Center for Environmentally Sustainable Transportation in Cold Climates

Guidelines for the Use of Synthetic Fluid Dust Control Palliatives on Unpaved Roads

David Barnes Ph.D., P.E.
Billy Connor P.E.
Department of Civil and Environmental Engineering
University of Alaska, Fairbanks

Date: 7/6/2017

Prepared by: David Barnes and Billy Connor

Center for Environmentally Sustainable Transportation in Cold Climates
University of Alaska Fairbanks
P.O. Box 755900
Fairbanks, AK 99775

U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

INE/AUTC 17.16

REPORT DOCUMENTATION PAGE			Form approved OMB No.
Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-1833), Washington, DC 20503			
1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE 7/2017	3. REPORT TYPE AND DATES COVERED Final Report: 06/2014 – 7/2017	
4. TITLE AND SUBTITLE Guidelines for the Use of Synthetic Fluid Dust-Control Palliatives on Unpaved Roads			5. FUNDING NUMBERS
6. AUTHOR(S) David Barnes, Ph.D., P.E. Billy Connor, P.E. University of Alaska Fairbanks			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Environmentally Sustainable Transportation in Cold Climates University of Alaska Fairbanks Duckering Building, Room 245 P.O. Box 755900 Fairbanks, AK 99775-5900			8. PERFORMING ORGANIZATION REPORT NUMBER INE/AUTC 17.16
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Midwest Industrial Supply, Inc. 1101 3rd Street, SE Canton, OH 44707			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLENMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT No restrictions			12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Please write a brief abstract.

The amount of small soil particles, dust, lost from typical unpaved roads to fugitive dust is staggering. A 1 km stretch of unpaved road can contribute over 2400 kg of dust to the atmosphere (4.2 ton/mile) in a typical 3-month summer season. Road managers typically manage dust from unpaved roads with various dust-control palliatives, which are effective for up to 1 year. Synthetic fluids are a relatively new category of dust-control palliatives. Unlike the more commonly used dust-control palliatives, such as salts, engineering guidelines do not exist for the application and maintenance of synthetic fluids on unpaved roads. To fill this void, we present through this document guidelines for road design and maintenance, palliative selection, application, and care of synthetic fluid-treated roadways.

14- KEYWORDS :Dust Management, Dust Palliative Application, Road Dust			15. NUMBER OF PAGES 38 16. PRICE CODE N/A
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT N/A

Guidelines for the Use of Synthetic Fluid Dust-Control Palliatives on Unpaved Roads

Prepared by

David Barnes, Ph.D., P.E.
Billy Connor, P.E.
University of Alaska Fairbanks

Prepared for

Center for Environmentally Sustainable Transportation in Cold Climates
University of Alaska Fairbanks
Duckering Building, Room 245
P.O. Box 755900
Fairbanks, AK 99775-5900

and

Midwest Industrial Supply, Inc.
1101 3rd Street SE
Canton, OH 44707

July 6, 2017

INE/AUTC 17.16

DISCLAIMER

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document. The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Opinions and conclusions expressed or implied in the report are those of the author(s). They are not necessarily those of the funding agencies.

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
Note: Volumes greater than 1000 L shall be shown in m^3				
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

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 (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

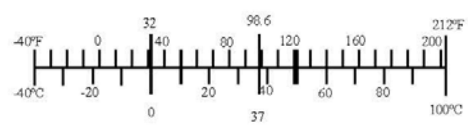

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

The production of dust from typical gravel roads without dust management can be immense. Under typical conditions, vehicle traffic on these roads can produce around 2400 kg/km (4.2 ton/mi) of fugitive dust during a 3-month summer. The large quantity of fugitive dust impacts communities on multiple levels. Application of chemical dust palliatives on gravel roads is a common method for controlling dust. Synthetic fluids are a relatively new category of dust palliatives. While gravel airport and road managers have been using this type of dust palliative for a number of years, engineering guidelines for the best use of this type of dust-control palliative do not exist. The objective of this study was to develop guidelines for the application and maintenance of synthetic fluid dust-control palliatives on unpaved roads.

Multiple sources contribute to the generation of dust form unpaved roads. The fine soil particles that comprise road dust are dislodged from the road surface and become airborne through the shearing action of vehicle tires on the road surface and the turbulence created by moving vehicles. Increased vehicle speed increases shearing forces at the road surface resulting in increased dust production. Once airborne, fugitive dust degrades the quality of life, impacts health, becomes a transportation safety hazard, and impacts community economics. Use of dust control palliatives lessens these impacts.

We have developed two field methods for determining the effectiveness of dust palliatives and a laboratory method for predicting the effectiveness of dust palliatives applied to any particular aggregate. Each method quantifies dust production from palliative treated aggregate. We developed the guidelines presented in this report using results from these different tests.

Effective dust management using any type of dust control palliative requires a well-designed and maintained gravel road. Drainage of water off and away from the road is critical. Roads should be crowned (sloped) at a 4% grade. Drainage ditches on each side of the road should be maintained to allow for water flow. Selection of the right roadway materials is also a key factor in successfully managing dust. Each layer must be able to carry the material above it and vehicle loadings. Failure of the roadway to support vehicle loads results in deep rutting and failure of dust management.

The effectiveness of a synthetic fluid over time is a function of the aggregate and fluid properties that control the retention of the fluid in the top 2 cm of the road surface and the traffic volume (average daily traffic, ADT) and the type of vehicles the road supports. Factors that impact fluid retention near the road surface are aggregate gradation, fluid viscosity, and average daily traffic. Synthetic fluids are less effective in controlling road dust when the fines content (silt and clays) is too low or too high. The appropriate fluid viscosity is a balance between a high enough viscosity so the fluid does not rapidly drain through the aggregate and a viscosity that will allow spraying of the fluid onto the road surface. Longevity in the effectiveness of synthetic fluid palliatives will be lower on roads that accommodate high ADT due to the more frequent shearing of particles on the road surface created by vehicle tires. Results from our measurements indicate that synthetic fluid palliatives effective control dust on gravel roadways for approximately one-year. On gravel runways, synthetic fluid palliatives effectively control dust for approximately two-years. The difference in longevity of the fluids on the two different surfaces is primarily due to the decreased occurrence of shear forces on gravel runways. On gravel runways, the primary factor that controls the longevity of synthetic fluid palliative effectiveness is the rate at which the fluids drain through the aggregate out of the top 2 cm.

Application rates also impact synthetic fluid performance and longevity on unpaved roads. Too light an application of fluid results in poor dust-control effectiveness and a short effective life span. However, applying too much synthetic fluid can result in loss of fluid to surface drainage during rain events and adhesion of the fluid to tires. Our experience indicates that a synthetic fluid application rate of 30 to 40 ft^2/gal is appropriate for most unpaved roads.

The key to applying palliatives is to achieve a uniform application rate over the entire area to be treated. Uniform application requires good equipment and careful attention to setting up the equipment correctly, including the spray bar height, ensuring constant operating pressures, clean nozzles, properly overlapped spray fans, and carefully controlled application speed. Applicators should apply synthetic fluid palliatives to the road surface in multiple passes with adequate time between passes to allow the fluid to penetrate into the aggregate. Synthetic fluids should never be applied to a gravel surface using a water truck.

The increased shearing forces created between vehicle tires and the roadway surface, such as around curves, on inclines, and on areas prone to acceleration and deceleration such as road intersections, result in greater decay of synthetic fluid dust-control effectiveness. Increased fugitive dust production on roads also occurs at intersections of unpaved roads and at driveways that have not been treated with dust-control palliatives. These areas of roadway require additional attention after the synthetic fluid application. Road managers should consider frequent applications of synthetic fluids to areas that experience greater shear forces. A simple method of observing the dust produced by passing vehicles can be used to determine Frequency. At intersections of treated roads with untreated roads, road managers should plan on applying palliative to untreated connecting roads for approximately 100 to 150 ft back from the intersection with treated roads.

CHAPTER 1.0 – INTRODUCTION

On a typical gravel road that supports a daily traffic volume of 25 vehicles, over 35 kg of dust per kilometer (125 lb/mi) 30 microns in size and smaller become airborne every day (U.S. EPA 1995). Extrapolating this loss of fine particles from the road over a 3-month summer season, accounting for rainy days (25% of the season), results in nearly 2400 kg of lofted dust per kilometer (4.2 ton/mi). These quantities illustrate the air quality challenges in rural communities served by unpaved roads. Not only do the airborne particles sourced from unpaved roads present air quality challenges, the loss of these small particles from the road lead to degradation in road quality, impacting driver safety as well as community economics owing to the frequent maintenance and repair required on these roads.

Solutions to road dust range from controlling vehicle speed to application of road surface treatments that suppress lofting of the fine aggregate particles. Applying water to unpaved road surfaces is most likely one of the oldest means of managing road dust. However, the dust suppression effect is short-lived, often lasting only a few hours. There are several different categories of chemical dust-control palliatives that, when used properly, effectively control dust from unpaved roads for up to a year, in some cases longer. Synthetic fluids are a relatively new category of dust-control palliatives. By definition, a synthetic fluid is a fluid derived through a chemical transformation process. This definition separates synthetic fluid from the category of petroleum-based organic fluids produced by physical separation (fractionation, distillation) in the refining process (U.S. EPA 1996, Federal Register 2001). While unpaved road and airport managers in different regions have been using these fluids for a number of years to reduce dust, there is a lack of engineering guidelines for the best use of this type of dust-control palliative.

The objective of this study was to develop engineering guidelines for the application and maintenance of synthetic fluid dust-control palliatives on unpaved roads.

CHAPTER 2.0 – BACKGROUND

Multiple sources contribute to the generation of dust from unpaved roads. As vehicles pass over the surfacing aggregate, the shearing force created at the interface of the vehicle tires and the aggregate break the cohesive and apparent cohesive forces binding particles, resulting in the generation of road dust. The weight of the vehicle also results in particle-to-particle grinding as the tires rolls over the aggregate. This repetitive grinding breaks down the particles, generating dust (Pinnick et al. 1985). Airborne dust from other sources (agricultural fields, unpaved lots, etc.) can settle onto the road surface resulting in lofting as vehicles pass. Finally, deposition of dust attached to vehicles and vehicle tires by vehicles entering the road is another likely source of dust.

The U.S. EPA categorizes the plumes of dust generated as vehicles pass across unpaved road surfaces as *fugitive dust* due to the lack of discharge of these particles from a confined flow stream (U.S. EPA 1995). Two mechanisms are responsible for creating fugitive dust from unpaved roads. First, the aerodynamic drag of moving vehicles causes a turbulent wake, with air speeds that result in lift forces at the road surface. For a particle to become entrained in air flow, the force created by the turbulent wake must exceed the adhesion forces between particles and the attached surface, as well as the resisting forces characteristic of the particles (e.g., size and density) (Sehmel 1973, Moosmüller et al. 1998, Nicholson and Branson 1990). Road surface characteristics impact the entrainment of particles in a flow stream. Lift forces created by turbulent wakes at the road surface are greater for relatively smooth surfaces such as concrete than for rough surfaces such as unpaved roads (Sehmel 1973).

The action of vehicle tires on the road surface results in the second mechanism for creation of fugitive dust. Bonse and Kuhn (1959) showed that forces imparted from the tires of a moving vehicle onto the road surface in a plane parallel with the tire are vertically downward as the vehicle travels at a steady speed. In contrast, resultant forces at the interface of the tires and road for accelerating vehicles are in a direction opposite to the direction of vehicle travel (Bonse and Kuhn 1959). The result of the force direction for an accelerating vehicle is the creation of shearing forces at the road surface and the entrainment of particles into the vehicle's turbulent wake. The same shearing entrainment mechanism applies to vehicles ascending grades and traversing curves in the roadway. During vehicle acceleration and assentation of steep grades, excessive wheel torque results in tire slip that exceeds the elastic deformation of the tire, causing the tire to slide on the road surface (Wong 1978). This sliding action increases the shear between the tire and road surface, increasing fugitive dust production. Lateral shear forces at the interface of the tires and road as well as tire slip cause increased dust production as vehicles round curves in the roadway. The increased shear forces in areas of acceleration, on grades, and around curves hasten the degradation of the unpaved road surface, resulting in increased dust production over time. Turbulence created by the compression and expansion of air beneath the tire as it rolls over the road surface is an additional mechanism that entrains particles into the vehicle's turbulent wake (Nicholson and Branson 1990).

These mechanisms result in fugitive dust from unpaved roads ranging over three orders of magnitude in size (equivalent particle radius), from as small as the sub-micrometer to several hundred micrometers (Pinnick et al. 1985, Hinds 1999). To put this into perspective, these particles can range in size from fine sand to particles as small as those found in smoke.

In 2014, these dust-generating mechanisms on unpaved roads resulted in the creation of 10^9 kg (11 million tons) of fugitive dust in the aerodynamic size range of 10 microns and smaller, or PM_{10} (U.S. EPA 2015). Exposure to these small particulates has associated health effects. The health effects related to short-term exposure to $PM_{10-2.5}$ (particulate matter with aerodynamic diameters of 2.5 to 10 µm) are discussed in a study by the U.S. EPA (2009), in which multiple epidemiological, controlled human exposure, and toxicological studies were analyzed. The EPA concluded that the studies suggest a relationship between short-term exposure to $PM_{10-2.5}$ and cardiovascular effects, respiratory effects, and mortality.

Dust affects human safety in two different ways. On the dustiest of roads, dense dust clouds from leading vehicles greatly reduce the sight distance of following drivers to less-than-safe stopping distances (Figure 1a) (FHWA 1998). Additionally, the loss of small particles that bind the surface aggregate results in degradation of the road surface. With the loss of fine particles that bind the aggregate, loose gravel on the road surface creates a projectile hazard to passing and following vehicles. Loss of the binding particles to fugitive dust also results in the development of corrugations (washboard) on the road surface (Figure 1b), which can result in loss of driver control.

(a) (b)

Figure 1. Vehicle safety issues resulting from road dust

Degradation of the road surface has economic impacts as well. The Federal Highway Administration (FHWA) notes that as much as 25 mm of surface gravel may be lost annually from dusty roads, resulting in an annual aggregate replacement of approximately 70,000 kg/km

(124 ton/mi) (FHWA 1998). This replacement aggregate requires mining, processing, transportation, and finally placement into service, all of which are costly activities. Assuming an aggregate cost of $30/10^3 kg equates to a replacement cost of $2100/km ($3400/mi) annually for unpaved roads that do not incorporate some form of dust control measures.

Managing dust from unpaved roads starts with a well-designed and well-constructed road. Skorseth and Selim (2000) describe proper design of gravel roads, and the FHWA (2015) provides guidance on the construction and maintenance of gravel roads. For dust control, the most critical aspects of gravel road design are aggregate gradation, road crown, and drainage.

In some cases, gravel roads that are designed, constructed, and maintained well have minimal dust issues. On dusty unpaved roads, institutional controls (e.g., speed control) and dust-control palliatives are effective means of managing dust if implemented properly.

Several categories of chemical dust palliatives comprise the complete family of chemicals. Barnes and Connor (2014) and FHWA (2015) describe these groups of palliatives. We will focus our discussion specifically on synthetic fluid dust-control palliatives, since the objective of this study is to develop guidelines for use of this specific palliative type. Synthetic fluid palliatives control dust by increasing the apparent cohesive forces over the forces that would exist if water were the only liquid present in the aggregate pore space. Owing to the greater viscosity of synthetic fluid compared with water, the apparent cohesive forces developed in the aggregate will be sufficient to bind particles for a longer period than water alone. Moreover, the thin film of synthetic fluid that coats the soil-water in aggregate reduces the evaporation of water, resulting in greater water content in the surface aggregate. Because synthetic fluid palliatives are unique in the way they control dust production from unpaved roads in comparison with other dust palliatives (e.g., salts and lignosulfonates), guidelines for selection, application, and maintenance of synthetic fluid palliatives are needed.

Measurements of the Effectiveness of Dust Palliatives

To develop guidelines for synthetic fluid palliative use, a means of measuring palliative effectiveness is needed. Until recently, the only means of evaluating the effectiveness of different palliatives and application rates on any unpaved road prior to applying the palliative was to rely on the manufacturer's claims and by trial and error. We developed three tests for measuring palliative effectiveness: a laboratory test and two field tests. The laboratory test, known as the *Dustfall Test*, consists of three parts (Barnes and Connor 2017a). Samples of road aggregate are compacted in a standard mold and treated with the synthetic fluid to be tested at the application rate to be evaluated. After a suitable maturation period, the top of the sample is abraded with an abrasion device specific to the test. The potential of the aggregate to generate fugitive dust is then quantified by dropping the sample into a 1.83 m (6 ft) tall column (*Dustfall Column*) and measuring the PM_{10} concentration over time with a nephelometer attached near the bottom of the column (Figure 2). To evaluate different treatments on any given aggregate, the test is repeated for different products at different application rates. Effectiveness of a treatment is reported as a *mean particle residence time,* determined from the inverse of the slope of the linearized exponential decline in measured PM_{10} concentration overtime (Barnes and Connor 2017a).

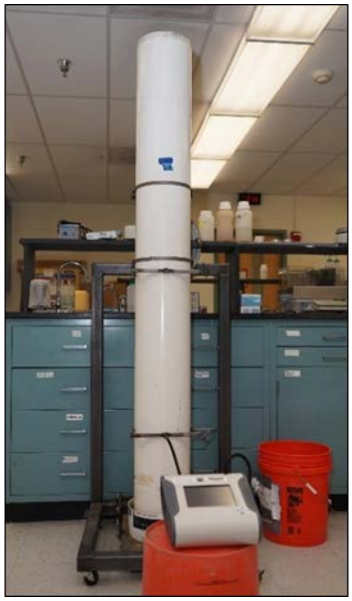

Figure 2. Dustfall Column

Figure 3 shows typical results from a Dustfall Test on an untreated sample of aggregate (upper graphs) and a sample of the same aggregate treated with a palliative that performs well (lower graphs). The left-side graphs for the untreated and treated aggregate samples show an exponential decline in PM_{10} concentration over time. The right-side graphs for both show the linearization of the exponential concentration trends. Results from the untreated aggregate show a distinct two-part linear relationship: a relatively rapid rate of decline in PM_{10} concentration prior to 300 seconds, followed by a slower rate of decline up to the end of the test. Results from the treated sample show only the initial rapid rate of decline that lasts until the airspace in the Dustfall Column reaches the initial background PM_{10} concentrations. Additionally, the duration of the initial rapid rate of decline (first phase of settling) is an order of magnitude shorter in comparison with the untreated sample. Barnes and Connor (2017a) describe this first phase of settling as "puffing" of particles upward as the sample encounters a pool of water, the splash pool, positioned at the bottom of the column. The splash pool helps suppress the rebounding of particles upon reaching the bottom of the column. Furthermore, the submergence of the bottom of the column into the splash pool blocks air from flowing into the column from the bottom of the column. As the sample descends from the top of the column and nears the splash pool, air displaced by the volume of the sample puffs the smallest particles upward toward the intake of the nephelometer. The PM_{10} concentration with time trend measured in the first phase of settling represents the settling of these puffed particles along with any other PM_{10}-sized particles descending from the top of the column.

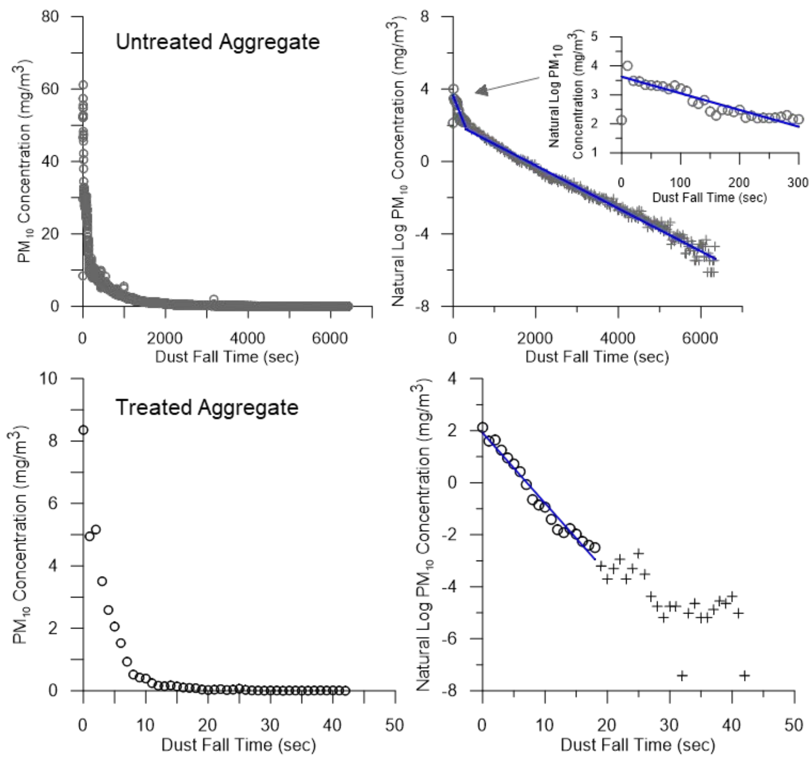

Figure 3. Typical Dustfall Column results for untreated and treated aggregate

For the untreated sample, the PM_{10} concentration trend measured in the second phase of settling is solely a measure of the settling of particles from the top of the column. The second phase of settling will not exist in an aggregate treated with a well performing palliative due to the effective aggregation of particles created by the presence of the palliative. Moreover, the rate of PM_{10} concentration decline in the first phase of settling for an aggregate treated with a well performing palliative will be rapid. Hence, the mean particle residence time will be short. Barnes and Connor (2017a) note that for aggregate treated with well performing palliatives, the mean particle residence time will be equal to or less than 6 seconds, and a second phase of settling will not exist.

We developed two different field tests for evaluating the effectiveness of palliatives after application to unpaved roads. In the first test, a mobile monitor that we named UAF-DUSTM (University of Alaska Fairbanks Dust Monitor) is used. The instrument is portable (one suitcase-sized case and one toolbox) and straps onto the back of any all-terrain vehicle (ATV) (Figure 4). Dust lofted from the back tire of a moving ATV is continuously drawn through a laser that measures the opacity of the dust-laden air stream. Opacity is converted into concentration values, resulting in an accurate comparison of the palliative's effectiveness every approximately 9 m (30 ft) along the measured section (Figure 5).

Figure 4. Mobile road dust monitor (UAF-DUSTM)

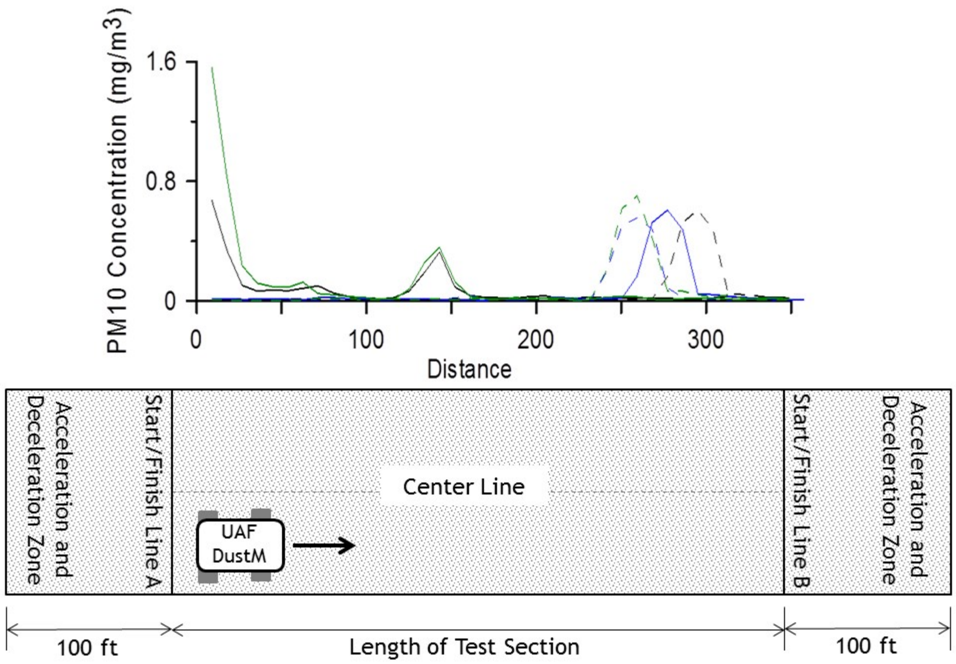

Figure 5. Typical UAF-DUSTM results

A typical test of palliative performance on an unpaved road consists of three passes with the UAF-DUSTM on both lanes of the road, for a total of six spatial measurements with the UAF-DUSTM. Typical statistical characterization of the UAF-DUSTM results consists of the mean value of the measurements as a measure of the central tendency, and the standard deviation of the measurements as a measure of the variability in palliative performance on the roadway surface. Our experience on multiple sites treated with synthetic fluid palliatives indicates that a well performing palliative measured approximately 2 weeks after application will have an overall mean PM_{10} concentration value measured by the UAF-DUSTM equal to or less than 0.065 mg/m^3

We also developed a test for determining the effectiveness of palliatives by taking random samples of aggregate obtained from a treated section of gravel road and measuring the PM_{10} content. This measurement is conducted in a laboratory using the Dustfall Column discussed previously. The test is conducted by first abrading multiple samples from random locations on the treated section of roadway (Figure 6). After air-drying in the laboratory for a set time, the sample is sieved to remove particles greater than 1.18 mm (0.0469 in.). The PM_{10} content in the sieved sample is then quantified by measuring the settling characteristics in the Dustfall Column. From these results, the mean particle residence time is determined (discussed previously). Effectiveness of the palliative is evaluated with this number. The only difference between this test methodology and the laboratory Dustfall Test is the preparation and abrasion of the treated aggregate. In the laboratory test aggregate, samples are compacted in standard molds, treated, and abraded after an appropriate maturation period. In the field abrasion methodology, the samples are obtained directly from treated unpaved road surfaces. We have not had as much experience with this test as we have had with the two previously discussed tests. Evidence suggests that the resulting mean particle residence times measured for a well performing palliative abraded in the field will be greater than the 6 seconds or less determined to be the range of well performing palliatives for laboratory-abraded samples.

Figure 6. Abrasion of a sample to be tested using the Dustfall Column

CHAPTER 3.0 – GUIDELINES

Effective dust control on unpaved roads starts with a well-designed and maintained road. Inadequate aggregate gradation and road crown and lack of drainage negatively impact the stability of any unpaved road, resulting in raveling, washboarding, and potholes. Any dust-control palliative will be less effective on unpaved roads that have these types of structural problems. To be effective at controlling dust from unpaved roads, the applied dust palliative needs to be present and remain in the top approximately 2 cm of surface aggregate. The effectiveness of synthetic fluid palliatives attenuate over time due to downward movement of the fluid away from the top of the road surface by gravity and capillary forces and by mechanical shearing forces created by moving vehicles and excessive road grading. Thus, the factors that control the longevity and effectiveness of a synthetic fluid palliative include aggregate properties, fluid properties, and traffic characteristics. Controlling vehicle speed, grading the road only when necessary, and paying attention to zones that experience accelerated attenuation extend the overall longevity of a palliative.

Road Design and Maintenance

Two main design and maintenance factors govern the ability to manage dust on unpaved roads: drainage and aggregate properties. Proper drainage off the road surface and away from the road prism is critical to a well performing road, hence, to dust management. Ponded water on or around the roadway prism results in soil-moisture contents that weaken the ability of soil to carry a load. Unfortunately, too often, budget constraints or poor management result in postponement or insufficient oversight of drainage maintenance. However, drainage issues should be a maintenance priority for unpaved roads, since maintaining the surface, including dust reduction, is often impossible if drainage issues are not adequately addressed.

A properly crowned road is essential to dust management. An inadequate crown, or at the extreme, the lack of a crown, leads to water ponding on the road surface, resulting in the loss of structural integrity of the road surface and subbase. The loss of structural integrity leads to rutting and potholes (Figure 7). Each of these road distresses exacerbates the problem of dust management. Moreover, the loss of structural integrity decreases the effective life of any synthetic fluid palliative applied to the road surface owing to change in the pore structure and, hence, the retention of fluid in the top 2 cm of road surface where the fluid is needed. Even the presence of ponded water on the road surface results in increased production of fugitive dust. The passing of vehicle tires in and out of these water puddles on the road surface results in hydraulic erosion. This erosion process causes the washing out of fine aggregate material (silts and clays) from the aggregate mix into the water puddles. Subsequent drying of the road surface results in discrete locations of high dust production.

Figure 7. Improperly graded road resulting in poor drainage off of the road surface

Experience has shown that a 3–4% roadway crown is ideal. A crown on the road of this range allows water to move off the surface with low enough velocity to minimize riling. In addition, with a 3–4% crown, rutting in the road surface up to ½ in. will not cause ponding and related hydraulic damage to the surface. Finally, a proper crown has consistently proven to reduce the need for grading by as much as 50%.

The road design must accommodate for the water once removed from the road surface. Ponded water edging the road prism results in the same road structure stability issues addressed earlier. Hence, side ditches and culverts are a necessity. FHWA (1998, 2015) and Skorseth and Selim (2000) address ditch design, construction, and maintenance. For ditches to perform properly, they require frequent clearing and cleaning. Again, minimal budgets for maintaining unpaved roads often cause this function to be overlooked.

Selection of the right material for the roadway is the second requirement. Each layer must be able to carry the material above it and vehicle loadings. In addition, the material must be compatible with the environment including freezing, thawing, and rainfall. The gradation of the soil provides insight into the performance of the roadway. The gradation is a good predictor of mechanical strength, which transfers tire loading from the surface downward.

At the surface, tire loading is approximately the tire pressure; that is, a tire inflated to 35 psi will exert pressure on the surface of approximately 35 psi. This tire pressure is typical for a passenger car or pickup. Most commercial trucks have tire pressures between 80 and 120 psi. Consequently, it is important to know the traffic mix to design the roadway template. Referring to Figure 8, the stress is reduced by about 90% in the top 2 ft. Consequently, the material quality of the upper 2 ft of the roadway should be carefully controlled.

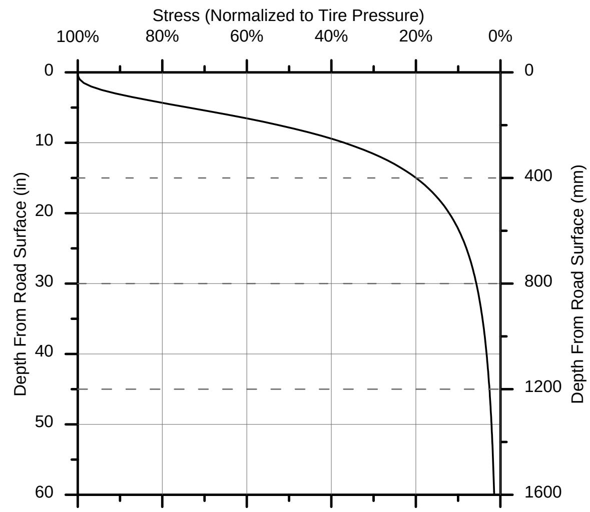

Figure 8. Propagation of stress with depth from road surface

A 40% reduction in stress occurs in the upper 150 mm (6 in.) of the roadway. The upper 100 to 150 mm (4 to 6 in.) is typically the thickness of the surface course. This layer carries the full wheel loading, which requires the material be of the highest quality. In addition, the surface course is exposed to shear loading of the tire, abrasion caused by the tire, and the full impact of the weather. Consequently, the surface course material must be durable, capable of carrying tire loadings, and moisture resistant, and it must produce low dust. The gradation is a critical property of the surface course. If the gradation is too open or too coarse, the material will washboard and produce high levels of dust. If the gradation is too fine, it will weaken in the presence of water. Dense gradation with fines content of between 10 and 14% has proven to work well.

A roadway engineer with experience in designing gravel roads can provide valuable designs to ensure good performance of the gravel surface. The engineer will work with the community to evaluate locally available material to ensure the best performance for the cost.

In summary, owners of unsurfaced roads should focus on three elements:

- Crown (use 3–4% crown so that water moves off the surface quickly)

- Drainage (this is the most important feature and the best use of funding)
- Proper material (use the best material on the surface)

Palliative Selection

Laboratory testing and field testing show that synthetic fluid palliatives are effective at controlling dust for approximately 1 year. Figure 9 shows the results from laboratory testing of the effectiveness of a typical synthetic fluid palliative over time applied at two different application rates. These results were generated following the Dustfall Test method detailed previously. Field testing has shown similar results. In a comprehensive field test of palliative performance on four unpaved road sections in a rural Alaska community, Barnes and Connor (2017b) used UAF-DUSTM monitoring results and field-abraded Dustfall testing to show that the effectiveness of two different palliatives lasted approximately 1 year.

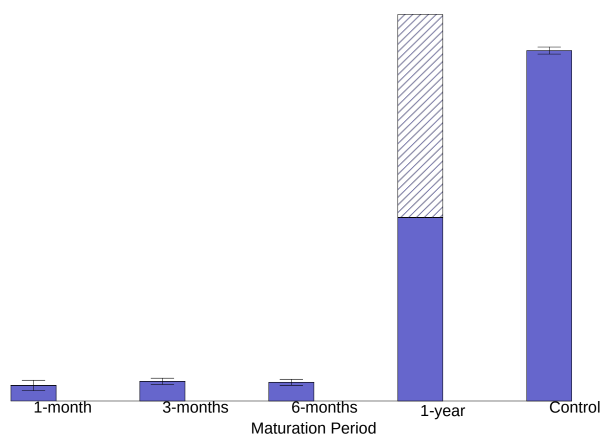

Figure 9. Longevity of a typical synthetic fluid measured with the Dustfall Column

The effectiveness of a synthetic fluid over time is a function of the aggregate and fluid properties that control the retention of the fluid in the top 2 cm of the road surface and the traffic volume (average daily traffic, ADT) and the type of vehicles the road supports. In an extensive study of synthetic fluid performance on gravel runways, Barnes and Connor (2014) found that peak performance of a synthetic fluid occurred with an aggregate fines content (grain size less than 0.075 mm) of between 8 and 14%. A fines content of less than 8% results in low fluid retention in the top 2 cm of the road surface. A palliative is unable to efficiently infiltrate and spread into aggregate with a fines content exceeding 14%, resulting in diminished performance. The compaction density of surface aggregate also influences the effectiveness of synthetic fluid. Synthetic fluids are unable to penetrate overly dense surface aggregates; they will pond and possibly run off the road surface during application (Barnes and Connor 2014). The water content of aggregate influences the infiltration of applied synthetic fluid as well. Synthetic fluid will not infiltrate dry aggregate, nor will it enter saturated aggregate. In some cases, chemical reactions between surface aggregate material and the applied synthetic fluid impact (positively or negatively) the ability of the fluid to control dust.

The viscosity of synthetic fluids is a key contributing factor in performance. The increased viscosity of a synthetic fluid aids in the retention of the fluid in the top 2 cm of surface aggregate. However, if the fluid's viscosity is too great, infiltration of the fluid into the aggregate may be problematic. Furthermore, a highly viscous fluid is difficult to apply topically by pumping through sprayers. Synthetic fluid suppliers will typically adjust the fluid's viscosity according to the climate of the region where the fluid will be applied.

At the time of this study, there were two main providers of synthetic fluid dust-control palliatives in the United States. Synthetic fluids sold by these two companies are appropriate for both unpaved roads and gravel runways (non-corrosive products). We have found little difference between the various commercially available fluids in terms of dust-control longevity when the fluid is applied on properly prepared and maintained unpaved roads. Our opinion is that the lack of difference in performance is likely due to the main mechanism that reduces dust-control product longevity on unpaved roads—that is, the mechanical shearing forces created by moving vehicles at the interface of the tires and road surface. Acceleration, braking, ascending inclines, and rounding curves and corners create the shearing forces that produce dust, as discussed earlier, and cause decreases in the effectiveness of dust-control palliatives over time.

Application rates also impact synthetic fluid performance and longevity on unpaved roads. Too light an application of fluid results in poor dust-control effectiveness and a short effective life span. However, applying too much synthetic fluid can result in loss of fluid to surface drainage during rain events and adhesion of the fluid to tires. Our experience indicates that a synthetic fluid application rate of 30 to 40 ft^2/gal is appropriate for most unpaved roads. However, the synthetic fluid manufacturer should be consulted and laboratory testing should be conducted to determine the appropriate fluid application rate for an unpaved road.

Application

The key to applying palliatives is to achieve a uniform application rate over the entire area to be treated. Uniform application requires good equipment and careful attention to setting up the equipment correctly, including the spray bar height, and ensuring constant operating pressures, clean nozzles, and carefully controlled application speed. Failure to apply the palliative uniformly will result in unacceptable performance (see Figure 10). While it is tempting to use a locally available water truck, this type of truck *is not* capable of applying the palliative in a controlled uniform manner, as shown in Figure 11. While the example shown in this figure is an extreme case, it does illustrate the lack of uniformity of the palliative and the lack of application rate control.

Figure 10. Example of non-uniform application and the result after 1 year (photo curtesy of ADOT&PF)

Figure 11. Incorrect application of synthetic fluid with a water truck (photo curtesy of ADOT&PF)

Several low-cost applicators will apply the palliative at a uniform controlled rate. One option is to build your own applicator using off-the-shelf pumps, piping, and nozzles, such as what is shown in Figure 12. In this figure, note that the fan pattern of the fluid being applied has a triple overlap. Configuring the sprayer to develop such an overlap helps ensure uniformity of the applied fluid. A double overlap in the spray is acceptable, but the operator must take additional care to make sure that the overlap remains constant, as the weight of the liquid decreases changing the elevation of the spray nozzles from the ground surface. Gasoline or electric (powered by a generator) are the two power options for pumps used to apply synthetic fluid. If shipping the application equipment by air is a consideration, then one must consider restrictions on air transport of flammable liquids when choosing the type of pump for a sprayer (gasoline or electric). If an appropriate generator is located and accessible in the village where the fluid will be applied, an electric-powered pump may be the best option.

Figure 12. Low-cost synthetic fluid applicators

Commercial applicators such as the one shown in Figure 13 are available. These systems cost around $12,000 and are available in easily transportable cases (excluding electrical generator, trailer, and tow vehicle) . Assembly of the system takes about 2 hours.

Figure 13. Commercial portable applicator

With some care, the home-built systems and the commercial systems are capable of applying the palliative in a uniform controlled manner. Both of these transportable systems require two or more passes to apply the palliative. Multiple passes have proven desirable for two reasons. First, multiple passes help ensure uniformity and accuracy of application rates by masking any deficiencies in the system. Second, experience has shown that most soils will not readily accept the desired application rate in a single pass. Consequently, multiple passes are required even though the application equipment may be capable of applying the palliative in a single pass.

Once the proper equipment has been procured, consider the soil moisture content to maximize penetration of the palliative. A dry surface will cause synthetic fluid to simply remain on the surface; this occurs due to the high electrical charge on the dry particles, which tend to repel most liquid. Therefore, it is recommended that the surface be damp with no standing water. This condition will help the palliative penetrate the surface.

Another aid to penetration is to tight blade the surface with a motor grader, with the blade rolled all the way forward and light down pressure. The goal is to loosen the upper ½ in. to 1 in. of the surface.

Adverse weather during application of the fluid and during the period of distribution in the aggregate is always a concern. Delay the application immediately during a rain event until the soil has dried somewhat. If rain is anticipated within a few hours of application, delay the application. If rain does fall before the palliative has time to penetrate the soil fully, the palliative will float on the surface of the water, as shown in Figure 14.

In summary, choose application equipment that can apply a uniform controlled quantity of palliative, and use the equipment in a manner that ensures the fluid works properly. Make sure that the soil moisture is slightly damp to help the palliative penetrate the surface. Do not apply palliative if there is standing water. Finally, do not apply the palliative if it is likely to rain before the palliative has fully penetrated the surface. Violating any of these parameters will likely result in unacceptable performance.

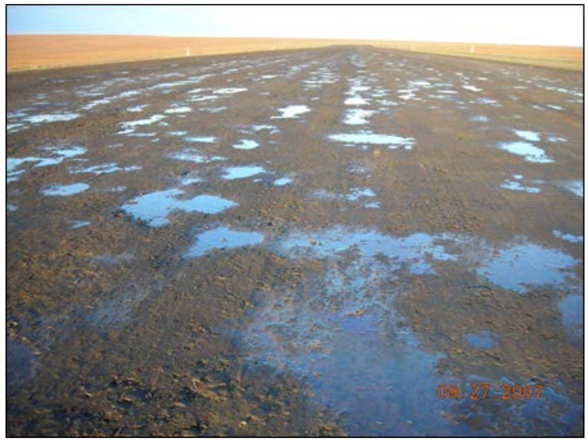

Figure 14. Poor synthetic fluid application due to rain

<u>Areas Requiring Special Attention</u>

The increased shearing forces created between vehicle tires and the roadway surface, such as around curves, on inclines, and on areas prone to acceleration and deceleration such as road intersections, result in greater decay of synthetic fluid dust-control effectiveness. Increased fugitive dust production on roads also occurs at intersections of unpaved roads and at driveways that have not been treated with dust-control palliatives. These areas of roadway require additional attention after the synthetic fluid application.

Eckhoff (2012) used DUSTM to illustrate the increased production of fugitive dust in areas that experience increased shear. These results, with a detailed discussion of increased shear forces, are included in Barnes and Connor (2014) and reproduced in Figure 15. For this study, the researchers applied a synthetic fluid palliative to a 1.2 mi stretch of unpaved main road in Eagle, Alaska. Barnes and Connor (2017b) conducted a similar study in Ruby, Alaska. Figure 16 shows these results. Both of these figures show increased PM_{10} at intersections and around curves, areas prone to increased shearing forces. Intersections also are prone to more fugitive dust production due to a process known as “track on.” As vehicles travel from intersecting roads that are not treated with a dust-control palliative onto treated roadway, a fraction of fine aggregate from the untreated roadway is carried (tracked) onto the treated roadway (see Figure 17).

Sustained control of dust in high shear force areas requires frequent applications of synthetic fluid. Observing the amount of dust produced as vehicles travel through these locations and comparing the level of dust produced with straight flat stretches of treated road are reasonable means of determining when to re-apply synthetic fluid in such areas. Most often, the synthetic fluid can be re-applied at a reduced application rate. The dust at segments of road that experience increased dustiness due to track-on from connector roads may be controlled by treating the connector road 100 to 150 ft back from its intersection with the primary treated roadway (Figure 18).

Maintenance

Observing the amount of dust produced from vehicles is an excellent means of determining when to re-apply palliative. Taking photographs of a dust plume behind vehicles before palliative is applied and once every few weeks after application on days that are prone to be dusty (warm, low humidity, and dry road) is a reasonable method of qualifying the decrease in palliative effectiveness. This qualified evidence can then be used to make re-application decisions. Depending on the level of effectiveness of the existing synthetic fluid, re-application of the fluid can most likely be at a lower application rate than the original rate.

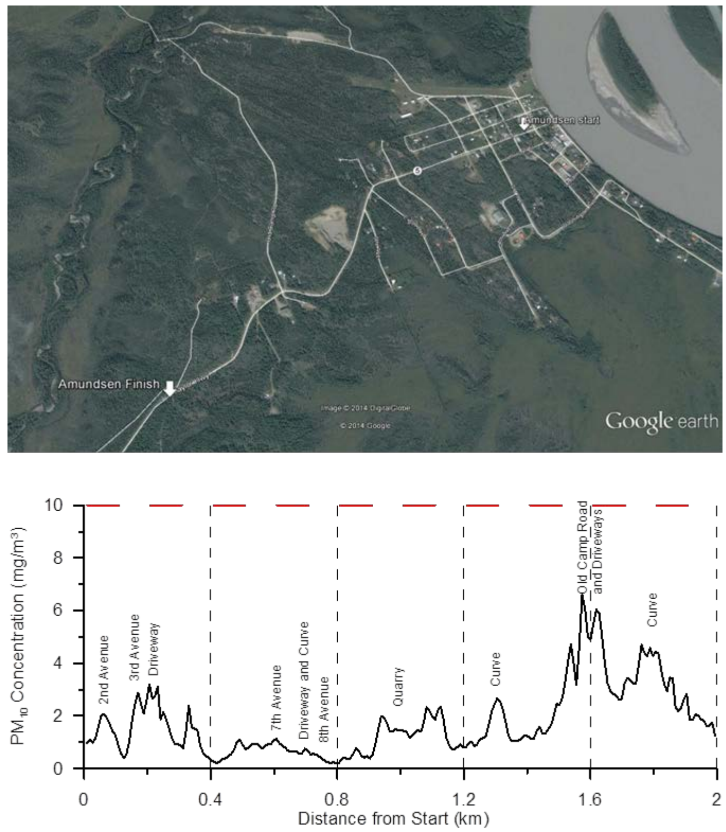

Figure 15. Increased dustiness at curves and intersections in Eagle, Alaska

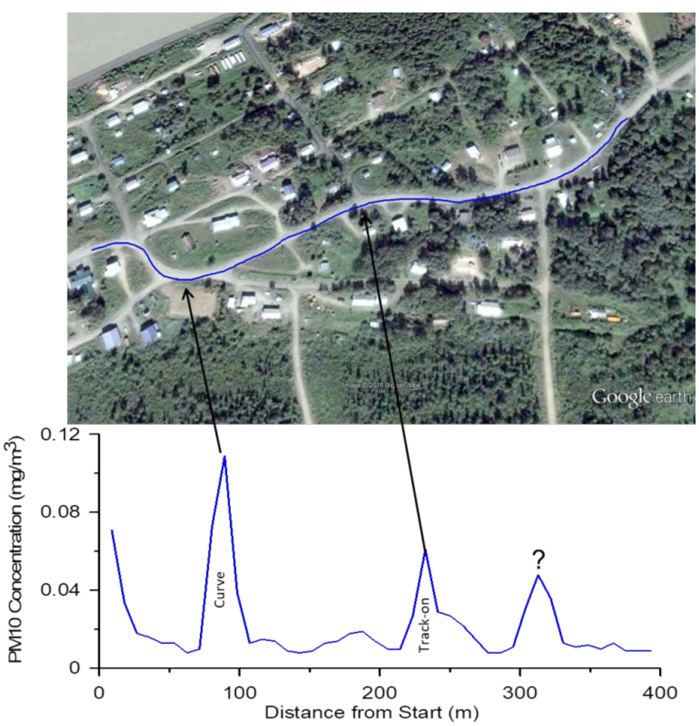

Figure 16. Increased dustiness at curves and intersections in Ruby, Alaska

Figure 17. Evidence of track-on

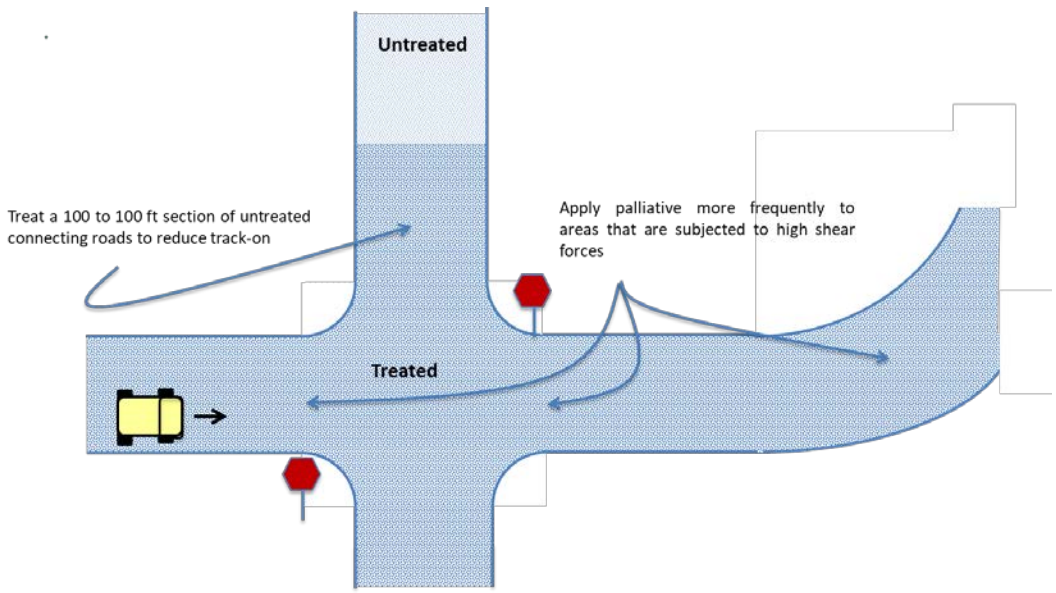

Figure 18. Treated zones requiring special attention

As previously discussed, shear forces created by vehicles are the greatest degrader of synthetic fluid dust-control palliative effectiveness. Hence, controlling vehicle speed and eliminating aggressive driving are reasonable means of extending the effective life of a synthetic fluid applied to a roadway. Higher speeds require increased periods and rates of acceleration. A high acceleration rate can cause the drive tires to slide on the road surface, creating even greater shear forces, and hence accelerated palliative degradation. Curves, which are already areas of high shear forces as discussed, are prone to even greater rates of degradation in palliative effectiveness when the vehicles travel around the curves at speeds high enough to cause tire sliding. Strong community outreach to residents concerning speed control and elimination of aggressive driving is required to extend the effective life of synthetic fluid palliatives applied to unpaved roads.

Most road managers have a strong inclination to grade roads at the first signs of pothole formation and washboarding. While grading is necessary to repair such road distress, grading will decrease the effective life of dust-control palliatives. If grading is done with care, the graded material can be remolded onto the road surface, preserving some of the effectiveness of the synthetic fluid. For any palliative application, the fundamental rule is to begin with a road that is designed, constructed, and maintained well. If these conditions are met, minimal grading will be required. Care should also be taken during snow removal to not remove surface aggregate.

CHAPTER 4.0 – SUMMARY

In rural communities, road dust presents challenges to public health, safety, quality of life, and economics. Several distinct categories of dust-control palliatives are available for managing road dust. Synthetic fluids are a relatively new category of dust-control palliatives. While these fluids effectively control road dust, engineering guidelines do not exist for these dust-control products. The purpose of this study was to develop these guidelines.

Synthetic fluids control dust by increasing the cohesive and apparent cohesive forces between particles in road surface aggregate. The effectiveness of synthetic fluids in controlling road dust diminishes over time due to movement of the fluid out of the top 2 cm of surface aggregate where it is needed and by shearing forces created by vehicle traffic.

Several methods have been developed to assess the effectiveness of synthetic fluids on surface aggregate both before (laboratory test) and after (laboratory and field tests) (Barnes and Connor 2014, Barnes and Connor 2017a, Barnes and Connor 2017b). If concern remains about the potential effectiveness of a synthetic fluid, a test section on the road to be treated is recommended prior to full-scale application. Using these methods to measure palliative effectiveness, we conclude that synthetic fluids applied to unpaved roads effectively control dust for approximately 1 year. Since shear forces are the main attenuating mechanism, control of vehicle speed and reduction of aggressive driving will extend the effective life of synthetic fluids in most cases.

The key to a well performing dust-control palliative is a properly designed, constructed, and maintained road. Road crown and drainage are the most important features of an unpaved road. A crown of 4–5% is optimum for water drainage off the road surface. Drainage ditches should line both sides of the road and be kept clear of excessive vegetation and sediment.

Synthetic fluids should be applied using proper equipment. Synthetic fluids *should not be applied* using a water truck. Best results will be realized if the synthetic fluid is applied through spray nozzles configured such that the spray forms a fan pattern and the fan patterns are triple overlapped. Nearly all applications of synthetic fluids require multiple passes, allowing time for the synthetic fluid to infiltrate the aggregate between passes.

Curves, intersections, and inclines on unpaved roads are areas that require special attention. These areas are prone to greater shear forces created at the interface of the vehicle tires and road surface than the forces created on straight, level road. Accelerated degradation of palliative effectiveness results from these greater shear forces. Observing the dust production from vehicles traveling on a road and applying synthetic fluid when the road appears to become dusty are reasonable means of extending dust-control performance for the entire treated road. Intersections are prone to increased dust production from vehicles tracking fine particles from untreated connecting roads onto the treated road. Applying synthetic fluid onto approximately 100 ft of the connecting road starting at the intersection reduces the dust created by this process.

Extending the longevity of synthetic fluid dust-control palliatives begins with a road that is designed and constructed well. Correct drainage decreases grading frequency by 50%. Reduction in the need for grading is paramount, since grading greatly reduces the longevity of synthetic fluid's dust-control effectiveness. The longevity of a synthetic fluid's dust-control effectiveness can also be extended on an unpaved road by decreasing vehicle speed and aggressive driving.

CHAPTER 5.0 – REFERENCES

Barnes, D. L., and Connor, B. (2014). Managing Dust on Unpaved Roads and Airports. Alaska University Transportation Center, University of Alaska Fairbanks, INE/AUTC 14.14, 83 pp.

Barnes, D. L., and Connor, B. (2017a). A Laboratory Procedure for Measuring the Effectiveness of Dust Control Palliatives. In preparation.

Barnes, D. L., and Connor, B. (2017b). Ruby Dust Management Demonstration Project. In preparation.

Bonse, R.P.H., and Kuhn, S. H. (1959). "Dynamic forces exerted by moving vehicles on a road surface. *Flexible Pavement Design Research, Highway Research Board Bulletin,* Issue 233, 9–32.

Eckhoff, E. W. (2012). Evaluating Dust Palliative Performance and Longevity Using the UAF-DUSTM. Unpublished Master's Thesis, University of Alaska Fairbanks, 83 pp.

Federal Register. (2001). *Effluent Limitations Guidelines and New Source Performance Standards for the Oil and Gas Extraction Point Source Category; OMB Approval Under the Paperwork Reduction Act: Technical Amendment*, 40 CFR Parts 9 and 435, Vol. 66, No. 4, Washington, DC, 70 pp.

FHWA. (1998). Problems Associated with Gravel Roads. U.S. Department of Transportation, Federal Highway Administration, Publication No. FHWA-SA-98-045, 168 pp.

FHWA. (2015). Gravel Roads Construction and Maintenance Guide. U.S. Department of Transportation, Federal Highway Administration, Washington, DC, 153 pp.

Hinds, W. C. (1999). *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, 2nd ed., John Wiley & Sons, Inc.: New York, 504 pp.

Moosmüller, H., Gillies, J.A., Rogers, C. F., DuBois, D. W., Chow, J. C., and Watson, J. G. (1998). "Particulate emission rates for unpaved shoulders along a paved road." *Journal of the Air & Waste Management Association*, 48(5), 398–407.

Nicholson, K.W., and Branson, J. R. (1990). "Factors affecting resuspension by road traffic." *The Science of the Total Environment*, 93, 349–358.

Pinnick, R. G., Fernandez, G., Hinds, B. D., Bruce, C. W., Schaefer, R. W., and Pendleton, J. D. (1985). "Dust generated by vehicular traffic on unpaved roadways: Sizes and infrared extinction characteristics." *Aerosol Science and Technology*, 4(1), 99–121.

Sehmel, G. A. (1973). "Particle resuspension from an asphalt road caused by car and truck traffic." *Atmospheric Environment*, 7(3), 291–309.

Skorseth, K., and Selim, A. A. (2000). *Gravel Roads Maintenance and Design Manual.* South Dakota Local Transportation Assistance Program, Brookings, SD, 104 pp.

U.S. EPA. (1995). *Compilation of Air Pollution Emission Factors,* 5th ed., AP-42. Research Park: U.S. Environmental Protection Agency, Office of Air Quality and Standards.

U.S. EPA. (1996.) *Development Document for Final Effluent Limitations Guidelines and Standards for the Coastal Subcategory of the Oil and Gas Extraction Point Source Category*. EPA-821-R-96-023. U.S. Environmental Protection Agency, Office of Water, Washington, DC, 640 pp.

U.S. EPA. (2009). Integrated Science Assessment for Particulate Matter. EPA/600/R-08/139F. U.S. Environmental Protection Agency, Washington, DC, 1071 pp.

U.S. EPA. (2015). Profile of Version 1 of the 2014 National Emissions Inventory. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

Wong, J. Y. (1978). *Theory of Ground Vehicles.* John Wiley & Sons, New York: 330 pp.