DETERMINATION AND EVALUATION OF ALTERNATE METHODS FOR MANAGING AND CONTROLLING HIGHWAY-RELATED DUST

FINAL REPORT

June 30, 2002
Sponsored by

Iowa Highway Research Board
Iowa Department of Transportation
TR449

R.A. Lohnes and B.J. Coree

Department of Civil and Construction Engineering
IOWA STATE UNIVERSITY

DETERMINATION AND EVALUATION OF ALTERNATE METHODS FOR MANAGING AND CONTROLLING HIGHWAY-RELATED DUST

FINAL REPORT

Sponsored by

Iowa Highway Research Board

Iowa Department of Transportation

TR449

R.A. Lohnes and B.J. Coree

Department of Civil and Construction Engineering

IOWA STATE UNIVERSITY

ABSTRACT

Road dust is caused by wind entraining fine material from the roadway surface and the main source of Iowa road dust is attrition of carbonate rock used as aggregate.

The mechanisms of dust suppression can be considered as two processes: increasing particle size of the surface fines by agglomeration and inhibiting degradation of the coarse material. Agglomeration may occur by capillary tension in the pore water, surfactants that increase bonding between clay particles, and cements that bind the mineral matter together.

Hygroscopic dust suppressants such as calcium chloride have short durations of effectiveness because capillary tension is the primary agglomeration mechanism. Somewhat more permanent methods of agglomeration result from chemicals that cement smaller particles into a mat or larger particles. The cements include lignosulfonates, resins, and asphalt products. The duration of the cements depend on their solubility and the climate. The only dust palliative that decreases aggregate degradation is shredded shingles that act as cushions between aggregate particles. It is likely that synthetic polymers also provide some protection against coarse aggregate attrition.

Calcium chloride and lignosulfonates are widely used in Iowa. Both palliatives have a useful duration of about 6 months. Calcium chloride is effective with surface soils of moderate fine content and plasticity whereas lignin works best with materials that have high fine content and high plasticity indices.

Bentonite appears to be effective for up to two years and works well with surface materials having low fines and plasticity and works well with limestone aggregate.

Selection of appropriate dust suppressants should be based on characterization of the road surface material. Estimation of dosage rates for potential palliatives can be based on data from this report, from technical reports, information from reliable vendors, or laboratory screening tests. The selection should include economic analysis of construction and maintenance costs. The effectiveness of the treatment should be evaluated by any of the field performance measuring techniques discussed in this report.

Novel dust control agents that need research for potential application in Iowa include; acidulated soybean oil (soapstock), soybean oil, ground up asphalt shingles, and foamed asphalt. New laboratory evaluation protocols to screen additives for potential effectiveness and determine dosage are needed. A modification of ASTM D 560 to estimate the freeze-thaw and wet-dry durability of Portland cement stabilized soils would be a starting point for improved laboratory testing of dust palliatives.

DETERMINATION AND EVALUATION OF ALTERNATIVE METHODS FOR MANAGING AND CONTROLLING HIGHWAY-RELATED DUST

1 INTRODUCTION

1.1 Problem Statement

Secondary roads are a vital component of Iowa's transportation system as the means of getting agricultural crops to market and sustaining the lives of farmers. Approximately 69,000 miles of these roads are stabilized with gravel or crushed limestone because their low traffic volume does not justify paving with asphalt or Portland cement concrete. Unpaved roads deteriorate by degradation of crushed rock generating fine-grained material that is the major source of dust created by moving vehicles. Dow Chemical Company estimated in 1993 that the average untreated road loses 300 tons of aggregate per mile per year and; in a survey by Better Roads in the mid 1990's, respondents listed dust control as their worst unpaved road maintenance problem (Anonymous, 1998). Road dust presents a safety hazard by reducing visibility and creates additional wear on vehicles. At the very least, dust is annoying to travelers on and residents along unpaved roads.

Air borne particles less than 0.01 mm in diameter are considered a health hazard and median particle diameters of road dust have been reported to range from 0.002 mm to 0.049 mm (Hoover et al, 1981). Iowa air quality standards recommend a concentration of particulates in air less that 75 mg/m3 for human health, while some studies in Iowa have reported particulate concentrations in road dust greater than 1.2 million mg/m3 (Lustig, 1980). Dust from secondary roads needs to be eliminated or reduced to protect public health.

Unpaved roads are an important component in the agricultural economy of Iowa; however they are a source of dust that is a health and safety problem at worst and an annoyance at best. Although the search for economical dust palliatives has continued for nearly a century, a need still exists for an economical and durable method of dust control.

1.2 Objective and Scope

The objectives of this study are to evaluate current and potential dust control technology and products and to identify new, alternative methods for controlling dust. The scope of the research includes: descriptions of laboratory and field measurements of dust palliation effectiveness, characteristics of road dust, mechanism of dust production and control, a literature review of local and international research, and conclusions and recommendations relevant to dust control on secondary roads in Iowa.

2. ROAD DUST MEASUREMENTS

Road dust measurement can be divided in two categories, laboratory screening tests and field tests. Laboratory screening tests are used to determine if a control agent actually works and to determine the dosage or treatment rate. Field tests are used to evaluate effectiveness of palliatives after they have been applied.

Laboratory tests include traffic simulators, rainfall simulators, unconfined compression tests, and durability tests. Field tests include static dust collectors and mobile dust measuring devices.

2.1 Laboratory Tests

Specimen preparation for erosion resistance and unconfined compression tests consisted of compacting treated soils in a 2 in diameter 2 in high mold (Denny, 1973). The compaction process involved using a drop hammer that replicated the energy per unit volume of the standard Proctor density test. The (2x2) specimens were extruded and cured for various time periods and tested.

Unconfined compression tests consist of subjecting the 2x2 specimens to vertical compression at a loading rate of 0.1 in/min until failure as indicated by cracking. The load, measured with a proving ring, that caused the cracking is reported as the unconfined compression strength. The weight, height and diameter of the specimens were measured prior to loading and the unit weight of each specimen calculated (Denny, 1973)

Erosion resistance was measured by subjecting compacted specimens of known weight to an overhead spray of distilled water and collecting the material that was dislodged from the specimen. The eroded material was dried, weighed and the weight fraction of the original specimen calculated and described as the "erosibility index".

Traffic simulator tests were designed to evaluate the material retention, water proofing, and stability of the test specimens. The device applied a simulated wheel load of 85 to 135 psi. The device consisted of a horizontal steel frame 11 ft long and 3 ft wide on legs bolted to a concrete slab. The frame supported a carriage that moved across test specimens (Bergeson, 1972). The carriage operated in an oscillating motion with a 1.25 inch wide solid rubber tire imposing the load on the test specimens. A motor propelled the wheel across the specimens and,; after going full distance, the carriage was reversed with the wheel lifted. The process was repeated at a speed of 4 miles per hour so that approximately 1000 passes could be made per hour. An air pressure ram on the loading wheel applied the contact pressure and an electronic counter recorded the number of passes. A modified paint sprayer, mounted in front of the carriage, applied distilled water to the test specimens to simulate rain. Six 4 in diameter test specimens could be mounted on the frame for testing. The soil specimens were molded in rings and placed on the frame. A dial gage attached to the loading wheel allowed vertical deflection measurements. Rut depth in the specimens was plotted versus number of passes to evaluate the relative stability of specimens with various chemical treatments. It is not clear how this related to dust palliation, but presumably deeper rutting indicated less effective fine retention.

Freeze thaw tests were conducted to evaluate durability or resistance to weathering (Denny, 1973). The 2x2 specimens used in unconfined and erosion tests were also used in this test. After a 24 hour curing period with the various additives, each specimen was placed in a thermos flask and the height was measured. The specimens and flasks were placed in a freezer at 20º (F or C?) for 16 hours; the specimens were then removed and allowed to thaw for 8 hours. The 24 hour period represented one freeze thaw cycle: height measurements were made at the end of each cycle. A light bulb at the base of the thermos maintained water at the base at about 35ºF so that capillary moisture was available during both freeze and thaw events.

Moisture tension tests were conducted on soil specimens treated with the various palliatives (Denny, 1973) to evaluate the tendency of the soil to attract capillary moisture. The device, described in detail by Russell (1965), consists of a 6 inch diameter disk that accommodates a soil specimen about 0.5 inch thick. Air pressure is applied to treated soil specimens mixed to a slurry or paste at moisture contents above their liquid limits. The water in the specimens is forced from the soil through a permeable membrane and out a drain line until equilibrium between the soil suction and applied pressure is reached, usually within 16 hours. Samples were removed from the pressure plate and their moisture content determined. From these data, moisture content versus tension curves were developed for each additive.

2.2 Field Tests

An early technique for measuring road dust in the field is to place containers at various positions along a roadway and allow air-entrained dust to settle into the containers over a period of time. The dust captured in the containers is weighed and the relative effectiveness of various dust suppressants can be evaluated by comparing the amounts of dust from untreated roads with dust quantities from roads with various types of treatments (Hoover et al, 1973 and Hoover et al, 1984). A number of variables including traffic numbers, changing wind directions, topography, and contamination with foreign matter affect the reliability of these measurements. Also because the measurement depends on sedimentation, only particles larger than 2 microns are trapped. Even with these limitations, this technique has been standardized as ASTM D 1739 (Sanders and Addo, 2000).

Another type of static dust monitoring device records the amount of interference between an infrared transmitter and receiver (Jones, 1999). This infrared device is triggered when a vehicle passes the measuring station; however not all infrared wavelengths from sunlight can be filtered out and under some circumstances this affects the accuracy of these measurements. Static dust measuring devices have been described that employ photometric devices that depend on light scattering or interference between a light source and a sensor (Sanders and Addo, 2000).

The accuracy of measuring dust at points along the road has been challenged and mobile devices mounted behind the rear wheels of a moving vehicle have been developed to measure dust generated by the vehicle along a length of road. These devices employ infrared sensors (Jones, 1999) and cyclones that collect the dust in a container or on filter paper (Sanders and Addo, 2000). The accuracy of mobile measuring devices can be affected by vehicle aerodynamics, speed variations, and road roughness.

3. ROAD DUST CHARACTERISTICS AND MECHANISM OF DUST PRODUCTION

Road dust consists of inorganic material in the size range of silt and clay particles along with some organic matter. Quantitatively, the dust contains about 50% (by weight) of particles less than 0.074 mm and 25% less than 0.005 mm (Hoover et al, 1981).

Potential sources of dust in roads are silt and clay size material in the subgrade and degraded coarse limestone and dolomite aggregate. Glacial till, loess, and alluvial top strata that comprise the surface geology of Iowa contain significant silt and clay fractions; however mineralogical analyses revealed that dust samples from an untreated road contained by weight 50% carbonates, 23 % clay and 13% organic matter (Hoover, 1973). Presumably, the remaining 14% was quartz (silicate ?). Recognizing that most Iowa roads have limestone and dolomite as the road metal and that carbonate minerals dominate dust samples, it is clear that coarse aggregate attrition is the most important mechanism of dust production on Iowa's unpaved roads.

The particle size distribution of road dust samples collected at various distances from the roadway indicated coarser particles near the road and finer particles farther away. Mineral content also varies with distance from the source. Carbonate contents were near zero several hundred feet from the road while clay and organic matter increased with increasing distance from the road. Low specific gravity of organics and very small particle size of clays accounts for this depositional pattern.

4. CLASSIFICATION OF DUST PALLIATIVES

Several classifications of dust control additives have been suggested. A South African classification combines chemical composition and stabilizing mechanisms to arrive at 10 categories (Jones, 1999). The Road Research Laboratory in the United Kingdom uses five categories based on composition of the palliatives (cited by Hoover et al, 1981). The U.S. Forest Service has 10 categories based upon composition (Bolander and Yamada, 1999). An Iowa State University classification used three categories based upon application method (Hoover et al, 1981). Table 4.1 is a synthesis of the U.S., U.K, South African and Australian classifications. The same or similar materials are grouped in rows. The numbers indicate the different materials in each system.

Table 4.1 Correlation of Dust Suppressants

South Africa	United Kingdom	U.S. Forest Service	Australia
1.Water	1. Water	1.Water	
2.Hygroscopic materials	2. Hygroscopic and deliquescent material	2.Magnesium chloride 3.Calcium chloride and 4. Sodium chloride	1. Chlorides and salts
3.Waste oils, 4. Tars, and bitumens	3.Tars and bituminous materials	5. petroleum and cutback emulsions	2. Petroleum based products
5.Lignosulfonates	4.Organic non-bituminous binders	6. Lignin sulfite paper process 7. Tall oil, sulfate paper process	3. Organic non-bituminous
6. Sulfonated oils		8.Electrochemical, sulfonated oils, enzymes, ionic products	4. Electrochemical, sulfonated petroleum, ionic products, enzymes
	5.Other inorganic chemicals	9. Clays	
		10. Vegetable oils	
7. Modified waxes			
8. Other products			

5. MECHANISMS OF DUST PALLIATION

In order for dust abatement to be effective, the quantity of silt and clay particles that are easily entrained by wind action must be reduced. The U.S. Forest Service identified three mechanisms for suppressing dust: agglomerating fine particles, binding surface particles together, and increasing road surface density (Langdon and Williamson, 1983 and Bolander and Yamada, 1999). Jones (1999) identified hygroscopic action and binding as mechanisms for dust control. The role of capillary moisture imparting a temporary, apparent cohesion was listed as an additional consideration (Langdon and Williamson, 1983). Guimmarra et al (1999) listed five dust palliative actions: surrounding and adhering to particles, attracting moisture from the atmosphere, adhering to and cementing particles, acting as a dispersant making clay more plastic, and agglomerating dust. The last study cited is the only one to suggest that decreasing particle size enhances dust control.

In the broadest sense, dust control can be considered as making big particles out of small particles. Hygroscopic or deliquescent materials attract capillary water that creates moisture tension bonds between the fine particles, chemicals act as cement between the silt and clay particles, or surfactant materials alter the surface chemistry of clay to create physical-chemical bonds between clay particles. All of these processes can be classified as agglomeration and would result in a dense road surface.

The moisture tension bonds are temporary and account for the short duration of the effectiveness of the chloride salts. These capillary bonds will be less effective in dry environments.

Chemical bonds tend to be more permanent depending on the solubility of the chemical. Insoluble additives should be effective in a wide range of environments whereas soluble chemicals are more effective in dry environments. Surfactants provide weaker bonds under high moisture conditions and are therefore less effective in humid environments.

Extending the concept of bonding smaller particles into larger particles (agglomeration) leads to the principle of stabilization, in which all particles are more closely bound together. One problem with agglomeration of smaller particles is that these new, larger particles are still loose on the pavement surface and subject to movement, abrasion and fracture under the action of traffic; all of which tend to break the newly agglomerated particles back down to their constituent elements. Stabilization, though obviously more expensive (first cost), leads to a more coherent solid mass, which may still dust in dry conditions, but is less likely to break down into discrete gravel-sized particles and therefore is more resistant to abrasion and fracture. This may be considered as a method by which aggregate degradation may be reduced or prevented.

Based on the mineralogical analyses of Iowa road dust, it appears that prevention of aggregate degradation is another possible dust control mechanism so that aggregate protection becomes distinct from the agglomeration mechanism. In summary, one dust control mechanism is fine particle agglomeration with capillary tension, surfactants, and cements as sub categories. Coarse aggregate protection is a second, separate mechanism.

6. SELECTION OF DUST PALLIATIVES

Selection of an appropriate dust palliative requires determining the most effective additive and the optimum treatment rate or dosage for that suppressant with a given road surface material or soil. The selection of an appropriate dust suppressant should involve: measurement of road dust, road dust prediction, definition of acceptability criteria, and evaluation of acceptable performance criteria (Jones, 1999). The influence of traffic, characteristics of road surface material, environmental implications, and economics are also determining factors in the selection of dust palliatives (Bolander and Yamada, 1999).

The dust suppressant method suggested by Jones (1999) is indeed a rational approach; however dust measurement and prediction prior to application seems to be a moot point if public perception is that too much road dust exists at a given location. Because perception is reality, it behooves the engineer to respond with the most economical treatment for the road surface material. The economics will be dictated by initial cost and durability. Durability will be affected by traffic and climatic factors that cause deterioration of the treated surface.

Environmental safety should be considered along with economy in selecting an appropriate dust palliative. A method of chemical analyses screening tests combined with mathematical models for assessing groundwater pollution has been described (Kimball, 1997). This study recommends leaching tests on the soil with the additive and chemical analyses of the leachate. For petroleum based additives analyses should include: semi-volatile organic compounds (EPA Method 8260), volatile organic compounds (EPA Method 8270), mercury (EPA Method 7470) and metals (EPA method 6010).

A careful review of the product literature, Material Safety Data Sheet, and manufacturer's instruction should occur before selecting a suppressant (Bolander and Yamada, 1999). Depth to groundwater, proximity to surface water, and soil permeability should be made as part of the environmental assessment. Minimum screening tests should include toxicity (LC50) and biological oxygen demand (BOD) for organic non-petroleum suppressants, lignosulfonates, and chlorides (Bolander and Yamada, 1999).

Waste oil, although an effective palliative under a wide range of conditions, can be especially deleterious to the environment because of its toxic constituents and is not recommended (Giummarra et al, 1997).

7. LITERATURE REVIEW

Effective dust mitigation on unpaved roads dates back to 1909 when the Office of Public Roads recommended clay binders combined with stone (Federal Highway administration, 1976). Over the years, a variety of materials including calcium chloride, magnesium chloride, liquid asphalt, petroleum resin, and lignin sulfonate have been used.

7.1 Dust Control Research in Iowa

Iowa State University researchers have studied a variety of agents for both road-bed stabilization road dust palliation beginning in the mid 1950's under the direction of D.T. Davidson and his associates. This review summarizes only the research that has dust palliation as the primary or peripheral objective and is presented in approximate chronological order.

Although it was noted that salt had not been widely used as a dust palliative because it is only slightly hygroscopic (Woods, 1960), a field study of a sodium chloride stabilized road in Franklin County emphasized the effect of the additive on the production of float or the amount of loose material on the road surface, but recognized the additional benefit as a possible dust suppressant (Marley and Sheeler, 1963). This study showed that the amount of float from the treated road was reduced over a four-year period as compared with untreated road. After 3 years, the float from the stabilized road was 0.83 lb/ft2 as compared with 1.57 lb/ft2 on the untreated road and that the silt and clay content was reduced from 13% to 7%. These measurements suggest indirectly that sodium chloride can be somewhat effective in reducing dust.

In one of the earliest studies emphasizing dust control, ammonium lignosulfonate in combination with calcitic lime and alum as secondary additives was researched (Fox, 1972). Laboratory studies, on weathered glacial till, lead to the conclusion that unconfined compressive strength, dry density at optimum moisture content, and resistance to slaking increased with increasing additive content. Field investigations in Clinton, Floyd, and Marshall Counties used containers placed at intervals along the roadway to capture dust raised by passing vehicles. Unfortunately the unstabilized road surface materials were not described. The dust collection containers showed that all treatments reduced dust production up to 80% compared to untreated roads and that 1% lignosulfonate treatment was as effective as 1% lignosulfonate plus 0.5% either of the secondary additives. Increasing lignosulfonate from 1% to 2 % was not recommended because of higher cost and little improvement in performance; however more improvement at lower cost was realized by inclusion of secondary additives. Material cost for 1% lignosulfonate and 0.5% secondary additive were estimated in (1972 dollars) at $3,600 per mile. Negative results were: treated roads tended to become slick if aggregate content was less than 1800 tons/mile, runoff was discolored, and the high cost of shipping the product to Iowa.

Unconfined compression testing and a traffic simulator were used in an evaluation of three cutback asphalts, two latex emulsions, and one cationic asphalt emulsion (Bergeson, 1972). The soil materials used here were Bedford limestone a low quality aggregate used for road surfacing that classifies A-1-b and loess that classifies A-4(8). The loess is 79.8% silt whereas the limestone is 73.2% gravel. Based on the results of the laboratory study, the cutback asphalt and alsphalt emulsion were recommended for field trials. The latex emulsions were not recommended because of cost, $1.50/gal for the latex and $0.19/gal for the asphalt. The study also concluded that unconfined compression tests on specimens that were air cured and then immersed in water prior to testing provided an indication of the additives effectiveness as a waterproofer, but was inadequate as a measure of stability. Unconfined strength results for the asphalt stabilized materials had maximum strengths at optimum additive content of about 1% with asphalt contents up to 7% having lower strengths. In contrast the latex emulsions had higher strength with increasing additive contents. Maximum strengths of the asphalt-stabilized materials were about 150 lbs as compared with the latex treated materials at 450 lbs. The traffic simulator gives valid indications of the materials stability under moving loads, retention of fines, and waterproofing. The results of those tests concluded that the waterproofing and fines retention of the three additives were essentially the same; however the latex emulsion and asphalt emulsion resisted rutting better than the cutback asphalt. The recommended application rates for the asphalt emulsions are about 4%.

Sixteen polyester and thermoplastic resins were initially considered as soil stabilization and dust palliatives for laboratory studies; however half were rejected because of their water insolubility that hindered dilution and ease of application (Denny, 1973). The rejected materials were polystyrene, polypropylene, and several polyester resins because they required benzene for solution and polyvinyl alcohols that dissolve only in hot water. The remaining materials were a polyester resin and five proprietary chemicals of unknown chemical composition. All of these additives were tested with a sandy loam that with an AASHTO classification of A-2-4(0). The cost of these additives ranged (in 1973 dollars) from about $0.4 to $1.2 per square yard for the concentrations between 0.1% and 1.0%. In addition to unconfined compression tests the stabilized specimens were tested with a rainfall simulator and a traffic simulator to evaluate erosion resistance and durability. Based on these laboratory test results, it was recommended that the following products and treatment concentrations be subjected to field trials: Petro D Dust from 0.1% to 0.25%, Stypol 40-5020 (polyester resin) at 0.5%, Kelpak from 0.1 to 0.2%, and SA-1 at 0.1%. Apparently, Clapak and Claset were not recommended because of their inability to effectively control subgrade moisture. The treatment costs for the recommended additives are: Petro D Dust $0.12/sq.yd to $0.31/sq.yd., Stypol $0.80/sq.yd., SA-1 $0.67/sq.yd., and Kelpak $0.42 to 0.84/sq.yd. Based on these laboratory test results, it was recommended that the following products and treatment concentrations be subjected to field trials: Petro D Dust from 0.1% to 0.25%, Stypol 40-5020 (polyester resin) at 0.5%, Kelpak from 0.1 to 0.2%, and SA-1 at 0.1% production,

The theses by Bergeson (1972), Denny (1973), and Fox (1972) were edited and compiled in a report to the Iowa State Highway Commission (Hoover, 1973). This compilation suggested six criteria for dust palliatives:

1. additive cost less than $5,000/mile (1973 dollars) and certainly not exceed $10,000/mile
2. water soluble on application but becoming insoluble after incorporation with the soil to provide bonding, waterproofing, or other resistance to dust,
3. no specialized handling or construction equipment,
4. adequate dust control with possible strength improvement,
5. ease of surface penetration or easily mixed in-situ up to 6 inches in depth with existing road materials, and
6. additive quantities not to exceed 4% to 5% by dry weight.

The following table lists the additives that were recommended for further field trials. The table also shows palliative treatment rates and the classification of the soils with which the additive is most likely to be effective.

Table 7.1 Additives recommended for Iowa field trials in 1973

Additive	Soil type	Soil classification	Effective Treatment rate (% dry weight)
KC-800 Cutback asphalt	Gravelly Sandy loam	A-1-b	1 - 6
	Silt	A-4	3 - 4
RedicoteE-36 Cationic asphalt emulsion	Silty loam	A-4(8)	3-6
	Gravelly sandy loam	A-1-b	2 -5
Lignin	Sandy loam	Not determined	0.5- 2
Lignin and lime	Glacial till	Not determined	1.5 - 2.5 + 0 - 2
	Silty clay alluvium	Not determined	1.5 - 2 + 0 - 0.5
Chemplex waste	Glacial till	Not determined	4
Petro B dust	Sandy loam	A-2-4(0)	0.1 - 0.25

Organic cations and sodium chloride were studied as general soil stabilizing agents recognizing that dust control was one of many benefits (Buzke, 1974). The soil used in this study was collected from the surface of a aggregate stabilized road in story County that classified as A-2-6(1) with 66% sand and gravel. The stabilizing agents were Arquad (quaternary ammonium chloride), Armac T (tallow amine acetate), Duomac T (high molecular weight N-alkl trimethylene diamene), and sodium chloride. The testing procedures included the erosion simulator and traffic simulator. The study concluded that sodium chloride decreased soil strength while increasing density and decreasing optimum moisture content. Erosion resistance, moisture retention, freeze-thaw durability, and trafficability all improved with salt treatment. In general, all three organic cationic additives improved moisture retention, freeze-thaw durability, and resistance to traffic abrasion. Strength was reduced with increasing organic cationic content. Little benefit was observed by combining salt with the organic agents. The recommended treatment level of organic cationic stabilizing agents is about 0.1% while sodium chloride dosage is recommended at 1%. It was noted that treatment amounts could vary with soil type. The cost of the organic cationic additives was reported to be twice as expensive cationic asphalt emulsions (in 1974 dollars); however the low treatment rates for the organic chemicals make them 20 times less expensive than the asphalt.

Field trials were conducted with three asphalt emulsions added to soils in Buchanan, Franklin, Marion and Plymouth Counties where the soils all classified as A-2-4(0), at three sites in Pottawattamie County where the soils were A-4(0), A-6(4) and A-7-5(12), and in Story County with an A-6(4) soil (Lustig, 1980). The asphalts were all CSS-1 asphalts with asphalt content varying from 57% to 61% and zeta potentials ranging from 0 to 80 millivolts. The study describes a protocol based on lab testing to match the soil type and asphalt for maximum effectiveness. No clear generalized relationship between zeta potential and soil classification resulted from the study; however it is clear that not all emulsions perform with all types of soils.

Field trials were conducted with a surface application in Franklin County and mixed-in-place applications at two sites in Pottawattamie County. Although dust palliation occurred at the Franklin County site, it was short-lived. Data from the mixed-in-place sites indicate the emulsions performed satisfactorily. Total construction costs, based on 1980 dollars, for the Pottawattamie County were about $60,000/mile as compared with approximately $103,000/mile for Portland cement concrete.

Eight dust suppressants were included in laboratory tests and field trials that included nine sites (Hoover et al, 1981). The palliatives were: liquid calcium chloride, asphalt emulsions, Coherex (stable emulsion of petroleum oils and resins), Polybind Acrylic (co-polyer resin emulsion), Amasco Res Ab 1881 (styrene butadiene latex), ammonium lignosulfonate, Type I Portland cement, and flyash. Coherex is usually applied at rates of 0.5 to 1.5 gal/yd2, Polybind at 40 gal/acre, and Amsco at 500 lb/acre. Lignin is applied at rates of 1.0 to 1.5 gal/yd2 and oils at 0.25 gal/yd2 . In comparison, liquid calcium chloride is applied at rates of 0.3 gal/yd2. Application methods consited of three categories: 1) surface application, 2) mixed-in-place, and 3) mixed-in-place with seal coat. It was concluded from laboratory results that only category 3 stabilization with fly ash and Portland cement was effective with most soil-aggregates and lignosulfonate, Coherex, Polybind, and Amsco varied from negative to potentially effective depending on aggregate type. Field test results indicated that effective dust abatement occurred with category 3 application of cement and fly ash or emulsified asphalt. Amsco, Polybind and emulsified asphalt were effective with category 1 construction whereas Coherex was most effective with non-absorptive aggregate. Both calcium chloride and lignosulfonate are comparably cost-effective with category 1 construction. The preferences of the County engineers at each test site excluded category 2 construction as a possible test method and so no data are available.

The study identified the following procedure when considering dust palliation alternatives:

1. Determine how much dust is being produced and what minimum levels are necessary to provide desirable results.
2. Identify practices currently in use.
3. Identify products and techniques currently in use.
4. Perform demonstration tests using various different materials.
5. Evaluate test results.

The laboratory tests were conducted on MC-800 cutback asphalt, a cationic asphalt emulsion, lignin, lignin plus alum, lignin plus lime, and a residual waste product of the Chemplex Plastics Co. Dust quantities were reduced 33 to 80 percent of the dust quantities resulting from and untreated surface; however, the results were dependent on application method. Also found was that aggregate replacement could be reduced by 2 to

4 times the average annual rate by the use of these materials. Correlation between observed field performance and laboratory results using the traffic-simulator test was "reasonably good."

Field tests in Linn County, Iowa, evaluated five mixed-in-place treatments, utilizing 4 to 6 inches of the surface, and one surface-applied treatment of calcium chloride. Lignin, lignin plus a herbicide, and two cationic asphalt emulsions were mixed-in-place and found to have significant dust control one year later. After one year, Kelpak, a "proprietary chemical," was found to have negligible dust control. Surface-applied calcium chloride provided dust control for less than 6 months. The Linn County studies showed mixed-in-place techniques to be a better approach than "topically-applied" techniques.

Conclusions from a variety of previous studies also were summarized described in the 1981 report (Hoover, 1981) as follows. Roadways in Taylor County were tested with 0.75, 1.00, and 1.25 percent by soil weight of Bindtite (a lignosulfonate). "All test sections remained nearly free of dust". On the basis of a 1.00 percent lignin solids content, the cost of materials, labor, and equipment was $6600/mile for a 6-in stabilized base. Calcium chloride was considred for this project, but cost estimates were twice that of the lignin products.

The City of Des Moines used CSSI emulsified asphalt. The palliative was found to work best where sand to mechanically-well graded conditions existed. The process included a 2-inch in-depth palliation, followed by a fog application of 0.1 to 0.15 gal/yd2 of a 9:1 water dilution of the emulsion, then periodic re-applications as necessary.

Cement, fly ash, or emulsified asphalt can be used to provide effective dust control when used as mixed-in-place base stabilizers with seal coast surfacing.

Several chemicals provided little dust control, Amsco Res AB 1881, Polybind Acrylic DLR 81-03, and cationic asphalt emulsion, when used as surface-applied dust palliatives. Surface-applied, Coherex provided good dust control but was expensive. Surface-applied calcium chloride and ammonium lignosulfonate were effective in dust control as well as cost.

Recently, bentonite has been demonstrated to be an economical dust palliative with an effective time span of 2 or 3 years (Wahbeh, 1990, Iowa Transportation Center, 1995). Using cost data for 1993, the cost of annual dust control with calcium chloride is $3,200 per mile while bentonite treatments cost $1,750 per mile. If the bentonite treatment lasts for two years, the latter figure would be cut in half (Bergeson and Broka, 1996). These costs are for dust control only and do not include costs for structural maintenance. The long-term effect of bentonite treatment on structural stability of unpaved roads is yet to be demonstrated. These studies also indicated that while bentonite is effective on roads stabilized with crushed limestone, it is less effective on gravel-stabilized roadways. After nearly a century of research on stabilization of unpaved road the ideas have come full circle by suggesting mixing clay with coarse aggregates.

Recycled materials are currently under consideration as dust control agents. Ground roofing shingles were applied to an unpaved road in Benton County with some success (Marks and Petermeier, 1997); however in another county, ineffective separation of the roofing nails from the shingles led to the obvious disastrous results. This second project dampened enthusiasm for ground shingles but qualitative observation of the Benton County indicates the material is performing well five years after application (Steffes, 2000).

Undocumented evaluations of soapstock (acidulated soybean oil) have also been conducted in Iowa (Riley, 1999). The only data on the product found in this study is from a promotional brochure as will be described in a following section of this report.

In May, 2000 soy oil was applied as a dust palliative to a road in Carroll County (Danzer, 2000). This additive is not a scrap material and its estimated cost is $0.15 / lb as compared with soap stock at $0.05/lb. No data on dosage rates were found, however the obvious connection with Iowa's agricultural base may make it an interesting potential dust control agent.

7.2 Summary of and Observations on Iowa Studies

ISU research on dust palliatives spanned over 30 years. Although the studies were not continuous, they included sodium and calcium chloride, lignosulfonate, asphalt emulsions, cutback asphalt, organic cationic chemicals, resins, and bentonite clay.

The research included both laboratory evaluations and field trials. Although unconfined strength tests appear to be a part of all laboratory studies, it seems to have little relevance to dust control. The most relevant measure from the traffic simulator seems to be the production of "float". If the dust control chemicals had deleterious effects such as increasing the tendency for rutting, the trafficability test produces useful results. Field studies included dust collection from both treated and untreated road surfaces and are the most relevant measure of a given dust control agent's efficacy.

The following paragraphs attempt to synthesize the most important results from the Iowa studies of dust control agents. All lignosulfonate treatments reduced dust production up to 80% compared to untreated roads and suggest that 1% lignosulfonate treatment was as effective as 1% lignosulfonate plus 0.5% of the secondary additives. Increasing lignosulfonate from 1% to 2 % was not recommended. Disadvantages of lignosulfonate treatment are: roads become slick if aggregate content was less than 1800 tons/mile and runoff from treated surfaces was discolored indicating leaching and suggesting a pollution potential.

Based on laboratory test results, it was recommended that the following products and treatment concentrations be subjected to field trials: Petro D Dust from 0.1% to 0.25%, Stypol 40-5020 (polyester resin) at 0.5%, Kelpak from 0.1 to 0.2%, SA-1 at 0.1%. Cutback asphalt and asphalt emulsion also were recommended for field trials. Latex emulsions were not recommended because of cost. No information on subsequent field measurements was found.

Waterproofing and fines retention of latex emulsion, asphalt emulsion, and cutback asphalt were essentially the same; however the latex emulsion and asphalt emulsion resisted rutting better than the cutback asphalt. The recommended application rates for the asphalt emulsions are about 4%; however it is clear that not all emulsions perform equally well with all types of Iowa soils. Field trials were conducted with a surface and mixed-in-place applications. Although dust palliation occurred with surface application, it was short-lived. Data from the mixed-in-place sites indicate the emulsions performed satisfactorily for longer durations.

In the 1960's field measurements on float production with sodium chloride treated roads suggest that sodium chloride can be effective in reducing dust. A decade later sodium chloride combined with organic cations was studied. Little benefit was observed by combining salt with the organic agents. Erosion resistance, moisture retention, freeze-thaw durability, and trafficability all improved with salt treatment. Sodium chloride dosage is recommended at 1%; however treatment amounts could vary with soil type.

In general, organic cationic additives improved moisture retention, freeze-thaw durability, and resistance to traffic abrasion. The recommended treatment level of organic cationic stabilizing agents is about 0.1%. The low treatment rates for the organic chemicals make them 20 times less expensive than asphalt.

Bentonite has been demonstrated to be an economical dust palliative with an effective time span of 2 or 3 years but long-term effect is yet to be demonstrated. Bentonite works well on roads stabilized with crushed limestone, but less effective on gravel-stabilized roadways.

Potential dust control agents are ground up shingles and soybean oil. These materials have been subjected to limited field trials, but with little quantitative data on effectiveness and treatment rates. Both deserve at least some screening tests and possibly field evaluations.

7.3 Calcium Chloride as a Dust Suppressant

The Swedish Royal Institute of Technology studied magnesium and calcium chloride and found that magnesium chloride uses less water to go into solution, therefore calcium chloride is possibly more suitable for dust palliation than magnesium chloride. Both solutions were generally the same when tested for corrosive behavior with the exception being that magnesium chloride is more aggressive towards concrete (Reyier, 1972 as cited in Hoover, 1981).

Calcium chloride is one of the most popular dust suppressants used nationally and the most widely used in Iowa. In a survey of county engineers, 62 reported they used calcium chloride (Steffes, 2000).

Calcium chloride has been describes as both hygroscopic (Kirchner and Gall, 1991) and deliquescent (Bolander and Yamada, 1999). It attracts moisture and increases the surface tension of water in the pores. The higher moisture tension results in slower evaporation rates which is beneficial to dust control (Bolander and Yamada, 1999). It also lowers the freezing point of the pore water resulting in greater freeze-thaw resistance and benefits compaction as well as enhancing coarse aggregate retention (Kirchner and Gall, 1991).

The material comes in three forms: a liquid brine with 38% solids and as solid flakes and pellets. The dosage rates are 0.27 gal/yd2 for liquid, 1.54 lb/yd2 for flakes, and 1.32 lb/yd2 for pellets with a second application application in late summer (Kirchner amd Gall, 1991). Treatment rates of 0.29 to 0.36 gal/yd2 for brine and 1.5 to 1.9 lb/yd2 for flakes have also been reported (Anonymous, 1997). The road surface should be bladed to sufficient depth to remove potholes and then smoothed so as not to retain water on the surface (Kirchner and Gall, 1991).

The soils on which calcium chloride is most effective are those with 10 to 20% particles less than 0.075 mm (Bolander, 1997). It has also been recommended that calcium chloride should not be used on soils containing more that 25% clay particles (Kirchner and Gall, 1991).

The limitations of calcium chloride as a dust suppressant are that it can create a slippery surface with too much moisture and high fines content, it is somewhat corrosive, and it can be harmful to vegetation (Bolander and Yamada, 1999).

7.4 Forest Service Research

Some of the most extensive field studies regarding dust control on unpaved roads have been conducted by the U.S. Forest Service in the Pacific Northwest (Langdon and Williamson, 1983; Borlander, 1997; Borlander, 1999; and Borlander and Yamada, 1999).

Field trials between 1988 and 1992 evaluated 16 products and concluded that the most economical products for dust abatement are: lignin sulfonate, magnesium, chloride brine, calcium chloride flakes and clay (Borlander, 1997). The same study pointed out that synthetic polymer emulsions, tall oil emulsions, and modified asphalt emulsions are promising but need further field trials. Cost data in the report indicates the polymers to be approximately five times more expensive than the chlorides in the Table 7.2 summarizes the dosage rates, fines content (material finer than 0.074 mm) of most appropriate soils, date of study, and cost per mile (materials, preparation and application rate) of the most economical products. A summary of the 1997 Bolander study is also published in Better Roads (Anonymous, 1997)

Table 7.2 Application rates, cost, and acceptable fines content of most economical dust suppressants data from Bolander (1997)

Additive	Fines content Of soil (%)	Application rate	Cost ($/kilometer)	Date of evaluation
Magnesium chloride	10 to 20	1 shot@ 2.26 l/m2	1740	1988
Magnesium chloride	10 to 20	2 shots @ 1.13 l/m2	1490**	1992
Calcium chloride	10 to 20	1 shot @ 1.13 l/m2	1240*	1988
Lignin sulfonate	8 to 20	2 shots @ 2.26 l/m2	930	1988
Clay	Less than 15	1 to 3% by dry weight	No data given	1992

* cost data for brine ** materials cost only

Recently, Bolander and Yamada (1999) described the accumulated results of U.S. Forest Service research in a very comprehensive paper. The report identifies 62 dust suppressant products with specific references to appropriate soil types, dosage rates, climatic constraints, and environmental effects. This document includes manufacturers' names, phone numbers, and in some case their Web sites for the listed suppressants. Duration of dust control effectiveness is a primary concern in selecting an economical dust palliative because this will affect the overall economy of the product. Table 7.3 contains data extracted from Bolander and Yamada (1999) showing dosage or treatment rate, limitations or problems, treatment methods, and longevity. Obviously the duration of effectiveness of the suppressant will be affected by climatic variations, however the data presented here provide a relative measure of the various products.

Table 7.4 shows the dust control mechanisms and attributes as identified by Bolander and Yamada (1999) as well as characteristics of the soils for which the additives are most effective. The soil characteristics are percent fines (less than 0.074 mm) and the plasticity index (PI).

The data in Table 7.4 indicate that all the road surface materials would classify as A-1 or A-2 by the AASHTO system. By comparing data in the Tables 7.3 and 7.4 it can be seen that the hygroscopic additives have much shorter longevity than the binder or agglomerating additives. No pattern exists between longevity and soil characteristics.

7.5 Soapstock as a Dust Palliative

Unpublished studies suggest that soapstock, Acidulated soybean oil, a byproduct of soybean oil production, offers promise as a stabilizing agent (Riley, 1999). Although no reports were found in engineering or scientific journals, the Minnesota Soybean Association (1998) produced a brochure that suggests that application rates of 0.25 gal/yd2 will control dust on gravel roads for an entire summer season; however application rates are "still being evaluated". ` The cost of the product varies with commodity prices but is in the range of $1.12 to $1.50/ gallon. This material has an odor that some consider offensive when first applied. The producers of soapstock are currently studying possible additives to make this material more effective in dust control as well as modifying the odor to make it less offensive.

Table 7.3 Dust suppressants ranked according to duration of effectiveness. Data from Bolander and Yamada (1999)

Dust Suppressant	Longevity	Dosage	Limitations or problems	Treatment method
Clay	1-5 years	1-3% by weight	Rutting wet conditions	Mix with uniform distribution
Polymers	1+ years	2.3 L/m2		Mix or spray
Electrochemical	?	Diluted 1/100 or 1/600	Depends on clay mineralogy	Mix with light compaction
Tall oil	1+ years	2.3 L/m2	Highly soluble	Mix or spray on loosened surface
Vegetable oils	1 year	1.1 - 2.3 L/m2	Limited availability, becomes brittle	
Lignin	6 mo	2.3 L/m2	Potential pollution from leaching	Mix
Petroleum	6 mo	0.5 - 4.5 L/m2	Rutting in weak bases, might be toxic	Mix or spray low viscosity product
Mg Chloride	6 mo	1.6 L/m2	Corrosive, potential pollution potential	Mix solids or spray brine
Ca Chloride	6 mo	1.6 L/m2	Corrosive, potential pollution	Mix solids or spray brine
Water	1 day	A lot	Very short duration	Spray
Molasses	?			Mix

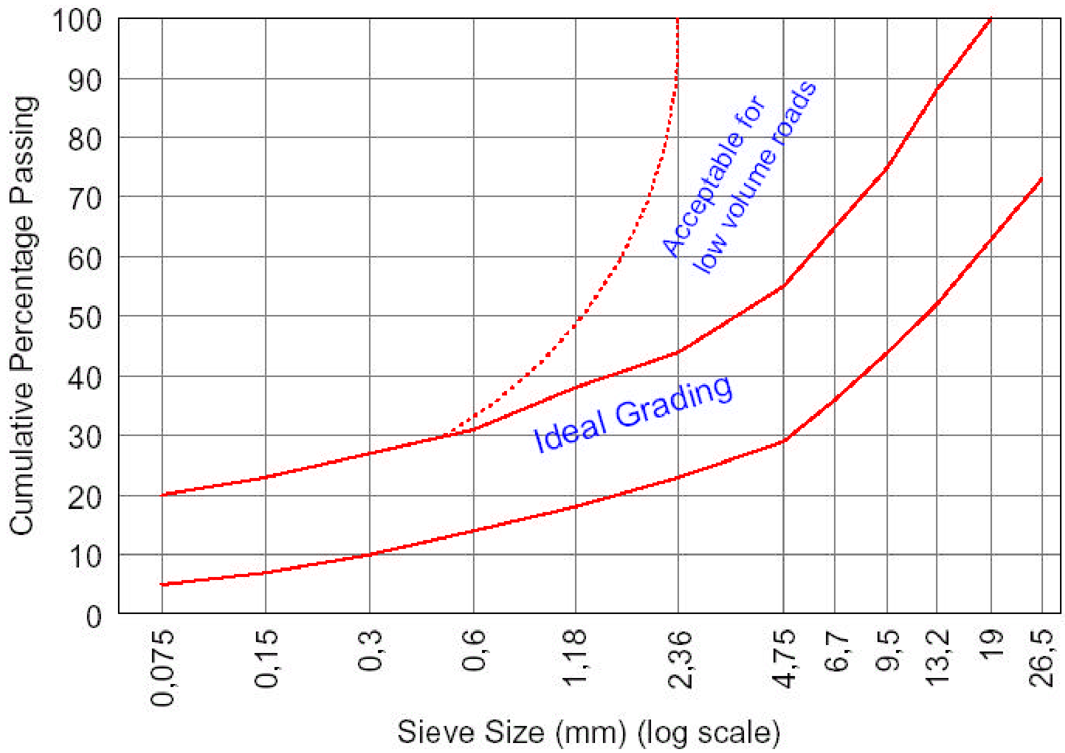
7.4 Dust control mechanisms based on data from Bolander any Yamada (1999)

Dust Suppressant	Mechanism	Other attributes	Soil for best performance	
			% fines	PI
Clay	Agglomerates fines	High strength when dry	< 5	< 8
Polymers	Adhesive binder		5 - 20	< 3
Electrochemical	Flocculates clays	Effective regardless of climate	> 10	> 8
Tall oil	Causes adhesion	High strength when dry	10 - 20	< 3
Vegetable oils	Agglomerates		10 - 30	fair for all
Lignin	Binder	Most effective when dry	20 - 30	> 8
Petroleum	Binds or agglomerates	Acts as waterproofing agent	Fair for all	< 3
Mg Chloride	Water absorption	Absorbs water @32% relative humidity independent of temperature	10 - 20	> 8
Ca Chloride	Water absorption	Absorption depends on relative humidity and temperature	10 - 20	> 8
Water	Capillary tension	Readily available	Spray	All
Molasses	Temporary binding			

7.6 Foamed Asphalt as a Dust Palliative

Foamed asphalt, which was developed at Iowa State University in the late 1950's, is more commonly used as a means of soil stabilization. Csanyi (1957, 1962) proposed its use on rural roads as an economical alternative to paving. Lee (1981) proposed its use to beneficiate marginal aggregates. This technique, which introduces a mixture of air, water and asphalt into a soil or aggregate mixture, results in a relatively disperse distribution of asphalt in a moist soil/aggregate material, which, when compacted can provide a sound, bound material. In the 1970's the method of foamed asphalt fell out of use in the U.S., but was adopted and continued to be developed in Europe and South Africa. It has recently been re-introduced into the U.S. as a means of stabilizing road base and recycled asphalt pavement. In South Africa, a formalized mix design procedure has been developed (SABITA & CSIR-Trasnportek (1998)), which recognizes the benefits of foamed asphalt in low volume roads, and provides feasible gradation limits, which would encompass many of the aggregate surface materials found in rural Iowa (Figure 7.1).

Figure 7.1. Feasible Aggregate/Soil Gradations for Foamed Asphalt Applications (SABITA)



The use of foamed asphalt as a dust palliative may be more costly than is preferred in many situations, however, it brings with it a number of longer term benefits: increased unconfined strength, increased resistance to moisture and freeze-thaw and, in general, significantly improves the overall pavement strength, stability and traffic capacity.

8. CONCLUSIONS

Road dust is caused by wind action entraining fine material, less than 0.074 mm in particle size, from the roadway surface. Although the soil base may have a high content of fines because of its geologic origin, mineralogy characterizations of Iowa dust provide convincing evidence that the main source of road dust is attrition or degradation of carbonate rock used as aggregate.

The mechanisms of dust suppression have been variously described as agglomeration, binding, imparting cohesion, increasing the road surface density, hygroscopic action and stabilization. It is suggested here that the mechanism can be considered as two processes: increasing particle size of the surface fine material by agglomeration and inhibiting degradation of the coarse material. Fine particle agglomeration may occur by capillary tension in the pore water, surfactants that increase bonding between clay particles, and cements that bind the mineral matter together. Coarse aggregate protection is a second, separate mechanism.

Negative pore pressure in moisture films between the solids. This type of bond is ephemeral because as the soil dries out the number of these bonds decreases and the cohesion decreases, and as the soil becomes wetter the radius of curvature of the menisci increases causing the tension to decrease. This is likely why the hygroscopic dust suppressants have longevity of about 6 months and why the palliative action of water is limited to hours or days. It is likely that the capillary tension is also the reason that dense roadway surfaces are less prone to produce dust than lower density surfaces. The denser surfaces have smaller pores thereby increasing the moisture tension within those voids, and creating higher apparent cohesion. The hygroscopic dust control agents are likely to be less effective in arid climates.

A more permanent method of agglomeration results from chemicals that act as a cement or glue to bond smaller particles into a mat or aggregates coarser than 0.074 mm. The bonding agents include all dust suppressants other than water and hygroscopic agents including lignosulfonates, resins, and asphalt products. These palliatives are effective in a wide range of environments however the resins tend to be more expensive

Surfactants that alter the surface charge on clays in the road surface will vary in effectiveness based on the mineralogy of clays and moisture content. Surfactants are likely to be less effective dust suppressants in humid environments.

At present the only obvious dust palliative that decreases aggregate degradation is the use of shingles. The relatively soft shreds of shingles act as a cushion between aggregate particles. It is likely however that some suppressants such as the synthetic polymers also provide some protection against attrition of the coarse aggregate.

Although the cementing action of some dust palliatives implies greater strength, there is no consistent relationship between the strength of the stabilized soil and its effectiveness as a dust palliative.

Because the major source of road dust in Iowa is degradation of limestone aggregate, dust palliatives that bond with carbonates, such as bentonite, or additives that protect the aggregate from degradation would be most effective.

The two most widely used dust control agents are calcium chloride and lignosulfonates. Both of these agents have a useful duration of 6 months.   Calcium chloride is effective with soils that have moderate fine content and higher plasticity indices and in a humid environment. Lignin works best with surface materials that have high fine content and high plasticity indices in a dry environment.

Clay appears to have the longest duration of effectiveness but is best with surface materials having low fine contents and low plasticity indices. Clays work best in relatively dry environments.

Laboratory tests used in previous studies to screen additives for potential effectiveness and to determine dosage rates appear, for the most part, to be unrelated to performance in field trials. Modified laboratory evaluation protocols are needed. A modification of ASTM D 560 to estimate the freeze-thaw and wet-dry durability of Portland cement stabilized soils would be a starting point for improved laboratory testing of dust palliatives.

Selection of appropriate dust suppressants should include characterization of the road surface material including engineering index tests and classification by AASHTO and Unified systems. Estimation of dosage rates of several potential palliative candidates should be based on data from this report, from technical reports, information from reliable vendors, or laboratory screening tests. An excellent reference in the preliminary selection stage is Dust Palliation Selection and Application Guide (Bolander and Yamada, 1999). The selection should be followed preliminary economic analysis that would include original construction costs and maintenance costs based on product longevity. The effectiveness of the treatment should be evaluated by any of the field performance measuring techniques discussed in this report.

8.1 Recommendations for Further Consideration

Novel dust control agents that need research for potential application in Iowa include; acidulated soybean oil (soapstock), soybean oil, ground up asphalt shingles, and foamed asphalt. These products deserve further consideration with laboratory tests followed by field trials that include dust collection from both treated and untreated road surfaces.

9. ACKNOWLEDGEMENTS

The Authors acknowledge the assistance of the many individuals who have provided background, reflections on personal experience and offered opinions on the relative merits of various dust suppressants. Finally, the sponsorship and funding of the Iowa Highway Research Board is gratefully acknowledged, as is the helpful assistance and guidance provided by Mr. Mark Dunn, of the Iowa Department of Transportation.

10. REFERENCES CITED

Anomyous, 1997. "Dust control some improvements", Better Roads 22(7): 35-35.

Anonmyous, 1998. "Controlling dust, which materials should you use?", Better Roads 23(6): 23-25.

Bergeson, K.L. and S.G. Broka, 1996. "Bentonite treatment for fugitive dust", Proceeding of Semi-sesquicentennial Transportation Conference, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.

Borlander, P. and A Yamada, 1999. "Dust Palliative Selection and Application Guide" Project Report 9977-1207-SDTDC San Dimas Technology Development Center, U.S. Dept. of Agriculture, Forest Service, San Dimas, CA.

Borlander, P. 1997. "Chemical additives for dust control - what we have learned", Transportation Research Record 1589: 42-49.

Borlander, P. 1999. "Laboratory testing of nontraditional additives for dust abatement and stabilization of roads and trails", Transportation Research Record 1652, vol. 2:

Butzke, M.R., 1974. "Organic cationic and sodium chloride soil stabilization", Unpublished M.S. Thesis, Library, Iowa State University, Ames, Iowa

Csanyi, L.H., 1957. “Foamed Asphalt in Bituminous Paving Mixtures”, Highway Research Board Bulletin No. 160 (1957), 108.

Csanyi, L.H., 1962. “Foamed Asphalt for Economical Road Construction”, Civil Engineering, 32(6) (1962), 62

Danzer, M., 2000. Personal Communication. West Central Soy, Ralston, Iowa.

Denny, C.K., 1973. "Soil-chemical additives as surface improvement agents for unpaved roads", Unpublished M.S. Thesis, Library, Iowa State University, Ames, Iowa

Federal Highway Administration, 1976. America's Highways, 1776-1976, US Department of Transportation, Washington D.C.

Fox, D.E. 1972. "Ammonium lignosulfonates as dust palliatives and surface improvement agents for unpaved secondary roads", Unpublished M.S. Thesis, Library, Iowa State University, Ames, Iowa

Guimmarra, G., G.Foley, and S. Cropley, 1997. "Dust control-Australian experiences with various chemical additives", Transportation Research Record 1589: 50-53.

Hesketh, H.E. and F.L. Cross, 1983. Fugitive Emissions and Controls, Ann Arbor Science Publishers, Ann Arbor, Michigan

Hoover, J.M., K.L. Bergeson; D.E. Fox; C.K. Denny; and R.L. Handy 1973. "Surface improvement and dust palliation of unpaved secondary roads and streets", Final Report Iowa Highway Research Board Project HR-151, Iowa Department of Transportation, Engineering Research Institute, Iowa State University, Ames, Iowa

Hoover, J.M., J.M.Pitt, M.T.Lustig, and D.E.Fox, 1981. "Mission oriented dust control and surface improvement processes for unpaved secondary roads and streets" Final Report Iowa Highway Research Board Project HR-194, Iowa Department of Transportation, Engineering Research Institute, Iowa State University, Ames, Iowa.

Iowa Transportation Center, 1995. Technology News, Iowa State University, February.

Jones, D., 1999. "Holistic approach to research into dust and dust control on unsealed roads", Transportation Research Record 1652: 3-9.

Kimball, C.E., 1997. "Evaluating groundwater pollution susceptibility of dust suppressants and roadbed stabilizers, Transportation Research Record 1589: 64-69.

Kirchner, H.; and J.A. Gall (1991) "Liquid calcium chloride for dust control and base stabilization" Transportation Research Record 1291:

Langdon, B. and R.K. Williamson, 1983. "Dust abatement materials: evaluation and selection", Transportation Research Record 898: 250-256.

Lee, D.Y., "Treating marginal aggregates and soil with foamed asphalt", Proceedings of the Association of Asphalt Paving Technologists, Vol. 50, 1981.

Lustig, M.T., 1980. "Control of unpaved road dust with emulsified asphalts", Unpublished M.S. Thesis, Library, Iowa State University, Ames, Iowa

Marley, J.J. and J.B. Sheeler, 1963. "Studies on soil-aggregate sodium chloride stabilized roads in Franklin County, Iowa." Highway Research Record 7: 47-62.

Marks, V.J. and G. Petermeier, 1997. "Let me shingle your roadway", Interim Report for Iowa DOT Research Project HR-2079, Iowa Department of

Transportation, Ames, Iowa 50010 also in Transportation Research Record 1589: 54-57.

Minnesota Soybean Association, 1998. Brochure on Soapstock as a Dust Control Agent, 360 Pierce Ave. #110, North Mankato, Minnesota 56003.

Reyier, J, 1972. "A comparison between calcium chloride and magnesium chloride as dust binding agents of gravel roads", Tack 70 S-10044, Royal Institute of Technology, Stockholm Sweden.

Riley, R., 1999. Personal communication, Seed Energy Corp. Des Moines, Iowa.

Russell, E.R., 1965. "A study to correlate soil consistency limits with soil moisture tensions" Unpublished M.S. Thesis, Library, Iowa State University, Ames, Iowa.

SABITA & CSIR-Transportek, “Foamed Asphalt Mixes – Mix Design Procedure”, Report No. CR-98/077, 1988

Sack, W.A. and R.W.Eck, 1985. "Potential for use of natural brines in highway applications", Transportation Research Record 1019: 1-8.

Sanders, T.G.; J.Q. Addo, A.Ariniello; and W.F. Heiden, 1997. "Relative effectiveness of road dust suppressants", Jour. Transportation Engineering, ASCE, 123(5): 393-397.

Sanders, T.G. and J.Q. Addo, 2000. "Experimental road dust measurement device", Jour. Transportation Engineering, ASCE, 126(6): 530-535.

Steffes, R.F. 2000. Personal communication, Office of Materials, Iowa Department of Transportation, Ames, Iowa 50010.

Wahbeh, A.M. 1990, "Dust control for secondary limestone roads using bentonite", Unpublished M.S. Thesis, Library, Iowa State University, Ames, Iowa.

Woods, K.B., 1960. Highway Engineering Handbook, McGraw Hill Co., New York.