity to swell is lost. Thus shifts in the quality of the environment of a clay, from a basic to an acidic, can result in a complete change in the molecular structure of the clay over long periods of time.

Organic Cations

Organic cations generated by the growth of vegetation and bacteria also have the capacity to exchange positions with other ions in the clay lattice(5). Many organic cations are huge in size when compared to those of the mineral salts, sometimes equaling the size of the smaller clay particles. The larger flat organic cations can blanket an entire clay molecule, effectively neutralizing its negative charges and rendering it insensitive to moisture. Certain soil bacteria make use of this chemistry to stabilize their environment, producing specific enzymes that catalyze the reactions between the clays and the organic cations, producing clods of stable soil among the roots of the vegetation.

These organic phenomena sometimes occur during deposition of clays in a shallow lake of water containing a heavy concentration of decomposing vegetation. When such deposits are subsequently buried and subjected to the pressures of overburden, they produce extremely stable shales, sometimes black in color due to the excess carbon present from the organics(7).

STABILIZER CHEMISTRY AND CHARACTERISTICS

POZZOLANS

Pozzolans originate from lime manufacturing and from coal burning power plants. Pozzolans differ from other chemical stabilizers in several ways. They are waste or by products from other processes and lack the quality control of commercially produced stabilizers. Their chemical content varies with the type of process and with the type of coal used in that process. Lime kiln dust is drawn from a rotating kiln where both coal and limestone are being burned at high temperatures in nearly equal quantities. Thus the lime content, from the burned limestone is high, varying from 35 to 55 percent. Class "C" flyash is drawn from the stacks of power plants burning coal from the Powder River Basin in Wyoming. The deposits in this area contain limestone which is burned with the coal, producing comparable percentages of lime. Coal from most of the mines in the area contains 20 to 30 percent limestone. Coal from mines along the edge of the field may contain only 9 to 12 percent limestone, providing correspondingly less lime in the ash. The Powder River Basin coal field is the largest deposit in the US, with coal veins over 100 feet in thickness. The coal is sulfur free, and thus does not produce the atmospheric polution caused by eastern coal. However it does have a lower BTU content and a higher moisture content than eastern coal. Because it is "clean coal" and plentiful, it is used in many plants across the US, providing a source of the flyash containing lime for those areas.

The lime in these byproducts is quicklime; that is, it has not been hydrated, and requires more water to be added when reacting with a pozzolan. When reacting with water it releases heat and can cause skin burns. The resulting solution is caustic, with a pH above 12. This caustic environment is very different from that produced by the other chemical stabilizers. The solubility of silica and alumina is greatly increased at a high pH, resulting in drastic changes in the clay lattice structure(8). These changes can not occur at a lower pH except in the presence of certain solvents.

When a lime kiln dust or a Class "C" flyash is introduced into a soil or aggregate with moisture present, the quick lime in the additive ionizes and produces a calcium cation which can exchange with the clay mineral lattice, and a hydroxyl anion which in concentration quickly raises the pH of the solution to above 12. If clays are present in the soil, The calcium cation exchanges with the sodium and potassium in the clay lattice much in the same way that the commercially produced chemical stabilizers exchange ions. Because the calcium ion is relatively large, it cannot migrate far into the clay lattice, and thorough mixing is required to achieve maxium affect. The stronger ionization energy of the calcium ion tightens up the lattice strucure of the clays, releasing moisture and breaking down the clay clods. This action alone is enough to improve the strength of the soil, but this is only the first step in the stabilizing process. The high pH releases alumina and silica from the pozzolans provided by the additive, and from the clay lattice if clays are present in the aggregate. Even if the clay minerals are not present, the pozzolan materials from the coal ash in the additive still provide the silica and alumina ions to the solution. This free alumina and silica reacts irreversibly with the calcium ions to form calcium aluminum silicates which are similar to the compounds in Portland cement. These silicates have a net negative electrical charge which attracts ionized water molecules. These molecules act as dipoles, like tiny magnets, with a positve charge on one end and negative on the other, They align themselves on the surface of the silicates with the negative end out, attracting still other molecular dipoles in row after row to form a network of hydration bonds in channels and cavities throughout the aggregate mass, effectively cementing the aggregate particles together(9,10).

CHEMICAL STABILIZER CHARACTERISTCS AND DISTRIBUTORS

Stabilizers for clayey soils and clayey aggregates are chemical substances that can enter into the natural reactions taking place in the aggregate and control the moisture getting to the clay particles, thereby converting the clay fraction from a lubricant to a permanent cement that binds the aggregate mass together. In order to perform well as a stabilizer, a chemical must provide strong, soluble cations that can exchange with the weaker clay cations to force water from the clay lattice, resulting in a permanent structural change and significantly higher densities in the soil mass. In addition the chemical stabilizer must be non-toxic, easily applied, and readily available. The availabilty implies that it is commonly in use in industry.

The types of clay stabilizers encountered in this study included bioenzymes, sulfonated naphthalene, sulfonated D-limonene, and ammonium chloride. Each of these chemicals meet the requirements listed above. The sulfonated naphthalene and D-limonene produce powerful H+ ions which penetrate deep into the clay lattice, disrupting the structure and releasing moisture, resulting in a dense, dry mass. The ammonium chloride produces NH4+ ions that adhere strongly to the edges of the clay particles, releasing surficial moisture and permanently altering the surface structure to eliminate capillarity. The bioenzymes produce large flat organic molecules that exchange with the clay molecules and blanket them to prevent further moisture change. In each case, the stabilizer enters into the natural process to permanently alter the nature of the clays, producing a stable material.

Sulfonated Oils

The oils perform chemically as weak organic bases and when combined with the strong sulphuric acid, the reaction proceeds in the direction of forming a weaker species, resulting in a weaker acid with useful properties. These chemicals are particularly effective as soil electrolytes because of their high chemical stability, the affinity of ringed structures for metal ions, and their powerful ionizing capability. In soil solutions, they are effective in producing elevated concentrations of hydrogen ions at near normal pH, and thus present no environmental hazard. This is an oxidation process, and the presence of plentiful oxygen provides for maximum effect. The concentrate is diluted for application to the soil, and undergoes further dilution with soil moisture. The compact size of the hydrogen ion permits effective penetration of the clay mineral lattice structure; the high ionization energy of the hydrogen ion enables it to exert a strong force on the layers in the clay lattice, removing ionized water and drawing the mineral sheets together, resulting in a significant increase in density and strength. The reaction is driven in part by the affinity of the exchanged Na and K ions for the ring structured anion provided by the stabilizer solution. Reaction between the ringed anions and the Aluminum ions in the clay lattice results in the destruction of the lattice. The resulting hydrogen clay does not have high stability and will exchange with Aluminum ions present in the clay lattice to form an aluminum clay and further improve the strength. The latter phenomena is also observed in electro-osmosis where an electric current is applied to produce the gradient, providing aluminum or iron ions from the electrode materials. The hydrogen ions will not however exchange with the weaker Na or K ions, and thus the clay cannot revert back to its original state. The change is permanent and the clay mass becomes insensitve to variations in moisture. When well compacted it can provide for bearing equivalent to solid rock.

Sulfonated Naphthalene

This chemical has its most common industrial application in the manufacture of fabric dyes, where it is used as a dye intermediate(11,12). The dilution ratio in soils varies from 1:100 to 1:500 depending on the method of application and the soil moisture content. The highly stable, double ringed structure and the compact size of the hydrogen ion permits easy migration on the osmotic gradient through the clay lattice, traveling several inches to several feet from the point of application, depending upon the amount of oxygen introduced by the method of application used. The presence of the double ringed anions helps in breaking down the clay lattice. Intimate mixing of the soil with the stabilizer solution is not required, as the ions migrate through the natural moisture present in the soil following their application. Unfortunately the combination of the naphthalene with the clay produces a very slippery substance when wet, and some coarse material must be present to provide traction.

For deep stabilization of clay subgrades, the injection method is by far the most effective method. The solution is injected through a 3/8 inch nozzle under a pressure of 1500 psi, at velocities of 16 to 30 fps. The high velocity entraps air and carries it with the solution, effectively pumping quantities of oxygen deep into the subgade clays to sustain the oxidation process that produces the stabilizing H+ cations from the solution. When scarification is used, air infiltration is usually limited to the depth of penetration of the scarifiers, and the H+ cations rarely can migrate more than a few inches beyond.

Condor SS is distributed by Earth Science Products Corp., POB 327, Wilsonville, OR 97070, Leonard Reinesten, 503-678-1216; in the Dallas- Ft. Worth area by the Pro Chemical Stabilization Co., P.O. Box 180775, Dallas, Texas 75218, Johnny Sherwood, 817-447-9907 or Bob Horn, 214-681-8359; in California, the Soil Stabilization Products Co.(209-383-3296).

Sulfonated D-limonene

D-limonene (citrus stripper oil) is a by product of citrus processing used as a solvent or as an intermediary in organic synthesis by the chemical industry(12). Solvation with sulfuric acid produces a mildly corrosive acid which is environmentally harmless when diluted with water at the recommended ratios of 200:1 to 600:1. The autoionization capability of this solution provides for continuing renewal of hydrogen cations and limonene anions which can attack the clay lattice and mineral salts present in the aggregate mixture. Migration by osmosis has not been found extensive enough to consider in application, and the solution must be intimately mixed with the aggregate to obtain an adequate reaction for stabilization. Following thorough mixing the moisture content is adjusted to optimum by adding water if necessary, and the aggregate is compacted to optimum density to provide a hard, durable, all weather surface with adequate traction for traffic.

Road Bond EN1 is a sulfonated D-limonene distributed by C.S.S. Technology, Inc., 1-800-541-3348.

Ammonium Chloride

The most common industrial use of ammonium chloride is as an electrolyte for dry cells. It is non toxic and has no harmful effect on the environment. It sometimes occurs naturally, especially in volcanic deposits. The affect of the ammonium ion on soil is somewhat different from that of the sulfonated naphthalene because of its larger size as compared to the hydrogen ion. However its ionization energy is comparable, and it can replace both calcium and magnesium ions in clays. The slightly acid pH of the solution assists in driving the reaction. Because of its size, it cannot easily penetrate the clay lattice, and most of its effect is seen at the edges of the clay particles where its powerful force removes ionized water and draws the lattice together(5). The resulting osmotic gradient established pulls moisture from the particle interior, creating a permanent drying effect. While the ammonium ion is found naturally in clays, supplied by the decomposing vegetation, concentrations are extremely small. The exchange rate with other cations increases dramatically with increased concentrations of the ammonium ion, and results in the destruction of soil capillarity. However this same phenomena tends to block penetration of the ion solution into larger clods of clay, and thus considerable effort must be applied to achieve adequate mixing during the construction process. After breaking down the clods to one or two inch size, with each clod surrounded by a layer of stabilized clay, the clay mass consists of an intricate webb of stabilized membranes which block capillarity into the still susceptible clod nucluеii. When well compacted, the mass of clods provide support similar to an equivalent lift of compacted crushed aggregate.

Consolid 444 is an Ammonium Chloride soil stabilizer distibuted by American Consolid Inc., 319-386-0620.

Bioenzymes

Several thousand enzymes are currently known and put to many uses. Common uses are found in cosmetics, hair shampoos, detergents, and industrial cleaning agents. Soil enzymes occur naturally, produced by soil bacteria to catalyze reactions with nitrogen, carbon dioxide. and other soil nutrients(13). Many enzymes are adsorbed by both the expanding and the nonexpanding clay lattices, and then released upon exchange with metal cations present. In the expanding clay lattice they may be adsorbed internally as well as externally. Studies have shown the enzymes have a profound effect on these lattices, intially causing them to expand, and then to tighten. Enzymes also can be adsorbed by colloids, and by humic matter, enabling them to transport organic molecules, and to be transported through the soil electrolyte media by the colloids. The association with humic matter increases the resistance of the enzyme to biological degredation and denaturation, but tends to inhibit the enzymatic activity. This inhibitory effect is reversed by contact with metal cations. Soil bacteria can also liberate hydrogen ions, resulting in significant pH gradients at the surfaces of clay particles which assist in breaking up the lattice to increase permeability and provide entry for the colloid-enzyme-humic transport. These enzymes can be manufactured by fermentation processes. They are non toxic and environmentally harmless. An enzyme is by definition an organic catalyst which rapidly carries a chemical reaction to completion without becoming a part of the end product, the reaction being one that would normally take place at a much slower rate. To better understand what is happening in the case of the compaction enzymes, we can look at the compaction of clays and silts in nature: the formation of shale.

Most shales are formed in a marine environment which contains some organic matter. Following initial deposition in still waters, the sediments are ultimately buried under thousands of feet of overlying material which compresses them and expels much of the water they contain. The color of the shale offers interesting clues about its makeup. As the iron present is reduced from a +3 valence to a +2, the color shifts from red towards olive and gray. This reduction is aided by the the presence of the organics, which lend a carbon black color to the mixture. If sufficient organic material is present to convert all +3 iron to +2 iron, the carbon color begins to show, visibly darkening the shale(7).

The organic material present does more than simply reduce the iron or darken the color. Studies indicate that large organic molecules exchanged to the surface of the clay molecules produced a coverup effect which prevented further reactions from taking place, resulting in the clays losing their tendency to swell by water sorption(5). This effect can be noted in the greater durability of the darker shales used for road surfacing, as compared to the red shales which often slake rapidly.

Similar processes take place when a compaction enzyme is added to the mixture in soil and aggregate compaction, but at a greatly increased reaction rate. Processes that normally take millions of years are rushed through in a matter of hours and days. The enzyme combines with the large organic molecules to form a reactant intermediary, which exchanges with the clay lattice, breaking down the clay structure and causing the coverup effect which prevents any further sorption of water or the resultant swelling with loss of density. The enzyme is regenerated by the reaction and goes on to perform again. Because the ions are very large, little osmotic migration takes place, and intimate mixing is required. This is generally aided by the destructive effect of the organic ions on the clay lattice. Compaction of the aggregate mass near optimum moisture by construction equipment produces the desired high densities characteristic of shales. The resultant surface has many of the chacteristics of a solid, durable shale, yet produced in a fraction of the time required by nature.

It is common knowledge in the enzyme industry that in a reaction such as one taking place between clays and organic materials to 'waterproof' the clay, large quantities of organic material are required. Since in most processes supplying this amount of material directly would not be practical, a biotechnique is used where a bacteria culture is introduced to the system to generate the organics from the carbon dioxide present in the air. This is a commonly used method in industry.

Pure enzyme solutions are not damaged by freezing. In fact freezing is a method used for storing them. However, bioenzyme solutions must be protected from freezing because freezing will kill the bacteria.

Since all three producers of the compaction enzymes require that their product be protected from freezing, all indications are that these products are bioenzyme systems. While the mixture is being sprinkled over the road surface and mixed into the soil and aggregate, the bacteria come in contact with the carbon dioxide in the air, begin multiplying rapidly and producing large amounts of organic material. The enzyme then attaches the organics to the clays, completing this reaction before the bacteria reach their maximum growth rate and begin to die off, probably after the fourth day judging from reports of construction personnel.

Perma-Zyme (also called Endurazyme) is a bioenzyme stabilizer distributed by National Perma-Zyme, 1-800-648-0313.

Bio Cat and EMC Squared are bioenzymes distributed by Soil Stabilization Products Co, 209-383-3296.

PSCS-320 is a bioenzyme distributed by Alpha Omega Enterprises, 214-840-5503

MINERAL PITCHES

The distillation of pine tar provides the source of this strong, hard resinous pitch; an organic material that is soluble in organic solvents but not in water. In application it is contained by an emulsifying agent in a water emulsion with 26 percent solids, and performs similarly to an emulified asphalt but is capable of developing over 3 times the strength of an asphaltic cement.

The pitch emulsion is manufacture in Tennesee and marketed under the name of Road Oyl by the Soil Stabilization Products Co. (209-383-3296), and as Pine Tar by Hammond and Associates (615-542-3900).

CLAY FILLERS

Natural deposits of bentonite and Fuller's earth are found in locations across the US, providing the available sources for these materials. Bentonite can consist of either a sodium or a calcium montmorillonite. Sodium Montmorillonite has a greater affinity for moisture, and is capable of swelling to 10 times its dry volume, while the calcium variety swelling is limited to 2 to 3 times. Fuller's earth is similar, but without plasticity.

American Colloid Company in Illinois (708-392-4600 ext 161) is a major distributor throughout the US.

Stabilite is an eastern Oregon sodium bentonite distributed by the Soil Stabilization Products Co. (209-383-3296).

ACRYLIC POLYMERS

Latex acrylic co-polymers are prepared in emulsion form with 40 to 60 percent solids; they are non-toxic and non-flammable. After curing they are not water soluble.

Soil Seal is an acrylic polymer distributed by the Soil Stabilization Products Co., 209-383-3296.

Exxon Polybuilt 4178 has been discontinued and is no longer available.

SELECTION CRITERIA

Stabilizers may be separated into categories for treatment of aggregate surfaces and base courses, treatment of subgrade soils to replace the aggregate course, and treatment of subgrade soils to support the surface course. The pozzolans and some bioenzymes best fit the first, while the bioenzymes, sulfonated D-limonene and ammonium chloride fall into the second. Sulfonated naphthalene fills the reqirements of the third. There is some overlap between them all, and final selection should be based on economies as well as effectiveness.

In general, the pozzolans, bioenzymes, sulfonated D-limonene, and ammonium chloride are limited to materials where 4 to 8 inches of surfacing is adequate to support all weather traffic over the subgrade soil, as determined by standard design procedures such as CBR or R-Value. Where weak or highly expansive clays capable of excessive moisture contents are present, a thicker section will be necessary to provide a stable roadbed, and the sulfonated naphthalene is the most practical solution because of the penetrating, migrating power of its hydrogen cations, which may be injected several feet into the subgrade, converting the sensitive clays into a hard, durable layer.

APPLICABILITY TO FROST HEAVE

Pavement frost heave is one of the most difficult and confusing subjects highway engineers must deal with. Frost heave occurs during sub freezing temperatures as ice lenses form and grow in the interstices of the soil and aggregates(14). Moisture is drawn in by capillary action, increasing the volume of heave. A moisture free, well drained surfacing is not susceptible to frost heave. Silts are known to be most susceptible to frost heave because they have both capillarity and permeability. In order to benefit from chemical stabilization, any given silty soil must have ion exchange capability. This capability provides the soil particles with a net negative charge which in turn attracts ionized water and maintains a high moisture content in the soil mass. The chemical stabilizer releases and/or permanently stabilizes the moisture content, and assists in densification, reducing both capillarity and permeability, and eliminates the frost heave. If the ion exchange capacity is not present, then the moisture present in the soil interstices is not ionized and the chemical stabilizer has nothing to react upon and will have no effect on the chemically inert soil particles.

Arid climates with annual rainfall less than 10 inches will experience less frost heave due to absence of moisture in the soil; during the freeze periods. In these areas silt soils are less of a concern for cold weather.

LABORATORY TESTING

Soils and aggregates treated in the laboratory with chemical stabilizers generally show improvement in standard test results, including Atterburg limits, CBR, unconfined compression, Proctor density, and linear shrinkage in expansive soils, but results are often erratic and marginal, and may be considered inconclusive by laboratory managers looking for profound changes. Some of this problem may be due to a failure to adopt adequate modifications to procedures which permit the chemicals to perform as they do in the field. The use of metal pans and mixing implements may provide one source of interference. Chemical stabilization is an ion exchanging phenomena in which the stabilizer ions exchange with ions in the clay lattice. Both aluminum and iron provide exchangeable ions to the system in close proximity that may interfere with the normal processes, either before the stabilizing reaction takes place, or afterwards(4). In the bioenzyme process, an organic ion exchanges with the sodium or potassium in the clay lattice. The aluminum ion can also exchange with the sodium or potassium, and is more difficult for the organic ion to displace, and thus may result in only partial treatment of the laboratory sample. In the electrolyte process, particularly with the sulfonated oils, a hydrogen clay is formed by the treatment. Again the metal ions will interfere with the exchange processes underway. If this occurs before the hydrogen ion and the osmotic pressure gradients have had ample opportunity to exude the ionized water from the clay lattice, the water will remain after treatment and the sample will fail to show the full improvement occurring in the field where the metal ions are not available in such proximity.

Likewise the mixing and curing procedures should duplicate field conditions as closely as possible to avoid interference with normal processes. The molding moisture for the linear shringage test (AASHTO T92) should be at optimum rather than in excess of the liquid limit as used for untreated soils because the treated soils will not take on excess moisture in the field. In the bioenzyme process, a bacteria culture present in the stabilizer employs the carbon dioxide in the air in its metabolism to produce the organic ions needed to exchange with the clay lattice. Conditioned air often contains 1000 to 2000 ppm carbon dioxide as compared to 300 ppm in fresh air. Such high concentrations may alter the products of the metabolisum and render the ions useless or only partially effective. Thus the laboratory mixing and curing must take place in the presence of circulating fresh air to provide the required dosage of carbon dioxide to the sample. An open window or door near the bench, with a fan circulating air across the sample, would best duplicate field conditions. Prior to mixing, the solution should be aerated to duplicate filling of the tanker in the field. After mixing in the enzyme solution containing adequate water to provide optimum moisture, the soil should be aerated for at least two hours and preferably four in the draft of fresh air to duplicate field mixing conditions. Before placing in the mold for compaction, the moisture should be checked and additional water containing a trace of enzyme added as required to reestablish optimum. After compaction the specimen should be cured for five days prior to testing. In the case of the electrolyte sulfonated oils, the sample must be saturated with the stabilizer solution, thoroughly aerated, and then allowed ample time to dry thoroughly, four full days with drainage from the bottom of the container, in an environment free from metal ions, prior to preparation for testing. This drying period increases the density and prevents future penetration of moisture into the lattice structure.

Table 2: CTIP Study F-5 laboratory Data Summary

Project	*Stabilizer*	*#4*	*#40*	*#200*	*2u*	*PI*	*LL*	SL
Yellow Gap NC	Bio Cat	49	28	14	4	NP	20	
Headwaters NC	Lime kiln dust	52	30	9	0	NP	ND	
Burrel's F SC	Bio Cat/EMC	80	66	35	11	1	25	
Rd 204 TX	Bio Cat	76		13		15	26	
		89		29		18	32	
Rd 204 SG TX	Condor SS			51		49	66	
Rd 126 TX	Condor ss	87	76	43	24	45	65	
Tallula RR GA	Bio Cat	44	28	11	1	NP		
Rd 202 MS	Lime kiln dust	83	51	14		NP		
Rain Mine NV	Bio Cat		54	32	26	10		
NC DOT NC	Perma Zyme	82	58	26	10	6		
Bay Way SC TX	Raw Soil	Sandy Clay		32	51	11		
Bay Way SC TX	8% Lime					8	51	5
Bay Way SC TX	Condor SS					30	51	2

Two extremely important soil and aggregate properties substantially affected by the chemical stabilizers are probably not adequately measured by the standard testing procedures. These properties are capillarity and cohesion. Treatment with any of the stabilizers discussed here results in reduction or elimination of capillarity and an increase in the permanent cohesion. Lambe(15) has provided a procedure for measuring the capillary head that may be appropriate for comparing stabilized materials with an untreated sample. The USFS PNW materials laboratory in Portland, OR has developed a split ring tension test that may provide a better measure of cohesion than the unconfined compression test (see Appendix).

CONSTRUCTION EQUIPMENT

Construction procedures include initial shaping of the roadbed if required, scarification to the depth of treatment, application of the stabilizer, mixing, checking for optimum moisture and adjusting as required, compaction and shaping to finish lines. The thickness of treatment determines the type of scarification equipment required. Front mounted grader scarifiers are effective only to about four inches. Rear mounted grader scarifiers will do well to eight inches, although the number of teeth may have to be limited depending on the density of the surface and the percentage of coarse material present. For deeper scarification, bulldozer rippers are required. Mixing can be accomplished with the same equipment or with farm equipment which is often more efficient and faster. Following an initial scarification with front mounted grader scarifiers, a tractor drawn extra heavy duty chisel plow will mix effectively to eight inches or more, depending on the resistance the material. Tractor drawn heavy duty farm disks will mix efficiently provided the material has been well scarified. In denser material, the disk tends to ride on the surface, resisting penetration. Rotary mixers are highly efficient, fast at shallow depths but slow at eight inches or more. Their efficiency is generally not required with pozzolans, bioenzymes or sulphonated oils due to the effects of ion migration in breaking down clods. However their use is mandatory with ammonium chlorides because of the crusting effect of this chemical which produces hard clods as mixing proceeds.

In the injection procedure used optionally with the sulfonated naphthalene, holes are punched through the pavement on 6 ft. centers using a rock breaker operated by a utility wagon. Ceramic washer pumps developing 1500 psi minimum pressure with 5.5 gpm minimum flow (Landa Pressure Washer or equivalent) are used with 3/8 inch hose, a 3/8 inch x 5 ft pipe equipped with a dump gun valve and nozzle to jet through the subgrade clay and inject the solution at depth into the subgrade strata. The 16 fps minimum jet velocity injects quantities of air along with the solution, vital to the oxidation process associated with the stabilization of the clays.

Developing the best moisture content for compaction is critical to work performance. This varies with the aggregate gradation and the type of stabilizer. The Proctor curve provides a guideline to the correct approach. Coarse grained aggregates have a peaked curve and need to have the moisture close to optimum to compact quickly. In hot, windy conditions this requires working in short sections with the roller directly behind the water truck. Silty materials have a flat proctor curve and can be more easily compacted dry of optimum, permitting work to proceed in longer sections. Bioenzymes contain wetting agents and compact best dry of optimum, are difficult to dry back if too much water is added. Pozzolans require additional water to hydrate the lime beyond what is needed for optimum. Sulfonated naphthalene may release ionized water from subgrade clays, increasing the effective moisture content and reducing the optimum moisture, requiring drying for compaction.

The size and number of water tankers on any given project often determines the output of the work. Roundtrip haul time may be an hour or more, and if two tankers are not available, other equipment will be waiting, particularly for the pozzolans which require extra moisture for hydration of the lime, and for the sulfonated naphthalene which requires dilutions of 300:1. Gravity flow through the spreader bar is adequate but requires multiple passes of light applications to approximate an even spread over the section. A metered flow can be accomplished in one pass with pumping, provided the meter and the plumbing are large enough to accommodate the required flow. A four to six inch meter may be required in some cases. When sulfonated naphthalene is pumped, the pump must have teflon seals as this chemical attacks any dead organic material, incuding fiber, linen, cotton and leather.

Dry application of pozzolans is best done with pneumatic pumping from a tanker through a spreader bar. Not all tankers are equipped with spreader bars, and some suppliers may require a second tanker at the job site to do the spreading. However usually the spreader bar can be arranged with some persistance. To accommodate these tankers, the road alignment must be adequate for eighteen wheelers. On short radius curvature in mountainous areas, dump trucks can be used by cracking the tail gate and controlling the flow with the speed of the truck.

EVALUATION FACTORS

In evaluating the benefits of non-standard stabilizers, several factors have dominated the concerns and benefits under consideration. These include aggregate gradation, surfacing resilience, and economy.

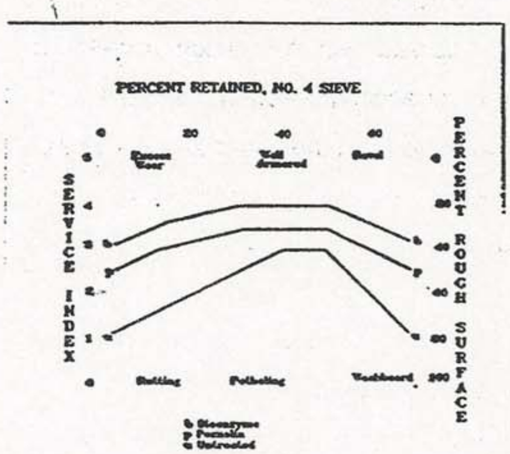

Figure 1. The performance of treated surfaces is related to the percentage of coarse material in the aggregate.

AGGREGATE GRADATION

Aggregate gradation was noted to be an important factor in the performance of the treated aggregate surfaces, regardless of the type of stabilizer used (Figure 1). The best performance was obtained from aggregates containing 30 to 50 percent retained on the No. 4 sieve, and within this range the better graded aggregates showed the least surface damage under prolonged use without maintenance. These surfaces developed a well armored appearance under traffic, similar to a bituminous surface treatment. Aggregates with less than 20 percent retained on the No.4 developed excessive fines on the surface and developed shallow ruts. Aggregates with more than 50 percent retained on the No. 4 developed excessive surface ravel in large aggregate which has an abrasive effect on the surface under traffic. As this layer of loose material thickens, corrugations occasionally developed on grades.

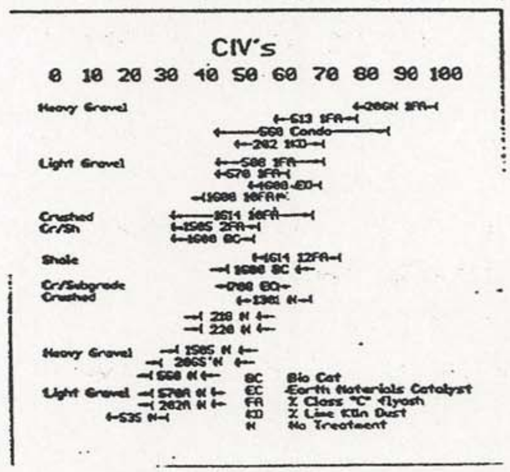

Figure 2. The Clegg Impact Values (CIV's) for aggregate surfaces show a trend of increase from untreated to treated aggregates.

SURFACING RESILIENCE

The absence of any standard testing procedures designed for evaluating the performance of these stabilizers leaves much to be desired in developing an objective report.

The Clegg Impact Hammer has however provided some small measure of improvements in surface resilience following treatment. The 10 lb. hammer imparts only a small impact to the aggregate mass, enough to loosen an unbound aggregate, but not enough to differentiate between a clay binder and the more effective stabilizer binder. Therefore the Clegg Impact Values (CIV's) obtained show the greatest benefit for treatment to non plastic aggregates, and generally no improvement for those aggregates with plasticity. There is definitely a trend of increasing CIV's from the tests on untreated aggregates to those on treated aggregates (Figure 2).

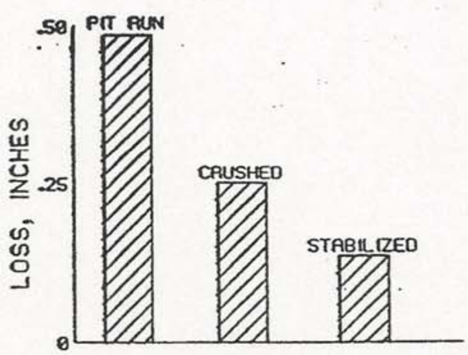

Figure 3. Treated aggregate surfaces show a substabtial reduction in aggregate loss, compared with untreated crushed or pit run aggregates.

ECONOMY

The short and long term cost benefits are of paramount importance in evaluating a stabilizer. Surface aggregate replacement is the single most costly item in maintaining aggregate surfaced roads (Figure 3). The cost of blading is less related to grader operation than to the influence of blading on surface degredation and increasing the rate of aggregate loss. To provide the long term benefit, an effective stabilizer locks the aggregate particles in place and maintains indefinitely the original compacted density achieved during construction, preventing or substantially reducing aggregate loss, and reducing or eliminating the damaging effects of frequent blading (Figure 4). In the short term, the cost of initial stabilization should be in the same cost range as a single aggregate replacement operation (Figure 5) to avoid unwanted increases in already strained budgets.

Any aggregate surfacing can perform only as well as the subgrade support will permit. Moisture sensitive subgrade soils will yield beneath traffic loads, resulting in failure of an otherwise adequate surface course. Where subgrade soil is the problem, an aggregate stabilizer must be considered inadequate by itself. An electrolyte stabilyzer is available to deal with these problems economically.

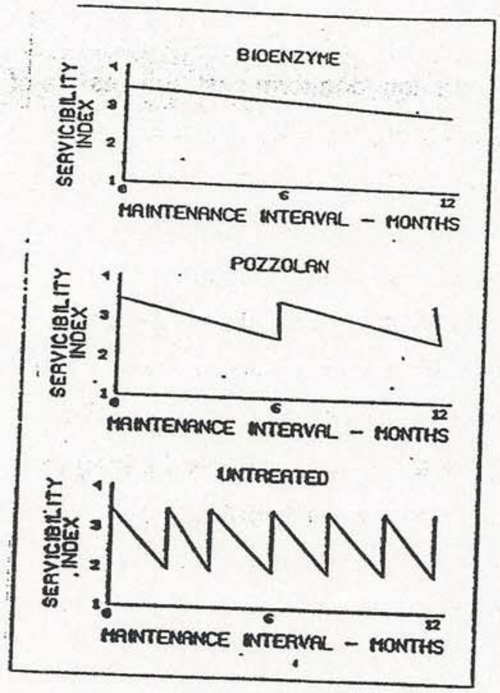

Figure 4. Treated aggregate surfaces provide for better service, with reduced maintenance frequency.

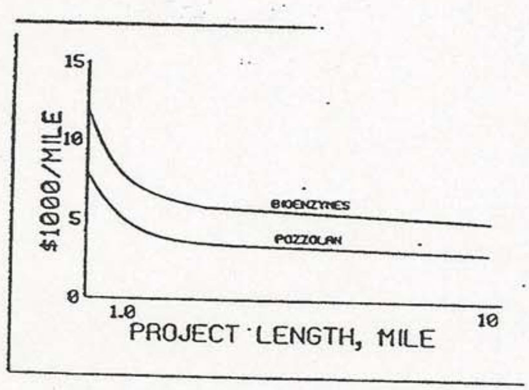

Figure 5. 1988 construction costs for aggregate surface treatment with non-standard stabilizers.

Other long term benefits include reduced wear on user vehicles, resulting in substantial savings to haulers, school buses, local residents and recreationists. User satisfaction promotes a greater willingness to pay for more of the same.

DETERIORATION MODEL

The observations made of a broad variety of project materials, geometrics, and conditions permit the formulation of a road deterioration model which expresses numerically the subjective evaluations of the various deterioration factors affecting road performance, as discussed in this report. These factors include the aggregate gradation, aggregate shape and stability, plasticity, type of stabilizer, subgrade condition, rainfall, grade and horizontal curvature, blading interval, and the average daily light and heavier traffic.

Thus the road roughness in ft./mile is expressed as:

$RG = 25K1K2 + BRG$ where RG is the road roughness, BRG is the bladed roughness, and K1, K2 are functions of the deterioration factors. The bladed rougness is calculated from:

$BRG = 20(1 + RF)$, where RF is the ravel factor,

RF = [(100-P1.5)/10 + (100-P2.5)/10]^2,

and P1.5, P2.5 are the percent passing 1.5 and 2.5 inches.

The resulting loss of aggregate in inches during any blading interval is expressed as:

GL = K1K2/32 where GL is the aggregate loss. GL = approximately 1/8 inch per blading at RG = 100 ft./mile.

Aggregate gradation has been known to be critical in the performance of untreated aggregates and was observed during this study to be a critical factor in the performance of a stabilized aggregate. In the model, aggregate gradation is expressed as a function of the Talbot equation, and modified according to extent of crushing involved which determines the stability of the aggregate mixture, and for the effect of subgrade conditions:

nx = (LnPx/100)/(Ln(dx/D), Talbot equation,

and nx = gradation exponent

Px = percent passing dx size

D = maximum (d95) size.

The constant K2 is calculated from:

LnK2 = (n'4 + n'200 + PI' +(I)(CF) + SGF),

where n4 and n200 are determined from the Talbot equation, and n' optimizes K2 when n is between .3 and .5. n'4 and n'200 are determined by:

n'4 = abs(n4 - .48)

n'200 = abs(n200 - .40).

PI' is determined from the aggregate PI or the % passing 2 microns(hydrometer analysis), whichever is greatest, by:

PI' = abs((PI/100) - .12)

The instability factor I is given as 1 for stabilized aggregates and 10 for untreated aggregates.

The Crusher Factor CF is given as 0 for crushed stone, 0.1 for crushed gravel, and 0.2 for rounded stream gravel.

The subgrade factor SGF is given as 0 for rock, sand, or stabilized materials; 0.2 for silt, and 1.0 for clay. Mixtures will be intermediate values.

The constant K1 contains the effects of grade and curvature as related to traffic density, and the effects of grade and curvature as related to rainfall. Thus the road condition will deteriorate under zero traffic if there is grade or curvature, and rainfall. The effect of the blading period is included here, which accelerates with increasing lengths. A stabilizer constant expresses the increase in strength due to the stabilizer.

The constant K1 is calculated from:

K1 = [(.01ADL + ADH)(.1G + .001CV)^.5

+ MRF(.1G + .001CV)](.001)(T^1.34)/Ks, where

ADL is the average daily light traffic, vehicles,

ADH is the average daily heavier traffic, vehicles, or 0.1 ADL,

G is the average percent grade,

CV is the horizontal curvature, degrees/mile,

MRF is the average monthly rainfall, inches, or the number of days per month where rainfall exceeds 0.1 inches (NOAA Climatological Data Reports).

T is the time between bladings, days,

Ks is a stabilizer constant, given as 6 for chemical stabilizers, 5 for pozzolans, and 1 for untreated materials.

The model has been tested on several of the roads included in this study, and the resulting condition curves are shown in the respective sections. The curves developed for the untreated aggregates generally agree with road conditions reported prior to stabilization of the aggregate. In the curves, units in ft./mile are for comparison only; 20 is defined as good, and 100 as bad.

Inputs to the model for the roads selected are as follows:

Andrew Pickens Burrel's Ford; d95=2.0, P4=66, P200=35, PI=11, CF=0, SGF=0, ADL=100, ADH=10, G=8, CV=1000 (curves only, untreated), CV=0 (tangents only, treated), MRF=8.

Pisgah Yellow Gap; d95=1.0, P4=49, P200=14, PI=3, CF=0, SFG=0, ADL=30, ADH=5, GCV, CV=600, MRF=4.

Desoto 202; d95=1.0, P4=60, P200=10, PI=0, CF=.2, SFG=.2, ADL=100, ADH=15, G=2, CV=60, MRF=8.

Sam Houston 204; d95=3.0, P4=68, P200=9, PI=9, CF=0, SFG=1, ADL=50, ADH=5, G=2, CV=0, MRF=8.

Sample plots are included in the text, in the appropriate section.

PROJECT CONSTRUCTION, TYPICAL PROBLEMS, AND PERFORMANCE

SUBGRADE STABILIZATION WITH SULFONATED NAPHTHALENE.

Chemistry

Sulfonated naphthalene produces a very small ion, the hydrogen ion, which can penetrate deeply into the clay lattice and destroy the expansive nature. This stabilizer affects the basic nature of the clay molecules in the aggregate, causing them to release absorbed water and coagulate into a dense, moisture free mass that resembles rock. The moisture released must be allowed to drain off in order to achieve maximum density. When expansive clays containing high moisture contents are included in the subgrade soil below the ditch line, drainage is hampered on the inside lane and more time will be required to allow the moisture to work its way to the surface and evaporate. Continued rainfall can aggravate the problem. Delays of up to two months in finishing the road surface have resulted in extreme cases, but once the moisture has escaped and density achieved, the stability is permanent and unaffected weather cycles. Aggregates must have 35 percent passing the No. 200 with a clay fraction. Once stabilized and compacted, they remain uneffected by wetting/drying or freeze/thaw cycles. The electrolyte travels through native soil moisture by osmosis, and thus does not have to be mixed mechanically with the soil layer. The treatment is best applied during periods of soil saturation, and is highly effective in permanently reducing the moisture content in expansive clays, eliminating subgrade and foundation problems associated with these troublesome soils. The stabilizer solution can be applied by injection for a deep treatment, or by scarifying and flooding for a shallow treatment. The latter produces an extremely slippery condition and requires addition of a traction course if no coarse aggregate is present.

Condor SS

Condor SS is currently the only electrolyte on the market known to this study that can be effectively used for soil stabilization. Condor SS is distributed by Earth Science Products Corp., POB 327, Wilsonville, OR 97070, Leonard Reinesten, 503-678-1216; in the Dallas- Ft. Worth area by the Pro Chemical Stabilization Co., P.O. Box 180775, Dallas, Texas 75218, Johnny Sherwood, 817-447-9907 or Bob Horn, 214-681-8359; in California, the Soil Stabilization Products Co.(See BIO CAT under bioenzymes).

Injection Procedure and Typical Problems

Gifford Pinchot NF

Condor SS was used on the Gifford Pinchot NF, Yakalt District east of Mt. St. Helen, on a service level "D" road off of Road 3421. Construction had been stalled at a steep downgrade (20%) on an unstable clay loam due to the high moisture content of the soil. An embankment beyond the grade section was too soft to support even a bulldozer which had to be pulled out by a large backhoe used on the job for loading operations.

The Condor solution was applied to the grade section by injecting 6 to 8 gallons to a depth of 4 feet across the road section, 6 feet on centers. Following treatment it was possible to back the water truck down the grade and open the valve to the spreader bar, allowing the solution to flood across the surface of the full section. The following day it was possible to drive a motor grader through the entire section with only minor rutting. All the treated soil had thoroughly consolidated and drained. Logs stacked along the road section were loaded onto trucks and hauled up the steep grade without problem.

Oregon DOT

Northwest of Portland the 17 mile Mist-Vernonia Road, a part of State Highway 47, is a two lane blacktop along the Nehalem River through low lying farmland, and has been plagued with problems associated with poor subgrade soils. Two one mile sections were injected with Condor SS solution to a depth of 4 feet, 6 feet on centers, 5 holes shoulder to shoulder, as a low cost alternative to excavating subgrade soils and importing quality subbase aggregates. A State Highway maintenance crew with backhoe and rock breaker attachment drilled holes in the pavement, and two men with jetting pipes attached to 3000 psi washer pumps injected 6 gallons of condor solution in each hole from a water truck. Production rate was reported at 100 holes per hour. Within a few weeks after the treatment, alligator cracking was reported to be sealing up and jetting holes closing under traffic over the hardened subgrade. During an inspection in August 1988, no evidence of pavement failure could be observed; the drilled holes were closing up under traffic.

City of Portland

A half mile section of the Kerr Parkway in Portland was injected with Condor SS in 1982 and has been without resurfacing since. Adjacent sections were repaved in 1986 and were already developing alligator cracking during an inspection in 1988, while the treated section continues to show no signs of stress.

City of Pocatello,ID

In a one mile section (see below, under Scarification Procedures) on a city street in Pocatello, Idaho Condor SS treatment prevented severe frost heave from developing in areas of moisture sensitive soils underlain by poorly draining lava deposits, as compared to adjacent untreated sections. In 1988 Pocatello began injecting 3 miles of these streets each year, with plans to continue until all problem areas have been completed. The project engineer reported a reduction in moisture content from 33% to 22%, and an increase in density from 85% to 95% immediately after treatment by injection and prior to applying any vibratory compactive effort.

Kisatchie NF, Louisiana

In May, 1990, the Kisatchie NF contracted work for injection of Condor SS into the subgrade of the Gum Springs Road, FDR 560. This road was originally constructed in the 30's by the CCC's and over the years has accumulated 16 to 20 inches of subbase and base material of every type available in the vicinity, topped off with a bituminous surface. The clay in the subgrade is so prone to shrink and swell that this amount of surfacing was insufficient to prevent heaving as much as 12 inches in the road surface. The contractor, Pro Chemical Co. of Dallas, Texas, apparently was unaware of the base thickness, trying at first to penetrate with an 8 inch drill and finally obtaining a 16 inch rock breaker mounted on a utility cart which was able to penetrate about 80 percent of the pavement. The remainder was completed by hand with a spike and hammer.

The Condor solution at a dilution of 300:1 was then injected through 5 foot wands of 3/8 inch pipe, supplied from 2500 psi ceramic pumps. The wands easily penetrated the subgrade clay with the resulting high velocity jet. Rows of holes at 6 feet on centers contained 5 holes each, also at 6 foot centers, to encompass the 20 foot pavement and 2 foot shoulders. The production rate with 2 wands was about 600 holes per day. A third wand was later added. Work took about 2 weeks to complete the two miles of road. The total cost of treatment was $50,000 or 20 cents/sf.

The road surface was repaved the following November. During the first winter a few localized failures developed adjacent to the road shoulders and required patching. Driving speed remains around 50 mph compared with 5 to 10 mph possible prior to regrading and injecting with the Condor SS. Investigation of the failed areas revealed excessive moisture in the base rock was causing the problem, while the subgrade under was hard. Apparently moisture continues to drain upward from the montmorillinite clays affected by the treatment, and is unable to evaporate through the bituminous layer. Rainfall was unusually heavy through the winter and may have been a contributing factor.

A second 2 mile section was injected with Condor SS during August of 1991. No problems have been encountered in this area.

Bay Way Center, Houston, TX

The subgrade soil for the shopping center parking area was an expansive clay with liquid limit above 60, PI above 40, and linear shrinkage above 10. The Proctor density was 98 pcf at 23.6 percent optimum moisture. The area was graded and injected with Condor on 6 ft centers to a depth of 3 feet in October of 1989. The treatment reduced the linear shrinkage to 2 percent, compared with 5 percent in a test with lime treatment (8 percent lime). Following injection the moisture content dropped to below optimum and the area was compacted to 100 percent maximum density with a vibratory roller. No problems related to the subgrade have developed in the pavement.

Scarification Procedures and Typical Problems

The stabilizer solution must be applied to deep, fresh furrows to penetrate effectively. To accommodate this requirement, the scarifiers must follow behind the rear wheels of the tractor or grader, and the water truck must be equipped with a side extension spreader bar, or it must back over the furrows during application. No traffic or equipment is permitted to pass over the fresh furrows until after the solution has been applied.

Any gravel surfacing is first windrowed off the section to be treated. On double lane roads, gravel from one lane can be moved to the other lane to support construction equipment. The surface of the subgrade is scarified to a depth of 8 the 12 inches, leaving fresh furrows without tire marks. The Condor is diluted at 300:1 when the moisture content of the clay soils present is below the Plastic Limit. If the moisture content is higher, the dilution ratio is reduced to 100:1. Approximately 45 percent of the solution is applied in one or more passes. Where gravity feed is used to the spreader bar, one pass forward and another in reverse at constant speed will result in a uniform spread. In a pumped application this is not problem, but the pump must be equipped with teflon seals because the stabilizer attacks dead organic matter such as fiber seals.

The first application is followed by two passes of the scarifiers to aerate the mixture and to assist the penetration of the stabilizer cations into the subgrade. A second 45 percent of the total solution is then applied, and the surface is allowed to drain until the moisture content drops below optimum. This may require several hours to several days or even weeks, depending upon moisture present prior to commencement of work, the quantity of moisture released from the clays, and atmospheric conditions. Kaolinite clays consistently require less than a week to drain, while montmorillinites can be very troublesome, especially when there is frequent rainfall during construction. An early pass with the compactor to seal the surface from rainfall may be necessary. Even with this precaution, moisture from the zone below the depth of scarification will drain toward the surface to increase the moisture content of the scarified material, prolonging the required length of the drying period. Using the reduced dilution ratio under moist conditions will help alleviate these problems.

When the moisture content has dropped below optimum, the surface is reshaped and compacted by two passes with a vibratory compactor. The gravel is then replaced and the remaining 10 percent of the stabilizer solution applied. The gravel is compacted by two passes of the vibratory roller.

Some montmorillonite clays have plastic limits approaching 200 percent and liquid limits greater than 600 percent. If substantial amounts of these clays are present, large amounts of water will be released and will drain off as the clay residual consolidates. Changes in the clay structure will substantially reduce the optimum moisture content, requiring additional drying. This moisture will continue to find its way into the base rock or gravel surfacing for weeks or months following treatment, causing temporary failures under traffic loads. A thorough investigation of these failures will verify that the subgrade clay is hard, but the lower portion of the aggregate layer is saturated, causing the failure.

City of Pocatello, ID

In 1985 the City of Pocatello Street Department stabilized a one mile section of road on moisture sensitive soils underlain by a poorly drained lava deposit. Prior attempts using a geotextile and aggregate base were unsuccessful. The street was frequently impassible.

The worst areas, which comprised large holes in the street, were ripped to a two foot depth and saturated with the Condor solution, then leveled and compacted with a vibratory roller. This entire procedure was repeated twice over until each area was stable.

The remainder of the section was ripped to a one foot depth and saturated with Condor solution. Gravel was spread on the road and blade mixed into the saturated surface. The process was repeated again, and the surface was rolled with a vibratory roller until the moisture was gone from the surface. After allowing the surface to cure for about 30 days, it could be swept with a power broom. It resembled concrete in density. The surface was then paved, and chip sealed the following year. There has been no settlement or expansion in the surface since construction.

Kisatchie NF

On the Kisatchie NF to demonstrate the effectiveness of his product in other modes, the contractor agreed to surface treat a hundred feet of an unsurfaced, heavily rutted side spur to the project, by scarifying and saturating the surface with the Condor solution to produce a hard, waterproof surface approximately 18 inches thick. This method would cost about $6000/mile, compared with the $20,000/mile the Forest currently spends on riprap and surface rock for these roads. The section was load tested the following April after a winter of extremely heavy rain. A flat bed truck loaded with a heavy tractor was able to drive the road without failure, except for a 20 ft section where a thick deposit of sand had prevented penetration of the Condor solution into the clay subgrade. At this point the truck sank to its axles and had to be pulled out by the tractor, a condition typical of untreated areas. This illustrates the importance of applying the solution to fresh open furrows in the clay soils.

Gila NF, Reserve, NM

During June of 1991, the Gila NF contracted construction on a 4 mile section of FDR 141, southeast of Reserve, NM. Sections of clay subgrade totaling 2.2 miles were stabilized with Condor SS solution to provide a subbase for 9 inches of crushed aggregate and a triple chip seal surfacing. The crushed aggregate, produced at a site adjacent to the road, contains a clay fraction and was also being stabilized with the Condor solution. The remainder of the subgrade contained a mixture of cobbles and clay, and was not in need of the stabilizer.

The contract called for windrowing aggregate to one half the 30 foot road width, scarifying to an 18 inch depth, and applying the Condor solution from the gravelled half using a side bar distributor on the water truck. The rate of application of the Condor concentrate was 1 gallon per 160 sq. yds. The initial dilution factor was 500:1, but this was found to provide too much moisture and was reduced to 300:1. The Condor solution was put down in two equal applications, with 4 mixing passes with the scarifiers after the first application only. After the second application, the surface was shaped and compacted to 95% density. Following a 20 hour curing period, the aggregate was respread and the process repeated on the other half of the road. Finally the Condor solution was applied with blade mixing to the aggregate surface, followed by shaping to finished grade and compacting. The application rate for the Condor concentrate on the gravel surface was 1 gallon per 1000 sq. yds., diluted at 1:300.

The contractor scarified with bulldozer rippers due to the large rock present. The subgrade in the treatment zones varied from pure plastic clay to a mix of clay and 12 to 24 inch boulders. Residual gravel from subgrade pumping under the old surface was also present. The Condor solution was applied from a 5000 gallon tanker, pressure discharged through a pump equipped with teflon seals, a 2 inch meter, and a side discharge pipe 15 ft. long. The 2 inch meter limits the flow rate; the contractor reported that a 4 or 6 inch meter would require only one pass per load.

During shaping and compacting the moisture content of the clay subgrade was measured at intervals using a nuclear gage until it droped below optimum. Initially at or above 25%, the moisture was observed to drop blow 10% within a few hours after the final Condor application. A rainfall during the first week of work increased the moisture content on the surface but did not interfere with moisture reduction at depth.

One section of the road began rutting along the ditch side under construction traffic after the aggregate surfacing had been replaced on the treated subgrade. The subgrade was firm but the base rock was saturated with moisture, apparently bleeding out of the subgrade clays under the influence of the Condor. The aggregate had to be scarified to permit drying before the pavement could be placed, causing a delay in completion of the project.

Uinta NF, Provo, UT

In July of 1991, Condor was used in the construction of Forest Highway 131 along the west side of Strawberry Reservoir, 60 miles east of Provo. Five miles of 24 ft double lane road originally had been designed for 9 inches of aggregate and 3 inches of hot mix, but the high bid price on the aggregate would have prevented full construction. To reduce costs to budget, a Condor treated subgrade on selected areas and spot aggregate to bring the existing surfacing up to a uniform 5 inches was selected.

The existing 3 to 5 inches of aggregate was bladed to one lane and the exposed subgrade was scarified using a Cat 140 motor grader with rear mounted rippers. A 500:1 dilution was selected for the Condor because of the low natural moisture content, ranging from 4 to 6 percent. On the first section this was found to be too much moisture, and a 300:1 dilution was used on the remainder of the project.

The solution was applied from a 5000 gallon water truck riding on the aggregate surface with a 6 inch diameter side mounted spreader bar, projecting across the scarified subgrade. Gravity feed to the spreader bar was used, requiring the speed of the truck to be varied to achieve a uniform spread as the head on the bar decreased with emptying the tank. On each of two passes, 45 percent of the solution was applied, followed by two mixing passes with the scarifiers after the first application only. The treated surface was bladed and given initial compaction as soon as it had dried sufficiently to permit equipment operation. Waiting time required 2 to 36 hours depending on weather conditions. After completion of the subgrade the aggregate was spread and the final 10 percent of solution applied for compaction.

Immediately following the application of the solution, the moisture content was high, and the grader tires were rutting the treated surface up to 3 inches on the first passs. Pumping action continued in wetter areas for up to 48 hours after treatment. After 72 hours the clay hardened significantly in most areas and no longer yeilded to the tires of construction equipment, including the dump trucks hauling gravel through the construction area.

Where rutting of the treated surface resulted from early blading and compaction to accommodate gravel hauling to the far end of the project, a later pass with the compactor after 24 to 36 hours helped to remove deformations prior to replacing the gravel layer. Due to the broad variations in materials in the subgrade, the rate of drying and hardening was not uniform and some small areas remained soft longer. Two substantial sections overlying deep moisture laden clays failed to support construction traffic without rutting until the contractor was ready to pave. An additional 5 inches of gravel base was placed, and the pavement was completed. No subgrade failures were noted during an inspection in October of 1991, although some problems associated with asphalt stripping and aggregate segregation were causing pavement failures.

Two short problem areas on the project were given early treatment to eliminate the need for maintenance under haul traffic. The subgrade in the soft, wet areas was scarified through the gravel surface and Condor solution was applied to the furrows. The mixed subgrade clay and surface gravel were then shaped and compacted, leaving clay patches exposed within the gravel surface. Treated on the previous Thursday, by Monday both sections had dried and hardened enough to support haul traffic without needing maintenance. The treated crushed gravel contains a clay fraction and also responded well to Condor treatment. A hole excavated through this treated section for an electrical conduit access revealed a lower moisture content with increasing depth. Some moisture was still present in the deeper clays, and cation migration into this zone should continue over the year following construction, providing a substantially thicker stabilized section under the pavement.

AGGREGATE REPLACEMENT

Ammonium Chloride; Consolid 444

The principal ingredients of the Consolid 444 solutions are ammonium chloride and propylene, combined in an inverted emulsion that has the properties of a surfacant and ion exchanger, and a pH of 6; the solutions were tested at the University of Iowa Environmental Laboratory and found to be harmless. A clay mixture treated with the solution undergoes an ion exchanges at the surface of the clods, releasing moisture and resulting in a dramatic reduction in capillarity. The interior of the clods show no change in properties. When compacted, the resultant mass is finely divided by the moisture resistant membranes of treated clay.

Ammoniun chloride is an electrolyte, but differs from the sulfonated oils in the size of the ion. The ammonium ion is much larger than the hydrogen ion and the result is a loss of mobility. Because of its large size, the ammonium ion affects the clay molecules only in the immediate vicinity of the contact with the stabilizer solution. In order to spread the effect of the ion throughout the soil layer, intimate mixing is required. The immediate affect of the contact with the ion is the removal of ionized water at the periphery of the clay lattice and collapse of the lattice structure along the edges. This results in sealing off individual particles of clay with impermeable membranes and a loss of capillarity through these membranes. As the mixing procedes, the stabilizer affects the exterior of the clods, drying and hardening them on the outside, effectively increasing their resistance to breaking down under mechanical action. The use of high speed rotary mixers is absolutely essential to obtaining adequate mixing. As the first treatment is to the full depth of the surface layer, usually 8 or 9 inches, two to three passes are required to break down a heavy clay to the required 2 inch minus size. This treatment results in a network of impermeable membranes being formed throughout the clay soil mass. The second and final treatment affects only the top 4 inches, and a single pass is usually adequate, reducing the clod size to one inch minus. While these clods are waterproofed on the surface, traffic abrasion will wear through the protective coating, releasing the wet clay interior and creating a muddy surface. To avoid this problem, the surface must by sealed with a chip seal or a hot mix bituminus pavement prior to opening to extensive use by traffic.

Chickasaw NRA, Sulfur, OK

In June of 1991, the Federal Highway Administration included a 1500 ft. section of Consolid stabilized base during construction of the entry road to the Chickasaw NRA at Arbuckle Reservoir, near Sulfur,OK. The solutions are put down in two applications; the first, called Consolid 444, is combined with water and mixed into 8 inches of subgrade clay, with resulting moisture content at or slightly above optimum moisture. The second, called Conservex, is combined with MC-30 and mixed into the top 4 inches of the previously treated and compacted material. Clods must be reduced to below 2 inches, and a density equivalent to 95% of Standard Proctor must be achieved. The surface is then paved with 3 inches of bituminous hot mix.

The surfacing design for other sections on the project called for 9 inches of crushed rock on the compacted subgrade, with a hot mix bituminous surfacing. The 1500 by 33 ft wide section to be treated with the Consolid system was graded to blue tops at finished grade. It was then scarified to a 9 inch depth using a Cat 140E motor grader with a rear mounted ripper bar. Only two teeth were used due to the high resistance of the compact clay, requiring multiple passes to cover the full width, and leaving gaps between the scarified furrows. The sole purpose of the scarifying is to entrap the applied liquids. No time limit is specified between application and mixing; once applied, the chemicals will not evaporate or erode, and will protect the surface from saturation by rainfall.

The weather was hot and dry, 85 - 95 degrees. 1500 gallons of water were added over the 6000 sy in combination with the Consolid 444. The minimum dilution required is 4:1. A total of 75 gallons of Consolid 444 was mixed with the water for a concentrate application of 0.0125 gallons per sy. The solution contains additives that promote quick mixing with the water.

Following application of the Consolid 444 and water solution from a bitminous distributor truck in two full coverages, a Bomag mixer was used to mix the full 9 inch depth, leaving a fluffed depth of 11 inches or more. Two full passes were required to achieve the 2 inch max size of clods. The Bomag would do 1500 ft per hour, 6 ft wide. Following mixing and shaping, compaction was achieved with an articulating sheeps foot roller.

The second and final application, with the Conservex and MC-30 mixture, was at a similar rate of concentrate to the first, 0.0125 gal. per sy, but diluted 19:1 with MC-30, for a total of 1280 gallons of the mixture. Scarification for this application is confined to the top 4 inches of the previously treated layer, and mixing was again achieved by another pass with the Bomag.

The major problem encountered with the consolid system was the intimate mixing required with 9 inches of heavy clay. Heavy Spring rains has raised the moisture content to near the 17% optimum, and the clay clods resisted breaking down. Some of the more moist areas required 3 passes to achieve the 2 inch max size. The chemicals apparently played no part in breaking down the clods, as is observed when applying lime or bioenzyme. Moist clods stayed hard and held size until losing moisture through aeration. Even after drying, most refused to break down below the 2 inch size. A primary function of the chemicals is to eliminate capillarity and release free moisture. On large clods this results in a hard crust on the surface which inhibits loss of moisture from the center, increasing the resistance of the clod to the mechanical breakdown by the Bomag. The finished loose course of material is a windrow of 2 inch clods, each with a chemically dried hard shell. When compacted, the treated shells form a network of resistant diaphrams surrounding the balls of plastic clay, blocking the path of capillary moisture movement and maintaining the strength of the soil mass through wet periods.

With the 4th of July weekend coming up, heavy traffic was expected before the paving could be placed. A temporary single chip seal was placed, however without a tack coat; the chip layer deteriorated rapidly and some shallow rutting with mud exposed developed during the holiday traffic. After the weekend the section was paved with 3 inches of hot mix and has performed satisfactorily since.

Bioenzymes; Perma-Zyme

Emery County, UT

The Emery County Road Department began using Pera-Zyme in 1987 and has over 40 miles of connector roads stabilized currently. A typical road section is 24 feet wide with a 6 inch stabilized base and chip seal. The aggregate base with fines is blade mixed with the Perma-Zyme solution and compacted in two 3 inch lifts. Both regraveling and blading frequency have been sustantially reduced on these roads, while the servicibility has improved. Heavy coal hauling severely damages or strips the chip seal but does very little damage to the exposed stabilized base.

Jerome County, ID

The Jerome County Road Department began using Perm-Zyme in 1985 and now has over 40 miles with stabilized base. About 6 miles is done annually, by treating 3 inches of existing gravel base in the Fall and overlaying in the Spring with an additional 3 inches of crushed containing 20 percent passing the 200, also treated with Perma-Zyme. Chip sealing may be delayed up to two years. Minor frost damage after a severe winter is the only damage that has occurred on these roads.

City of Stillwater, OK

Two city streets in Stillwater, Oklahoma have been paved with 6 inches of silty clay subgrade material(PI,20; LL,40) stabilized with the Perma-zyme 12. No other surfacing was added other than an inch of gravel to improve traction and provide a slime free surface.

Perma-Zyme is incorporated in the compaction water, mixed in with rotory mixer or discing, and compacted under sheepsfoot roller. The distributor recommends a minimum of 20 percent fines in the soil. The mix can be dryed back by blading if too wet, or water added if too dry without reducing effectiveness, offering considerable flexibility to construction conditions.

A half mile of Richmond Road was completed in 1981 and has not required maintenance since that time. This is the oldest bioenzyme test section on record. Adjacent untreated sections rut easily following rainfall and become impassible during spring thaw. The test section was used year around without problem or sign of rutting, chuckholing or washboarding, remaining as hard and firm as the dry, baked clay of mid-summer. As most of the gravel layer had been lost to traffic, the surface appears to be clay with gravel fines imbedded.

The Streets Superintendant reports he has been completly satisfied with this performance and as a consequence treated another half mile on 26th Street in 1987, which performed in a similar manner throughout the winter. He plans additional use of the Perma-Zyme during the coming years to relieve his overloaded maintenance operation and improve service to users.

North Carolina DOT, Raleigh

In September of 1989, a mixture of crushed aggregate and clayey silt subgrade soil on a 600 foot section of SR 1305 south of Raleigh was stabilized with Endurazyme(Perma-Zyme) to a depth of 4 inches under supervision of the Planning and Research Branch. Only about 10 percent of the mixture was retained on the No. 4, and the PI ranged from 6 to 13 with 26 to 45 percent passing the 200. The solution was applied to thin layers bladed from windrows and compacted with a pneumatic roller. A heavy rainfall the previous week had saturated the soil, and the natural moisture content was 3 percent above optimum. Application of the solution increased the moisture, and during rolling several sections were too soft to compact. However the next day these had set up hard and were performing well. Field CBR's taken averaged 63 for the treated section compared with 44 for the control section in spite of the above optimum construction.

Performance was monitored periodically over the following 18 month period. With only occasional scheduled bladings the treated section remained smooth, hard and uniform without evidence of raveling, while the untreated control section showed considerable rutting during the wetter periods. The stabilizer was recommended to the Districts for optional use, subject to cost restraints.

Bioenzymes; Bio Cat 300-1

Ottowa NF, Iron Mt, MI

In August of 1987, the Ottowa NF completed two half mile sections of FDR 214 using Bio Cat as a stabilizer. The 4 inch aggregate surface, a crushed glacial till, had been in place for 20 years. The plan was to combine the top 8 inches of aggregate and subgrade with Bio Cat and compact. A heavy rain on the eve of construction combined with high soil moisture to produce a supersatuated mixture which proved incapable of being compacted during the first pass along the road shoulder. This area still shows the ruts of the rubber tired roller.
The mixing depth was cut to 4 to 6 inches, substantially reducing the total moisture and permitting adequate compaction on the remainder of the test sections, although still high in moisture. The first section, immediately adjacent to State Highway 45, was formerly a problem area which rutted severely during the spring.

In March of 1988, 7 months following construction, the Forest brought in a loaded gravel truck to make approximately 50 passes over the treated and untreated sections of the road. The treated sections remained firm while the untreated rutted about an inch. However during a hard winter, freezing would penetrate to 5 or 6 feet, and during thawing would produce an undrained, supersatuated subgrade. These conditions have not occurred since construction.

Although the winters have been unusually mild and failed to provide a good test thaw in the spring, this section did appear much more uniform on the surface during an inspection in June of 1988 than the adjacent untreated section which showed more tire wear in the wheel paths and more loose material in the center as compared to the treated section. The first 10 feet of the section, adjacent to the pavement, also received no treatment and showed signs of potholing and an uneven surface.

Pozzolans

Construction Problems

While during the mixing process with pozzolan stabilizers the ionization is instantaneous, with the breakdown of clays taking up to a week for the heavier clays, and the formation of silicates in sandy mixes requiring only a few hours, the forming of hyration bonds is a slow process and a function of the heat input to the system. An estimated 3000 degree-days at temperatures above 50 F are required to fully cure the mixture, or two to three months at 80 to 100 degrees. If the surfacing contains a substantial clay fraction and is placed too late in the year to recieve adequate curing, and resultant failures cause prolonged aeration of the mixture, the pH will drop and the calcium ions will carbonate, resulting in a weak, water soluble cement rather than the permanent calcium aluminum silicates. In addition, the free lime in the aggregate mixture lubricates the clay fraction present and tends to produce a slimy, slippery mess that often becomes impassible to traffic during the wet winter weather. Thus climate and timing are important considerations when using pozzolans as stabilizers. This problem is less critical when the aggregate is nonplastic and contains coarse material. In these cases slippery conditions will not develop; however some benefit may be lost to carbonation if there is prolonged aeration. In either case, plastic or nonplastic materials, curing will resume in the Spring when warm weather returns.

Early Studies

Initial efforts were based upon reports from New Zealand(1) on their experimentation with modifying soils and aggregates by using low percentages of cement or lime. During the early '80's interest centered on subgrade stabilization as a low cost alternative to aggregate surfacing, and the first test sections were constructed using hydrated lime or lime kiln dust in low percentages selected on the basis of laboratory testing results (Tables 3 & 5).

The initial testing by the USFS Southern Region using lime or Portland cement was done with a variety of soils from the southeastern states at Georgia Institute of Technology under the supervision of Quentin Robnett during 1982/83 (Table 4). 2 inch diameter by 4 inch specimens were compacted at optimum plus 2 percent to AASHTO-T99 density of the soil alone, sealed in plastic bags for 48 hours at 120 degrees fahrenheit, removed from the plastic bags and soaked in a water bath for 4 days, and tested in unconfined compression.

Initial testing using lime kiln dust was done by the dealer at their facility in 1982 for the construction of 4 miles of road in Alabama. During 1983 some additional testing was done at the FHWA laboratory at Sevierville, Tennessee, using a Proctor mold to form the specimens. In 1984 the Forest Service zone materials engineer in South Carolina set up a small facility and began testing soils, also by using a Proctor mold, but compacting at optimum plus 5 percent to 95 percent AASHTO T-99 density of the soil alone to provide higher moisture for hydration. The remainder of the procedure is the same as that used by Robnett.

Table 3: Early Work, Project History

NATIONAL FRST	*PROJECT TYPE*	*RANGER DIST*	DATE *CONSTRUCTED*
Oakmulgee	Lime kiln dust	Oakmulgee RD	Oct.,1983
Road 724	modified soil	Talladega NF	
Middle Cedar	Lime kiln dust	Oconee RD	Aug.,1983
Road 1045	modified soil	Oconee NF	
Flatwoods	Lime modified soil	Watanga RD	Sept,1982
Flatwoods	Lime kiln dust mod	Watanga RD	June,1984
Road 87N	soil w/gravel top	Cherokee NF	
Calf Pasture	Lime modified	Dry River RD	July,1984
Road 96	gravel-soil surf	G.Washgtn NF	
Tuckaho	Lime kiln dust mod	Pedlar RD	Sept,1984
Road 52	soil w/gravel top	G.Washgtn NF	
Enoree	Lime kiln dust mod	Enoree RD	Sept,1984
Road 391	soil w/gravel top	Sumter NF	
Wamba	Lime KD/FA & PC/FA	Wamba RD	June,1984
Road 5084	mod sand w/gv.top.	Francis M NF	
Sorghum Hlw	Cl.C flyash mod	MtMagazine RD	Aug.,1984
Road 1614	pit run shale	Ozark NF	
Trinity	Cl.C flyash mod.soil	Trinity RD	Oct.,1984
Road 510B	w/gravel topping	Texas NF	
Natches 511	Cl.C f.a.mod soil,gv.	Natches RD,TX	Oct.,1984

Table 4. Early Work, Types of materials

PROJECT	MILES	PERCENT MODIFIER	DES/USC/AASHTO
724	3.5	5% Lime kiln dust	Sand/SW/A-2-4
1045 1	.5	3% Lime kiln dust	Clay/CH/A-7
1045 2	.6	3% Lime	Clay/CH/A-7
87S	4.0	2% Lime	Clay/CL/A-4
87N	4.0	2% Lime kiln dust	Clay/CL/A-4
96	1.9	2% Lime	Clay/CL/A-4
52	2.0	4% Lime kiln dust	Clay/CL/A-4
391	1.5	5% Lime kiln dust	Clay/CL/A-7
1614	0.2	10% Cl.C flya	
5084 1	1.0	8% LKD, 10% flyash	Sand/SP//A-3
5084 2	1.0	4% P.C.,6% f.a.	Sand/SP/A-3
510B	2.5	16% Cl.C flyash	Silt/MH/A-5
566	0.7	16% Cl.C flyash	Silt/MH/A-5

Table 5. Specific cost data, 1985 $/sy

PROJECT	CHEM MODIF	AGG TOP	TOTAL	ALT. CRUSHED AGG	
724	0.56	None	0.56	1.80	
1045 Sect 1	0.70	0.50	1.20	1.80	
1045 Sect 2	1.10	0.50	1.60	1.80	
87S	0.97	None	0.97	1.90	
87N	0.67	1.00	1.67	1.90	
96	0.72	None	0.72	1.80	
52	1.19	0.63	1.82	2.50	
391	0.90	0.63	1.53	1.90	
5084 Sect 1	3.41	0.90	4.31	3.60	
5084 Sect 2	1.83	0.90	2.73	3.60	
1614	1.03	None	1.03	1.80	
724	0.90	None	0.90	1.80	
510.B	2.75	2.70	5.45	5.40	
566	2.75	2.70	5.50	5.40	

The trial chemical contents are determined by plotting the results of a series of pH tests using varying amounts of additive and determining the percentage where the curve flattens, usually between 11.5 and 12.4. Several specimens are then prepared with chemical contents ranging from below to above this point to determine the unconfined compressive strength. The final selection is based upon the strength requirements, and generally falls between 40 and 100 psi but may drop to 20 psi in the case of coarse aggregates.

4 day soaking is considered to be conservative since most projects on the National Forests are well drained with ditching and sidehill construction. The unsoaked strength, when determined has been 2 to 3 times the magnitude of the soaked soaked strength. However, severe frost penetration and thaw may reduce the strength to below that obtained after the 4 day soak.

The Atterberg limits are usually determined for clays for the soil alone and for the design mix to estimate the change in consistency to be expected during construction mixing. Clays with high sodium contents experience a substantial reduction in plasticity due to ion exchange, while those associated with calcium or iron bearing minerals will show only a minor reduction in PI.

Oakmulgee NF, AL In 1983, 4.2 miles of FDR 724/749 were surfaced by mixing 5% lime kiln dust with the top 6 inches of the native silty sand subgrade, a nonplastic soil with an AASHTO Class of A-2-4. The contractor employed a motor grader, a tractor drawn disc harrow, and a 1000 gallon water truck to perform the mixing and control moisture. The lime kiln dust was delivered to the site and spread pneumatically from 24 ton tankers. Compaction was accomplished with a pneumatic roller. Problems in contracting procedure delayed start of construction until October, reulting in inadequate curing and failures during January log hauling following a hard freeze in December. The road was closed until it could be regraded in the Spring and log haul resumed. Following these initial first winter problems due to late construction and inadequate cure, the mixture set up very hard, forming a surface resembling a high strength soil cement which would ring under a hammer blow. While this surface has performed well under generally low volume traffic and has required only minor maintenance in areas of montmorillanite clay outcrop which failed to react with the lime kiln dust, the high strength will require it to be completely broken up by ripping and disking to permit maintenance of erosion channels developing on steep grades (up to 16%).

In May of 1991 an inspection was made of FDR 724/749. Seven years after construction with minimal blading the surface still performed well. Sections on gentle grade had not changed. During heavy rain some grades became slippery. On steeper grades, some up to 15 percent, erosion in shallow ruts started by slipping tires had nearly eaten through the original 4 inch thickness. Maintenance had been primarily concerned with filling in these erosion channels, and with rocking areas of montmorillonite clay unaffected by the lime kiln dust.

It was anticipated that as the erosion finally works through the stabilized layer into the soft subgrade below, the surface would begin to undermine, and another solution would be needed. A similar situation, however with potholing, occurred on a soil cement surface on the Camel Lake Road in the Appalachicola NF in Florida. The solution used there was to disc the surface to clods 8 inches or less in size and recompact. This produced a durable, if somewhat lumpy surface that has provided continuing service. This has been proposed for FDR 724/749 and may be tried on the worst sections to observe the benefits. The sections of montmorillonite clay have been proposed for scarification and saturation with Condor SS solution, followed by regraveling and compaction to produce a stable layer for the road surface.

Cherokee NF, TN: Flatwoods Road 87

Sections totaling 12 miles of the Flatwoods Road were restored in 1982 with lime and in 1984 and 1986 with lime kiln dust and a layer of surface gravel. This road receives logging, recreational and local traffic throughout the year. Prior to restoration its condition suffered from frequent potholing and washboarding, and Springtime rutting. The subgade material is a weathered silty marine shale with a PI of around 9, an AASHTO Class of A-4. During the year prior to construction the road was used as access for construction at Little Oak Campground through an extremely severe Winter and Spring thaw, and suffered many failures including deep rutting in the south end access from Hickory Tree. This 4 mile section was the first to be restored in 1982. Two percent lime was selected because the lime kiln dust was unknown to the Forest Service at that time, and laboratory tests showed some increase in strength. The road bed was treated to a 6 inch depth, and several short sections received 12 inches. Contrary to accepted practice, work was done in the Fall without adequate curing time available before Winter, to convenience Forest contracting procedures. The mixture did not cure and became hazardously slippery during the Winter from the uncured lime, forcing closure of the road until it could dry out in the Spring. The surface has since had thin applications of crushed rock in a few areas, but for the most part no other surfacing. While this section has performed well over the past 9 years under mild climatic conditions, requiring blading only two or three times per year, it has never stood well through repeated freeze and thaw cycles that occur occasionally. Under these more severe conditions the road bed softens and deep rutting occurs in a few areas under vehicles with knob tires or with tire chains. The clay content was marginal for lime treatment, and the inadequate curing further diminished any potential strength gain.

The two remaining 4 mile sections were treated with 2 percent lime kiln dust to a 6 inch depth and covered with 1 to 3 inches of crushed stone to provide a traction and wearing course. Subsequently traffic worked most of this rock into the surface to provide a hard roadbed which has required only minor maintenance ove the past 5 to 7 years. A few potholes have developped in sections with high cutbanks, possibly due to seepage in the subgrade. The lime kiln dust is hydraulic cement and needs no clay to provide strength gain as the hydrated lime does. Lime kiln dust has proven effective as a stabilizer in a number of A-4 soils where hydrated lime has failed to perform.

George Washington NF, VA: Calf Pasteur Road 96 This 1.9 mile road was surfaced with a mixture of crushed rock and shale overa weathered shale subgrade. Both have a low PI and an AASHTO Class of A-4. The road supports log hauling as well as recreational and local traffic, and required frequent maintenance to deal with severe potholing and corrugations. Lime kiln dust was unknown to the Forest Service during the design period and 2 percent hydrated lime was selected, based of laboratory test results; however the aggregate samples were taken during the Winter when the ground was frozen and may not have been representative of much of the project. The contractor used a motor grade with rear scarifiers and a tractor drawn chisel plow to mix the lime to a depth of 4 inches. Water was hauled to provide optimum moisture for compaction with a vibratory roller. Construction was completed in July of 1984, allowing ammple warm weather for the initial curing. The road performs well during moderate weather, but develops potholing on several short sections during the Winter months. There is no sign of any permanent strength gain from the lime. A mile of this section was restabilized with a bioenzyme in September, 1991. See below.

George Washington NF: Tuckaho Road 52 This one mile road provides access to Sherando Lake recreational area and gets heavy seasonal use. The road surfacing had almost completely washed away, exposing the cobble subgrade. A kaolin mine waste, a silty clay with an AASHTO Class of A-4, was hauled from a nearby dump and placed to an 8 inch thickness over the cobbles. The upper 4 inches was then treated with 4 percent lime kiln dust, and overlain with 2 inches of crushed rock to provide traction. The same contractor from the Calf Pasteur Road did the work, using similar equipment and methods. The road is closed and gated during the Winter months. It has performed exceptionally well under seasonal use, but has required replenishment of the crushed rock every two to three years due to traffic erosion. There has been no potholing or corrugations developing. Here again, the hydraulic cementing capabilities of the lime kiln dust provided for a notable strength gain in the treated layer, enabling it to support traffic over an extended period with only minor maintenance. The problem with surfacing attrition was dealt with in September of 1991, using a bioenzyme stabilizer in the gravel layer. See the section on Surfacing.

Evaluations In March 1985 a region wide inspection was made of 11 of the projects constructed through 1984. See Table 2. The purpose of the inspection was to compare the performance of the modified soil surfacings with traditional surfacings on adjacent roads during the period of spring thaw or generally saturated subgrade conditions. In general, all projects were in usable condition, and most were found in excellent condition. The two projects in Tennessee and one project in Virginia showed that plastic deformation had occurred in some areas. These projects had been subjected to severe freezing during the winter, followed by a sudden thaw coinciding with apparent heavy wheel loads. During this period of thaw, the road surfaces were somewhat slippery in areas where surface aggregate was not present.

The modified soil surfacings have been observed to reharden rapidly and regain strength during hot weather following plasticising by severe freeze-thaw. A light blading while moisture remains in the material should satisfactorily remove surface irregularities. Excessive blading or blading after drying should be avoided as this results in a layer of loose material scattered over the surface which will dust and turn to mud during a heavy rain shower. Areas which have suffered severe and deep deformation can be covered with gravel. Experience to date indicates that a thin gravel overlay such as obtained by tailgate spreading to one particle thickness is effective in preventing a slippery surface from developing during periods of saturation due to freeze-thaw or heavy rainfall.

Although it is difficult to develop an exact cost comparison with full depth gravel surfacing, it has been possible to make comparative estimates on each project which indicate that the modified surfacing cost 40 to 100 percent of the full depth gravel, averaging 50 percent without gravel topping and 90 percent where gravel topping was added. In the latter case, gravel in excess of the recomended thin layer was used on several projects which markedly increased the cost and resulted in loose gravel piling on the shoulders and road center. See Table 4.

A second inspection of the Tuckaho Rd 52 and the Flatwoods Rd 87 was made in September,1988. The road was receiving heavy annual recreational use throughout the summer months(50 to 100 vpd) but was gated during the winter. Since restoration the surface had been bladed annually and had recieved two additional thin layers of gravel. Three inches of gravel covered the modified base which remained intact except for a few isolated shallow erosion channels. Clegg impact values (CIV) on the base varied from 20 to 30, corresponding to Resilient Modulii of 18000 to 35000, indicating continuing strength due to the Pozzalime. The untreated soil had CIV's of 10 to 15.

The wide variation in modulii of the base may be a result of variations in freeze-thaw cycles with depth and with location relative to exposure to the afternoon sun. Stabilized soils lose 10 to 12% strength with each cycle, but regain strength during the hot months.

The Flatwoods Rd 87, normally is bladed three times per year, and prior to the inspection was last bladed in the Spring of 1988. The previous Winter was mild and the Summer hot and dry; the road appeared in excellent condition except for occasional potholing in a few areas with high cut banks, possibly due to seepage in the subgrade.

The lime treated section showed little evidence of strength gain. The CIV's taken during this inspection ranged from 15 to 30 over most of the section, and District personnel reported deep rutting this past winter in one area that had been lime treated to a 12 inch depth. The entire lime treated section has had only minor graveling since restoration, although considerable residual gravel was present in the surface mixture at the time the lime was added.

In contrast, the two lime kiln dust treated sections showed considerable gain. CIV's ranged from 60 to 90, corresponding to modulii of 90,000 to 160,000. An untreated section that had received 8 inches of crushed aggregate, located between the two Pozzalime sections had CIV's ranging from 50 to 60.

Recent Projects

Department of Energy, Laramie, WY At the Department of Energy (DOE) in Laramie, WY, plans were developed during 1989 for implementing a $350,000 project to determine the chemistry and mechanics behind the successful use of Class "C" flyash by using the facilities at the Western Research Institute and the University of Wyoming. These facilities include electron microscope, xray and spectrographic analyses, a full scale climate and hydrology simulation laboratory, and geotechnical engineering testing capabilities. Concurrent with a one year laboratory study to determine optimum percentages of flyash and to develop standard testing procedures and specifications, test strips will be constructed by state, county and Forest Service organizations in Wyoming. These will be monitored over a three year period after which the technology will be extended state wide and to other areas as appropriate. One of the goals will be to develop a standard laboratory procedure that can predict performance of flyash treated aggregates. Wyoming's arid climate results in large areas of soils of low plasticity, which provide poor binders for road surfaces. The experience gained in the U.S. Forest Services Southern Region indicates that the flyash produced at these power plants should be highly effective in stabilizing these soils.

The project is initially funded by Pacific Power and Light, Dave Johnston Power Plant, U.S. DOE, and Science Technology and Energy Authority of Wyoming. Electrical power for large areas of the U.S. is generated by power plants located in Wyoming, taking advantage of the state's huge coal reserves. Disposal of the flyash generated at these power plants has become a major problem, and will be addressed by the study, using rural road stabilization as the potential disposal area.

Converse County, WY On Tuesday, July 23, 1991, the Western Research Institute, Coverse County, WY, and the Dave Johnston Power Plant at Glenn Rock, WY, constructed the first 1000 ft test section for this program on the Converse County Tank Farm Road at the North Platt River bridge. The project consisted of mixing 240 tons of flyash into the top 9 inches of subgrade soil, an A-2-4 nonplastic silty sand. The flyash added amounted to nearly 25 percent of the total mix. Construction equipment was provided by the County, and the flyash by the power plant. The Powder River Basin coal fields in the NE portion of Wyoming generally contain 20 to 30 percent limestone, which converts to lime during the burning and mixes with the flyash collected by electrostatic precipitators in the stacks. The Glenn Rock mine, which provides coal to the Dave Johnston Power Plant, is on the edge of the field, and the coal contains ony 9 to 12 percent limestone. Thus a higher percentage of flyash is required to achieve an equivalent amount of lime.

The unsurfaced subgrade was scarified to 9 inches by rear mounted rippers on the Cat 140 grader, and watered by 5000 and 10,000 gallon water tankers. Class "C" flyash containing 12 percent lime was delivered by tankers in 30 ton loads and applied directly through hopper bottom valves after pueumatic charging. A steady cross wind 10 to 15 mph blew the dust cloud downwind. Each dump was preceded by watering and blading to provide a damp runway between windrows, and followed by scarifier mixing and more watering. Optimum moisture content of the soil was around 13 percent and dry density 115 pcf, and natural moisture estimated at 5 percent. The first 30 ton load of flyash arrived on the job at 10:30 AM. Five of the eight load total had been incorporated by 2:30 PM. Without coarse aggregate present, the yellow soil and black ash were not blending well, yeilding a mottled pattern and indicating that a farm disc would provide better mixing. However, the full 25 percent applied did yeild a uniform black color. The eighth and last load was applied at 5:00 PM, and was incorporated as easily as the first due to ample moisture present. The surface was shaped by the grader and compacted under the equipment tires of a loaded scraper. Moisture content was estimated; Sand Cone density tests were taken.

Several methods of preparation for application were tested, including a furrowed surface, a flat surface, and a flat surface between windrows. The furrows tended to concentrate the flyash in the center of the lane, while the flat surface allowed the flyash to flow as a liquid to an even depth across the surface. The windrows confined the flow, and after flyash application and mixing, provided a source of material to the blade for mixing. A control section, also of a 1000 ft was constructed adjacent to the test section. The control section was scarified to the 9 inch depth, water was added to optimum by estimation, and the scraper was again used for compaction.

The silty sand soil provides a flat Proctor curve, and compaction was performed dry of optimum to avoid pumping. After drying on the surface the untreated soil began to ravel immediately under traffic, while the black flyash treated surface remained compacted and firm, held in place by the moisture of hydration. However within a week after construction traffic wear produced a thin layer of fines on the surface and dusting became objectional. A shallow layer of coarse bottom ash from the power plant was placed to provide a dust free wearing surface and for traction during occasional rainfall.

The section had 5 weeks of hot weather before cooler weather and night frosts began in September. This will provide an estimated half of the 3000 degree-days required for a full cure.

An initial evaluation of the treatment indicated that the selected 25 percent flyash fraction was considerably more than needed, and that future sections would be constructed with reduced additive.

Additional test sections are planned for construction over the next three years, including at least one demonstration section in each county in Wyoming. A variety of soil and aggregate types will be included. A second section in Converse County will involve a clay soil.

Wyoming DOT Tom Atkinson, DOT Materials Engineer, described DOT use of flyash since 1978 as a base stabilizer. 2 to 4 percent flyash has been added to well graded crusher run aggregate on an estimated 30 miles of state highway, and 3 percent flyash has been incorporated in 200 miles of CTB replacing half the Portland cement. Constructed sections include interstate as well as primary and secondary highways. Visual evaluations by DOT engineers indicate flyash is as effective as Portland cement. A full technical evaluation of these sections has been proposed.

AGGREGATE STABILIZATION

Bioenzymes

Applications

Bioenzyme soil and aggregate stabilizers were developed as a by-product of the enzyme industry, which specializes in food processing, cleaning agents, and cosmetics. Industry personnel have only vague notions about procedures used in earth construction. Effective communication with the construction industry has been achieved only through the efforts of the better trained product distributors.

The mechanisms of bioenzyme stabilizers are proprietary and secret. However, the general nature of these mechanisms is understood by biochemists, and is alluded to in advertising material. Bioenzyme stabilizers provide a bacterial culture in an enzyme solution. When exposed to the CO_2 in the air, the bacteria multiply rapidly and produce hydrogen ions that break down the clay lattice, and large organic molecules which the enzyme attaches to the clay molecules in the aggregate, blanketing ion exchange points in the clay. This prevents further absorption of moisture and results in a stable construction material. During the hydration that follows compaction, ionized water forms linkages between the closely packed particles, providing the cementing bond. The stabilizing effect of organic ions on clays has been discussed in the literature.(5)

There is no constant dilution factor for bioenzyme stabilizers. A minimum dilution of about 55 gallons per 1000 gallons of water (one drum per tank load) should be maintained to ensure adequate distribution of the stabilizer throughout the aggregate layer. This dilution rate will increase the moisture content about one percent, and thus the natural moisture content must be one or two percent below optimum proir to application.

Water requirement is calculated as the quantity needed to raise the moisture content to slightly below optimum. Stabilizer requirement is calculated seperately at one gallon per 9 to 12 cy of aggregate, depending on the stabilizer brand. The solution concentration is developed from these two calculations. The tanker is filled halfway, the bioenzyme concentrate is added, and the tanker is filled up. This procedure ensures adequate mixing prior to application.

The road surface is scarified to the full treatment depth, and the solution applied in several passes to ensure even distribution. Scarifyer mixing must be thorough to bring all of the aggregate in contact with the applied stabilizer solution. Two hours per lane mile at 5 mph is usually more than adequate. The surface is then shaped, and compacted at optimum moisture.

The bioenzymes contain a wetting agent, and tend to make the aggregate mix appear dryer than actual. They may also lower the optimum one or two points below the value obtained with a Proctor test using plain water, and they retard evaporation from the aggregate mix. All this tends to produce a wetter than desired mixture that is difficult to dry back for compaction. Thus water should be added with caution. Under extremely dry or windy conditions where evaporation is rapid, shorter sections can be mixed and brought to optimum for immediate rolling to maximum density where longer sections would dry before density could be achieved. Good compaction is essential to achieving a durable surfacing.

Construction Observations

The observations made during and after construction on several projects support the premise that an ion exchange is taking place between the alkali ions in the clay lattice and the organic ions provided by the biochemistry of the stabilizer solution. During mixing on the project in Montana with ample clay present, clay lumps were noted to break down rapidly and loose plasticity. On that project, and those in Texas and South Carolina which also had clay present, the road surface hardened noticeably after 24 hours indicating that hydration was causing cementation of adjacent sand grains. Full strength is reached well within the 4 or 5 days curing time recommended by the manufacturers (Figure 7).

The stabilized surface can be lightly bladed with moisture present and will again harden with compaction under maintenance equipment and traffic, providing essentially the same performance as immediately after construction. Blading in a dry condition will result in dusting and erosion, spoiling the surface.

With clean crushed basalt in Washington and Oregon where the only fines were rock dust, no reaction was observed and there was no reduction in maintenance reported. Some clay content is essential to a successful bioenzyme project; a well graded mix provides the best performance.

With the North Carolina limerock and the Florida limerock mixes where clay fines were negligible or lacking completely, no reaction was observed although substantial reduction in maintenance was reported. Some limerock pits are contaminated by clay lenses, which would improve the reaction in sections with the clay present, and the sandclay fraction mixed with the limerock contains a small percentage of silt, and possibly some clay.

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In Benton County, Oregon, Bio Cat provided a solution where MgCl could not. When gravel roads through poorly drained farm land were treated with MgCl, excess moisture collected during winter months attracted by the hygroscopic nature of the MgCl, causing mud to pump through and coat the surface. A Bio Cat treated section provided an effective seal against moisture and a firm base for a subsequent chip seal which has performed well. The treated gravel layer included considerable clay fines from the subgrade to react with the organic ions of the bioenzyme solution.

Treated subgrades on BLM projects near Medford, Oregon suffered from subgrade deformation under the treated layer due to frost heave, while treated clay in New Mexico suffered from abrasion by chained tires on heavy gas well rigs, but both sections survived the Spring and looked good through the Summer. It was apparent that a better graded material would improve performance, and that some surface rock is necessary to protect fine grained soils where heavy abrasive forces are present. Laboratory tests are currently planned to determine whether the addition of a small percentage of bentonite to the Florida sandclay will improve the reaction of that material with Bio Cat. The Bentonite is available in bulk from a source near Montgomery, Alabama at a cost effective price.

Ozark NF, AR

Aggregate treatment in Arkansas, on the Ozark NF, included 6 miles of bioenzymes. All of the work was done with blade mixing, traditional to contractors in the area. The Ozark NF is in a mountainous area where steep grades are common. The New Blaine Road, FDR 1600, has a traffic count of around 200 ADT. A half mile section was surfaced with subgrade material treated with Bio Cat in July of 1988. This section has been given a light blading twice per year and provide excellent service in all weather. Another 1.9 miles of this road was surfaced with a 3/4 inch minus well graded crushed rock with clay fines, mixed in equal parts with the black shale, and treated with Bio Cat on half and Earth Materials Catalyst on the other half in July of 1990. This section has a hard, uniformly graded surface throughout.

The White Rock Road, FDR 1505, is a high use road with grades up to 9 percent; both aggregates and subgrade soils tend to be silty and low PI, with marginal clay content. A quarter was mile treated with Bio Cat in the summer of 1988. The road has been bladed once per year plus one time following a heavy hauling contract. No washboard has been noted on grades of 5 percent or less, which include the Bio Cat section. A uniform thin float of coarse aggregate was noted on all sections including the Biocat section which indicates marginal clay content for a bioenzyme treatment. Another half mile of the road was surfaced with the 3/4 inch minus mixed in equal quantities with the silty clay subgrade by scarifying, and treated with Bio Cat on half the section and with Earth Materials Catalyst on the other half, in August of 1990. The road surface is hard and uniform, and has no float in this section.

On 3 miles of the Rich Mountain road, Biocat was used in the Fall of 1990 to stabilized the top 2 inches of the crushed Arkansas SB-2 aggregate containing some shale. Prior to treatment the aggregate would pile up in the road center within a week after blading. Since treatment the surface has developed a hard glaze and remained flat and ravel free throughout the winters, without potholing or rutting.

Rain Mine, Carlin NV

The Newmont Gold Company's 13 mile long access road to the Rain Mine south of Carlin, Nevada was constructed in 1987 and surfaced during Fall of 1987 using a well graded pit run siltstone talus with a 10 percent clay content, stabilized with Bio Cat and surface crusted with MgCl. The 20 to 30 ft wide balanced cut and fill road winds upslope at grades up to 10 percent to the ridge top mine location. The late season construction limited surface thickness to 4 to 6 inches in the first 5 miles and 2 to 3 inches over the remaining 8 miles. Following compaction under grid rollers, the Bio Cat treated material was covered with .6 to .75 g/sy MgCl which crusted on the surface with minimal penetration.

Traffic throughout the winter months included daily commuting of 500 construction personnel working at the site, and transport of equipment and materials for the rock crusher and ball and roller processing plants. The only maintenance required during this period was snow removal accomplished with grader blade scraping the hard aggregate surface, and applications of a sand/salt mix.

Some sections were subjected to repeated freeze-thaw cycles while others endured prolonged freezing and a spring thaw, depending upon exposure. The road surface remained free from rutting, potholing and washboarding, although in the 2 inch sections some surface ravel was noted on curves. The subgrade over most of the road is of broken shale and siltstone, and in some areas bedrock can be seen in the surfacing.

Some bathtub problems developed where 8-18 inches of poorly drained surfacing was employed to fill hollows in bedrock on saddles, resulting in pumping on the surface. This material was removed and recompacted in thin lifts to alleviate the softness. Good compaction is essential to obtaining a hardened surface. Subsequently during 1988 the aggregate surface thickness was brought up to 6 inches over the entire road, treated with Bio Cat and crusted with MgCl.

Initially maintenance consisted of roller brushing the surface at two week intervals, snow removal during the winter, and an annual spring application of MgCl. The completed surface gives the impression of a paved road rather than gravel. During an inspection in summer of 1991, no serious failures or maintenance problems had developed over the life of the road, other than a few short sections of potholing due to poor subgrade drainage. The surface remained well cemented with only minor ravel; maintenance consisted of an annual light blading with a serrated blade, followed by watering with a dilute Bio Cat solution and rolling. A light application of MgCl is then applied.

The surface was very hard and free of ravel except for a short section where the blade had been working the previous day. The surface quality showed a uniformly fine gradation of about 1" minus, tightly knit and well armored by the coarser aggregate particles. In a few areas it was apparent that a coarser fraction had been included, up to 3" minus, which provided a distinctly rougher riding surface, but still retained the ravel free, tightly knit, well armored surface. Two short sections of about 50 ft each with obvious subgrade drainage problems had several small, shallow potholes. In general the road surface had the appearance of a bituminous surface treatment, and was performing equally as well.

Allegheny NF, PA

Portions of F.R. 185 on the Allegheny National Forest were stabilized with Bio Cat during June of 1988. The original surfacing was 6 to 14 inches of pit run 5 inches minus rock, high in fines with a PI of about 1, over a silty subgrade. Additional surfacing up to 8 inches thick of the same type was placed during the previous Fall on the thin sections.

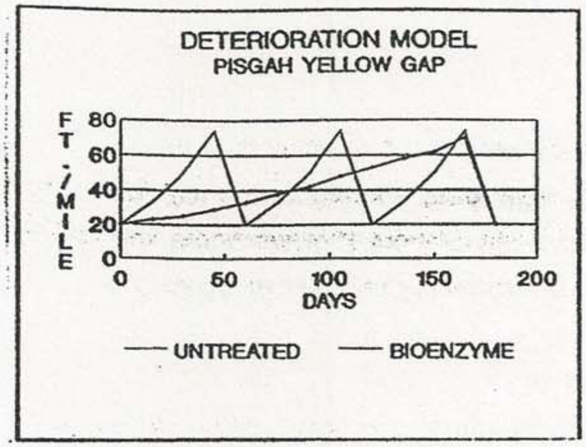
During early June of 1988, three sections 1200 to 1500 feet in length were treated with Bio Cat to 8 inches of depth. Mixing was accomplished with farm tractor and grader, both equipped with rippers capable of 8 inches penetration. Excessive moisture in two sections caused delays in the compacting process(rubber tired followed by steel vibratory rollers). All sections were observed to be set up hard after the fifth day, performing well under heavy loads without rutting. A fourth control section of 200 feet was processed without Bio Cat to determine the effect of the processing. Following compaction the entire road was graded.

Since construction the road has supported continual sale traffic without additional blading. During an initial inspection trip, two months after treatment, all Bio Cat sections appeared in excellent condition, with uniform section and no evidence of rutting or chuckholing, or loss of surface fines around larger aggregate particles. Two of the Bio Cat sections which were formerly the road's worst problem areas due to organic silts in the subgrade are now the best looking sections on the road. No change in this performance has been reported through 1991.

In contrast, untreated sections including the control section showed loss of surface fines and loosening of larger aggregate particles due to traffic abrasion, resulting in shallow rut formation, start of chuckholes, and considerable loose material across the section.

Pisgah NF, NC

On October 23, 1987 an application of Bio Cat soil stabilizer was mixed with a crushed aggregate base over a 1/2 mile section of the Yellow Gap road on the Pisgah NF. This road carries local, logging and recreational including hunter traffic throughout the year. The crushed aggregate is a crushed gneiss meeting the North Carolina State specs for aggregate base course which allow 12 percent passing the 200 sieve. These fines have some clay content which gives the compacted surface a yellow clay appearance. The contractor attempted to blade mix but found this process slow. A full blade on any pass will hold a maximum of 2 inches of aggregate and thus cannot mix to the required depth. He was forced to make many passes with his scarifiers, a less efficient procedure than a tractor drawn chisel plow. He also mistakenly observed the aggregate mix to be too dry following application of all of the stabilizer, and elected to add an additional load of water. Since Bio Cat acts as a wetting agent, the dry appearance at optimum is not unusual and the additional water placed the mix over optimum, causing it to stick to the drum of the vibratory roller. The contractor continued to work the mix with the blade for another hour but was unable to dry it enough. The surface was lightly compacted at days end to protect it from a light frost expected that night.



The following morning the Bio Cat had begun to react with the aggregate, giving the mix a dough like consistency not observable in the untreated aggregate. Enough drying had occurred to permit final shaping and compacting. When pulling aggregate mix in from the shoulders and ditches where it had been deposited during the previous day's blading and spreading it to form the roadway crown, a layering effect was noted with the previous day's surface. However because of the amount of moisture present it was felt that the action of traffic would result in the layers knitting together.

A month following construction the surface appeared unchanged despite heavy rains and hunting traffic over the Thanksgiving holidays. Good traction has been noted under both wet and dry conditions. The treated section held its moisture well through the dry days as compared to untreated sections and was noticably free from dusting, indicating that Bio Cat can be an excellent dust pallative with this aggregate in this climate.

This road section continued to perform with only minor blading on the shoulders and ditches through 1991. The surface has a well armored appearance similar to a chip seal and a notable lack of ravel for a gravel surface. There has been no rutting, potholing or corrugations developing.

Gifford Pinchot NF, WA

In August of 1988, 2 one mile sections of clean crushed basalt surfacing on Rds 21 and 30 were scarified to 4 inches, Bio Cat solution was applied and mixed by blade and windrowing. Compaction to maximum density was achieved with a vibratory roller. Within 2 months, extensive ravel, large berms, scattered potholes, and minor corrugations had developed on both sections, indicating that no reaction had occurred. The fines in the aggregate were all crusher dust; no clay fines were present to react with the bioenzyme stabilizer.

Willamette NF, OR

In July of 1989, 2000 ft of clean crushed basalt surfacing on Rd 1802 was scarified to 4 inches, Bio Cat solution was applied and mixed by blade and scarifiers, and the surface was compacted to maximum density with a vibratory roller. During an inspection 6 weeks following construction, extensive raveling and scattered potholes were observed; there was no sign of any reaction by the Bio Cat solution. No clay fines were present in the aggregate, only non reactive crusher dust.

BLM, Medford, OR

In October of 1988, a mixture of creek gravel and clay subgrade soil on a one mile section of the Ditch Creek Road was scarified to 6 inches and Bio Cat solution was applied and mixed in by blade and scarifiers. Compaction to maximum density was achieved with pneumatic and vibratory rollers. Due to extremely dry conditions the surface was pre-wetted with a dilute 1:3000 Bio Cat:water solution on the day before mixing to permit easier scarification and more effective dispersion of the stabilizer into the road material. No traction course was applied and the finished surface was primarily a fine grained material.

After a month of log hauling at 6-8 trucks per day and casual use traffic with 8 inches of rain and some freeze thaw in shaded areas , a half to one inch of slop and 2-3 inch ruts on centerline had developed primarily in the shaded areas of the treated section, compared to 4-6 inch ruts in untreated sections. Following a deep freeze in February of 1989 and a Spring thaw, subgrade rutting developed in shaded draws of the treated section and where snow had accumulated, resulting in a plastic deformation of the stabilized surface layer to shallow wheel ruts and indicating that the 6 inch thickness was too thin for the weak saturated clay subgrade. The stabilized surface material was too hard to blade and a thin layer of crushed aggregate was applied to even the surface.

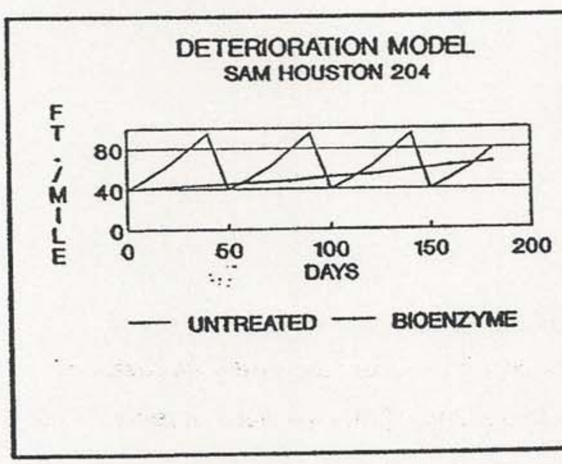
Carson NF, NM

In October of 1988 a 500 ft section of clayey silt subgrade on FDR 310 was treated with Bio Cat solution to a 12 inch depth. Mixing was accomplish by disking and blading, and compaction with a pneumatic roller. Traffic on this road is primarily extremely heavy gas well drilling and maintenance vehicles operating in all seasons. During the Winter and Spring these vehicle use tire chains and all wheel drive to plow along the frozen or saturated surface. The traditional method of Spring maintenance involves periodic blading to the roadside of saturated soil to expose the dry subgrade. This practice continues throughout the thaw, leaving windrows of material on either side of the road. During the summer this material is bladed back onto the roadway.

The Bio Cat treated section performed well until the Spring thaw when the surface abrasion from the tire chains cut 6 inch ruts into the somewhat slippery surface of the stabilized material. The surface was rebladed as it dried out and during an inspection in October of 1989, was very hard and supported traffic easily. It was apparent that a traction layer of coarse aggregate would improve the performance of the treated layer.

Sam Houston NF, TX

During August 1989 an application of Bio Cat was made to 4.5 inches of aggregate surfacing on 2.5 miles of 20 ft double-lane Road FDR 204, in the Sam Houston NF. The road has been in use for many years, providing access to residential and day use areas, and lake use as well as log hauling. Several applications of surfacing over this period has resulted in a wide variety of crushed materials, some with very poor gradation. Frequent maintenace had failed to prevent severe corrugations and excessive potholing, so severe in some areas that traffic diverted to the shoulder to avoid the large holes. The road was not closed during construction, and the occasional traffic caused no problems.



The mix of materials used during maintenance work resulted in at least 5 material types along the road including various combinations of quartz gravels and crushed river rock mixed with small amounts of sand and red or brown clay binder(7%), crushed sandstone, and clay balls from the gumbo subgrade in one 200 ft section.

The aggregate moisture was 4.5% compared to the optimum moisture of 8.5%. Application began on the first 1/2 mile adding 88 gallons of Biocat in 12000 gallons of water. The section had been scarified. Equipment included two 5400 gallon tankers, one for haul and one for spread; a grader/scarifier, Seaman mixer, and pnuematic roller. Specs called for 4 passes with the mixer and 6 passes with the roller, at optimum moisture. During rolling several areas were found to be over optimum and reduction of water on the next section was discussed. The Proctor tests had been run without Bio Cat. Addition of the stabilizer was probably increasing the density and reducing the optimum.

On the 2nd day, an early shower(est. 1/2 inch) saturated the remainder of the road surface to 9% moisture. As clear weather was forecasted for the remainder of the week, the day was spent scarifying and drying the remainder of the road surface. A second grader/scarifier was on the job. Dryer areas of the first section were very hard by late afternoon, could not mark with finger nail. Wetter areas were still soft.

On the 3rd day, the aggregate moisture measured 7%, temperature was 85 degrees. 84 gallons of Bio Cat in 4500 gallons of water were applied to the second half mile section. This still proved wet in some areas, and water was reduced to 4000 gallons on a subsequent section. This proved to be the best mix and compacted easily. As the graders were being used in the mixing, windrowing material for the mixer to work, the mixer passes were reduced to two. A section of crushed sandstone surfacing was found to be exceptionally dry, dusting under traffic after initial compaction. Five hundred gallons of solution at the same dilution were added to the surface. This knitted and hardened the surface area and stopped the dusting.

A few of the wetter areas on the first two sections still could not be compacted by the end of the third day. These areas were crusting over but would move under pressure and ravel under traffic. The roller returned on the 4th day to continue rolling as drying proceeded. All areas were hardening well.

An unusually wet winter followed construction, with over 36 inches of rain falling between October and January, resulting in a softening of the clay subgrade, with minor potholing developing along the centerline and shallow rutting in the wheel path near the shoulder. In February 1990 the road surface was lightly scarified and recompacted; in August of 1990 select areas totaling a half mile were injected with Condor SS to firm up the subgrade without disturbing the surfacing. During the year following, the surface performed well, remaining free of potholes and corrugations and rutting. Because some of the aggregate is poorly graded with a 3 to to 4 inch maximum size and a deficiency of intermediate sized aggregate, traffic tends to wear the fines around the large (3 to 4 inch) aggregate particles leaving them exposed to tire loads, and a moderate layer of ravel has developed where the larger aggregate predominates. These sections are experiencing more rapid wear than those with the better gradation.

Chattahoochee NF, GA

In April of 1990, 0.5 miles of the Tallulah River Road were surfaced with a degraded crushed aggregate stabilized with Bio Cat. This road serves a camp ground and a farming area, and receives 50 to 100 vpd of all types. The section surfaced has a nearly flat grade over the entire length. The existing aggregate surfacing was mixed with subgrade material to increase the clay content; however only about 1 percent clay was achieved due to the primarily silty nature of the weathered bed rock in the area.

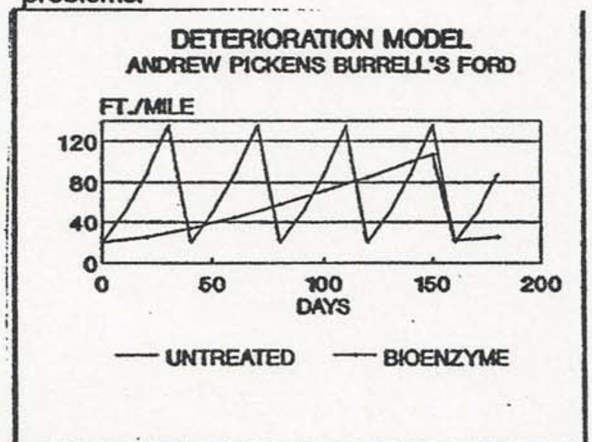
The Bio Cat solution was spread from a 1000 gallon water wagon. Mixing was accomplished with scarifiers and blade, and compaction with a small vibratory roller. In hot, dry weather it was necessary to work in short sections to avoid excessive evaporation from the aggregate mixture.

A month following construction the roadway was smooth and firm, with a notable absence of loose aggregate. A series of small, shallow pothole formed along the crown due to traffic working fines in puddles during the frequent rainfall. During the summer months, several small potholes formed in the inside wheel track along a steep bank over looking the river, apparently from subgrade deformation caused by seepage. These were too shallow to be noticeable to traffic.

The section has received a light blading twice a year since construction, and continues to perform well for a graveled surface.

Andrew Pickens NF, SC

In July of 1990 a bio-enzyme stabilized aggregate surfacing was placed on 2.7 miles of the Burrell's Ford road, No. 708, between SC 108 and the Chattooga River. This road is one of few that accesses the river in this area, and receives heavy recreational traffic from fishermen, rafters and hikers. West of the river, the road continues in Georgia through the Chattahoochee National Forest to intersect Highway 28. Originally constructed over 30 years ago, the road has many curves, and grades ranging from flat to near 12 percent. Heavy corrugations and potholing have resulted in many complaints over the road condition. The limited maintenance budget has often failed to keep up with the problems.



The Contractor had a motor grader, a large tractor pulling a 9 point heavy duty chisel plow, 2 tractor drawn 1000 gallon water tanks, and a vibratory steel wheel roller on the job. Beginning initially with 800 foot sections, the contractor increased the length to 1000 feet, requiring 25 gallons of BioCat on the first half of the road, then 17 gallons of Earth Materials Catalyst (EMC) on the second half. An additional 3 gallons was added to each completed section as a surface treatment. 4 drums of Bio Cat and 3 drums of EMC were supplied. Water requirements to reach optimum of near 7 % ranged from 2000 to 3000 gallons per section. The residual moisture was determined at 3.5 % at the beginning of work. On the evening of the 2nd day, a heavy thunder shower thoroughly drenched the area, raising the residual moisture to near 6%. No additional rain fell through the completion of work on the 11th day.

Each section was scarified with the grader, the bio-enzyme solution applied with the water wagons followed by mixing with the chisel plow for approximately 1/2 hour, shaping with the grader and compacting with the vibratory roller. Densities achieved were generally in excess of 100% proctor, determined by nuclear gage. On a few sections, excess moisture resulted, and the contractor re-scarified to permit drying. On sections where density was not achieved due to low moisture, the contractor re-scarified, added water containing 2 gallons of bio-enzyme per 1000 gallons, remixed with the chisel plow and re-compacted until density was achieved. The contractor deliberately scarified deep to bring fines from the subgrade into the crushed aggregate surface which contained only 2% passing 2 microns, ultimately raising the passing 2 microns to over 10%. There was considerable variation in gradation along the 2.7 miles, both in the aggregate and in the subgrade. The aggregate is gap graded, lacking material between the 3/8 and No. 4 sieves, and in some sections is very high in coarse rock, particularly on grades where more rock had been added over the years of use. This resulted in raveling of the excess large aggregate from several sections after a few days of traffic. The subgrade material appeared to range in PI from a clay of low plasticity to a non-plastic silty clay, thus providing a tighter surface in sections with more clay. The amount of subgade material scarified into the aggregate was difficult to control and also varied from section to section.

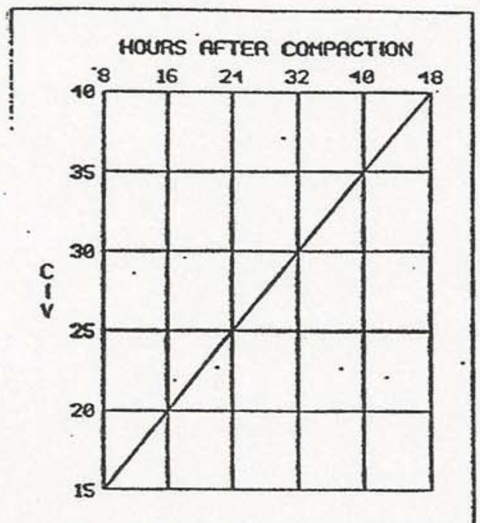


Figure 6. Rate of curing for bioenzyme stabilizers, expressed as a function of the CIV's.

The Clegg Impact Hammer was used to evaluate the rate of hardening of the treated aggregate following completion of compaction (Figure 6). Within 2 to 4 hours of compaction the CIV's varied from 14 to 20 in most areas, with a few sections high in fines ranging from 7 to 20. After one day the CIV's had increased to a range of 25 to 40, and after three days to a range of 40 to 60. Little change was noted at 7 days, although a few sections showed a range of 50 to 70. These appeared to be the sections with a well graded aggregate. CIV's on the compacted, untreated surface prior to scarification ranged from 30 to 50. The bio-enzyme producers generally indicate 5 days curing time to reach maximum strength. At the completion of work, the road had a good appearance and was easy to drive. The steep grades, many curves and heavy use provide an excellent test area for these stabilizers.

In September of 1990 an inspection found raveling and moderate washboarding on about 50 feet of each of 6 sharp curves located at intervals along the 2.8 miles of road, and on one steep 12 percent tangent about 300 feet in length located midway on the project adjacent to the drainage. All of these curves are steeply banked and on grade. This had resulted in development of cross rill erosion during the high intensity rainfall occurring with thunder storms, and the rills had developed into washboard under the heavy traffic. The tangent section had a high percentage of coarse rock in the base material, and is the steepest grade on the road. These two factors had resulted in an excessive amount of large loose aggregate across the road surface, which was beginning to washboard. The combined problem areas total about 600 feet out of the 2.8 miles, or 4 percent of the project. The remainder of the road surface, whether on grade or level, remained in essentially the same condition as immediately following construction. Severe washboarding over much of the road surface, the usual condition prior to treatment, was noticeably absent, and the road provided a smooth, fast ride for the user.

In November of 1990 erosion corrugations, caused by runoff from heavy rainfall, in excess of 3 inches per hour, running across the road on superelevation, were noted on short sections of 7 curves. The loose gravel and corrugations had disappeared from steep (12%) tangent above the middle creek. The road surface was hard, clean, without loose gravel except in minor areas. Coarse aggregate was well locked into the fines matrix, dust free. Poor gradation was evident with considerable space between larger surface aggrgate, exposing the fine aggregate to suface wash, but was resisting well.

Shallow one inch erosion features were developing on long tangents; a centerline depression that carries runoff to superelevation where it can escape to the ditch. These did not impede traffic except in appearance.

After 3 1/2 months of heavy Fall traffic and several rainfalls, the road appeared in excellent condition, was easy and pleasasant to drive, slow or fast.

Downhill drive was comfortable at 25 - 40 mph; uphill OK at 20 - 35 mph, a few rough spots on corrugated curves. Road curvature was the primary control on speed. Centerline erosion depression distracts driver's attention but was drivable.

The road condition worsened during the hunting season in the latter part of November with continued heavy rains and heavy hunter traffic increasing the corrugations and erosion channels. The District had it bladed on 12/1/90 (first blading).

Two weeks later the surface was uniform, had moisture, and was healing under traffic. Some areas had clay fines, others did not. There was excess 1" plus over most of the surface rolling loose under the wheels. Driving speed was 20 to 30 mph compared to 25 - 40 in mid November due to this loose rock. The blade operator was unable to remove the corrugations with blade only and tried to fill them instead; they were reappearing gradually.

Through the winter months the surface hardened again and lost most of the loose rock. Three short, steep curves developed heavy corrugations. Heavy rains in April caused some shallow erosion features, but driving speed remained in the 25 to 40 mph range, limited primarily by the frequent curvature. District maintenance personnel were in agreement that whatever problems remained, there was little comparison to what the road had been prior to treatment with the bioenzyme stabilizers, with its long sections of potholing, loose aggregate and severe corrugations.

Appalachicola NF, FL

In August of 1989 a section of FDR 309 south of the Wakula Work Center 1.8 miles of sandclay/limerock mix was stabilized with Bio Cat. Five inches of limerock had been placed over the existing sandclay surface prior to adding one 55 gallon drum of Bio Cat per 1000 feet of road and mixing to an 8 inch depth. The Bio Cat was added in sufficient water to bring the moisture content to optimum. On the section observed, this amounted to about 700 gallons of water per 55 gallon drum of Bio Cat spread in 6 passes of the water truck over the 20 foot width.

Each section was thoroughly scarified to full depth using grader front double scarifiers prior to applying the Bio Cat solution. Mixing followed using a cross shaft rotary mixer making a full pass over the road surface, then initial compaction with a vibratory steel wheel directly behind the mixer, and several passes with a pneumatic roller during finish blading. When a mixer breakdown occurred shortly after application of the Bio Cat solution on the final section for the day, the contractor completed mixing by windrowing the material and making multiple passes with a disk harrow before spreading and compacting the mix.

The road surfacing stabilized with Bio Cat in 1988 on another section of FDR 309 has required no blading since for regular haul traffic. Eight bladings per year is normal for the untreated material. Repairs were required where four wheelers chained two vehicles together and ground down through the surface (a local sport) to leave holes in the roadway. Adjacent sections treated with Pozzalime required one blading during the same period.

Some clay fines are present in the mix, in nominal amounts. As the limerock is normally bedded with clay in the natural deposits, some clay is derived here, usually less than 5 percent. The fines in the sandclay are often less than 10 percent with half of this in clay. As this amount is insufficient to fill the voids in the mix, a dense, hardened surface does not result as in the case of some gravel, sand, clay mixes treated with Bio Cat. Because the 4 inches of sand clay applied to the surface on this project was mixed into 8 inches of lime rock and sand, the clay fraction was too highly diluted to provide a strong binder after treatment with the Bio Cat. A higher clay content, or an overlay of sand clay treated with a bioenzyme should provide greater protection against excessive moisture changes. Lime rock is a calcium carbonate, a water soluble cement which remains hard within certain moisture limits. Under drier conditions the surface ravels, while under wetter conditions it softens and ruts. Within the optimum moisture range it performs much like a concrete pavement.

In April of 1991 an inspection of Road 309 was made to evaluate the performance of the Bio Cat stabilization of the sand/clay and lime rock mix completed in 1989. Although not bladed for over a month, the treated section had a hard, smooth, concrete like finish over much of the surface. This could be compared with the ravel and rutting in evidence on adjacent sections treated with lime kiln dust or untreated. During periods of prolonged wetting or drying, the surface softens and ravels, but to a lesser extent than the untreated mix. This probably indicates that the Bio Cat treatment is stabilizing and preserving the clay fines present which helps to maintain an optimum moisture content necessary for the lime rock to set up.

Ouachita NF.

During early May of 1988, 500 feet of FDR 643 on the Fourche RD was stabilized with Bio Cat. This section is adjacent to bituminous pavement and is in an easement through a residential area. Property owners had complained of dust and had requested a chip seal. The intent had been to mix to a 5 inch depth, but the rocky subgrade limited scarifying to only 2 inches. 15 gallons of Bio Cat were added to 1200 gallons of water and sprayed over the scarified surface. Mixing was completed with scarifiers and blade, and compaction was accomplished with grader and dual truck tires. A 2 inch rain immediately following construction had no apparent effect on the surface. After 3 years of use the surface remains unchanged. Dusting has been reduced to a slight haze from silt washing onto the roadway, and the local residents have made no complaints.

Lewis & Clarke NF, MT

During September of 1989, the Lewis and Clark NF, southeast of Great Falls, Montana, applied Bio Cat aggregate stabilizer on sections of the Spring Creek Road, No 274 and 478.

Ten miles of Road 487 north of Corral Creek were included in the current contract and had been completed. The contract called for adding an inch of clay shale to the existing 4 inches of crushed sandstone surfacing over 32 miles of road to provide a binder; blending and compacting the two materials. However, the contractor had been incorporating the shale fraction by blade mixing only, and the blending had not been satisfactory, as evidenced by clumps of shale separated from zones of the sandstone aggregate.

5 drums of Bio Cat were required to stabilize 2.5 miles of this surfacing. The sections selected for application of the Bio Cat are on grades that had caused notable problems with washboarding during past performance. These sections are at MP 6.0 to 7.0, MP 7.9 to 8.4, MP 12.0 to 12.5, and a half mile at the junction with the Ettien Ridge Road, No 821, adjacent to Big Hill Creek, near MP 18.5. A control section of a quarter mile without shale was left at MP 5.0.

The first application of Bio Cat over 0.5 miles at the junction with the Ettien Ridge Road was on partially mixed and compacted aggregate. The initial mixing had been inadequate, and clumps of shale and clay could be observed in the road surface. This surface was now rescarified and mixed with the grader scarifiers, and 55 gallons of the Bio Cat were applied in 3500 gallons of water (estimated as sufficient to achieve optimum), the water tanker making 3 and a half passes over the 0.5 mile section.

Mixing was accomplished with a combination of scarifiers and windrow blading. The grader made a full pass with the scarifiers across the road surface, and then windrowed to one side and back again, followed by compaction under a steel wheel vibratory with two wide tires following. During the mixing process it was noted that the clay and shale clods broke down readily following application of the Bio Cat, and dispersed well into the sandstone aggregate. This phenomena is a direct result of the ion exchange taking place between the Bio Cat and the clay molecules, similar to the ion exchange occurring in lime stabilization, except that an organic ion is involved instead of Calcium. In an adjacent section which received the same rescarification and scarifier mixing without the benefit of the Bio Cat, the clay and shale clods mixed better than they had by blade mixing alone, but still refused to disperse into the sandstone aggregate, resulting in a patchy appearance to the compacted surface.

Initial scarification began about 11:30 am and the surface was sealed by 2:30 pm. Rolling continued until quitting time. Two areas in the shade were over optimum and required additional rolling the following day. During the mixing operation, moisture was noted to evaporate rapidly from the aggregate surface in direct sunlight, leaving much of the section dry of optimum. Except in the shaded areas, the compacted surface was very hard and uniform, and after 24 hours major portions had indurated and could not be scratched with a fingernail.

Subsequent sections for the Bio Cat had the shale windrowed to one side and on top of the sandstone aggregate. The shale was first spread over a roller width of the road. The roller made several passes to break down the larger chunks of shale to minus 1-3/4 inches. The crushed shale was then distributed evenly across the road, and the surface was thoroughly scarified and partially mixed prior to application of the Bio Cat. With the Bio Cat applied in the compaction water, the grader continued mixing with the scarifiers and finally by windrowing to one side and back, with the roller following to seal and compact the surface.

Log hauling on the new surfacing began in November of 1990, and continued throughout the winter except for a 6 weeks period during the Spring breakup. During the winter months, the road was snowplowed, leaving only a 2 inch snow pack on the aggregate surface. Following the breakup period in 1991, the road recieved its first touchup blading where needed, but the Bio Cat sections were ommitted from this maintenance. The log Hauling continued through the Summer of 1991.

In July of 1991 an inspection was made of the condition of the Bio Cat and adjacent control sections on the road just prior to the commencement of the rehabilitation contract for the entire 33 miles. The two mile section from MP 6.0 to MP 8.0 has in the past provided the poorest performance and has been the worst maintenance problem of the entire road. Prior to resurfacing, the corrugations became so severe that light vehicles had great difficulty in staying on the road. During the inspection, both the Bio Cat treated section from MP 6.0 to MP 7.0 and the untreated beyond MP 7.0 were in about equal need for a blading, even though the Bio Cat section had not received the earlier touch up blading. The untreated MP 7.0 to 7.9 showed deeper rutting and /or a higher center ridge than the Bio Cat section. Grades were steeper on the Bio Cat section, at 8 percent compared to 6 percent on the untreated. Both sections showed occasional broad corrugations in the lighter, shale thin areas. Corrugation frequency varied inversely with the darkness of the surface, but were never serious enough to impede traffic. Ravel was greatest in light, shale thin areas of the untreated section. The road condition was much better until November of 1990, then deteriorated during log hauling.

On other Bio Cat sections, no rutting or corrugation was noted, while on the adjacent control sections which also received the shale, occasional fine corrugation was noted, having formed since the earlier Spring touchup blading. As noted above, dusting under traffic was noticeably less on the Bio Cat sections.

While the addition of the shale fraction provided for the greatest improvement to the performance of the aggregate, it was obvious that the Bio Cat had given those treated sections an advantage in enduring the punishment from log hauling. The full advantage of the moisture protection provided by the bioenzyme may not be realized in the Montana climate where 80 percent of the traffic occurs during dry conditions.

The Lick Creek Road had a crushed aggregate surfacing with 10/12 passing the 200 and a PI of 4/5. Three sections of a quarter mile each on the steeper areas were treated with EMC2. The difference in performance appeared more related to the snow pack location, around the clumps of trees, and the resulting volume of erosion water, than to whether treated or untreated. The low PI may indicate too little clay fraction for a significant reaction with the EMC2 considering the grades of 6 to 8 percent.

George Washington NF, VA

In August of 1991, 0.6 miles of th Pitt Springs Road were surfaced with an EMC Squared stabilized aggregate. The 12 foot wide roadway had a 3 inch thick, 1 inch max aggregate mixed with clay shale over most of the section, except for 700 feet of steeper grade where the thickness was increased to 6 inches. The wide variety of materials along the route resulted in variations in optimum moisture, from 11.5% to 15.8%, and made moisture control difficult. The bioenzyme solution was spread from a water truck on the scarified roadbed. Mixing was accomplished with a tractor drawn chisel plow after it found the aggregate mix would pile up on the grader scarifiers, preventing effective mixing. The surface was shaped and then compacted with an 8 ton vibratory roller. A thin layer of crushed rock was spread on the compacted surface and rolled in to provide a wearing surface.

Following completion of the project the crushed rock layer was noted to ravel under traffic due to lack of binder around the rock particles. This should have been mixed into the top layer of stabilized material before compacting.

In September of 1991, 1.0 miles of the Calf Pasteur Road had the existing agregate surfacing stabilized with EMC Squared. The same contractor from the Pitt Springs project did the work, using the same equipment and methods. The aggregate was a mixture of crushed limestone and shale, and moisture requirements varied along the project with variations in the composition of the mixture. A thin layer of crushed stone was spread and rolled into a 0.3 mile section of steep grade to improve traction.

In October of 1991, 1.0 miles of the Tuckaho Road had 3 inches of the existing aggregate stabilized with EMC Squared. Once again the same contractor from the Pitt Springs and Calf Pasteur Road performed the work. The aggregate was a mixture of fine crushed rock, 97% passing 3/4 inch, and the silty clay base that had been treated with lime kiln dust several years ago.

These three projects received a new stabilized surface using primarily existing aggregate at a considerable savings in cost and with reduced maintenance and improved performance over the traditional crushed aggregate surface which suffers from ravel, corrugations, and potholing.

Sulfonated D-limonene

Ozark NF, AR

Roadbond EN1, a sulfonated D-limonene product was used in August of 1991 to stabilize two 500 foot sections of steep grade on the Jethro Road. These sections of coarse aggregate surfacing were noted for severe corrugations prior to the treatment. Subgrade fines were scarified and mixed into the aggregate, and the Roadbond solution was applied from a water truck to the agregate mixture. Mixing was accomplished by blade and windrow, and constuction equipment was used for compaction. The surface set up very hard, comparable to a bioenzyme stabilized surface, and has eliminated the corrugation problem since.

Pozzolans

Applications

The benefits offered by pozzolan treatment include reduced aggregate loss and improved servicibility, with maintenance reduced to one or two light bladings per year on roads carrying ADT's of 50 to 400, including logging trucks and oil well maintenance vehicles. At least half of the test sections, in Arkansas and North Carolina, are subjected to freeze-thaw during one or two months each year. Investigators report that lime stabilized soils lose an estimated 10 to 12% strength with each cycle, but regain strength during the hot months (16).

The pozzolans currently under test include cement kiln dust, lime kiln dust, Class "C" flyash, hydrated lime with Class "F" flyash. These materials are similar in that all are hydraulic cements. While they are waste materials, the distributors provide for chemical analyses periodically and make the results available to the prospective user. Although effects of variations in chemistry have not been noted in the field, some differences might be observed in laboratory test results where smaller quantities are used. They differ from Portland cement in not having a quick set. Strength gain is due to hydration and develops uniformly from initial compaction. The pozzolans are very effective in small percentages with nonplastic coarse grained aggregates and coarse sandy gravels. These treated aggregates can be scarified or rebladed at any time with moisture present, and will resume strength gain upon recompaction. Silts and fine sands require substantially more additive, with resulting problems in mixing, and development of slabs of cemented material in the road bed that complicate maintenance. Pozzolan treated aggregates with plasticity become extremely slippery during wet weather and must be covered with a traction course of crushed rock or washed gravel; the bioenzymes are a far more effective stabilizer for these aggregates.

The percentage of additive used in the test sections has varied from 0.5 to 2 for lime kiln dust, and from 1 to 10 for Class "C" flyash. 6 percent cement kiln dust has been used in several projects, and 1 and 2 percent lime/Class "F" flyash 1:1 has been used on two 2 mile sections. The evaluation periods for these projects ranges from a few months to 7 years. Based upon observations to date, the percentage of additive required for satisfactory performance of a coarse aggregate is estimated to vary with the road grade, from 1 percent for grades less than 2 percent, to 3.5 percent kiln dust or 7 percent Class "C" flyash for grades over 7 percent (Figure 7). Using lower percentages than those indicated has resulted in development of surface corrugations. Occasional shallow potholing develops on flat graded sections due to washing of fines in puddles under traffic. A light blading once or twice each year provides for optimum service.

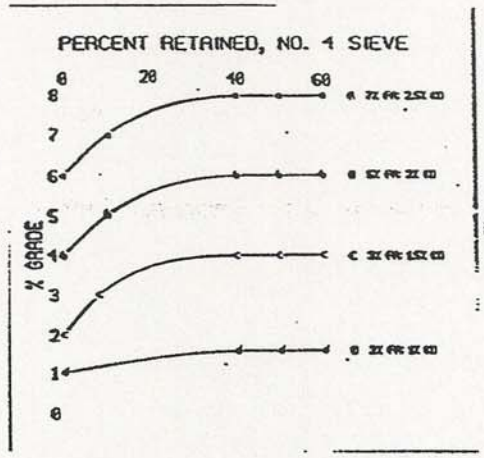


Figure 7. Estimated minimum percentages of Class "C" flyash or kiln dust required to prevent corrugations on grades.

Kiln dust and Class "C" flyash are both applied dry, by pneumatic pumping through a spreader bar on the 24 ton tanker or by spreading from a dump truck with the tailgate cracked open. The road surface is shaped and scarified, and wet down thoroughly just prior to application to blot the powder. In extremely windy areas it may be necessary to use a slurry application; however the problem of dusting may be solved by using the bottom ports in lieu of a spreader bar and hanging a tarp along the windward side of the tanker during application. If possible the tanker should be equipped with remote lever control to the hopper valves to allow operation of the valves out of the dust cloud. Breathing masks, goggles and hoods should be worn by the valve operators to aviod a dust bath in the caustic dust.

With dry application of kiln dust, 24 hour storage in the tanker following loading at the plant is mandatory to insure adequate cooling of the kiln dust prior to application. Without this cooling period, hot kiln dust applied will rob the aggregate of its natural moiature and substantially increase the water haul, both to cool the heated aggregate mixture and finally to reach the optimum moisture content. This problem does not exist with flyash, since the ash is already cooled in the power plant stacks. Mixing can be accomplished with scarifiers, rippers, chisel plow, or rotary mixers. The use of rotary mixers is limited to aggregates and fine grained soils containing no large stones that could damage the rotor tines. The high mixing efficiency of these mixers is rarely required except in highly plastic clays. For shallow applications, up to 4 inches, front mounted grader scarifiers are adequate. For deeper applications, rear mounted grader scarifiers, tractor drawn chisel plows, or bulldozer mounted rippers can be used. The chisel plow is often the most efficient. In fine grained silty and clayey soils a 24 to 36 inch disc can speed the mixing process. Mixing with these scarifiers and farm implements is not hindered by the presence of cobbles and small boulders in the subgrade. However, if subgrade material is to be blended with aggregate surfacing, it will be necessary to separate these out during shaping operations.

In calculating water needs to achieve optimum, 3 to 5 percent extra is allowed for hydration of the quicklime fraction in the additive. Unless the work is done early in the Spring when the ground is wet, considerable water haul may be involved. A large water truck of 2500 gallon capacity or greater will expedite the work. If the haul distance is long, two of these trucks will be necessary to keep the other equipment busy. During hot dry weather and especially with windy conditions, the final watering to bring the mixture to optimum moisture content should be done in short sections to facilitate quick mixing and compaction before the moisture can evaporate. Coarse aggregate mixtures have a peaked Proctor curve and must be near optimum to compact.

Attempting to water, mix and compact long sections under drying conditions will result in low densities and a poor quality surfacing. Fine grained, silty aggregates have a relatively flat Proctor curve and should always be compacted one or two percent dry of optimum to avoid excessive moisture and susequent pumping under the roller. Excess moisture must be removed by time consuming scarifying and blading to aerate the aggregate mixture. Compaction with pnuematic or vibratory roller should be to 95 percent of Standard Proctor or better, and is followed by final shaping. Construction costs range from $3500 to $7000 per mile (1988 dollars), varying inversely with the project length (Fig. 5). Work production averages about 1 mile per day.

Cement Kiln Dust

Sources Cottrell Flour is a trade name for Portland cement kiln dust formerly marketed by the cement plant in Portland, Oregon, and used to stablize aggregate surfacing on several timber sale roads during the early to late 70's on the Siuslaw National Forest located in Oregon's south coast range . Cement kiln dust generally contains 25 to 35 percent quick lime. This plant is now closed and the product is no longer available in the immediate area.

Cement kiln dust is distributed by Industrial Rock Mineral By-Products Co., 1008 Montgomery Highway, Suite 201, Birmingham, Al 35216, Shelby Gilbert, 205-822-9441. There may be other sources.

Siuslaw NF, OR The climate in this area is moderate, seldom experiences freezing weather, and stabilizers do not have to resist the effects of repeated freeze-thaw cycles.

On the Waldport District, three sale roads of half to three-quater mile in length off bituminous surfaced Forest Road 51 were surfaced in 1980 with commercial crushed stone stabilized with 7.5 percent cement kiln dust, all on Buy Back sales. Two were logged in 1988, and the third in 1989. These roads were possibly bladed 0 to 3 times in 8 years, yet all remain in excellent shape. There was no blading done during or after the logging. Untreated surfaces must be bladed annually or more frequently after logging, depending on damage from RV's. Another sale road off of Forest Road 53 was surfaced with crushed aggregate and cement kiln dust during the early 70's. This road was bladed in 1989 and spot rock added under an adjacent BLM sale. Sections with the original surface exposed are still hard and resistant to damage.

On the Mapleton Ranger District, 2 miles at the south end of Road 4811 near the Smith

River Basin had the top 2 inches of the 6 inch aggregate surface treated with cement kiln dust in 1975. This aggegate was Umpqua Navigation Rock which is dredged from the river and crushed, has no binder. The treated sections showed less rutting and required less blading than the untreated. On steep grades the treated rock developed minor washboard due to movement under the thin treated layer, but still allowed less wheel spin and washboard than the untreated sections.

Another 2.5 miles of Five Mile Bell Road, also surfaced with 6 inches of Umpqua Navigation Rock, was treated full depth with cement kiln dust in 1978 by blade mixing in 2 inch lifts. Although supporting timber and rock haul, the surface has not required blading for several years. Steep grades over 15 percent show no washboarding or wheel slippage, a marked difference with the untreated sections of the unbound aggregate. A dead end section has heavily grassed over and shows some shallow rutting on grades in narrow wheel tracks from RV's, possibly due to confined erosion paths.

Lime Kiln Dust

Sources Lime kiln dust is a by-product of the lime manufacturing process. Crushed limestone and coal are fired together in a revolving kiln at high temperatures to produce quicklime. During this process, a waste dust is drawn from the kiln. The dust has a similar finess to Portland cement and contains 35 to 45 percent quicklime, the remainder being coal ash. When mixed with water the dust hydrates, reacts and hardens to form a cemented mass. It must be provided with dry storage and cooled for use as a stabilizer. Pozzalime is a lime kiln dust distributed by Mineral By-Products Inc., 777 Franklin Rd, Marietta Ga 30067, Al Hays, 404-424-0247. Soildry is a lime kiln dust distributed by Industrial Rock Mineral By-Products Co., 1008 Montgomery Highway, Suite 201, Birmingham, Al 35216, Shelby Gilbert, 205-822-9441.
Projects using lime kiln dust are located in Alabama, Virginia, Tennessee, North Carolina, Mississippi and Florida, all constructed by the USFS.

National Forests in North Carolina In 1985, the NF's in North Carolina agreed to construct a test section on the Davidson River road using a very small percentage of lime kiln dust with crushed rock containing about 25% fines. 24 tons of lime kiln dust were spread over 2 miles of 18 foot road and mixed in with a chisel plow, blade and scarifiers to a 4 inch depth, watered and compacted to 95% of T-99 density. This amounted to about 0.6% additive overall, and 2.4% in terms of the fines only, in an attempt to stabilize the crushed gravel surfacing against washboarding and scattering, under the 3000 vehicles per week normally experienced on that road.

In October of 1985, the FS grader operator reported the treatment reduced gradings during the summer months from 9 to 2 as compared to requirements of adjacent sections. This was especially significant on the second section, which contains the steepest grades on the road, and washboarded severely prior to treatment due to dual wheel spinning of log trucks climbing the grade on the loose gravel.

During a September 1986 inspection a meeting was held with the contract grader working the road. He had previously graded in April and in July, and had just completed the lower first section. He reported that the treated surface was very firm and a deep cut with the blade was virtually impossible without prior scarifying.

He noted the absence of washboarding on the second section, and stated that extensive washboarding would normally be encountered on that grade after two months of summer traffic without blading. He said that during this and previous bladings he had noted fewer pot holes and less dusting during dry periods and that there had been less gravel loss from the road surface on the treated sections as compared with the untreated sections.

During the Winter of 1985/86 the treated surface experienced several cycles of freeze/thaw, which should have resulted in a strength loss. The contract grader confirmed this, stating that the surface had hardened noticeably since April and that sections in the shade where freezing is more severe and summer heat is lower, were still softer than sections in sunlight, indicating that strength is increasing again during the summer months in proportion to the heat experienced, as predicted by theory.

The indications were that this type of treatment would result in substantial savings in road maintenance and rock replacement cost. Retirement of the District grader in January of 1986, and the subsequent reduction of gradings from 9 to 3 under contract would had been severely felt by users of the Davidson River Road, had the surface not been stabilized first. The inspection revealed that no change in the road conditions had occurred since before the lime kiln dust was added, when gradings were 3 times more frequent. In October the first section on the flat grade was reported to be potholing. The grader operator had previously noted that the gravel layer was getting thin and would need additional rock but it was unclear as to whether he had referred to the treated section.

Potholing could be due to a thin surface or a weak and poorly drained subgrade or both.

An unusually warm winter occurred during 86-87 resulting in many cycles of freeze-thaw in this area (estimated one per day thru the winter!). During a Summer, 1987 inspection, it was not possible to discern any difference in hardness between the treated and untreated sections. This loss of strength indicated an increase in the application rate was in order to provide greater resistance to freezr-thaw cycles.

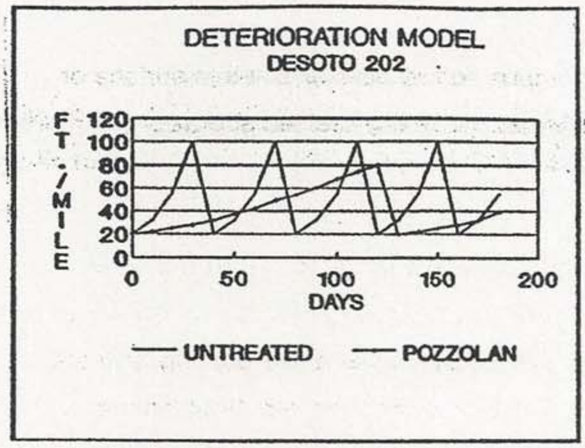
In November of 1987 the lime kiln dust application rate was increased to 24 tons per mile on an additional 13.1 miles of gravel surfaced road under construction: Davidson River Road, 1.7 miles; Yellow Gap Road, 3.5 miles; Cathy's Creek Road, 1.4 miles; Headwaters Creek Rd, 6.4 miles. The locations selected were primarily on grades where maximum gravel loss had been occurring. Mixing was accomplished with blade and scarifiers; a vibratory roller was used to compact at optimum moisture.

The lime kiln dust sections have been bladed once in the Spring and once in the Fall since construction. The lime kiln dust has been effective in preventing separation of the coarse and fine fractions and in holding the shape of the section. However shallow potholing on flat sections and corrugations on grades has occurred in a few areas that required blading to repair. This damage occurs primarily in the Spring following the period of freeze/thaw when some strength is lost. The blading was accomplished with moisture present and the bladed material knitted well to the roadbed, again providing performance superior to the untreated road sections . Annual inspections reveal that the performance of these sections is improving with time, with lower incidence of potholing and corrugations, indicating an overall gain in strength with each year.

Desoto NF, MS Following the initial success with stabilizing a crushed aggregate surfacing on the Davidson River road in North Carolina, it was decided to try other types of sufacing materials in the region to see if similar improvements in performance could be obtained. Mississippi had been searching for some method of binding their clay gravels for better performance and had a particularly serious problem on FDR 202 on the Chick district near Laurel, where the annual gravel loss approaches one inch per year, and blading every two weeks throughout the year is required to maintain a passable road. Truck traffic on 202 averages 25 vpd.

Although lab testing of Pozzalime treated samples from 202 had shown negligible strength gains, it was felt that the testing procedure was too severe and not typical of field conditions for a well drained road surface. Therefore a test section was proposed to the Forest. Clay gravel in the area generally has about 35 percent rounded gravel, the remainder being a sand silt mixture of low plasticity. Because of the increased fines in the clay gravel as compared with the crushed aggregate, the proposed test section was one mile in length with similar width, half the area of the Davidson River road, providing a Pozzalime application rate of approximately 1.5 percent of the total mix and 2.3 percent of the fines only.

Construction of the 202 test section, consisting of the 1st mile of road east of State Highway 15, was completed under contract early October 1986. Performance has exceeded all expectations. Nearly a year later, and following some extremely heavy rains including storms exceeding 10 inches of rainfall, the road surface remained essentially unchanged in condition since completion of construction. During that period the only maintenance done consisted of 2 light bladings, both when adequate moisture was present to ensure recompaction of the loosened material. Throughout that period the truck traffic continued without interruption.



Since gravel replacement and renovation of 11 additional miles of 202 was already planned for 1987, the Forest decided to include Pozzalime treatment in the project. A 20 year design at 9000 18kip single axle loads per year required 5 inches of Pozzalime treated gravel over 4 inches of untreated gravel. Assuming an annual surfacing loss of 1/8th inch, sufficient surfacing will remain throughout the 20 year life to support traffic without further gravel replacement. The project was completed under contract in early September, 1987. The cost of the Pozzalime treatment was $3000 per mile, compared to $7000 for the initial one mile test section. When compared to the $5000 per mile for the four miles of the Yellow Gap road in North Carolina it is apparent that the length of project has an important effect on the unit bid price.

During an inspection in February of 1990, FDR 202 was found in excellent condition over most of the road from Highway 15 to the intersection with FDR 206. All of this section has a sandy silt subgrade. East of

FDR 206 much of the subgrade is clay and failures are in evidence wherever poor drainage conditions have softened the clay, or saturated the lower layers of gravel above a sandy silt section. Credit for the durability of FDR 202 through the trying period may in part be due to higher lime content of the Pozzalime (50% vs 25 in flyash) but is primarily due to the 3 to 4 years of strength gain that has occurred since construction. These binding cements gain strength at a uniform rate from construction for as long as they exist, retarded only by an occasional frost, and kneading by unusually heavy loads.

During an inspection in August, 1990, the first mile of FDR 202, which had no gravel added with only 18 percent retained on the No. 4, appeared to lack coarse aggregate, and had a full inch of loose silty sand showing wheel tracks and occasional shallow ruts. The section provided a smooth ride with a slight fishtailing. The remainder of FDR 202 (11 miles) was treated with added gravel, had a thin float of sandy gravel over a hard, cemented or packed aggregate with no corrugations, potholes, or ruts on the 8 miles west of FDR 206, and some slight corrugations east of FDR 206 due to sections of steeper grade or poor subgrade. The entire road provided a pleasant, easy ride at 40 mph with good control on smooth curves.

This surfacing has continued to perform superbly throughout the seasons under continuous use by commercial haulers in all kinds of weather ranging from long periods of light rain through heavy downpours of 11 inches and extended hot dry periods. Blading since construction has been limited to 2 or 3 times per year, while traffic speed has has continued to average 35 to 40 mph. This must be compared to the bi-weekly bladings of former years and traffic speeds of 10 to 15 mph to appreciate the vast improvement in this surfacing material. Gravel loss has been reduced from 1 inch to 1/8th inch per year.

During August of 1989, 8.4 miles of FDR 319 were stabilized with lime kiln dust and lime/flyash in varying percentages of additive: 2 miles of 2 percent lime kiln dust, 2 miles of 1 percent lime kiln dust, 2 miles of 1 percent hydrated lime class "F" flyash, and 2.4 miles of 2 percent hydrated lime/Class "F" flyash. The hydrated lime and the Class "F" flyash were applied 50/50. The road has remained in excellent condition under year around use by local and haul traffic with 2 light bladings per year. Through 1991 no difference in performance was discernable between sections. Grades are less than 2 percent over most of the road.

National Forests in Florida. During September of 1988, 5.0 miles of surfacing were completed on FDR 235 on the Oceola NF, incorporating lime kiln dust with a limerock and sandclay mixture, and on FDR 309 on the Appalachicola NF 0.5 miles of sandclay were treated with lime kiln dust, and 0.5 miles of limerock/ sandclay mixture were treated with lime kiln dust. These sections were spaced with 100 foot control sections which received mixing operations without stabilizing additives. The aggregate was first thoroughly watered to optimum, the lime kiln dust spread and mixed, and additional water added prior to compacting. The surface has performed better than the untreated aggregate, but not as well as several other sections that had been bioenzyme treated. The lime kiln dust treated surface softens with heavy rainfall and ravels during dry weather; both types of failure are more severe than those occurring on the bioenzyme treated roads. The reason is probably moisture control in the limerock fines. Within a range these stay well cemented, but ravel when too dry and slake when too wet. The bioenzyme does the best job of maintaining the optimum moisture range in the aggregate.

Class "C" Flyash

Sources Class "C" flyash is collected by electrostatic precipitators from the stacks of power plants burning coal from the Powder River Basin in northeastern Wyoming. This coal contains limestone which converts to quicklime during combustion. Flyash developed from this coal contains about 25 percent quicklime, considerably less than the 40 percent in the lime kiln dust.

Projects using Class "C" flyash are located in Mississippi, Louisiana, Arkansas and Texas all constructed by the USFS R8. Class "C" flyash is distributed across the South by the Ash Management Corp., 404-424-1900. There are other local distributors as well. (In Little Rock, Arkansas, Flyash Products Inc, 501-534-4600.)

Ozark National Forest in Arkansas The Ozark NF agreed to construct a 1000 ft test section of modified shale surfacing on the heavily traveled Sorghum Hollow road in August of 1984, using Class "C" fly ash from Little Rock. This road is in an area of generally flat or gentle grades. A fly ash content of 10 percent was selected following lab testing of shale specimens and noting that the CaO content of the fly ash is about 30 percent, giving a total CaO addition of 3 percent. During construction two 24 ton loads of fly ash were blade mixed with shale imported from a nearby borrow pit, watered to optimum moisture and compacted to T-99 density. During the seven years following, this section has remained essentially unchanged in condition and without blading or other maintenance, while adjacent sections surfaced in 1984 with crushed aggregate have suffered from severe potholing and have required frequent blading to support the mixed traffic in excess of 50 vpd.

On a 1.5 mile section of nearby FDR 1614, a 2 inch open graded base aggregate (Arkansas Gradation SB-2) was mixed in equal quantities with the black shale and treated with 10 percent Class "C" flyash in 1988, has not been bladed since, and provides a smooth ride to the user.

The New Blaine Road, FDR 1600, has gentle grades and a traffic count of around 200 ADT. On 2 miles of this road, a mixture of SB-2 and GB-3 was mixed with equal quantities of silty clay subgrade by scarificaton and treated with 10 percent Class "C" flyash in 1988. These sections have been given a light blading twice per year and provide excellent service in all weather.

The Shores Lake Road with similar grades and traffic to FDR 1600 had 5.0 miles of SB-2 aggregate mixed with subgrade soil and treated with 10 percent Cl "C" flyash in October of 1988. This section has been given a light blading twice per year and provides excellent service in all weather. Untreated sections in the area continually develop corrugations and pot hole, provide generally poor service except for a week following each blading.

The White Rock Road, FDR 1505, is a high use road in a mountainous area with grades up to 9 percent. On 5 miles of this road the 3/4 inch minus well graded rock wih clay fines was treated with 2 percent, 5 percent and 10 percent Class "C" flyash on separate sections in 1988. The road has been bladed once per year plus one time following a heavy hauling contract. Moderate corrugations have developed on all grades over 5 percent in the 2 percent flyash section. No corrugations have been noted in the 5 percent flyash section, which includes grades of 6 percent; no corrugations have been noted in the 10 percent flyash section, which includes grades of 9 percent; no corrugations have been noted in the 2 percent flyash section on grades of 5 percent or less. A uniform thin float of coarse aggregate was noted on all sections.

These sections have provided particularly useful insights to the percentages of additives required to prevent corrugations on steeper grades (Figure 6).

The 1990/91 winter was particularly severe with sub zero freezing and extended wet periods, resulting in local rutting, potholing on a number of sections of these projects. While initial concerns centered on the effectiveness of the stabilizers, a careful inspection of these problem areas revealed that subgrade failures combined with inadequate surfacing thicknesses for the volumes of traffic being carried were the most probable causes. While the stabilized aggregate thicknesses on these roads varied from 2 to 4 inches, the subgrade material in most cases is a silty clay of low bearing strength that fails readily when subjected to moisture. Types of failures noted, rutting and potholing, are most often associated with subgrade failures. Traffic volumes as high as 150 vpd have been noted on some of these roads, with up to 10 percent in heavy trucks. A ten year design under these conditions calls for 18 inches of crushed aggregate or 9 inches of stabilized surfacing to maintain a moderate level of service. Subsequently all damage areas were rebladed with moisture in the Spring of 1991 and have been observed to regain their former level of performance.

The Harkey Valley Road was unsurfaced when the subgrade silty clay was treated with 10 percent flyash to a depth of 4 inches during December of 1990, and received almost no curing prior to onset of the bad weather. Under traffic the surface became extremely muddy and slippery because of the uncured lime present in the plastic fines of the subgrade soil. During a dry spell in March of 1991 the road surface dried out and performed well, but was expected to be slippery again with new rains. A traction coat of aggregate was applied to alleviate this situation, and the road now provides excellent service with only minor blading on ditches and shoulders.

Bienville NF, MS FDR's 508 & 513 were surveyed in April, 1988, and found to have 0-2" residual gravel. Gravel replacement began during Fall of '88. Eight inches were placed on 513 in November '88, and 4" to 6" were completed on 508 in April '89. The strength of the clay subgrade was not considered in the design because the drought during the previous 8 year period kept the clay dry and hard through the year. One percent Class "C" flyash was mixed with the aggregate during June of 1989 following a Spring of heavy rains which left a softened subgrade to compact the treated mixture on.

The surface reportedly hardened during July and August, 1989 but began to show signs of failure in September. Serious failures developed in November on both and complete failure had occurred by January 1990. Over 30 inches of rain fell during the November to February period, the wettest winter on record. During an inspection in February of 1990, some cementing was noted in the top 2 inches but the lower layers were very loosely compacted. Failures were primarily rutting and large potholes. Occasional washboarding consisted of series of closely spaced potholes. Subgrade intrusion was evident throughout. Although FDR 513 received nearly twice the gravel as FDR 508, little difference in condition could be noted.

FDR's 508 & 513 lie in the Yazoo Clay formation having a PI range of 30-50 and LL 50-80, contains montmorillonite and is highly expansive. Heavy rainfall was beyond doubt the major contributing factor to the failure. Rain during winter '88-'89 was substantial, enough to provide initial damage to the new gravel on FDR 513 and the residual gravels on FDR 508. Fourteen inches of rain fell in June and July of '89, during and immediately after placement of the flyash, possibly contributing to a preliminary softening of the subgrade and reducing the effect of compactive effort in the lower layers of gravel. While August was dry, 2 inches fell in September, another inch in October, and 34 inches between November 1 and February 16, 1990. Another 6 to 10 inches fell on February 18, and another inch was reported February 22.

Once saturated, the Yazoo Clay is slow to dry out; the dry spells in August and October, sandwiched between periods of heavy rain, probably did not harden the ground enough to completely eliminate subgrade swelling due to expansion of the clay. Subgrade swelling effectively reduces the density and strength of the soil. While compaction under these conditions may produce a dense surface in the top 2-3 inches, density in underlying material grades off towards the bottom of the layer where the upper layers of the subgrade intrude into the gravel. With less than minimum compaction occurring in the lower half of the 5" stabilized layer, the aggregate grains are too widely spaced to permit effective strength gain during hydration of the lime/flyash cementing compounds formed during mixing, and the effective stabilized thickness is reduced by half. Due to the heavy rains that fell immediately prior to and during placement of the flyash, these were probably the conditions present during compaction, accounting for the early failures.

Considering the events of the winter which followed construction, it is doubtful that even 12 to 15 inches of gravel could have survived subgrade failures. The flyash treatment provides a binder rather than a high strength cement which would produce an undesirable slab effect. An unreinforced slab surface would ultimately break up over the swelling subgrade and cause a disposal problem. The flyash binder must have a stable base to continually renew strength under traffic loads. The kneading action provided by construction equipment and traffic over a swelling subgrade only weakens the bonds between particles.

The flyash remained in the gravel mixture and during an inspection in August of 1990 FDR 513, 2.5 miles long, had a hard cemented appearance, with coarse aggregate well locked up in the fines, no washboarding or chuckholes, wheel tracks are dished out from slight to occasional heavy indicating subgrade deformation. There was a thin float on the shoulders but no raveling, and it provided a smooth, easy ride. FDR 508, 14.8 miles long, had been recently bladed, had a uniform, hard surface without washboard, rutting, or potholes. During a hard rain the surface exibited a firm, clean graveled surface with only slight vehicle tracking, and gave a smooth ride. While this hardened surfacing should help seal off the clay subgrade from falling rain, another prolonged wet season may result in subgrade clay expansion and softening, and temporary crumbling of the surfacing until dry conditions return.

In June of 1991 the District Office reported following a Spring blading, these roads had developed a hard, firm surface and were performing at a higher level of service than before construction of the stabilized surface.

Desoto NF, MS FDR 206 North had gravel added and the top 5 inches treated with 1 percent Class "C" flyash. This road carries heavy oil well maintenance traffic year around. Completed in August of '89, this 4 mile road has the sandy silt of the Citronelle formation for a subgrade, similar to that of the adjacent highly successful FDR 202 where lime kiln dust was used. During the February, 1990 inspection, failures encountered consisted of two types, subgrade and top surface. The subgrade failures all occurred where heavy rains and poor drainage in shallow ditches brought the water table into the lower part of the gravel layer. No amount of gravel or stabilizer can cure this problem. Only reconstruction of ditches and drainage structures can successfully relieve these conditions.

The top surface failures were found on sections of zero grade where water could pond in shallow surface rutting, causing a washout of fines by traffic action and formation of a series of small shallow potholes resembling a washboard in the wheel tracks. The continuing heavy rains, bringing downpours every other day for two months, had prevented proper repair of these spots as they developed, resulting in gradually increasing depth of the pothole. Under dryer conditions, scarifying and recompacting at optimum moisture would permit the lime/flyash compounds present in the binder to renew hydration and strength gain through the summer months. On other sections of the road where grades are present the road was in excellent condition after 3 weeks without blading, and aggregate fines appeared to be cementing to the full depth of the stabilized layer.

During another inspection in August of 1990, FDR 206 North had an extremely hard, cemented, well gravelled surface with minor float and no potholes or rutting, occasional minor washboard; easy driving at 40 mph. FDR 206 South, surfaced with the same aggregate as the northern section, has not been treated and exhibited extremely heavy washboarding, especially on the curves. This section is difficult to drive, and loss of steering control occurs at 35 mph.

Kisatchie NF,LA. During October of 1988 4.7 miles of surfacing were completed on FDR 570 using Cl "C" flyash, a 24 ton load on each 3/4 miles. FDR 570 has gentle rolling or flat grades over much of the road, with a few sections of 5 percent. A mixture of sand clay and washed gravel was placed on 3.7 miles to thicken up the surfacing prior to treatment. The sand clay source was an unfortunate selection, having a PI of 17, much too plastic for the flyash treatment. The mile of existing surfacing treated was a non plastic sandy gravel, an ideal material for flyash treatment. Three loads of flyash had been cut in with tandem rotory mixers when heavy rains forced a work stoppage while the 17 PI clay gravel surfacing dried out. Work was completed the following week.

The late construction, and the cold front accompanying the rains retarded initial curing and caused slippery road conditions with some resultant rutting. An inch of gravel was tailgated over most of the slippery areas to alleviated the problem; however a section of gentle grade at the beginning of the project was left with the clay surface and has resulted in shallow rutting during wet weather requiring frequent maintenance. During an inspection in July of 1990, the top 1 to 2 inches was found to be soft when wet, while the underlying material was well cemented and hard. The thickness of the soft layer is about the depth of the rutting.

The one mile section of stabilized NP sandy gravel had no problems with the rains. This section has set up hard and requires no blading other than occasional skimming to remove grass. It remains free of rutting, potholes and corrugations throughout the year.

Mineral Pitches

Another product available that has been successfully used as a dust pallative and stabilizer is a pine tar derivitive. Manufactured in Tennesee, the product is sold as Road Oyl by the Soil Stabilization Products Co. (209-383-3296), and as Pine Tar by Hammond &Associates, Inc.,(615-685-0255). This material is an asphalt substitute with 3 times the strength of asphalt. It is applied at 0.15 gal per sy as a dust pallative and as a stabilizer at 0.3 gal per sy, mixed into about 1 1/2 inches of surfacing.

To apply as a dust pallative, no surface preparation or compaction is required. The only equipment needed is a hand pump and a water truck. Two applications are made; one of 0.1 gpsy diluted at 5 water to 1 pine tar, and a second some time later after traffic has acted (two weeks/months), of 0.05 gpsy diluted at 10:1. The road must be closed to traffic for 4 to 5 hours until the surface is no longer tacky.

To apply as a stabilizer, the surface is lighly bladed to develop an inch or so of loose material. The Road Oyl is applied at 0.3 gpsy without dilution in repeated passes; blade mixed into the loose material and compacted. Again the road must be closed until no longer tacky.

To stabilize sandy roads against washboard the Road Oyl is applied at 0.25 gpsy in two applications. The first half is diluted at 5:1 and applied to a compacted, pre-soaked surface in several passes. On the following day the second half is diluted at 10:1 and applied in a similar manner but without presoaking. Traffic is kept off the surface until no longer tacky in both applications.

This pine tar product is currently being tested by the Dechutes NF in Oregon, and the Atlanta GA Parks Department as an aggregate surfacing stabilizer for motor bike and wheel chair trails. Initial results are good.

Clay Fillers

Dechutes NF, Bend OR

Ground Hog Quarry project. In August of 1980, three sections of about 3 miles each on flat ground were surfaced with 6 inches of crushed and screened volcanic lava. The first section near the state highway had 2 percent Central Oregon Bentonite (COB) blended with the aggregate in a pugmill prior to placement with a Barber Green paving machine. The second section was blended with Stabilite, a bentonite from Idaho with a greater capacity for holding moisture, and placed in a similar fashion. The COB is less expensive because of the proximity of the source, but it is a small pit and not always available when needed. The third section was of the same aggregate without either clay additive. The surfacing had a base course of volcanic cinders of 12 inches of less in thickness, and a pumice silty sand subgrade.

During construction the Stabilite was found to be extremely sensitive to moisture content, the aggregate mix remaining unstable near and above the optimum of 15 percent. The best moisture content for placement was near 10 percent, and resulted in a tight, impermeable surface. The COB by contrast was less sensitive and the aggregate mix remained stable through moisture levels from 5 to15 percent even though the optimum was 12 percent. The finished surface was more permeable than the Stabilite surface, and allowed greater penetration by the lignon.

The surface was maintained annually in May or June following construction, excepting 1991. Maintenance consisted of scarifying to one inch or the bottom of the potholes, adding moisture and compacting, and spraying with Lignon sulfonate. The lignon provides a tight, hard surface, but dissolves with excessive moisture and allows the surface to ravel where binder is absent.

During an inspection in July of 1991, the COB section appeared smooth and tight with only occasional potholing on either the crown or the lower side of a super elevated curve. Since these areas are typically thin on base, and the sugrade is an exceptionally resilient material, the potholing may be due to large difference in modulus between the stiff surface and the resilient subgrade.

The Stabilite surface was tight but generally rough on the surface apparently due to a thin layer of ravel. Since Stabilite tends to hold a higher moisture content, it may be more susceptible to frost action, prevalent in the area for nine months out of the year. A slight penetration into the top of the layer may be resulting in expansion of the clay moisture and the subsequent ravel; however this needs further study before drawing any definite conclusion. The ravel results in or from a loss or drying of the lignon coating and further slight raveling under traffic, although nothing compared to the plain aggregate section. Some slight corrugation was observed in the raveled material. Occasional potholing has been reported in this section. These may also have been due to the stiff section over the resilient subgrade.

The Aggregate section was suffering from severe raveling and corrugations in the ravelled material. A few areas were smooth and tight, but showing cracking preliminary to breaking out as the lignon dries up. Either of the other sections were far superior in performance to the plain aggregate section.

Benham Falls Road. A 3.5 mile section of double lane was surfaced with a reddish crushed volcanic lava and 2 percent Stabilite in the Fall of 1990. The crushed rock and the Stabilite were mixed in a pugmill and delivered to the project site and spread from bottom dump trucks. The mix was bladed and compacted in two 3 inch lifts. With the exception of a few loads, the moisture content was maintained between 9 and 11 percent. Loads with excess moisture caused severe problems until the areas dried out.

During an inspection in August, 1991, it was noted that a thin layer of ravel had developed on the otherwise uniform and tight surface as the lignon dried or was wedged off by frost penetration. One severely ravelled area had developed at the railroad crossing due to poor sugrade drainage and the sudden stopping of traffic, resulting in shoving, potholing and large corrugations. A better surfacing agent than the lignon is needed to preserve the surface integrety. A mineral pitch emulsion such as Road Oyl might provide a solution.

Acrylic Polymers

Chattahoochee NF, GA In July of 1990 a slide occurred on Rd 1178 at the Chattooga River Bridge. In widening the entrance curve for improved access to the bridge, a cut was made into the 60 percent slope which extended several hundred feet to the ridge top. The material was a deeply weathered granite schist saprolyte with little strength. The saprolyte failed in a series of rotational blocks extending upslope for an estimated 200 feet. The base of the slope was subsequently buttressed with large rip rap from an adjacent rock cut, and the area above was partially graded to a uniform slope, leaving a broad expanse of highly erodable, soft sandy saprolyte exposed to the weather.

Rainfall in the area is frequent and often intense; 8 inches over a weekend and intensities of 3 inches per hour are not uncommon. To protect the highly sensitive surface, an application Exxon Polybuilt 4178 was made with the seed and mulch cover. 55 gallons of this acrylic polymer were applied with a hydroseeder in 1200 gallons of water over the one acre site. The resulting surface crust adequately protected the soft underlying surface from erosion through one of the wettest winters on record, while allowing a heavy growth of grass to develop across the slope.

Ocala NF, FL

In March of 1991, a section of 900 feet of the Road 573 adjacent to the Florida State Highway 19 pavement had been causing dust complaints from local residents at the edge of the National Forest land. The road surfacing consists of a mixture of sand clay and lime rock, and is a sandy material with enough fines to generate dusting during dry weather. While several dust inhibitors are available on the market, these are water soluble and must be reapplied periodically. A more permanent treatment was desired, and one that would resist the erosion of the intense rainfalls common to the area.

The Exxon Polybuilt acrylic polymer was reported as an effective road surface stabilizer in sands by the University of Iowa at Ames. Recommendations by Iowa were for a two inch thickness using 0.2% stabilizer by weight in a water solution, or about one gallon per 1.5 cy of surfacing.

The Forest provided a 55 gal drum of Polybuilt, enough to treat 83 cy of soil or a 900 ft by 15 ft by 2 inch section. The County agreed to provide construction equipment, including a water truck, a rotary mixer and a vibratory steel wheel roller. The District maintenance contractor provided a motor grader.

The water required to provide optimum moisture during compaction was determined. However, strong dry winds were blowing at the site, and excess water added was needed to make up for the high rate of evaporation. The water solution containing the 55 gallons of Polybuilt was applied from the water truck spreader bar by repeated passes over the section after an inital scarification by the grader. After 2/3 of the solution had been applied, a full pass was made with the mixer to the 3 inch depth. The remainder of the solution was then applied, followed by another pass with the mixer.

The roller made an initial pass over the mixed material, followed by final shaping by the grader blade. The roller then made multiple passes over the surface to obtain full density. Excess moisture caused pickup on the roller until the wind dried the material enough to compact properly.

Following treatment the surface developed a hard sheen and stood up well to traffic. Although dusting stopped the day after construction, it resumed the second day as traffic abrasion released fines from the mixture. Apparently the acrylic forms a webb around the aggregate grains but cannot permanently seal off the surface, thus is not effective as a dust pallitive.

On the weekend following, the area received 4 1/2 inches of rain over two days. The treated section remained hard and relatively smooth except for a few small, shallow potholes on the center line, caused by traffic washing fines in the puddles. As the adjacent untreated section which had been bladed and rolled at the same time as the treatment developed severe potholing following the rainfall, it was evident that the polybuilt was providing protection to the sandclay and lime rock mix. The surface remained relatively smooth during the following month, as compared to severe potholing developing on the adjacent untreated section wich was bladed and compacted at the same time.

Exxon has recently discontinued the Polybuilt. Another acrlylic is available, called Soil Seal, with similar properties and a higher solids content.

exercised on poorly drained sugrades where the hygroscopic nature of these salts can saturate clay rich soils during the wet winter months. Users have complained of corrosion problems on their vehicles, particularly on aluminum parts.

Lignon sulfonate was used on Washington Rds 21 an 30(Gifford Pinchot NF), one mile each; on the Oregon Carmel Rd(BLM, Medford), one mile; on New Mexico Rd 310(Carson NF), 1000 ft; and on the North Carolina Catfish Rd, 5 miles. Lignon is a hygroscopic and highly soluble sugar. In a dry season it forms a dark, hard crust over the surface of the aggregate which draws moisture from the air and effectively prevents raveling and dusting. An occasional light rain or watering will rejuvenate its effectiveness, but excess moisture softens the surface and can result in severe rutting, as happened on the New Mexico Rd 310 during the Spring thaw. Since the runoff was minimal in that case, the heavier application of lignon(0.7 gpsy) remained in the aggregate to harden again during the summer. In North Carolina, a heavy summer rainfall(8 inches) occurred soon after application. The resulting heavy runoff completely removed the lignon coating. Under more favorable conditions, lignon can be expected to last through a dry season until heavy or prolonged rainfall occurs.

Dope 30 (Dust Oil Penetrating Emulsion) was used by BLM, Medford, OR, on the Cabin Creek Road. The andesite tuff aggregate is non plastic and without binder on this road which has sharp turns and moderate grades. The Dope 30 was lost on the grade sections after only 9 loads of logs were hauled. Without binder the aggregate on grade moves under load and breaks up the oiled crust. Loose aggregate must be bladed off the road prior to application, a waste of the aggregate. The District is considering an initial application of lignin to provide binder and save the loose aggregate prior to application of the Dope 30, which would in turn protect the lignin from being dissolved.

On the Pleasant Creek Road, a surfacing of 2 inches of crushed basalt over a pit run base was treated with 2 applications of Dope 30. Grades on this road are gentle throughout and the entire surface looks excellent, similar to a chip seal, after a month of hauling 1.5 mmbf timber.

CONCLUSIONS

The performance of test sections through September 1991, shows an exceptional improvement over non stabilized control sections wherever the appropriate stabilizer has been used. Failures in the test sections have been attributed to misuse of the stabilizer, or poorly graded aggregates.

The observed improvements in performance and reductions in maintenance far exceed those of control sections or any other untreated aggregate surfaces. The bioenzymes, EN1 and Condor SS have been particularly outstanding, in some cases extending maintenance frequencies from bi-weekly to bi-annually for similar performance. The low construction costs for these materials and the pozzolans can easily be offset in reduced aggregate loss, reduced maintenance, and improved servicibility. (Figures 1, 2 and 3).

The primary drawback is the absence of standard testing procedures capable of predicting performance. The proposed laboratory study by DOE Laramie may provide some relief.

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REFERENCES

1. Robin J. Dunlop, Some Aspects of Pavement Design and Performance for Low Volume Roads in New Zealand: Proceedings, Low Volume Roads; Second International Conference, Transportation Research Record No 702, Transportation Research Board, 1979, pp47-54.

2. Helmut J.F. Winkler, Petrogenesis of Metamorphic Rocks, Fifth Edition, Springer-Verlag, N.Y., 1979.

3. Steven M. Colman and David P. Dethier, Rates of Chemical Weathering of Rocks and Minerals, Academic Press, N.Y., 1986.

4. James K. Mitchell, Fundamantals of Soil Behavior, John Wiley & Sons, Inc., 1976, pp 49-54, 112-134, 260-269, 353-373.

5. Ralph E. Grim, Clay Minerology, McGraw-Will, 1968, pp 214, 224, 264, 353-411.

6. William B. Mills et. al., Literature Review and Model(COMET) for Colloid/Metals Transport in Porous Media: Ground Water, Vol. 29, No. 2, MArch-April, 1991.

7. Paul E. Potter, et. al., Sedimentology of Shale, Springer-Verlag, 1980, pp 53-58.

8. Ara Arman and George Munfakh, Stabilization of Organic Soils with Lime: Division of Engineering Research, Bulletin No. 103, Louisiana Stae Universtiy, Baton Rouge, LA 70803, pp 28-30.

9. A. Kezdi, Stabilized Earth Roads, Elsevier Scientific Publishing Co., N.Y., 1979, pp 107-116.

10. F.M. Lea, The Chemistry of Cement and Concrete, Third Edition, Chemical Publishing Co., Inc., N.Y., 1971, pp 330-337.

11. Norman Donaldson, The Chemistry and Technology of Naphthalene Compounds, Library call QD391 .D72., Georgia Institute of Technology.

12. Websters Third International Dictionary, Unabridged, Merriman-Webster, 1980.

13. R.G. Burns, Soil Enzymes, Academic Press, N.Y., 1978, pp 298-305.

14. E. Penner, The Mechanism of Frost Heaving in Soils: Highway Pavement Design in Frost Areas, A Symposium, Part 1., Basic Considerations, Highway Research Board, Bulletin 225, Washington, D.C., 1959.

15. T. William Lambe, Soil Testing for Engineers, John Wiley, N.Y., 1951.

16. M. R. Thompson and J. L. Eades, Autogenous Healing of LIme Soil Mixtures, Highway Research Record No. 263, Highway Research Board, 1969, pp 1-7.