November 2017
Guideline: UCPRC-GL-2017-03

Guidelines for the Selection, Specification and Application of Chemical Dust Control and Stabilization Treatments on Unpaved Roads

Author:
D. Jones

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NUMBER UCPRC-GL-2017-03	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Guidelines for the Selection, Specification, and Application of Chemical Dust Control and Stabilization Treatments on Unpaved Roads		5. REPORT PUBLICATION DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D. Jones		8. PERFORMING ORGANIZATION REPORT NO. UCPRC-GL-2017-03
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California Pavement Research Center Department of Civil and Environmental Engineering, UC Davis 1 Shields Avenue Davis, CA 95616		10. WORK UNIT NUMBER 11. CONTRACT OR GRANT NUMBER
12. SPONSORING AGENCY AND ADDRESS University of California Pavement Research Center Department of Civil and Environmental Engineering, UC Davis 1 Shields Avenue Davis, CA 95616		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES

16. ABSTRACT

Unacceptable levels of dust, poor riding quality, impassability in wet weather, and unsustainable maintenance and gravel replacement practices are experienced on most unpaved road networks, and although it is acknowledged that unpaved roads are fundamental to local, regional, and national economies, many current management practices used on these roads leave much to be desired.

Over the past 100 years a range of chemical treatments has been developed to fill the need for reducing the environmental and social impacts of road dust, improving the performance and safety of unpaved roads, and/or improving the properties of marginal materials to the extent that a road can be given all-weather status or upgraded to a paved standard. Most of these chemical treatments are proprietary and there is often little documented information regarding the chemistry of the treatment, the results of experimental trials to determine under what conditions the chemical treatment will work best, or guidelines on where and how to use the treatment. Most unpaved road chemical treatments carry no formal specification nor do they adhere to formal environmental testing requirements. Consequently, there has been no large-scale effort to establish and/or implement formal unpaved road chemical treatment programs anywhere in the world, other than those used in site-specific industrial applications such as mining operations.

This guide introduces a new process for selecting an appropriate chemical treatment category for a specific set of unpaved road conditions using ranked potential performance. The process is based on the practitioner setting an objective for initiating a chemical treatment program and understanding the road in terms of materials, traffic, climate, and geometry. Using the information collected, the most appropriate chemical treatment subcategories for a given situation can be selected from a series of charts and ranked using a simple equation. This process can be completed manually using a paper form, or by using a web-based (www.ucprc.ucdavis.edu) or spreadsheet tool. Matrices for each of the objectives were developed based on documented field experiments and the experience of a panel of practitioners. Guidance on specification language for procuring and applying unpaved road chemical treatments is also provided, along with comprehensive guidance on understanding unpaved road wearing course material performance.

17. KEY WORDS Unpaved road; gravel road; unsealed road; fines preservation; dust control; stabilization; unpaved road management		18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161
19. SECURITY CLASSIFICATION (of this report) Unclassified	20. NUMBER OF PAGES	21. PRICE None

Reproduction of completed page authorized

DISCLAIMER

The contents of this guideline reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

The University of California Davis does not endorse the use of any specific product for dust control and stabilization of unpaved roads.

ACKNOWLEDGEMENTS

The author would like to thank the following individuals for their inputs and guidance during this project: Roger Surdahl (Federal Highway Administration), Peter Bolander (U.S. Forest Service), John Rushing (U.S. Army Corps of Engineers), Ken Skorseth (South Dakota Local Technical Assistance Program), George Huntington (Wyoming Local Technical Assistance Program), Bruce Drewes (Idaho Local Technical Assistance Program), Eli Cuelho (Montana State University), Billy Connor (University of Alaska Fairbanks), David James (University of Nevada, Las Vegas) Mark Nahra (Woodbury County), Bethany Kunz (U.S. Geological Survey), Shawna Ballay (Pueblo of Isleta), Josh Trujillo and Steve Bytnar (Envirotech), Robert Vitale and Cheryl Detloff (Midwest Industrial Supply), Griff Williams (Terratech), and Bruce Coultard (PZS Stabilization).

The author acknowledges the following individuals for allowing the use of their photographs.

Photographer	Figure Numbers
Robert Vitale:	2.9
Ken Skorseth:	2.12, 5.24
John Snyder:	5.14, 5.15
Jason Paas:	5.16

All other photographs appearing in the guideline were taken by the author

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in.	inches	25.4	Millimeters	mm
ft.	feet	0.305	Meters	m
yd.	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb.	pounds	0.454	Kilograms	kg
T	short tons (2000 lb.)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd.
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb.
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb.)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	Newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003)

Blank page

1. INTRODUCTION

Around the world there are millions of miles/kilometers of unpaved (or unsealed, or gravel) roads and road networks that are managed by numerous different agencies including national road authorities, state or provincial road agencies, local and tribal governments; federal land management agencies; private forestry, mining, and oil and gas extraction companies; tourism, railroad, and utility companies; farmers, and even unincorporated communities. Unacceptable levels of dust (Figure 1.1), poor riding quality (Figure 1.2), and impassability in wet weather (Figure 1.3) often result from unsustainable maintenance and gravel replacement practices. Although it is acknowledged that these roads are fundamental to national, state, and local economies, many of the practices currently used to manage them leave much to be desired since procedures for best-practice material selection, construction, and maintenance; programs for dust control (fines preservation), stabilization, maintenance, and gravel replacement optimization; and consideration of low-cost upgrading all remain largely overlooked.

Figure 1.1: Unacceptable levels of dust.

Figure 1.2: Poor riding quality.

Figure 1.3: Impassability in wet weather.

Many of the problems with unpaved roads can be overcome by following more appropriate and sustainable road management practices that can lead to safer driving conditions, reduced environmental impact, and increased intervals between maintenance and gravel replacement activities. These practices include but are not limited to:

- Better selection of base and wearing course materials, using knowledge of how materials are likely to perform under different conditions;
- Strict enforcement of prescribed construction procedures and use of quality control and quality assurance systems;
- Use of effective unpaved road maintenance practices; and
- Use of appropriate chemical treatments to preserve fines and to improve the properties of marginal materials.

This guideline focuses on understanding linkages between the performance of unpaved roads and their material properties. It provides background information on the various categories of chemical treatments available for unpaved roads, as well as how to select, specify, procure, and apply them to optimize performance. The guide is based on the philosophy that chemical treatments should be used to "keep good roads in good condition" (Figure 1.4), rather than trying to use them to "fix" roads that are poorly constructed or have been allowed to deteriorate to poor condition (Figure 1.5).

Figure 1.4: Treatment used to keep a good road in good condition.

Figure 1.5: Unsuccessful attempt to fix a bad road with a chemical treatment.

1.1 Background to the Study

To date, in the United States, no comprehensive coordinated national research has been undertaken—that is, research based on a scientific experiment design covering region, climate, material type and properties, traffic, and chemical treatment categories—to understand the interrelation between the performance of unpaved roads, their material properties, and the chemical treatments applied. There are also no formal specifications for unpaved road chemical treatments, or a national agency overseeing the development and promulgation of these specifications. Consequently, most currently available guides to unpaved roads maintenance, and specifically on chemical treatments, are based on the experiences of their authors, who have pieced together the results from multiple independent, uncoordinated, and often short-lived field trials. A comprehensive study incorporating the long-term evaluation of the use of the treatments through multiple rejuvenation applications is needed. Results from such a study could be used to quantify the benefits of unpaved road chemical treatments, and to develop performance-based unpaved road material specifications, selection criteria for chemical treatments, performance criteria for different chemical treatment categories, life-cycle assessment criteria for undertaking cost-benefit analyses for different treatment options, and to provide criteria for determining potential environmental impacts *(1)*. All this information could then be used to better justify the use of chemical treatments as part of unpaved road management practice.

Many agencies manage their unpaved road networks and make decisions on whether or not to use dust control and/or stabilization treatments using the available published information discussed above, past experience of how the treatment performed, its local availability, and/or its price when the treatment is needed. In the absence of appropriate guidance and documentation, the primary data on which practitioners must base their selection and application decisions often comes from vendor marketing and product manufacturing information.

The US Forest Service (USFS) published a document in 1999 titled *Dust Palliative Selection and Application Guide (2),* which summarized much of the then-available information. This USFS document identifies families of dust suppressants and where they are likely to be most effective. Since that time, a number of other guides have been developed *(1,3-10)* that include updates and alternative approaches to selecting the most appropriate treatment for a given set of conditions.

Until such time as a comprehensive national study on unpaved road chemical treatment performance is undertaken in the United States, there continues to be a need to reorganize existing and newly collected information from localized studies to provide prioritized lists of recommended treatments and their effectiveness—based on specific treatment-objective inputs, materials, climate, traffic, and load. Guidance is also needed on how to procure and specify these recommended treatments, many of which are proprietary, to ensure that only safe and environmentally compatible products are used.

In recent years, a number of unpaved road chemical treatment manufacturers have developed new additives or adapted existing ones to provide soil and pavement layer stabilization, in addition to dust control. These developments have contributed to an additional need for information and guidance on how to best select and use treatments for stabilization, especially considering that road stabilization is often thought to be performed only with asphalt or cementitious treatments.

The objective for the development of this guideline is to provide unpaved road practitioners and managers working in any road agency with an updated document that builds on the USFS and others' research to provide specific selection, specification, and procurement guidelines for safe, cost-effective, unpaved road chemical treatments. The approach is based on a literature review of currently available guidelines and other publications that document research studies on unpaved road chemical treatment applications, as well as the experience of the author and that of numerous practitioners in the United States and other countries.

1.2 Project Approach

This guideline is intended to fill the gap in available information regarding unpaved roads described above. It is based on the 1999 US Forest Service Guide together with more recent documented research and experience from around the world. Content for this new guideline in general, and for the selection procedure specifically, was obtained from a review of national and international literature on unpaved road chemical treatment research since 1999 *(2),* as well as from interviews with practitioners and treatment manufacturers and distributors. The matrices that form the basis of the selection procedure were reviewed by a panel of practitioners, researchers, and representatives of treatment manufacturers. The writing of the suggested generic specifications in these guidelines was based on a literature search and safety data sheet analysis, and was done in conjunction with representatives from treatment manufacturers with products in each of the generic categories referenced in this guide.

1.3 Guideline Layout

This guideline is primarily focused on the selection of appropriate chemical treatments for unpaved roads. It attempts to follow a logical approach, first helping the practitioner set an objective for initiating a chemical treatment program, and then providing the information necessary to understand the road to be treated in terms of its traffic, climate, geometry, and materials. Based on this information, a practitioner can use a form and a series of charts to select the most appropriate chemical treatment categories for a given situation and then rank them using a simple arithmetical formula. An internet web-based tool that simplifies the selection process is also available *(www.ucprc.ucdavis.edu/dustcontrol).* The selection approach is illustrated in the flowchart in Figure 1.6. The guide includes the following chapters, with supplemental information provided in appendices:

- Chapter 2: Unpaved road chemical treatment categories
- Chapter 3: Selecting unpaved road chemical treatments

- Chapter 4: Procuring and specifying chemical treatments
- Chapter 5: Considerations for applying chemical treatments
- References cited in the text
- Appendix A: Chemical treatment category details
- Appendix B: Understanding unpaved road materials
- Appendix C: Example mix design test program
- Appendix D: Example suggested specification language
- Appendix E: Safety data sheet information

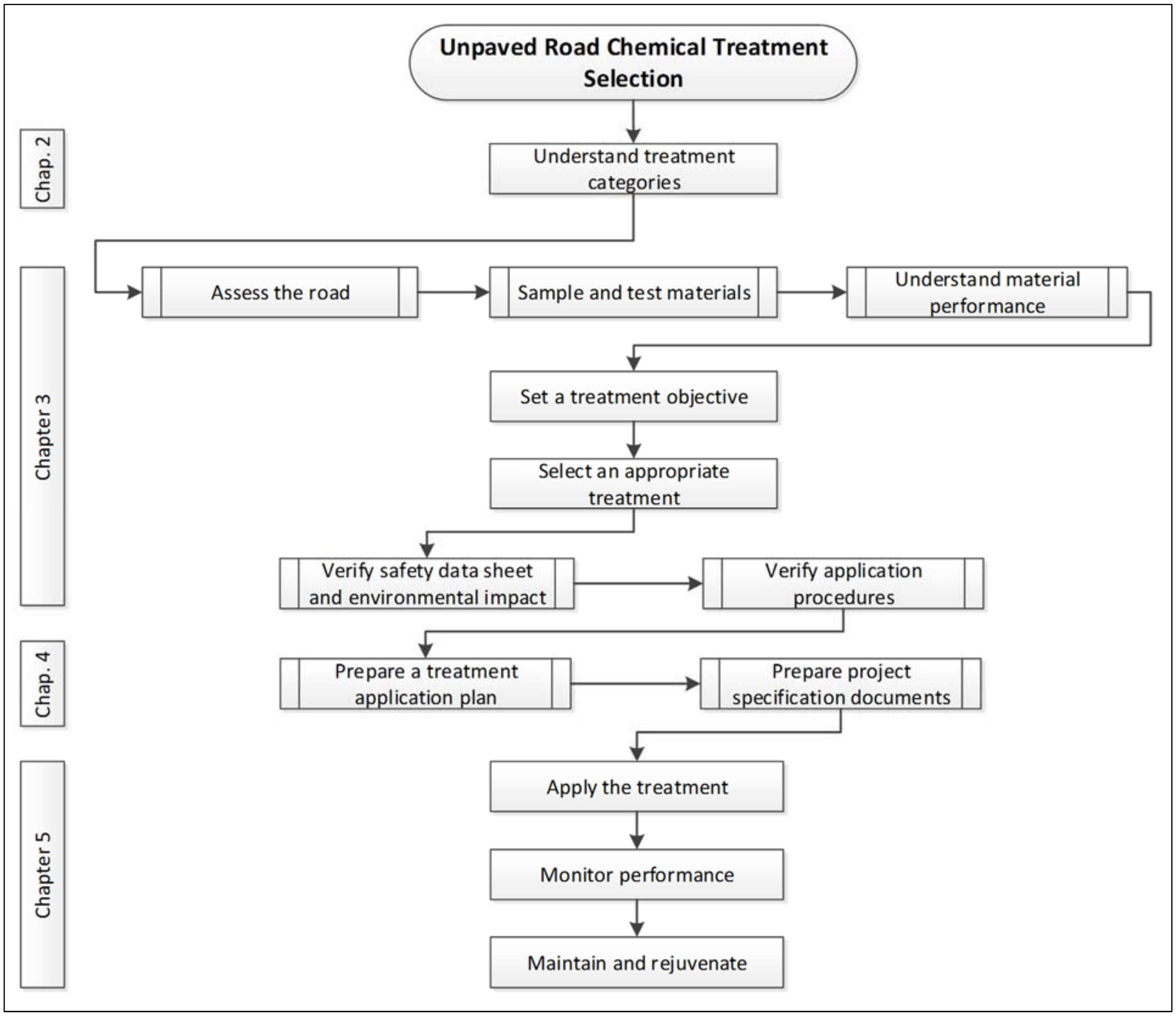


Figure 1.6: Approach to selecting, specifying, and applying unpaved road chemical treatments.

1.4 Terminology

Various terminologies are used for roads that have no asphalt concrete, asphalt/bituminous surface treatment, or portland cement concrete surfacing. Terms include:

- *Earth* or *dirt road* is usually used to describe roads that are formed on the existing subgrade/natural soil and which have limited or no imported gravel, and
- *Unpaved, unsealed, gravel, unsurfaced, aggregate-surfaced,* or *metaled roads* are usually used to describe roads constructed with one or more imported compacted gravel layers.

Since the concepts discussed in this guideline are applicable to all types of roads without a formal surfacing, the generally accepted term *unpaved roads* is used throughout.

Chemical treatments are essentially used on unpaved roads for two main purposes: dust control/fines preservation and/or stabilization. These are defined as follows for the purposes of this document:

- Dust control/fines preservation on unpaved roads involves the use of chemical treatments, either as spray-on or mix-in applications, to agglomerate fine particles in the wearing course material and prevent their entrainment by vehicles and wind, and without any significant improvements in shear strength in the wearing course or underlying base or subgrade materials.
- Stabilization on unpaved roads involves the use of mixed-in chemical treatments to agglomerate fine particles in the wearing course material (and possibly the underlying materials as well) and prevent their entrainment by vehicles and wind; to bind agglomerated fine particles to coarser particles; and/or to chemically alter the clay mineralogy to increase shear strength and improve wet weather passability.

1.5 Further Reading

A number of other guides covering the use of chemical treatments on unpaved roads have been produced in recent years. Although the methods for selecting an appropriate treatment for a given set of conditions differ among these guides, they all provide valuable information to understand how to best use these treatments. Examples of other guides that can be studied in conjunction with this guide include the following:

- *Dust Palliative Selection and Application Guide* (US Forest Service) *(2)*
- *Dust Control Guidance and Technology Selection Key* (US Army Construction Engineering Research Laboratories) *(3)*
- *Context Sensitive Roadway Surfacing Selection Guide*. (Federal Highway Administration) *(4)*
- *Dust Control Field Handbook* (US Army Engineer Research and Development Center) *(5)*
- *Stabilization Selection Guide for Aggregate and Native-Surfaced Low-Volume Roads* (US Forest Service) *(6)*
- *Maintenance Guide for Unpaved Roads: A Selection Method for Dust Suppressants and Stabilizers*. (FP Innovations) *(7)*
- *Stabilization and Rehabilitation Measures for Low-Volume Forest Roads*. (US Forest Service) *(8)*
- *The Sulfonated Petroleum Products Toolkit 1 for Decision Makers*. (Global Transport Knowledge Partnership) *(9)*
- *The Sulfonated Petroleum Products Toolkit 2 for Engineers*. (Global Transport Knowledge Partnership) *(10)*

- *Unsealed Roads Manual: Guidelines to Good Practice*. (Australian Road Research Board) *(11)*
- *Unsealed Roads: Design, Construction and Maintenance*. (South African Department of Transport) *(12)*
- *Unpaved Road Dust Management: A Successful Practitioner's Handbook*. (Federal Highway Administration) *(13)*

Blank page

2. UNPAVED ROAD CHEMICAL TREATMENT CATEGORIES

2.1 Introduction

A 2013 University of California Pavement Research Center (UCPRC) study *(1)* revealed that there are more than 200 proprietary unpaved road chemical treatments available on the market in the United States through almost as many product manufacturers, vendors, and distributors. Most of these can be placed in one of the following seven main categories centered on their base chemistry or mechanism of function:

- Water and water with surfactant
- Water absorbing
- Organic non-petroleum
- Organic petroleum
- Synthetic polymer emulsion
- Concentrated liquid stabilizer
- Clay additive (used for mechanical stabilization)

There is also a growing trend among manufacturers to blend treatments from two or more categories to optimize performance for specific road conditions. Common blends include water absorbing with organic non-petroleum and organic non-petroleum with organic petroleum.

The seven categories and their subcategories are discussed below. Additional information on each category with respect to uses, origins, attributes, limitations, application, and potential environmental impacts is provided in Appendix A.

Cementitious products (e.g., portland cement, lime, fly-ash, etc.) are generally inappropriate for dust control on, or stabilization of, unpaved roads and are not discussed in this guide.

2.2 Chemical Treatment Category Descriptions

2.2.1 Water and Water with Surfactant

Water is probably the most commonly used dust suppressant. It provides a temporary agglomeration of fine particles, preventing them from being entrained by vehicles or wind. The period of agglomeration, which is affected by material properties, temperature, and relative humidity can be slightly extended with the use of selected surfactants. Maintaining acceptable levels of dust control this way requires applying water to the road at frequent intervals, which entails having equipment dedicated to this task. But even though water itself is usually available at minimal cost, the costs of operating and maintaining the dedicated equipment often result in making this the least cost-effective dust control option. A number of other disadvantages arising from the regular use of water have also been identified, and they include slipperiness, pumping of fines to the surface (which aggravates the dust problem and causes material segregation leading to washboarding and raveling), potholes (Figure 2.1), erosion (Figure 2.2), and adhesion of mud to vehicles. The use of polluted water for dust control (e.g., on industrial and mine haul roads) can result in corrosion and runoff, and leachate can affect surface and groundwater resources over time. Since average annual rainfall is low in many areas where dust control is practiced, the continual spraying of significant quantities of water onto unpaved roads is often regarded as an unacceptable practice, especially in circumstances where these limited water resources could be used for domestic or agricultural purposes instead. Given these concerns, the use of water as a dust control treatment is recommended only for very short-term dust control activities where applying a chemical treatment is not practical or cost-effective.

Figure 2.1: Potholes caused by repeated water spraying.

Figure 2.2: Erosion caused by repeated water spraying.

2.2.2 Water-Absorbing Products

The most common water-absorbing product treatments are calcium chloride (Figure 2.3) and magnesium chloride (Figure 2.4), both of which are widely used for dust control in North America. Sodium chloride brines are also used but to a much lesser extent. These hygroscopic treatments function by absorbing small quantities of water from the atmosphere, agglomerating the fines and holding the aggregate matrix together through suction forces.

There is a long history and considerable published record on the use of calcium chloride and magnesium chloride on unpaved roads. These products are both most effective when used for dust control and fines preservation in either topical or mix-in applications. Although marginal increases in the shear strength of the wearing course layer are possible over time, mostly due to improved compaction, these chlorides are water soluble and do not routinely provide sufficient strength improvement to be considered as soil, base course, or wearing course layer stabilizers. Roads treated with them can be maintained with conventional unpaved road techniques (i.e., grader blading after light rain or water application). They require periodic rejuvenation, typically on an annual basis and usually at a lower dosage than was used in their first application. Chloride-based dust suppressants do not meet the requirements of the United States Department of Agriculture (USDA) *BioPreferred*® Program (www.biopreferred.gov) that some federal agencies must consider when procuring certain products.

Figure 2.3: Road treated with calcium chloride.

Figure 2.4: Road treated with magnesium chloride.

2.2.3 Organic Non-Petroleum Products

This category includes, but is not limited, to glycerin/glyceride-based treatments, lignosulfonates, molasses- and sugar-based treatments, plant oils (e.g., soy, linseed, rapeseed, canola, or palm oils), and tall oil pitch rosins. The main constituents in organic non-petroleum treatments are mostly derived from plant-based industries. Blends of one or more of these treatments or blends of one of these treatments with calcium or magnesium chloride, base/mineral oils, synthetic fluids, or synthetic polymers are increasingly being used. These products act as a "glue" that agglomerates the fines and coarser particles in the wearing course. Their composition is variable and depends on the plant matter and chemicals used during processing. Most are water soluble. They are most effective when used for dust control or fines preservation, either as topical or mix-in treatments. They rarely provide enough sustained strength improvement in the wearing course layer to be considered as stabilizers, unless they are blended with another binder. Treated roads can generally be maintained with conventional unpaved road techniques (i.e., grader blading after light rain or water application), although some treatments may need to be reapplied after maintenance. Organic non-petroleum products require periodic rejuvenation, typically on an annual basis and usually at a lower dosage than was used for the original application. Most of the dust suppressants listed on the USDA *BioPreferred*® Program fall into this category.

Glycerin/Glyceride Based

Most glycerin is derived from renewable resources (plant or animal based), and to a lesser extent from biodiesel production processes or petroleum feedstock. Various grades of glycerin are available, with technical grade (between 95 and 97 percent purity) generally being blended with other organic non-petroleum products (e.g., lignosulfonate and tall oil pitch rosin) for unpaved road chemical treatments. In addition to the humectant (moisture retaining) properties provided by the glycerin, these blends act as a glue that agglomerates the fines and coarser particles, usually providing greater enhanced binding and leaching resistance properties than those of the individual products. Depending on the type of binder, some darkening of the road surface usually occurs with their use (Figure 2.5).

Figure 2.5: Road treated with glycerin-based product.

Lignosulfonate

Lignosulfonates are produced as by-products during pulp and paper production. Their attributes depend on the chemistry (calcium-, ammonium-, or sodium-based) used in the separation of the lignin and the cellulose, and their effectiveness varies, depending on the plant species from which the lignosulfonate was obtained, the sugar content, and the percentage of lignosulfonate content in the solution. Lignosulfonates in powder form are more consistent but more expensive to produce, and consequently are more commonly used in applications of higher value than unpaved road dust control (e.g., concrete additives, drilling fluids, and binders in animal feed). Lignosulfonates generally impart a dark color to the road surface (Figure 2.6).

Molasses/Sugar

Molasses-based and sugar-based treatments are produced as by-products from sugar refining. Their attributes and effectiveness depend on the procedures used to process the plants and the type and quantity of complex sugars remaining after refining. Improvements in sugar-refining processes have generally resulted in lower dust suppression effectiveness and consequently these treatments may require frequent rejuvenation. Use of these products is typically restricted to roads in relatively close proximity to sugar refineries.

Figure 2.6: Road treated with lignosulfonate.

Plant Oil

Plant oils are by-products from the processing of various crops for food. Those most commonly used in unpaved road treatments include soybean, linseed, rapeseed, canola, corn, and palm oils. Their performance is dependent on the level of processing. As with other plant-based treatments, competing industries with higher-value uses may limit the availability of these oils for unpaved road treatments.

Tall Oil Pitch Rosin

Tall oil, or "liquid rosin," is another by-product from processing tree resin during wood pulp manufacture. As with lignosulfonate, its attributes depend on the chemistry used to separate the cellulose and on the species of tree used as a source. Tall oils have a wide range of high-value applications, including as adhesives and emulsifiers, and are consequently not widely available for unpaved road treatments. They have better water resistance than other organic non-petroleum treatments.

2.2.4 Organic Petroleum Products

These treatments are derived from petroleum refining and include diluted asphalt emulsions, base and mineral oils, petroleum resins, and synthetic fluids. Asphalt emulsions, petroleum resins, and synthetic fluids with binders, when mixed into a base course or wearing course layer, will have a cementing action providing both fines preservation and stabilization. Base oils and synthetic fluids without binders are generally used for dust control/fines preservation and provide limited strength improvement in the wearing course layer. When used for dust suppression, organic petroleum products require periodic rejuvenation, typically on an annual basis and usually at a lower dosage than was used in the original application. Organic petroleum-based dust suppressants generally do not meet the requirements of the USDA *BioPreferred®* Program unless they contain a sizeable organic non-petroleum binder component.

Asphalt Emulsion

The use of asphalt emulsions for dust control and stabilization on unpaved roads is typically limited to slow-set emulsions (e.g., SS-1). The use of other types of emulsions (e.g., medium- and rapid-set) is generally limited in many areas because of air quality concerns related to the volatiles that are released while the emulsion is breaking. The use of asphalt emulsions for spray-on fines preservation/dust control is generally limited by the length of the drying/curing period required before treated surfaces can be trafficked. When mixed into the layer, they provide both fines preservation/dust suppression and stabilization. They are more effective on sandy materials than on materials containing clay. Asphalt emulsions typically form a hard crust that cannot be easily maintained with a grader (Figure 2.7).

Figure 2.7: Road treated with asphalt emulsion.

Base/Mineral Oil

These treatments are produced during crude oil refining through physical separation processes. They do not dissolve in water and cannot be diluted prior to application. Although they are insoluble in water, they can be displaced from aggregate particles by rainfall or watering. Base oils are effective for fines preservation/dust control, but will have limited effect as a stabilizer on wearing course layer strength unless they are mixed with a binder (e.g., organic non-petroleum, another organic petroleum, or a synthetic polymer emulsion treatment). They do not form a crust and can be maintained with conventional unpaved road maintenance techniques without any significant loss in effectiveness. A light rejuvenation may be required after blading to maintain their effectiveness. Color changes to the road surface are usually insignificant.

Petroleum Resin

Petroleum resin treatments are a combination of petroleum resin (derived from refinery vacuum tower bottoms during the refining of highly paraffinic crude oils), water, emulsifiers, surfactants, and vacuum residuum. Petroleum resins are insoluble in water and will not leach from the road. They generally impart a dark color to the road surface (Figure 2.8). When mixed into the wearing course layer, they provide both fines preservation/dust suppression and stabilization. Petroleum resins typically form a weak crust on the road surface, which can be maintained with a grader after light watering without any significant loss in effectiveness. A light rejuvenation may be required after blading to maintain effectiveness.

Figure 2.8: Road treated with petroleum resin.

<u>Synthetic Fluid and Synthetic Fluid with Binder</u>

Synthetic fluids (Figure 2.9) have general properties and performance similar to base oils, but they are produced from a reaction of specific purified chemical feedstock, as opposed to simple physical separation such as temperature/vacuum refining. Synthetic fluids are also distinguished from base oils by how the US Environmental Protection Agency (EPA) defines them (U.S. EPA 40 CFR part 435 *[14]*). This more complex synthesis production process results in a product that is more refined than base oils, which although usually more expensive to purchase, has less environmental impact and consequently less restrictions on where it can be used. Like base oils, they do not dissolve in water and cannot be diluted prior to application, but they can be displaced from aggregate particles by rainfall or watering.

Figure 2.9: Road treated with synthetic fluid.

Synthetic fluids are effective for fines preservation/dust control, but will have a limited effect on wearing course layer strength. They can be blended with a binder (e.g., organic non-petroleum, another organic petroleum, or synthetic polymer emulsion treatment) for use as a combination dust suppressant/stabilizer. Synthetic fluids do not form a crust and can be maintained with conventional unpaved road maintenance techniques without loss of effectiveness. Synthetic fluids with binders can also be maintained with a grader after light watering without any significant loss in effectiveness. Light rejuvenation after blading may be required to sustain their full effectiveness.

2.2.5 Synthetic Polymer Emulsion Products

These treatments include, but are not limited to, acrylates (homopolymers and co-polymers), acetates (homopolymers and co-polymers), and styrene butadiene copolymer emulsions, either neat or in combination. They are usually manufactured specifically for unpaved road treatments; however, some products are derived from waste streams from paint, adhesive, or other industrial applications. Synthetic polymer emulsions are thermoplastic in nature, providing a flexible bond with the aggregate particles in the wearing course layer. They can be diluted in water when applied, but once they have dried they should not re-emulsify or leach from the road. They are often not effective as spray-on applications due to their forming a "skin" on the surface of the road that typically abrades relatively quickly under traffic. However, some manufacturers have introduced specific formulations that when applied as spray-on applications, will penetrate the road surface to a sufficient depth to adequately bind the particles without forming a skin on that surface. As mix-in treatments, they can be used for both fines preservation/dust control and stabilization (Figure 2.10). Although treated roads can be maintained with conventional unpaved road techniques, the treatments will typically require reapplication after grader blading. Synthetic polymer-based dust suppressants generally do not meet the requirements of the USDA *BioPreferred*® Program unless they contain a sizeable organic non-petroleum binder component.

Figure 2.10: Road treated with synthetic polymer emulsion.

2.2.6 Concentrated Liquid Stabilizer Products

Concentrated liquid stabilizers are a group of treatments that are all proprietary in nature, with little published information on their exact composition and stabilization mechanisms. Consequently, they are difficult to group and classify accurately. They stabilize soils and pavement layer materials in a complex electrochemical and/or enzymatic cementing bond that reduces the material's affinity for water (Figure 2.11). Studies indicate that acidity is one appropriate method of grouping these treatments. Although binding of fine particles does occur in a successful reaction, the level of fines preservation/dust control over long periods is often insufficient for the treatments to be considered as dust suppressants. In these instances, a separate dust suppression treatment may have to be used on top of the stabilized surface to reduce fines loss/dust to an acceptable level. Treated roads can generally be maintained with conventional unpaved road techniques (i.e., grader blading after light rain or water application). Compliance with USDA *BioPreferred*® Program requirements will depend on the base chemistry of the stabilizer.

Figure 2.11: Road treated with concentrated liquid stabilizer.

High-Acidity Concentrated Liquid Stabilizers

High-acidity concentrated liquid stabilizer treatments (also termed *electrochemical additives, sulfonated oils, sulfonated petroleum products* [SPPs], or *ionic stabilizers)* rely on ionic exchange reactions to perform their expected functions satisfactorily *(10)*. Their active ingredients are mostly hydrocarbon mineral oils modified with sulfuric acid to form sulfonic acid. Sulfonated oils are all surface active agents (surfactants) and have the ability to fix, displace, or replace exchange cations in clays and to render the materials in the road (particularly clay minerals but not necessarily only clays) hydrophobic by displacing adsorbed water and the water of hydration. The reaction should also prevent re-adsorption of this water. These treatments are highly susceptible to ion exchange reactions in which appropriate inorganic ions present on mineral surfaces (particularly clays) and in clay interlayers are replaced by, or attached to, the organic molecules. This reduces the mobility of the ions and functionally reduces the plasticity of the material. Once an ion exchange reaction has occurred and the sulfonic acid is attached to a mineral particle, the so-called hydrophobic tails of the sulfonated oils are directed away from the particle and form an oily protective layer around it. In theory, this has the effect of reducing the thickness of the electrical double layer and of preventing water from gaining access to the clay mineral particle. With this reduced double layer thickness, it now becomes theoretically possible to achieve a greater degree of compaction in the material, with resultant higher shear strengths and reduced water absorption of the material in the long term.

Low Acidity/Neutral Concentrated Liquid Stabilizers

These treatments are mostly enzymatic emulsions containing protein molecules that lower surface tension in water and catalyze very specific chemical reactions with soil molecules to form a cementing bond that stabilizes the subgrade or road layer and reduces the treated material's affinity for water. Theoretically, these products will work on a wider range of materials than high acidity treatments (which require relatively high clay contents, and sometimes specific clay minerals, for a satisfactory reaction) but they still require the presence of clay and a relatively high fines content (typically more than 20 percent passing the #200 [0.075 mm] sieve) to work effectively. Although the actual stabilization mechanism is less well understood than that of high-acidity stabilizers, the end result and performance are similar. The better compaction associated with the additive's surfactant properties additive can increase density and layer strength, and reduce pore water, which leads to better moisture intrusion resistance.

2.2.7 Clay Additives

Clay additives are used to mechanically stabilize unpaved road materials that have low fines contents and/or too low plasticity (Figure 2.12). Bentonite is the most commonly used clay additive, but other locally available clays (e.g., from side drain or nearby agricultural excavations) have also been used successfully. Application rates are based on grading analyses and plasticity index (or preferably bar linear shrinkage) test results. Thorough mixing of the clay into the existing material is required for optimal performance and to prevent localized soft spots. Although the addition of clay does lead to agglomeration of fine particles, the level of fines preservation/dust control is often insufficient for clay additives to be considered as dust suppressants. In these instances, a separate dust suppression treatment may have to be used on top of the mechanically stabilized surface to reduce fines loss/dust to an acceptable level. Roads treated road this way can be maintained with conventional unpaved road techniques (i.e., grader blading after light rain or water application).

Figure 2.12: Mechanical stabilization with bentonite.

2.3 Unpaved Road Chemical Treatment Manufacturers, Vendors, and Distributors

As noted earlier in this chapter, a recent study *(1)* revealed that there are more than 200 proprietary chemical treatments available for unpaved roads on the market in the United States through numerous product manufacturers, vendors, and distributors. A list of unpaved road chemical treatments and manufacturers/ distributors was compiled as part of this study and can be accessed on the UCPRC website under the "City and County Pavement Improvement Center" (CCPIC) section *(www.ucprc.ucdavis.edu/ccpic)*. Entries in the list were sourced from references to their use in the literature published since 1999, as well as an internet search. Product names found in the literature that could not also be located in an internet search were not included in the list. *Note:* product names have been provided for information purposes only and their appearance does NOT constitute a recommendation. The University of California, Davis does not endorse the use of any specific product for dust control and stabilization of unpaved roads. The authors make no claim that:

- The list includes all products currently available in the United States.
- The products have been correctly categorized.
- Any product will provide satisfactory performance.
- The products are safe to use.
- The products will not have any negative environmental impact.
- The products listed are available in all states.

No product was intentionally excluded from the list. It is likely that some products were missed in the search, possibly because they are marketed by local distributors who do not maintain an internet website. A link for sending updates, changes, corrections, and/or additions to the list is provided on the CCPIC website.

Blank page

3. SELECTING UNPAVED ROAD CHEMICAL TREATMENTS

3.1 Introduction

The new selection procedure discussed in this chapter was adapted from the procedure used in the 1999 U.S. Forest Service Guide *(2)* and updated to present new knowledge and experience. The main enhancements made in the new procedure include the following:

- Updated chemical treatment categories
- Additional information on understanding unpaved road material properties and how the materials perform on the road in the untreated and treated state
- Differentiation into four different treatment objectives, each with a separate set of selection criteria, for implementing an unpaved road chemical treatment program, namely:
  - Objective 1. Short-term dust control using a spray-on surface treatment
  - Objective 2. Long-term fines preservation using a spray-on surface treatment
  - Objective 3. Long-term fines preservation/surface stabilization using a mix-in application
  - Objective 4. Long-term stabilization using a mix-in application
- Additional plasticity index classes as part of the wearing course material properties input
- Consideration of percentage trucks in the traffic count
- Consideration of steep grades and sharp curves, if road maintenance activities have to be focused in these areas to repair erosion, material displacement, and/or rutting
- The use of simple equations to rank expected performance
- Revised environmental considerations, based on ongoing research undertaken by the United States Geological Survey (USGS)
- Consideration of the effects of soil chemistry
- Consideration of the maintainability of the treated surface using conventional unpaved road maintenance techniques
- Inclusion of suggested specification language for procurement and application of chemical treatments
- A web-based version of the unpaved road chemical treatment selection procedure to simplify the selection process (accessed at *www.ucprc.ucdavis.edu/dustcontrol)*

Additional treatment situations (e.g., high-traffic roads, mine haul roads, airfield pavements, environmentally sensitive areas, etc.) will be added to updated versions of this guideline (and the accompanying web-based selection tool) as more documented field performance data on these specific types of applications become available.

3.2 Selection Procedure Overview

The following chapter sections offer a new approach to the selection of an appropriate chemical treatment. This approach is centered around the practitioner understanding the different chemical treatment categories discussed in Chapter 2; understanding the roads that require treatment in terms of traffic, climate, geometry, and materials; and then choosing an objective for applying a chemical treatment. Based on the information collected and the objectives set for the project, the most appropriate chemical treatment categories for a given situation can be selected using a series of charts and then ranked using a simple equation (this process is automated in the web-based tool). The ability to rank the different treatments available distinguishes this procedure from those documented in the literature. This selection procedure also provides basic guidance on environmental considerations, the effects of soil chemistry, and maintainability with a grader.

3.2.1 Data Input Requirements

The chemical treatment selection procedure requires the following input data:

- Material properties of the subgrade, base, or wearing course layer aggregates that will be treated
- Traffic (average daily traffic [ADT] and percentage of trucks)
- Climate (average humidity, annual average rainfall, and knowledge about storm intensity)
- Road geometry (specifically whether sharp curves and/or steep slopes dominate routine maintenance efforts)

3.2.2 Material Properties

Unpaved road chemical treatments are best used to keep a "good road in good condition" (Figure 3.1), rather than to try to correct serious material, construction, and/or maintenance deficiencies (Figure 3.2). Using inappropriate materials in the wearing course will probably have the biggest impact on dust levels, slipperiness, and all-weather passability, and how quickly the road deteriorates due to washboarding, raveling, and erosion. Consequently, considerable information is provided in Appendix B on understanding material properties to ensure that the best possible road performance is achieved.

Figure 3.1: Good gravel road.

Figure 3.2: Poor gravel road (note cross-drain pipe exposed after excessive gravel loss).

An unpaved road is only as good as the materials used in its layers and the way they are shaped and compacted to form a riding surface. Much of the imported aggregate used in base and wearing course layers on unpaved roads in the United States comes from commercial sources who primarily serve the needs of their largest clients. Consequently, the aggregate supplied for unpaved roads will often meet the specifications of the supplier's main clients, which are typically those for asphalt concrete, asphalt surface treatments (chip seals), portland cement concrete, or aggregate base for paved roads. Unfortunately, many practitioners assume that if materials meet those specifications, then those materials will also work well for an unpaved road wearing course. This is an incorrect assumption! The aggregate base used in paved roads is confined by the chip seal, asphalt concrete, or portland cement concrete on the surface, and therefore gradings are optimized for shear strength (and frost-heave protection where applicable) as the base is not directly subjected to traffic abrasion or rainfall. Instead, a different set of material selection criteria and specifications *(e.g., 15-18)* are needed for unpaved road wearing courses to compensate for this lack of surface protection. Adjustment of the fines content and clay content (usually an increase) are usually the most important considerations.

> *Many practitioners mistakenly believe that if materials meet the specifications for aggregate base in a paved highway, they will also work well as an unpaved road wearing course. This is an incorrect assumption!*

The key material properties influencing unpaved road wearing course performance include the grading or particle size distribution, particle shape, the fines content, the clay content, and the material shear strength. The steps listed below should be followed to determine key material input data for the selection tool.

1. Collect representative samples of the existing wearing course; of the underlying materials, if blending is anticipated (sample down to the anticipated mixing depth); and/or from the quarry stockpile if new aggregates are going to be imported onto the road. Sampling is best done during an evaluation of the road and can be done in conjunction with checks on layer thickness and assessments of road shape, drainage, and localized areas requiring repair.
2. If available, use a dynamic cone penetrometer (DCP) test (Figure 3.3) to measure layer thicknesses and bearing capacity, and to identify areas with weak subgrade.
3. Subject the sampled materials to the following basic material indicator tests:
    - A grading analysis (e.g., AASHTO T 27 or ASTM C136),
    - A plasticity test (e.g., Atterberg limits [AASHTO T 89 and T 90 or ASTM D4318] or bar linear shrinkage [Caltrans CT 228, Texas Tex-107-E, or method provided in Appendix B.1]), and
    - A strength test (e.g., California Bearing Ratio [AASHTO T 193 or ASTM D1883]) if all-weather passability is an issue and stabilization is being considered.

Figure 3.3: DCP

All these tests are simple to perform and cost very little (at commercial laboratories in 2017, grading analysis and Atterberg limit tests cost approximately $250 and $150, respectively, and a California Bearing Ratio [CBR] test cost approximately $750). These costs are negligible in terms of the costs of gravel replacement and chemical treatment, and are potentially recovered many times over when better material selection results in extended road life, longer periods between treatment applications, and reduced grader maintenance requirements. The very small savings enjoyed up front by skipping material testing will invariably mean higher costs later on because of early replacement of gravel and the need for more frequent maintenance. Most unpaved road specifications are based on these or similar tests.

4. Check the test results against the specification to see that all requirements are met.

Detailed information on interpreting test results and predicting unpaved road performance from them is provided in Appendix B.

3.2.3 Traffic Data

Traffic information is typically collected from manual or automated traffic counts. A precise number is not required given that only three categories are used in the selection procedure, namely, *less than 100, 100 to 250,* and *more than 250.* On roads carrying seasonal traffic (e.g., in agricultural areas where significant increases in traffic occur during harvest season), traffic counts should be done during the periods with highest traffic volumes to ensure that an appropriate treatment is selected for this busy period. Since trucks typically cause the most damage on unpaved roads, an indication of what percentage of the traffic count consists of trucks should be included. A precise percentage is not required and only two categories are used in the selection process, namely, less than *10 percent trucks* or *more than 10 percent trucks.*

3.2.4 Climate Data

The performance of most unpaved road chemical treatments is influenced by moisture. Water-absorbing treatments rely on absorbing small amounts of moisture from the atmosphere, and are therefore dependent on average daily humidity levels. Treatments in a number of categories are prone to leaching from the road during heavy and/or repeat rainfall events and rainfall patterns. Average rainfall amounts and rainfall intensity (i.e., rainfall amount in a given period of time) are therefore important for selecting the most appropriate treatment for a given situation. Other climatic parameters, such as temperature, freeze-thaw, wind, and solar radiation have limited effects on the actual performance of the different treatment categories, but can have a general effect on the overall performance of the road. Consequently, only three climatic categories are used in the selection process, namely *dry* (average daily ambient air humidity is less than 40 percent), *damp* (average humidity is higher than 40 percent), and *wet* (high rainfall or high intensity storms).

Climate data can be obtained from local weather stations or online at websites such as *www.noaa.gov.*

3.2.5 Road Geometry

Steep slopes and sharp curves may affect the performance of treatments in certain subcategories, primarily because of erosion of the surface or leaching of the product as water runs over the surface, or because of higher levels of traffic abrasion. Actual geometric data (i.e., percentage slope or degrees of curvature) are not required. Instead, the selection procedure bases the influence of geometry simply on whether or not the predominant maintenance work on the road occurs on steep slopes and/or sharp curves. This information is typically based on experience, or obtained from maintenance records.

3.3 Selection Procedure

This section covers a step-by-step guide to using the unpaved road chemical treatment selection procedure. The procedure requires completing one form (Form 3.1 [(a) is US units and (b) in metric units] in Section 3.5) using the data discussed in Section 3.2 and information provided in one of four charts (Chart 3.1 through Chart 3.4 in Section 3.5) depending on which treatment objective is being considered. The entries on Form 3.1 are then summed to give expected performance values. These values are ranked, and the treatments with the lowest ranking will be the most suited to the objective and set of conditions entered. Another chart (Chart 3.5) is then used to check for any potential limitations that the selected treatments may have (i.e., leaching stability, aquatic impacts, plant impacts, mammal and human health impacts, effects of soil chemistry on treatment effectiveness, and whether the road can be maintained with a grader). Guidance on interpreting the results and examples are also provided. The web-based version of the procedure automates much of the process, but will provide the same results as the manual method using the forms.

As noted, the selection procedure is based on four charts (included in Section 3.5) that detail the expected performance (good, fair, or poor) of each family of treatments for each treatment objective, and the influence (none, some, or significant) of each of the input parameters (traffic, climate, plasticity index, and fines content) on this expected performance. These charts—numbered Chart 3.1 through Chart 3.4 (one for each objective for starting/changing a chemical treatment program)— were developed by a panel of unpaved road practitioners (representing the Federal Highway Administration, US Forest Service, US Army Corps of Engineers, Local Technical Assistance Programs, and county road agencies), academia, and chemical treatment manufacturers. The charts are based on the panel members' subjective experience and the results of documented field experiments *(1)*. Users can modify individual cells in the charts to suit specific conditions based on past experience or on the experience of others (note that modification of the web-based version is not possible). The ratings in the charts should be considered as a general guide only and interpreted as follows:

- A rating of 1 (green cell) implies that the input parameter should have little negative influence on how the chemical treatment will perform.

- A rating of 7 (orange cell) implies that the input parameter could have some influence on how the chemical treatment will perform and although it does not exclude use of the treatment, the user should be aware of the potential limitation(s) and should check if the limitation is relevant to the specific intended application. Each limitation is detailed on the charts.
- A rating of 50 (red cell) implies that the input parameter could have considerable negative influence on how the chemical treatment will perform. Users should carefully consider this before using the treatment in this particular application. Each reason is detailed on the charts.

3.3.1 Data Input

Use Form 3.1 (in Section 3.5 below [versions for both US (Form 3.1a) and metric (Form 3.1b) units are provided]) to perform this procedure:

1. Enter the date of the analysis.
2. Enter the road number or name and key details (e.g., start and end post miles, etc.).
3. Enter the material properties (from laboratory test results discussed in Section 3.2.2):
   + Percent passing the 1 in. (25 mm), #4 (4.75 mm), #8 (2.36 mm), #40 (0.425 mm), and #200 (0.075 mm) sieves. The first three are required to calculate the grading coefficient (GC) (see Appendix B for explanation of the grading coefficient and how it is used to predict unpaved road performance, keeping in mind that chemical treatments are best used to keep good roads in good condition). The percent passing the #40 sieve is required to calculate the shrinkage product (see Appendix B), and the percent passing the #200 sieve is used to select a fines content range in the selection procedure.
4. Enter the plasticity index (PI) or bar linear shrinkage (BLS). This is required to determine the shrinkage product (SP) in order to understand the likely material performance and to identify an appropriate plasticity index range required for the selection procedure. After calculating the shrinkage product, use it and the grading coefficient to obtain a likely indication of performance (see Appendix B, Figure B.7).
5. Select an objective for starting/changing a chemical treatment program:
   + Short-term dust control (spray-on [STDC-Spray on Form 3.1]). Select this objective for temporary dust control such as for detours, or for short-term vehicle access such as logging operations, fire control access, military exercises, temporary runways, etc.
   + Long-term fines preservation (spray-on [LTFP-Spray on Form 3.1]). Select this objective if you plan to spray a chemical treatment on existing road surfaces as part of a longer-term management strategy to control dust for safety/health/quality-of-life reasons as well as to preserve fines, and thereby reduce maintenance costs and increase gravel replacement intervals. Rejuvenations will be required.
   + Long-term fines preservation/surface stabilization (mix-in [LTFP-Mix-in on Form 3.1]). Select this objective if you plan to mix the chemical treatment into the road surface (either during reshaping or as part of a regravelling operation) for the same reasons as those for LTFP-Spray but with improved performance due to depth of mixing and subsequent compaction and surface sealing. This is considered the most appropriate management strategy for fines preservation on unpaved roads, and is the preferred objective because a longer period of effectiveness will usually be achieved.

- Long-term stabilization (mix-in [LTS-Mix-in on Form 3.1]). Select this objective if the purpose of the treatment is to improve all-weather passability as well as to preserve fines, like the LTFP-Spray and LTFP-Mix-in options. Note that concentrated liquid stabilizers may not reduce dust to the same levels as other treatments, and that a separate dust control treatment may be required in addition to the stabilization.

6. Select a traffic level (<100, 100 to 250, or >250 vehicles per day). Note that some treatments are effective at traffic levels higher than 250 vehicles per day; however, engineering judgment and experience will be required to determine whether sustained acceptable performance can be obtained for a specific set of conditions. At these higher traffic levels, more frequent rejuvenations may also be required.
7. Select a climate factor:
   - *Dry* applies to areas where average daily relative humidity levels are less than 40 percent for periods of more than 20 consecutive days annually and high intensity rainfall events are uncommon.
   - *Damp* implies that average daily humidity levels are generally above 40 percent and that high intensity rainfall events are uncommon.
   - *Wet* implies that high intensity storm events are common, which may lead to leaching of treatments, temporary slipperiness, and/or temporary impassability. Areas with high annual average rainfall are also considered within this climate factor, and although dust control/fines preservation is not commonly required or practiced in these areas because of the higher moisture content in the materials, improvements in all-weather passability (i.e., stabilization) may be of interest.
8. Select the corresponding range of plasticity index (<3, 3 to 5, 6 to 15, or >15).
9. Select the corresponding range of fines content (percent passing the #200 [0.075 mm] sieve) (<5, 5 to 10, 11 to 20, 21 to 30, or >30).
10. Check the box if more than 10 percent of the daily traffic is trucks.
11. Check the box if the road to be treated has steep gradients and if the predominant road maintenance activities involve dealing with distresses on these grades.
12. Check the box if the road to be treated has sharp curves and if the predominant road maintenance activities involve dealing with distresses on these curves.

Transfer data from the appropriate selection chart (Chart 3.1 through Chart 3.4) as follows:

13. Depending on the selected objective for starting an unpaved road chemical treatment program, choose the correct selection chart as follows:
    - Chart 3.1 for short-term dust control using a spray-on treatment (STDC-Spray)
    - Chart 3.2 for long-term fines preservation using a spray-on treatment (LTFP-Spray)
    - Chart 3.3 for long-term fines preservation using a mix-in treatment (LTFP-Mix-in)
    - Chart 3.4 for long-term stabilization using a mix-in treatment (LTS-Mix-in)
14. Copy all the numbers from the cells in the relevant "Traffic" column (e.g., 100-250 if this is the traffic level that was selected during data input [Item #6 in Section 3.3.1]) in the chart to the cells in the "Traffic" column on the form.

15. Copy all the numbers from the cells in the relevant "Climate" column (e.g., Damp if this is the climate factor that was selected during data input [Item #7 in Section 3.3.1]) in the chart to the cells in the "Climate" column on the form.
16. Copy all the numbers from the cells in the relevant "Plasticity Index" column in the chart to the cells in the "PI" column on the form.
17. Copy all the numbers from the cells in the relevant "Fines Content" column in the chart to the cells in the "Fines" column on the form.
18. If the ADT consists of more than 10 percent trucks (i.e., the ">10% trucks" option was selected in Item #10 during data input), copy all the numbers from the cells in the "% Trucks" column in the chart to the cells in the "Trucks" column on the form. If this was not selected, leave the column blank.
19. If the road has steep grades (i.e., the "Steep grades" option was selected in Item #11 during data input), copy all the numbers from the cells in the "Steep Grades" column in the chart to the cells in the "Grades" column on the form. If this was not selected, leave the column blank.
20. If the road has sharp curves (i.e., the "Sharp curves" option was selected in Item #12 during data input), copy all the numbers from the cells in the "Sharp Curves" column in the chart to the cells in the "Curves" column on the form. If this was not selected, leave the column blank.

3.3.2 Performance Scores, Performance Ranking, and Result Interpretation

1. Calculate the expected performance for each chemical treatment subcategory as follows:
   + For each row of chemical treatment subcategories on the form (i.e., "Water" through "Clay additive", add up the values in each of the completed cells across the row and enter the sum in the column for performance score (i.e., "Perf. Score" on the form).
   + Rank their performance in the "Ranking" column. The lowest performance score will have the highest ranking.
2. Interpret the results as follows:
   + A performance score of between 4 and 7 on the forms—with scores depending on whether truck, steep grade, and/or sharp curve scenarios were included in the input values—indicates that the chemical treatment subcategory is worth consideration and should perform satisfactorily provided that mix design results indicate good performance, that the road is prepared appropriately, and that the treatment is applied according to specification.
   + A performance score of between 10 and 49 indicates that at least one of the input parameters (i.e., inputs with a value of 7 on the forms) could have a negative influence on the performance of the treatment and requires additional consideration before it is selected. Check which parameter(s) is influencing the score and decide whether this is an actual concern and/or if additional investigation and/or discussion with treatment manufacturers/ distributors is warranted. Higher scores within this range imply that more than one of the input parameters could influence performance of the treatment.
   + A performance score greater than 53 indicates that one or more of the input parameters (i.e., one or more inputs on the form has a value of 50) could have a significant negative effect on the performance of the treatment and requires more serious consideration before it is selected. Potential implications should be discussed with other experienced practitioners and/or treatment manufacturers/distributors before a decision is made. If the input parameter of concern is

material related (i.e., plasticity index or fines content), mechanical stabilization (adding coarse aggregate, fines, or clay depending on the problem) can be considered to correct the problem before applying the chemical treatment (see Appendix B for guidance).
    + A performance score greater than 200 implies the treatment subcategory is not appropriate for that objective.
3. Select the most appropriate treatment subcategories and add their names to the "Selection" row at the bottom of the form.
4. Check the expected performance of these top-ranking selections in terms of wearing course material shrinkage product and grading coefficient using the expected performance predictor charts in Appendix B (Figure B.20).
5. Check Chart 3.5 for any environmental considerations for your selections. This chart provides a general indication of the potential environmental implications associated with the use of chemical treatments if applicable. Remove problem treatments from the selection.
6. Check Chart 3.5 to determine if soil chemistry could influence performance of the selected treatment subcategories and needs to be considered prior to a final choice being made. Consult the manufacturer if there are any doubts.
7. If relevant to your situation/decision, check Chart 3.5 to determine whether the selected treatment subcategories can be maintained with conventional unpaved road maintenance techniques. Consult the manufacturer if there are any doubts.
8. Identify products that meet the subcategory requirements of the selected treatments and manufacturers/distributors that supply them. A list of unpaved road chemical treatments and manufacturers/distributors can be accessed on the UCPRC website (see Section 2.3). In addition to having checked the considerations summarized in Chart 3.5, consider the following when identifying potential products:
    + Always review safety data sheets before making a decision and take required measures to ensure safe use.
    + Request proof of environmental testing by an accredited laboratory from treatment manufacturers/distributors before making a decision (discussed in Chapter 4).
9. Run a cost analysis using actual costs. These should include those of specific products from identified manufacturers/distributors, transport of the product, specific road preparation requirements, special application equipment required, etc.). Obtain these costs and realistic estimates of rejuvenation/reapplication intervals from the manufacturers/distributors. Cost analyses are best completed using an *Excel*® spreadsheet, which allows rapid sensitivity analyses and comparisons using different input values and assumptions. An example spreadsheet for analyzing the costs and benefits of unpaved road chemical treatment programs can be accessed at *www.ucprc.ucdavis.edu/ccpic.* Note the following:
    + Actual costs should be calculated for specific projects based on cost of the product (including transport), application rate, expected performance, number of rejuvenations required, and the potential savings for your specific agency *(13)*.
    + Note that price per treated area to achieve a predetermined level of performance is considered to be the best indicator of relative cost, rather than simply price per gallon (liter) or pound/ton (kilogram/metric ton). Take care to ensure that different treatments are appropriately compared. For example:

- A 28 percent magnesium chloride solution from one supplier may be cheaper per gallon (liter) than a 32 percent solution from another supplier, but it will need to be applied at a higher application rate to achieve the same level of performance. Total project costs using the lower concentration may therefore be higher due to the cost of transporting and applying more product.
- The initial cost of a synthetic fluid with binder may be considerably more expensive than synthetic fluid on its own, but the blend may require less frequent rejuvenations than the unmodified product, resulting in lower life-cycle costs.

10. Select the most appropriate chemical treatment product from your list to suit the particular needs of the project. If agency policy dictates that a USDA *BioPreferred®* dust suppressant should be considered, then select an appropriate listed product *(www.biopreferred.gov)* if satisfactory performance can be expected (i.e., the subcategory ranks high). Ensure that all environmental and safety concerns are addressed before making a final decision. Discuss with the manufacturer/distributor if there are any doubts.

3.3.3 Chemical Treatment Selection Examples

Examples of completed forms are provided on Form 3.2 through Form 3.5 in Section 3.5. Two projects are considered, as follows:

- Example 1: A road for which the agency has set an objective of long-term fines preservation using a spray-on treatment. This road carries 90 vehicles per day of which about 7 are trucks (i.e., less than 10 percent) in what is considered a "damp" climatic zone. The agency is also using the procedure to evaluate the impacts of good (Form 3.2) and marginal (Form 3.3) materials on the likely performance of the treatment.
- Example 2: A road for which the agency has set an objective of long-term fines preservation using a mix-in treatment. This road carries 220 vehicles per day, of which about 45 are trucks (i.e., more than 10 percent) in what is also considered to be a "damp" climatic zone. Both good and marginal wearing course materials materials (Form 3.4 and Form 3.5, respectively) are also assessed.

Screenshots of the output from the web-based tool using the same input as that used in Examples 1 and 2 are shown in Figure 3.4 through Figure 3.7 in Section 3.5. Note that the web-based tool normalizes performance scores between 4 and 7 on Form 3.1 to a treatment rating of 1 in a green-colored cell, scores between 10 and 49 to a treatment rating of 2.0 to 2.6 (depending on the performance score) in an orange-colored cell, scores between 50 and 199 to a treatment rating of 3.0 to 3.6 in a red-colored cell, and scores above 200 to a treatment of NA (i.e., not applicable) in a grey-colored cell. The web-based tool ranks products with the same treatment rating alphabetically.

Using the results on the forms in conjunction with the information provided in Chapter 2, Appendix A, and Appendix B, the following observations are made from the different examples:

- Example 1a, Good Material (Form 3.2 and Figure 3.4)
  - Tests on the aggregate revealed an acceptable grading (grading coefficient [GC] of 33 as detailed in Appendix B), quantity of fine material (16 percent passing the #200 [0.075 mm] sieve), and plasticity (shrinkage product [SP] of 125). The material would be expected to perform well in an unpaved road wearing course.
  - Water, water plus surfactant, concentrated liquid stabilizers, and clay additives are ranked as not applicable because these treatment categories are not suited to this objective.
  - All other subcategories except sodium chloride brine, asphalt emulsion, and synthetic polymer emulsion have a ranking of 1 based on expected performance scores of 4.
  - In the lower-ranking subcategories, sodium chloride would likely be less effective than that of calcium chloride or magnesium chloride in terms of absorbing moisture from the atmosphere and retaining it. Asphalt emulsion typically works best on low plasticity materials. Synthetic polymer emulsions are more effective when applied as a mix-in treatment than as a spray-on treatment.

- Example 1b, Marginal Material (Form 3.3 and Figure 3.5)
  - Tests on the aggregate revealed an acceptable grading (grading coefficient of 33) and quantity of fine material (16 percent passing the #200 [0.075 mm] sieve). However, the material was determined to be non-plastic (i.e., plasticity index and shrinkage product of 0) and consequently unpaved roads surfaced with this material would likely have washboarding and raveling distresses.
  - Water, water plus surfactant, concentrated liquid stabilizers, and clay additives are ranked as not applicable because these treatment categories are not suited to the objective (water and water with surfactant are not viable long-term treatments, clay additives cannot be sprayed, and concentrated liquid stabilizers are not intended for fines preservation).
  - Nine treatment subcategories (calcium chloride, magnesium chloride, glycerin-based, lignosulfonate, tall oil pitch rosin, base oil, petroleum resin, synthetic fluid, and synthetic fluid with binder) have a ranking of 1, but performance scores of 10 (based on them having a probability of diminished performance due to the non-plastic material in the wearing course).
  - Two treatment subcategories have performance scores of 16 and a ranking of 10. Asphalt emulsion typically works best on low plasticity materials, while synthetic polymer emulsions are more effective when applied as mix-in treatments.
  - Three treatment subcategories have performance scores of above 50 with corresponding lower rankings. Molasses, plant oils, and sodium chloride brine are unlikely to be effective because of the non-plastic material used in the wearing course.

- Example 2a, Good Material (Form 3.4 and Figure 3.6)
  - Tests on the aggregate revealed an acceptable grading and plasticity as discussed in Example 1a.
  - Water and water plus surfactant are ranked as not applicable because these treatment categories are not suited to the objective.
  - Eight treatment subcategories (calcium chloride, magnesium chloride, glycerin-based, lignosulfonate, base oil, petroleum resin, synthetic fluid, and synthetic fluid with binder) have performance scores of 5 and a ranking of 1.
  - Two treatment subcategories have performance scores of 11 and a ranking of 9. Tall oil pitch rosin and synthetic polymer emulsions may have diminished performance because of the high vehicle and truck counts, respectively.

    - Three treatment subcategories have performance scores ranging from 17 to 23 with corresponding lower rankings, indicating that two or more input parameters will probably influence the performance of the treatments.
    - The remaining three treatment subcategories have performance scores higher than 50, indicating that at least one input parameter will have a significant negative impact on performance. Molasses is unlikely to perform effectively under the high traffic volumes, clay additives are likely to increase the plasticity index/shrinkage product to unacceptable levels, and concentrated liquid stabilizers are unlikely to react effectively given the limited amount of clay in the material. Concentrated liquid stabilizers are also intended to be used for stabilization and not fines preservation.

- Example 2b, Marginal Material (Form 3.5 and Figure 3.7)
    - Tests on the aggregate revealed an acceptable grading and quantity of fine material. However, the material was non-plastic and would therefore be susceptible to washboarding and raveling.
    - Water and water plus surfactant are ranked as not applicable because these treatment subcategories are not suited to the objective.
    - All treatment subcategories except clay additives have a rating of 7 or higher in terms of expected performance with regard to plasticity, which gives an indication to the practitioner that washboarding and raveling may still occur after treatment, especially given the relatively high traffic volume. Mixing small amounts of clay into the surface material would increase the shrinkage product and change the plasticity rating to 1; however, the added fines would then impact the fines content input parameter.
    - Eight treatment subcategories have performance scores of 11 and would be expected to provide acceptable performance (possibly with some washboarding and raveling depending on specific site conditions).
    - Four of the treatment subcategories (tall oil pitch rosin, asphalt emulsion, synthetic polymer emulsion, and clay additive) have slightly lower performance scores (17 to 23) with corresponding lower rankings due to potential concerns about the relatively high traffic/truck traffic numbers in combination with the low plasticity.
    - The remaining treatment subcategories received even poorer scores (66 to 109) also due to concerns with regard to relatively high traffic/truck traffic numbers in combination with the low plasticity.
    - Concentrated liquid stabilizers received a score of 115 because these treatments are generally intended for and used to improve strength characteristics of the material rather than for fines preservation/dust control, which was the objective of this treatment. The plasticity index of the material is also generally too low for these products to react effectively.

3.4 Mix Design/Performance Testing

The procedure discussed above provides a general guide for selecting the most appropriate types of chemical treatments for a given set of general road conditions. There are currently no formal laboratory tests for assessing the performance of products selected for dust control/fines preservation (Treatment Objectives 1 through 3) and consequently product selection and application rate should be based on documented experience and information provided by the manufacturer/distributor.

For projects where a treatment is required for improving the properties of marginal materials and all-weather passability (Treatment Objective 4), formal AASHTO/ASTM tests are available and mix design and/or performance tests should always be undertaken on the actual materials that are present on the road, or that will be placed on the road during construction with the treatment, to determine optimal application rates and whether expected performance is likely to be obtained. Example tests and their associated limits are discussed below. An example mix design testing program is provided in Appendix C.

3.4.1 Long-Term Stabilization (Mix-In)

The performance tests for this objective will depend on the project design requirements, but they are usually linked to strength improvement, moisture sensitivity and/or plasticity change. Formal AASHTO or ASTM methods should be followed for these tests, and include:

- California Bearing Ratio (CBR, AASHTO T 193 or ASTM D1883), for measuring shear strength. This is an appropriate test for assessing the use of a treatment for improving all-weather passability, provided that the four-day soak requirement in the test method is followed. The test method usually needs to be modified to accommodate curing of the chemical treatment prior to soaking and testing. Pass/fail criteria are usually linked to design and/or specification requirements. A soaked CBR of 15 (determined at 95 percent of AASHTO T 180 or ASTM D1557 compaction) after treatment can be considered as a minimum acceptance level in the absence of design specifications, based on international research studies *(12,19,20)*. Note that CBR values in excess of 100 are essentially meaningless and treatments achieving these values should be tested instead in terms of unconfined compressive strength and/or indirect tensile strength.
- Unconfined compressive strength (UCS, AASHTO T 208 or ASTM D2166). This is an appropriate test for treatments intended to stabilize/increase strength, where relatively strong cementation occurs. The four-hour soak requirement after an appropriate curing regime (treatment specific) should be adhered to for assessing potential moisture sensitivity. Pass/fail criteria are usually linked to design and/or specification requirements. A UCS of 110 psi (750 kPa, determined at 100 percent of AASHTO T 180 or ASTM D1557 compaction) after treatment can be considered as a minimum acceptance level in the absence of design specifications. Specifications for cement- or lime-stabilized materials are generally not applicable or appropriate for unpaved road treatments (they are typically between 300 psi and 500 psi [~2.0 MPa and 3.5 MPa]) and should not be targeted for unpaved road applications.
- Indirect tensile strength (ITS, AASHTO T 283 or ASTM D6931). This is an alternative or supplementary test to the UCS test and is used to measure tensile strength. It is appropriate for testing stabilization treatments in the organic petroleum and synthetic polymer emulsion categories. An appropriate soaking period after curing can be specified to assess any moisture sensitivity issues. Testing in both unsoaked and soaked conditions is useful for determining a dry-to-wet tensile strength ratio. A soaked ITS of 30 psi (200 kPa, determined at 100 percent of AASHTO T 180 or

ASTM D1557 compaction) after treatment can be considered as a minimum acceptance level in the absence of design specifications.

- Atterberg limits (AASHTO T 89 and T 90 or ASTM D4318). This test is used to assess the ability of a treatment to reduce the plasticity index of gravel, if this reduction is claimed as a benefit of the treatment by the manufacturer/supplier. Pass/fail criteria are usually linked to design and/or specification requirements.

3.4.2 Short-Term Dust Control and Long-Term Fines Preservation

No formal performance tests for these objectives are available; however, a number of tests are currently under development *(21)* for assessing abrasion resistance and leaching or erosion resistance that can be undertaken in most soil testing laboratories. Informal abrasion resistance tests include:

- Mechanical brush tests, where treated and untreated compacted specimens are first weighed, subjected to brushing with a wire brush (usually 500 brush strokes/revolutions), and then weighed again. Performance is assessed in terms of percentage of material loss. Typical acceptance criteria require that weight loss on the treated specimen does not exceed 10 percent of the original weight and/or 10 percent of the loss recorded on the untreated control specimen *(21)*.
- Air blast tests, which are similar to the mechanical brushing test, except that wind erosion is simulated rather than tire abrasion *(23)*. Specimens are usually placed in a tube and subjected to blasts of air from a compressor airline, blower, or fan for a fixed period of time. Acceptance criteria are typically the same as those for the mechanical brushing test.

Informal erosion/leaching tests include:

- Capillary rise tests, in which treated and untreated compacted specimens are placed in a tray of water and the height of water movement is measured after a fixed period of time. Acceptance criteria for the treated specimens are typically set at a percentage of that of the untreated specimens *(23,24)*.
- Erosion tests, in which treated and untreated compacted specimens are first weighed, subjected to a flow of water for a fixed period of time, and then weighed again. Performance is assessed in terms of percentage of material loss. Typical acceptance criteria require that weight loss on the treated specimen does not exceed 10 percent of the original weight and/or 10 percent of the loss recorded on the untreated control specimen *(21)*.

3.5 Forms, Charts, and Web-Based Tool Screenshots

The forms and charts discussed in this chapter, along with screenshots from the web-based version of the selection tool are shown on the following pages.

Form 3.1a: Chemical Treatment Selection Form (US Units)

Unpaved Road Chemical Treatment Selection (US Units)								Date:	
Road No./Name			Details						
Material properties	Pass 1 inch		Pass #4		Pass #8		Pass #40		Pass #200
	PI		BLS		GC		SP		Predicted Performance
Objective	STDC-Spray		LTFP-Spray		LTFP-Mix-in		LTS-Mix-in		
Traffic	<100		100-250		>250				
Climate	Dry		Damp		Wet				
Plasticity Index (PI)	< 3		3 - 5		6 - 15		> 15		
Fines (% Passing #200)	< 5		5 - 10		11 - 20		21 - 30		> 30
Other input	>10% trucks		Steep grades		Sharp curves				
From Charts 3.1 – 3.4	Traffic	Climate	PI	Fines	Trucks	Grades	Curves	Perf. Score	Ranking
Water									
Water + surfactant									
Calcium chloride									
Magnesium chloride									
Sodium chloride brine									
Glycerin-based									
Lignosulfonate									
Molasses/sugar									
Plant oil									
Tall oil pitch rosin									
Asphalt emulsion									
Base oil									
Petroleum resin									
Synthetic fluid									
Synthetic fluid + binder									
Synthetic polymer									
Conc. liquid stabilizer									
Clay additive									
Selection	1		2		3		4		5
Checks (Chart 3.5)	Environmental		Safety Data		Soil Chemistry		Maintenance		Specifications

Form 3.1b: Chemical Treatment Selection Form (Metric Units)

Unpaved Road Chemical Treatment Selection (Metric Units)								Date:	
Road No./Name			Details						
Material properties	Pass 25mm		Pass 4.75		Pass 2.36		Pass 0.425		Pass 0.075
	PI		BLS		GC		SP		Predicted Performance
Objective	STDC-Spray		LTFP-Spray		LTFP-Mix-in		LTS-Mix-in		
Traffic	<100		100-250		>250				
Climate	Dry		Damp to Dry		Wet				
Plasticity Index (PI)	< 3		3 - 5		6 - 15		> 15		
Fines (% Passing 0.075)	< 5		5 - 10		11 - 20		21 - 30		> 30
Other input	>10% trucks		Steep grades		Sharp curves				
From Charts 3.1 – 3.4	Traffic	Climate	PI	Fines	Trucks	Grades	Curves	Perf. Score	Ranking
Water									
Water + surfactant									
Calcium chloride									
Magnesium chloride									
Sodium chloride brine									
Glycerin-based									
Lignosulfonate									
Molasses/sugar									
Plant oil									
Tall oil pitch rosin									
Asphalt emulsion									
Base oil									
Petroleum resin									
Synthetic fluid									
Synthetic fluid + binder									
Synthetic polymer									
Conc. liquid stabilizer									
Clay additive									
Selection	1		2		3		4		5
Checks (Chart 3.5)	Environmental		Safety Data		Soil Chemistry		Maintenance		Specifications

Chart 3.1: Selection Chart for Short-Term Dust Control (Spray-On)

Additive Category/ Sub-Category	Traffic: Average Daily Traffic <100	100-250[1]	>250[1]	Climate: Humidity/Storm Intensity Dry[2]	Damp	Wet[3,4,5]	Wearing Course Material: Plasticity Index <3[6]	3-5[6]	6-15	>15[5,7]	Fines (% Passing #200 [75 µm] Sieve) <5[1]	5-10[1]	11-20	21-30[7,8]	>30[5,7,8]
Water and Water plus Surfactant															
Water	7[1]	50	50	50	7	1	50	7	1	50	50	7	1	7	7
Water + surfactant	7[1]	50	50	50	7	1	50	7	1	50	50	7	1	7	7
Water absorbing															
Calcium chloride	1	1	7	50[9]	1	50[10]	7	1	1	50	50	7	1	7	50
Magnesium chloride	1	1	7	7[9]	1	50[10]	7	1	1	50	50	7	1	7	50
Sodium chloride brine	1	7	50	50[9]	7	50[10]	50	1	1	50	50	7	1	7	50
Organic Non-Petroleum															
Glycerin-based	1	7	50	1	1	50	7	1	1	50	50	7	1	7	50
Lignosulfonate	1	1	7	1	1	50	7	1	1	50	50	7	1	1	7
Molasses/sugar	1	50	50	1	1	50	50	1	1	50	50	50	1	7	50
Plant oil	1	7	50	1	1	50	7	1	1	50	50	7	1	1	50
Tall oil pitch rosin	1	7	50	1	1	7	7	1	1	50	50	7	1	1	50
Organic Petroleum															
Asphalt emulsion	1	7	50	1	1	1	7	1	7[8]	50	7	1	7	50	50
Base oil	1	7	7	1	1	7	7	1	1	50	50	7	1	1	50
Petroleum resin	1	7	50	1	1	7	7	1	1	50	7	7	1	7	50
Synthetic fluid	1	1	7	1	1	7	7	1	1	50	50	7	1	1	7
Synthetic fluid + binder	1	1	7	1	1	7	7	1	1	50	50	7	1	1	7
Synthetic Polymer Emulsion															
Synthetic polymer[11]	7	7	50	7	7	7	7	7	7	50	50	7	7	50	50
Conc. Liquid Stabilizer															
Conc. liquid stabilizer	Not suitable as a spray-on treatment for fines preservation/dust control														
Clay Additive															
Clay additive	Not suitable as a spray-on treatment for fines preservation/dust control														

Additive Category/ Sub-Category	% trucks >10[1]	Geometry: Steep Grades[4,5]	Sharp Curves[1,5]
Water	7	1	1
Water + surfactant	7	1	1
Calcium chloride	1	7	7
Magnesium chloride	1	7	7
Sodium chloride brine	1	7	7
Glycerin-based	1	7	7
Lignosulfonate	1	7	7
Molasses/sugar	7	7	7
Plant oil	7	7	7
Tall oil pitch rosin	1	7	7
Asphalt emulsion	50	1	7
Base oil	7	1	1
Petroleum resin	1	1	1
Synthetic fluid	1	1	1
Synthetic fluid + binder	1	1	1
Synthetic polymer	7	7	7
Conc. liquid stabilizer	Not suitable as a spray-on fines preservation treatment		
Clay additive	Not suitable as a spray-on fines preservation treatment		

Key to Colors and Explanation Notes in Selection Charts

Key	Meaning
1	No significant influence on performance
7	Some influence on performance
50	Significant influence on performance

1 Cars and trucks at higher speeds may break surface crust and accelerate washboarding and raveling, if so more frequent rejuvenation will be required
2 More than 20 days with less than 40% relative humidity
3 High intensity storms
4 Likely to leach out and/or down into lower layers during storm events
5 Soaked California Bearing Ratio (CBR) and abrasion resistance must be checked / increased with increasing number of trucks to ensure all-weather passability
6 Materials have little or no effective binder content and are prone to washboarding and raveling. Treatments may leach down into road structure
7 May become slippery when wet
8 High fines content may require higher application rates to be effective
9 Requires a minimum humidity level to perform effectively
10 May leach down into layer, but dry back of the material plus a light water spray / rejuvenation will return it to surface
11 Generally not suitable as a spray-on application. A "skin" can form on the surface which is damaged by traffic

Chart 3.2: Selection Chart for Long-Term Fines Preservation (Spray-On)

Additive Category/ Sub-Category	Traffic: Average Daily Traffic <100	100-250[1]	>250[1]	Climate: Humidity/Storm Intensity Dry[2]	Damp	Wet[3,4,5]	Wearing Course Material: Plasticity Index <3[6]	3-5[6]	6-15	>15[5,7]	Fines (% Passing #200 [75 µm] Sieve) <5[1]	5-10[1]	11-20	21-30[7,8]	>30[5,7,8]
Water and Water plus Surfactant															
Water	Not cost effective as a long-term fines preservation strategy														
Water + surfactant	Not cost effective as a long-term fines preservation strategy														
Water absorbing															
Calcium chloride	1	1	7	50[9]	1	50[10]	7	1	1	50	50	7	1	7	50
Magnesium chloride	1	1	7	7[9]	1	50[10]	7	1	1	50	50	7	1	7	50
Sodium chloride brine	1	7	50	50[9]	7	50[10]	50	1	1	50	50	7	1	7	50
Organic Non-Petroleum															
Glycerin-based	1	7	50	1	1	50	7	1	1	50	50	7	1	7	50
Lignosulfonate	1	1	7	1	1	50	7	1	1	50	50	7	1	1	7
Molasses/sugar	1	50	50	1	1	50	50	1	1	50	50	50	1	7	50
Plant oil	1	7	50	1	1	50	50	1	1	50	50	7	1	1	50
Tall oil pitch rosin	1	7	50	1	1	7	7	1	1	50	50	7	1	1	50
Organic Petroleum															
Asphalt emulsion	1	7	50	1	1	7	7	1	7[8]	50	7	1	7[7]	50	50
Base oil	1	7	7	1	1	7	7	1	1	50	50	7	1	1	50
Petroleum resin	1	7	50	1	1	7	7	1	1	50	7	7	1	7	50
Synthetic fluid	1	1	7	1	1	7	7	1	1	50	50	7	1	1	7
Synthetic fluid + binder	1	1	7	1	1	7	7	1	1	50	50	7	1	1	7
Synthetic Polymer Emulsion															
Synthetic polymer[11]	7	7	50	7	7	7	7	7	7	50	50	7	7	50	50
Conc. Liquid Stabilizer															
Conc. liquid stabilizer	Not suitable as a spray-on fines preservation/dust control treatment														
Clay Additive															
Clay additive	Not suitable as a spray-on fines preservation/dust control treatment														

Additive Category/ Sub-Category	% trucks >10[1]	Geometry: Steep Grades[4,5]	Sharp Curves[1,5]
Water	Not cost effective as a long-term fines preservation strategy		
Water + surfactant	Not cost effective as a long-term fines preservation strategy		
Calcium chloride	1	7	7
Magnesium chloride	1	7	7
Sodium chloride brine	1	7	7
Glycerin-based	1	7	7
Lignosulfonate	1	7	7
Molasses/sugar	7	7	7
Plant oil	7	7	7
Tall oil pitch rosin	1	7	7
Asphalt emulsion	50	1	7
Base oil	7	1	1
Petroleum resin	1	1	7
Synthetic fluid	1	1	1
Synthetic fluid + binder	1	1	1
Synthetic polymer	7	7	7
Conc. liquid stabilizer	Not suitable as a spray-on fines preservation treatment		
Clay additive	Not suitable as a spray-on fines preservation treatment		

Key to Colors and Explanation Notes in Selection Charts

1	No significant influence on performance
7	Some influence on performance
50	Significant influence on performance

1. Cars and trucks at higher speeds may break surface crust and accelerate washboarding and raveling, if so more frequent rejuvenation will be required
2. More than 20 days with less than 40% relative humidity
3. High intensity storms
4. Likely to leach out and/or down into lower layers during storm events
5. Soaked California Bearing Ratio (CBR) and abrasion resistance must be checked / increased with increasing number of trucks to ensure all-weather passability
6. Materials have little or no effective binder content and are prone to washboarding and raveling. Treatments may leach down into road structure
7. May become slippery when wet
8. High fines content may require higher application rates to be effective
9. Requires a minimum humidity level to perform effectively
10. May leach down into layer, but dry back of the material plus a light water spray / rejuvenation will return it to surface
11. Generally not suitable as a spray-on application. A "skin" can form on the surface which is damaged by traffic

Chart 3.3: Selection Chart for Long-Term Fines Preservation (Mix-In)

Additive Category/ Sub-Category	Traffic: Average Daily Traffic <100	100-250[1]	>250[1]	Climate: Humidity/Storm Intensity Dry[2]	Damp	Wet[3,4,5]	Wearing Course Material: Plasticity Index <3[6]	3-5[6]	6-15	>15[5,7]	Fines (% Passing #200 [75 µm] Sieve) <5[1]	5-10[1]	11-20	21-30[7,8]	>30[5,7,8]
Water and Water plus Surfactant															
Water	Not cost effective as a long-term fines preservation strategy														
Water + surfactant	Not cost effective as a long-term fines preservation strategy														
Water absorbing															
Calcium chloride	1	1	7	50[9]	1	50	7	1	1	50	50	7	1	7	50
Magnesium chloride	1	1	7	7[9]	1	50	7	1	1	50	50	7	1	7	50
Sodium chloride brine	1	7	50	50[9]	7	50	50	1	1	50	50	7	1	7	50
Organic Non-Petroleum															
Glycerin-based	1	1	50	1	1	50	7	1	1	50	50	7	1	7	50
Lignosulfonate	1	1	7	1	1	50	7	1	1	50	50	7	1	1	7
Molasses/sugar	1	50	50	1	1	50	50	1	1	50	50	50	1	7	50
Plant oil	1	7	50	1	1	50	50	1	1	50	50	7	1	1	50
Tall oil pitch rosin	1	7	50	1	1	7	7	1	1	50	50	7	1	1	50
Organic Petroleum															
Asphalt emulsion	1	7	50	1	1	1	7	1	7[8]	50	7	1	1	50	50
Base oil	1	1	7	1	1	7	7	1	1	50	50	7	1	1	7
Petroleum resin	1	1	50	1	1	7	7	1	1	50	7	7	1	7	50
Synthetic fluid	1	1	7	1	1	7	7	1	1	50	50	7	1	1	7
Synthetic fluid + binder	1	1	7	1	1	7	7	1	1	50	7	1	1	1	7
Synthetic Polymer Emulsion															
Synthetic polymer	1	1	50	1	1	7	7	1	1	50	50	1	1	7	50
Conc. Liquid Stabilizer															
Conc. liquid stabilizer	7	50	50	7	7	7	50	50	50	7	50	50	7	7	7
Clay Additive															
Clay additive	1	1	7	1	1	7	1	7	50	50	1	1	7	50	50

Additive Category/ Sub-Category	% trucks >10[1]	Geometry: Steep Grades[4,5]	Sharp Curves[1,5]
Water	Not cost effective as a long-term fines preservation strategy		
Water + surfactant	Not cost effective as a long-term fines preservation strategy		
Calcium chloride	1	7	7
Magnesium chloride	1	7	7
Sodium chloride brine	1	7	7
Glycerin-based	1	7	7
Lignosulfonate	1	7	7
Molasses/sugar	7	7	7
Plant oil	7	7	7
Tall oil pitch rosin	1	7	7
Asphalt emulsion	7	1	7
Base oil	1	1	1
Petroleum resin	1	1	7
Synthetic fluid	1	1	1
Synthetic fluid + binder	1	1	1
Synthetic polymer	7	7	7
Conc. liquid stabilizer	1	1	1
Clay additive	7	7	1

Key to Colors and Explanation Notes in Selection Charts

1	No significant influence on performance
7	Some influence on performance
50	Significant influence on performance

1 Cars and trucks at higher speeds may break surface crust and accelerate washboarding and raveling, if so more frequent rejuvenation will be required
2 More than 20 days with less than 40% relative humidity
3 High intensity storms
4 Likely to leach out and/or down into lower layers during storm events
5 Soaked California Bearing Ratio (CBR) and abrasion resistance must be checked / increased with increasing number of trucks to ensure all-weather passability
6 Materials have little or no effective binder content and are prone to washboarding and raveling. Treatments may leach down into road structure
7 May become slippery when wet
8 High fines content may require higher application rates to be effective
9 Requires a minimum humidity level to perform effectively

Chart 3.4: Selection Chart for Long-Term Stabilization (Mix-In)

Additive Category/ Sub-Category	Traffic: Average Daily Traffic <100	100-250[1]	>250[1]	Climate: Humidity/Storm Intensity Dry[2]	Damp	Wet[3,4,5]	Wearing Course Material: Plasticity Index <3[6]	3-5[6]	6-15[5,7]	>15[5,7]	Fines (% Passing #200 [75 µm] Sieve) <5[1]	5-10[1]	11-20	21-30[5,7,8]	>30[5,7,8]
Water and Water plus Surfactant															
Water	Not suitable as a mix-in treatment for stabilization														
Water + surfactant	Not suitable as a mix-in treatment for stabilization														
Water absorbing															
Calcium chloride	7	7	50	50[9]	1	50	7	7	7	50	50	7	7	7	50
Magnesium chloride	7	7	50	7[9]	1	50	7	7	7	50	50	7	7	7	50
Sodium chloride brine	7	7	50	50[9]	7	50	50[1]	7	7	50	50	7	7	7	50
Glycerin-based	Not suitable as a mix-in treatment for stabilization														
Lignosulfonate	7	50	50	1	1	50[7]	7	7	7	50	50	7	7	7	50
Molasses/sugar	Not suitable as a mix-in treatment for stabilization														
Plant oil	Not suitable as a mix-in treatment for stabilization														
Tall oil pitch rosin	7	50	50	1	1	7[7]	7	7	7	50	50	7	7	7	50
Organic Petroleum															
Asphalt emulsion	1	7	50	1	1	7	7	1	7	50	7	1	7	50	50
Base oil	Not suitable as a mix-in treatment for stabilization														
Petroleum resin	1	7	50	1	1	7	7	1	1	50	7	7[1]	1	7	50
Synthetic fluid	Not suitable as a mix-in treatment for stabilization														
Synthetic fluid + binder	1	7	7	1	1	7	7	1	1	7	7	1	1	7	50
Synthetic Polymer Emulsion															
Synthetic polymer	1	7	50	1	1	7	7	1	1	50	50	1	1	7	50
Conc. Liquid Stabilizer															
Conc. liquid stabilizer	1	7	50	1	1	7	50	50	7	1	50	50	7	1	1
Clay Additive															
Clay additive	1	1	7	1	1	7	1	7	50	50	1	7	50	50	50

Additive Category/ Sub-Category	% trucks >10[1]	Geometry: Steep Grades[4,5]	Sharp Curves[1,5]
Water	Not appropriate for stabilization		
Water + surfactant	Not appropriate for stabilization		
Calcium chloride	7	7	7
Magnesium chloride	7	7	7
Sodium chloride brine	7	7	7
Glycerin-based	Not suitable as a mix-in treatment for stabilization		
Lignosulfonate	1	7	7
Molasses/sugar	Not suitable as a mix-in treatment for stabilization		
Plant oil	Not suitable as a mix-in treatment for stabilization		
Tall oil pitch rosin	7	7	7
Asphalt emulsion	7	1	7
Base oil	Not suitable as a mix-in treatment for stabilization		
Petroleum resin	7	1	7
Synthetic fluid	Not suitable as a mix-in treatment for stabilization		
Synthetic fluid + binder	1	1	1
Synthetic polymer	7	7	7
Conc. liquid stabilizer	1	1	1
Clay additive	7	7	1

Key to Colors and Explanation Notes in Selection Charts

1	No significant influence on performance
7	Some influence on performance
50	Significant influence on performance

1 Cars and trucks at higher speeds may break surface crust and accelerate washboarding and raveling, if so more frequent rejuvenation will be required
2 More than 20 days with less than 40% relative humidity
3 High intensity storms
4 Likely to leach out and/or down into lower layers during storm events
5 Soaked California Bearing Ratio (CBR) and abrasion resistance must be checked / increased with increasing number of trucks to ensure all-weather passability
6 Materials have little or no effective binder content and are prone to washboarding and raveling. Treatments may leach down into road structure
7 May become slippery when wet
8 High fines content may require higher application rates to be effective
9 Requires a minimum humidity level to perform effectively

Chart 3.5: Treatment Selection Considerations

Additive Sub-Category	Leaching Stability	Aquatic Impacts	Plant Impacts	Mammal/Human Impacts	Soil Chemistry	Grader Maintainability
Water	Stable	No impact[1]	No impact	No impact	No effect	Yes
Water/surfactant	Stable	No impact[1]	No impact	No impact	No effect	Yes
Calcium chloride	Leaches down[2,3]	Potential impact[5]	Potential impact[7]	Potential impact[8]	Check[9]	Yes[12]
Magnesium chloride	Leaches down[2,3]	Potential impact[5]	Potential impact[7]	Potential impact[8]	Check[9]	Yes[12]
Sodium chloride brine	Leaches down/out[2]	Potential impact[5]	Potential impact[7]	Potential impact[8]	Check[9]	Yes[12]
Glycerin-based	Leaches down/out[2]	Potential impact[6]	No impact	Potential impact[8]	No effect	Yes[12]
Lignosulfonate	Leaches down/out[2]	Potential impact[6]	No impact	No impact	No effect	Yes[12]
Molasses/sugar	Leaches down/out[2]	Potential impact[6]	No impact	Potential impact[8]	No effect	Yes[12]
Plant oil	Leaches down/out[2]	Potential impact[6]	No impact	No impact	No effect	Yes[13]
Tall oil pitch rosin	Stable	No impact	No impact	No impact	No effect	Yes[12]
Asphalt emulsion	Stable	No impact	No impact	No impact	Check[10]	No[14]
Base oil	Leaches down[4]	No impact	No impact	No impact	No effect	Yes
Petroleum resin	Stable	No impact	No impact	No impact	No effect	Yes[13]
Synthetic fluid	Leaches down[4]	No impact	No impact	No impact	No effect	Yes
Synthetic fluid + binder	Stable	No impact	No impact	No impact	No effect	Yes[15]
Synthetic polymer	Stable	No impact	No impact	No impact	No effect	No[14]
Conc. liquid stabilizers	Stable	No impact	No impact	No impact	Check[11]	Yes
Clay additive	Stable	No impact	No impact	No impact	No effect	Yes[12]

1 Regular water spraying uses large quantities of water which can impact water reserves in dry areas.
2 Likely to leach out/and or down into lower layers during storm events.
3 May leach down into layer. Dry back of gravel plus light water spray/rejuvenation will return it to surface.
4 Migrates to lower levels in pavement with water movement.
5 May raise chloride levels in nearby streams and groundwater.
6 May affect aquatic life due to high biological oxygen demand.
7 Chloride levels may affect chloride intolerant roadside vegetation.
8 May attract animals and/or insects to roadway.
9 In rare instances, can react with some elements in the soil if abundant to form non-hygroscopic compounds.
10 Choice of anionic or cationic emulsion may influence performance.
11 Requires clay minerals (usually expansive) to react with.
12 Grader maintenance is possible provided that road surface is watered prior to blading to soften crust.
13 Same as 4, but treatment will need to be reapplied after maintenance.
14 Grader maintenance will cause permanent damage to crust. Treatment will need to be reapplied.
15 Dependent on binder.

Form 3.2: Example Completed Selection Form (Example 1, Good Material)

Unpaved Road Chemical Treatment Selection (US Units)

Unpaved Road Chemical Treatment Selection (US Units)							Date:		07/25/2013	
Road No./Name	CR15B		Details	Mile post 10.0 to 20.0						
Material properties	Pass 1 inch	100	Pass #4	61	Pass #8	46	Pass #40	25	Pass #200	16
	PI	10	BLS	5	GC	33	SP	125	Predicted Performance	
Objective	STDC-Spray		LTFP-Spray	X	LTFP-Mix-in		LTS-Mix-in		Good, tending to	
Traffic	<100		100-250	X	>250				a little raveling	
Climate	Dry		Damp	X	Wet					
Plasticity Index (PI)	< 3		3 - 5		6 - 15	X	> 15			
Fines (% Passing #200)	< 5		5 - 10		11 - 20	X	21 - 30		> 30	
Other input	>10% trucks		Steep grades		Sharp curves					

From Charts 3.1 – 3.4	Traffic	Climate	PI	Fines	Trucks	Grades	Curves	Perf. Score	Ranking
Water	50	50	50	50	-	-	-	200	NA
Water + surfactant	50	50	50	50	-	-	-	200	NA
Calcium chloride	1	1	1	1	-	-	-	4	1
Magnesium chloride	1	1	1	1	-	-	-	4	1
Sodium chloride brine	1	7	1	1	-	-	-	10	12
Glycerin-based	1	1	1	1	-	-	-	4	1
Lignosulfonate	1	1	1	1	-	-	-	4	1
Molasses/sugar	1	1	1	1	-	-	-	4	1
Plant oil	1	1	1	1	-	-	-	4	1
Tall oil pitch rosin	1	1	1	1	-	-	-	4	1
Asphalt emulsion	1	1	7	7	-	-	-	16	13
Base oil	1	1	1	1	-	-	-	4	1
Petroleum resin	1	1	1	1	-	-	-	4	1
Synthetic fluid	1	1	1	1	-	-	-	4	1
Synthetic fluid + binder	1	1	1	1	-	-	-	4	1
Synthetic polymer	1	1	7	7	-	-	-	16	13
Conc. liquid stabilizer	50	50	50	50	-	-	-	200	NA
Clay additive	50	50	50	50	-	-	-	200	NA

Selection	1 Ca or Mg Chloride		2 Any organic NP		3 Pet res/Base oil		4 Synthetic fluid		5 Syn fluid + Bind	
Checks (Chart 3.5)	Environmental	Y	Safety Data	Y	Soil Chemistry	Y	Maintenance	Y	Specifications	Y

Form 3.3: Example Completed Selection Form (Example 1, Marginal Material)

Unpaved Road Chemical Treatment Selection (US Units)								Date:	07/25/2013	
Road No./Name	CR15B		Details	Mile post 10.0 to 20.0						
Material properties	Pass 1 inch	100	Pass #4	61	Pass #8	46	Pass #40	25	Pass #200	16
	PI	0	BLS	0	GC	33	SP	0	Predicted Performance	
Objective	STDC-Spray		LTFP-Spray	X	LTFP-Mix-in		LTS-Mix-in		Prone to washboard	
Traffic	<100	X	100-250		>250				and raveling.	
Climate	Dry		Damp	X	Wet				Needs clay	
Plasticity Index (PI)	< 3	X	3 - 5		6 - 15		> 15			
Fines (% Passing #200)	< 5		5 - 10		11 - 20	X	21 - 30		> 30	
Other input	>10% trucks		Steep grades		Sharp curves					

From Chars 3.1 – 3.4	Traffic	Climate	PI	Fines	Trucks	Grades	Curves	Perf. Score	Ranking
Water	50	50	50	50	-	-	-	200	NA
Water + surfactant	50	50	50	50	-	-	-	200	NA
Calcium chloride	1	1	7	1	-	-	-	10	1
Magnesium chloride	1	1	7	1	-	-	-	10	1
Sodium chloride brine	1	7	50	1	-	-	-	59	14
Glycerin-based	1	1	7	1	-	-	-	10	1
Lignosulfonate	1	1	7	1	-	-	-	10	1
Molasses/sugar	1	1	50	1	-	-	-	53	12
Plant oil	1	1	50	1	-	-	-	53	12
Tall oil pitch rosin	1	1	7	1	-	-	-	10	1
Asphalt emulsion	1	1	7	7	-	-	-	16	10
Base oil	1	1	7	1	-	-	-	10	1
Petroleum resin	1	1	7	1	-	-	-	10	1
Synthetic fluid	1	1	7	1	-	-	-	10	1
Synthetic fluid + binder	1	1	7	1	-	-	-	10	1
Synthetic polymer	1	1	7	7	-	-	-	16	10
Conc. liquid stabilizer	50	50	50	50	-	-	-	200	NA
Clay additive	50	50	50	50	-	-	-	200	NA

Selection	1 Ca or Mg Chloride		2 Glyc/Lign/Tall oil		3 Petroleum resin		4 Base oil/ Syn flu		5 Syn Flu + Bind	
Checks (Chart 3.5)	Environmental	Y	Safety Data	Y	Soil Chemistry	Y	Maintenance	Y	Specifications	Y

Form 3.4: Example Completed Selection Form (Example 2, Good Material)

Unpaved Road Chemical Treatment Selection (US Units)

Date: 07/25/2013

Road No./Name	CR15B		Details	Mile post 10.0 to 20.0					
Material properties	Pass 1 inch	100	Pass #4	61	Pass #8	46	Pass #40	25	Pass #200 16
	PI	10	BLS	5	GC	33	SP	125	Predicted Performance
Objective	STDC-Spray		LTFP-Spray		LTFP-Mix-in	X	LTS-Mix-in		Good, tending to a little raveling
Traffic	<100		100-250	X	>250				
Climate	Dry		Damp	X	Wet				
Plasticity Index (PI)	< 3		3 - 5		6 - 15	X	> 15		
Fines (% Passing #200)	< 5		5 - 10		11 - 20	X	21 - 30		> 30
Other input	>10% trucks	X	Steep grades		Sharp curves				

From Charts 3.1 – 3.4	Traffic	Climate	PI	Fines	Trucks	Grades	Curves	Perf. Score	Ranking
Water	50	50	50	50	50	-	-	250	NA
Water + surfactant	50	50	50	50	50	-	-	250	NA
Calcium chloride	1	1	1	1	1	-	-	5	1
Magnesium chloride	1	1	1	1	1	-	-	5	1
Sodium chloride brine	7	7	1	1	1	-	-	17	11
Glycerin-based	1	1	1	1	1	-	-	5	1
Lignosulfonate	1	1	1	1	1	-	-	5	1
Molasses/sugar	50	1	1	1	7	-	-	60	14
Plant oil	7	1	1	1	7	-	-	17	11
Tall oil pitch rosin	7	1	1	1	1	-	-	11	9
Asphalt emulsion	7	1	7	1	7	-	-	23	13
Base oil	1	1	1	1	1	-	-	5	1
Petroleum resin	1	1	1	1	1	-	-	5	1
Synthetic fluid	1	1	1	1	1	-	-	5	1
Synthetic fluid + binder	1	1	1	1	1	-	-	5	1
Synthetic polymer	1	1	1	1	7	-	-	11	9
Conc. liquid stabilizer	50	7	50	7	1	-	-	115	16
Clay additive	1	1	50	7	7	-	-	66	15

Selection	1 Ca or Mg Chloride		2 Glycerin/Ligno		3 Petroleum resin		4 Base oil		5 Synthetic Fluid	
Checks (Chart 3.5)	Environmental	Y	Safety Data	Y	Soil Chemistry	Y	Maintenance	Y	Specifications	Y

Form 3.5: Example Completed Selection Form (Example 2, Marginal Material)

Unpaved Road Chemical Treatment Selection (US Units)								Date:	07/25/2013	
Road No./Name	CR15B		Details	Mile post 10.0 to 20.0						
Material properties	Pass 1 inch	100	Pass #4	61	Pass #8	46	Pass #40	25	Pass #200	16
	PI	0	BLS	0	GC	33	SP	0	Predicted Performance	
Objective	STDC-Spray		LTFP-Spray		LTFP-Mix-in	X	LTS-Mix-in		Prone to washboard	
Traffic	<100		100-250	X	>250				and raveling.	
Climate	Dry		Damp	X	Wet				Needs clay	
Plasticity Index (PI)	< 3	X	3 - 5		6 - 15		> 15			
Fines (% Passing #200)	< 5		5 - 10		11 - 20	X	21 - 30		> 30	
Other input	>10% trucks	X	Steep grades		Sharp curves					
From Chars 3.1 – 3.4	Traffic	Climate	PI	Fines	Trucks	Grades	Curves	Perf. Score	Ranking	
Water	50	50	50	50	50	-	-	250	NA	
Water + surfactant	50	50	50	50	50	-	-	250	NA	
Calcium chloride	1	1	7	1	1	-	-	11	1	
Magnesium chloride	1	1	7	1	1	-	-	11	1	
Sodium chloride brine	7	7	50	1	1	-	-	66	13	
Glycerin-based	1	1	7	1	1	-	-	11	1	
Lignosulfonate	1	1	7	1	1	-	-	11	1	
Molasses/sugar	50	1	50	1	7	-	-	109	15	
Plant oil	7	1	50	1	7	-	-	66	13	
Tall oil pitch rosin	7	1	7	1	1	-	-	17	9	
Asphalt emulsion	7	1	1	1	7	-	-	17	9	
Base oil	1	1	7	1	1	-	-	11	1	
Petroleum resin	1	1	7	1	1	-	-	11	1	
Synthetic fluid	1	1	7	1	1	-	-	11	1	
Synthetic fluid + binder	1	1	7	1	1	-	-	11	1	
Synthetic polymer	1	1	7	1	7	-	-	17	9	
Conc. liquid stabilizer	50	7	50	7	1	-	-	115	16	
Clay additive	1	1	1	7	7	-	-	17	9	
Selection	1 Ca or Mg Chloride		2 Glycerin/Ligno		3 Petroleum resin		4 Base oil		5 Synthetic Fluid	
Checks (Chart 3.5)	Environmental	Y	Safety Data	Y	Soil Chemistry	Y	Maintenance	Y	Specifications	Y

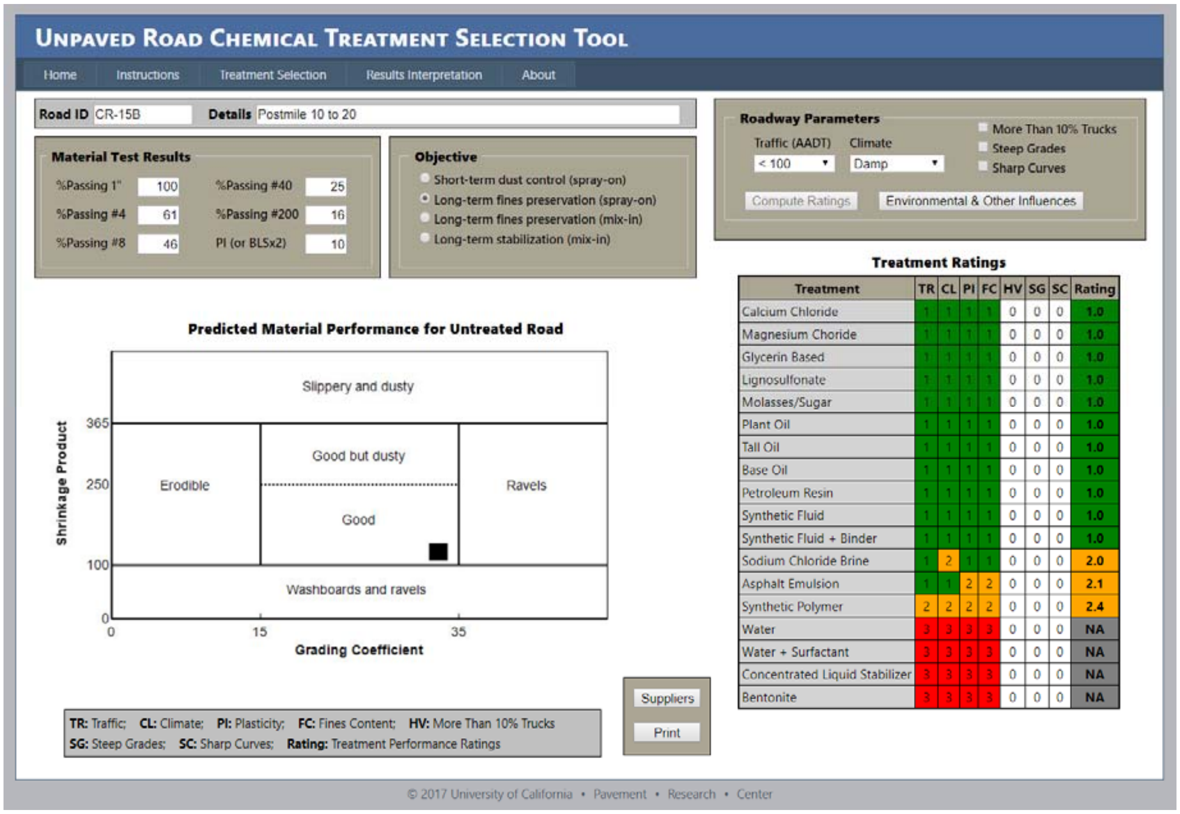


Figure 3.4: Screenshot of web-based selection tool output for Example 1 with good material.

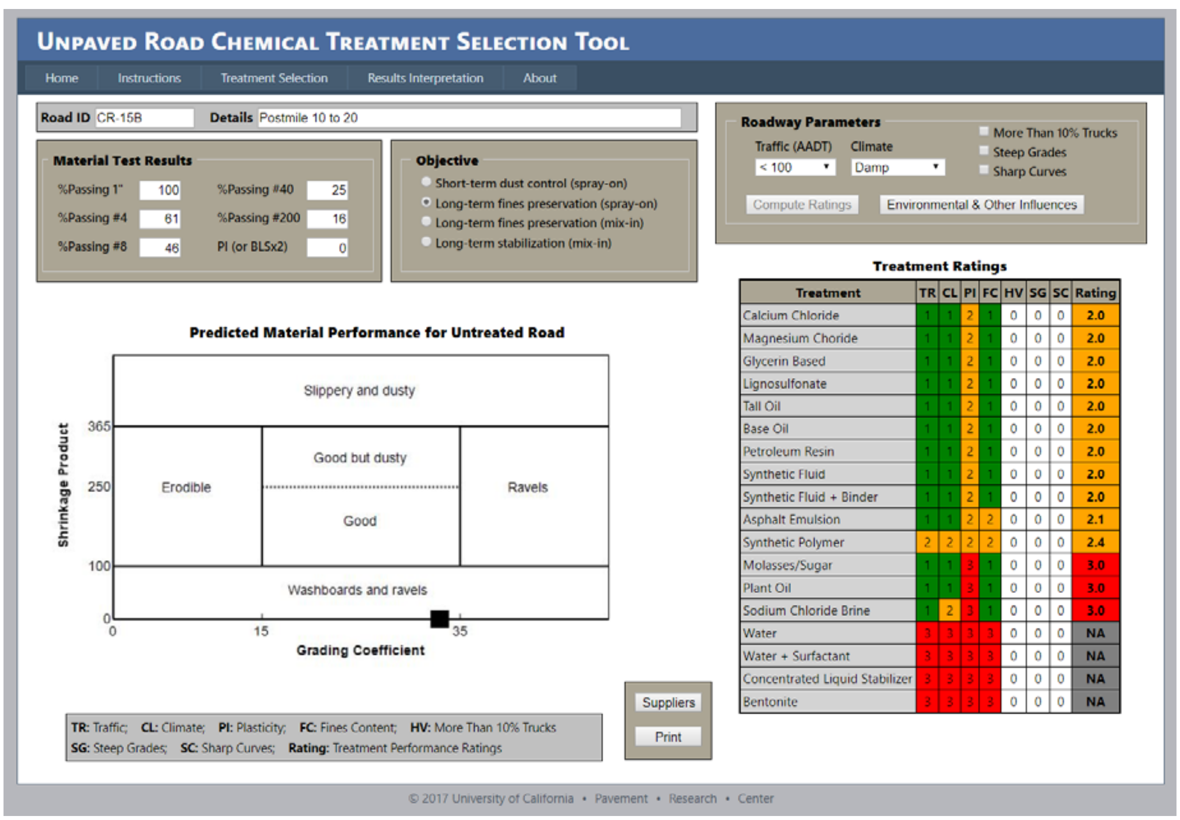


Figure 3.5: Screenshot of web-based selection tool output for Example 1 with marginal material.

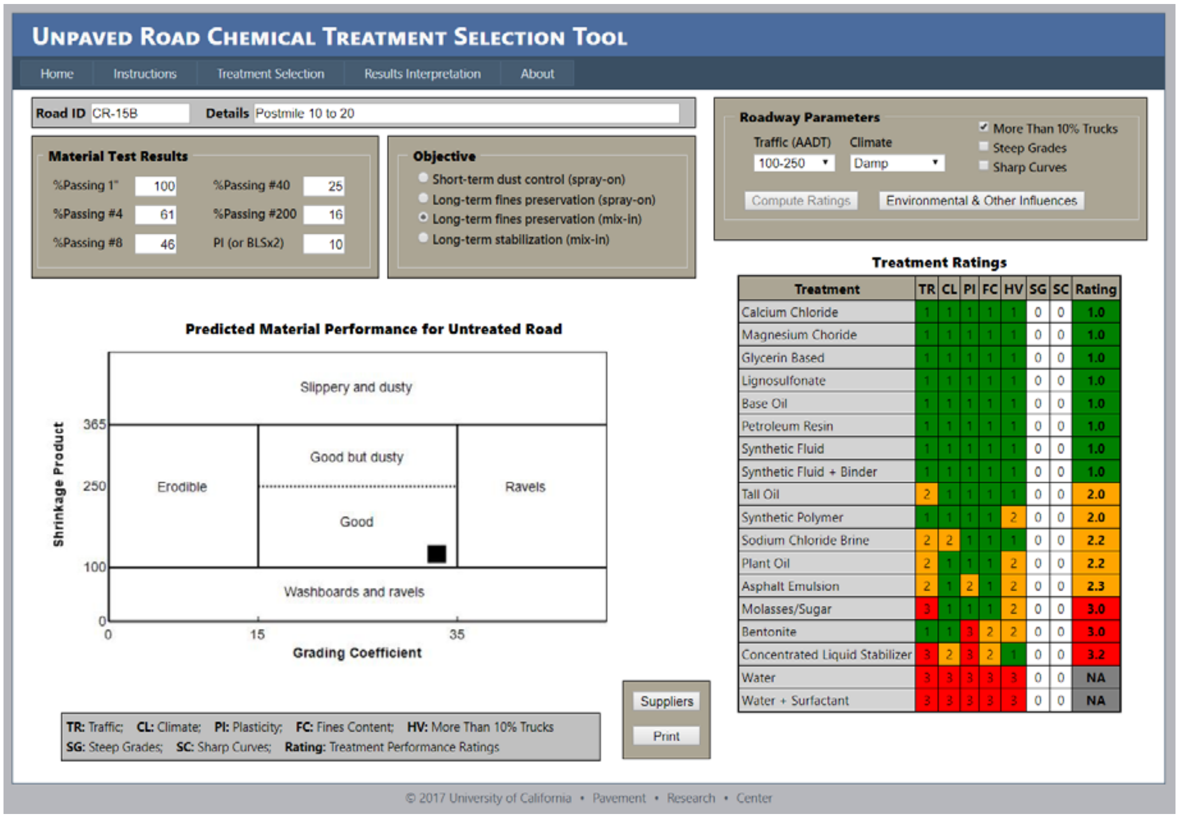


Figure 3.6: Screenshot of web-based selection tool output for Example 2 with good material.

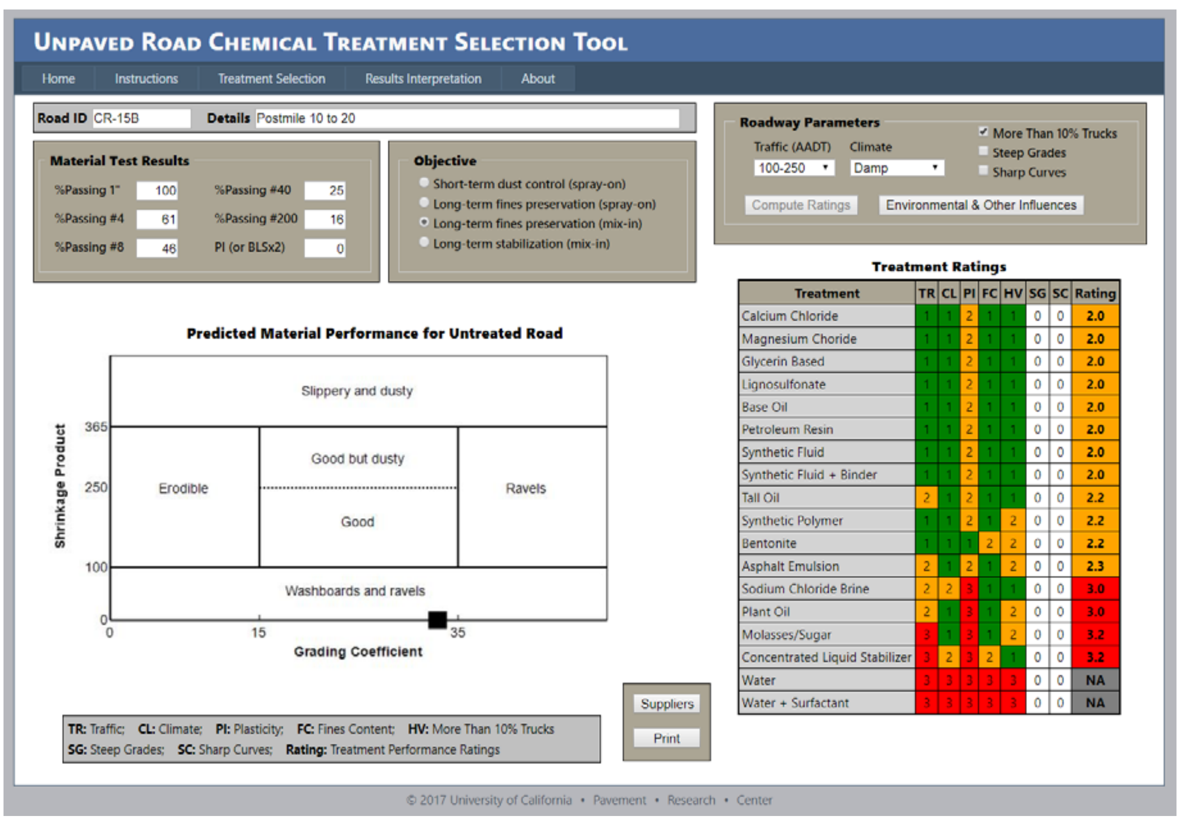


Figure 3.7: Screenshot of web-based selection tool output for Example 2 with marginal material.

Blank page

4. PROCURING AND SPECIFYING CHEMICAL TREATMENTS

4.1 Introduction

The requirements for specifying and procuring chemical treatments differ among various road agencies and road owners. Some agencies must use an open bidding system for construction contracts (e.g., regravelling and chemical treatment application) and cannot specify proprietary product names. Other agencies might have preferred products lists or preferred suppliers from whom chemical treatments can be sourced without having to revert to a bidding process. Product manufacturers/distributors need to meet specific requirements to be included on these lists. Other agencies and private road owners might not have these limitations. Given these differences, it is clear that a single specification and procurement procedure will not meet every agency's requirements. Instead, a number of considerations are discussed below to assist agencies and practitioners in making informed decisions about procuring and specifying chemical treatments. In addition to establishing good working relationships with responsible manufacturers and distributors, these considerations include:

- Following formalized procurement procedures
- Using lists of qualified products
- Compiling chemical treatment category specifications, construction and treatment application specifications, environmental and safety specifications, and project design specifications
- Using other approaches for overcoming the lack of formal product specifications
- Reviews of safety data sheets

Regardless of the process followed, practitioners are encouraged to mandate that manufacturers/distributors provide the following:

- A certificate of compliance stating that the supplied product meets a minimum category specification (see Section 4.4) and that the chemical formulation is safe for living organisms (humans, animals, birds, reptiles, invertebrates, and plants, etc.) (see Section 4.5).
- A comprehensive safety data sheet (SDS, previously known as material safety data sheet [MSDS]).
- Mix design test results, if the objective of the treatment is long-term stabilization, showing that the required minimum strength (e.g., CBR) can be achieved at the proposed application rate (see Section 3.4). A formal test method for mix design for long-term fines preservation is currently under development and once it is available, the results of this testing should also be required (see *www.ucprc.ucdavis.edu/ccpic* for updates on unpaved road chemical treatment test methods).

4.2 Formalized Procurement Procedures

Most road agencies and even many private companies have formalized procurement procedures that must be adhered to when purchasing items and services such as chemical treatments for unpaved roads. Since these procedures are agency/company specific, they are not discussed in this guideline. However, where appropriate, practitioners may wish to supplement or revise these procurement procedures based on the information provided in this guideline.

4.3 Lists of Qualified Products

Federal agencies can select chemical treatments for unpaved roads from a number of lists of qualified products managed by the Federal General Services Administration (GSA), the US Department of Agriculture (USDA), and the Environmental Protection Agency (EPA), which are detailed below. A number of states and many counties also maintain lists of approved unpaved road chemical treatments, primarily as part of air resource board initiatives to reduce air pollution (e.g., California EPA Air Resource Board [CARB] *Equipment and Process Precertification Program*).

- USDA *BioPreferred* Program *(www.biopreferred.gov/biopreferred).* This list certifies that products contain at least 85 percent bio-based materials as defined by the program. Dust suppressants are categorized under *Minor Construction*, which, at the time of writing this guide, had 33 federally procured products listed, although not all are intended for use on unpaved roads. Of the 33 products, only one unpaved road chemical treatment had a *BioPreferred* label. Federal law, the Federal Acquisition Regulation, and Presidential Executive Order, mandates that *BioPreferred* products be considered where appropriate.
- Federal General Services Administration (GSA) eLibrary *(www.gsa.gov).* Unpaved road chemical treatments are listed in the *Food Service, Hospitality, Cleaning Equipment and Supplies, Chemicals and Services* source category (Source Category #73) in the *Road Stabilization/Ice Melting Chemicals or Chemical Formulations* subcategory (Category 681 1). This subcategory includes chemicals defined as "*commercial non-hazardous chemicals/formulations designed primarily for road stabilization or to safely melt/remove ice from roadways, walkways, runways, and roofs with minimal negative environmental impact.*" At the time of writing this guide, 21 different chemical treatments from 10 different suppliers were listed in Category 681 1.
- Environmental Protection Agency's *Environmental Technology Verification (ETV) Program.* Unpaved road chemical treatments are listed under the *Air Pollution Control Technology Center* in the *Dust Suppression and Soil Stabilization Products* category. Support for this program ended in 2013 and the website is no longer maintained. Five products were listed.
- California EPA ARB *Equipment and Process Precertification Program (www.arb.ca.gov/eqpr).* Unpaved road chemical treatments for dust suppression are listed under *Precertified Equipment*. Two products were listed at the time of writing of this guide.
- The Center for Dirt and Gravel Roads at the Pennsylvania State University maintains an approved products list primarily for the state of Pennsylvania *(www.dirtandgravel.psu.edu/pa_program/products).* The approval process focuses on environmental impacts, but also considers performance. Twelve unpaved road chemical treatments were listed at the time of writing this guide.

The following factors should be considered when using lists of qualified products:

- A limited number of chemical treatments are documented on these lists and the lists may not be regularly updated.

- Some manufacturers who offer a range of products may not have all of their product offerings on the qualified products lists.
- Inclusion of a product on any list does not guarantee that the treatment will work under all conditions or that it meets the minimum environmental requirements listed later in this section.
- Material testing and project design are still required to identify the most suitable treatment and application rate for a specific situation.
- The absence of the product name from a qualified products list does not imply that a specific product is not "approved" for use on unpaved roads, only that alternative procurement procedures will need to be followed to acquire it.

4.4 Unpaved Road Chemical Treatment Category Specifications

The development of unpaved road chemical treatment category and subcategory specifications is extremely difficult and complex given the extensive range of treatments that are currently available, the different chemical composition of these treatments, and the proprietary nature and associated secrecy of product formulations.

4.4.1 Currently Available Treatment Specifications

Calcium chloride and asphalt emulsion are the only unpaved road chemical treatments that have formal AASHTO and ASTM specifications. Although they have not been formalized by AASHTO or ASTM, specifications for magnesium chloride products are also readily available due to its widespread use for both unpaved road fines preservation/dust control and paved road winter maintenance.

The Federal Highway Administration (FHWA) has published specifications for unpaved road chemical treatments (part of *Standard Specifications for the Construction of Roads and Bridges on Federal Highway Projects [FP] [18]*) that prospective suppliers must meet when selling their products to federal road agencies. Section 725.02 refers to AASHTO specifications for calcium chloride liquid and flake (AASHTO M 144), and lists limited specifications for magnesium chloride (percent magnesium chloride by mass, percent water by mass, and specific gravity). Section 725.20 lists limited specifications for lignosulfonate liquid (percent solids, specific gravity, and pH).

Many other road agencies use the FHWA specification as a basis for theirs, with adaptations to suit specific requirements (e.g., in Arizona, the Maricopa Association of Governments has issued *Uniform Standard Specifications for Public Works Construction [22];* its Section 792 refers to dust suppressants and lists generic specifications for acrylic copolymer and polymer, lignin-based, organic resinous, petroleum resinous, and tall oil pitch emulsion dust suppressants).

4.4.2 Suggested Category Specifications

Appendix D of this guide provides example suggested specification language for supplementing or compiling agency specifications for purchasing unpaved road chemical treatments and/or contracting their application. This language is more detailed than that found in the federal and county documents discussed above and the content, level of detail, language, style, and format may need to be changed to suit specific agency requirements. A list of suggested minimum specifications for each subcategory of unpaved road chemical treatment is provided in Section D.11 of that appendix. These can be used as a guide for preparing project specifications, purchase orders, or bid documents based on the desire to use specific treatment categories or subcategories.

4.4.3 Certificate of Compliance

Chemical treatment manufacturers/distributors and/or contractors should be able to provide a certificate of compliance, which shows that their product meets the category/subcategory specifications discussed in Section 4.4.2. Providing this certificate should be a requirement of the project specification documentation. There is no standard content for this certificate; however, the following is proposed:

- Confirmation that the chemical treatment supplied conforms to the category/subcategory requirements specified (example provided in Appendix D, Section D.11). Require a copy of the test results to be included as an attachment to the certificate.
- Confirmation that the chemical treatment complies with the safety data sheet. Require a copy of the safety data sheet to be included as an attachment to the certificate and stipulate that the safety data sheet list all chemical compounds present in the undiluted product in concentrations greater than one percent.
- Confirmation that the chemical treatment complies with the specified environmental requirements (see Section 4.5 below and the example in Appendix D, Section D.12). Require a copy of the environmental testing results to be included as an attachment to the certificate. Note that the products that appear on the qualified product lists discussed above may not necessarily meet these suggested environmental requirements.

Testing should be specific to the proposed chemical treatment or blend of chemical treatments and not generic to similar products from the same or different categories. Testing should be performed by independent AASHTO/ASTM and/or EPA-accredited laboratories. Justifications for not conforming to any of the category/subcategory or environmental requirements, along with potential implications if applicable, should be provided to the agency/road owner in writing.

4.5 Environmental and Safety Specifications

The same issues that complicate the development of category specifications for unpaved road chemical treatments (a wide range of product types, variable chemical compositions, and the proprietary nature of some formulations) also complicate the development of environmental specifications. Site-specific conditions also play a critical role in determining the potential adverse impacts of chemical treatments. Environmental concerns will vary depending on the proximity of the road to streams or wetlands, the depth of the water table, and the presence of potentially sensitive plant and animal species, among many other influences. Therefore, the information provided below and in Appendix D is offered as general guidance for the development of site- or regionally-specific specifications.

4.5.1 Environmental Specifications

At a minimum, chemical treatments intended for use on unpaved roads must not be classified as exhibiting the characteristic of toxicity (one of the categories of hazardous waste identification) as defined by the US EPA for the Resource Conservation and Recovery Act (RCRA). The *Synthetic Precipitation Leaching Procedure* (SPLP; US EPA Method 1312), which simulates leachates from materials exposed on the surface to rainfall, is considered the most appropriate for testing unpaved road chemical treatments. (Note that although the *Toxicity Characteristic Leaching Procedure* [TCLP; US EPA Method 1311] is the most common procedure used in formal hazardous material determinations, it simulates leachates from materials buried in landfills and is therefore not considered appropriate for road applications). If analysis of a treatment's leachate indicates that any of the contaminants listed in Table D.1 in Appendix D are present at a concentration equal to or greater than the respective value given in that table, the treatment should be disqualified from consideration.

In many cases, more stringent requirements should be applied, depending on the local environmental setting in which the treatment application is planned. In all cases, environmental specification language should be tailored to reflect local and state government concerns, standards, regulations, and legislation. The allowable concentration of chlorides is an example of a standard that will likely vary substantially depending on regional concerns (or lack thereof). Examples of other requirements include the following:

- The Pennsylvania Dirt and Gravel Road Maintenance Program requires SPLP leachates from chemical treatments to meet concentration limits for 27 inorganic and 23 organic constituents (listed in Appendix D). These concentration limits are based on the Pennsylvania Department of Environmental Protection Land Recycling Program's Statewide Health Standards.
- Depending on the level of concern for aquatic species exposure or human exposure through drinking water, other concentration limits can be considered, including the EPA National Aquatic Life Criteria (*https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table*) or the EPA National Primary Drinking Water Regulations (*https://www.epa.gov/ ground-water-and-drinking-water/national-primary-drinking-water-regulations*).

In addition to analysis of SPLP leachates, a number of other tests may be helpful in developing environmental specifications. In particular, acute and chronic toxicity tests with standard freshwater and brackish water test organisms are recommended, because many unpaved road chemical treatments lack basic aquatic toxicity information. Depending on the setting in which the treatment will be applied, specifications limiting treatment toxicity to other organisms (e.g., mammals, birds, or insects) may be useful. Example limits are provided in Table D.2 in Appendix D.

All tests listed in specifications should be performed at an accredited laboratory using standardized protocols (e.g., following ASTM or EPA standard methods) with documented quality control/quality assurance procedures. Confirmation that test results meet specified limits must be provided as part of the procurement documentation. Complete testing reports should be available on request.

Although not formally required by road agencies in the United States, a number of unpaved road chemical treatment manufacturers currently hold certificates of conformity for their products from the EPA's Environmental Technology Verification (ETV) Program and/or the *Bureau de Normalisation du Quebec*. These programs focus on environmental safety as well as production quality control and their certificates verify compliance with the respective program's requirements.

Example suggested environmental specification language is provided in Appendix D, Section D.12 for supplementing/compiling agency specifications. This language is more detailed than is typically found in currently available specifications, and the content, language, style, and format may need to be changed to suit specific agency requirements.

4.5.2 Safety Specifications

A comprehensive safety data sheet (SDS) should be requested for any unpaved road chemical treatment procurement. Closely scrutinize the contents of the SDS to check that the product is safe to use from both a health and an environmental perspective. Beware of safety data sheets that simply state that the product description and constituents are "proprietary" or a "trade secret" or that the result for a particular parameter is "unknown," as the purchaser/person authorizing the purchase can be held responsible for worker injuries/illness or environmental damage related to the use of the product. Suggested SDS content that can be used as a checklist to ensure that all relevant information is provided by the manufacturer/supplier is included in Appendix D. If this safety information is not provided or cannot be provided, alternative treatments from manufacturers/distributors who can provide SDSs with the required safety information should be considered.

The SDS should include all the chemical constituents present in concentrations greater than one percent in the undiluted product, and any requirements needed to conform to the applicable EPA Spill Prevention, Control, and Countermeasure Rules *(www.epa.gov/oem/content/spcc/)*.

4.6 Project Design Specifications

Project design specifications are an integral part of paved road construction. Subgrade, base, and surfacing materials (asphalt concrete, portland cement concrete, chip seals, etc.) on paved roads must all meet specifications before they are approved for use and the same should apply for unpaved road layers and chemical treatments applied to them to ensure that the treatment will result in improved performance on the road or roads under consideration.

4.6.1 Wearing Course Materials

Federal agencies managing unpaved roads must follow federal unpaved road wearing course material specifications and guidelines. Most other road agencies either implement an in-house specification (this specification should be reviewed based on the discussion in Appendix B) or use guidelines proposed by the Federal Highway Administration *(15,18)* or US Forest Service *(8)*. Where possible, the materials used on the road should meet these specifications prior to chemical treatment, given that chemical treatments are best used to keep good roads in good condition. However, in some areas suitable materials are unavailable or are too expensive to transport, and consequently mechanical stabilization (see Appendix B) or a chemical treatment can be considered to improve the properties of the material and the performance of the road under traffic. In these instances, the materials should either meet the specification after treatment (e.g., reduced plasticity index and/or minimum CBR) or meet a design performance specification (e.g., minimum CBR).

4.6.2 Dust Control/Fines Preservation

There are currently no formal (i.e., AASHTO or ASTM) laboratory tests that are appropriate for assessing the performance of chemical treatments for dust control and fines preservation. A number of mechanical tests have been developed by various research organizations, mostly focusing on abrasion resistance, and these may be formalized in the future.

4.6.3 Stabilization

Federal specifications currently do not list a strength requirement for stabilization of unpaved roads. There are a number of formal tests that are appropriate for this, the most commonly used being the California Bearing Ratio (CBR) test, which is essentially an evaluation of the shear strength of the material. Materials with a low CBR typically have poor all-weather passability and any chemical treatment being considered to improve this would need to increase the CBR to an acceptable level, either by mechanical stabilization, by chemically bonding/gluing the soil particles together, by chemically altering the material, or by increasing the density of the material through improved compaction. The standard AASHTO (T 193) or ASTM (D1883) CBR test methods should be followed and must include the four-day soaking period. The test method should, however, be adjusted to accommodate adding the chemical treatment to the compaction water at the recommended dilution (or replacing the compaction water with the chemical treatment) and for curing the treated specimens prior to the four-day soak. Application/dilution rates and curing procedures should follow the manufacturer's recommendations. Example curing periods are provided in Appendix C if no recommendations are available. Untreated control specimens should be subjected to the same curing procedures before being tested to evaluate the level of improvement provided by the treatment.

Project designs should specify a minimum soaked CBR result after treatment that will depend on rainfall, traffic volume, and percentage of heavy trucks. A minimum soaked CBR of 15 (determined at 95 percent of AASHTO T 180 or ASTM D1557 compaction) after treatment is typically specified for roads with low traffic volume and limited numbers of trucks. Note that the CBR is directly related to fines and clay content, both of which are required to bind materials together to prevent washboarding and raveling. High CBR materials typically have relatively low fines contents and no plasticity index and are therefore more prone to these distresses, which typically makes them inappropriate for unpaved road use without modification. Practitioners should aim for an appropriate balance between these parameters, but keep to a minimum shrinkage product of between 50 and 100.

4.7 Construction/Application Specifications

Federal agencies managing unpaved roads must adhere to published construction specifications, which include limited information on the application of chemical treatments *(18)*. Most other agencies and organizations that manage unpaved road networks have some form of published specifications for unpaved road construction, some of which may include information on the application of chemical treatments. Example specification language to supplement agency specifications for applying chemical treatments to unpaved roads is provided in Appendix D.8. This language is more detailed than what is typically found in FHWA and other agency specifications, and the content, level of detail, language, style, and format may need to be changed to suit specific agency requirements.

The example specification language in Appendix D introduces the concept of a chemical treatment application plan, which the project engineer (if the work is being done by the agency) or contractor will need to compile in accordance with the chemical treatment manufacturers recommendations and then submit to the engineer in charge prior to the start of any work. The agency/road owner and the contractor must agree on the application plan. These plans should include but are not limited to the following:

- The name of the product that will be used, the category and subcategory into which it falls, and the manufacturer's name;
- The certificate of compliance (Section 4.4.3);
- A detailed proposed methodology for preparing the road, applying the chemical treatment, and for shaping, compacting, and finishing the road surface;
- Dilution rates, application rates, and number of passes to apply the required active content or residual without any runoff;
- The procedure that will be followed to ensure that the correct amount of chemical treatment has been applied;
- The curing time required before traffic can use the road;
- The equipment that will be used during all phases of application;
- The procedure that will be followed for safely accommodating traffic and ensuring that vehicles do not travel on the roadway before the chemical treatment has penetrated and/or cured;
- Weather conditions under which the chemical treatment can be applied, including but not limited to ambient and road surface temperature, wind, and allowable period before expected precipitation; and
- Procedures that will be followed in the event of a product spill.

4.8 Approaches if No Formal Product Specifications Are Available

No formal product specifications are currently available for many of the chemical treatments used on unpaved roads. However, a number of other approaches can be considered as interim measures until these specifications are available to reduce the risk of using proprietary products—or blends of those products—that come with limited information on the dust suppression/stabilization mechanism, limited documented research, and/or limited documented past performance history. These approaches include:

- Product performance guarantees (risk is shared between the road agency/owner and the manufacturer)
- Performance/warranty specifications (risk is taken by the manufacturer/distributor)
- Maintenance contracts (risk is taken by the manufacturer/distributor)
- Fit-for-purpose certification (risk is taken by the road agency/owner based on an informed decision using published literature and/or information provided by the manufacturer/distributor)

4.8.1 Product Performance Guarantees

Product performance guarantees are a means to fast-track the implementation of new unpaved road chemical treatments or those with only limited research/testing, with the risk being shared between the road agency/owner and the product supplier. Guarantee parameters are set and agreed to through consultation between the agency and the chemical treatment manufacturer or contractor. Performance typically covers level of dust control (visual or measured), reduced maintenance (number of days between grader maintenance or average ride quality improvement, with both based on International Roughness Index (IRI) measurements collected using a simple smart phone application), and/or reduced rate of gravel loss (inches or millimeters per year) compared to the expected performance of the road with no chemical treatment. In setting the limits for the guarantee, the expected performance of the untreated gravel road is usually obtained from agency maintenance records, while the expected performance of the treated road is provided by the manufacturer or contractor based on research experiments and experience. The guarantee parameters are usually set between the current/expected performance on the untreated road and the predicted performance of the treated road, but they should focus on proving cost-effectiveness over a period of time in terms of reduced maintenance and gravel loss. An example of guarantee parameters for unpaved road chemical treatments is provided in Table 4.1.

Table 4.1: Example Product Performance Guarantee Parameters

Parameter	Expected Performance		Guaranteed Performance
	Untreated	Treated	
Blading interval (days based on average IRI[1])	40	200	150
Gravel loss (in./year [mm/year][2])	0.75 [19]	0.35 [9]	0.55 [14]
Dust level (visual assessment[3])	5	1	2
Days impassable	5	0	2

[1] Can be supplemented by average ride quality measurement (e.g., International Roughness Index in inches/mile or m/km) if available (a number of simple, inexpensive smart phone applications are commercially available for measuring IRI on low-volume roads). Suggested IRI limits are 580 in./mile (9.2 m/km) for untreated, 390 in./mile (6.2 m/km) for treated, and 490 in./mile (7.7 m/km) for guaranteed performance, respectively.
[2] Gravel loss determined by rod-and-level survey
[3] Based on photographs *(26)*. Actual dust measurements can be used if suitable equipment is available (e.g., *Dusttrak*)

If the terms of the guarantee are not met, the manufacturer or contractor must carry the cost of additional treatment applications and/or maintenance in order to meet those terms. If the terms are met or exceeded, the road agency/owner undertakes to continue the treatment program and include the prediction factors in a road management system that identifies where the chemical treatment can be used cost-effectively on other roads.

4.8.2 Performance/Warranty Specifications

Performance or warranty specifications are similar to product performance guarantees, except that the contractor chooses and accepts full risk for performance of the chemical treatment instead of sharing it with the road agency/owner. Consequently, these specifications are suitable for procuring chemical treatments without specifying a product name or category. Specification parameters may be one or more of those listed in Table 4.2, while specified performance is typically closer to the expected performance levels. Warranty periods will depend on the treatment objective and the warranty parameter being considered, and could vary from a few months for dust control treatments to a number of years for fines preservation and stabilization projects. Contractors will usually only bid on warranty projects if the chemical treatments they intend to use have been evaluated for a number of years on a range of different projects and the manufacturer/distributor/contractor is confident in predicting expected performance. Any chemical treatments proposed must still be shown to meet the safety and environmental requirements discussed above.

Table 4.2: Example Warranty Parameters and Limits

Parameter	Expected Performance		Warranty
	Untreated	Treated	
Blading interval (days based on average IRI[1])	40	200	200
Average ride quality (IRI)	9.2	6.2	6.5
Gravel loss (mm/annum)	19	9	10
Dust level (visual assessment[2])	5	1	1
Days impassable	5	0	0

[1] International Roughness Index [2] Based on photographs or actual dust measurements

Project specifications will need to be carefully worded to ensure that any required steps do not potentially affect enforcement of the warranty (e.g., the specification cannot prescribe application rates or application methods). Unplanned or unscheduled maintenance or unanticipated changes in traffic volume or type may also void the warranty.

4.8.3 Performance-Based Maintenance Contracts

Performance-based maintenance contracts are similar to performance/warranty specifications except that the contractor is paid for, and takes full responsibility for, maintaining the road at an agreed upon level of service, which must be met or exceeded at all times for the duration of the contract period. Parameters may include one or more of those discussed in Sections 4.8.1 and 4.8.2. In setting a price, prospective contractors will need to be able to confidently predict likely performance over the contract period and the amount of chemical treatment required to meet the level of service, as well as application rates and application and maintenance intervals.

Specification details are typically limited to the level of service required and the methods that will be used to determine whether those levels are being met. The type of chemical treatment and application rates, application intervals, and application methods are typically decided by the contractor. Safety and environmental considerations will, however, still apply to the choice of treatment.

4.8.4 Fit-for-Purpose Evaluation

Fit-for-purpose evaluation *(27,28)* entails an independent review of the research conducted on a specific unpaved road chemical treatment, and the documentation developed from it, to determine whether sufficient information is available for an engineer or road manager to make an informed decision on its use. Evaluation systems can also be used in conjunction with safety data sheets to ensure that treatments comply with certain minimum standards, particularly those related to potential environmental impacts. Fit-for-purpose evaluation systems can be initiated and managed by road agencies, industry associations, or an independent standards organization. The EPA's *Environmental Technology Verification (ETV) Program*, although based on a single field experiment, is a form of fit-for-purpose evaluation. At the time of preparation of this guideline, there was no organization in the United States offering comprehensive fit-for-purpose evaluation of unpaved road chemical treatments, although successful programs have been developed and implemented internationally (e.g., South Africa *[27]* and Australia *[www.arrb.com.au/ Infrastructure/TIPES.aspx])*.

Evaluation procedures are based on a relative performance evaluation methodology, which should do the following:

- Provide potential users with a measure of the performance of the chemical treatment relative to the performance of a range of treatments, as well as to the standard specifications of more traditional dust suppressants (e.g., calcium or magnesium chloride) and stabilizers (e.g., asphalt, cement, and lime).
- Identify the strengths and limitations of the chemical treatment, thereby better defining suitable applications.
- Facilitate judgment regarding the engineering and economic advantages of using the chemical treatment instead of more traditional approaches, such as water spraying.

The process typically involves the following *(28)*:

1. Establishing a technical assessment team;
2. Assessing the manufacturers quality management system;
3. Assessing environmental compatibility and the validity of the safety data sheet;
4. Reviewing the research procedures followed and the background research that has been conducted on the chemical treatment;
5. Reviewing guideline documentation;
6. Control testing to validate the manufacturer's claims if considered necessary;
7. Issuing a fit-for-purpose evaluation statement; and
8. Conducting an annual evaluation statement review.

Fit-for-purpose evaluation is ***not*** intended to serve as a formal acceptance or rejection of a chemical treatment based on an absolute performance evaluation. It also does not serve as a guarantee of performance or obviate the need to carry out an engineering investigation, including material testing, for every project where use of the chemical treatment is being considered. It simply acknowledges that appropriate research has been conducted on the chemical treatment, and that the documentation and guidelines are representative of this research and provide sufficient information for a practitioner to make an informed decision on whether or not a particular treatment is appropriate for a particular project.

5. CONSIDERATIONS FOR APPLYING CHEMICAL TREATMENTS

5.1 Introduction

Preparing the road for a chemical treatment and the process followed when applying it are critical for successful performance (Figure 5.1). Depending on the objective, different treatments are applied in different ways: either by direct spraying onto the prepared road surface or by mixing them in during regravelling or reworking of the surface. Spray-on applications are more popular because they are the least expensive for initial application, but because some treatments have limited penetration they need to be rejuvenated more frequently, which often makes them more expensive than mix-in treatments in the longer term. Mix-in treatments are required when a chemical treatment is being used to preserve fines/reduce dust as well as to improve all-weather passability, or as a stabilizer to increase shear strength. This is important because the treatment needs to be distributed through the top 2 in. to 3 in. (50 mm to 75 mm) of material for dust control and the top 4 in. to 6 in. (100 mm to 150 mm) of material to increase strength and/or improve all-weather passability. Good compaction after mixing in the chemical treatment is critical for optimal performance of the road.

Figure 5.1: Applying a chemical treatment to a well-prepared road.

The process of preparing an unpaved road before applying a chemical treatment generally follows standard procedures and uses standard road construction and maintenance equipment. However, on many projects standard practice is often overlooked or has been "forgotten," and consequently, substandard construction is often accepted; this can lead to less-than-satisfactory performance that is not directly related to the treatment type itself. Variations from standard practice are usually caused by, but are not limited to, poorly trained equipment operators; use of inappropriate construction specifications or not using/enforcing specifications at all; use of aggregates with properties that are inappropriate for unpaved roads; insufficient crown and drainage; poor compaction or none; spraying chemical treatments onto dry surfaces; spraying the full dose of product in a single pass; and/or poor quality control (i.e., quantity of product applied, gravel thickness, road shape, compaction density, etc.).

Providing detailed application procedures for each chemical treatment is beyond the scope of this guideline. Instead, road managers and practitioners are encouraged to obtain and follow detailed application procedures provided by the chemical treatment manufacturers and distributors. However, key issues to consider are summarized in the following sections. Additional information and knowledge are available in published guidelines (e.g., the FHWA *Gravel Roads Construction and Maintenance Guide [15]*).

5.2 General Information

5.2.1 Time of Application

Treatment applications at the end of the rainy season are usually the most effective. Do not apply treatments if rain, strong winds, or hot and dry conditions are imminent.

5.2.2 Safety and Environment

Prior to working on the roadway, ensure that appropriate traffic control and safety devices are in place to inform drivers on what to expect ahead. These devices must be installed in accordance with all of the agency's requirements, which may include the *Manual of Uniform Traffic Control (MUTCD) for Workzone Traffic Control (29).*

Take appropriate safety precautions during application, following the recommendations in the treatment manufacturer's guidance document and in the safety data sheet (SDS). Take care to ensure that the application is restricted to the road surface and that there is no runoff or overspray. Any chemical ending up off the traveled way in drains or on roadside vegetation is a reduction in both the application rate and potential effectiveness of the program, and could have undesirable impacts on vegetation and surface water.

5.2.3 Road Closures

Always follow the supplier's recommendations for applying the chemical treatment and allowing it to cure. Some treatments (e.g., synthetic polymer emulsion and organic petroleum treatments) may require a road closure while the treatment is being applied and for the duration of curing (typically 15 minutes to 2 hours). Even when not required by the supplier, where possible, ask road users to wait at the start of the section until spraying is complete. This will reduce the risk of collisions with application equipment, limit unsafe driving conditions (e.g., slipperiness), and reduce the amount of product adhering to vehicles.

5.2.4 Application Rates

Application rates depend on a number of factors including whether the application is an initial one or a periodic rejuvenation, material properties, traffic volume and speeds, and climate. Always follow the supplier's recommendations. Avoid diluting treatments beyond the manufacturer's recommendations since excessively diluted applications will not survive or remain in service as well or as long, will be subject to more rapid degradation and runoff during rainfall events and, even when freshly applied, may not control fines or dust as effectively as the recommended dilution (Figure 5.2). In some cases, a residual build-up of a treatment in the roadway will provide an opportunity to reduce the reapplication rates and still restore the road to its original full first-application performance. The product supplier should have researched application rates in detail and should provide guidance in the form of charts along with the treatment. If they cannot, it means that the road manager will be doing research on their behalf and consequently any performance claims that the supplier has made should be considered with care. While values for various general categories are shown in Table A.5 in Appendix A, no recommendations on specific treatment application rates are made in this guideline.

Figure 5.2: Insufficient chemical treatment application.

5.3 Spray-On Treatments

5.3.1 Road Preparation

Spraying chemical treatments onto unprepared roads is a waste of time and money. The dust control effect will be short lived, ride quality will not be improved, and the road will soon require some form of maintenance, which will reduce the life of the treatment (Figure 5.3). Conversely, spraying a chemical treatment onto a well-prepared road should slow the rate of deterioration, providing improved and safer driving conditions for extended periods before maintenance is required.

Prior to any spray-on application, the road must be shaped, to ensure that an adequate crown is present (typically four to five percent), and then bladed to provide a quality driving surface. Avoid shaping a road when it is dry as this will loosen up sections of crust, segregate the materials, break down softer aggregates, and invariably result in a thin "biscuit" layer on the surface after treatment (Figure 5.4), which will break down quickly and ravel to the side, leading to rapid loss of the new crown. If dry, spray the road surface with water to bring the moisture content of the material that needs to be reworked to a suitable level. This can be determined with a simple "squeeze" test (i.e., a handful of material when squeezed should hold the shape of a ball without exuding water [too wet, leaving a sheen of water on the skin], or crumble [too dry] when released [Figure 5.5]).

Figure 5.3: Poor performance after treatment application to a poorly prepared road (loose gravel).

Figure 5.4: Effect of biscuit layer on treated surface.

[a] [b] [c]

Figure 5.5: Squeeze test for assessing moisture content.

([a] too dry, [b] too wet, and [c] acceptable)

Once the material is adequately moistened, use a motor grader equipped with a slope meter or electronic grade control to achieve/maintain the required crown (typically four to five percent). The grader blade should have good, straight edges to avoid rounding the surface. Material from the side drains should NOT be bladed onto the road since it is often silt and will result in a dusty "biscuit" layer that will be displaced by traffic in a short time. Uniformity of depth of the surface material should be maintained.

Compact the road with a grader-mounted rubber-tire roller (Figure 5.6), standard rubber-tire roller, or smooth-drum steel roller (no vibration), if one of these is available, to consolidate the material and seal the surface.

Figure 5.6: Grader-mounted roller.

Good drainage is imperative for the optimal performance of unpaved roads, especially in terms of all-weather passability, reduced slipperiness and erosion, and pothole prevention. Drainage includes two components that need to be taken care of during preparation of the road:

- The water must drain off the road as quickly as possible without eroding the surface. This is a function of road shape, so providing an adequate crown is very important. A target crown of 4 to 5 percent ensures that the road surface will shed rain (Figure 5.7). A crown of less than 4 percent can lead to water ponding on the road (Figure 5.8), which is dangerous for road users and will create soft spots that will quickly turn into potholes. A crown of more than 6 percent (Figure 5.9) will exacerbate erosion during runoff, and can also cause truck trailers to slip off the road. Relax crown requirements on steep grades and super-elevations to maintain safe driving conditions, but ensure that the crown's shape prevents water from running down the road and keeps water velocities to a minimum at all times. Maintain target crowns during all subsequent maintenance.
- Water should not be allowed to pond next to the road (Figure 5.10). This will lead to water ingress, softening of the material, and, ultimately, impassability (i.e., vehicles will get stuck). Consider culverts, ditches, and miter drains as an integral part of the road geometry to channel ponded water away. Keep them clear and open at all times. Understand and manage where the water goes to ensure that no pollution of streams or damage to adjacent property and vegetation occurs.

Additional information on road preparation and drainage is provided in the guides and manuals listed in Chapter 1 and Chapter 2.

Figure 5.7: Good crown (4 to 6 percent).

Figure 5.8: Insufficient crown (<4 percent).

Figure 5.9: Too much crown (>6 percent).

Figure 5.10: Water ponding next to road.

5.3.2 Spray-On Applications

When using spray-on applications, always follow the supplier's recommendations, but consider the following:

- First dampen the road surface (typically considered as the top 2 in. [50 mm]) with water to assist penetration of the treatment. Applying treatments to dry roads results in a concentration at the surface that traffic will quickly remove (see Figure 5.11 and Figure 5.12 for the different results seen between no pre-wetting and pre-wetting). Avoid overwatering as this may lead to ponding and/or runoff. Lightly scarifying the road at the same time also helps the treatment to penetrate.

Figure 5.11: Poor penetration without pre-wetting.

Figure 5.12: Good penetration with pre-wetting.

- Most chemical treatments are best applied in a series of applications (typically three over a number of hours) rather than in a single pass. Allow sufficient time between applications to promote penetration to an appropriate depth and even distribution through the material. Avoid overspraying to ensure that the treatment does not puddle or run off (Figure 5.13) and is not picked up by vehicle tires (product adhering to a vehicle is product that is lost for controlling dust).

Figure 5.13: Overspray leading to ponding and runoff of treatment.

- If feasible, complete this initial application over a longer period, with the first and second pass as described above and then the third light application (approximately 15 to 20 percent of the total application rate) approximately two to three weeks later. This allows the first applications to penetrate and uniformly treat the layer, with the follow-up application treating lean areas and providing a new seal after any early traffic disturbances that have occurred while the road was drying out/curing. Slippery conditions are often also reduced if this approach is followed. The road surface must be lightly watered before the final application to facilitate even penetration of the treatment.
- Use a tanker with a calibrated, pressurized spray bar to apply the treatment. Avoid gravity-fed bars as the distribution is too uneven, which leads to areas of over- and underapplication. Application rates can be checked by placing a pan in the road and measuring the treatment volume after each distribution pass.
- Compact the road with a rubber-tired roller or grader-mounted roller after the final application has penetrated. This will seal the surface and limit uneven traffic compaction and wheel tracks that can become permanent if a crust forms.
- For chloride applications in dry areas, occasional light applications of water may be required during periods of low humidity to keep the treatment in the upper layer of the road and prevent dusting and raveling on the surface.
- Follow the supplier's recommendations for traffic closures and curing of the treatment.

5.4 Applications of Flake- or Pellet-Form Chlorides

Calcium and magnesium chloride can also be applied in flake or pellet form. These can either be simply spread onto the road surface or dissolved in a water tanker and then sprayed on to the road as discussed above. Beware that dissolving chlorides in water is an exothermic chemical reaction, and that significant, possibly dangerous, temperatures may be reached depending on the dilution ratio. Always follow the manufacturer's recommendations, but consider the following for applications by dry spreading:

- Spray the road surface with water until the top 1 in. (25 mm) is moist (not wet—use the squeeze test to decide).
- Prepare the road appropriately and lightly scarify the surface (top 1 in. [25 mm]) to promote penetration.
- Spread the flakes or pellets at the design rate (Figure 5.14), checking with a tray to ensure that there is no under- or overapplication (Figure 5.15). Overapplication will usually lead to slippery and even impassable conditions.
- Lightly scarify the surface material again to obtain a uniform mix.
- Depending on humidity levels, spray another light application of water to speed up flake dissolving and to promote penetration. Do not overwater as this can lead to runoff or overpenetration.
- Restrict vehicles from driving on the road until the flakes or pellets have dissolved and the road surface appears dry.
- Follow-up light applications of water may be required to distribute the treatment through the upper layer of material. Do not overwater.

Figure 5.14: Flake application of calcium chloride.

Figure 5.15: Checking application rate of calcium chloride flakes.

5.5 Mix-In Applications

A mix-in process will typically provide effective dust abatement and/or gravel retention for longer periods than spray-on applications. The higher costs incurred during construction will usually be offset by longer intervals between rejuvenation, by improved performance, and by less frequent road maintenance. Mixing depths will depend on the type of chemical treatment being used and the purpose of the treatment. For dust control treatments, mixing depth is typically 2 in. to 3 in. (50 mm to 75 mm). For stabilization treatments, mixing depth is typically 4 in. to 6 in. (100 mm to 150 mm) depending on the thickness of the layer, the type of treatment used, truck traffic, and the purpose of the application.

Mix-in treatments should be compacted with a smooth-drum roller, followed by a rubber-tired roller. Consider rolling until refusal density is achieved (i.e., proof rolling a representative test strip with density checks taken with a nuclear gauge, stiffness gauge, dynamic cone penetrometer [DCP], or similar device after each roller pass reveal no further increases in density) rather than just aiming for a percentage of a laboratory-determined density. This will result in higher shear strengths (i.e., better all-weather passability) and better gravel retention. However, take care to avoid aggregate breakdown through overcompaction.

All mix-in treatments require compaction and the importance of good compaction cannot be overemphasized. Good compaction results in higher bearing strengths, slower rates of gravel loss, and greater resistance to road shape degradation, distresses, and moisture ingress. No compaction (i.e., leaving compaction to traffic) or poor compaction (i.e., incorrect roller, too light a roller, too few roller passes, or inconsistent roller coverage) will lead to rapid loss of road shape, potholing, rutting, poor passability, and loss of gravel. The cost of good compaction is negligible when compared to the costs of early maintenance and more frequent gravel replacement.

5.5.1 Mix-In Applications for Stabilization/All-Weather Passability

For mix-in applications where the objective is primarily stabilization and/or all-weather passability, consider the following:

- Where feasible, use a recycler/reclaimer to apply the treatment, with the additive pumped through the recycler's mixing chamber (Figure 5.16 and Figure 5.17). The costs of using this equipment are usually offset by the speed, accuracy, and efficiency of the process compared to a rip-and-recompact operation using a grader. Strictly control the mixing depth and forward speed to ensure that the correct application rate is adhered to (deeper than planned mixing or fast forward speed will result in lower than designed application rates).

Figure 5.16: Equipment-mounted recycler.

Figure 5.17: Full-depth recycler.

- If a recycler is not available, rip the road surface to the required depth with a grader (Figure 5.18). Break down large cohesive lumps of material with a single pass of the roller and remove large stones (i.e., larger than one-third of the layer thickness).
- Dilute the treatment to an appropriate level in the water that will be applied to bring the roadway material up to its optimum moisture content (i.e., compaction water.) Spray this onto the ripped material (Figure 5.19) in a series of applications and mix it thoroughly with the grader, a disc plough, or other mixer. Satisfactory mixing will require multiple passes of the equipment. When the application is completed the moisture content should be as close as possible to the optimum moisture content (note that the existing material moisture content needs to be determined prior to application and factored into the amount of fluid that is applied). If it is too low, spray a little more water to raise the moisture content to the required level. Check the moisture contents using a nuclear moisture-density gauge or the "squeeze" test described earlier.

Figure 5.18: Ripping with a grader.

Figure 5.19: Spraying the chemical treatment.

- Shape (Figure 5.20) and compact the road (Figure 5.21 and Figure 5.22), and then apply a light application of the chemical treatment (10 to 15 percent of the design application) to seal the surface (Figure 5.23). Avoid ponding or runoff of the final treatment.

Figure 5.20: Shaping the road.

Figure 5.21: Compaction with a smooth-drum roller.

Figure 5.22: Compaction with a rubber-tired roller.

Figure 5.23: Light application of treatment to seal the surface.

5.5.2 Mix-In Applications for Fines Preservation/Dust Control

Mix-in applications for fines preservation/dust control are usually applied in a shallower lift than that for stabilization, typically not exceeding 2 to 3 in. (50 to 75 mm). Consider the following if applying treatments to meet this objective:

- A recycler/reclaimer can be used as described above, provided that mixing depth is strictly controlled.
- Alternatively, use a grader-mounted pulverizer (Figure 5.24) to loosen the top 2 in. (50 mm) of material. The road should be lightly watered to soften the material prior to pulverizing. Spray approximately 75 percent of the predetermined treatment application onto the prepared material, diluting where necessary to ensure that there is sufficient moisture for mixing and compaction. Repeat the pulverization process to thoroughly mix the treatment into the loose material. Shape and compact the road and then apply the remaining 25 percent of the application to seal the surface. Avoid ponding or runoff of the treatment.
- If recyclers or pulverizers are not available, scarify and blade the top 2 in. (50 mm) of the material to the sides of the road and then redistribute the loose material evenly over the road surface. Spray approximately 75 percent of the predetermined application onto this loose material, diluting where necessary to ensure that there is sufficient moisture for mixing and compaction. Mix the treated material back and forth over the road to thoroughly blend the treatment and the aggregate (Figure 5.25). Several passes will be required before the treatment and material are uniformly mixed. Shape and compact the road and then apply the remaining 25 percent of the application to seal the surface.

5.5.3 Mix-In Applications during Regravelling Operations

Regravelling operations provide an ideal opportunity for incorporating chemical treatments. In most instances, the treatments can be used as the compaction fluid together with or in place of water. Care must be taken to ensure that the gravel meets the required specification (see discussion in Appendix B) and that it is placed to the best possible construction standard. Detailed guidance on construction is beyond the scope of this handbook, but the key processes include the following:

Figure 5.24: Grader-mounted pulverizer.

Figure 5.25: Blade mixing application.

- Scarify or tine the existing surface to a depth of 1 in. to 2 in. (25 mm to 50 mm) to ensure a good bond between the old and new surface.
- Spread the new material evenly to achieve a consistent thickness, ensuring that there is no segregation of the fine and coarse aggregates.
- Follow the manufacturer's recommendations for diluting the chemical treatment into the compaction water. Use this to raise the moisture content to the optimum for compaction. Note that some treatments cannot be diluted with water (e.g., minerals oils and synthetic fluids) so additional compaction water will need to be sprayed separately if required.
- Mix the material thoroughly and uniformly throughout the total stabilization depth using a recycler, pulverizer, rotavator, disc plough, or grader.
- Properly shape and compact the road.
- Apply a final light application of the treatment (about 10 to 15 percent of the application rate) to seal the surface. Avoid ponding or runoff of the final treatment.

5.6 Maintaining Treated Roads

Treated roads should be maintained according to the manufacturer's recommendations. Consider the following:

- Most treatments require a light water spray to soften the crust prior to blading. Failing to do this will result in damage to the crust that will require extensive reworking of the surface and reapplication of the treatment.
- Synthetic polymer emulsion and asphalt emulsion treatments usually form a hard surface that cannot be softened with water or lightly bladed. Reworking of the surface and reapplication is usually required.
- Where possible, combine maintenance with a light rejuvenation spray to ensure continued optimal performance of the treatment.
- Always ensure that an adequate crown is maintained and that drainage systems are open and clear.
- Where possible, compact the road after blading and/or the light rejuvenation spray to seal the surface and extend the life of the treatment. Grader-mounted rollers are ideal for this.

REFERENCES

1. JONES, D. 2013. **Literature Review on Selection and Specification of Unpaved Road Chemical Treatments.** Davis and Berkeley, CA: University of California Pavement Research Center. (Technical Memorandum UCPRC-TM-2013-02).
2. BOLANDER, P. and Yamada, A. 1999. **Dust Palliative Selection and Application Guide.** San Dimas, CA: US Forest Service, San Dimas Technology and Development Center. Report No. 9977 1207-SDTDB.
3. GEBHART, E.L, Denight, M.L. and Grau, R.H. 1999. **Dust Control Guidance and Technology Selection Key.** Champaign, IL: US Army Construction Engineering Research Laboratories. Report No. USCERL 99/21.
4. MAHER, M., Marshall, B., Harrison, F. and Baumgaertner, K. 2005. **Context Sensitive Roadway Surfacing Selection Guide.** Lakewood, CO: Federal Highway Administration Central Federal Lands Highway Division. Report No. FHWA-CFL/TD-05-004.
5. RUSHING, J.F. and Tingle, J.S. 2006. **Dust Control Field Handbook.** Vicksburg, MS: Geotechnical and Structures Laboratory US Army Engineer Research and Development Center. Report No. ERDC/GSL SR-06-7.
6. KESTLER, M.A. 2009. **Stabilization Selection Guide for Aggregate and Native-Surfaced Low-Volume Roads.** US Forest Service, San Dimas Technology and Development Center. Report No. 0877 1805-SDTDB.
7. BEAULIEU, L., Pierre, P., Juneau, S. and Légère, G. 2011. **Maintenance Guide for Unpaved Roads: A Selection Method for Dust Suppressants and Stabilizers.** Pointe-Claire, Quebec: FP Innovations.
8. KELLER, G., Wilson-Musser, S., Bolander, P. and Barandino, P. 2011. **Stabilization and Rehabilitation Measures for Low-Volume Forest Roads.** US Forest Service, San Dimas Technology and Development Center. Report No. 1177 1801-SDTDB.
9. **The Sulfonated Petroleum Products Toolkit 1 for Decision Makers.** Undated. Global Transport Knowledge Partnership (United Kingdom). *www.gtkp.com.* (Accessed June 2013).
10. **The Sulfonated Petroleum Products Toolkit 2 for Engineers.** Undated. Global Transport Knowledge Partnership (United Kingdom). *www.gtkp.com.* (Accessed June 2013).
11. GIUMMARRA, G., Editor. 2009. **Unsealed Roads Manual: Guidelines to Good Practice, 2009 Edition.** Melbourne, Australia: Australian Road Research Board.
12. **Unsealed Roads: Design, Construction and Maintenance.** 2009. Pretoria, South Africa: Department of Transport. Technical Recommendations for Highways, No.20.

13. JONES, D., Kociolek, A., Surdahl, R., Bolander, P. Drewes, B., Duran, M., Fay, L., Huntington, G., James, E., Milne, B., Nahra, M., Scott, A., Vitale, R. and Williams, B. 2013. **Unpaved Road Dust Management: A Successful Practitioner's Handbook.** Denver, CO: Federal Highway Administration Central Federal Lands Highway Division. Report No. FHWA-CFL/TD-13-001.
14. Oil and Gas Extraction Point Source Category; **Final Effluent Limitations Guidelines and Standards for the Coastal Subcategory; Final Rule.** 1996. Washington, DC: US Environmental Protection Agency. (40 CFR Part 435. Federal Register, Vol. 61, No. 242).
15. SKORSETH, K., Reid, R, and Heiberger, K. 2015. **Gravel Roads Construction and Maintenance Guide.** Washington, DC: Federal Highway Administration, (FHWA-OTS- 15-0002).
16. BOLANDER, P., Marocco, D. and Kennedy, R. 1996. **Earth and Aggregate Surfacing Design Guide for Low Volume Roads.** US Forest Service, San Dimas Technology and Development Center.
17. BOLANDER, P., Barandino, V. and Keller, G. 2013. **Guidelines for Surfacing Aggregate.** San Dimas, CA: US Forest Service, San Dimas Technology and Development Center.
18. **Standard Specifications for the Construction of Roads and Bridges on Federal Highway Projects (FP).** Washington, DC: Federal Highway Administration.
19. JONES, D. 1999. **Dust and Dust Control on Unsealed Roads.** PhD Thesis, University of the Witwatersrand, Johannesburg, South Africa.
20. PAIGE-GREEN, P. and Bam, A. 1991. **Passability Criteria for Unpaved Roads.** Pretoria, South Africa: Department of Transport (Research Report RR-91/172).
21. JONES, D. 2007. Development of Performance Based Tests for Nontraditional Road Additives. **Transportation Research Record, Journal of the Transportation Research Board, No 1989.** Washington, DC: National Academy of Sciences.
22. **Uniform Standard Specifications and Details for Public Works Construction.** 2012. Phoenix, AZ: Maricopa Association of Governments.
23. RUSHING, J.F. and Newman, K. 2010. Investigation of Laboratory Procedures for Evaluating Chemical Dust Palliative Performance. **Journal of Materials in Civil Engineering, Vol. 22.** American Society of Civil Engineers. (pp. 1148-1155).
24. **Australian Standard AS 1141.53-1996.** 1996. Methods for sampling and testing aggregates—Absorption, swell and capillary rise of compacted materials. Standards Australia.
25. **Technical Overview of Ecological Risk Assessment (Pesticides).** Washington, DC: US Environmental Protection Agency. *http://www.epa.gov/oppefed1/ecorisk_ders/toera_analysis_eco.htm#Ecotox.* (Accessed June 2013).
26. JONES, D. 2008. **Guidelines for Visual Assessment of Unpaved Road Performance.** Davis, CA: University of California Pavement Research Center.

27. JONES, D. 2003. Towards Fit-For-Purpose Certification of Road Additives. **Transportation Research Record, Journal of the Transportation Research Board, No. 1819.** Washington, DC: National Academy of Sciences.
28. JONES, D. 2015. **Fit-for-purpose Evaluation: Guidelines for Evaluating Unpaved Road Chemical Treatments.** Davis, CA: University of California Pavement Research Center (UCPRC-GL-2015-04).
29. **Manual on Uniform Traffic Control Devices (MUTCD) (2009 Edition incl. Revisions 1 & 2).** 2012. Washington, DC: Federal Highway Administration.
30. **Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT ≤ 400), 1st Edition.** 2001. Washington, DC: American Association of State Highway and Transportation Officials (AASHTO).
31. HUNTINGTON, G. and Ksaibati, K. 2010. **Gravel Road Management: Implementation Guide.** Laramie, WY: Wyoming Technology Transfer Center.
32. PAIGE-GREEN, P. 1989. **The Influence of Geotechnical Properties on the Performance of Gravel Wearing Course Materials.** PhD Thesis. University of Pretoria, Pretoria, South Africa.
33. **Standard Specifications for Road and Bridge Works for State Road Authorities.** 1998. Pretoria, South Africa: Committee of Land Transport Officials.
34. **Standard Specifications for Road and Bridge Works.** 1998. Maputo, Mozambique: Southern Africa Transport and Communications Commission.
35. **Guide to Pavement Technology Part 6: Unsealed Pavements.** 2009. Sydney, Australia: Austroads. Publication No. AGPT06/09.
36. VAN ZYL, G.D., Henderson, M.G. and Uys, R. 2007. Applicability of Existing Gravel Road Deterioration Models Questioned. **Proceedings 9th International Conference on Low-Volume Roads.** Transportation Research Record, Journal of the Transportation Research Board, No. 1989. (pp. 217-225).
37. VAN ZYL, G.D., Henderson, M.G. and Uys, R. 2008. Work Effects of Alternative Maintenance Measures on Unsurfaced Roads in the Western Cape. **Proceedings 7th International Conference on Managing Pavements and other Roadway Assets.** Calgary, Canada.
38. HENNING, T.F.P., Flockhart, G., Costello, S.B., Jones, V. and Rodenburg, W. 2015. Managing Gravel Roads on the Basis of Fundamental Material Properties. **Proceedings 94th Transportation Research Board Annual Meeting.** Washington, DB.

Blank page

APPENDIX A: CHEMICAL TREATMENT CATEGORY DETAILS

This appendix contains a summary of the origins, form supplied, attributes, limitations, application, and potential environmental impacts of the various chemical treatment categories and subcategories. Each topic is discussed in a separate table as follows:

- Table A.1: Chemical treatment uses
- Table A.2: Chemical treatment origins
- Table A.3: Chemical treatment form of supply
- Table A.4: Chemical treatment attributes
- Table A.5: Chemical treatment application rates and methods
- Table A.6: Chemical treatment environmental impacts
- Table A.7: Chemical treatment limitations

The summary information provided in the tables is based on literature reviews and the experience of a panel of practitioners, and should be updated as new information becomes available. This information should not be used as the sole basis for a choice of chemical treatment, for absolute determination of application rates, or for determining the potential level of environmental impact. Specific information, including proof of environmental testing, should always be requested from the chemical treatment supplier.

Table A.1: Chemical Treatment Category Uses

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as the sole basis for a choice of chemical treatment. Specific information should always be requested from the chemical treatment supplier.		
Category	**Sub-Category**	**Use**
Water and water with surfactants	Water	▪ Short-term dust control
	Water with surfactant	▪ Short-term dust control
Water absorbing	Calcium chloride	▪ Fines preservation/dust control
	Magnesium chloride	▪ Fines preservation/dust control
	Sodium chloride brine	▪ Fines preservation/dust control
Organic non-petroleum	Glycerin/glyceride based	▪ Fines preservation/dust control
	Lignosulfonate	▪ Fines preservation/dust control
	Molasses/sugar	▪ Fines preservation/dust control
	Plant oil	▪ Fines preservation/dust control
	Tall oil pitch rosin	▪ Fines preservation/dust control
Organic petroleum	Asphalt emulsion	▪ Stabilization/all-weather passability if mixed into top 6 in. (150 mm) ▪ Fines preservation/dust control
	Base and mineral oils	▪ Fines preservation/dust control
	Petroleum resin	▪ Fines preservation/dust control ▪ Stabilization/all-weather passability if mixed into top 6 in. (150 mm)
	Synthetic fluid	▪ Fines preservation/dust control
	Synthetic fluid plus binder	▪ Fines preservation/dust control ▪ Stabilization/all-weather passability if mixed into top 6 in. (150 mm)
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Fines preservation/dust control ▪ Stabilization/all-weather passability if mixed into top 6 in. (150 mm)
Concentrated liquid stabilizers	High acidity	▪ Stabilization/all-weather passability if mixed into top 6 in. (150 mm)
	Low acidity/enzyme	▪ Stabilization/all-weather passability if mixed into top 6 in. (150 mm)
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Mechanical stabilization ▪ Fines preservation/dust control

Table A.2: Chemical Treatment Category Origins

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as the sole basis for a choice of chemical treatment. Specific information should always be requested from the chemical treatment supplier.		
Category	**Sub-Category**	**Origin**
Water and water with surfactants	Water	▪ Any water source ▪ May include contaminated water from industrial or mining processes/ operations
	Water with surfactant	▪ Any water source plus a surfactant to increase the "wetting ability" of the water ▪ Surfactants are typically soap based
Water absorbing	Calcium chloride	▪ Evaporated from naturally occurring brines (lake or sea water) ▪ By-product brine from the manufacture of sodium carbonate by ammonia-soda process or separation of bromine from natural brines ▪ Manufactured by neutralizing by-product hydrochloric acid (e.g., from sodium hydroxide production) with limestone or similar calcium source
	Magnesium chloride	▪ Evaporated from naturally occurring brines (lake or sea water)
	Sodium chloride brine	▪ Evaporated from naturally occurring brines (lake or sea water) ▪ Mined from rock salt
Organic non-petroleum	Glycerin/glyceride based	▪ By-product from plant oil and biofuel manufacturing ▪ Recycled from used cooking oil
	Lignosulfonate	▪ By-product from sulfite paper-making process (i.e., Kraft process) ▪ Chemistry depends on extraction process chemicals (ammonium, calcium, or sodium) and to a certain extent tree species ▪ Performance depends on tree species ▪ Active constituent is neutralized sulfuric acid containing sugars
	Molasses/sugar	▪ By-product from the sugar cane and sugar beet processing industry
	Plant oil	▪ Manufactured as part of plant oil extraction ▪ Commonly used plants include soy, canola, sunflower, cotton, linseed, and palm
	Tall oil pitch rosin	▪ Distilled product from lumber pulping process ▪ Performance can depend on tree species
Organic petroleum	Asphalt emulsion	▪ Slow-set asphalt (bitumen) emulsions, usually SS-1 (anionic) or CSS-1 (cationic) ▪ SS-1h and CSS-1h are not used unless a thicker crust/less penetration is required (e.g., very sandy soils) ▪ Cutback slow cure asphalt (bitumen) emulsions, usually SC-70, SC-250, or SC-800, are usually not used due to environmental limitations on volatiles
	Base and mineral oils	▪ Derived from crude oil in a physical separation process during refining ▪ Mineral oils can also be derived from industrial process by-products
	Petroleum resin	▪ Combination of petroleum resins derived from certain crude oil sources/refining processes and lignin
	Synthetic fluid	▪ Manufactured specifically for dust control and surface stabilization from reaction products of specific chemical feedstock ▪ "Synthetic" is defined by US EPA environmental regulatory testing requirements [40 CFR 435]
	Synthetic fluid plus binder	▪ Synthetic fluid together with binder from organic non-petroleum, organic petroleum, or synthetic polymer emulsion categories. Mix proportions will differ depending on objective.
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Manufactured specifically for dust control and surface stabilization to meet engineered specifications ▪ Can be by-product from adhesive or paint manufacturing processes
Concentrated liquid stabilizers	High acidity	▪ Proprietary sulfuric/phosphoric acid based products
	Low acidity/enzyme	▪ Proprietary enzymatic protein-based products
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Mined/excavated from natural clay deposits

Table A.3: Chemical Treatment Form of Supply

Category	Sub-Category	Form of Supply
Water and water with surfactants	Water	▪ Liquid
	Water with surfactant	▪ Liquid ▪ Added surfactants can be liquid or powder ▪ Surfactant is usually highly concentrated
Water absorbing	Calcium chloride	▪ Liquid with 28 to 42% calcium chloride content, remainder water ▪ Flake with >75% calcium chloride content ▪ Pellet with >94% calcium chloride content
	Magnesium chloride	▪ Liquid with 28 to 33% magnesium chloride content, remainder water
	Sodium chloride	▪ Liquid with varying quantities of sodium, magnesium, and calcium chloride, remainder water ▪ Salt crystals
Organic non-petroleum	Glycerin/glyceride based	▪ Liquid
	Lignosulfonate	▪ Liquid with >25% lignosulfonate content, remainder water ▪ Powder
	Molasses/sugar	▪ Liquid, active solids content vary depending on refining
	Plant oil	▪ Liquid, active solids content vary depending on refining
	Tall oil pitch rosin	▪ Liquid, active solids content vary depending on refining
Organic petroleum	Asphalt emulsion	▪ Liquid
	Base and mineral oils	▪ Liquid. Cannot be diluted with water
	Petroleum resin	▪ Liquid
	Synthetic fluid	▪ Liquid. Cannot be diluted with water
	Synthetic fluid plus binder	▪ Liquid. Cannot be diluted with water
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Liquid ▪ Some products supplied as a powder, but not common
Concentrated liquid stabilizers	High acidity	▪ Liquid, highly concentrated
	Low acidity/enzyme	▪ Liquid, highly concentrated
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Powder

Table A.4: Chemical Treatment Category Attributes

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as the sole basis for a choice of chemical treatment. Specific information should always be requested from the chemical treatment supplier.

Category	Sub-Category	Attributes
Water and water with surfactants	Water	▪ Temporary agglomeration of the road material particles
	Water with surfactant	▪ Improved, but still temporary agglomeration of the road material particles
Water absorbing	Calcium chloride	▪ Hygroscopic[1], deliquescent[2], and exothermic[3] ▪ Agglomerates road material particles and holds them through surface tension ▪ Ability to absorb water is a function of temperature and relative humidity; for example, at 77°F (25°C) calcium chloride starts to absorb water from the air at 29% relative humidity and at 100°F (38°C) it starts to absorb water at 20% relative humidity ▪ Increases surface tension of water film between particles, helping to slow evaporation and further tighten compacted soil as drying progresses ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR), but can act as a compaction aid ▪ Increases soil electrical conductivity (this can be used to track movement in the soil) ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
	Magnesium chloride	▪ Hygroscopic[1], deliquescent[2], and exothermic[3] ▪ Agglomerates road material particles and holds them through surface tension ▪ Absorbs water from the air at >30% relative humidity, independent of temperature ▪ Increases surface tension of water film between particles, helping to slow evaporation and further tighten compacted soil as drying progresses ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR), but can act as a compaction aid ▪ Increases soil electrical conductivity (this can be used to track movement in the soil) ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
	Sodium chloride brine	▪ Agglomerates road material particles and holds them through surface tension ▪ Water-absorbing ability is dependent on percentages of magnesium, calcium, and sodium chloride ▪ Sodium chloride absorbs water from the air at 80% relative humidity independent of temperature ▪ Increases surface tension of water film between particles to a lesser degree than calcium and magnesium chloride ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Increases soil electrical conductivity (this can be used to track movement in the soil) ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance

1 Hygroscopic: absorbs moisture from the air
2 Deliquescent: salt in solid form can dissolve into a liquid by absorbing atmospheric moisture
3 Exothermic: gives off heat as it dissolves from a solid to a liquid

Table A.4: Chemical Treatment Category Attributes *(continued)*

Category	Sub-Category	Attributes
Organic non-petroleum	Glycerin/glyceride based	▪ Usually combined with other organic non-petroleum binders ▪ Agglomerates road material particles through gluing and humectant (hygroscopic) properties. Duration/effectiveness is dependent on constituents. ▪ Effective at very low temperatures ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) unless mixed with other stabilization treatment ▪ Treated road can be bladed and recompacted after light watering with some effect on performance. May require retreatment after maintenance.
	Lignosulfonate	▪ Lignins and complex carbohydrates glue road material particles together ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
	Molasses/sugar	▪ Complex carbohydrates glue road material particles together providing temporary binding of the road surface particles ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with some effect on performance ▪ Typically requires retreatment after maintenance
	Plant oil	▪ Agglomerates road material particles ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with some effect on performance. May require retreatment after maintenance.
	Tall oil pitch rosin	▪ Rosins glue road material particles together ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Has better water resistance than other organic non-petroleum treatments ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
Organic petroleum	Asphalt emulsion	▪ Asphalt binds and agglomerates road material particles together ▪ Will reduce moisture sensitivity of material ▪ Increases soaked shear strength (e.g., CBR) when mixed into material, but does not chemically reduce plasticity index ▪ Usually forms a crust on the surface of the road that cannot be maintained with a grader ▪ Requires reapplication after maintenance
	Base and mineral oils	▪ Agglomerates road material particles ▪ Retains effectiveness during long dry periods with low humidity ▪ Effective at low temperatures ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with no effect on performance

Table A.4. Chemical Treatment Category Attributes *(continued)*

Category	Sub-Category	Attributes
Organic petroleum	Petroleum resin	▪ Agglomerates road material particles ▪ Will reduce moisture sensitivity of material ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases soaked shear strength (e.g., CBR), but does not chemically reduce plasticity index ▪ Treated road can be bladed and recompacted after light watering with some effect on performance. Typically requires rejuvenation after maintenance.
	Synthetic fluid	▪ Agglomerates road material particles through cohesive binding mechanism ▪ Retains effectiveness during long dry periods with low humidity ▪ Retains effectiveness at extreme temperatures (hot or cold) ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
	Synthetic fluid plus binder	▪ Agglomerates road material particles through adhesive and cohesive binding mechanism ▪ Retains effectiveness during long dry periods with low humidity and in extreme temperatures (hot and cold) ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index but may increase soaked shear strength (e.g., CBR) depending on type of binder ▪ Treated road can be bladed and recompacted after light watering. Effect on performance depends on type of binder used.
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Binds surface particles through adhesive properties ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases soaked shear strength (e.g., CBR) when mixed into material, but does not chemically reduce plasticity index ▪ Usually forms a crust on the surface of the road that cannot be maintained with a grader ▪ Requires reapplication after maintenance
Concentrated liquid stabilizers	High acidity	▪ Highly concentrated, therefore low transport costs ▪ Cation exchange alters clay mineral structure to reduce moisture sensitivity of the material ▪ Retains effectiveness during long dry periods with low humidity ▪ Effective compaction aid ▪ Increases soaked shear strength (e.g., CBR) when mixed into material, but does not reduce plasticity index ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
	Low acidity/enzyme	▪ Highly concentrated, therefore low transport costs ▪ Stabilization mechanism is not clearly understood, but protein molecules react with soil molecules to form a cementing bond that stabilizes the soil structure and reduces the soil's affinity for water ▪ Strength increases, when mixed into the material, are often associated with compaction aid properties ▪ Does not reduce plasticity index ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Clay is used to increase fines content of material and mechanically bind larger particles together to prevent washboarding and raveling ▪ Will increase plasticity index, but will not increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with limited or no effect on performance

Table A.5: Chemical Treatment Application Rates and Frequency

Category	Sub-Category	Typical Application Rate and Frequency
The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as the sole basis for determining application rates. Specific information should always be requested from the chemical treatment supplier. Supplied concentrations and recommended dilution rates should be fully understood to ensure that treatments from different distributors are compared fairly.		
Water and water with surfactants	Water	▪ Spray-on application only ▪ Application rate depends on material properties, with higher rates on sandy materials ▪ Application frequency depends on temperature and humidity, but generally only effective for 0.5 to 12 hours
	Water with surfactant	▪ Spray-on application only ▪ Application rate depends on material properties, with higher rates on sandy materials ▪ Application frequency depends on temperature and humidity, but generally only effective for 0.5 to 12 hours
Water absorbing	Calcium chloride	▪ Spray-on or mix-in treatments. Mix-in will have longer effectiveness. ▪ Initial application: - Liquid: 35 to 38% residual @ 0.2 to 0.35 g/yd^2 (0.9 to 1.6 L/m^2), typical application is 38% residual concentrate applied undiluted @ 0.35 g/yd^2 (1.6 L/m^2) - Flake: 1.0 to 2.0 lb./yd^2 (0.4 to 1.1 kg/m^2), typical application 1.7 lb./yd^2 (0.9 kg/m^2) @ 77% purity - Pellet: 1.0 to 1.8 lb./yd^2 (0.4 to 0.7 kg/m^2), typical application 1.4 lb./yd^2 (0.5 kg/m^2) @ 94% purity ▪ Spray-on applications are best applied in multiple light applications to optimize penetration ▪ Rejuvenation is 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first one applied at end of wet or winter season
	Magnesium chloride	▪ Spray-on or mix-in treatments. Mix-in will have longer effectiveness. ▪ Initial application is 28 to 35% residual @ 0.3 to 0.5 g/yd^2 (1.4 to 2.3 L/m^2), typical application is 30% residual concentrate applied undiluted @ 0.5 g/yd^2 (2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to optimize penetration ▪ Rejuvenation is usually 50% of initial application rate ▪ Generally 1 to 2 treatments per season; first one applied at end of wet or winter season
	Sodium chloride	▪ Usually spray-on treatments ▪ Application rate depends on calcium and magnesium chloride content ▪ Rejuvenation rate and interval dependent on calcium and magnesium chloride content
Organic non-petroleum	Glycerin/glyceride based	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment ▪ Initial application rate dependent on properties of glycerin and added binders, but typically 0.25 to 0.5 g/yd^2 (1.1 to 2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to optimize penetration. Higher product temperatures improve penetration. ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season depending on temperature and humidity, with first one applied at end of wet or winter season

Table A.5: Chemical Treatment Application Rates and Frequency *(continued)*

Category	Sub-Category	Typical Application Rate and Frequency
Organic non-petroleum	Lignosulfonate	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. ▪ Initial application rate dependent on lignosulfonate content: - 10 to 25% residual @ 0.5 to 1.0 g/yd² (2.3 to 4.5 L/m²), typical application is 25% residual concentrate applied undiluted @ 0.5 g/yd² (2.3 L/m²) - 50% residual applied diluted 1:1 with water @ 1.0 g/yd² (4.5 L/m²) - Powder form mixed with water to give equivalent to 50% residual applied diluted 1:1 @ 1.0 g/yd² (4.5 L/m²) ▪ Spray-on applications are best applied in multiple light applications to optimize penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season, with first one applied at end of wet or winter season
	Molasses/sugar	▪ Usually spray-on treatments ▪ Application rate depends on sugar content ▪ Rejuvenation rate and interval dependent on sugar content
	Plant oil	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. ▪ Initial application rate dependent on type of oil and oil content, but typically 0.25 to 0.5 g/yd² (1.1 to 2.3 L/m²) ▪ Spray-on applications are best applied in multiple light applications to optimize penetration. Higher product temperatures improve penetration. ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first one applied at end of wet or winter season
	Tall oil pitch rosin	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. Mix-in treatments must be used for stabilization. ▪ Initial application rate dependent on rosin content: - 10 to 20% residual @ 0.3 to 1.0 g/yd² (1.4 to 4.5 L/m²) - 40 to 50% residual applied diluted 1:4 with water @ 0.5 g/yd² (2.3 L/m²) ▪ Spray-on applications are best applied in multiple light applications to optimize penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 treatment every 1 to 2 years
Organic petroleum	Asphalt emulsion	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. Mix-in treatments must be used for stabilization. ▪ Initial application rate typically 0.1 to 0.3 g/yd² (0.25 to 1.5 L/m²) residual asphalt content ▪ Generally 1 treatment per season
	Base and mineral oils	▪ Usually spray-on treatment, but mix-in treatment will have longer period of effectiveness ▪ Initial application rate typically 0.33 g/yd² (1.5 L/m²) ▪ Spray-on applications are best applied in 2 or 3 light applications to optimize penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first one applied at end of wet or winter season
	Petroleum resin	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. Mix-in treatments must be used for stabilization. ▪ Initial application rate typically 0.11 to 0.55 g/yd² (0.5 to 2.5 L/m²) depending on material properties ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first one applied at end of wet or winter season

Table A.5: Chemical Treatment Application Rates and Frequency *(continued)*

Category	Sub-Category	Typical Application Rate and Frequency
Organic petroleum	Synthetic fluid	▪ Usually spray-on treatment, but mix-in treatment will have longer period of effectiveness. Mix-in treatment must be used for stabilization. ▪ Initial application rate typically 0.22 g/yd^2 (1.1 L/m^2) ▪ Spray-on applications are best applied in 1 or 2 light applications to optimize penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first one applied at end of wet or winter season
	Synthetic fluid plus binder	▪ Mix-in treatment for stabilization ▪ Initial application rate dependent on binder type and properties, and on intended outcome or engineering specification, but typically 0.22 g/yd^2 (1.0 L/m^2) ▪ Annual rejuvenation typically synthetic fluid plus binder applied at 0.11 to 0.17 g/yd^2 (0.5 to 0.75 L/m^2)
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Spray-on or mix-in treatments. Spray-on treatments might have limited effectiveness due to skin forming on surface. Mix-in treatments must be used for stabilization. ▪ Initial application rate dependent on residual polymer content: - 5 to 15% residual @ 0.3 to 1.0 g/yd^2 (1.4 to 4.5 L/m^2) - 40 to 50% residual applied diluted 1:9 with water @ 0.5 g/yd^2 (2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light, highly diluted applications to optimize penetration ▪ Spray-on applications require reapplication after maintenance ▪ Rejuvenation on mix-in treatments is usually 50 to 80% of initial application rate ▪ Generally 1 to 2 treatments per season for spray-on treatments ▪ Generally 1 treatment per year for mix-in treatments
Concentrated liquid stabilizers	High acidity	▪ Mix-in treatments only ▪ Application rates typically vary between 0.01 and 0.03 L/m^2 (0.002 and 0.01 g/yd^2) ▪ Reaction is theoretically permanent so rejuvenation is not required
	Low acidity/ Enzyme	▪ Mix-in treatments only ▪ Application rates typically vary between 0.01 and 0.03 L/m^2 (0.002 and 0.01 g/yd^2) ▪ Reaction is theoretically permanent so rejuvenation is not required
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Mix-in treatments only ▪ Application rate dependent on material grading and plasticity index, with best results obtained when fines content after treatment is between 11 and 20 percent and plasticity index is between 6 and 10% (typically 1 to 3% clay by dry weight of aggregate) ▪ Rejuvenation is not required

Table A.6: Chemical Treatment Environmental Impacts

Category	Sub-Category	Environmental Impacts
The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as a basis for determination of the potential level of environmental impact. Proof of environmental testing should always be requested from the chemical treatment supplier.		
Water and water with surfactants	Water	▪ Depends on water source. Industrial water can have significant impacts. ▪ Social impacts associated with using water that could otherwise be used for domestic or agricultural purposes
	Water with surfactant	▪ Depends on water source. Industrial water can have significant impacts. ▪ Social impacts associated with using water that could otherwise be used for domestic or agricultural purposes ▪ Impacts to fresh water aquatic biota: when added to water or plant oils for dust control, may target gill tissue after spills/leaching into small streams
Water absorbing	Calcium chloride	▪ Considerable documented research and testing on environmental impacts ▪ Some impacts are confused with snow and ice control for which application rates are higher and application intervals more frequent ▪ Impacts to water quality: generally negligible if an appropriate buffer zone is maintained between road and water ▪ Impacts to fresh water aquatic biota: may develop at chloride concentrations as low as 400 ppm for trout and up to 10,000 ppm for other fish species. Application rates for fines preservation/dust control typically do not lead to runoff of the treatment into streams. ▪ Impacts to plants: some species may be susceptible to damage, such as pine, hemlock, poplar, ash, spruce, and maple if frequent high application rates are used ▪ Impacts to mammals: salt may attract animals to road ▪ Potential concerns with spills
	Magnesium chloride	▪ Considerable documented research and testing on environmental impacts ▪ Some impacts are confused with snow and ice control for which application rates are higher and application intervals more frequent ▪ Impacts to water quality: generally negligible if an appropriate buffer zone is maintained between road and water ▪ Impacts to fresh water aquatic biota: may develop at chloride concentrations as low as 400 ppm for trout and up to 10,000 ppm for other fish species. Application rates for fines preservation/dust control typically do not lead to runoff of the treatment into streams. ▪ Impacts to plants: some species may be susceptible to damage, such as pine, hemlock, poplar, ash, spruce, and maple if frequent high application rates are used ▪ Impacts to mammals: salt may attract animals to road ▪ Potential concerns with spills
	Sodium chloride	▪ Considerable documented research and testing on environmental impacts ▪ Some impacts are confused with snow and ice control for which application rates are higher and application intervals more frequent ▪ Impacts to water quality: generally negligible if an appropriate buffer zone is maintained between road and water ▪ Impacts to fresh water aquatic biota: may develop at chloride concentrations as low as 400 ppm for trout and up to 10,000 ppm for other fish species ▪ Impacts to plants: some species may be susceptible to damage, such as pine, hemlock, poplar, ash, spruce, and maple ▪ Impacts to mammals: salt may attract animals to road ▪ Potential concerns with spills

Table A.6: Chemical Treatment Environmental Impacts *(continued)*

Category	Sub-Category	Environmental Impacts
Organic non-petroleum	Glycerin/glyceride based	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: none recorded ▪ Impacts to fresh water aquatic biota: none recorded ▪ Impacts to plants: none recorded ▪ Impacts to mammals: may attract animals to road ▪ Unrefined recycled food-based glycerides may have unpleasant odor ▪ Potential concerns with spills
	Lignosulfonate	▪ Considerable documented research and testing on environmental impacts ▪ Impacts to water quality: none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills
	Molasses/sugar	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: unknown/none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: unknown, none expected ▪ Impacts to mammals: animals and insects may be attracted to road ▪ Potential concern with spills
	Plant oil	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: unknown/none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: unknown, none expected ▪ Impacts to mammals: animals and insects may be attracted to road ▪ Potential concern with spills
	Tall oil pitch rosin	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: unknown/none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: unknown, none expected ▪ Impacts to mammals: unknown, none expected ▪ Potential concern with spills
Organic petroleum	Asphalt emulsion	▪ Considerable documented research and testing on environmental impacts ▪ Impacts to water quality: none after curing ▪ Impacts to fresh water aquatic biota: none after curing ▪ Impacts to plants: none provided no direct application ▪ Impacts to mammals: none after curing ▪ Cutbacks are not permitted in some areas due to impact of volatiles on air quality ▪ May have regulatory storage and reporting requirements ▪ Potential concern with spills
	Base and mineral oils	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ May have regulatory storage and reporting requirements ▪ Potential concern with spills and leaching prior to curing

Table A.6: Chemical Treatment Environmental Impacts *(continued)*

Category	Sub-Category	Environmental Impacts
Organic petroleum	Petroleum resin	▪ Considerable documented research and testing on environmental impacts ▪ Impacts to water quality: none after curing ▪ Impacts to fresh water aquatic biota: none after curing. May be a concern if large volumes are spilled. ▪ Impacts to plants: none provided no direct application ▪ Impacts to mammals: none after curing ▪ May have regulatory storage and reporting requirements ▪ Potential concern with spills
	Synthetic fluid	▪ Must meet EPA environmental-based criteria for synthetic (sediment toxicity, biodegradability, PAH content, aquatic toxicity, and oil sheen free) ▪ Impacts to water quality: none. May be a concern if large volumes are spilled ▪ Impacts to fresh water aquatic biota: none ▪ Impacts to plants: none ▪ Impacts to mammals: none ▪ Potential concerns with spills
	Synthetic fluid plus binder	▪ Impacts are dependent on specific binder chemistry but combination usually still meets EPA environmental based criteria for synthetic ▪ Impacts to water quality: none expected ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concerns with spills
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ Impacts to water quality: none expected. May be a concern if large volumes are spilled. ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills
Concentrated liquid stabilizers	High acidity	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ pH of undiluted product is very low ▪ Impacts to water quality: none expected. May be a concern if large volumes are spilled. ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills of concentrate
	Low acidity/enzyme	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ Impacts to water quality: none expected ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills of concentrate

Table A.6: Chemical Treatment Environmental Impacts *(continued)*

Category	Sub-Category	Environmental Impacts
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Natural soil material ▪ Impacts to water quality: may increase sediment in water if erosion from road surface is not managed ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected

Table A.7: Chemical Treatment Limitations

Category	Sub-Category	Limitations
The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as the sole basis for the choice of chemical treatment. Specific information should always be requested from the chemical treatment supplier.		
Water and water with surfactants	Water	▪ Short-term dust control only, evaporates readily ▪ Generally the least cost-effective and most labor-intensive form of dust control in the long term
	Water with surfactant	▪ Short-term dust control only, evaporates readily, but some improvement compared to water only ▪ Generally the least cost-effective and most labor-intensive form of dust control in the long term
Water absorbing	Calcium chloride	▪ Requires minimum humidity level to absorb moisture from the air ▪ Performs better than magnesium chloride when high humidity is present, but does not perform as well as magnesium chloride in long dry spells ▪ Slightly corrosive to metal, corrosive to aluminum and its alloys, attracts moisture thereby prolonging active period for corrosion ▪ Rainwater tends to leach out soluble chlorides if surface is not compacted ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Solutions with <20% residual calcium chloride have similar performance to water spraying
	Magnesium chloride	▪ Requires minimum humidity level to absorb moisture from the air ▪ Corrosive to steel in concentrated solutions (some products may contain a corrosion-inhibiting additive), attracts moisture thereby prolonging active period for corrosion ▪ Rainwater tends to leach out soluble chlorides if surface is not compacted ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Solutions with <20% residual magnesium chloride have similar performance to water spraying
	Sodium chloride	▪ Performance is dependent on calcium and magnesium content ▪ Calcium chloride and magnesium chloride provide better performance ▪ Requires minimum humidity level to absorb moisture from the air ▪ Corrosive to steel in concentrated solutions and moderately corrosive in dilute solutions ▪ Rainwater tends to leach out soluble chlorides if surface is not compacted ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm])
Organic non-petroleum	Glycerin/glyceride based	▪ Requires minimum humidity level to retain moisture in aggregate matrix ▪ Pricing closely linked to biodiesel, grain, and competing markets, therefore can fluctuate
	Lignosulfonate	▪ Performance varies depending on tree species, extraction process, and level of refining (i.e., sugar content) ▪ Higher value competing markets may affect availability and product quality (i.e., lower active binder content) ▪ May cause corrosion of aluminum and its alloys ▪ Surface binding action may be reduced or completely destroyed by heavy rain, due to solubility of solids in water ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Surface may deteriorate during extended dry periods

Table A.7: Chemical Treatment Limitations *(continued)*

Category	Sub-Category	Limitations
Organic non-petroleum	Molasses/sugar	▪ Performance varies depending on extraction process and level of refining ▪ Limited period of effectiveness compared to other organic non-petroleum treatments ▪ Surface binding action may be reduced or completely destroyed by heavy rain, due to solubility of solids in water ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Surface may deteriorate during extended dry periods ▪ Generally only available in close proximity to sugar mills. Usually not cost-effective if transported long distances.
	Plant oil	▪ Performance varies depending on extraction process and level of refining ▪ Can oxidize rapidly and become brittle ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Higher value competing markets (e.g., food related) may affect availability and price
	Tall oil pitch rosin	▪ Performance varies depending on tree species, extraction process, and level of refining ▪ Higher value competing markets may affect availability and product quality ▪ Surface binding action may be reduced by heavy rain, due to solubility of solids in water ▪ Surface may deteriorate during extended dry periods
Organic petroleum	Asphalt emulsion	▪ Price directly linked to crude oil prices and can therefore fluctuate ▪ Can oxidize rapidly and become brittle ▪ Difficult to maintain. Most treatments cannot be maintained with conventional unpaved road techniques. ▪ Usually requires reapplication after maintenance ▪ May have regulatory storage and reporting requirements
	Base and mineral oils	▪ Wide variety of products available with performance dependent on chemistry and level of processing. Products from waste streams may have variable performance over time. ▪ Price often linked to crude oil prices and can therefore fluctuate ▪ May have regulatory storage and reporting requirements
	Petroleum resin	▪ Price often linked to crude oil prices and can therefore fluctuate ▪ Surface may be difficult to maintain if thick, hard crust forms
	Synthetic fluid	▪ Price often linked to crude oil prices and can therefore fluctuate
	Synthetic fluid plus binder	▪ Price often linked to crude oil prices and can therefore fluctuate
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Price often linked to crude oil prices and can therefore fluctuate ▪ Wide variety of products available with performance dependent on source and level of processing. Products from waste streams may have variable performance over time. ▪ Spray-on treatments usually have limited period of performance due to formation of skin or crust on the surface ▪ Can break down under ultraviolet light ▪ Difficult to maintain. Most treatments cannot be maintained with conventional unpaved road techniques. ▪ Usually requires reapplication after maintenance

Table A.7: Chemical Treatment Limitations *(continued)*

Category	Sub-Category	Limitations
Concentrated liquid stabilizers	High acidity	▪ Wide variety of products available ▪ Requires relatively high clay and fines content for satisfactory reaction to take place ▪ Performance is highly dependent on clay mineralogy of the material ▪ Actual stabilization mechanism is difficult to assess in a laboratory ▪ Period until stabilization (i.e., required strength gain) has been achieved may be several months ▪ Product formulations are often changed to suit specific applications ▪ May require separate dust control treatment to prevent fines loss ▪ Limited independent scientific research to back up manufacturers claims
Concentrated liquid stabilizers	Low acidity/ Enzyme	▪ Wide variety of products available ▪ Requires relatively high clay and fines content for satisfactory reaction to take place ▪ Performance is highly dependent on mineralogy of the material ▪ Actual stabilization mechanism is difficult to assess in laboratory ▪ Period until stabilization (i.e., required strength gain) is achieved may be several months ▪ Product formulations are often changed to suit specific applications ▪ May require separate dust control treatment to prevent fines loss ▪ Limited independent scientific research to back up manufacturers claims
Mechanical stabilization	Bentonite or suitable locally available clay	▪ Surface may become slippery if fines content and plasticity design limits are exceeded

Blank page

APPENDIX B: UNDERSTANDING UNPAVED ROAD MATERIALS

B.1 Introduction

Unpaved road chemical treatments are best used for keeping a "good road in good condition" (Figure B.1), rather than trying to use them to correct serious material, construction, and/or maintenance deficiencies (Figure B.2). In addition to traffic and climate, unpaved road performance is also linked to subgrade, base, and wearing course layer properties, road geometry, road shape, and drainage, and to construction and maintenance quality. An understanding of all these factors is therefore required before an appropriate chemical treatment can be selected and a treatment program initiated. Using inappropriate materials in the wearing course will probably have the biggest impact on dust levels, slipperiness, all-weather passability, and how quickly the road deteriorates due to washboarding, raveling, and erosion. Consequently, considerable information is provided in this appendix on understanding material properties to ensure that the best possible road performance is achieved.

Figure B.1: Good gravel road.

Figure B.2: Poor gravel road.

How well an unpaved road performs depends on the materials used on it and how those materials are shaped and compacted to form a riding surface. It is important to consider that much of the imported aggregate used for base and wearing courses on unpaved roads in the United States comes from commercial sources whose primary focus is supplying materials for paved roads and building projects. Consequently, the aggregate commonly supplied for unpaved roads will meet the specifications for asphalt concrete, asphalt surface treatments (chip seals), portland cement concrete, or aggregate base for paved roads. Many practitioners mistakenly believe that if materials meet the specifications for aggregate base in a paved highway that they will work as well in an unpaved road wearing course. This is an incorrect assumption! For example, aggregate base used in paved roads is confined by the chip seal, asphalt concrete, or portland cement concrete on the surface, and therefore gradings are optimized for strength (and frost-heave protection where applicable) as the base is not directly subjected to traffic abrasion or the weather. Therefore, a different set of material selection criteria and specifications is needed for unpaved road wearing courses to compensate for this lack of surface containment. Adjustment of the fines content and clay content are usually the most important considerations.

B.2 Material Testing

Key material properties influencing unpaved road wearing course performance include the grading (or particle size distribution), particle shape, the fines content, the clay content, and the material shear strength. These are determined from basic material indicator tests including:

- A grading analysis (e.g., AASHTO T 27 or ASTM C136)
- A plasticity test (e.g., Atterberg limits [AASHTO T 89 and T 90 or ASTM D4318] or bar linear shrinkage [Caltrans CT 228, Texas Tex-107-E, or method provided in Appendix B.1]), and
- A strength test (e.g., California Bearing Ratio [AASHTO T 193 or ASTM D1883]).

Representative samples for the testing should be collected from the existing wearing course, underlying materials, if blending is anticipated, or from the quarry stockpile, if new aggregates are going to be imported prior to treatment. These samples should then be subjected to the tests listed above to check that they meet the required specifications. All of these tests are simple to perform and cost very little (at a commercial laboratory in 2017, grading analysis and Atterberg limit tests cost approximately $250 and $150, respectively, and a California Bearing Ratio [CBR] test cost approximately $750). These costs are negligible in terms of the costs of gravel replacement and selection of the correct chemical treatment, and can potentially be recovered many times over when better material selection results in extended road life and reduced grader maintenance requirements. The very small up-front savings enjoyed by skipping material testing will invariably mean higher costs later on because of early replacement of gravel and more frequent maintenance. Most unpaved road specifications are based on these or similar tests.

B.3 Unpaved Road Specifications

There is a range of recommendations, guidelines, and specifications available for the design of unpaved roads, covering geometry, thickness, shape, base and wearing course materials, and construction. Although this document discusses how these topics pertain to unpaved road chemical treatments, readers are referred to their organizations' in-house specifications or to the example documents listed below, for more information regarding unpaved roads in general. Note that national or general specifications must often be adapted to suit local conditions and material availability.

- *Stabilization and Rehabilitation Measures for Low-Volume Forest Roads*. (U.S. Forest Service) *(8)*
- *Unsealed Roads Manual: Guidelines to Good Practice*. (Australian Road Research Board) *(11)*

- *Unsealed Roads: Design, Construction and Maintenance*. (South African Department of Transport) *(12)*
- *Gravel Roads Construction and Maintenance Guide.* (Federal Highway Administration) *(15)*
- *Earth and Aggregate Surfacing Design Guide for Low Volume Roads. (U.S. Forest Service) (16)*
- *Guidelines for Surfacing Aggregate. (U.S. Forest Service) (17)*
- *Standard Specifications for the Construction of Roads and Bridges on Federal Highway Projects (Federal Highway Administration) (18)*
- *Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT ≤ 400)* (American Association of State Highway and Transportation Officials [AASHTO]) *(30)*
- *Gravel Road Management: Implementation Guide.* (Montana Local Transportation Assistance Program) *(31)*

Examples of Federal Highway Administration (FHWA) specifications *(18)* and FHWA and US Forest Service (USFS) guidance *(15,16)* for unpaved road wearing course materials are shown in Table B.1.

Table B.1: Example Specifications/Guidelines for Unpaved Road Surfacing Materials

Parameter			FHWA Specification *(18)*		FHWA and USFS Guidelines		
			Target	Tolerance	FHWA *(15)*	USFS *(16)*	
						Haul	General Use
Sieve size	1	(25)	100	--	100	97 – 100	100
(U.S. [mm])	3/4	(19)	97 – 100	--	90 – 100	76 – 89	97 – 100
	#4	(4.75)	41 – 71	±7	50 – 78	43 – 53	51 – 63
	#8	(2.36)	--	--	37 – 67	23 – 32	28 – 39
	#40	(0.425)	12 – 28	±5	13 – 35	15 – 23	19 – 27
	#200	(0.075)	9 – 16	±4	4 – 15	10 – 16[1]	10 – 16[1]
Plasticity Index			8	±4	4 – 12	2 – 9 if passing #200 is <12% <2 if passing #200 is >12%	
[1] Range for #200 (0.075 mm) sieve is 6.0 to 12.0% if the PI is greater than 0							

B.4 Influence of Material Properties on Performance

B.4.1 Current Approach for Interpreting Laboratory Test Results in the United States

Interpreting laboratory test results in terms of understanding actual performance on the road is difficult when grading analysis and plasticity index results are simply listed in guidance and specifications, as shown in Table B.1. Uncertainty also arises when guidance and/or specifications from two or more reputable organizations are compared and the proposed ranges differ considerably (e.g., the FHWA and USFS guidance shown in Table B.1), which can lead to confusion in determining which one is “correct” or more appropriate for a given set of climate, traffic, and road alignment conditions. The problem is worsened when an aggregate supplier cannot meet the specification or when a road owner uses gravel from a source located on their own property (i.e., will the material still provide satisfactory performance if it does not meet the specification and/or will the costs of maintenance on the road be higher?). To overcome these problems, a number of procedures have been developed for interpreting grading analyses in terms of expected performance of the material on the road; an example of the grading interpretation chart used by the USFS is shown in Figure B.3 *(8)*.

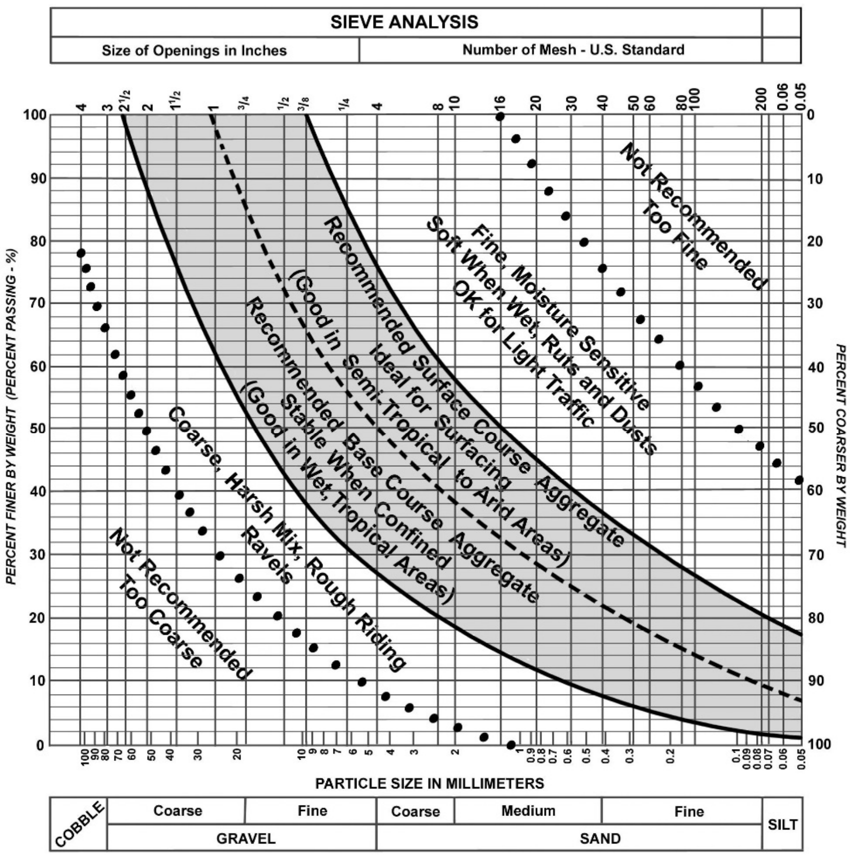
Grain Size Distribution	Plasticity
	As a surfacing material, crushed aggregate should provide structural support, but it also needs to be very well graded and have some plastic binder to reduce raveling and washboarding. Maximum density is achieved with between 6 and 12% fines. Ideally aggregate used for road surfacing materials or a wearing surface should have 10 to 15% fines and a Plasticity Index (PI) of 2 to 9. In a wet climate the PI requirement is less critical, and too many clay fines can contribute to local water quality degradation. In a wet region, the ideal PI range may be 0 to 5. In a dry, semi-arid climate a PI range of 5 to 9 appears more desirable

Figure B.3: Example guidance for interpreting grading and plasticity test results *(8)*.

In most available guidelines, the recommendations for grading and plasticity are usually presented separately (USFS example also provided in Figure B.3), which can be misleading since the influence of plasticity on unpaved road performance is always linked to the fines content (i.e., the higher the fines content, the greater the influence of the plasticity on road performance). Very few of these methods, including the USFS guide, combine the grading analysis and plasticity test results in a single performance prediction chart, and therefore they often tend to give a wider range of potentially "acceptable" materials that do not necessarily always relate to year-round good performance on the road.

B.4.2 An Alternative Approach for Interpreting Laboratory Test Results

Research in southern Africa in the 1980s and 1990s *(12,19,32)*, which entailed a comprehensive statistical analysis of results from the long-term monitoring of more than 100 test sections selected according to a scientific experimental design and from the laboratory tests on materials sampled from each road during the evaluation, found that unpaved road performance can be better understood if the grading analysis and plasticity test results are interpreted together instead of being considered independently. A simple three-step procedure, based on this research and described below, can be used to interpret test results, assess the applicability of local material specifications, and understand how an unpaved road is likely to perform if a particular material with a specific grading and plasticity index is used. The procedure can also be used to make a decision regarding material choice, road design specifications, and chemical treatment selection. Although this approach is used as the basis for specifications in many countries worldwide, in this guideline it is only proposed as a guide for interpreting test results from individual projects and refining current specifications and NOT necessarily as a new specification; nor is it intended that it necessarily replace existing specifications. This approach may need to be refined for particular situations and calibrated for local conditions, specifically traffic and climate. Although the South African approach has been widely published, and adopted and implemented in numerous countries worldwide *(11,12,33-35)*, it has not been formally evaluated or implemented in the United States.

B.4.3 Step-1 – Test Result Analysis

<u>Grading Analysis</u>

In this recommended approach, five key sieve sizes from a standard laboratory grading analysis test are required for understanding material performance and selecting an appropriate chemical treatment. These key sieve sizes are 1.0 in., #4, #8, #40, and the #200 (~25 mm, 4.75 mm, 2.36 mm, 0.425 mm, and 0.075 mm). The first three are used to check for an appropriate mix of coarse, intermediate, and fine particles using the following simple formula known as the *grading coefficient* (G_c) *(12,32)*:

G_c = ((P1.0 in. – P#8) × P#4) / 100 or

G_c = ((P25 mm – P2.36 mm) × P4.75 mm) / 100

where P is percent passing

The percentage of material passing the #200 (0.075 mm) sieve is also a useful indicator of how an unpaved road will perform, and will influence the decision of what chemical treatment to use. High percentages of material passing this sieve (i.e., more than 20 percent) signal that the road will be dusty when dry and may become slippery when wet. Low percentages (i.e., less than 10 percent) signal that the road will likely washboard and require frequent grader maintenance. Many unpaved road wearing course specifications that are based on paved road base course specifications limit this fines content to a maximum of about five to eight percent in the mistaken belief that this will reduce dust. However, determining the percent passing the #200 sieve (usually done using a wet process as part of a standard grading analysis) is not as simple as determining the percent passing the #8 (2.36 mm) sieve (which can be done in a dry sieve analysis, if necessary, as a quick indicator in the field). Consequently, to obtain a basic understanding of how materials are likely to perform, this approach factors the #200 material into the grading coefficient equation as part of the material passing the #8 sieve. The percent passing the #200 sieve is, however, still required for the chemical treatment selection procedure discussed in Chapter 3.

The percentage of material passing the #40 (0.425 mm) sieve is used together with a plasticity test to understand the effects of clay in the material and is discussed in the following section.

Although the grading coefficient is determined using material passing the 1 in. (~25 mm) sieve, and many specifications list this as a maximum size, some larger aggregate (1½ in. to 1¾ in. [40 mm to 45 mm]) is usually acceptable to provide adequate all-weather passability. The use of aggregates larger than this will reduce ride quality, make the road noisy to travel on, and cause problems for the maintenance grader operator. As a general rule, the maximum aggregate size should never exceed one-third of the thickness of the compacted layer.

The angularity of the aggregate should also be visually checked during the sieve analysis. Cubic/angular material (Figure B.4) has better interlock than rounded material (e.g., uncrushed alluvial aggregates [Figure B.5]), and consequently rounded aggregate should be crushed to obtain at least two fracture faces to enhance interlock and prevent raveling.

Figure B.4: Cubicle aggregate.

Figure B.5: Rounded aggregate.

<u>Clay Content</u>

The plasticity index, determined from the Atterberg limit tests (or preferably the less commonly used bar linear shrinkage [BLS] test), is used together with the percent passing the #40 sieve (0.425 mm, i.e., the material on which the Atterberg limit and BLS tests are conducted) to evaluate the influence of clay content on likely performance, using the following simple formula known as the *shrinkage product* (S_p):

$S_p = (PI \times 0.5) \times P\#40$ if plasticity index is used (P#40 = 0.425 mm), or

$S_p = BLS \times P\#40$ if the bar linear shrinkage is used

Note that using the bar linear shrinkage to determine the shrinkage product is more accurate than using the plasticity index, especially for silty non-plastic or slightly plastic materials. These materials often have a plasticity index of zero, and consequently also a shrinkage product of zero if the formula is used with plasticity index results. However, these materials will usually have some measurable linear shrinkage [i.e., BLS > 1], thereby providing a non-zero number to work with to better estimate expected performance. Recommendations for dealing with these situations when only plasticity index values are available are as follows (Figure B.6):

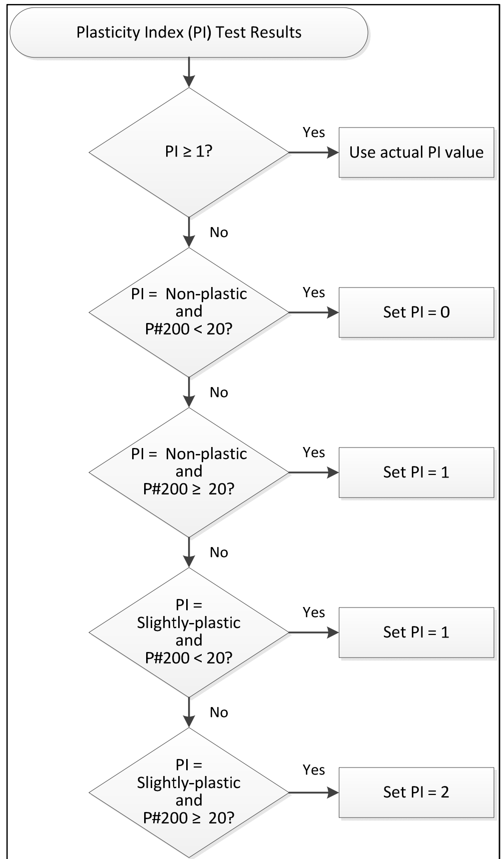


Figure B.6: Plasticity Index result interpretation.

- If the PI of the material is equal to or greater than one, use the actual PI value without modification.
- If the material is non-plastic (i.e., PI = 0) and the percent passing the #200 sieve is less than 20 percent, set the PI to zero in the shrinkage product equation.
- If the material is non-plastic and the percent passing the #200 sieve is more than 20 percent, set the PI to 1 in the equation.
- If the material is termed "slightly plastic" in the laboratory test results and the percent passing the #200 sieve is less than 20 percent, set the PI to 1 in the equation.
- If the material is termed "slightly plastic" and the percent passing the #200 sieve is more than 20 percent, set the PI to 2 in the equation.

Shear Strength

The California Bearing Ratio (CBR), which is performed on material in the laboratory, is the most commonly used shear strength or bearing capacity test for granular materials used in unpaved roads *(1)*. No formulas are required to interpret the results from this test.

B.4.4 Step-2 – Test Result Interpretation

Optimal unpaved road performance will usually be achieved when the wearing course materials meet the following criteria *(12,19,20,32)*:

- The grading coefficient is between 15 and 35. Although fines content is not directly measured in the grading coefficient formula, a fines content (material passing the #200 [0.075 mm] sieve) of between 12 and 20 percent is typically required to meet optimal grading coefficient requirements.

- The shrinkage product is between 100 and 365 (or between 100 and 250 if dust is a major concern and no dust control treatment is planned). Depending on the fine material fraction (percent passing the #200 sieve), the lower limit can usually be relaxed for lower traffic volumes (e.g., the shrinkage product can be relaxed to 50 and 75 for traffic volumes of 50 and 75 vehicles per day, respectively, provided that the fines content is between 12 and 20 percent). Many unpaved road specifications based on those for paved road base courses limit or exclude any clay content, incorrectly assuming that this will reduce dust. On the contrary, small amounts of clay bind aggregate particles together, preventing washboarding and reducing dust.
- Assuming that the road has a quality base course with adequate soaked CBR, the soaked CBR of the wearing course should be above a minimum of 15 percent (determined at 95 percent of AASHTO T 180 or ASTM D1557 compaction). If truck traffic predominates and the road is in a high rainfall area or storms of high intensity are common, a higher soaked CBR may be desirable if passability problems are an issue. However, higher soaked CBR materials tend to have low clay contents and consequently washboarding may be a problem. Therefore, a balance between soaked CBR and shrinkage product must be determined for optimal performance for specific traffic scenarios. Experience has shown that material complying with the grading coefficient and shrinkage product limits discussed above will invariably have a soaked CBR strength (compacted to 95 percent of the laboratory-determined maximum dry density [AASHTO T 180 or ASTM D1557]) in excess of about 20 percent *(20)*.

A simple chart plotting grading coefficient (x-axis) and shrinkage product (y-axis) along with the optimal limits described above can be used to obtain an indication of the expected performance of the material on the road (example in Figure B.7).

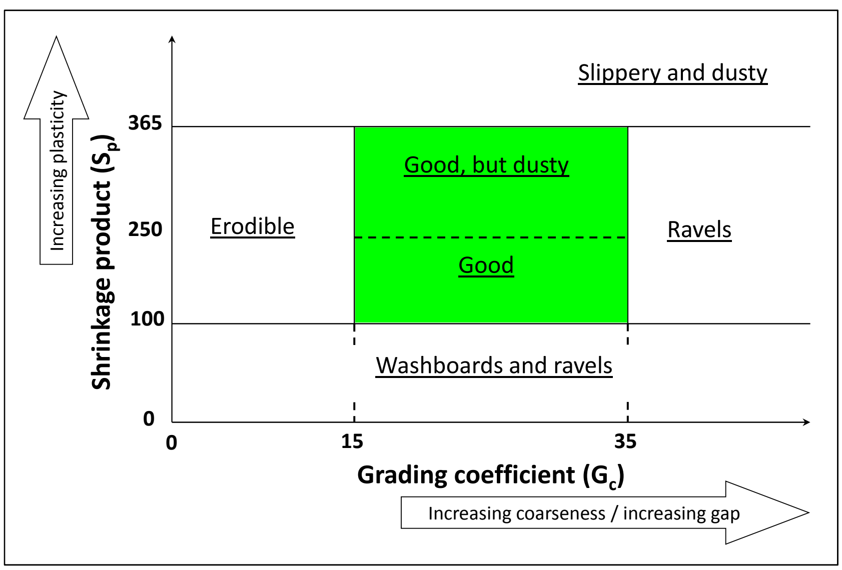


Figure B.7: Material performance predictor chart (adapted from Paige-Green *[12,32]*.)

Local calibrations of the grading coefficient and shrinkage product ranges may be needed. Examples of local refinements could include but are not limited to lowering the upper level of the shrinkage product range (e.g., to 250) on roads with high truck traffic volumes, roads that are shaded for most of the day, and roads in areas with high annual average rainfall and/or high-intensity storms. The lower level of the shrinkage product range can be reduced (e.g., to 50 or 75) for roads with very low traffic volumes and/or slow-moving vehicles, and also for roads that are shaded most of the day, and roads in areas with high annual average rainfall and/or high-intensity storms. For local calibrations, practitioners can sample materials from good and poor performing roads in their jurisdiction, test these materials, analyze the results according to Step-1 above, and plot the results on the chart shown in Figure B.7. The grading coefficient and shrinkage product ranges can then be adjusted to accommodate these local performance observations. Future material acquisitions can be based on these new defined ranges.

The factors that contribute to each of these predicted material performances are discussed below.

- Erodible materials are typically fine-grained and have some plasticity. They generally perform well when used in roads on flat terrain or in areas with very low rainfall. In other areas, they will quickly erode during rainfall, leaving channels in the road that are dangerous and unpleasant to drive over and expensive to maintain. Examples of roads built with materials falling in this area of the chart are shown in Figure B.8 and Figure B.9; grading coefficients and shrinkage products for the materials shown in the photographs are plotted on the chart in Figure B.10. The eroded material usually ends up where it is not wanted (e.g., blocking drains, or flowing into streams or onto adjacent land).

Figure B.8: Transverse erosion.

Figure B.9: Longitudinal erosion.

- Materials that washboard (corrugate) and ravel are usually poorly graded or gap-graded (absence or insufficient quantities of certain sizes leading to poor aggregate interlock) and lack fines and plasticity. Consequently, the particles do not bind together, leading to washboarding, raveling, and, ultimately, to gravel loss, and thus to a poor and unsafe ride on a surface requiring regular maintenance. These materials are also prone to erosion during rainfall. Examples of roads built with materials falling in this area of the chart (Figure B.10) are shown in Figure B.11 and Figure B.12.
- Materials that ravel, but do not usually washboard, have some plasticity, but are gap-graded. The presence of clay usually limits washboarding but does not prevent raveling. An example of a road built with materials falling in this area of the chart (Figure B.10) is shown in Figure B.13. Windshield damage from loose stones is a major problem on these roads.

- Materials that are both very dusty when dry and slippery when wet typically have high fines (and silt and/or clay) contents. Increasing clay content also results in decreasing CBR, leading to poor passability in addition to slipperiness during wet conditions. Examples of roads built with materials falling in this area of the chart (Figure B.10) are shown in Figure B.14 through Figure B.16.

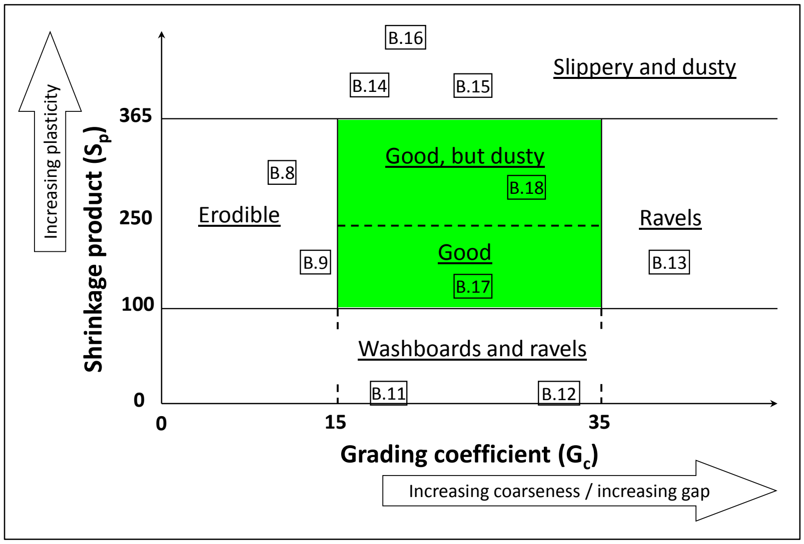


Figure B.10: Plot of materials for road examples in Figures B.8, B.9, and B.11 through B.18.

Figure B.11: Washboarding (corrugation).

Figure B.12: Washboarding and raveling.

Figure B.13: Raveling.

Figure B.14: Dusty when dry.

Figure B.15: Slippery when wet.

Figure B.16: Impassable.

- Well-graded materials with a small percentage of clay will perform well with a minimum of maintenance. Well-graded materials with moderate clay contents will also perform well, but may be dusty during dry conditions if the percent passing the #8 (2.36 mm) sieve is high. Examples of roads built with materials falling in this area of the chart (Figure B.10) are shown in Figure B.17 and Figure B.18.

Figure B.17: Good but dusty.

Figure B.18: Good material.

B.4.5 Step 3 – Material Selection Decision

If materials that fall within the good-performing area on the chart are readily available, the decision is easy: use these materials to construct a good road and keep the road in a good condition with appropriate maintenance, and if justified apply a suitable chemical treatment. If these materials are not readily available, then decide on an appropriate course of action as follows:

- Weigh the potential consequences of the problems listed above with the probability of them occurring, taking the following into consideration:
  - Erodible materials can be used in flat areas and areas with low rainfall or low intensity rainfall events. Chemical treatments may reduce the erosion problem, but are unlikely to prevent it.
  - Materials that washboard or ravel can be used on roads with low traffic volumes traveling at low speeds or where the road carries mostly laden heavy vehicles traveling at low speeds. They can also be used if a road owner is prepared to regularly blade the road or to level the washboarding with a tire drag or similar device. The costs of this frequent maintenance should be compared with

mechanically stabilizing the existing material with more fines or some clay, or importing better wearing course gravel from elsewhere. If the road is generally only used to access residences, the homeowners may be willing to tow a simple tire drag themselves to smooth out washboarded and raveled areas. Chemical treatments will retard the rate of washboarding, but will not prevent it. Nor will they prevent raveling.

  + Materials that are slippery or impassable can be considered for low-traffic volume roads in low rainfall areas if the road can be closed during problem rainfall events. Some chemical treatments can be used to modify or "waterproof" the clay particles causing the slipperiness. Appropriate signs warning of potential slipperiness should be provided.
  + Good but dusty materials can be used with appropriate speed restrictions or a suitable dust suppressant.
- Use the material "as is," but adjust maintenance programs accordingly:
  + Blade the road more frequently to remove erosion channels or washboarding and redistribute raveled material.
  + Close the road during slippery or impassable conditions.
- Seek alternative aggregate suppliers who can provide the requested material.
- Blend two materials to meet the required grading coefficient and shrinkage product. This is often achieved by mixing some of the subgrade or side drain material into the wearing course using a grader or pavement recycler, and then reshaping and compacting the road. Alternatively, add small amounts of clay (e.g., bentonite) to typical base course-type aggregates (i.e., aggregate that meets base course specifications for paved roads) to raise the shrinkage product. Optimal ratios can be determined using Steps 1 and 2 above. Guidance on determining optimal blend ratios is provided in Appendix B.2.
- Use a chemical treatment at higher than normal application rates to provide additional binding to the material, but remember that it is usually cheaper to use fines to fill voids (i.e., meet the grading coefficient and shrinkage product requirements) than to use a chemical.

> It has been clearly shown internationally that roads constructed with materials that are processed to meet the requirements of "good" materials identified in Figure B.7, and when constructed according to specification, result in significant improvements in performance as well as up to 60 percent reductions in gravel loss compared to what are considered more "conventional" strategies *(36)*. Entirely new maintenance strategies have evolved around these findings in road agencies that have adopted this alternative approach *(37,38)*.

B.4.6 Comparing Alternative Approach with FHWA and USFS Guidance

As the previous section made clear, presenting unpaved road material selection parameters as independent grading and plasticity index ranges (e.g., current FHWA and USFS guidance) can be less descriptive and useful than grading coefficient and shrinkage product envelopes in conjunction with a plot of the results (i.e., alternative approach described above), even though the information used in both approaches is derived from the same sources (i.e., grading analysis and Atterberg limit test results). To further illustrate the limitations of using tabulated grading and plasticity ranges for interpreting test results from projects without weighting the plasticity value, the FHWA and USFS guidelines listed in Table B.1 *(15,16)* were analyzed in terms of grading coefficient and shrinkage product. Low, middle, and high ranges were calculated from Table B.1 as follows and the results plotted on the chart in Figure B.19.

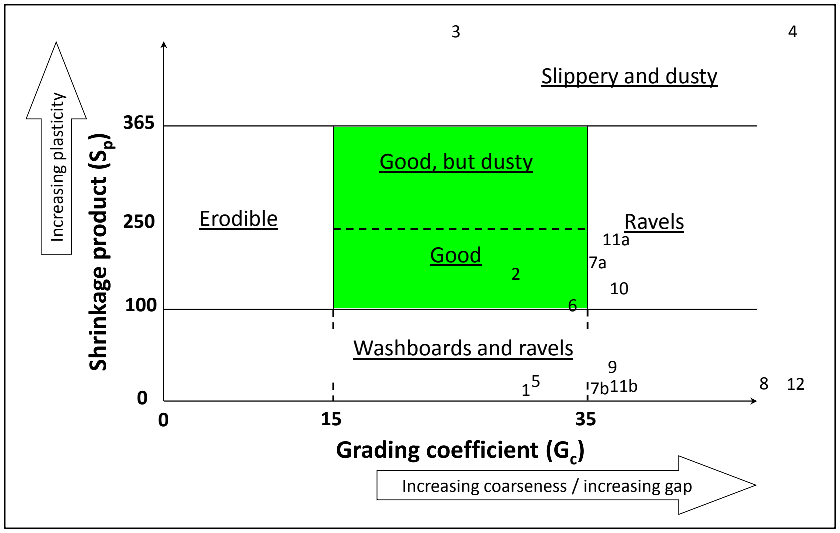


Figure B.19: Plot of FHWA and USFS unpaved road material selection envelopes.

<u>FHWA *(15)*</u>

- Low range of envelopes (number 1 in Figure B.19)
  - + Grading coefficient: ((100 – 37) × 50) / 100 = 32
  - + Shrinkage product: 2 × 13 = 26
- Mid-range of envelopes (number 2 in Figure B.19)
  - + Grading coefficient: ((100 – 52) × 64) / 100 = 31
  - + Shrinkage product: 8 × 24 = 192
- High range of envelopes (number 3 in Figure B.19)
  - + Grading coefficient: ((100 – 67) × 78) / 100 = 26
  - + Shrinkage product: 12 × 35 = 420
- Example worst case (number 4 in Figure B.19)
  - + Grading coefficient: ((100 – 37) × 78) / 100 = 49
  - + Shrinkage product: 12 × 35 = 420

<u>USFS Haul Roads *(16)*</u>

- Low range of envelopes (number 5 in Figure B.19)
  - + Grading coefficient: ((97 – 23) × 43) / 100 = 32
  - + Shrinkage product: 2 × 15 = 30
- Mid-range of envelopes (number 6 in Figure B.19)
  - + Grading coefficient: ((99 – 28) × 48) / 100 = 34
  - + Shrinkage product: 5.5 × 19 = 105

- High range of envelopes (numbers 7a and 7b in Figure B.19)
  - + Grading coefficient: ((100 – 32) × 53) / 100 = 36
  - + Shrinkage product: 9 × 23 = 207 if percent passing 0.075 mm is <12%
  - + Shrinkage product: 1 × 23 = 23 if percent passing 0.075 mm is >12%
- Example worst case (number 8 in Figure B.19)
  - + Grading coefficient: ((100 – 23) × 53) / 100 = 41
  - + Shrinkage product: 1 × 23 = 23

<u>USFS General Use *(16)*</u>

- Low range of envelopes (number 9 in Figure B.19)
  - + Grading coefficient: ((100 – 28) × 51) / 100 = 37
  - + Shrinkage product: 2 × 19 = 38
- Mid-range of envelopes (number 10 in Figure B.19)
  - + Grading coefficient: ((100 – 34) × 57) / 100 = 38
  - + Shrinkage product: 5.5 × 23 = 126
- High range of envelopes (numbers 11a and 11b in Figure B.19)
  - + Grading coefficient: ((100 – 39) × 63) / 100 = 38
  - + Shrinkage product: 9 × 27 = 243 if percent passing 0.075 mm is <12%
  - + Shrinkage product: 1 × 27 = 27 if percent passing 0.075 mm is >12%
- Example worst case (number 12 in Figure B.19)
  - + Grading coefficient: ((100 – 28) × 63) / 100 = 45
  - + Shrinkage product: 1 × 27 = 27

The chart in Figure B.19 clearly shows that materials selected for a project that meet the guidance listed in Table B.1 may not necessarily perform well when used as wearing course materials on that unpaved road. Only two of the 14 potential material sources are likely to provide good performance. Most of the materials are likely to washboard and/or ravel, leading to expensive maintenance and gravel replacement requirements. Two of the materials are likely to be very slippery and possibly impassable when wet, indicating that the use of a weighted plasticity factor (i.e., multiplying the plasticity index or bar linear shrinkage value by the percent material passing the sieve that the test is conducted on [typically #40 (0.425 mm)]) is very important when interpreting likely performance.

B.5 Effect of Chemical Treatments on Unpaved Road Performance

The unpaved road chemical treatments discussed in Chapter 2 will agglomerate fine materials and/or provide some level of shear strength improvement or "waterproofing," which in turn can improve all-weather passability. Although the best possible materials should be used for wearing courses on unpaved roads, the use of an appropriate chemical treatment can lead to acceptable performance over a larger range of shrinkage products and grading coefficients due to this agglomeration and/or waterproofing. Expanded expected-performance predictor charts for the different chemical treatment categories are shown in

Figure B.20 and can be used to better understand the selection of appropriate treatments for a specific material. Guidance on how various chemical treatment categories perform in terms of the material grading coefficient and shrinkage product is as follows *(19)*:

- Erodible materials: The problems with erodible materials are usually related to grading and/or drainage, both of which are difficult to overcome with chemical treatments. Non-water-soluble polymer emulsions or bituminous-based treatments can be tried on gentle to moderate slopes in combination with drainage improvements. Water-soluble treatments (for example, chlorides and plant-based polymers such as lignosulfonate) will reduce dust but not prevent erosion. Neither will concentrated liquid stabilizers, as the clay content is usually insufficient for a reaction that will bind the particles satisfactorily to prevent the shear action of flowing water. Increased compaction (often enhanced by some of the chemical treatments that also perform as compaction aids) in combination with optimal drainage design and control will also assist in reducing erosion.

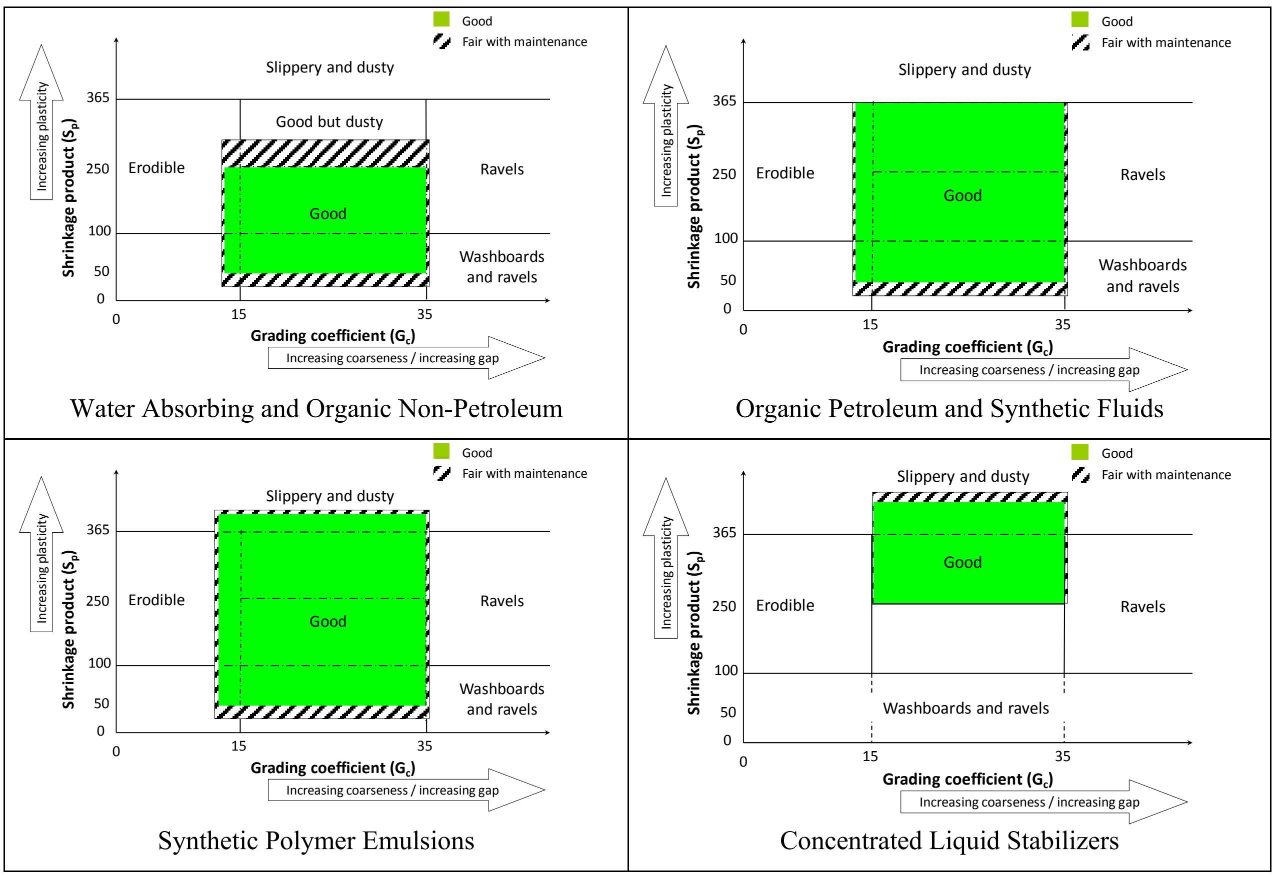


Figure B.20: Expected performance of unpaved roads after chemical treatment.

- Materials that washboard and ravel: These materials lack fines and plasticity. Depending on the traffic, chemical treatments lose effectiveness if the shrinkage product is less than 50 because uneconomically high application rates are required to fill the voids between the particles. Wind-shear and tire-shear forces usually also exceed the binding ability of the treatments used under these circumstances, leading to continued problems. If the shrinkage product is above 50, most chemical treatments except concentrated liquid stabilizers (these products typically require much higher plasticity to react effectively) can be used to improve the materials by enhancing binding, which will lead to significant reductions in dust and washboarding. Incorporating a clay additive or other source of fines (often readily available from adjacent landowners or waste piles at quarries), can be considered to raise the shrinkage product to 50 before applying an appropriate chemical treatment.

- Materials that ravel: Chemical treatments are generally ineffective on these materials because of their coarse- or gap-grading. They will control dust initially, but will not prevent raveling (Figure B.21). Some success may be achieved at very high application rates (i.e., using the chemical to fill the voids before a satisfactory bond is obtained). Alternatively, the addition of the "gap" material can be considered to adjust the grading coefficient before treatment. If the grading is not adjusted, dust levels will increase as the coarse material gets displaced to the side of the road under traffic.

Figure B.21: Raveling on road surface after applying a chemical treatment.

- Slippery or impassable materials: Chemical treatments used on these materials need to either chemically alter the clay minerals to reduce the plasticity or "waterproof" the clay particles to prevent them from expanding/shearing when wet. Synthetic polymer emulsions, synthetic fluids with binders, and concentrated liquid stabilizers can all be considered. Atterberg limits and soaked California Bearing Ratio (CBR) tests should be carried out to check that a suitable reduction in plasticity and/or sufficient increase in soaked shear strength (e.g., CBR) is achieved with the selected treatment before it is applied on the road. Depending on the material grading, it may also be necessary to increase the percentage of coarser aggregate to improve tire/road traction and friction. Chlorides and other water-soluble treatments (e.g., most organic nonpetroleum treatments) should not be considered for treating slippery or impassable materials.
- Good and good but dusty materials: Most chemical treatments can be effectively used on roads with these materials to minimize dust and limit fines loss, reduce the rate of gravel loss, and increase the intervals between grader maintenance. All chemical treatment categories except concentrated liquid stabilizers (clay contents are typically too low for these to work effectively) can be considered.

B.6 Summary

Numerous, often contradictory, specifications and guidance exist for the selection of unpaved road wearing course materials in the United States, and they often provide little information on what research and data were used to compile them. Consequently, it is very difficult for practitioners to decide what specification or guideline to follow to select the most appropriate materials for a given unpaved road project. The discussion in this appendix proposed the use of a simple procedure, using the results from routine, inexpensive laboratory tests, to obtain an indication of the likely performance of unpaved road wearing course materials. The procedure can also be used to select, modify, or compile an appropriate specification (grading envelope and plasticity index combination) if a traditional specification format is required, as well as to guide the selection of chemical treatments.

Blank page

APPENDIX B-1: BAR LINEAR SHRINKAGE TEST METHOD

SCOPE

This method covers the determination of the linear shrinkage of soil when it is dried from a moisture content equivalent to the liquid limit to the oven-dry state.

DEFINITION

The linear shrinkage of a soil for the moisture content equivalent to the liquid limit, is the decrease in one dimension, expressed as a percentage of the original dimension of the soil mass, when the moisture content is reduced from the liquid limit to an oven-dry state.

APPARATUS

- Bar linear shrinkage (BLS) mold, stainless steel or brass, with inside dimensions of 150 mm ± 0,25 mm long by 10 mm ± 0,25 mm wide, and 10 mm ± 0,25mm deep
- Flat stainless steel or brass plate 200 mm by 200 mm by 6 mm
- Flexible spatula, with a blade approximately 100 mm (4 in.) long × 19 mm (0.75 in.) wide
- Pair of dividers and a millimeter scale ruler
- Drying oven, maintained at 110°C ± 5°C (230°F ± 9°F)
- Small, thick-bristle paint brush, about 6 mm (0.25 in.) wide

MATERIALS

- Petroleum jelly
- Distilled or deionized water

PREPARING THE MOLD

Prepare the mold by spreading a thin, even layer of petroleum jelly over inside of the mold using the paint brush. Place the prepared mold on the plate.

PREPARING THE SAMPLE

The bar linear shrinkage test is done on material passing the 0.425 mm (#40) sieve and should be done in conjunction with the Atterberg limit tests (AASHTO T 89 and T 90 or ASTM D4318). The moist soil sample remaining after the completion of the liquid limit test (AASHTO T 89) should be used to form the soil bar. This should be done immediately so that the moist material can be used without further mixing. If insufficient material is available, prepare a new sample as described in AASHTO T 89.

PROCEDURE

1. Fill one half of the mold with the moist soil by taking small pieces of soil on the spatula and pressing the soil down against one end of the mold and working along until the whole side is filled and the soil forms a diagonal surface from the top of one side to the bottom of the opposite side.
2. Turn the mold around and fill the other portion in the same manner.
3. Fill the hollow along the top of the soil in the mold so that the soil is raised slightly above the sides of the mold.
4. Remove the excess material by drawing the blade of the spatula once only from the one end of the mold to the other. Press down on the blade with an index finger so that the blade moves along the sides of the mold. Gently push the wet soil back into the mold with the spatula if it pulls away from the end of the mold during this process. **The soil surface should on no account be smoothed or finished off with a wet spatula.**
5. Air dry the soil bar at room temperature until the soil color starts to change, then place the mold and plate with wet material in the drying oven and dry at a temperature of between 105°C and 110°C (221°F and 230°F) until all shrinkage has stopped and constant mass has been reached. As a rule, the material is dried out overnight (12 hours), but three hours is usually sufficient.
6. Remove the mold and plate from the oven and allow to cool in the air.
7. If the bar has curved after drying, gently press it back into the mold, blow any dust and loose particles away, and then gently push the pieces together at one end of the mold to ensure that the individual pieces fit together tightly but without causing any further abrasion.
8. Measure the length of the dry bar with a steel ruler or dividers together with a steel ruler to the nearest 0.5 mm.

CALCULATIONS

1. Determine the linear shrinkage as a percentage of the original length of the bar using the following formula:

$$LS = 100 \times (L_W - L_D) / L_W$$

where:

L_W = length of the wet soil bar (150 mm)

L_D = length of the dry soil bar in mm

REPORT

Report the linear shrinkage to the nearest whole percent.

APPENDIX B-2: GUIDE FOR DETERMINING BLENDING RATIOS

B-2.1 Introduction

The blending of two or more materials can be considered if wearing course material that meets the specification is not available. This procedure involves mixing two materials that have different properties (typically particle size distribution and/or plasticity) to form a material having improved characteristics, given the limitations of the source materials. Although improvements in strength are usually the primary reason for considering blending/mechanical stabilization, the discussion in Appendix B shows that slower deterioration of riding quality and reduced dust levels can be achieved by optimizing the particle size distribution and plasticity of the material to within the limits prescribed.

A number of methods are available for determining optimum blending ratios. Three are discussed in this appendix, namely:

- Arithmetical
- Graphical
- Ternary diagram

All three methods are based on particle size distribution and require material grading tests for both materials for the input data. A second grading test together with Atterberg limits or bar linear shrinkage tests are required after the analysis to check that the results of the blended material meet the design requirements. A strength test (e.g., California Bearing Ratio) should also be done on the blended material to check that project strength requirements have been met if improved strength (i.e., all-weather passability) is also a reason for improving the material.

The arithmetical method is the simplest procedure to follow, but it does not provide a range of potential blends, as the graphical and ternary diagram methods do.

B-2.2 Arithmetical Method

Use the following procedure to determine an optimal blend of two materials using the arithmetical method.

1. Prepare a calculation table or spreadsheet (example templates for US and metric units in Table B-2.1) and complete Columns 1 through 5 with available information from the grading analyses and target grading envelope or specifications. Table B-2.2 provides example gradings for two materials and a target grading envelope (FHWA Guideline *[15]*) that were used to complete the example calculation table provided in Table B-2.3.

Table B-2.1a: Template for Arithmetical Method of Soil Blending (US Units)

<table>
<tr><th colspan="12">Column</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th colspan="2">11</th></tr>
<tr><th rowspan="2">Sieve Size</th><th rowspan="2">Material A</th><th rowspan="2">Material B</th><th colspan="2">Target Limits</th><th rowspan="2">Target Mid-Point (TMP)</th><th rowspan="2">|TMP - A|</th><th rowspan="2">|TMP - B|</th><th colspan="2">Ratio (A:B)</th><th colspan="2">Blend</th></tr>
<tr><th>Low</th><th>High</th><th></th><th></th><th>%</th><th>?</th></tr>
<tr><td>1”</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3/4”</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>#4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>#8</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>#40</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>#200</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>Σ|TMP - A| =</td><td>Σ|TMP - B| =</td><td></td><td></td><td></td><td></td></tr>
</table>

Table B-2.1b: Template for Arithmetical Method of Soil Blending (Metric Units)

<table>
<tr><th colspan="12">Column</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th colspan="2">11</th></tr>
<tr><th rowspan="2">Sieve Size (mm)</th><th rowspan="2">Material A</th><th rowspan="2">Material B</th><th colspan="2">Target Limits</th><th rowspan="2">Target Mid-Point (TMP)</th><th rowspan="2">|TMP - A|</th><th rowspan="2">|TMP - B|</th><th colspan="2">Ratio (A:B)</th><th colspan="2">Blend</th></tr>
<tr><th>Low</th><th>High</th><th></th><th></th><th>%</th><th>?</th></tr>
<tr><td>25</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>19</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4.75</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2.36</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>0.425</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>0.075</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>Σ|TMP - A| =</td><td>Σ|TMP - B| =</td><td></td><td></td><td></td><td></td></tr>
</table>

Table B-2.2: Example Gradings for Potential Blend Materials

Sieve Size		Percent Passing		
US	Metric	Material A	Material B	Target or Specification Limits[1]
1”	25	100	100	100
3/4”	19	92	72	90 - 100
#4	4.75	82	27	50 - 78
#8	2.36	74	15	37 - 67
#40	0.425	52	5	13 - 35
#200	0.075	33	1	5 – 15

[1] Based on FHWA guidance document *(15)*

2. Complete Column 6 by determining the midpoint of the target or specification range for each sieve size.
3. Complete Column 7 by subtracting the value in Column 2 from the value in Column 6 for each sieve size.
4. Complete Column 8 by subtracting the value in Column 3 from the value in Column 6 for each sieve size.
5. Sum the values in Columns 7 and in Column 8. Change negative totals to a positive number.
6. Calculate multipliers for each material using the following formulas. These multipliers will be the approximate percentages of the two materials used in the blend.
   Material A = Sum of Column 8 / (Sum of Column 7 + Sum of Column 8)
   Material B = Sum of Column 7 / (Sum of Column 7 + Sum of Column 8)
7. Complete Columns 9 and 10 by determining the optimal percentages of each sieve size using the following formulas. These values will be used to check whether the target for each sieve size is met.
   Percentage Material A = Value in Column 2 × (Material A multiplier from Step 6)
   Percentage Material B = Value in Column 3 × (Material B multiplier from Step 6)
8. Complete Column 11 by adding the values in Columns 9 and 10 for each sieve size, to check whether the blend will fall within the target range. Add a “Y” (yes) or “N” (no) if the blend falls within the target range. In this example, the percent passing the #200 (0.075 mm) sieve exceeds the target range.
9. Prepare a sample blend and check the grading to determine whether it meets the target (e.g., in the example, a blend of 5.9 lb./kg of Material A and 4.1 lb./kg of Material B would provide 10 lb./kg of material for testing).
10. Test the Atterberg limits or bar linear shrinkage (and CBR if required) of the proposed blend to check that they fall within the required design and/or specification. Use these results together with the grading analysis to calculate the grading coefficient and shrinkage product and check likely performance using the chart in Figure B.7. Adjust the blend percentages and retest if necessary.

Table B-2.3a: Example for Arithmetical Method of Soil Blending (US Units)

Column											
1	2	3	4	5	6	7	8	9	10	11	
Sieve Size	Material A	Material B	Target Limits		Target Mid-Point (TMP)	|TMP - A|	|TMP - B|	Ratio (A:B)		Blend	
			Low	High				0.59	0.41	%	?
1"	100	100	100	100	100	0	0	59	41	100	Y
3/4"	92	72	90	100	95	3	23	54	30	84	Y
#4	82	27	50	78	64	-18	37	48	11	59	Y
#8	74	15	37	67	52	-22	37	43	6	50	Y
#40	52	5	13	35	24	-28	19	31	2	33	Y
#200	33	1	5	15	10	-23	9	19	0	20	N
						Σ|TMP - A| = 88	Σ|TMP - B| = 125				

Table B-2.3b: Example for Arithmetical Method of Soil Blending (Metric Units)

Column											
1	2	3	4	5	6	7	8	9	10	11	
Sieve Size (mm)	Material A	Material B	Target Limits		Target Mid-Point (TMP)	|TMP - A|	|TMP - B|	Ratio (A:B)		Blend	
			Low	High				0.59	0.41	%	?
25	100	100	100	100	100	0	0	59	41	100	Y
19	92	72	90	100	95	3	23	54	30	84	Y
4.75	82	27	50	78	64	-18	37	48	11	59	Y
2.36	74	15	37	67	52	-22	37	43	6	50	Y
0.425	52	5	13	35	24	-28	19	31	2	33	Y
0.075	33	1	5	15	10	-23	9	19	0	20	N
						Σ|TMP - A| = 88	Σ|TMP - B| = 125				

B-2.3 Graphical Method

Use the following procedure to determine an optimal blend of two materials using the graphical method. The example grading used in the arithmetical method is also used to illustrate this method.

1. Plot the gradings of the two materials on the x_1 and x_2 axes on a comparative chart (a template is provided in Figure B-2.1.) and connect the corresponding points with lines (Figure B-2.2).

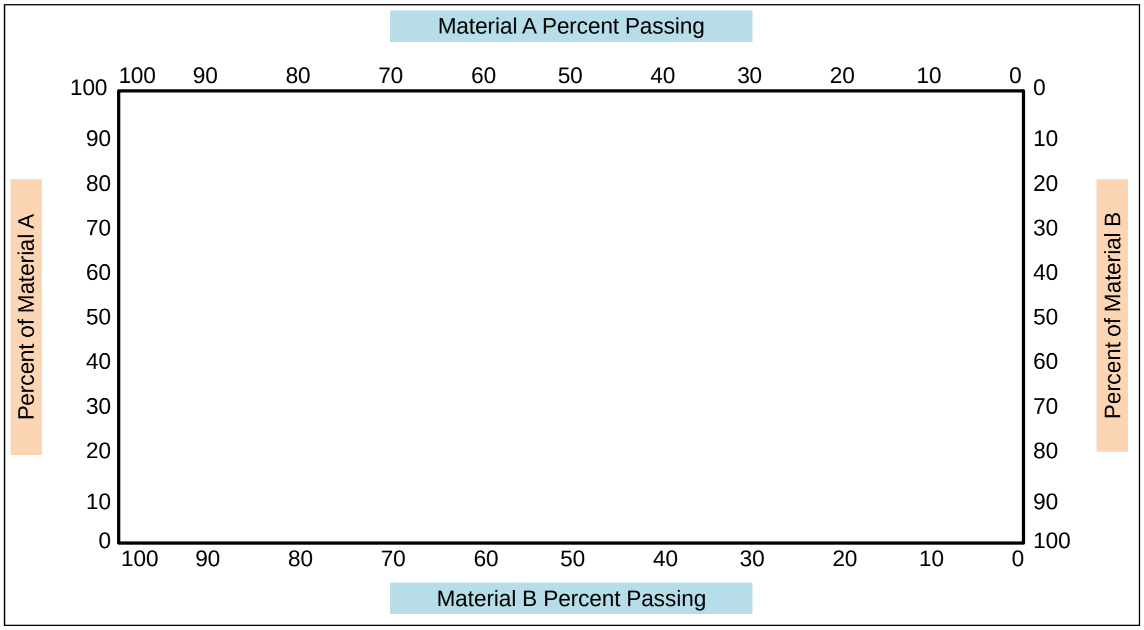


Figure B-2.1: Template for graphical method of material blending.

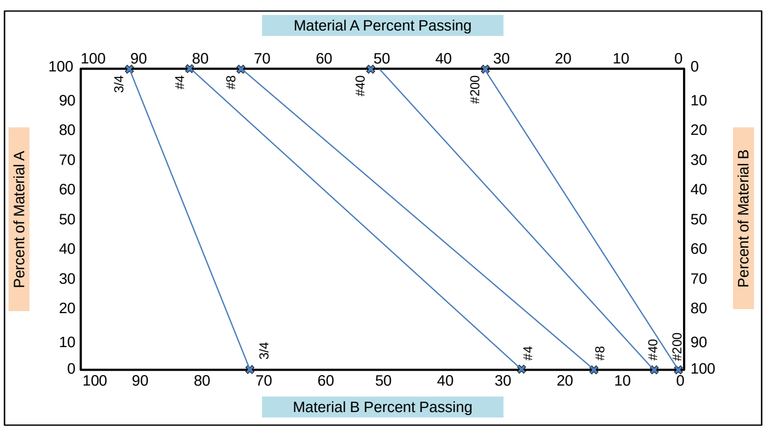


Figure B-2.2: Example plot of potential blend materials (Step 1).

2. Mark the minimum and maximum target or specification limits for each of the sieve sizes on these connected lines (using the x_1- and x_2-axes). Draw perpendicular lines from each target or specification limit point to the x_1-axis. These lines represent the allowable range for each sieve size in the blend (Figure B-2.3)

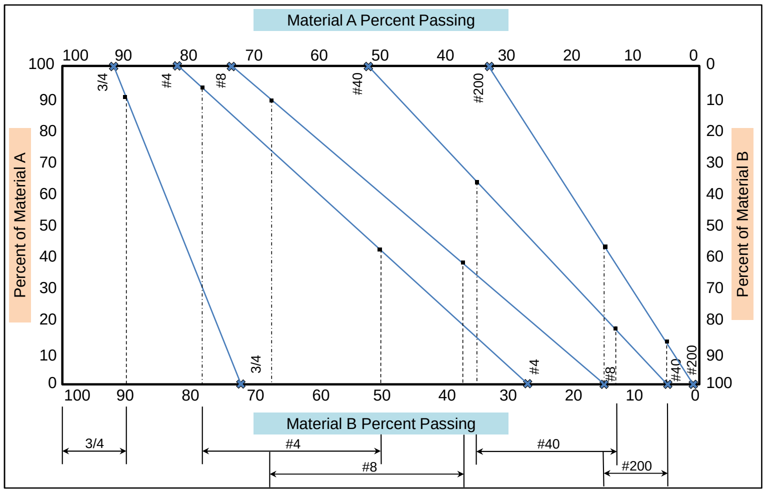


Figure B-2.3: Example plot of potential blend materials (Step 2).

3. Identify the closest minimum and maximum target limit points. Draw horizontal lines through these two points to connect to the y-axes. These lines represent the minimum and maximum percentages of each material that can be used in the blend (Figure B-2.4).

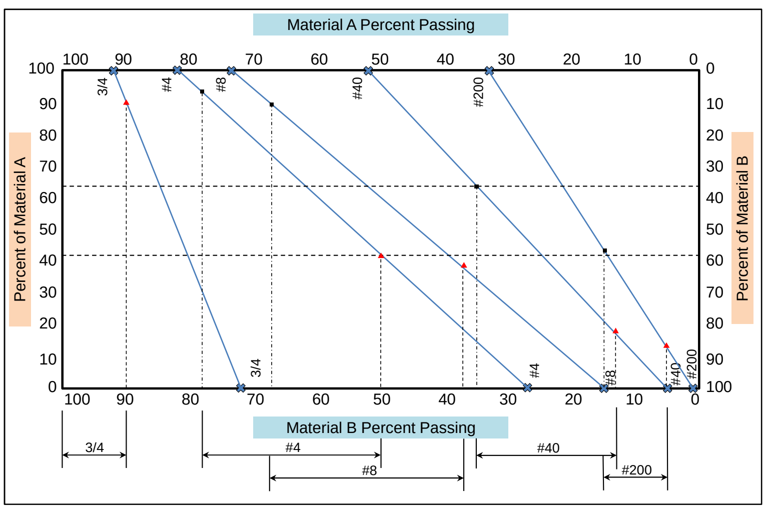


Figure B-2.4: Example plot of potential blend materials (Step 3).

4. Select a realistic blend within these ranges (e.g., 42 to 64 percent of Material A and 36 to 58 percent of Material B in Figure B-2.4) based on material availability, but generally avoiding the extremes of each range. Since Material A has a very high fines content and Material B a very low fines content, choosing a ratio with a low proportion of Material A might be more appropriate for meeting the target values (e.g., a blend of 43 percent of Material A and 57 percent of Material B might be an appropriate initial choice).
5. Use a modified arithmetical method to check the proposed blend as shown in Table B-2.4. Complete Columns 6 and 7 by determining the optimal percentages of each sieve size using the following formulas. These values will be used to check whether the target for each sieve size is met.

Percentage Material A = Value in Column 2 × (Material A proportion [i.e., 43%])

Percentage Material B = Value in Column 3 × (Material B proportion [i.e., 57%])

Complete Column 8 by adding the values in Columns 6 and 7 for each sieve size, to check whether the blend will fall within the target range. Add a "Y" (yes) or "N" (no) if the blend falls within the target range.

Table B-2.4: Example Revised Arithmetical Method to Check Graphical Method

Column									
1		2	3	4	5	6	7	8	
Sieve Size		Material A	Material B	Target Limits		Ratio (A:B)		Blend	
US	Metric			Low	High	0.43	0.57	%	?
1"	25	100	100	100	100	43	57	100	Y
3/4"	19	92	72	90	100	40	41	81	Y
#4	4.75	82	27	50	78	35	15	51	Y
#8	2.36	74	15	37	67	32	9	40	Y
#40	0.425	52	5	13	35	22	3	25	Y
#200	0.075	33	1	5	15	1	1	15	Y

6. Prepare a sample blend and check the grading to determine whether it meets the target (e.g., in the example, a blend of 4.3 lb./kg of Material A and 5.7 lb./kg of Material B would provide 10 lb./kg of material for testing).
7. Test the Atterberg limits or bar linear shrinkage (and CBR if required) of the proposed blend to check that they fall within the required design and/or specification. Use these results together with the grading analysis to calculate the grading coefficient and shrinkage product and check likely performance using the chart in Figure B.7. Adjust the blend percentages and retest if necessary.

B-2.4 Ternary Diagram Method

A ternary diagram is shown in Figure B-2.5. The shaded area in the diagram corresponds to a grading coefficient of between 15 and 35 as shown in Figure B.7. Use the following procedure to determine an optimal blend of two materials using the ternary diagram. The example grading used in the arithmetical method is also used to illustrate this method.

1. Determine the percentages of silt and clay (passing #200 [0.075 mm]), sand (retained on #200, passing #8 [>0.075 mm, <2.36 mm]), and gravel (retained on #8 and passing 1 in. (>2.36 mm, <25 mm) for each source.
2. Plot the material properties on the ternary diagram as points A and B respectively (an example of the grading listed in Table B-2.2 is shown in Figure B-2.6).
3. Connect the points. When the two points are connected, any point on the portion of the line in the shaded area indicates a feasible mixture of the two materials. The optimum mixture is typically at point C in the center of the shaded area, but it often needs to be adjusted to balance specific sieve sizes (Figure B-2.7). Moving point C closer to point A implies that a larger proportion of Material A will be used in the mix and vice versa. The mix proportions are then the ratio of the line AC:BC, determined as follows:
   + Measure the length of the line AB on the ternary diagram with a ruler.
   + Measure the lengths of AC and BC.
   + Divide BC by AB to determine the ratio for Material A, and divide AC by AB to determine the ratio for Material B.

+ In Figure B-2.7, the ratios are 0.43 for Material A and 0.57 for Material B.

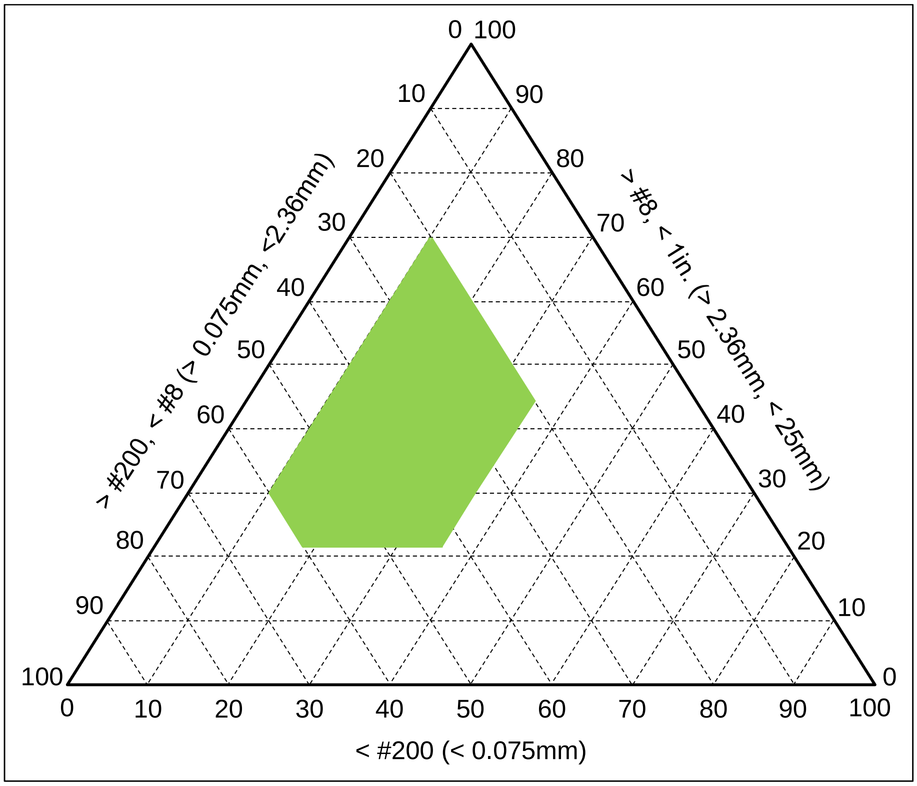


Figure B-2.5: Example ternary diagram.

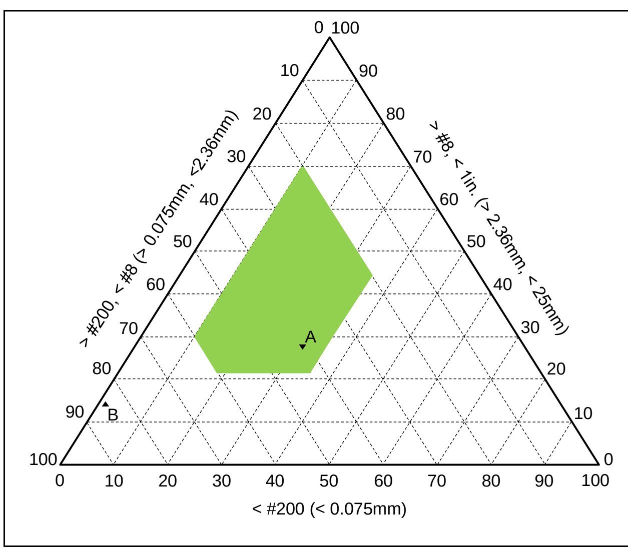


Figure B-2.6: Example ternary diagram (Step 2).

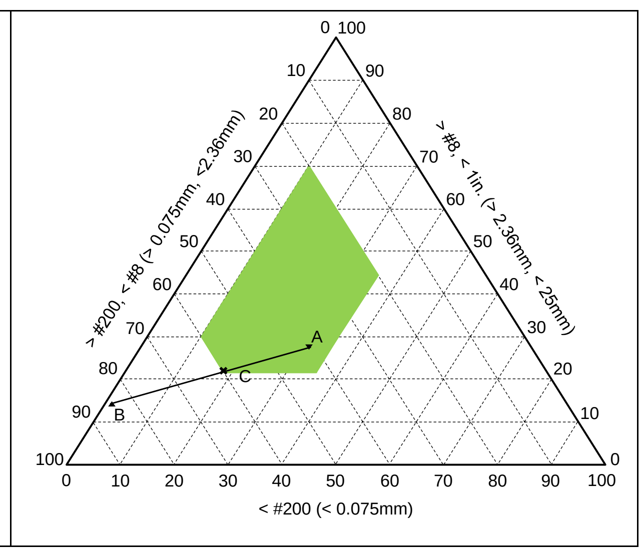


Figure B-2.7: Example ternary diagram (Step 3).

4. Use a modified arithmetical method to check the proposed blend as shown in Table B-2.5. Complete Columns 6 and 7 by determining the optimal percentages of each sieve size using the following formulas. These values will be used to check whether the target for each sieve size is met.
   Percentage Material A = Value in Column 2 × (Material A proportion [i.e., 0.43])
   Percentage Material B = Value in Column 3 × (Material B proportion [i.e., 0.57])

Complete Column 8 by adding the values in Columns 6 and 7 for each sieve size, to check whether the blend will fall within the target range. Add a "Y" (yes) or "N" (no) if the blend falls within the target range.

Table B-2.5: Example Revised Arithmetical Method to Check Ternary Diagram Method

Column									
1		2	3	4	5	6	7	8	
Sieve Size		Material	Material	Target Limits		Ratio (A:B)		Blend	
US	Metric	A	B	Low	High	0.43	0.57	%	?
1"	25	100	100	100	100	43	57	100	Y
3/4"	19	92	72	90	100	40	41	81	Y
#4	4.75	82	27	50	78	35	15	51	Y
#8	2.36	74	15	37	67	32	9	40	Y
#40	0.425	52	5	13	35	22	3	25	Y
#200	0.075	33	1	5	15	1	1	15	Y

5. Prepare a sample blend and check the grading to determine whether it meets the target (e.g., in the example, a blend of 4.3 lb./kg of Material A and 5.7 lb./kg of Material B would provide 10 lb./kg of material for testing).
6. Test the Atterberg limits or bar linear shrinkage (and CBR if required) of the proposed blend to check that they fall within the required design and/or specification. Use these results together with the grading analysis to calculate the grading coefficient and shrinkage product and check likely performance using the chart in Figure B.7. Adjust the blend percentages and retest if necessary.

B-2.4.1 Additional Example of Ternary Diagram Method

Ternary diagrams are useful for determining the optimal application rates of clay additives that are used to mechanically stabilize unpaved road materials that have low fines contents and/or too low plasticity. An example blend determination using a ternary diagram, based on the grading analyses of material sampled from the road and a sample from a clay source near the road (Table B-2.6) is shown in Figure B-2.8.

Table B-2.6: Example Material Properties from Unpaved Road and Potential Clay Source

Column									
1		2	3	4	5	6	7	8	
Sieve Size		Material	Material	Target Limits		Ratio (A:B)		Blend	
US	Metric	Road	Clay	Low	High				
1"	25	85	100	100	100				
3/4"	19	81	100	90	100				
#4	4.75	42	97	50	78				
#8	2.36	38	96	37	67				
#40	0.425	20	94	13	35				
#200	0.075	7	92	5	15				
% silt/clay (<#200)		7	92	-	-				
% sand (#8 - #200)		31	4	-	-				
% gravel (100 - #8)		62	4	-	-				
Linear shrinkage		0	5	-	-				
Grading coefficient		20	4	100	365				
Shrinkage product		0	470	15	35				

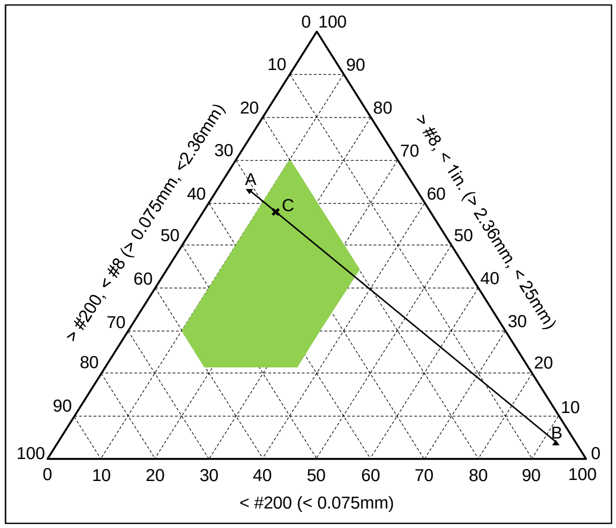


Figure B-2.8: Example #2 ternary diagram (Step 3).

Given that the target limits require between 5 and 15 percent material passing the #200 (0.075 mm) sieve, point C was moved closer to point A (the material sampled from the road) to ensure that this limit is not exceeded. In Figure B-2.8, the ratios are 0.94 for the material sampled from the road (point A) and 0.06 for the clay material (point B), which would equate to adding 6 percent clay to the existing road material in order for the material to be considered "Good" in Figure B.7. The arithmetical check and recalculation on the grading coefficient and shrinkage product are shown in Table B-2.7.

Table B-2.7: Example Material Properties from Unpaved Road and Potential Clay Source

Column									
1		2	3	4	5	6	7	8	
Sieve Size		Material Road	Material Clay	Target Limits		Ratio (A:B)		Blend	
US	Metric			Low	High	0.94	0.06		
1"	25	85	100	100	100	78	8	86	N
3/4"	19	81	100	90	100	75	8	83	Y
#4	4.75	42	97	50	78	44	8	52	Y
#8	2.36	38	96	37	67	37	8	44	Y
#40	0.425	20	94	13	35	18	8	26	Y
#200	0.075	7	92	5	15	6	7	14	Y
% silt/clay (<#200)		7	92	-	-				
% sand (#8 - #200)		31	4	-	-				
% gravel (100 - #8)		62	4	-	-				
Linear shrinkage		0	5	-	-			4	-
Grading coefficient		20	4	100	365			22	Y
Shrinkage product		0	470	15	35			104	Y

APPENDIX C: EXAMPLE MIX DESIGN TEST PROGRAM

The following suggested test methods can be used to assess the performance of unpaved road chemical treatments to determine optimal application rates and/or develop mix designs.

C.1 Scope

This method covers the determination of abrasion resistance, change in density, moisture sensitivity, strength improvement (modified California Bearing Ratio [CBR] and unconfined compressive strength [UCS]), and plasticity change of materials treated with unpaved road chemical treatments. The tests have been developed to compare performance between treated and untreated materials.

C.2 Apparatus

1. Balance capable of weighing 10 lb. (5.0 kg) having a sensitivity of 0.004 oz (0.1 g)
2. 3.5 oz (100 mL) beaker
3. Spatulas, pans, etc.
4. Stopwatch
5. Soaking bath
6. Wire brush made of 2 in. (50 mm) by 1/16 in. (1.6 mm) flat 26-gauge wire bristles assembled in 50 groups of 10 bristles and mounted to form 5 longitudinal rows and 10 transverse rows on an 8 in. (200 mm) by 2.5 in. (65 mm) wooden block
7. Perforated aluminum disc, 3 in. (75 mm) in diameter and 1/8 in. (3 mm) thick
8. Standard drying oven capable of maintaining a temperature of between 122°F and 230°F, ± 10°F (50°C and 110°C, ± 5°C)
9. Apparatus required to determine the liquid limit and plastic limit per AASHTO T 89/T 90 or ASTM D4318.
10. Apparatus required to determine the optimum moisture content and maximum dry density (OMC/MDD) per AASHTO T 180 or ASTM D1557.
11. Apparatus required to determine the California Bearing Ratio per AASHTO T 193 or ASTM D1883.
12. Apparatus required to determine the unconfined compressive strength per AASHTO T 208 or ASTM D2166.

C.3 Specimen Preparation

C.3.1 Compacted Specimens

1. Prepare the material to be tested using the procedures prescribed in AASHTO T 193 or ASTM D1883. For the abrasion resistance test, discard all material greater than 1/4 in. (6.7 mm).
2. Determine the optimum moisture content at the proposed chemical treatment content mixing the required percentage of additive into the soil and testing the mix according to AASHTO T 180 or

ASTM D1557. It is advisable to add the required quantity of chemical treatment to the water to be added to the sample as this will assist with the dispersion of the treatment throughout the soil.

3. Determine the mass of dry material required to fill the mold using data from Step-2.
4. Weigh the calculated quantity of additive by pouring it into the beaker, and add the required amount of water to bring the material to optimum moisture content.
5. Add the contents of the beaker to the dry material and mix well. Cover the bowl with a moist cloth and let this stand for 30 minutes (or as directed by the manufacturer) to allow the moisture to equilibrate throughout the soil. After this, remix the material.
6. Prepare molds and compact specimens as described in AASHTO T 193 or ASTM D1883.
7. Dry/cure the specimen as prescribed by the chemical treatment manufacturer or per the guidelines provided in Table C.1.
8. Remove the specimens from the oven and allow to cool to room temperature.

Table C.1: Recommended Curing Procedure for Chemical Treatment Testing

Category	Curing Procedure
Water absorbing	Dry to constant mass in an oven at 122°F (50°C). Place specimen on a stand 2 in. (50 mm) above a basin of water in an environment with a temperature of at least 77°F (25°C) and relative humidity of at least 50% and allow to reabsorb atmospheric moisture for 24 hours prior to testing.
Organic non-petroleum Organic petroleum Synthetic polymer	Dry to constant mass in an oven at 122°F (50°C). Allow to cool before testing.
Concentrated liquid stabilizer	Dry to constant mass in an oven at 122°F (50°C). Remove from oven and shelf cure at approximately 77°F (25°C) and 50% relative humidity for 7 days.

C.3.2 Plasticity Index

1. Prepare material as described in AASHTO T 89/T 90 or ASTM D4318, but add chemical treatment to the distilled water at the rate specified by the manufacturer prior to mixing it into the soil fines. Allow for a suitable reaction time as prescribed by the manufacturer before testing.

C.4 Method

C.4.1 Abrasion Resistance

1. Weigh the specimen.
2. Place the specimen on the edge of a firm surface and apply 50 brush strokes, rotating the specimen after each stroke to ensure even brushing around the edges. The brush must be held with its long axis parallel to the longitudinal axis of the specimen. Apply the brush strokes to the full height of the specimen with a firm stroke corresponding to 3 lb. (1.35 kg) of force. Ensure that the specimen is not knocked or dropped.
3. Weigh the specimen after brushing.
4. Record the amount of material lost as a percentage of the original weight (recorded in Step-1).
5. If less than 10 percent of the original weight is recorded on the untreated control specimens after brushing, repeat the test on all specimens in increments of 50 brush strokes.

C.4.2 Density Change

1. Test as described in AASHTO T 180 or ASTM D1557.

C.4.3 California Bearing Ratio

1. Test as described in AASHTO T 193 or ASTM D1883.

C.4.4 Moisture Sensitivity

1. Place the aluminum marker disc in the center of the treated specimen and place the specimen in an aluminum pan.
2. Place the pan in the water bath, start the stopwatch and check that the water cover is approximately 1 in. (25 mm) above the specimen.
3. Observe the rate of disintegration.
4. Stop the stopwatch as soon as the specimen has disintegrated to the edge of the marker disc.
5. Record the time (moisture sensitivity in minutes).
6. If the specimen has not disintegrated to the marker disc after 120 minutes of soaking, remove the specimen from the water bath.
7. Record the moisture sensitivity as >120 minutes.
8. Surface-dry the soaked specimen with a paper towel.
9. Immediately proceed with the unconfined compressive strength test.

C.4.5 Unconfined Compressive Strength

1. Test as described in AASHTO T 208 or ASTM D2166.
2. After recording the load at failure, place the crushed material in a moisture tin and weigh.
3. Dry the sample in an oven set at 220°F (105°C) for 24 hours.
4. Determine the moisture content.

C.4.6 Plasticity Change

1. Test as described in AASHTO T 89/T 90 or ASTM D4318.

Blank page

APPENDIX D: EXAMPLE SUGGESTED SPECIFICATION LANGUAGE

The following suggested specification language is provided as an example to be used when compiling or supplementing road agency specifications for purchasing and/or contracting the application of unpaved road chemical treatments. The content, level of detail, language, style, and format will need to be changed to suit specific road agency requirements.

D.1 Description

This Section covers the application of unpaved road chemical treatments for dust control, fines preservation, and/or surface stabilization of unpaved road wearing course and/or base course materials.

Unpaved road chemical treatments consist of various chemical dust suppressants, fines preservation treatments and/or stabilizers that work by agglomerating and/or binding the soil particles together, and/or chemically altering some component of the soil to improve its performance. Treatments intended for dust control and/or fines preservation may be applied as topical spray-on treatments to a prepared surface, or as mix-in treatments to an existing road, or as part of regravelling or reshaping activities. Treatments intended for stabilization can only be applied as a mix-in treatment.

D.2 Definitions

- Dust control/fines preservation on unpaved roads involves the use of chemical treatments, either as spray-on or mix-in applications, to agglomerate fine particles in the wearing course material and prevent their entrainment by vehicles and wind, without any significant improvements in shear strength in the wearing course or underlying base or subgrade materials.
- Stabilization on unpaved roads involves the use of mixed-in chemical treatments to agglomerate fine particles in the wearing course material (and possibly the underlying materials as well) and prevent their entrainment by vehicles and wind; to bind agglomerated fine particles to coarser particles; and to increase shear strength to improve wet weather passability.

D.3 Types of Chemical Treatments

The specific chemical treatment, chemical treatment category, or blend of chemical treatments to be used must be as shown on the plans or as directed by the Engineer. Alternative treatments that can be shown to perform similarly or better than the specified treatment can be proposed.

Unpaved road chemical treatments must be categorized under one of the following categories, or be a blend of one or more of the following categories: wetting agent/surfactant; water absorbing; organic non-petroleum; organic petroleum; synthetic fluid; synthetic polymer; concentrated liquid stabilizer, or clay additive.

D.4 Chemical Treatment Application Plan

At least two weeks prior to the start of work, the Contractor must provide the Engineer with a detailed Chemical Treatment Application Plan, prepared in accordance with the chemical treatment manufacturer's recommendations. The Plan must include:

(a) The name of the product that will be used, the category and subcategory under which it falls, and the manufacturer's name;
(b) The Certificate of Compliance as detailed in Section D.5.3;
(c) A detailed proposed methodology for preparing the road, applying the chemical treatment, and for shaping and compacting the road after application;
(d) Dilution rates, application rates, and number of passes to apply the required active content or residual without any runoff;

(e) The procedure that will be followed to ensure that the correct amount of chemical treatment has been applied;
(f) The curing time required before traffic can use the road;
(g) The equipment that will be used during all phases of application and which is in conformance with Section D.6;
(h) The procedure that will be followed for safely accommodating traffic and ensuring that vehicles do not travel on the roadway before the chemical treatment has penetrated and/or cured;
(i) Weather conditions, including but not limited to ambient and road surface temperature, wind, and allowable period before expected precipitation, under which the chemical treatment can be applied; and
(j) Procedures that will be followed in the event of a spill.

The Engineer must approve the Chemical Treatment Application Plan before any work can be started.

D.5 Contractor Compliance

D.5.1 Permits

At least two weeks prior to the start of work, the Contractor must provide copies of all required permits and any required notices of intent. The Engineer must approve these documents prior to start of work.

D.5.2 Certificate of Compliance for Chemical Treatments

At least two weeks prior to the start of work, the Contractor must provide a certificate of compliance for the chemical treatment that:

(a) Names the chemical treatment category, or categories if the chemical treatment is a blend, from the list provided in Section D.3.
(b) Confirms that the chemical treatment supplied conforms to the category/subcategory requirements listed in Section D.11. A copy of the test results must be attached to the certificate.
(c) Confirms that the chemical treatment complies with the safety data sheet, which must be attached to the Certificate and which must include a list of all chemical compounds present in the undiluted product in concentrations greater than 1%; and
(d) Confirms that the chemical treatment complies with the environmental requirements listed in Section D.12. A copy of the environmental testing results must be attached to the Certificate.

Confirmation testing must be specific to the proposed chemical treatment or blend of chemical treatments and not generic to similar products from the same or different categories. Testing must have been performed by independent laboratories accredited by AASHTO/ASTM and/or EPA for each specific test listed on the certificate. The Contractor is responsible for any costs associated with this testing.

The Agency has the right to qualify or disqualify, and/or accept or reject chemical treatments based on the materials used to produce that chemical treatment. The Agency will assess the chemical treatments for the potential of negatively impacting public safety and/or the environment. The right to qualify or disqualify, accept or reject a chemical treatment based on manufactured composition rests solely with the Agency.

D.5.3 Product Verification

The Contractor must provide a test report showing that the minimum acceptable limits as specified in the Certificate of Compliance have been met for the delivered product.

The Contractor, in the presence of the Engineer or his designee, must obtain samples of the bulk, undiluted liquid chemical treatment as it is delivered to the job site. Samples must be taken from each bulk tanker that delivers the chemical treatment for verification testing purposes if deemed necessary. If the bulk undiluted chemical treatment is delivered in containers, a sample must be taken from each container delivered to the job site. The Engineer will select the exact locations and times of sampling.

The chemical treatment samples must be split in three equal portions. The Contractor retains one sealed portion, and the Engineer retains two sealed portions. At the Engineer's discretion, one portion of the Engineer's samples will be sent to an AASHTO/ASTM- and/or EPA-accredited test laboratory to verify that the chemical treatment meets the category specification. The other sample will be held for backup until the Engineer is satisfied with the road performance after treatment. Sample containers must be labeled and sealed under the supervision of the Engineer.

If directed by the Engineer, the accredited laboratory will test the chemical treatment sample in accordance with one or more of the tests listed in the relevant category/subcategory in Section D.11, or other relevant test approved by the Engineer, to confirm that the liquid chemical treatment meets the criteria detailed in the Certificate of Compliance.

If the test reports indicate that any of the minimum acceptable limits as specified in the Certificate of Compliance are not met, the quality of the chemical treatment will be deemed deficient by the Engineer. The delivery and application of a deficient chemical treatment will be stopped. Work will not resume until:

(a) All product verification testing is complete; or
(b) The Contractor replaces the chemical treatment and initial tests on the new chemical treatment show compliance; or
(c) Application rates are adjusted to compensate for any deficiencies.

The Contractor is responsible for the costs of removal and cleanup of any non-conforming chemical treatment, and supplying the new chemical treatment with the correct composition, or for the costs of applying additional chemical treatment to compensate for any deficiencies.

The Contractor may perform additional verification testing on the split samples. In case of a dispute where the verification tests produce different results by the Contractor than the Engineer, the Engineer will hire a different independent AASHTO/ASTM- and/or EPA-accredited testing laboratory to perform a third round of testing. This testing and the results of the testing will be considered final for verification by both the Engineer and Contractor.

D.5.4 Applicator Qualifications

The Contractor must provide the Engineer with the following qualifications at least two weeks prior to the start of work. If the application is being subcontracted, the name and qualifications of the subcontractor must also be provided.

(a) Acknowledgement that the Contractor has been trained to apply the specific chemical treatment in line with the manufacturer's recommended procedure;
(b) Information showing that the Contractor has at least two years of experience within the last five years serving as either a primary contractor or subcontractor in delivering and applying unpaved road chemical treatments;
(c) Acknowledgement that the Contractor is familiar with local environmental and permitting requirements associated with unpaved road chemical treatment applications;
(d) Acknowledgement that the Contractor is familiar with the procedures for preventing and dealing with spills of the chemical treatment; and
(e) A copy of the Contractor's State Contractors License.

The Engineer must approve these qualifications prior to start of work.

D.5.5 Supervision

The Contractor must provide chemical treatment manufacturer-trained personnel for on-site technical assistance during initial delivery and during application. This technical assistance is to assure that the chemical treatment is applied correctly and in accordance with the approved Chemical Treatment Application Plan.

D.5.6 Cleanup

The Contractor is responsible for removal and cleanup of any nonspecification chemical treatment that has been delivered to the site and not approved by the Engineer for application, and/or applied to a road or other surface, and/or any chemical treatment that is spilled anywhere on the property, and is cause for environmental concern. This includes but is not limited to cleanup measures as needed for roadways, roadsides, storage facilities, yards, and equipment, and may include removal and replacement of contaminated soils.

D.6 Equipment

The Contractor must provide all equipment necessary to complete the work as described in the bid document and Chemical Treatment Application Plan. Equipment may be:

(a) Limited to delivery trucks if the Agency is applying the chemical treatment;
(b) Limited to delivery trucks and distributor trucks if the Agency is preparing the road and the Contractor is applying the chemical treatment; or
(c) A full complement of equipment if the Contractor is responsible for all aspects of application of the chemical treatment.

Equipment may include but is not limited to delivery trucks, distributor trucks, motorized graders, mixing and pulverizing equipment, pad foot rollers, steel drum rollers, and pneumatic-tired rollers. All equipment used for this work is subject to approval by the Engineer. Equipment which fails to provide an acceptable application of properly diluted chemical treatment or does not perform satisfactorily must be removed from the job and replaced with acceptable equipment meeting the requirements of this specification.

For liquid application, distributor trucks must be designed, equipped, maintained, and operated so that the chemical treatment is applied uniformly through a pressurized spraybar on variable widths of surface up to 16 ft. (5 m) at readily determined and controlled rates from 0.03 to 1.0 gal./yd^2 (0.1 to 4.5 L/m^2), with an allowable transverse variation from any specified rate not to exceed 10% or 0.02 gal./yd^2 (0.1 L/m^2), whichever is less. Spray bars and extensions must be of the full circulating type. Valves that control the flow from nozzles must be of a positive active design so as to provide a uniform, unbroken spread of chemical treatment on the surface.

For powder, flake, or pellet application, distributor trucks must be designed, equipped, maintained and operated so that the chemical treatment is applied uniformly through a mechanical or pneumatic spreader on variable widths of surface up to 16 ft. (5 m) at readily determined and controlled rates from 0.5 to 2.0 lb./yd^2 (0.2 to 1.1 kg/m^2), with an allowable transverse variation from any specified rate not to exceed 10% or 0.2 lb./yd^2 (0.1 kg/m^2), whichever is less. Valves which control flow must be of a positive active design so as to provide a uniform, unbroken spread of chemical treatment on the surface.

Distributor equipment must be equipped with a tachometer and pressure gauge and one or more of the following to provide for accurate, rapid determination and control of the amount of chemical treatment being applied: accurate volume-measuring devices, a calibrated tank, and/or a certified meter or weight tickets and calibration charts relating to the specific gravity of the concentrate and/or diluted liquid, or powder, flake, or pellet.

Distributor equipment must be equipped with hand spraying/spreading equipment for applying the chemical treatment to corners or areas that cannot be accessed by the distributor truck.

Gravity feed spraybars are not permitted. No leaks are allowed on any part of the equipment.

The maintenance and calibration of the distribution vehicle must be checked periodically and a record of maintenance and calibration must be submitted to the Engineer for review upon request. Distributor trucks proposed for use must have been tested within 6 months from the date of the chemical treatment application to determine the rate of the transverse spread. If requested, the Contractor must furnish the Engineer with evidence that the transverse spread of the distributor truck, when the trucks were approved for use, was as uniform as practicable and under no condition was there a variance on any of the test pads greater than the allowable transverse variation. The Engineer may require that each distributor truck be tested on site to determine the rate of the transverse spread.

The Contractor is liable, as determined by the Agency, for causing any unanticipated extraordinary damage to Agency equipment used in the storage or distribution of the chemical treatments.

D.7 Weather Conditions

Ambient and road surface temperatures prior to start and during application must be in accordance with the approved Chemical Treatment Application Plan. Application must be stopped during high wind. Application must also be stopped when there is the chance of precipitation within the precipitation-free period specified by the chemical treatment manufacturer, or within the next 8-hour period if not specified. The Contractor is responsible for reapplying the chemical treatment at no additional cost if the application is degraded by weather within the first 24 hours of placement.

D.8 Chemical Treatment Application

D.8.1 Surface Preparation for Spray-On Surface Applications

The road surface must be prepared to conform to the approved Chemical Treatment Application Plan detailed in Section D.4. In all instances, the road must be bladed to provide a quality ride surface with a crown or cross slope of between 4% and 5%. All drains and drainage provisions must be cleared, opened, or prepared to facilitate efficient drainage of water off and away from the road. Surfaces must be pre-moistened in accordance with the chemical treatment manufacturer's recommendations detailed in the Chemical Treatment Application Plan. Chemical treatments must not be applied when the surface is excessively wet or saturated.

D.8.2 Spray-On Surface Applications

The chemical treatment must be applied according to the Chemical Treatment Application Plan detailed in Section D.4 and approved by the Engineer using equipment complying with the requirements detailed in Section D.6.

The Contractor must dilute the chemical treatment as needed to within the ranges detailed in the Chemical Treatment Application Plan to ensure that the required penetration depth and distribution of active content or residue is achieved. Chemical treatments may be applied in multiple passes at reduced application rates to meet the total application rate specified and/or assure uniform coverage and/or prevent any runoff of the chemical treatment.

Topical applications can be rolled/compacted only as detailed in the Chemical Treatment Application Plan. Complete penetration of the chemical treatment is required prior to any surface rolling. Complete penetration occurs when the compaction equipment will not track or pick up the chemical treatment and/or the top layer of the surface material.

D.8.3 Mix-In Applications

If the chemical treatment is being applied as part of a regravelling program, new gravel meeting agency specifications must be spread to the required thickness prior to starting the chemical treatment application process.

The chemical treatment must be applied according to the Chemical Treatment Application Plan detailed in Section D.4 and approved by the Engineer. Chemical treatments may not be applied when the soil is excessively wet or saturated.

Mixing depth must be measured and recorded by the Contractor every 150 ft. (50 m). If the mixing depth is less than the depth detailed in the Chemical Treatment Application Plan, that section of the road must be reworked to the correct depth but no additional chemical treatment will be applied. If the mixing depth is greater than the depth detailed in the Chemical Treatment Application Plan, that section of road must be reworked and additional chemical treatment applied so that the design application rate is met. The costs of applying any additional chemical treatment will be covered by the Contractor.

Dilution rates must be adjusted to ensure that the fluid content (existing soil moisture plus the chemical treatment) of the soil after processing is at the desired level for compaction.

All material, exclusive of gravel or stone, must pass a 2 in. (50 mm) sieve after processing. Surface gravel or stones must be thoroughly and uniformly mixed with the underlying materials to obtain a homogeneous mixture. All debris, weeds, organic material, and oversize stones must be removed from the road.

After processing, the material must be uniformly moist throughout the mixing depth. The moisture content must be determined in accordance with AASHTO T 310/ASTM D6938 or other Agency approved method. The blended material must be shaped to the required grade line and cross-section shown on the plans.

Treated roads must be compacted according to the approved Chemical Treatment Application Plan. The number of passes required to achieve refusal density should be determined on representative test strips with density measured in accordance with AASHTO T 310/ASTM D6938 or other Agency-approved method after each roller pass until there is no increase in density over that measured on the previous pass. For the remainder of the section being treated, primary rolling must continue for the determined number of roller passes.

Sufficient blading must be done to correct any drainage and grade issues within the limits of existing drainage patterns.

The final surface must be rolled to a smooth and even grade. A final topical application must be applied in accordance to the approved Chemical Treatment Application Plan. Application must be controlled to prevent ponding and runoff.

The length of road treated each day must be limited to that which the Contractor can thoroughly mix, compact, and safely open to traffic within that work day. No obstructions of any sort, including windrows of material, may be left on the road on completion of the day's work.

D.8.4 Curing

The treated road must be cured according to the approved Chemical Treatment Application Plan.

D.8.5 Record of Chemical Treatment Applied

The Contractor must measure the contents of the bulk tanker or drums at the start and end of each work day to verify the gallons (liters) of liquid chemical treatment at the job site. The distributor truck must be inspected at the end of the day to ensure that it is empty. The total gallons (liters) of chemical treatment applied on one day is calculated by subtracting the end-of-day quantity from the start-of-day quantity.

A daily "Gallon (Liter) Use Report" must be completed by the Contractor. The report must also identify the size of area treated for the day and the depth treated if a mix-in application is used. The report must be verified and signed by the Engineer or his designee. This report will be used to verify application rate and total chemical treatment used. If the report indicates that the minimum application rate was not achieved, the work will be deemed deficient by the Engineer.

D.9 Deficiencies and Warranty

If the application rate is lower than the design application rate, or the active solids content of the chemical treatments is found deficient per the Certificate of Compliance detailed in Section D.5.2, the Engineer may allow the Contractor to apply additional topical coats of the chemical treatment to any area already treated by the deficient product to remedy the deficiency.

The Engineer can require the Contractor to repeat all work with the correctly formulated chemical treatment if supplementary applications are considered likely to be ineffective in achieving the design performance.

Synthetic polymer emulsions, asphalt emulsions or other chemical treatments that do not dissolve in water after curing, or that cannot be reworked after applying water to the road, or that forms a permanent crust/skin on the surface must be reapplied at the original application rate detailed in the Chemical Treatment Application Plan.

For mix-in treatments, the Contractor must re-scarify the stabilized section to its full depth and apply the additional chemical treatment required to meet the design strength. All corrective treatments must be applied within 24 hours of the original treatment.

If a warranty period is included as part of the contract, the Contractor must provide and install additional chemical treatment at no cost if the finished chemical treatment fails to meet the design performance requirement and specification/criteria. The Contractor must provide additional applications within five working days of notification from the Engineer of performance failure.

D.10 Measurement and Payment

Chemical treatment spray-on surface application is measured by the square yard (square meter) and includes surface preparation, water spraying, treatment application, compaction, and any other activity detailed in the approved Chemical Treatment Application Plan.

Chemical treatment mix-in application is measured by the square yard (square meter) and includes surface preparation, water spraying, treatment application, mixing to the design depth, compaction, final grading, topical seal coats, and any other activity detailed in the approved Chemical Treatment Application Plan.

Chemical treatment materials are measured by the ton or gallon of undiluted material. Any conversion from volumetric quantities must use manufacturer-supplied calibration charts relating to the specific gravity of the concentrate and/or dilution.

Payment will be made for the applicable items at the Contract unit price and will constitute full compensation for the item complete in place.

D.11 Example Suggested Category/Subcategory Chemical Treatment Requirements

The following tables provide example suggested specifications for commonly used unpaved road chemical treatment categories and subcategories. Formal AASHTO or ASTM test methods specific to unpaved road chemical treatments currently only exist for calcium chloride and asphalt emulsion. Consequently, in most instances, the suggested test methods are not specific to the chemical treatment category or subcategory, but have been identified based on their use for assessing the properties of similar substances. Alternative equally or more appropriate test methods can be used in place of those suggested. Acceptance limits may need to be adjusted for a specific treatment based on the test method used. All ASTM test methods refer to the latest version of the method unless otherwise specified.

Example Suggested Specification: Calcium Chloride Solution[1]		
Clear odorless liquid intended for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Calcium chloride content	28 – 42%	ASTM E449
Total magnesium as $MgCl_2$	<6.0%	ASTM E449
Total alkali chlorides as NaCl	<6.0%	ASTM E449
Calcium hydroxide content	<0.2%	ASTM E449
pH (5% solution)	7.0 – 9.0	ASTM D1293
Specific gravity	1.28 – 1.44	ASTM D1429
Notes [1] ASTM D98/AASHTO M144		

Example Suggested Specification: Calcium Chloride Flake[1]		
White odorless flakes intended for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undissolved state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Calcium chloride content	>75%	ASTM E449
Total magnesium as $MgCl_2$	<6.0%	ASTM E449
Total alkali chlorides as NaCl	<6.0%	ASTM E449
Calcium hydroxide content	<0.2%	ASTM E449
pH (5% solution)	7.0 – 9.0	ASTM D1293
Passing 3/8 in. sieve	100%	ASTM C136
Passing #4 sieve	80 – 100%	ASTM C136
Passing #30 sieve	<5%	ASTM C136
Notes [1] ASTM D98/AASHTO M144		

Example Suggested Specification: Magnesium Chloride Solution		
Colorless or light amber, odorless liquid intended for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Magnesium chloride content	28 – 33%	ASTM D4691/D511[1]
Sulfate content (as magnesium sulfate)	<4.0%	ASTM D4691[1]
Potassium content (as potassium chloride)	<0.5%	ASTM E449
Sodium chloride content	<1.0%	ASTM E449
pH (5% solution)	7.0 – 9.0	ASTM D1293
Specific gravity	1.31 ± 0.02	ASTM D1429
Notes [1] Or similar documented appropriate atomic absorption spectrophotometry method (e.g., APHA-AWWA-WPCF "*Standard Methods for the Examination of Water and Waste Water*")		

Example Suggested Specification: Glycerin-Based		
Liquid consisting of non-petroleum-based organic esters and resins combined with other additives designed specifically for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties in its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Glycerin solids content	≥70%	ASTM D6584
Sodium chloride content	<8.0%	ASTM D4691
Methanol content	<0.1%	ASTM D7716
MONG[1] specification	<5.0%	-
pH	4.5 – 8.0	ASTM D1293
Specific gravity	≥1.20 @ 77°F (25°C)	ASTM D1429
Notes [1] Material organic not glycerin		

Example Suggested Specification: Lignosulfonate: Ammonium		
Dark brown lignin-based liquid or powder with woody odor derived from wood pulping using the sulfite process used in the manufacture of cellulose products and designed for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted/undissolved state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Lignin sulfonate content (ready to use)	>25%	ASTM D4900
Residue (total solids content)	≥52%	ASTM D4903/D2834
Lignin sulfonated content of residue	>50%	-
Reducing sugars content of residue	>25% of dry weight	ASTM D5896/D6406
pH	4.0 – 5.5	ASTM D1293
Specific gravity	≥1.20	ASTM D1429
Absolute viscosity (Brookfield)	<1,000 cP @ 77°F (25°C)	ASTM D2196

Example Suggested Specification: Lignosulfonate: Calcium		
Dark brown lignin-based liquid or powder with woody odor derived from the wood pulping using the sulfite process used in the manufacture of cellulose products and designed for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted/undissolved state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Lignin sulfonate content (ready to use)	>25%	ASTM D4900
Residue (total solids content)	≥52%	ASTM D4903/D2834
Lignin sulfonated content of residue	>50%	-
Reducing sugars content of residue	>25% of dry weight	ASTM D5896/D6406
pH	6.0 – 9.0	ASTM D1293
Specific gravity	≥1.20	ASTM D1429
Absolute viscosity (Brookfield)	<1,000 cP @ 77°F (25°C)	ASTM D2196

Example Suggested Specification: Lignosulfonate: Sodium		
Dark brown lignin-based liquid or powder with woody odor derived from the wood pulping using the sulfite process used in the manufacture of cellulose products and designed for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted/undissolved state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Lignin sulfonate content (ready to use)	>25%	ASTM D4900
Residue (total solids content)	≥52%	ASTM D4903/D2834
Lignin sulfonated content of residue	>50%	-
Reducing sugars content of residue	>25% of dry weight	ASTM D5896/D6406
pH	6.0 – 9.0	ASTM D1293
Specific gravity	≥1.20	ASTM D1429
Absolute viscosity (Brookfield)	<1,000 cP @ 77°F (25°C)	ASTM D2196

Example Suggested Specification: Molasses/Sugar		
Cane- or beet-based liquid derived from the sugar refining process and designed for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Residue (active solids content)	≥45%	ASTM D4903
Complex carbohydrate	>10% of dry weight	ASTM D5896
pH	3.0 – 9.0	ASTM D1293
Specific gravity	≥1.00	ASTM D1429
Absolute viscosity (Brookfield)	50 – 200 cPs @ 77°F (25°C)	ASTM D2196

Example Suggested Specification: Plant Oil (Soy, Canola, Rape, etc.)		
Dark-colored liquid with vegetable odor consisting of plant derived oils designed specifically for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Residue (active solids content)	>50%	ASTM D4903
Specific gravity	0.93	ASTM D1429
Absolute viscosity (Brookfield)	50 – 200 cP @ 77°F (25°C)	ASTM D2196
Flash point	>550°F (288°C)	ASTM D92

Example Suggested Specification: Tall Oil Pitch Rosin		
Light brown resinous emulsion with woody odor derived from distilled tall oil and designed for fines preservation, dust control and/or stabilization of unpaved roads. It must be non-water soluble once cured. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Rosin acid content	>10%	ASTM D1240
Residue (active solids content)	≥45%	ASTM D2834
pH	3.0 – 9.0	ASTM D1293
Specific gravity	≥1.00	ASTM D1429
Absolute viscosity (Brookfield)	50 – 200 cP @ 77°F (25°C)	ASTM D2196
Flash point	None	ASTM D92

Example Suggested Specification: Asphalt Emulsion, Anionic – SS1		
Dark brown asphalt emulsion with asphalt odor derived from petroleum refining and intended for fines preservation, dust control and/or stabilization of unpaved roads. It must be non-water soluble once cured. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Tests on emulsion		ASTM D244
Kinematic viscosity (Saybolt Furol)	20 – 100 SFS @ 77°F (25°C)	ASTM 7496
Sieve test (% passing 850 µm)	<0.1%	ASTM D6933
Residue by distillation	>57%	ASTM D6997
Settlement after 5 days	<5%	ASTM D6930
Storage stability, 24 hours	>1%	ASTM D6930
Tests on residue		ASTM D244
Penetration	100 - 200	ASTM D5
Ductility, 50 mm/minute	>16 in. at 77°F (405 mm @ 25°C)	ASTM D113
Solubility in Trichloroethylene	>97.5%	ASTM D2042

Example Suggested Specification: Asphalt Emulsion, Cationic – CSS1		
Dark brown asphalt emulsion with asphalt odor derived from petroleum refining and intended for fines preservation, dust control and/or stabilization of unpaved roads. It must be non-water soluble once cured. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Tests on emulsion		ASTM D244
Kinematic viscosity (Saybolt Furol)	20 – 100 SFS @ 77°F (25°C)	ASTM 7496
Sieve test (% passing 850 µm)	<0.1%	ASTM D6933
Residue by distillation	>57%	ASTM D6997
Settlement after 5 days	<5%	ASTM D6930
Storage stability, 24 hours	>1%	ASTM D6930
Particle charge test	Positive	ASTM D7402
Tests on residue		ASTM D244
Penetration	100 - 200	ASTM D5
Ductility, 50 mm/minute	>16 in. at 77°F (405 mm @ 25°C)	ASTM D113
Solubility in Trichloroethylene	>97.5%	ASTM D2042

Example Suggested Specification: Base/Mineral Oil		
Colorless, odorless, viscous synthetic liquid that does not dissolve in water and is specifically formulated for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Base/mineral oil content	>75%	-
Specific gravity	0.85 – 0.90	ASTM D1298
Absolute viscosity (Brookfield)	<250 cP @ 68°F (20°C)	ASTM D2196
Flash point	>300°F (>150°C)	ASTM D93

Example Suggested Specification: Petroleum Resin		
Dark brown asphalt emulsion with asphalt odor derived from petroleum refining and intended for fines preservation, dust control and/or stabilization of unpaved roads. It must be non-water soluble once cured. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Residue	≥60%	ASTM D6934
pH	4.0 – 7.0	ASTM D1429
Specific gravity	≥1.00 @ 60°F (16°C)	ASTM D1298
Kinematic viscosity	≥188 SFS @ 77°F (25°C)	ASTM D2170
Flash point	≥400°F (205°C)	ASTM D92
Particle charge test	Positive	ASTM D7402

Example Suggested Specification: Synthetic Fluid		
Colorless, odorless, viscous synthetic liquid that does not dissolve in water, meets US EPA 40 CFR part 435 and is specifically formulated for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Synthetic fluid content	>75%	-
Specific gravity	0.85 – 0.90	ASTM D1298
Absolute viscosity (Brookfield)	<250 cP @ 68°F (20°C)	ASTM D2196
Flash point	>285°F (140°C)	ASTM D92

Example Suggested Specification: Synthetic Fluid with Binder		
Color, odor, and viscosity dependent on binder used. Blend must still meet requirements for US EPA 40 CFR part 435 after blending with the selected binder and be specifically formulated for fines preservation, dust control and/or stabilization of unpaved roads. It has the following properties it its undiluted state.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Dependent on type of binder		

Example Suggested Specification: Synthetic Polymer[1]		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Residue (active solids content)	>40%	ASTM D2834
pH	4.0 – 9.5	ASTM D1429
Specific gravity	1.00 – 1.15 @ 60°F (16°C)	ASTM D1298
Absolute viscosity (Brookfield)	<1,000 cP @ 77°F (25°C)	ASTM D2196
Polymer film tensile strength – dry	>500 psi (3.5 MPa)	ASTM D412
Retained coagulum on #100 sieve	<0.1%	ASTM D1417
Ash content	<2%	ASTM D5040
Flash point	None	ASTM D92

Notes

1 Polymer emulsion type must be identified
Individual components >5% by volume in blends of polymers of different compositions must be identified
Polymer emulsion additives >2% by volume must be identified

Example Suggested Specification: Concentrated Liquid Stabilizer: Acidic		
Due to the proprietary nature of these chemical treatments, the wide range of constituents used in them, and continuing product development, only limited generic category specifications can be prepared at this time. Performance-based specifications (e.g., minimum soaked California Bearing Ratio [CBR]) together with the environmental specification detailed in Section D.12 should be used to source these products.		
Test Parameter	**Suggested Acceptance Limits**	**Suggested Test Method**
Solids content (dried at 212°F)	>25%	Evaporation
pH	0.2 – 2.0	ASTM D1429
Anion surfactant content	>16%	ASTM D3049
Specific gravity	0.9 – 1.1 @ 77°F (25°C)	ASTM D1429
Absolute viscosity (Brookfield)	700 – 900 cP @ 77°F (25°C)	ASTM D2169
Surface tension	>72 dynes/cm @ 77°F (25°C)	ASTM D1331

Concentrated Liquid Stabilizer: Neutral/Low Acidity/Enzyme
Due to the proprietary nature of these chemical treatments, the wide range of constituents used in them, and continuing product development, no suggested generic category specification can be prepared at this time. Performance based specifications (e.g., minimum soaked California Bearing Ratio [CBR]) together with the environmental specification detailed in Section D.12 should be used to source these products.

D.12 Example Suggested Environmental Requirements

The following text and tables provide examples of suggested environmental requirements for unpaved road chemical treatments. Few specific regulations for unpaved road chemical treatments exist, and no comprehensive national program regulates the application of these treatments. The ideal environmental specification is tailored to site- or regionally-specific environmental concerns. The language below is provided as general guidance for development of those specifications.

Any chemical treatment being considered for a project should have Hazardous Materials Identification System (HMIS) ratings equal to or less than the following for each category:

- Health (H) = 1
- Flammability (F) = 1
- Physical Hazard = 1
- Personal Protective Equipment (PPE) = B

Chemical treatments must be tested by appropriately accredited laboratories with documented quality control/quality assurance procedures using standardized protocols (e.g., ASTM- and/or EPA test methods). The following test results must be presented along with the certificate of compliance:

(a) Chemical analysis of leachate. Chemical treatments must be tested according to EPA SW-846 Method 1312 (Synthetic Precipitation Leaching Procedure [SPLP]) with analysis of the leachate for volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), chlorinated pesticides, chlorinated herbicides, and metals. Treatments must not contain any of the listed hazardous contaminants at levels above those given in Table D.1 (EPA 40 CFR 261.24 [2011]).

(b) Aquatic toxicity using *Oncorhynchus mykiss* (rainbow trout), *Pimephales promelas* (fathead minnow), and *Americamysis bahia* (mysid shrimp). When tested according to ASTM E729 or EPA/600/4-90/027F (acute toxicity) and EPA/600/4-91/002 (chronic toxicity), the chemical treatment must have an LC50 >10 ppm and be considered to have a rating of “slightly toxic” or better per EPA ecotoxicity categories (Table D.2). *Depending on the species of interest at the application site, it may be appropriate to specify a rating of “slightly toxic” or better for other groups of organisms (Table D.2), as determined by appropriate tests. Example test guidelines are also listed in Table D.2.*

Table D.1: Example Levels of Hazardous Contaminants Not to be Exceeded in Leachates

Contaminant	Regulatory Level (mg/L)	Contaminant Class	Analysis Method
1,1-Dichloroethylene	0.7		
1,2-Dichloroethane	0.5		
1,4-Dichlorobenzene	7.5		
Benzene	0.5		
Carbon tetrachloride	0.5		
Chlorobenzene	100.0	VOC	EPA 8260B
Chloroform	6.0		
Methyl ethyl ketone	200.0		
Tetrachloroethylene	0.7		
Trichloroethylene	0.5		
Vinyl chloride	0.2		
2,4,5-Trichlorophenol	400.0		
2,4,6-Trichlorophenol	2.0		
2,4-Dinitrotoluene	0.13		
Hexachlorobenzene	0.13		
Hexachlorobutadiene	0.5		
Hexachloroethane	3.0		
Nitrobenzene	2.0	SVOC	EPA 8270C
o-Cresol[1]	200.0		
m-Cresol[1]	200.0		
p-Cresol[1]	200.0		
Total Cresols[1]	200.0		
Pentachlorophenol	100.0		
Pyridine	5.0		
Chlordane	0.03		
Endrin	0.02		
Heptachlor (and its epoxide)	0.008	Chlorinated pesticide	EPA 8081
Lindane	0.4		
Methoxychlor	10.0		
Toxaphene	0.5		
2,4,5-TP (Silvex)	1.0	Chlorinated herbicide	EPA 8151A
2,4-D	10.0		
Arsenic	5.0		
Barium	100.0		
Cadmium	1.0		
Chromium	5.0	Metal	EPA 6010
Lead	5.0		
Selenium	1.0		
Silver	5.0		
Mercury	0.2	Metal	EPA 7470/7471

[1] If o-, m-, and p-cresols cannot be individually measured, the regulatory level for total cresols is used.

Table D.2: EPA Ecotoxicity Categories for Terrestrial and Aquatic Organisms *(25)*

Category	Aquatic. Acute Conc.[1] (ppm)	Wild Mammals. Acute Oral Conc. (mg/kg body wt.)	Avian. Acute Oral Conc. (mg/kg body wt.)	Avian. Dietary Conc. (mg/kg diet)	Non-target Insects. Acute Conc. (µg/bee)
	EPA/600/4-90/027F	OECD Guideline 425	EPA 850.2100	EPA 850.2200	EPA 850.3020
Very highly toxic	<0.1	<10	<10	<50	N/A
Highly toxic	0.1 – 1	10 – 50	10 – 50	50 – 500	<2
Moderately toxic	>1 – 10	51 – 500	51 – 500	501 – 1,000	2 – 11
Slightly toxic	>10 – 100	501 – 2,000	501 – 2,000	1,001 – 5,000	N/A
Practically non-toxic	>100	>2,000	>2,000	>5,000	>11

[1] Concentration

An example of regionally specific requirements from the Pennsylvania Dirt and Gravel Road Maintenance Program Product Approval Process (*https://www.dirtandgravel.psu.edu/pa-program-resources/products*; *accessed February 2018*) is listed in Table D.3. The process requires that chemical treatments are tested according to EPA SW-846 Method 1312 with analysis of the leachate for inorganic and organic constituents of interest. Treatments must not contain any constituent at levels above those listed in the table.

Table D.3: Example Regionally-Specific Requirements for Unpaved Road Treatments

Organic		Inorganic	
Constituent	**Max. Specific Concentration Limit (mg/L)**	**Constituent**	**Max. Specific Concentration Limit (mg/L)**
Benzene	0.5	Ammonia	360
Carbon tetrachloride	0.5	Antimony	0.6
Chlorobenzene	10	Arsenic	1.0
Chloroform	8.0	Barium	200
1,4-Dichlorobenzene	7.5	Beryllium	0.4
1,2-Dichloroethane	0.5	Boron	600.0
1,1-Dichloroethene	3.1	Cadmium	0.5
Methyl ethyl ketone	400	Chromium total	20
Tetrachloroethene	0.5	Cobalt	1.1
Trichloroethylene	0.5	Copper	100
Vinyl chloride	0.2	Cyanide	5.0
o-Cresol (2-Methylphenol)	180	Fluoride	44
m-Cresol (3-Methylphenol)	180	Mercury	0.2
p-Cresol (4-Methylphenol)	18	Manganese	30
2,4-Dinitrotoluene	0.21	Molybdenum	4.0
Hexachlorobenzene	0.1	Nickel	10
Hexachloro-1,3-butadiene	0.9	Lead	0.5
Hexachloroethane	0.1	Selenium	5.0
Nitrobenzene	7.3	Silver	10
Pentachlorophenol	0.1	Thallium	0.2
Pyridine	3.7	Vanadium	26
2,4,5-Trichlorophenol	370	Zinc	200
2,4,6-Trichlorophenol	3.7	Aluminum	5.0
		Chloride)	250
		Nitrate (NO_3)	10
		Nitrite (NO_2)	1.0
		Sulfate (SO_4)	250

APPENDIX E: SAFETY DATA SHEET INFORMATION

The following checklist (Table E.1) can be used to review the contents of safety data sheets. Missing information should be requested from the manufacturer/supplier. Actual SDS content may vary depending on the chemistry of the product. The information provided must be backed up with test result reports/documentation available on request and verifiable by a third party. Beware of safety data sheets that simply state that the product is "proprietary," "secret," or the result is "unknown," as the user or person approving use may be held responsible for worker injuries/illness or environmental damage related to the use of the product.

Table E.1: Checklist for Safety Data Sheet Content

Topic		Detail	✓	Notes
1.	Chemical product and company information	Supplier		
		Manufacturer		
		Trade name		
		Chemical name		
		Chemical family		
		ERG code		
		UN number		
		Uses		
		Emergency contact		
		Date that MSDS was prepared/updated		
2.	Composition/information on ingredients	Chemical name, CAS No, % by weight		
		EC Number		
		List of all components >1% by weight		
3.	Hazards identification	Classification		
		Main hazard		
		Flammability		
		Chemical hazard		
		Biological hazard		
4.	First aid measures	Eyes		
		Skin		
		Ingestion		
		Inhalation		
		Protection of first aiders		
		Notes to physician		
5.	Firefighting measures	Fire hazard		
		Extinguishing media		
		Special procedures		
		Special hazards		
		Protective clothing		
6.	Accidental release measures	Personal precautions		
		Environmental precautions		
		Small spills		
		Large spills		
7.	Handling and storage	Handling		
		Storage		
		Packaging material		
8.	Exposure control/ personal protection	Occupational exposure limits		
		Engineering control limits		
		Personal protection – respiratory		
		Personal protection – hands		
		Personal protection – eyes		
		Personal protection – skin		
		Other protection		
		Hygiene measures		
		Recommended monitoring procedures		
9.	Physical and chemical properties	Physical state/appearance		
		Color		
		Odor		
		Odor threshold		
		pH		
		Density		
		Specific gravity		
		Viscosity		

Topic		Detail	✓	Notes
10.	Physical and chemical properties	Boiling point		
		Melting point		
		Flash point		
		Flammability		
		Auto-flammability		
		Auto-ignition temperature		
		Explosive properties		
		Explosion limits		
		Oxidizing properties		
		Vapor density		
		Vapor pressure		
		Evaporation rate		
		Solubility – water		
		Solubility – solvent		
11.	Stability and reactivity	Stability		
		Conditions to avoid		
		Materials to avoid		
		Hazardous decomposition products		
		Hazardous polymerization		
		Toxicological information		
		Acute toxicity		
		Chronic toxicity		
		Skin contact		
		Eye contact		
		Ingestion		
		Inhalation		
		Routes of entry		
		Target organs		
		Carcinogenicity		
		Mutagenicity		
		Reproductive hazard		
12.	Ecological information	Aquatic toxicity – fish		
		Aquatic toxicity – algae		
		Biodegradability		
		Bioaccumulation		
		Mobility		
13.	Disposal considerations	Disposal method		
		Disposal of packaging		
14.	Transport information	UN number		
		Class		
		Packaging group		
		Label		
		Emergency response number		
		Tremcard number		
15.	Regulatory information	EEC Hazard Classification		
		Risk phrases		
		Safety phrases		
		National and state legislation		
16.	Other information			

Blank page