Road Dust Suppression:
Effect on Maintenance Stability, Safety and the Environment
Phases 1–3

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May 2004

Acknowledgements

Support for this project was provided by the Mountain-Plains Consortium (MPC) as part of the University Transportation Centers Program (UTCP). MPC member universities include North Dakota State University, Colorado State University, University of Wyoming, and Utah State University. The UTCP is funded by the U.S. Department of Transportation.

Special recognition is given to the Larimer County Department of Roads and Bridges for its full participation in this project.

Disclaimer

PREFACE

This report describes research conducted at Colorado State University to evaluate the effect of road dust suppression on unpaved road maintenance schemes. A field-based method was used to measure the effect of road soil physical characteristics on the effectiveness of some of the commonly used dust suppressants. The study also evaluated the stabilization of unpaved road base material because of the use of dust suppression. The effect of dust suppression on safety and driving conditions on unpaved roads was examined. The chloride compounds and ligninsulfonate commonly used as dust suppressants are water soluble and can be leached into the environment. They contain chlorides, heavy metals, and organic compounds that are regulated. Their potential to have adverse environmental impact was examined.

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EXECUTIVE SUMMARY

This research was undertaken at Colorado State University in cooperation with the Larimer County Department of Roads and Bridges.

A large portion of U.S. road network is made up of unpaved roads that usually carry a very small volume of the nation's vehicular traffic. Unpaved roads are mostly rural farm-to-market roads, forest service roads, and timber haul roads. They are easily and economically constructed using locally available soil usually with poor engineering properties or imported nearby soil with much better engineering properties. The use of unpaved roads causes dust emission into the atmosphere, loss of the road surface material over time, and frequent road surface deterioration in the form of ruts, washboarding, and potholes. Influenced by the traffic volume, these problems can lead to high economic cost.

To reduce the loss of road surface fines in the form of dust, chemical additives (dust suppressants) are applied to the unpaved road surface to control dust generation and to improve the road surface stability. Commonly used dust suppressants are chloride compounds $MgCl_2$, $CaCl_2$, and ligninsulfonate. The key to effective dust control and surface stabilization depends on the resulting interaction between the soil type and the additive. Chloride compounds (salts) and lignin exhibit different characteristics in controlling dust. The salts alter the moisture-holding characteristics of the soil by attracting and holding moisture from the atmosphere to keep the road surface fines moist so they bind to the coarser particles through capillary-dependent apparent cohesion. Lignin acts like a cementing material and binds all the soil particles together into a homogeneous mass. Both of these additive types modify the soil structure, thus affecting the long-term strength characteristics of the soil. The different road soil types also employ different mechanisms to ensure stability. Granular-type soils depend on the angularities of the particles to interlock particles during compaction to resist volume change and the lateral flow of the particles. Conversely, fine-grained or clayey soils depend on the moisture content of the soil to resist volume change and the lateral flow of particles.

Laboratory studies investigated the strength and density variation caused by different additive concentrations in different types of road soil (Palmer, et al., 1995). This study however, used field-based methods to measure the effect of road soil characteristics on the effectiveness of some commonly used dust suppressants in the context of unpaved road maintenance. The effect of dust suppression on the stabilization of the road soils in general was also examined. Safety and environmental concerns arising from the use of dust suppressants were reviewed as well.

Virgin road soil material from Larimer County's two main gravel borrow pits (Strang Pit and Horton Pit) were used in constructing test sections on County Roads (CR) 11 and 68 in the northeast part (Weaverly area) of the county. Each road soil material was treated with $MgCl_2$, lignin, and $MgCl_2$/lignin blend on half-mile test sections. In all, four pairs of test sections with one pair serving as a control untreated test sections were evaluated. The Colorado State University Dustometer was used to quantify the dust emission capability of each road soil type/suppressant combination. A few of the conclusions and summaries of the study are listed below:

- The Horton Pit material has more fines than the Strang Pit material. The fines portion of the Horton material is clayey, while the fines portion of the Strang material is cohesionless.
- Regardless of the road soil type, the use of the dust suppressant reduced the dust emission capacity of the unpaved road.

- Evaluation of the performance of the Strang $MgCl_2$ treated test section indicated the dust suppression capacity of the $MgCl_2$ had completely been depleted within a year of application such that the Strang $MgCl_2$ test section produced equal or more dust than the Strang untreated control section towards the end of the testing period. This also indicated that more than one treatment is required per year to maintain the effectiveness of the $MgCl_2$ when used with the Strang material.
- The lignin and the $MgCl_2$/lignin blend treatments performed nearly the same with both road soil materials.
- The Strang test sections produced less dust overall than the Horton test sections.
- The use of dust suppressants effects soil structure and can therefore influence soil stabilization but the degree of stabilization is still mixed.
- Although dust suppressants contain contaminants regulated by the EPA, their effect on water quality and other environmental impact is very small.

1. INTRODUCTION

1.1 Background and Problem Statement

Dust generation from unpaved roads because of vehicular traffic and wind means loss of road surface material (aggregate or native soil). Subsequently, the loss of surface material fines in the form of dust leads to the formation of ruts, potholes, and corrugation. The amount of dust generated and the consequent fines loss is determined primarily by the volume of traffic using the unpaved road as well as the speed, weight, and number of wheels of the vehicle. The abrasive resistance of the road surface material and the amount of fines in the initial road surface material mix are also important contributing factors (U.S. EPA, 1988). The climatic condition of a region is also a contributing factor affecting the dust generation equation. Long dry spells that often occur in semiarid and arid regions can aggravate unpaved road dustiness (Colorado Transp. Info Btg #3, 1989).

Fugitive dust from unpaved roads is noted as a major non-point source contributor to the particulate loading in atmospheric air pollution (AQMCP, 1985). To residents living along unpaved roads, the traffic-generated dust penetrates their homes causing a nuisance and health problems such as hay fever and allergies. Crops and vegetation near unpaved roads can be covered with the airborne dust stunting their growth due to the shading effect and clogging of the plant's pores. Fine particles resulting from traffic actions can also be washed off during precipitation events and carried into nearby creeks, streams, and lakes increasing their respective particulate loading. For motorists using the unpaved roads the traffic-generated dust can reduce visibility and cause driving hazards.

These conditions represent a significant material and economic loss. As a result, road departments that maintain unpaved roads spend a substantial part of their total budgets on aggregate replacement and maintenance. In Larimer County, Colo., for example, 12 percent of a total budget of $10 million in 1994 was spent on aggregate replacement cost alone. Another 18 percent of the total budget was spent on periodic maintenance of the county's unpaved roads. The county had nearly 1,100 miles of road under its jurisdiction. More than 700 miles (65%) were unpaved (Addo et al., 1995). Hoover, et al., (1981) reported that in 1978 the secondary road departments of Iowa's 99 counties spent about $32 million for aggregate replacement. The U.S. Forest Service, which is in charge of more than 325,000 miles of aggregate and earth-surface roads spent more than $64 million on unpaved road maintenance, which included more than $25 million on dust control alone in 1985 (Irwin, et al., 1986).

The age-old solution to the control of dust and the resulting road surface material loss has been dust suppression. Unpaved road dust suppression methods range from reduction of vehicle speed and application of water to the application of organic and non-organic chemical compounds. Not many studies have been done to test the relative effectiveness of the many proprietary dust suppressants. However, mixed effectiveness results have been reported by a few researchers (Hoover, et al., 1981; Lane, et al., 1984; Addo and Sanders, 1995). Review of these earlier studies indicate that more research is needed to compare the various dust suppressants' effectiveness, determine optimum application doses, and determine the most cost-effective application techniques. Due to the varied sources and different types of unpaved road surface material (aggregate) available, research to study the relationship between the aggregate distribution and the effectiveness of the dust suppressants need to be pursued. The value of dust suppression as part of an integrated unpaved road maintenance and road surface upgrade schemes is unknown. Likewise, the environment impact of the use/nonuse of dust suppressants is unknown.

1.2 Objectives

The objective of this research is to continue the research began at Colorado State University several years ago to establish the cost effectiveness of using chemical dust suppressants to increase the time between routine road maintenance on low-volume unpaved roads (Sanders, et al., 1997). This research study will investigate the quantitative contribution of road dust suppressants on the maintenance of unpaved roads. Since aggregate replacement in unpaved road maintenance is one of the main cost elements, the relationship between different aggregate characteristics and the quality and effectiveness of different dust suppressants or soil additives will be measured. A project measuring the effect of multiple dust treatments in stabilizing the road base prior to surface upgrade such as chip and seal in extending the life of the road will be initiated. The particle size distribution of the road dust with and without treatment will also be determined as will other environmental impacts. The effect of dust suppressants on the driving comfort and safety of unpaved roads will also be examined.

1.3 Scope of Work

To achieve the project objectives, the work breakdown, including but not limited to the following, shall be implemented:

- Consult with Larimer County road officials to determine a suitable unpaved county road as a candidate for testing. The selected road shall: 1) have reasonably high average daily traffic (ADT) count, 2) need aggregate replacement, 3) be long enough to accommodate eight 1/2-mile test sections, and 4) in the near future be a candidate for higher surface upgrade such as chipped and sealed.
- Prepare unpaved road and construct test sections using additional fresh aggregate material from the two different Larimer County gravel pits. Four of the test sections will use aggregate material A and the other four will use aggregate material B. Lignin-sulfonate-treated, magnesium chloride-treated, lignin- and magnesium-chloride blend-treated, and a control untreated test section will be provided for each of the two aggregate base materials being evaluated.
- Conduct a traffic survey to determine the volume and type of traffic using the test sections.
- Measure dust emission from each test section using the Colorado State University Dustometer.
- Perform vehicle braking (stopping) distance test on test sections under dry and wet driving conditions.
- Record all accidents on the test sections and investigate Larimer County records for traffic accidents on unpaved roads to determine if there is a relationship between the number of accidents and the type of road surface treatment (or lack thereof) on the unpaved roads.

2. ROAD DUST SUPPRESSION: EFFECT ON UNPAVED ROAD MAINTENANCE

2.1 Introduction

Two-thirds of the road network system in the United States and nearly 90 percent of the roads in the world are unsurfaced or lightly surfaced low-volume roads. In Colorado, about 70 percent of the more than 45,000 miles of local roads are unpaved (Colorado Transp. Info, 1989). Most of the unpaved roads are located in rural and forest areas, although cities and towns also have their fair share.

Most traffic volume is carried by the surfaced (paved) road system and thus much effort in research, construction, and maintenance has centered on paved roads. Nevertheless, to the federal, state, and local authorities in charge of unpaved roads, the problems associated with unpaved roads, maintenance and their costs, are not lost on them. In addition, especially in Colorado, almost all local roads are experiencing ever-increasing traffic volume and vehicle weights. Population growth and tourism are making ever-increasing demands. So are logging trucks and other commercial vehicles carrying much heavier loads. These higher volumes and greater loads are putting a strain on local road maintenance and reconstruction budgets.

2.2 Unpaved Road Definition and Classification

Unpaved road can be defined as engineered or tracks (Paterson, 1987).

a) Engineered Roads: unpaved roads with controlled alignment, defined width, cross-section profile, and drainage.
b) Tracks: unpaved roads that generally evolved from primitive trails – paths of least resistance. First created by wild animals, later used by settlers, and as user needs increased, evolved as part of the low-volume road network. They may have:
   i) topsoil removed
   ii) topsoil not removed.

In general, unpaved road classified as part of the low-volume road network are either engineered or partly engineered. Tracks are usually not considered as part of the low-volume road network. Most research studies relating to the effects of deterioration and maintenance of unpaved roads have mainly involved engineered unpaved roads because of available data for analysis (Boresi et. al., 1993).

There are many classifications for unpaved roads. The USDA Forest Service classifies its roads by maintenance levels. State highway departments also have different classification criteria and the criteria might be different from state to state. For the purpose of this report, the classification as provided by Paterson (1987) is considered here. The classification includes:

a) Gravel Surface Roads: usually engineered and the surface material includes sand and gravel or crushed rocks.
b) Earth Surfaced Roads: this terminology sometimes denotes:
   i) a track as opposed to an engineered road.
   ii) all unpaved engineered roads with surface material that does not meet the material gradation specification for gravel.

iii) unpaved roads that have a surface material of predominately fine soil with more than 35 percent finer than 0.075 mm (passing No. 200 sieve).

iv) unpaved roads with native soil ("dirt") as the surface material.

2.3 Unpaved Road Characteristics

Figure 2.1 illustrates the characteristics of good unpaved road. The main essential elements are the crown and drainage. A proper crown is required to enhance the roads usefulness, improve drainage, and ease maintenance. The crown is created in the center of the road and in general should be 1/3 inch to 1/2 inch higher than the shoulders for each foot of lane width (Colorado Transp. Info, 1989). For example a 20 ft. wide road (two 10 ft. lanes) will have a 3 inch to 5 inch crown as shown in Figure 2.1. This degree of slope is intended to drain surface water (snow melt and rain water) without washing off the road surface material. The road surface should also slope in a straight, uniform line from the crown to each shoulder edge. The crown may vary within a local jurisdiction because of the quality of gravel material, roadway grades, and weather conditions. The crown may be increased to 3/4 inch per foot, however this is the recommended maximum slope (Colorado Transp Info, 1989).

The other essential element of an unpaved road is drainage. Without proper and adequate drainage the road surface can become flooded during wet weather conditions. Ponding of water on the road surface can lead to structural damage of the base and subbase requiring costly maintenance. Proper drainage is achieved through cross surface drainage and side ditches collecting run-off from the shoulders and conveying it to streams and other natural drainages. The most economical ditch to construct is the V-shape (Figure 2.1). The foreslope of the ditch (next to the shoulder) is required to slope at least as much as the shoulder and usually more to prevent water from flowing back onto the shoulder. A slope of 4 to 1 or flatter is recommended (Colorado Transp Info, 1989). The backslope may be steeper than the foreslope.

Another important additional element is the use of good quality aggregate mix as the road surface material. The aggregate mix should consist of gravel or crushed rock, sand, and fines (silt and clay) in the right proportions to enable the road to support traffic loads, resist abrasion, shed water, and enhance the surface material's ability to absorb and disperse moisture. The percent of each component in a good aggregate mix can vary depending on the source of material. In general there should be 40-80 percent gravel or crushed stone, uniformly graded from 1/4-inch to 3-inch diameter size; 20-60 percent sand, smaller than 1/4 inch in diameter; and 8-15 percent fines of the total aggregate weight (Woods, 1960).

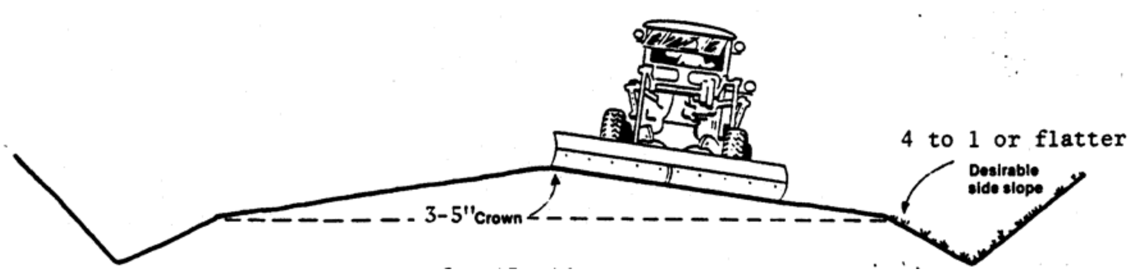

Figure 2.1 Unpaved Road Cross Section

2.4 Type of Aggregate (Gravel) Mixes)

The type of gravel material available for use in engineered unpaved road depends on the source of material for the area. In general gravel can be described as one of the following:

i) Pit Run Gravel: gravel mined out of natural deposit, very often an old stream or river bed.

ii) Washed Gravel: gravel in which excess fines have been removed by washing.

iii) Screened Gravel: pit run gravel with oversized stones removed. The maximum size in gravel mix should not exceed two-thirds of the thickness of the layer of road bed being placed (Woods, 1960).

iv) Crushed Gravel: this type of gravel is produced by running pit gravel including oversized stones through a mechanical crusher. The resulting material usually has angularities and uniform gradation. Crushed gravel is preferred for the construction of gravel roads because the angularities of the material provide better interlocking between particles. The voids between the large particles are also easily filled by the smaller and finer particles thereby forming a dense mass when compacted.

2.5 Unpaved Road Deterioration Mechanism

A properly engineered and constructed unpaved road comprised of a well-blended aggregate mix, compacted at optimum moisture, and featuring adequate drainage can provide an all-weather road surface capable of supporting high traffic volume over a considerable length of time before deteriorating.

For unpaved roads, unlike paved roads, the mechanism of surface deterioration is a simple progressive process. The fines in the road surface material mix with moisture to act as the binder or glue that holds the coarser aggregate together to provide the firm, smooth riding surface for traffic. The fines under the abrasive action of vehicle tires gets pulverized as surface moisture dries out, especially during dry conditions. The pulverized fines are then swirled off as dust. The persistent loss of fines in the form of dust leads to the coarser aggregate being pried loose by traffic action. Progressively, the road surface begins to unravel, leading to the formation of ruts, potholes, and corrugations.

Small ruts or depressions formed under traffic action accumulate snow melt and rainwater during wet weather conditions. When vehicle wheels roll over these water-filled depressions, the fines are immediately suspended and splashed out, starting the formation of potholes. Once started, potholes grow rather rapidly in the presence of water and additional traffic. Freezing and thawing during the winter months can also accelerate the pothole formation process. The accumulation of loose gravel material on the road surface in a wave-like pattern is called washboard effect or corrugation. This occurs as a natural result of the vehicle tire and loose surface material interaction.

According to many of the researchers that have studied deterioration and maintenance of unpaved roads (Robinson, 1980; Heath et. al., 1980; Visser, 1981; Paterson, 1987 and 1991), the main factor that strongly affects the deterioration of unpaved roads is the behavior of the road surface material under vehicular activities and the environment. Hodge et al., (1983), in a USDA Forest Service unpaved road deterioration study reported that there is a strong correlation between vehicle tire structure and pressure and unpaved road deterioration, particularly with regards to the tendency of unpaved roads to corrugate. Figure 2.2 and 2.3 show unpaved road surface corrugations. For unpaved roads, washingboarding effects or surface corrugations are a measure of the roughness of the road. Road roughness is a characteristic of the longitudinal profile of the road surface. However, as stated by Boresi and Palmer, (1993) "a significant measure of road roughness must include the effects of road surface profile, characteristics of the vehicles that travel over the road, and sensitivity of the vehicle occupants."

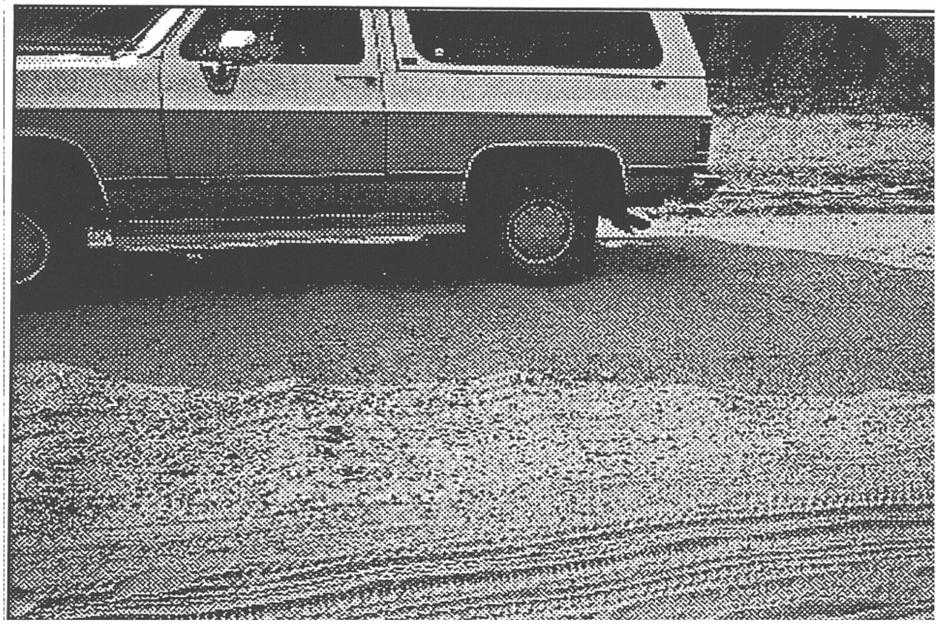

Figure 2.2a Transverse Road View of Corrugations

Note motor cycle tracks at road edge due to cyclists' attempts to avoid corrugations
Adapted from Boresi and Palmer (1993).

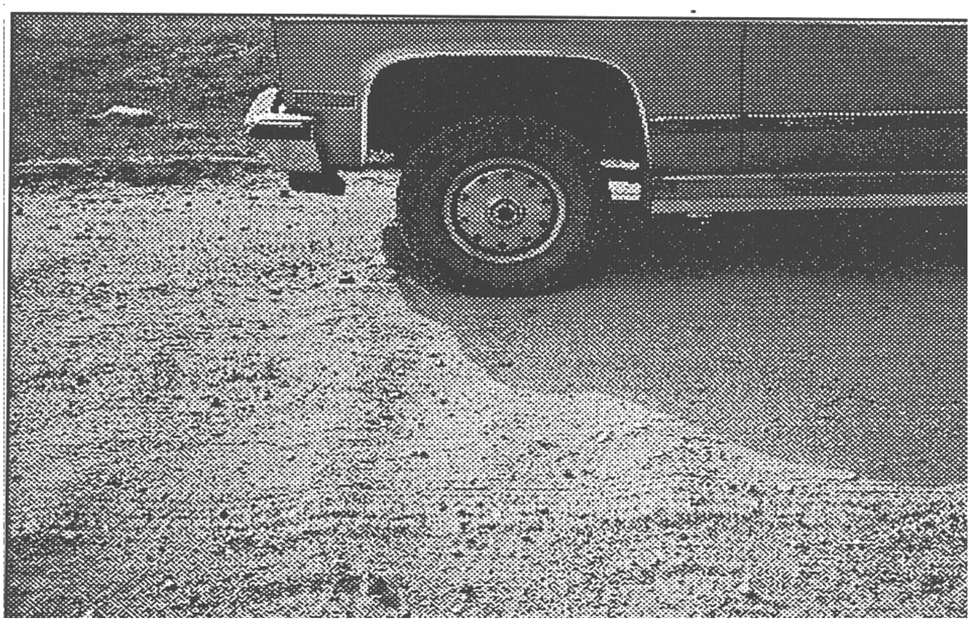

Figure 2.2b Transverse Road View of Corrugations

Longitudinal wave length corresponds approximately to footprints of 16-inch diameter tires.
Adapted from Boresi and Palmer (1993).

Figure 2.3a   Longitudinal Road View of Corrugations
Adapted from Boresi and Palmer (1993).

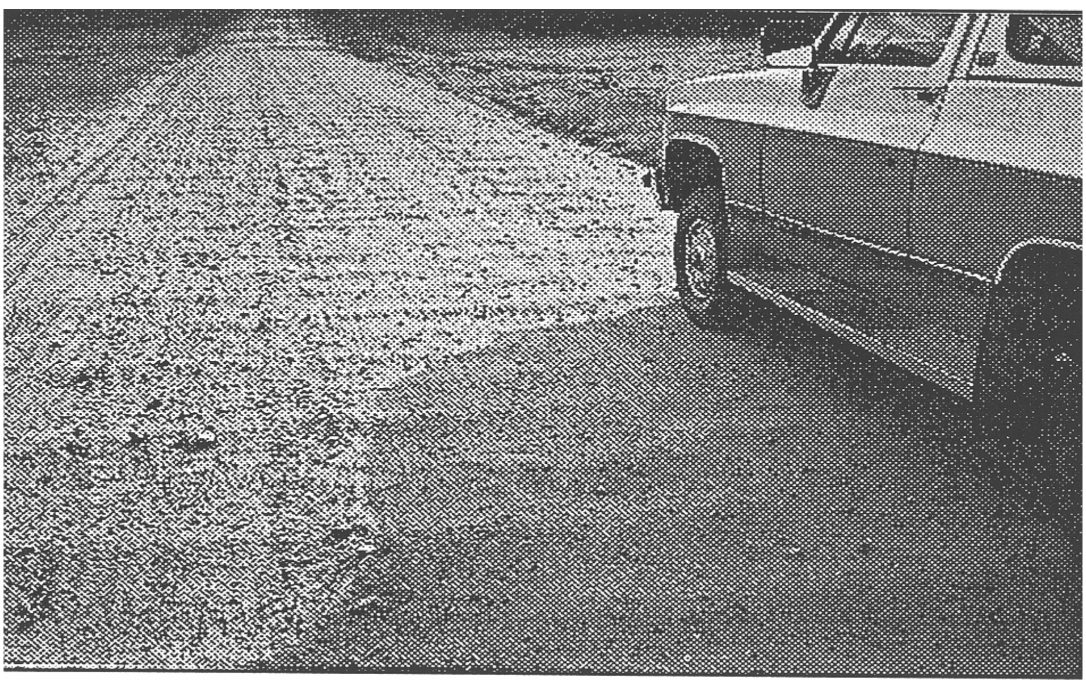

Figure 2.3b   Longitudinal Road View of Corrugations
Adapted from Boresi and Palmer (1993).

2.6 Dust Suppression Measures

The top problem associated with unpaved roads is traffic-generated fugitive dust and the resulting loss of fines. This problem lays the foundation for the eventual degradation of the road surface in the form of ruts, potholes, and corrugations. These conditions translate into high maintenance cost for road departments and as well as higher road user cost in the form of vehicle maintenance.

To maintain unpaved road surfaces at an acceptable standard, the frequency of periodic maintenance may have to be increased to keep the formation of ruts, potholes and washboards under control. The traffic type and volume as well as the base material characteristics, among other factors, influence the frequency of maintenance. At a moderate traffic volume of about 500 ADT, an estimated eight periodic maintenances per year was reported on a two-lane test section in Larimer County, Colo. (Addo and Sanders, 1995). The periodic maintenance involved scarifying, blading and compacting the road surface in the presence of adequate moisture. Once said, "When you see dust coming up from your roads you are seeing dollars thrown to the wind" (Nebraska T2, 1995).

To prevent the loss of road surface fines and prolong the useful driving life of unpaved roads, dust control measures are usually employed before maintenance is required. Commonly used dust control methods include: reduction of vehicular speed, application of water, and the use of dust suppressing chemicals. The use of dust suppressing chemicals have gained wide acceptance because of the many proprietary products available on the market and their effectiveness in controlling dust at a relatively low cost. Chemical suppressants range from organic and inorganic chemical mixes to synthetic fabric used to contain the road material. The primary dust suppressants in use are: water (fresh and sea), chloride compounds, lignin derivatives, and resinous adhesives.

2.6.1 Water (fresh and sea)

Water is probably the oldest of all dust palliatives, it is readily available and generally applied by spraying over the road surface. Its dust suppressing capacity is very temporary because of evaporation. Depending on weather conditions, several light applications should be carried out instead of one heavy application (Compendium 12, 1980). This application technique prevents the excess water from heavy application from turning the dust or fines into soft mud, washing away fines or even penetrating the road to the subbase and causing major road failure. Seawater is generally considered more effective in controlling dust than fresh water because of the presence of salts in it – chiefly magnesium chloride. Under sufficiently humid conditions, the salts will absorb and hold moisture to keep the road surface damp for a longer period of time than if fresh water is used.

2.6.2 Chloride Compounds

Calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$) are mainly used. Sodium chloride ($NaCl$) is also used on a limited basis. Proprietary products using combinations of these salts and other additives are also widely used. The properties of chloride compounds allow them to attract and absorb moisture from the atmosphere and retain it for extended length of time (Compendium 12, 1980). They also have low vapor pressure compared to water in the atmosphere at the same temperature. These properties are closely related to relative humidity and air temperature (Hogentogler, 1938). Relative humidity ranging from 30 to 40 percent has been reported as the cutoff at which $CaCl_2$ and $MgCl_2$ will cease to attract and absorb moisture from the atmosphere (Compendium 12, 1980).

When used as dust suppressants these chemicals keep the road surface damp especially in the early morning hours when the relative humidity is higher and temperature is low thus controlling dust generation. At a lower relative humidity and a higher temperature especially in the afternoons they are not so effective in attracting and absorbing moisture from the atmosphere. However, they significantly reduce the evaporation of moisture from the road surface thus making them effective dust suppressants.

Another important characteristic exhibited by chloride compounds is that they have a low freezing point depending on their concentration in aqueous solution. As reported in Woods (1960) a 30 percent $CaCl_2$ solution freezes at approximately –60F, a 22 percent $MgCl_2$ solution freezes at approximately –27F, while a 25 percent Na_2Cl solution freezes at –6F. When used as dust suppressants they minimize frost heave and reduce freeze-thaw cycles, which weaken unpaved roads. However, they have the disadvantage of being water soluble and therefore can be washed out during wet weather conditions. They are also corrosive.

2.6.3 Lignin Derivatives

These suppressants include a variety of industrial waste products, animal fats, and vegetable oils. Of these binders, the most widely available and used is ligninsulfonate. This is a waste product from the paper-making industry. Lignin is said to be the natural cement that binds the fiber of wood together in plants. During the paper-making process (pulping) the lignin polymers and wood sugars are released into the processing wastewater. The wastewater is generally called ligninsulfonate because of the sulfite process used for extracting the pulp. When used as dust suppressant, the lignin polymers act as glue binding the soil particles together. The ligninsulfonate is water soluble and therefore easily washed away during wet weather conditions.

2.6.4 Resinous Adhesive

Waste oils, tars, bitumen, and by-products from the plastic industry are in this class of dust suppressants. Of all these products, cutback asphalt and asphalt emulsions are most widely used as dust suppressants (Hoover, et al., 1973). Asphalt is a highly complex material, composed primarily of various hydrocarbon compounds (The Asphalt Handbook, 1995).

Cutback asphalts are formed by adding solvent to asphaltic cement. The type of solvent used determines the type of cutback produced. Highly volatile solvents such as gasoline or napthal produces rapid-curing cutback. Kerosene produces medium-curing cutbacks and light volatile solvents produces slow-curing cutbacks.

Asphalt emulsions are produced by dispersing asphalts as small droplets in water. The dispersion of the asphalt is maintained by adding an emulsifying agent during the formulation of the emulsion. Three classes of emulsions are available for road construction: rapid setting (RS), medium setting (MS), and slow setting (SS). The formulation and properties of emulsions are different from that of cutbacks; for detailed discussions see Bennett, (1968). Specifications on the use of these bituminous materials are set by the Asphalt Institute, American Society of Testing Materials (ASTM), the American Association of State Highway and Transportation Officials (AASHTO) standard testing methods. When used as dust suppressants resinous adhesives provide the most durable dust-free surfacing due to their adhesive properties and insolubility in water.

Common to the success of any dust suppressant is the structure and composition of the road surface material. As Squier (1974) stated “the road should have good mechanical stability in itself, because chlorides are not strong binders.” Of lignin derivatives, clay is a very important component of a good road soil. For bitumens and tars, the structure and composition of the aggregate is one of the most important factors that affects adhesion in an aggregate-asphalt system (Mertens, 1959; Day, 1965). For dust-suppressant-treated unpaved roads to perform well under the most adverse conditions, the road surface material must be mechanically stable.

The use of dust suppressants can be an important unpaved road maintenance technique. Their use can be justified when:

1) traffic volume is low

2) paving is not feasible because of budget constraints

3) the cost of suppressant and application is low, and

4) when stage construction is planned.

In selecting a dust suppressant, the performance characteristics to be evaluated include the type and volume of traffic, roadway condition, climate, and product cost to achieve the desired level of dust control. The attributes, limitations, typical application rates, and sources of the primary dust suppressant discussed are noted in Appendix A.

2.7 Effectiveness of Dust Suppressants

Treating an unpaved road with dust suppressants can, in a large measure, improve conditions of the road. To unpaved road users the dramatic difference can be observed in the difference between dust plumes coming off an untreated versus a treated road. Figure 2.4 and 2.5 depict the typical visual dust levels from an untreated and a treated unpaved road.

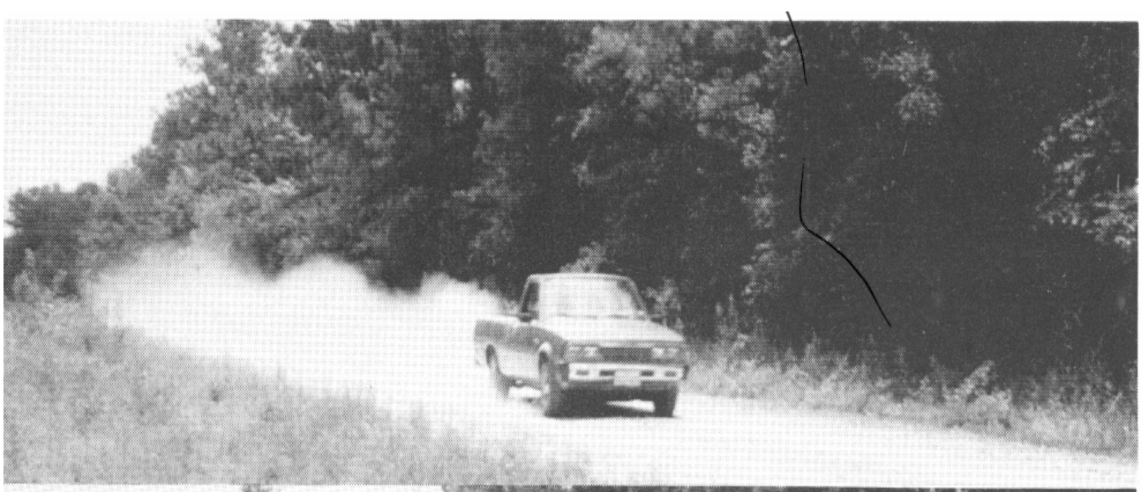

Figure 2.4 Untreated Unpaved Road Dustiness

Figure 2.5 Treated Unpaved Road Dustiness

Although dust suppressants have been used for several decades, research to quantify their relative effectiveness in controlling dust generation and preventing loss of fines and subsequent aggregate pullout are limited. Hoover, et al. (1973), in a highway research project, tested several dust suppressants and road surface improvement agents. Of the 22 tested in laboratory experiments, six were selected and applied on test sections for a controlled experiment. The suppressants tested included a cutback asphalt, a cationic asphalt emulsion, lignosulfonate, lignin/alum mixture, a lignin/lime mixture, and a by-product from Chemplex Plastic Company. Both laboratory and field experiments showed approximately 30 to 80 percent reduction in dust from the treated test sections as compared to the untreated. Aggregate pullout from the treated test section surfaces were found to be approximately 25-27 percent less than that of the untreated test sections.

Sanders, et al. (1997), in a field-based research study, quantified the relative effectiveness of three primary dust suppressants, $MgCl_2$, $CaCl_2$, and ligninsulfonate. The quantification was done by measuring the dust amount emitted from each of the four test sections using the Colorado State University Dustometer – a moving dust sampler developed during the research. Total aggregate lost over each test section was estimated. The research indicated that all three dust suppressants studied reduced fugitive dust emissions from the unpaved roadways by 50-70 percent. The treated test sections retained approximately 40-60 percent more aggregate than the untreated control test section. The cost savings of retaining aggregate on the treated test sections more than offset the cost of the dust suppressants, resulting in an estimated cost savings of 28-42 percent over the untreated test section.

The two above-cited projects demonstrated that the use of dust suppressants and road surface improvement agents can control dust generation from unpaved roads while reducing the annual aggregate replacement by a factor of two to four, the latter alone saving thousands of dollars in road maintenance cost.

For many recent years low-volume secondary and tertiary roads have being receiving some attention as exhibited by research studies such as Hoover, et al., (1973, 1981); Lane, et al., (1984); Irwin, et al., (1986); Boresi, and Palmer, (1993); Sanders, et al., (1997) to name a few. Most of the studies have been aimed at understanding and improving unpaved road surface conditions through the use of dust suppressants and other surface improvement agents and various maintenance methodologies. Much more value-add research needs to be done such as:

1) understanding the effect of road surface material characteristics and quality on the effectiveness of different types of dust suppressants, 2) determining optimum suppressant dosages and application rate, and 3) evaluating suppressant application method effect on effectiveness of the different types of suppressants. One of the objectives of this research project is to ascertain if unpaved road surface material characteristics have any effect on the performance of different types of dust suppressants. The following describes the work done.

2.8 Effects of Aggregate Distribution on Effectiveness of Dust Suppressants

Other research studies clearly indicate that the characteristics or structure of the road surface material has a significant influence on how well the road will hold up under traffic and environmental conditions (Paterson, 1987). In view of the fact that road aggregate material varies with different characteristics from one borrow pit to another and from region to region, it is paramount that the influence, if any, of road aggregate characteristics on the effectiveness of suppressants be thoroughly investigated. Furthermore, research of this type can help generate a catalogue of suppressants for use on various base and surface material characteristics that unpaved road managers can use in decision making regarding the use of dust suppressants. This section of the report describes work done to investigate the two different sources of aggregate in Larimer County, Colo., and their effect, if any, on the effectiveness of different types of dust suppressants.

2.8.1 Test Sections

The method of construction of the test sections, materials used, and the location of the test sections are described in this section. Larimer County Roads and Bridges Department, partners and local sponsors of this research project, constructed the test sections using their personnel and equipment.

The county operates two road aggregate mining sites: the Horten Pit and the Strang Pit. These two sites supply the county with all of its road base material needs. In all, eight test sections, each 1/2-mile long, were evaluated. Surface material for four of the test sections was supplied from the Horten Pit and the other four test sections received surface material from the Strang Pit.

2.8.1.1 Locations

The test sections evaluated were all located in Larimer County, Colo. They were part of two stretches of unpaved roads located in the Weaverly area of the county. One stretch is County Road (CR) 11 which hosted six of the eight test sections and the other stretch is CR 68 which hosted the other two test sections. CR 11 and CR 68 serve a rural community of crop and livestock farmers. They also provide access to four nearby lakes used for recreation by boaters and fishermen. Two of the lakes are private clubs where boating and camping occur. The other two are open to the general public and used mostly for fishing.

The climate in this region is semiarid with average annual precipitation in the test site area of about 14 inches per year. The general soil/aggregate characteristics in this location are glacial till with some silty clay, sand, and gravel. The average daily high temperature during the test period: June – October is approximately 85F with an average relative humidity of about 25 percent.

Figure 2.6 shows portion of the map of Larimer County with the location of the test site highlighted.

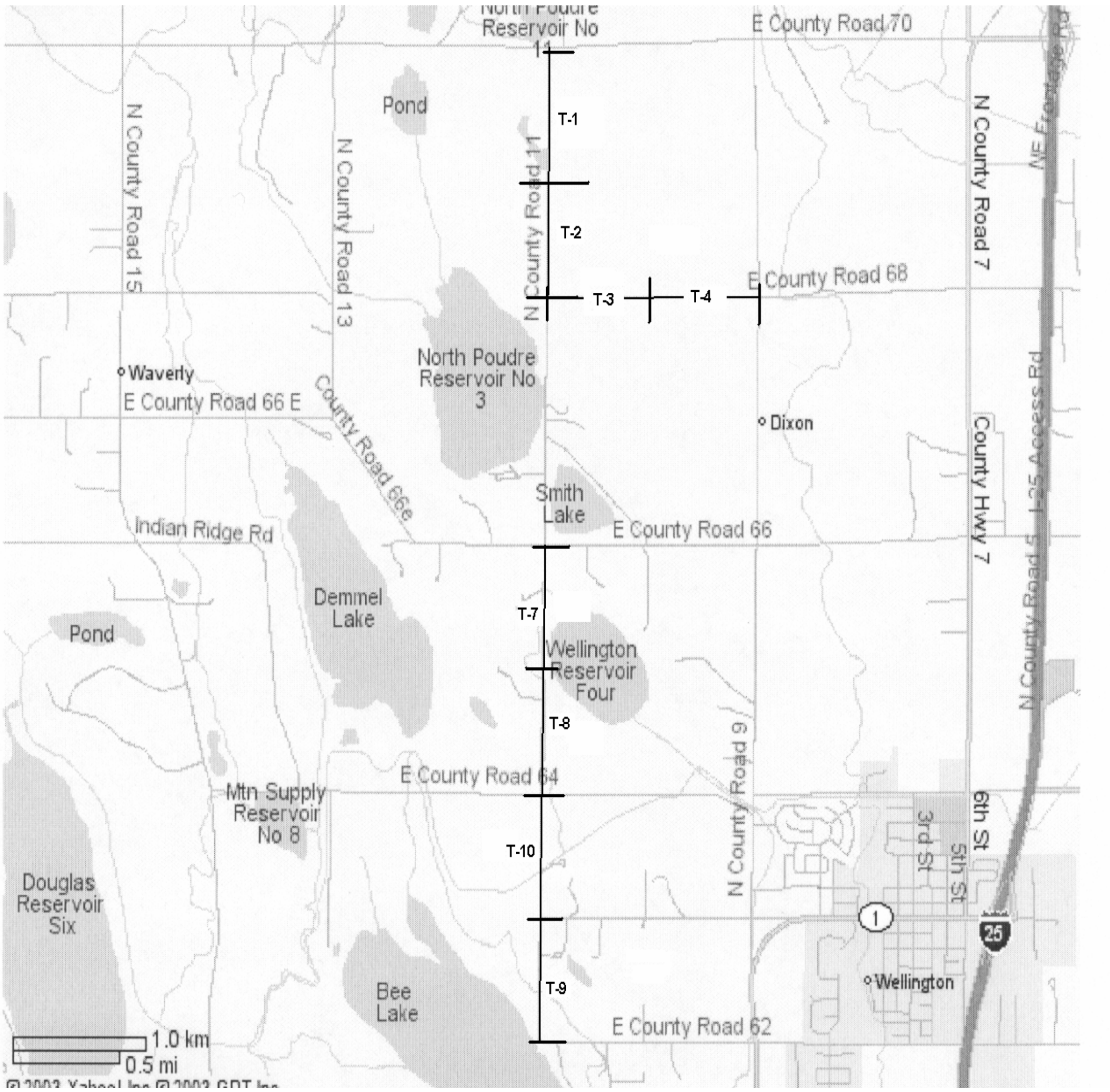

Figure 2.6 Larimer, County, Colorads – Road Map and Location of Test Sections

2.8.2 Materials

Larimer County operates two medium-size gravel mining sites from which all the road aggregate needs of the county are acquired. The two gravel borrow pits are called the Strang Pit and the Horton Pit. The Strang Pit is located in the Poudre River basin and thus produces material that appears cleaner with less fines. The Horton Pit is a non-river-basin-type quarry. Reddish weathered rock formations abound in the area, and the resulting aggregate appears less clean, with more clayey-type fines. There is a distinct color difference between the aggregate sources in that the Horton Pit gravel is reddish in color while the Strang Pit gravel is grayish in color.

The characteristics of each aggregate source were evaluated by performing a sieve analysis on material samples obtained from the two borrow pits. Other engineering property tests such as Atterberg limit, Los Angles abrasion, soundness, and specific gravity were not performed. Although these tests aid in providing a comprehensive description of the road surface material, the aggregate size distribution via sieve analysis testing turns out to provide a very representative characteristic value widely accepted for describing road aggregate material. Sieve analysis is quick, easy, and less expensive to perform and the results can readily be interpreted to arrive at a classification for the aggregate material using the AASHO Classification System or the Uniform Soil Classification System (USCS). The engineering properties of the Strang Pit gravel were reported in earlier research done at Colorado State University to study the effectiveness of road dust suppressants (Addo and Sanders, 1995).

The aggregate size distribution of the Horton Pit gravel and Strang Pit gravel are shown in Table 2.1/Figure 2.7 and Table 2.2/Figure 2.8, respectively. Figure 2.9 compares the two distribution size curves on the same axis. The quantity of material passing the No. 40 (0.425 mm) sieve is generally referred to as the fines fraction and is directly related to the amount of dust emission from unpaved road surface (Wood, 1960).

The results of the sieve analysis indicate that 10.6 percent of the Strang Pit material passed the No. 40 sieve. This is nearly the same as the 9.6 percent passing the No. 40 sieve reported in the suppressant effectiveness study (Addo and Sanders, 1995). The fines were determined to be non-plastic with no cohesion. An AASHO soil classification of A-1-a was assigned and poorly graded (GP) gravel was assigned under the USCS. The Horton Pit material had a 17.2 percent passing the No. 40 sieve, correlating very well with visual inspection of the material sample.

Various recommended aggregate mixes to achieve the best surface-wearing course performance has been published Horwell (1993); Woods, (1960). Table 2.3 compares the Horton and Strang materials with suggested aggregate mix as provided by Horwell (1993). Analysis of Table 2.3 data indicate that both Horton and Strang materials do not have enough fines to meet the 25 percent minimum suggested for passing No. 40 sieve. The lack of sufficient fines is more profound with the Strang Pit material than with the Horton Pit gravel.

Without sufficient fines the large-size aggregates cannot be bound into a tight matrix, and therefore aggregate pullout is easier. This results in rapid road surface degradation in the form of raveling and washboarding as vehicular activity increases. The lack of fines which serve as a binder for the coarser aggregate also means more a of driving hazard to vehicles passing each other as loose aggregate picked up by the tires of the vehicle are thrown around, breaking windshields and inflicting possible injuries. Insufficient fines also imply reduction in the total surface area available for ions in the dust suppressant, especially chloride compounds, to attach themselves to. As stated in Compendium 12 (1980), the greater the surface area the more moisture can be attracted to keep the road surface wet.

The chemical dust suppressants evaluated in this research include: magnesium chloride ($MgCl_2$), lignin, and a 50/50 blend of $MgCl_2$ and lignin.

Magnesium chloride (32 percent $MgCl_2$ in solution) is a concentrated brine that draws moisture out of the air to the keep the road surface damp to control dust. It is known to sink into the road surface and create a tight, hard, compact, surface that resists abrasion.

Lignin is a by-product of the paper pulp industry, usually containing 50 percent solids in concentrated water solutions. Dust palliation is achieved by gluing and bonding the soil particles together.

$MgCl_2$ and lignin is a blend of 50 percent of $MgCl_2$ and lignin by volume mixed together. The resulting suppressant exhibits the dust suppressing properties of both chemicals.

Table 2.1 Results of Sieve Analysis - Horton Pit Gravel

Sieve No.	Particle Size (mm)	Weight Retained between Sieves grams	%	Percent Passing
5/8"	16.00			89.7
3/8"	9.50			78.1
1/4"	6.70			67.6
#4	4.75			58.8
#10	2.00			39.1
#20	0.85			25.1
#40	0.43			17.2
		881.6	17.2	
	Total Wt	5133.2		

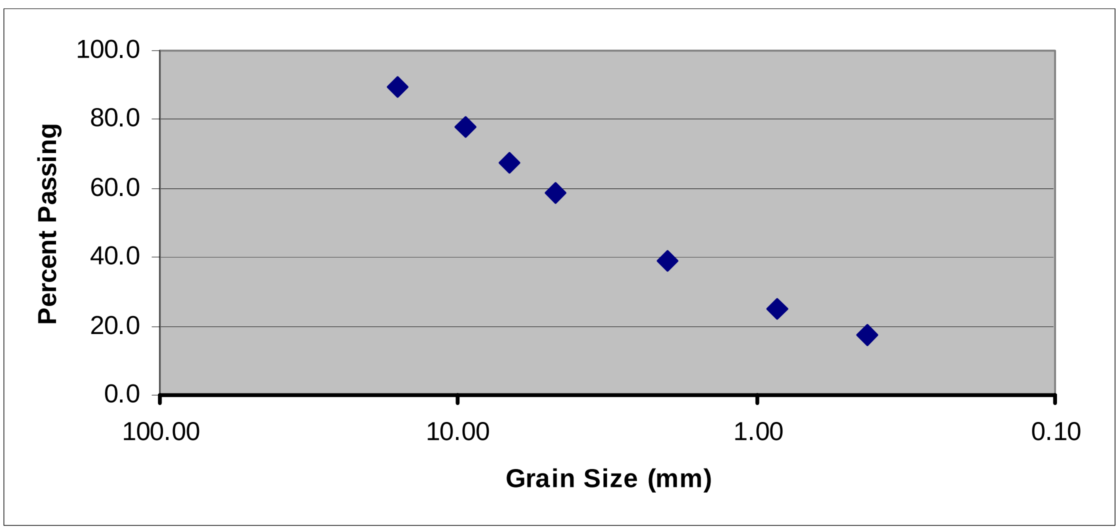

Figure 2.7 Aggregate Size Distribution – Horton Pit Gravel

Table 2.2 Results of Sieve Analysis - Strang Pit Gravel

Sieve No.	Particle Size (mm)	Weight Retained between Sieves grams	%	Percent Passing
5/8"	16.00			81.8
3/8"	9.50			66.9
1/4"	6.70			59.2
#4	4.75			53.8
#10	2.00			38.7
#20	0.85			21.2
#40	0.43			10.6
		321.8	10.6	
	Total Wt =	3032.5		

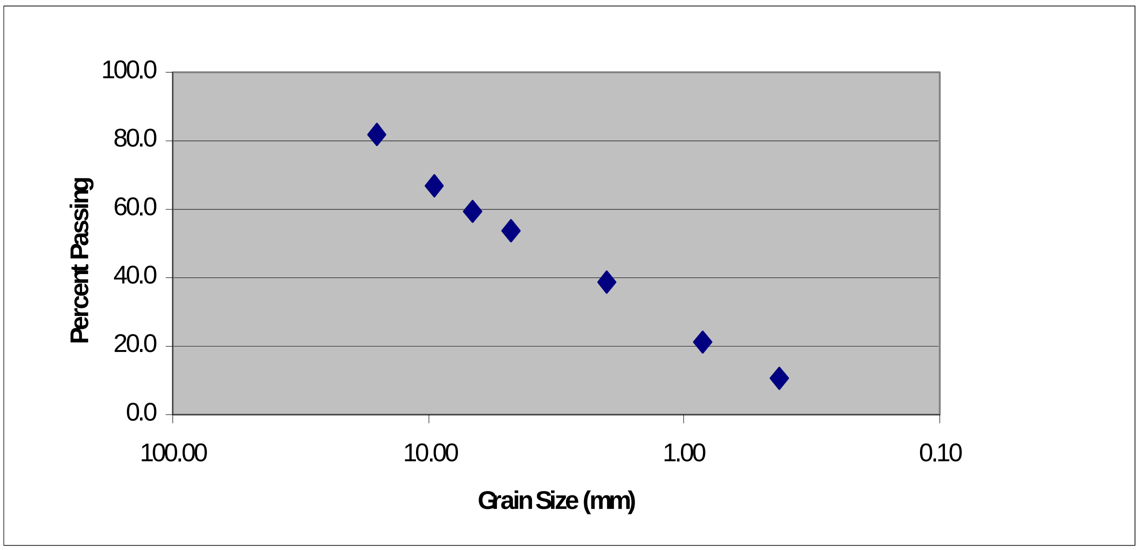

Figure 2.8 Aggregate Size Distribution – Strang Pit Gravel

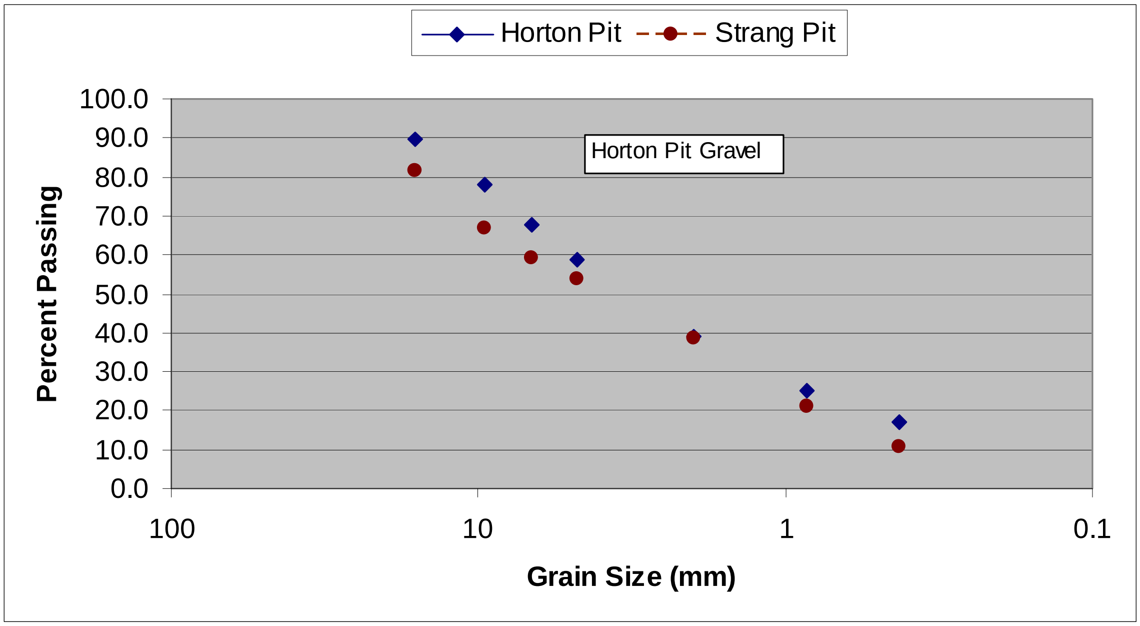

Figure 2.9 Aggregate Size Distribution – Horton vs. Strang

Table 2.3 Suggested Aggregate Mix Comparison

Designation	Percent Passing Sieve		
	Suggested Surface Course (Horwell, 1993)	Horton Gravel	Strang Gravel
5/8"	75 – 100	90	82
3/8"	65 – 100	78	67
#4	55 - 85	59	54
#10	40 - 70	39	39
#40	25 - 45	17	11

2.8.3 Construction

The construction of the test sections followed the procedure recommended in most road construction literature and that of the dust suppressant suppliers. Important construction steps include:

- road surface scarification to remove all corrugations and potholes,
- addition of new aggregate material if required,
- adequate grading and smoothing of the road surface,
- application of dust suppressant in quantities sufficient for effective dust control,
- proper road finishing procedures that include the formation of surface crown, and
- optimum compaction of the road surface and proper drainage (Rural Transportation Fact Sheet, 1984).

In all, eight test sections were constructed for evaluation in this project. Refer to Table 2.4 for the test section matrix. Virgin or fresh aggregate material was used for the construction of the test sections. As previously mentioned, four of the test sections were constructed using the Horton Pit material and the other four test sections were constructed using the Strang Pit material.

Table 2.4 Test Section Matrix

Strang Pit Gravel		*Horton Pit Gravel*	
Test Sec. No.	**Test Section Type**	**Test Sec. No.**	**Test Section Type**
T-1	Untreated	T-7	Untreated
T-2	$MgCl_2$ treated	T-8	$MgCl_2$ treated
T-3	Lignin treated	T-10	Lignin treated
T-4	$MgCl_2$ / Lignin blend treated	T-9	$MgCl_2$ / Lignin blend treated

Preconstruction of the test sections consisted primarily of blade dressing the road shoulders and ditchlines as well as reclaiming aggregate pullout using a motor grader. The construction of all the test sections followed the same construction procedure. Each test section surface was watered down and scarified to a depth below the deepest pothole or approximately 6 inches. Trucks brought in new aggregate which was spread on the surface to augment the existing scarified material. The new material averaged approximately 4 inches in thickness. The following provides additional details on the construction of the test sections.

Untreated Test Sections

For the control untreated test sections, water was added while the grader windrowed the loose material from one side of the road to the other to achieve a good mixture. The road surface was shaped to a crown, leveled, and compacted in the presence of more water to form a firm wearing course.

Treated Test Sections

Material for each test section was treated with sufficient water to achieve an optimum water content while the grader worked the material. Each selected dust suppressant was sprayed on the loose material by the supply truck at the supplier-recommended application rate. The grader windrowed the mixture until the suppressant was well mixed in with the aggregate material. This suppressant application technique is referred to as the mixed-in-place method. The road surface was leveled, shaped to crown, rolled and compacted to a firm wearing course using a rubber tire type pneumatic compactor. The dust suppressant application rates are:

- $MgCl_2$ (32% solution): ½ gal/yd^2
- Lignin (50% solids): ½ gal/yd^2
- $MgCl_2$ and lignin blend (50/50 by volume): ½ gal/yd^2

The test sections were opened to traffic immediately after construction.

2.8.4 Measurements

This research was intended to be a continuation of the "Relative Effectiveness of Road Dust Suppressants" studies started at Colorado State University (Addo and Sanders, 1995 and Sanders et. al., 1997). The emphasis of this study is to assess the effect that road surface material characteristics as described by aggregate size characteristics might have on the effectiveness of some commonly used dust suppressants (soil chemical admixtures).

Various laboratory studies have been reported (Palmer et al., 1995; DeCastro et. al., 1996 and etc.). All of them investigated strength and density modification of unpaved road soils due to chemical additives. The results of these laboratory studies have provided valuable quantitative physical and chemical measurements worth investigating further through more research.

This research study also will attempt to validate some of the laboratory findings under field conditions where the true effectiveness of unpaved road soil admixtures in improving overall road surface performance can be measured. Field measurements in unpaved road studies can be difficult because all the elemental factors (rain, snow, wind, traffic, construction procedure, and etc.) are in play. The lack of a standardize protocol, procedures, and equipment for performing field assessment adds to the challenge.

2.8.4.1 Traffic

The composition of traffic using an unpaved road is a major contributing factor to the degradation of the unpaved road. Therefore understanding vehicle type, size and weight, traveling speed, and volume are essential in any unpaved road maintenance studies. CR-11 and CR-68, which include the test sections, serve a rural community of crop and livestock owners. The roads also provide access to four recreational lakes in the area. A field traffic observation survey carried out during the research study indicated that nearly two-thirds of the vehicles using the roads are pickup trucks. They range in sizes from 1/4-ton to the full 1-ton size. About 30 percent of the trucks pulled a boat or horse trailer. The other third of the traffic volume composed of cars and farming equipment such as tractors. The average daily traffic (ADT) volume for the test sections is 25. The value was obtained from the latest Larimer County traffic count records. Traffic counters were installed at strategic locations along the test sections during the research period May – September 2001 to validate the ADT of 25.

2.8.4.2 Dust

To quantitatively measure the effect of aggregate distribution on the effectiveness of dust suppressants, dust emission from each of the test sections was monitored under field conditions. The Colorado State University Dustometer, a dust-sampling device developed and used in earlier dust studies at Colorado State University (Addo and Sanders, 1995), was used to monitor vehicular-generated dust from each of the test sections for comparative analysis. The variables in this research study are: type of dust suppressants, construction procedure, field/environment conditions, and traffic volume/activity. Different road aggregate material is used for the construction of the two sets of test sections.

Dustometer: The Dustometer can be described as a moving dust sampler that provides a real-time quantitative dust emission measurement for a section of a road. Its dust measurements are precise, reproducible, and easily obtained (Sanders and Addo, 2000). It provides a uniform procedure for gathering and comparing data from many test sections. Many data points can be generated within the shortest possible time. The device consists primarily of the following: a fabricated metal box designed to hold a 10 x 8 in (25.4 x 20.3 cm) glass fiber paper, mounted to the bumper of a pickup truck behind the driver's side rear tire; an electric power generator; high-volume vacuum pump; and a flexible plastic tube connecting the suction pump to the filter box. The fabricated filter box has a 12 x 12 in (30.5x30.5 cm) opening that is covered with a 450 μm mesh sieve that faces the tire. The 450 μm screen prevents any non-dust particles from being drawn onto the filter paper during dust measurement. The filter paper is supported near the bottom of the fabricated box by a sieve mesh. Figure 2.10 illustrates the Dustometer.

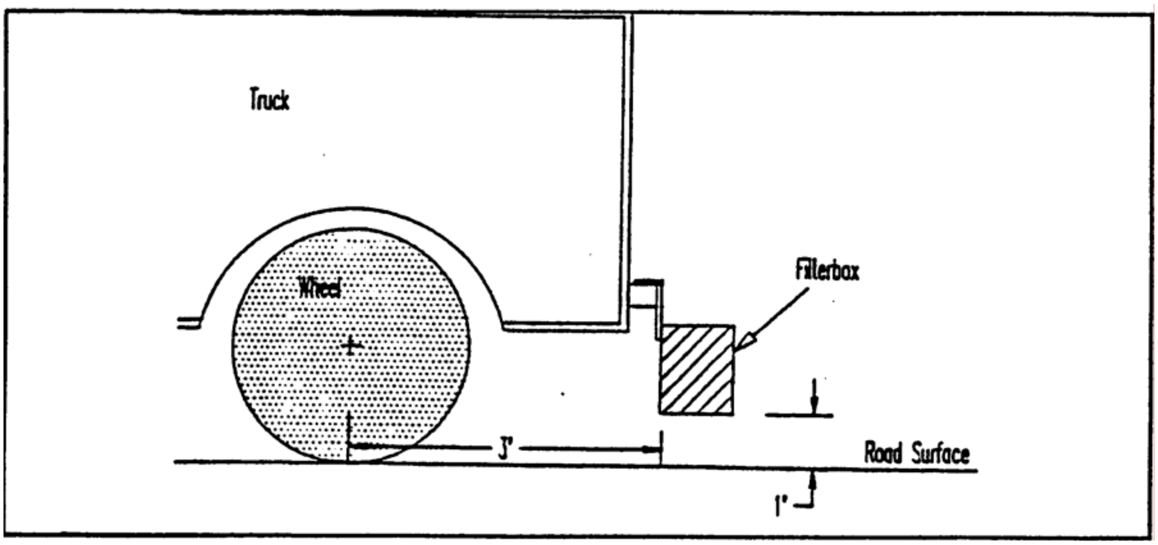

Figure 2.10 Schematic Diagram of Colorado State University Dustometer Setup

To perform a typical dust measurement in this research, a 1/2-ton pickup truck fitted with the Dustometer was used. A test speed of 35 mph – the designated driving speed for the roads was used. As the truck is driven at the constant speed of 35 mph a portion of the dust generated is collected on a pre-weighed filter paper in the filter box mounted on the bumper of the truck. At the end of a test run, the filter paper laden with dust is gently removed and put into in a very thin plastic bag and stored to be weighed later in the laboratory. The filter box is refitted with a new pre-weighed filter paper and another test is run. The difference between the pre-test weight and the post-test weight is the weight of dust sampled.

Each test section is 1/2-mile long. A test run consisted of driving the test truck in the driving lane in both directions for a total of one mile of dust measurement. Three test runs were performed per test section on a given test day. The average of the three runs is a data point for a test section.

2.8.5 Results

The dust measurements from the two sets of test sections were taken from the periods June 2000 through September 2000 and then from May 2001 through July 2001. After the snow season and before the second period dust measurement, all the test sections received a periodic maintenance of blading, grading, and compaction without adding new road material or treatment. Essentially the second period dust measurement was a continuation of the first period dust measurement.

Table 2.5 shows the dust measurement in grams for each of the test sections evaluated. Test sections TS-1 through TS-4 are of the Strang gravel and TS-7 through TS-10 are constructed using the Horton pit gravel. In all, 13 data points were acquired during the field measurement periods. Figure 2.11 and 2.12 represents the results of the dust measurements of the Strang gravel test sections and Horton gravel test sections respectively. No clear dust measurement pattern was established. The untreated control tests for both the Strang and Horton gravels on average produced more dust than the treated test sections as expected. But it is interesting to note (Figure 2.11) that near the end of the dust measurements the $MgCl_2$-treated Strang gravel test section produced equal or more dust than the untreated test section. This could be due to the fact that the $MgCl_2$ at that stage of the treatment life (more than a year old) has lost all of its dust-control properties through leaching and downward migration of the ions. This observation supports the recommendation by DeCastro et. al., (1996) that chloride compound soil admixtures should be applied twice a year for effective dust control.

Comparing the Strang gravel to the Horton gravel, Figure 2.13 through Figure 2.16 shows the comparative dust measurements of the different test sections. With the exception of the $MgCl_2$ test sections (Figure 2.11) all other test sections – untreated, $MgCl_2$/lignin blend, and the lignin test sections, indicate consistently that more dust was produced by the Horton gravel test sections as compared to the Strang gravel test section.

Table 2.5. Dust Measurements

Dust weight = average of three measurements

Length of run for each test section = 1.0 mile

Length of each test section = ½ mile

Passes are run on both driving lanes

Sampling speed = 35 mph

Sampling Date	Strang Test Sections				Horton Test Sections			
	Untreated (T-1)	$MgCl_2$ Treated (T-2)	Lignin Treated (T-3)	$MgCl_2$/Lignin (T-4)	Untreated (T-7)	$MgCl_2$ Treated (T-8)	Lignin Treated (T-9)	$MgCl_2$/Lignin (T-10)
6/8/2000	3.12	1.16	0.90	0.70	5.96	1.20	0.61	1.07
7/3/2000	2.58	2.13	1.75	0.64	4.19	4.04	5.24	4.17
7/13/2000	4.46	1.49	1.01	1.13	4.69	1.47	2.13	3.41
7/27/2000	5.29	1.00	0.53	0.49	6.04	1.76	1.25	1.30
8/8/2000	4.38	1.23	0.53	0.64	5.77	1.03	1.89	2.30
8/21/2000	2.47	2.58	1.85	1.23	3.50	1.36	1.33	1.29
9/16/2000	4.40	1.42	1.45	1.82	4.78	2.32	3.41	4.31
10/8/2000	3.11	2.43	1.24	0.64	3.77	1.75	1.98	2.13
5/17/2001	2.60	1.64	0.98	0.75	4.45	1.22	1.98	1.49
5/31/2001	2.63	3.16	1.17	1.50	2.93	1.01	1.82	2.33
6/21/2001	2.83	2.72	1.11	1.69	5.33	1.90	3.05	3.87
6/28/2001	1.26	2.02	1.55	0.61	3.25	2.51	2.83	2.47
7/18/2001	2.70	2.62	1.17	1.17	6.07	3.04	4.14	4.17

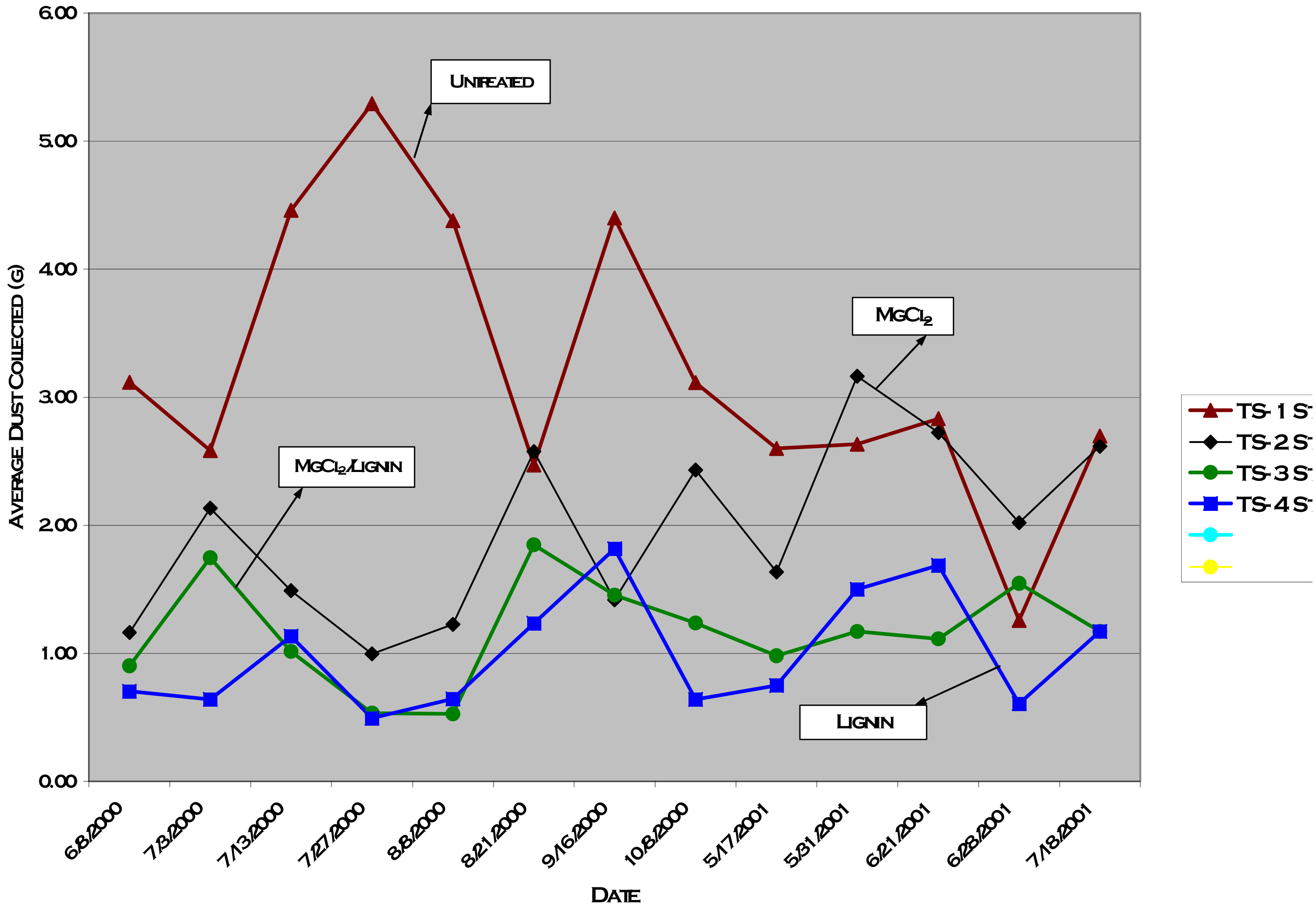

FIGURE 2-11. STRANG GRAVEL TEST SECTIONS - DUST DATA

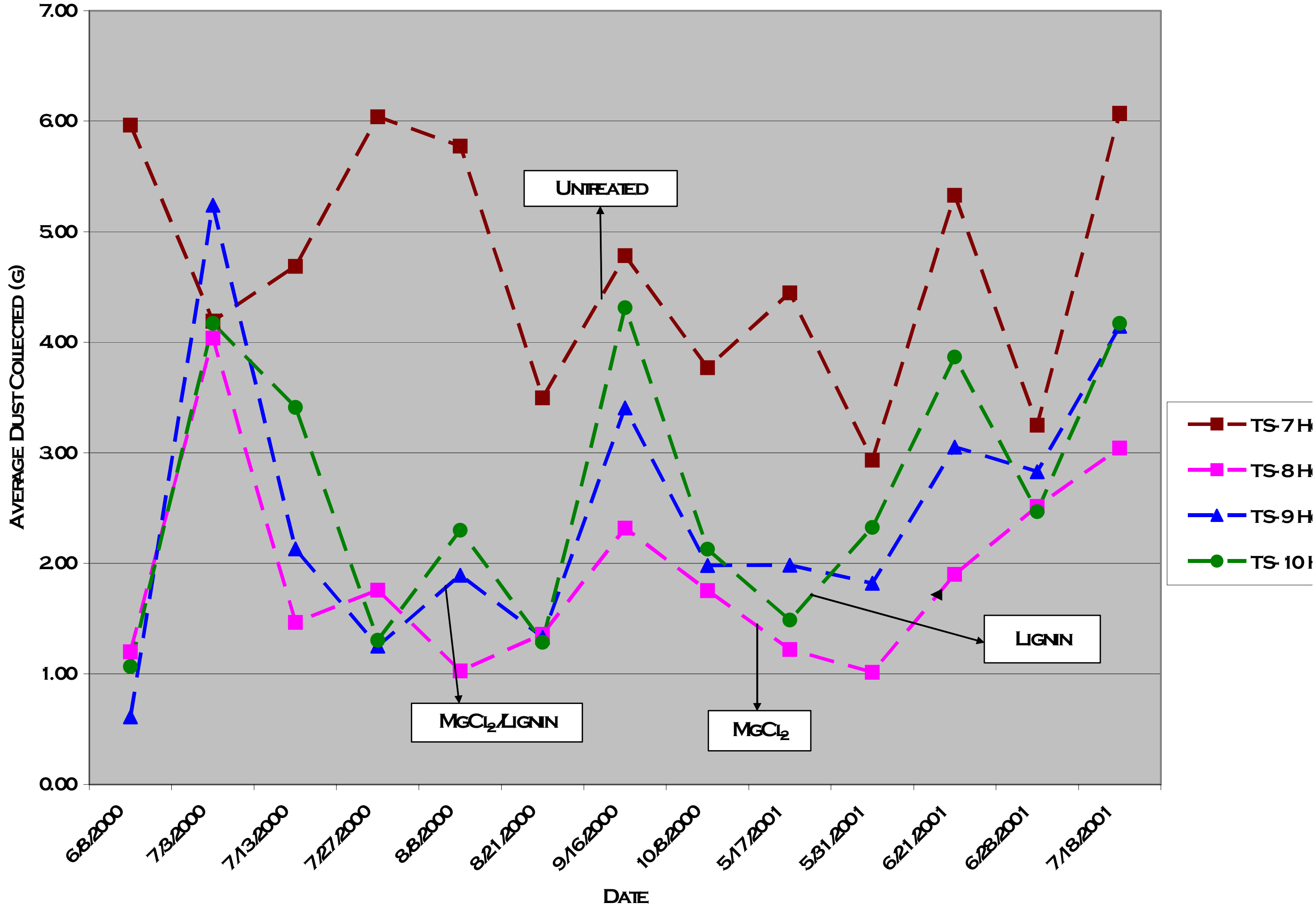

Figure 2-12 Horton Gravel Test Sections - Dust Data

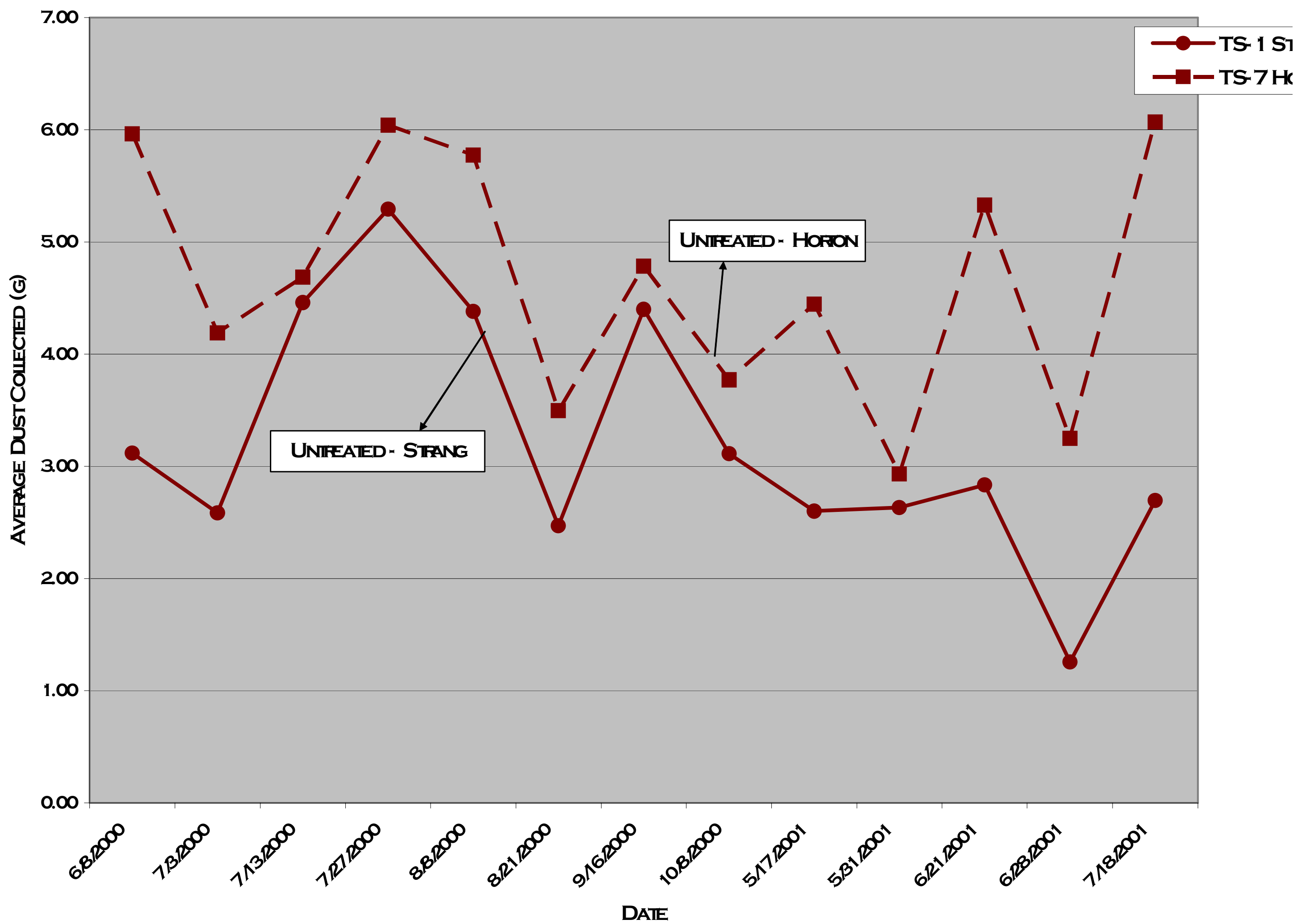

Figure 2-13 Untreated Test Sections - Dust Data Comparison

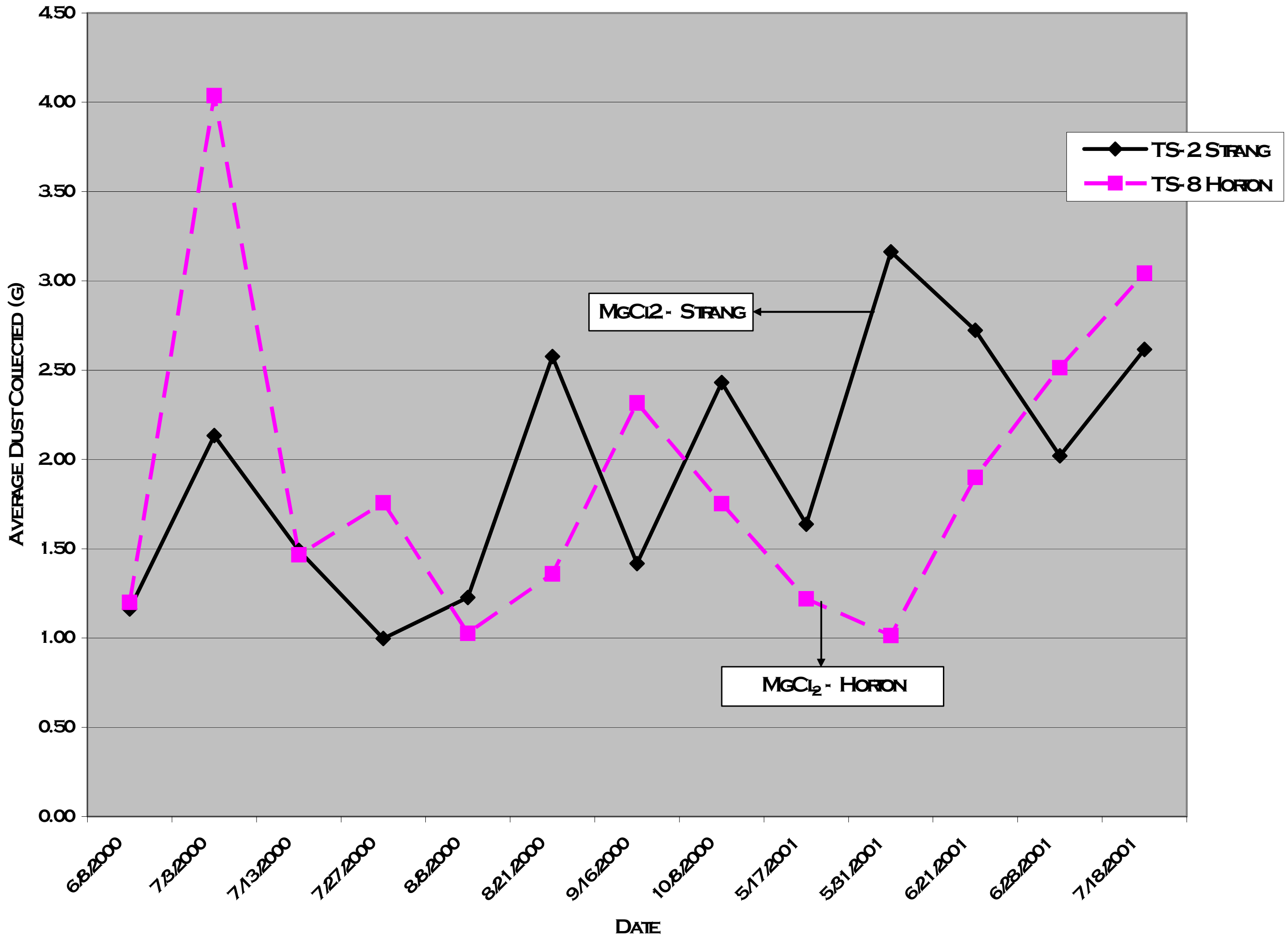

Figure 2-14 $MgCl_2$ Test Sections - Dust Data Comparison

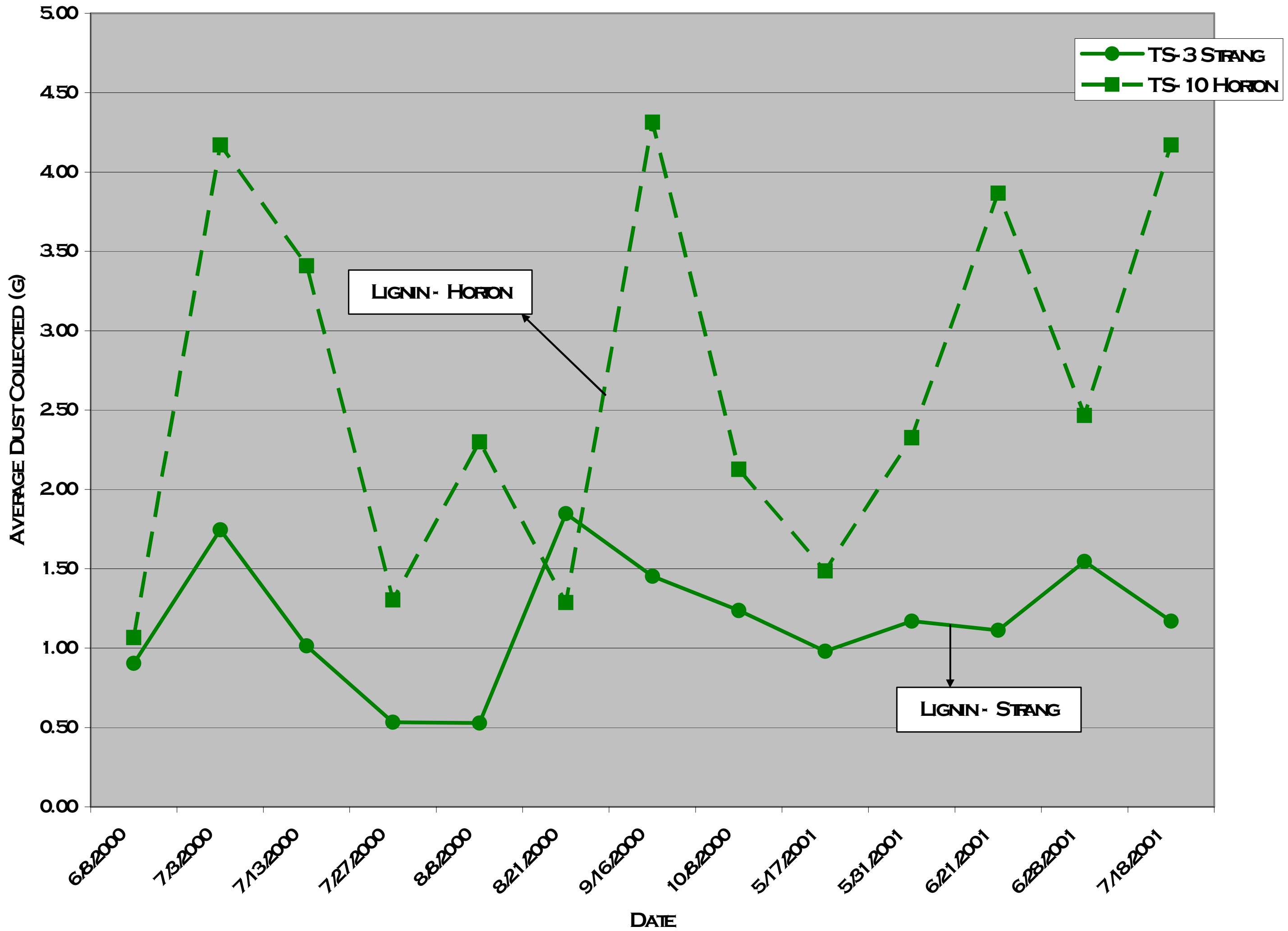

Figure 2-15 Lignin Test Sections - Dust Data Comparison

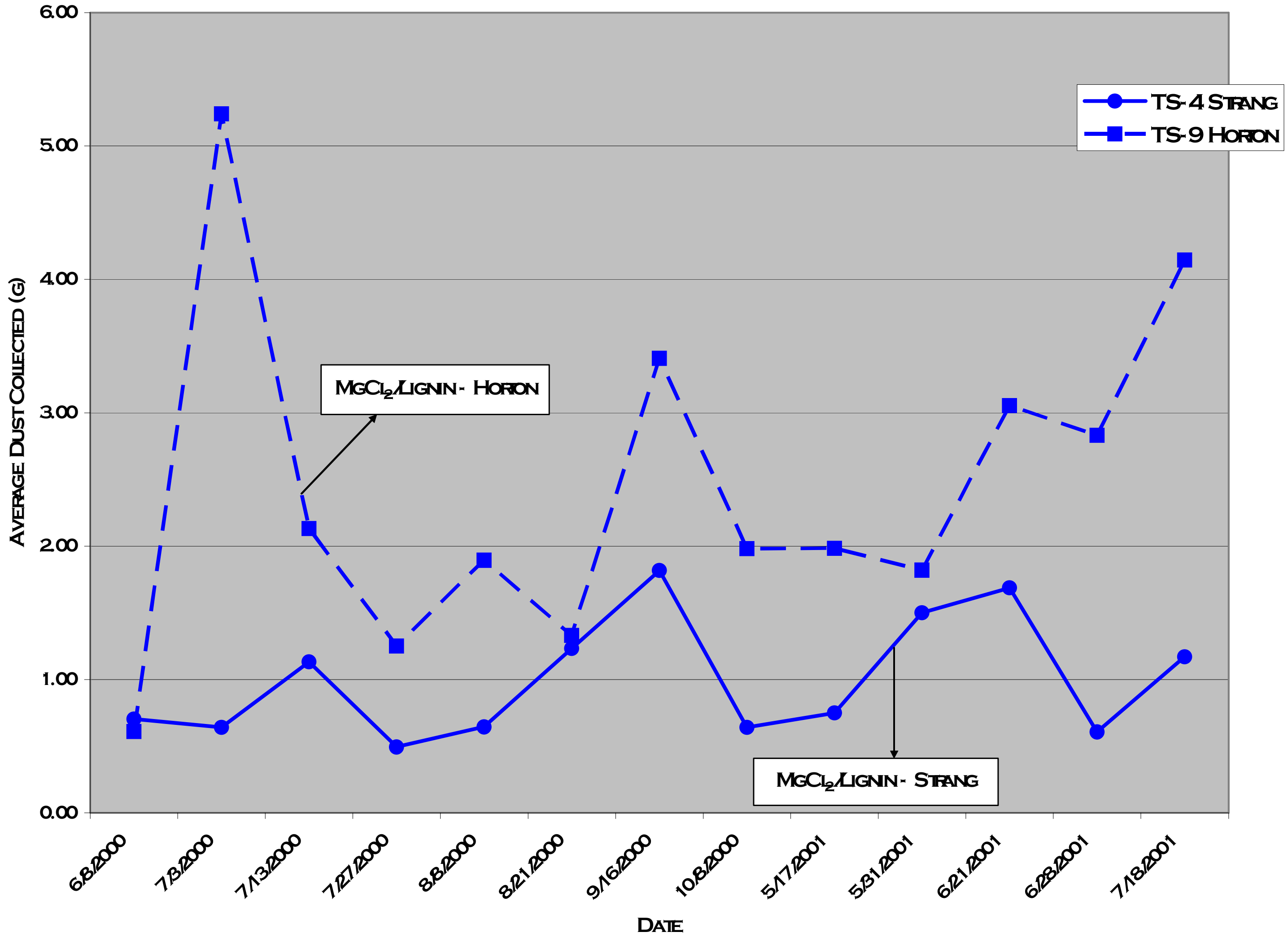

Figure 2-16. $MgCl_2$/Lignin Blend Test Sections - Dust Data Comparison

3. ROAD DUST SUPPRESSION: EFFECT ON UPAVED ROAD STABILIZATION

3.1 Introduction

A good road (paved or unpaved) requires a suitable foundation which in turn requires stability. A material is stable if it has little or no volume change and resists deformation under repeated or sustained loading conditions whether wet or dry (Transportation Research Board, 1982). The degree of stability is primarily a function of the road material resistance to lateral movement or flow (USDOT, 1979). Different types of road material employ different mechanism for resisting lateral movement. In general, granular soils count on their particle sizes, angularity, and interlocking ability to develop the internal friction required to resist lateral flow. However, in fine-grained soils such as clayey soils, the stability is very much moisture dependent.

There are many varieties of soil available for road construction. Unfortunately, many of the soil deposits do not naturally possess the requisite engineering properties to serve as a good foundation material for roads and highways. As a result, soil-stabilizing additives or admixtures are used to improve the properties of less-desirable road soils (ARBA, 1976). When used these stabilizing agents can improve and maintain soil moisture content, increase soil particle cohesion, and serve as cementing and waterproofing agents (ARBA, 1976; Gow et al., 1961). Unpaved road dust suppressants are considered soil additives because they produce changes in soil characteristics that influence soil stabilization (Gow et al., 1961; Ross, 1988).

For unpaved roads, dust control and road surface stabilization often go hand-in-hand. By controlling the generation of dust by preventing loss of fines, the road surface is stabilized for driving comfort and safety. By stabilizing the road surface, the essential fines which otherwise would be lost in the form of dust are firmly bonded to the coarse road surface material thus preventing road surface deterioration and reducing maintenance cost.

This section of the report examines the effect of the use of road dust suppressants on the stabilization of unpaved road material. The commonly used dust suppressing chemicals: ligninsulfonate (Lignin) and chloride compounds ($MgCl_2$ and $CaCl_2$) are evaluated. No specific field-based experiments were performed during this research to quantitatively measure the test sections strength increases as a result of the suppressants application. However, other quantitative laboratory studies on the subject of soil stabilization using lignin and chloride compounds are discussed. The field base methods of applying dust suppressants are also presented.

3.2 Methods of Application

There are two primary methods of incorporating suppressants into road surface soils. The methods are referred to as: 1) surface or topically sprayed and 2) mixed-in-place or in-depth application. Surface or topically sprayed application involves spraying the suppressants on the unpaved road surface after the road surface has been prepared (bladed, shaped with an “A” crown, and compacted). This method of application is simple, fast and cheap (Woods, 1960). Suppressants applied by this method are effective for a short period of time and repeated applications are necessary in a single dust generating season (Hoover, et al., 1973).

Mixed-in-place application involves the addition of the suppressant to the road surface soil in-situ (Woods, 1960). This in-depth treatment is achieved by mechanically mixing the suppressants with the soil using special mixing equipment. The mixing of the suppressants with the aggregate material can occur at the borrow pit and the resulting mixture hauled for placement on the pre-constructed road surface. This process is similar to asphalt placement on paved roads. Another way to achieve the in-depth treatment is to spray the suppressant over the scarified and/or new road material and mix by windrowing from side of the road to the other using the grader. Windrowing the mixture back and forth ensures a thorough mixing of the additive with the soil. As stated by Hoover, et al., (1973), "this method does not only achieve dust palliation but provides improved road surface resulting in reduced maintenance cost from continued suppressant applications and/or aggregate replacement. Furthermore, in-depth stabilization may improve the sub-base or base for further higher-type pavement."

3.3 Factors Influencing Stabilization

Soil is the foundation material for all roads and highways. A stable foundation is key to the durability and longevity of any road. Because most soil deposits for road construction lack the engineering properties required for foundation soil, the subject of soil stabilization has been widely studied. Soil stabilization has been defined as the process of improving certain soil properties (Kezdi, 1979; Mitchell, 1993). Ingles et al., (1973) also defined soil stabilization as the alteration of soil properties to meet specific engineering requirements.

The soil properties of concern that require improvement include, but are not limited to, strength, durability, permeability, and small volume changes. The soil property of strength, measured in terms of the shearing strength of the soil, has been noted to govern the ability of the soil deposit to support an imposing load (McCarthy, 1993). As a result, the shearing strength of soil has become an important design parameter in foundations, roadways, and airfield engineering. Soil stabilization means an increase in shearing strength of the soil corresponding to given engineering requirements (Kezdi, 1979).

In practical terms, the shear strength of a soil is a measure of the soil's strength and stability. Shear strength, like many other soil properties, is influenced by several factors. These factors can be grouped into: 1) compositional factors and 2) environmental factors (Mitchell, 1993).

1) Compositional factors: These factors are said to determine the potential range of values for any given soil property. They are:
   a. type of minerals making up the soil material,
   b. amount of each mineral making up the soil,
   c. type of adsorbed cation,
   d. the soil particles shape and size distribution,
   e. composition of the pore water.
2) Environmental factors: These factors are said to determine the actual value of a given soil property. They include:
   a. water content,
   b. density,
   c. confining pressure,
   d. temperature,
   e. the soil fabric (structure),
   f. availability of water.

The combination of these two groups of factors determines the shear strength of a soil (Mitchell, 1993). The shear strength of a soil is also divided into two components, internal friction and cohesion. These two components according to many researchers influence the stability of unpaved roads (Grow et al., (1961); Public Works, 1990). Mitchell, (1993) gives the relationship between shear strength, internal friction and cohesion as:

$$\tau = c + \sigma \tan\Phi \quad \textbf{(3.1)}$$

Where

τ	=	shearing strength
c	=	cohesion
σ	=	effective normal stress in the plane of failure, and
Φ	=	the angle of internal friction.

For cohesionless soils such as sand $c = 0$ and shear strength depends only on the normal stress and the angle of internal friction ($\tau = \sigma \tan\Phi$). The internal friction according to Rowe, (1962), Mitchell, (1993), and others is in turn influenced by four main factors:

- the sliding resistance between soil particles,
- soil particle rearrangement,
- dilation, and
- particle crushing.

For engineered (aggregate) roads the above factors produce change in internal friction during compaction of the unpaved road surface which increases the shear strength and stability of the road.

For soils with plasticity such as clays, cohesion plays an important contribution to the shear strength and stability of the soil. Two types of cohesion have been described by Mitchell (1993) true cohesion and apparent cohesion.

The proposed sources for true cohesion are:

1. Cementation (chemical bonding between particles),
2. Electrostatic and electromagnetic attraction (prevalent in small-size and closely spaced particles), and
3. Primary valence binding and adhesion.

The proposed sources for apparent cohesion are:

1. Capillary stresses (a combination of water attraction to soil particle surfaces and the surface tension of water) and,
2. Apparent mechanical forces (caused by interlocking rough surfaces) (Mitchell 1993).

The use of chemical additives can increase the shear strength of soils by increasing the internal friction and/or cohesion of the soil (Hemwall, et al., 1962). Unfortunately soils react differently to different admixtures. Hoover, et al., (1960) in a roadbase stabilization study, discovered that the stability of some road soil materials was improved by the addition of certain additives, whereas the stability of others was unaffected.

The interaction between a soil and an additive, among other things, depends on both the soil and the additive physical and chemical properties. Although two soil samples may have the same physical characteristics, i.e. particle size distribution and Atterberg limits, they may posses different chemical properties which in turn may affect their resulting interaction with the same additive. According to Mitchell (1993) the parent material of a soil and its weathering characteristics holds the key to the chemical makeup of that soil. Palmer et al. (1995) states that "a soil's composition, history, current state, and environment are reflected in its fabric and interparticle force system." The fabric and the interparticle forces, therefore, comprise the structure of the soil and the structure of a soil is not permanent. By rearranging the soil particles, changing the size and composition of the particle groups, or changing the size or number of pores spaces in the soil, the fabric (structure) of the soil can be changed (Mitchell, 1993).

For this reason the application of an additive such as lignin may cause soil particle rearrangement to occur because lignin, according to Gow, et al. (1961), can cause dispersion of the clay fraction of some soils. The compositional structure of some soils may also change due to solubility of soil minerals. Applications of some types of additives can increase solubility of soil minerals thus causing soil structure consolidation and cementation (Ross, 1988).

In addition to shear strength, the thickness of the soil layer also affects stability. According to Huang (1993), the stability of paved or unpaved roads depends on the strength of the entire road-layer system (i.e. the subbase, base, and wearing surface course). The following equation given by Huang (1993) shows the relationship between the depth of the soil layer and the amount of load supported at that depth.

$$\sigma_z = q\,[1-(z^3/((a^2 + z^2)^{1.5}))] \tag{3.2}$$

where

σ_z	=	the stress at a depth z, beneath the center of a flexible plate (in this case a vehicle tire) subjected to a uniform pressure,
q	=	the uniform pressure applied to the flexible plate,
z	=	the depth z in the layer below the center of the plate, and
a	=	the radius of the circular plate.

To achieve optimum stability of unpaved roads, the overall road-layer system should have sufficient depth such that the average vehicle load distribution can be reasonably supported by the unpaved road.

3.4 Ligninsulfonate (Lignin)

Various researches who have studied lignin as a soil additive have all concluded that lignin is primarily a cementing agent (Landon et al., 1983; Ingles et al., 1973; Woods, 1960). The natural cementing sugars that bind the wood fibers together also appear to perform the same fundamental function when combined with soil particles. The resulting lignin-treated unpaved road is one that exhibits concrete-like qualities of a hardened surface that gains strength over time. The cementing effect helps with stabilization by increasing the true cohesion between soil particles. Lignin has also been shown to posses the property of hygroscopicity, which may also contribute to soil strength by retarding evaporation (Gow et al., 1961).

Adding lignin to clayey soils increases soil stabilization by causing dispersion of the clay fraction (Gow, et al., 1961; Davidson, et al., 1960). As stated by Gow, et al., (1961) "dispersion of the clay fraction benefits stability of the soil-aggregate mix by:

a) plugging voids and consequently improving watertightness and reducing frost susceptibility,
b) eliminating soft spots caused by local concentrations of binder soil,

c) filling voids with fines thus increasing density, and

d) increasing the effective surface area of the binder fraction which results in greater contribution to strength."

Woods, (1960) also explains that lignin acts as a clay dispersant, making the soil more plastic at lower moisture content which, after compaction, leads to denser, firmer road surface. For this reason, fines or clay are an important component of the road surface material and a prerequisite for successful road surface stabilization with lignin.

Lignin like the other dust suppressants (soil additives) is introduced into the road surface layer for dust-control purposes. Lignin is water soluble and therefore during wet conditions leaches into the underlying base and subbase layers. When this occurs, the presence of lignin in the underlying layers can increase shear strength thus benefiting the overall stabilization of the unpaved road (Sultan, 1976; Apodaca et al., 1990).

The solubility of lignin is also considered a disadvantage because the surface binding action of the lignin may be reduced or completely destroyed by heavy rain (Langdon et al., 1983; Addo et al., 1995). Lignin is also corrosive to aluminum and its alloys because caustic compounds are used in the extraction process (Compendium 12, 1980). As reported by Schotte (1988), the corrosive and solubility effects of lignin can be reduced by the addition of calcium carbonate slurry to the lignin-soil mixture. Adding bichromate to lignin in a chrome-lignin-soil stabilization study revealed that the mixture formed a gel and acted as a waterproofing agent (Hough, 1951). Lignin has successfully been used to treat unpaved roads in Europe, Canada, and United States since the 1920s. It promotes stabilization and consolidation of roadway mixtures (Harmon, 1957; La Touche, 1959). The degree of stabilization has varied from study to study; some researchers have reported notable strength increases and others have reported no strength gains. Section 3.6 summaries the results of some of the soil stabilization studies done.

3.5 Chloride Compounds ($CaCl_2$ and $MgCl_2$)

Chloride compounds are probably the most widely used dust suppressant (additive) on unpaved roads. They also produce changes in soil that influences stabilization (Gow, et al., 1961; Ross, 1988; Compendium 12, 1980). The soil stabilization is generally attributed to the salt's hygroscopic and deliquescent properties, giving the soil the ability to resist drying out, and maintaining the soil at a semi-moist state. The salts may aid in the compaction of some soils by lubricating the soil particles and reducing friction between the particles (Gow, et al., 1961; Ross, 1988). The additional lubrication provided by the salts over and above water alone results in higher compactive densities without increasing compactive efforts.

Another benefit associated with the use of chloride compounds is that they introduce a divalent cation into the soil. This may affect the clay fraction of the soil by reducing spacing between the particles and thereby increasing flocculation (Mitchell, 1993). Increasing flocculation results in shear strength increases thus stabilizing the soil (Mitchell, 1993). Like lignin, $CaCl_2$ and $MgCl_2$ additives also cause dispersion of clay in soil-aggregate mixture. The benefit is that when salts leaching out because of rain or a high water table, the clay may disperse and fill the voids, thus retarding further leaching. The recrystallization of these salts in the pore spaces also makes them effective road material stabilizers (Squier, 1974).

The use of $CaCl_2$ and $MgCl_2$ significantly increases the surface tension of water molecules between soil particles (Hillel, 1980). The increased pore water surface tension causes an increase in apparent cohesion of the soil resulting in overall soil strength gains (Shepard et al., 1991).

Another major effect that chloride compounds have on soil stabilization is that they reduce vapor pressure in the soil structure. At lower vapor pressure, soils maintain a higher moisture content (Ross, 1988; Shepard, et al., 1991). The higher moisture content increases apparent cohesion and maintaining the moisture content is essential for maintaining unpaved road surface stability. A higher moisture content, along with other factors, prevents raveling and degradation of the road surface. For chloride compounds to be effective in attracting and holding moisture, the relative humidity which in turn is temperature dependent, must be above 29 to 40 percent (Langdon, et al., 1983, Ross, 1988; Shepard, et al., 1991).

$CaCl_2$ and $MgCl_2$ additives also depress the freezing point of aqueous solutions in relation to their concentration. As reported in Woods, (1960), a 30 percent $CaCl_2$ solution freezes at approximately –60F while a 22 percent $MgCl_2$ solution freezes at approximately –27F. In chloride treated unpaved roads this property minimizes frost leave and reduces freeze-thaw cycles, thus reducing maintenance cost (Woods, 1960; Ingles, et al., 1973).

The main disadvantages with the use of chloride compounds are that they are:

- water soluble and easily washed away by rain and may require more than one application in a single season to maintain their effectiveness.
- Corrosive to most metals – their corrosiveness depends on the air temperature, humidity and concentration.

Like lignin, mixed stabilization results have been reported on $CaCl_2$ and $MgCl_2$.

3.6 Summary of Research Studies

Laboratory methods as well as onsite testing have been done to quantify soil stabilization using chemical additives. In one such study, Lane, et al., (1984) used laboratory methods to measure soil cohesion increases resulting from the addition of some commercially available dust suppressants (additives). The laboratory methods included the unconfined compression (UC) test and a modified wet sieve analysis test. The UC (ASTM test No. C-39) was used to quantify the soil-additive cohesion strength gains under different sample-drying conditions. The modified wet sieving analysis (ASTM test No. C-117) was used as an indicator of the dust suppressant's ability to resist washout during intense rainfall and thunderstorms because that ability is critical to the longevity of the stabilized road surface. The additives tested include an emulsified petroleum residue, a processed chemical derived from petroleum residue, and calcium ligninsulfonate. The soil material used was classified as cohesionless. Because road surface moisture conditions may vary over time, the specimens were made at moisture contents of 4, 6, and 8 percent by weight. The suppressant manufacturers' recommended addition of 6 percent by weight was used. The testing was performed at three sample-drying conditions, 24-hour air-dried, 24-hour bag cured, and immediate sample testing.

Figure 3.1 shows the resulting cohesive strength measured for the 24-hour air-dried test condition. The results indicate that each additive tested varies in cohesive strength with a range of 4-55 psi. The calcium ligninsulfonate at each of the initial aggregate moisture content (4, 6, and 8 percent) showed a higher cohesive strength than the petroleum-based additives. Meanwhile the petroleum based additives resisted water striping better than the lignin under air-dry conditions. The researchers concluded that the initial moisture content of the road material mix is critical to the success of the soil stabilization effort.

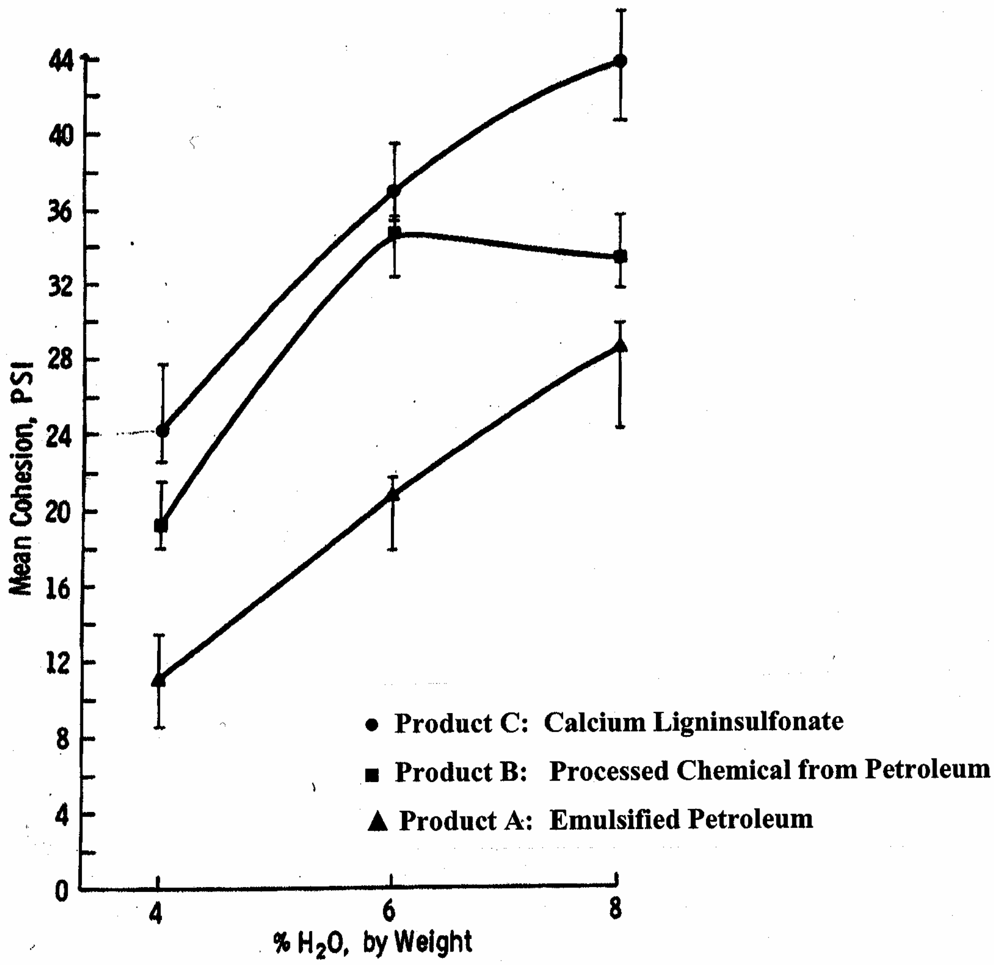

Figure 3.1 **Effect of moisture content on the cohesion of treated aggregate for the 24-hour air-dried test condition. Adapted from Lane et al., (1984)**

The Quebec Department of Roads conducted laboratory tests comparing the engineering properties of lignin-treated aggregate with that of raw aggregate and clay-mixed gravel (Hurtubise, 1953). The bearing capacity of the aggregate treated with 1.2 percent lignin was higher than that of the raw aggregate soil and clay-mixed aggregate. Cohesive strength increased with the addition of 2 percent lignin. The strength increase was also found to be nearly linearly proportional to the amount of lignin used. Water absorption tests indicated that water absorption through capillary action was reduced substantially. Moisture density relationship tests showed that an increase in the amount of lignin added to the soil increased the density and reduced the optimum moisture content.

Davidson, et al., (1957), in a similar study confirmed that lignin admixtures indeed do improve some engineering properties related to stability of soils. They also reported that the strength of lignin-treated soil increases rapidly with an increase in the length of air curing.

Palmer, et al., (1995), in a low-volume road study used laboratory methods to evaluate the strength and density modification of unpaved road soils because of chemical additives. The additives tested included lignin, $CaCl_2$ and $MgCl_2$ at different concentrations. Three different road soil materials with different soil classifications were used. The test procedures were designed to find changes in soil characteristics. The soil cohesion and density changes as affected by additive concentrations were evaluated. Moisture and density relationships using ASTM standard D698 were performed to measure the optimum moisture contents and dry densities of the test specimens. Unconfined compression (UC) tests were also performed to measure the cohesive strength changes. The tests were performed under wet conditions (immediately after the specimens were formed) and after seven-day air-dried conditions. The test results were evaluated based on measured changes in dry density and UC. The results were given as a comparison between water only as the additive, and lignin, $CaCl_{2,}$ and $MgCl_2$ as the additive.

The results of the cohesion and density measurements were mixed for all three additives at the different concentration tested. The lignin additive, for example, increased the dry density of some samples at certain moisture contents over the compaction with water alone. On the other hand, lower dry densities than the water only testing were measured for some soil samples at lower and higher moisture contents. The chloride compounds, for the most part, showed decreased dry densities when compared to soils compacted with only water at lower initial concentrations but showed increased dry densities as concentrations increased.

UC tests performed on wet specimens showed lower cohesive strengths than that of water-only specimens for all three additives. The seven-day air-cured samples exhibited large strength increases for the lignin-treated specimens at all concentration levels. Changes in UC strength however, were not as consistent for specimens formed with $CaCl_2$ and $MgCl_2$ additives. Figures 3.2 and 3.3 illustrate results of some of the measurements performed.

For each of the soils tested, lignin provided the greatest increase in strength as determined by the UC tests. Palmer, et al. (1995) concluded by noting, "Because each soil may react differently to the application of a particular additive, each soil should be tested with the additives being considered for purposes of dust control or stabilization. This testing can be done more economically in laboratories than in the field. Laboratory test results can be used to recommend additive choices, additive concentrations, and application methods that have the best chance of improving the stability of an unpaved road's surface."

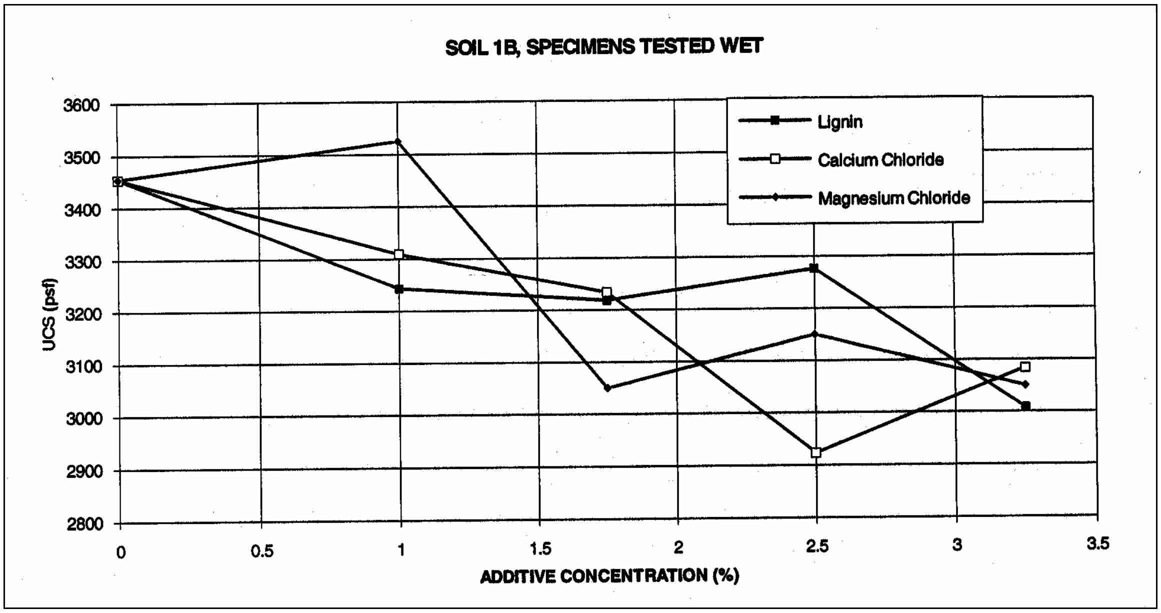

Figure 3.2 Average Peak UC Strength for Specimens Tested Wet
Adapted from Palmer et al., (1995)
Note: SOIL 1B – Classified as A-1-b by AASHTO designation M-145, and SM by USCS (PI = 0)

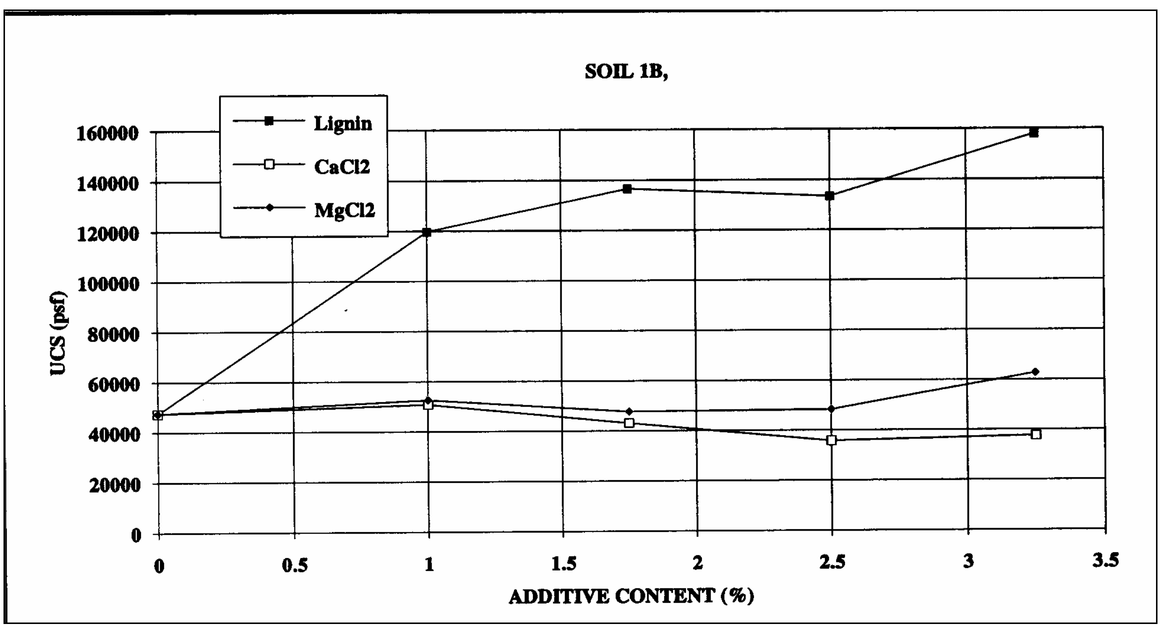

Figure 3.3 Average Peak UC Strength for Specimens Tested Dry
Adapted from Palmer et al., (1995)

Other research studies have evaluated the relative effectiveness of dust suppressants (i.e. lignin, $CaCl_2$ and $MgCl_2$) in controlling the generation and emission of fugitive dust from unpaved roads (Hoover, et al., 1973 and 1981; Squier, 1974; Addo and Sanders, 1995). Although most of these studies were aimed at dust control, they serve as a surrogate measure of unpaved road surface stabilization. The studies attempted to measure traffic-generated fugitive dust and aggregate pullout from the surface of unpaved roads, which is a fair measure of the stability of unpaved road surface.

3.7 Summary

Natural soils rarely possess the necessary engineering properties for road construction. Thus, adding chemicals to soil to improve the road soil properties, termed "soil stabilization," has become a common practice in construction of both paved and unpaved roads. For unpaved roads, the application of dust suppressants for the purpose of controlling fugitive dust generation has been noted to produce changes in the road soil characteristics that influence soil stabilization. With an improved road base and a stabilized road surface, the loss of road surface fines in the form of dust is reduced which in turn prevents the road surface from deteriorating and eventually reduces maintenance costs.

A stabilized unpaved road surface can serve as a base for a high type road surface such as "chip and seal" suitable for high traffic volume roads. Usually three to four successive dust suppressant treatments may stabilize the road surface enough to receive a higher type surfacing. In general, there are two methods of incorporating suppressants into the road surface soil: the surface or topically sprayed application method and the mixed-in-place or in-depth application method. The mixed-in-place application is relatively time consuming and therefore more costly compared to the topically sprayed application method. However, the mixed-in-place application is the preferred method because its stabilization effect is more pronounced.

Many factors influence soil stabilization. The most notable factors are the physical and chemical properties of the soil and the chemical additive. The stabilization effect of a soil additive is measured in terms of the increase in shear strength of the soil-additive mixture. Lignin as a soil additive causes dispersion of the clay fraction of some soils resulting in the shear strength increase of the soil. The application of some salt additives may cause the solubility of some soil minerals, thus causing soil structure consolidation and cementation which leads to shear strength increases.

4. ROAD DUST SUPPRESSION: EFFECT ON UNPAVED ROAD SAFETYAND THE ENVIRONMENT

4.1 Introduction

The dust cloud formed when vehicles use an unpaved road can impair the visibility of motorists, leading to accidents and other road hazards. The fine abrasive particles can also increase the wear and tear on the moving parts of vehicle using the unpaved road, resulting in higher road-user cost (Colorado Transpr. Info. Center, #3, 1989). The loose surface aggregate also can be dangerous to pedestrians and oncoming vehicles passing each other as the loose coarse aggregate can easily be turned into a projectile. This happens when the vehicle tires pick and throw the loose aggregate.

Although unpaved roads provide a cheap transportation route for vehicles, the fugitive dust generated by vehicular activity contributes significantly to the particulate loading in the atmosphere. According to air pollution studies, nearly 34 percent of the particulate matter in the atmosphere originates from unpaved roads nationwide, making unpaved roads one of the major man-made sources of fugitive dust (Barnard and Stewart, 1992).

Concern for unpaved road user comfort and safety as well as atmospheric air pollution are some of the reasons for unpaved road dust suppression. This section of the report evaluates the effect, if any, the use of dust suppressants (additives) has on the safety of unpaved road users and the environment. The issue of environmental impact is important because the additives commonly used, lignin, $CaCl_2$, and $MgCl_2$, may contain environmentally unacceptable contaminants such as chlorides, heavy metals, and organic compounds that are currently regulated by the U.S. Environment Protection Agency (EPA).

4.2 Safety Concerns

Unpaved aggregate surfaced roads treated with lignin or chloride compounds have demonstrated a significant reduction in the dust cloud formed when vehicles use the unpaved road (Sanders, et al., 1997; Hoover, et al., 1981; Squier, 1974). As a result, a driver's visibility is drastically improved. For those that have driven treated versus untreated roads, there is a significant improvement in driving comfort as washboarding, corrugations, and ruts are reduced on the treated roads.

Vehicle braking (stopping) on untreated unpaved road especially those with degraded surface with loose unstable aggregate can be tricky if not dangerous. Sudden braking at higher speeds can cause a vehicle to skid out of control as the loose surface material is not able to provide a firm gripping surface for the vehicle tires. Vehicle braking distance becomes longer and accidents such as a vehicle skidding into roadside ditches can occur.

Although accident data on unpaved roads that were studied were not available in this research, it would be worthwhile to accumulate such data in a future unpaved road safety study. Understanding the relationship between an unpaved road maintenance history and the number of accidents that occur on the road, considering factors such a driving speed, traffic volume, among others, should be an objective of such a study. There may be a legal issue if researchers know a specific treatment may cause more slipperiness than another.

Applying additives stabilizes the unpaved road surface by binding the road surface material together to form a firm driving surface. Unfortunately, treated unpaved roads have been noted to be slippery during wet weather conditions (Conversation, 1995). For example, during the Spring of 1995, the Larimer County Road & Bridges Department reconstructed and upgraded one of the county roads – the Stove Prairie road (CR 27). The reconstruction included blading, shoulder reclamation, reshaping of ditchlines and the addition of about 6 inches fresh virgin road surface material from the Horton Pit (one of the two gravel borrow pits operated by Larimer County). The road was treated with $MgCl_2$ using the mixed-in-place dust suppressant application method to stabilize the road surface and control dust. The physical characteristics of the Horton Pit material are given in Table 2.1.

According to county road officials (Conversation, 1995), shortly after the construction of the $MgCl_2$ treated road (without the road surface curing) the area received nearly 4 to 5 inches of rain over a two-day period. The county received numerous complaints from nearly all residents in the area about the poor driving conditions on the $MgCl_2$-treated road. They complained that the road was unacceptably slippery, resulting in some accidents. Their assertion was that the slipperiness was caused by the $MgCl_2$ additive.

Review of recent research done at the University of Wyoming (DeCastro, et al., 1996) to analyze the behavior of road soil-additive interaction provided some explanation as to why the $MgCl_2$-treated road became very slippery under the wet conditions. In the study, cohesionless road soil material samples were augmented with clay at varying clay content (0%, 4%, and 8%). The test sections were then treated with $CaCl_{2,}$ lignin and no treatment for a total of six test sections. Only $CaCl_2$ was used because it has the same transport and soil-additive characteristics as $MgCl_{2.}$ The test sections were compacted at a 2 percent slope as designated by AASHTO (1993) for construction of unpaved roads.

The test sections were then subjected to the same rainfall conditions using the University of Wyoming's rain stimulator. The rainfall study measured the surface erosion, runoff, solute concentration, and infiltration properties of the test sections. The results indicated that the samples with clay had lower infiltration rates and higher runoffs than those without clay. The lignin-treated test sections produced the highest runoff and the infiltration rates. The salt-treated test sections reduced infiltration to a rate about midway between that of the lignin and the untreated test sections.

Decastro et al., (1996) rain infiltration and runoff study supports the following explanation for treated road slipperiness:

- The addition of clay to road material was found to significantly reduce the infiltration rate of the treated road regardless of the additive type. So for the Larimer County road in question, the high clay fraction of the road material used (Horton Pit Gravel – Table 2.1) combined with the $MgCl_2$ additive reduced the infiltration rate of the treated road. As a result, the use of the road at the onset of the rain created ruts as vehicle tires made deep tracks in the uncured soft surface. The formed ruts consequently impeded the flow of surface runoff into the roadside drainage ditch and held the water on the road surface. The clayey soil in the presence of the double dose of lubricant, the $MgCl_2$ and water, became more plastic as more vehicles used the road and more rain showers occurred. The resulting road surface therefore provided no traction for the safe control of vehicles. The slippery conditions would have existed even if Lignin was used instead of $MgCl_2$.

- In dry weather conditions salt-treated roads give an illusion of slipperiness especially under humid conditions when enough moisture has been attracted from the atmosphere to make the treated road surface wet. If enough road fines are present in the road material mix, the clay, salt, and moisture can indeed affect stopping (braking) distances of vehicles traveling at higher speeds. In the case of lignin-treated roads, the lignin is known to form a hard crust on the top of the road surface as shown in Figure 4.1. The crust was measured to be about 1/4 inch (6 mm) in the case of the University of Wyoming study. This crust however, makes lignin-treated road surfaces very smooth. The smoothness of the road surface, unlike paved roads, can affect stopping distances on the lignin-treated road.

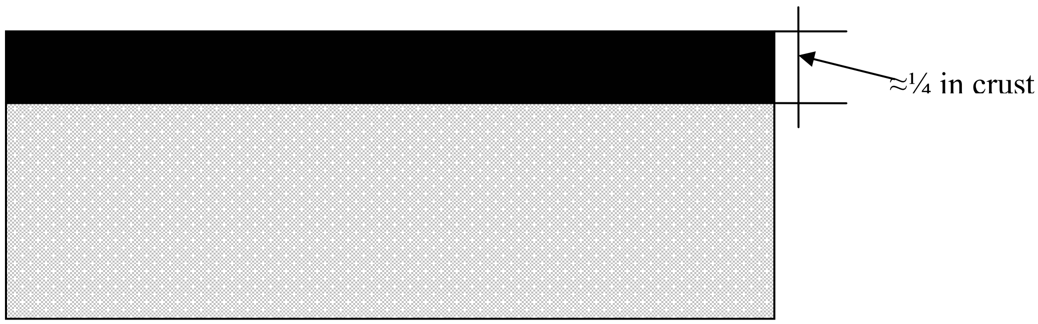

Figure 4.1 Lignin Crust Formed during Curing

Although vehicle stopping distance tests were not performed in this research study, future studies can include stopping (braking) distance tests on treated and untreated unpaved road under both wet and dry driving conditions. ASTM (E 503/E 503M) "Standard Test Methods for Measurement of Skid Resistance on Paved Surfaces Using a Passenger Vehicle Diagonal Braking Technique" can serve as guide for such studies.

4.3 Environmental Impact

Very little quantitative information currently exists on the environmental impact from the use of dust suppressants (additives). Although it is obvious that fugitive dust emissions from treated unpaved roads are significantly less than those of untreated roads (Sanders, et al., 1997), the real issue of the amounts and size distribution of the road dust particles with and without dust treatment is unknown. This may be particularly important as particles smaller than the PM10 (10 μm) constitute a health hazard because they can damage lungs (Gottschalk, 1994). The quality of runoff from treated roads and its impact on groundwater and surface water resources are not fully known either. Experience with deicers in the eastern part of the United States has demonstrated the tremendous impact deicers have on nearby water quality. As a result there is concern that the water quality and other environmental impacts are sufficiently high that the use of dust suppressants may become regulated in the future.

The dust suppressants, especially the chloride compounds, are the same compounds used for winter season road deicing because of their freezing-point-lowering properties. Addo and Sanders (1995), stated a few reasons why very little direct information exist on the environmental impact of dust suppressants. "The reason for the lack of research in this area may be attributed to the following:

1. Dust suppressing is mostly done on gravel-and-earth-surfaced roads which happen to be low-volume secondary roads located primarily in rural areas, and thus can easily be ignored.
2. Some of the most commonly used compounds for dust suppressing, namely; $CaCl_2$, $MgCl_2$, and NaCl, are the same compounds used for road deicing. As such, the results of environmental impact studies on the effect of road deicers can be extrapolated for dust suppressants.
3. The quantity of dust suppressants used annually, though on the rise, is still small in comparison with the quantity of deicers used annually.
4. Unlike deicers that immediately are washed off as snow and ice melts, dust suppressants stay mostly at one place in the road surface."

No experiments were designed and performed to measure any environmental impact from the use of the three additives studied in this research project. However, a review of the effects of road deicing salts on water quality, roadside vegetation, and animal life are presented because of the profound effects salts have the physiology and morphology of plants and animals.

4.3.1 Chloride Compound Additives

The use of salts for road deicing or dust suppressing can contribute substantial amounts of chloride ions to runoff from surface of roads treated with the compounds. The salts ($MgCl_2$ and $CaCl_2$) are very soluble in water and will dissociate as shown in equation 4.1 (Snoeyink and Jenkins, 1980).

$$MgCl_2 + \text{Water} \xrightarrow{\textit{ionization}} Mg^{2+} + 2Cl^- \qquad \textbf{(4.1)}$$

The chloride ion in drinking water is considered a problem when concentrations exceed 250 mg/l and therefore is regulated by the EPA's drinking water standards. The salts, when used on road surfaces, will dissolve during wet weather and be transported into the groundwater through infiltration and/or runoff into surface water bodies. The chloride concentration in the groundwater or surface water depends on several factors including: 1) application rate, 2) composition and type of soil, 3) type, intensity, and amount of precipitation, and 4) the drainage of the road system (Pollock and Toler, 1973). In addition, the chloride concentration in the surface water also depends on the size or flow rate of the water body and the resulting dilution achieved.

In chloride concentration studies carried out in Wisconsin during a winter deicing period, runoff from roadside drainages were analyzed. Schraufnagel (1965), reported up to 10,250 mg/l were measured, while surface runoff downstream from the drainages showed chloride concentrations of only 4.5 mg/l. The significant difference was attributed to dilution. In the same study, measurement in the summer showed up to 16 mg/l in roadside runoff while stream and rivers in the area had chloride concentration ranging from 0.5 to 2 mg/l. In similar work done in Maine, Hutchinson (1966) measured chloride concentration of spring runoff from a culvert that carried runoff from about a mile of Interstate Highway 95. The samples were taken daily over a 60-day period from March through April. The chloride concentration ranged from approximately 40 mg/l to 85 mg/l with a mean value of about 57 mg/l.

The chloride concentration in groundwater along highways has also been studied. The Massachusetts Department of Public Health sampled wells close to several highways and reported chloride concentrations of up to 250 mg/l in most of the samples. This is against a background concentration of 5-15 mg/l in public water supplies (Pollock, 1973). Hutchinson (1966), in a study of the contribution of chloride from deicing, sampled 20 wells in Maine. Of the 20 wells, three that were not close to any road had less than 1.0 mg/l of chloride concentration. The rest which were located close to highways had up to 460 mg/l of chloride in one well sample. This contamination level exceeds the maximum contaminant level (MCL) of 250 mg/l established by the EPA. Most of the highly polluted wells were noted to be hand-dug and shallow while those with low chloride levels were drilled and cased.

Many studies of surface waters contaminated by deicing salt studies have been done (Schraufnagel, 1965; Hutchinson, 1966/67; Demers and Sage, 1989). All these studies indicated that the chloride concentration increased as a result of deicing activities but the levels were still far below the MCL set by EPA. Demers and Sage (1989), analyzed four streams located near a salted highway and measured up to 35 mg/l of chloride concentration. Meanwhile analysis of a sample of one of the streams upstream from the highway had only about 2 mg/l of chloride. Although 2 mg/l to 35 mg/l is a significant increase in concentration, the chloride level is still lower than the MCL of 250 mg/l. Nevertheless, the long-term effect of this exposure is not known.

The EPA has set the maximum chloride concentration in water for domestic use as 250 mg/l. This restriction is base solely on taste and palatability rather than health (Addo and Sanders, 1995). Sawyer (1960) reported that water containing chloride levels as high as 2,000 mg/l has been used without any adverse effect once the human system has adjusted to it. Salty taste in some water can be produced by as little as 100 mg/l while in others as much as 700 mg/l would not affect the taste (Standard Methods; 16th Ed, 1985).

The presence of multivalent cations in water is the cause of water hardness, thus the objection of magnesium and calcium ions in water (Snoeyink and Jenkins, 1980). Hardness of more than 100 mg/l has been noted to cause excessive soap consumption (Phelp, 1984). Water hardness also cause scale in hot water boilers, heaters, pipes and utensils thereby decreasing their useful life.

Animals on the other hand are more tolerant to water with high salinity than humans. In California, water supplies with chloride levels as high as 1,500 mg/l are designated as suitable for livestock and widelife (Mckee and Wolf, 1963). In states such as Colorado and Montana water with chloride concentrations of about 2,000 mg/l are acceptable. In Western Australia the upper safe chloride levels allowed are: 2,860 mg/l for poultry, 4,300 for pigs, 6,400 mg/l for horses, 10,000 mg/l for cattle, and as much as 13,000 mg/l for adult dry sheep (Office of Dept of Ag., 1950). At excessively high levels, chloride is said to affect the health of animals (Heller, 1932; Peirce, 1966). As stated by the National Technical Advisory Committee to the Secretary of Interior (1968), "Salinity may have a two-fold effect on wildlife; a direct one affecting the body processes of the species involved and an indirect one altering the environment making living species perpetuation difficult or impossible." One major problem associated with the use of deicing salt as far as wildlife is concerned is that wildlife are known to have "salt craving" and therefore are attracted to salted highways which can be a traffic hazard to both the animals and motorists. Mountain sheep are seen more often near roads after deicers have been applied particularly on Route 34 in Colorado between Loveland and Estes Park.

As far as plants and vegetation are concerned, the accumulation of salts in the soil adversely affects their physiology and morphology. Allison (1964) stated that salts affect plant growth directly by: 1) increasing the osmotic pressure of the soil solution, 2) altering the plant's mineral nutrition, and 3) accumulating specific ions to toxic concentrations in the plants. Strong (1944), observed that trees along a roadside where $CaCl_2$ was sprayed for dust control were injured as exhibited by leaf scorch. Traaen (1950) also documented injuries to Norway Spruce trees by $CaCl_2$ sprayed to control dust on unpaved roads. He noted that the salt-coated dust particles accumulated on the tree leaves absorbed moisture from the air and the resulting salt solution was in turn absorbed by the leaves.

4.3.2 Lignin Additive

Lignin is considered biodegradable, therefore its presence in the environment can be considered less harmful. Lignin is very water soluble and can be dissolved and washed off into nearby streams and other water bodies under severe rainfall conditions especially when freshly applied. In such a situation, depending on dilution of the lignin, the receiving water body may experience pollution. Pollution from lignin can be measured in terms of biochemical oxygen demand (BOD). BOD is the amount of oxygen required by bacteria to degrade and stabilize organic waste, which are the lignin sugars.

In a typical pulp-paper making process, a ton of bleach sulfite pulp waste (lignin sulfonate) would require approximately 1,000 pounds of oxygen for decomposition as compared to only 0.17 pounds of oxygen to treat a daily human discharge of waste (DeCastro, 1996). Lapinskas, (1989) provided an example of lignin sugar degradation as shown by the following chemical equation:

$$C_nH_{2n+2} + O_2 \xrightarrow{\textit{Bacteria, } H_2O\textit{, Nutrients}} \text{Protein} + \text{Water} + CO_2 \quad \textbf{(4.2)}$$

4.4 Summary

The safety and environmental impact of unpaved roads have always been a concern because the presence of loose road surface gravel can cause damage to vehicle and threaten the safety of motorists as sudden vehicle braking can be difficult. The dust emission from an unpaved road is also noted to contribute significantly to the particulate loading in the atmosphere.

The use of dust suppressants addresses the obvious unpaved road safety and environmental air pollution concerns. By stabilizing the unpaved road surface, road users' driving comfort and safety is improved and by controlling dust emission the atmospheric particulate loading contribution from an unpaved road is significantly reduced. However, the application of dust suppressants has been noted to cause slipperiness on unpaved roads in wet weather conditions. The water-quality effects of the use of dust suppressants are still not entirely known, however the chloride compounds and the lignin additives commonly used contain contaminants such as chlorides, heavy metals and organic compounds that are regulated by the EPA. Although some dust suppressant is washed into the environment after applications, initial research indicates that the quantities are relatively small.

5. CONCLUSIONS

5.1 Introduction

The role of dust suppression in the context of unpaved road maintenance and associated benefits and problems has been examined and presented in the previous chapters. The three specified additives $MgCl_2$, lignin, and $MgCl_2$/lignin blend, were applied on two different sources of road surface material. The dust emission capacity of the resulting test sections were measured and from the results, conclusions can be drawn about the performance of each soil type-additive combination.

The body of knowledge about soil-additive interaction as it pertains to the specified dust suppressants has been reviewed. Conclusions can be drawn on the expected behavior change between the different soil types and the dust suppressant additives. Because the specified chemicals for dust suppression are the same compounds used for road surface deicing, the documented water quality and other environmental impact studies reported by other researchers have been reviewed and conclusions can be drawn about the potential contamination that can be expected for the long-term use of these chemical compounds.

5.2 Road Dust Suppression – Effect on Maintenance

A good quantifiable maintenance scheme is essential to the successful operation of an unpaved road network. In Larimer County, Colo., the Road and Bridge Department with jurisdiction over the county's unpaved road maintenance program has a comprehensive unpaved road maintenance program in place. The program includes: 1) routine maintenance of surface reblading, shaping and compaction to remove ruts, washboarding and potholes and 2) periodic maintenance which includes – shoulder and ditchline reclamation, road realignment if necessary, aggregate replacement, and judicious use of chemical dust suppressants ($MgCl_2$ and lignin).

From the dust sampling measurements it can be concluded that:

- the Strang Pit gravel possessed less fines (particle size passing No. 40 sieve) than the Horton Pit gravel and this was exhibited by the amount of dust measured from the two sets of test sections. On aggregate, the sample amounts of dust were less from the Strang test sections compared to the Horton test sections.
- Analysis of the Strang test sections (Figure 2.11) indicates that the $MgCl_2$ treatment produced equal or more dust than the untreated control Strang test section. This could be attributed to the fact that the Strang Pit gravel has less fines and thus the $MgCl_2$ molecules have less surface area which to attach themselves and to become effective. Therefore, to treat the Strang material with $MgCl_2$ implies that more than one treatment would be required to maintain the treatment effectiveness.
- Although it was a requirement for the dust measurement testing to be done on an unpaved road section with a reasonable amount of traffic count (between 100 to 250 ADT), for reasons beyond the researchers control the test roads had a much lower than expected traffic count of 25 ADT. At such a low traffic volume the test sections were not subjected to enough traffic pounding to accurately measure the performance of each road soil type and additive combination.
- The plots of the dust sample measurements (Figure 2.11 and 2.12) did not show any consistent increase in dust emission with treatment age as expected because with time

the treatments lose their effectiveness and the test sections become more dusty as a result. This lack of pattern in the dust emission can be attributed to the low traffic volume on the test roads.

5.3 Road Dust Suppression – Effect on Stabilization

Soil stabilizing agents are used to improve and maintain soil moisture content, increase soil particle cohesion, and serve as cementing and waterproofing agents for certain soils. The specified dust suppressants or additives used in this test produced changes in the soil properties that have influenced the test road surface stabilization.

The in-depth application of the lignin, for example, produced a road surface that was firm, smooth, dust free, and comfortable to drive for most of the test period of nearly a year. Field observation of the lignin-treated test sections indicated that the lignin acted like cement, binding the soil particles together into a hard surface that show strength gains over time. The $MgCl_2$ and $MgCl_2$/Lignin blend treated tests sections likewise showed physical changes indicating a stabilized road surface. Although no field-based testing was done to measure the soil strength increases due to the use of the dust suppressants, there was enough field-observed evidence to indicate surface stabilization. The measured dust amounts presented earlier are also an indirect measure of the stabilization achieved by each different treatment.

5.4 Road Dust Suppression – Effect on Safety and the Environment

Although the application of dust suppressants significantly reduce the emission of dust which impairs motorist visibility and leads to other road hazards, the suppressants are not without their negative effects. The use of the suppressants, especially chloride compounds, on soils with high clay content such as the Horton Pit gravel can produce a slippery road surface under wet conditions. Even under dry conditions they produce driving surfaces that are perceive by motorists as slippery.

In terms of environmental concerns, the use of the suppressants reduces the unpaved road particulate matter loading into the atmosphere by controlling the fugitive dust generated from the unpaved roads. Because dust suppressants are water soluble and contain contaminants regulated by the EPA, their use should be monitored for any environmental degradation. No environmental degradation from the use of the specified dust suppressants were measured in this study. However, results presented by other researchers indicate that only very small amounts of these contaminants enter the environment and therefore their impact is presently not an issue.

5.5 Recommendation for Future Studies

Although unpaved road dust control has been ongoing for several decades and some research studies have been done to measure the effect of dust suppressants on unpaved roads, there is still the need for more information about unpaved road maintenance in general and the strategic use of dust suppressants in the maintenance scheme.

As a start, a research study to review all studies done in this country and elsewhere on unpaved road dust control is recommended. Such a study should identify and categorized each study – whether laboratory, field-based or both; the objective of the studies; and the specific subject area addressed – environmental concern, suppressants effectiveness, road surface stabilization, soil-suppressant interaction, cost analysis, and etc. The study should also identify all areas of interest relating to unpaved road maintenance and the use of dust suppressants. A gap analysis should be performed to identify areas that need research. Such research should serve as a basis for a holistic appraisal of unpaved roads and the use of dust suppressants.

6. REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO) *Standard Specification for Transportation Materials and Methods of Sampling and Testing.* Sixteenth Ed., Parts I and II, Washington, D.C., 1993.

2. Addo J.Q. and T.G. Sanders. *Effectiveness and Environmental Impact of Road Dust Suppressants,* Mountain-Plains Consortium (MPC) Report No. 94-28, 1993.

3. City of Fort Collins. Air Quality Monitoring and Control Plan for the City of Fort Collins, Colorado. Vol. III: Technical Appendices, 1985.

4. American Road Builders Association. *Materials for Stabilization,* Washington, D.C., 1976.

5. Apodaca, M. and D. Huffmon. *Dust Abatement Review and Recommendation: Final Report.* Gifford Pinchot National Forest Supervisor's Office, Road Management. Region 4, Dept of Agriculture, Forest Service, 1990.

6. ASTM. *Annual Book of ASTM Standards*, *"Bituminous Materials; Soil and Rock; Skid Resistance."* Part II, 1193, 1993.

7. Barnard, W.R. and M.A. Stewart. *Improved Fugitive PM_{10} Emissions Estimates for Trends.* "Transactions: PM_{10} Standards and Nontraditional Particulate Source Controls," Air and Waste Management Association, Pittsburgh, Pa., 1992.

8. Bennett, H. *Practical Emulsions*. Chem. Publ Co. Inc., New York, 1968.

9. Boresi, A.P. and J.T. Palmer. *Appraisal and Application of Models for Unpaved Roads*. Mountain-Plains Consortium (MPC) Report No. 93-22, 1993.

10. Bohn, R., T. Cuscino, and C. Coward, Jr. *Fugitive Emissions From Integrated Iron and Steel Plants.* U.S. Environmental Protection Agency publication no. EPA-600/2-78-050, 1978.

11. Brauns, F.E. *The Chemistry of Lignin*. Academic Press, Inc., New York, 1952.

12. Casagrande, A. "*Classification and Identification of Soils*." Transactions of the American Society of Civil Engineers (ASCE), 113:922, 1948.

13. Colorado Transportation Information Center. Bulletin #5, *When to Pave a Gravel Road.* Dept of Civil Engineering, Colorado State University, Fort Collins, 1989.

14. Transportation Research Board, Compendium 12: *Surface Treatment*. Commission on Sociotechnical Systems, National Research Council, Washington D.C., 1980.

15. Day, A.J. and E.C. Herbert. "Anionic Asphalt Emulsions. Bituminous Materials, Tars and Pitches," Vol. 2, Part 1 *Interscience Publication*. New York, 1965.

16. Davidson, D.T. and R.L. Handy. *Highway Engineering Handbook*. "Section 21, Soil Stabilization." McGraw-Hill, 1960.

17. DeCastro, A., T.V. Edgar, D.H. Foster and A.P. Boresi. *Physical and Chemical Stability of Admixtures in Unpaved Road Soils*. Mountain-Plains Consortium (MPC) Report No. 96-52, 1996.

18. Eaton, R.A., S. Gerard and D.W. Gate. *Rating Unsurfaced Roads*. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Labanon, NH. 1988.

19. Eaton, R.A., S. Gerard and D.W. Gate. *Rating Unsurfaced Roads*. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Lebanon, NH. 1988.

20. Gottschalk, K. *Road Dust: A Survey of Particle Size, Elemental Composition, Human Respiratory Deposition and Clearance Mechanisms*. Unpublished Independent Study, Colorado State University, Ft Collins, CO. 1994.

21. Gow, A.J., D.T. Davidson, and J.B. Sheeler. *Relative Effects of Chlorides, Lignosulfonates and Molasses on Properties of a Soil-Aggregate Mix.* Highway Research Board Bulletin 309, National Academy of Sciences – National Research Council, Washington, D.C., 1961.

22. Harmon, J.P. *Use of Lignin Sulfonate for Dust Control on Haulage Roads in Arid Regions*. Information Circular 7806, U.S. Dept of Interior, Bureau of Mines. Washington D.C., 1957.

23. Hemwall, J.B., D.T. Davidson, and H.H. Scott. *Stabilization of Soil with 4-Tert-Butylpyrocatechol,* Highway Research Board Bulletin 357, National Academy of Sciences National Research Council Washington D.C., 1962.

24. Huang, Y.H. *Pavement Analysis and Design*. Prentice Hall. Englewood Cliffs, New Jersey, 1993.

25. Hegentogler, C.A. "Use of Calcium Chloride in Road Stabilization." Proceedings HRB 18: Part II, ppg 209-256, 1938.

26. Heller, V.G. "Saline and Alkaline Drinking Waters." *Journal of Nutrition*, 5:421-429 1932.

27. Hoover, J.M., D.E. Fox, M.T. Lustig, and J.M. Pitt. *Mission-Oriented Dust Control and Surface Improvement Processes for Unpaved Roads*. Final Report, Iowa Highway Research Board Project, H-194, 1981.

28. Horwell, B. *Reducing Maintenance Costs on Unpaved Roads with Calcium Chloride*. Tetra Chemicals, Houston Texas, 1993.

29. Hough, B.K. and J.C. Smith. *Sulfite Waste Liquor Chrome-Lignin Soil Process*. Paper Trade Journal 133, No. 24:40, Lincolnshire, Ill., 1951.

30. Hurtubise, J.E. *Soil Stabilization with Lignosol*. Canadian Chemical Process. 37:58-61. 1953.

31. Hoover, J.M., K.L. Bergerson, D.E. Fox, C.K. Denny, and R.L. Handy. *Surface Improvement and Dust Palliation of Unpaved Secondary Roads and Streets*. Final Report, Iowa Highway Research Board Project , HR-151. 1973.

32. Hutchinson, F.E. *The Influences of Salts Applied to Highways on the Levels of Sodium and Chloride Ions Present in Water and Soil Samples – Progress Report I.* Project No. R1084-8. 1966.

33. Hutchinson, F.E. *The Influences of Salts Applied to Highways on the Levels of Sodium and Chloride Ions Present in Water and Soil Samples – Progress Report II.* Project No. R1084- 8. 1967.

34. Irwin, L.H., D.J. Taylor, and D.J. Aneshansley. *Device to Measure Road Dustiness on Aggregate Surface Roads.* Cornell Local Roads Program Report 86-5. Dept. of Agricultural Engineering, Cornell University, Ithaca, NY. September.

35. Ingles, O.G. and J.B. Metcalf. *Soil Stabilization: Principles and Practices.* John Wiley and Sons, New York. 1973.

36. Nebraska Technology Transfer Center *Interchange Newsletter*, 1995.

37. Kezdi, *A. Stabilized Earth Roads*. Elsevier Scientific Publishing Company, New York.

38. Langdon, B. and R.K. Williamson *Dust-Abatement Materials: Evaluation and Selection.* Transportation Research Record 898. National Academy of Sciences – National Research Council Washington D.C. 1983.

39. Lane, D.D., T.E. Baxter, T. Cuscino, and C. Coward, Jr. *Use of Laboratory Methods to Quantify Dust Suppressants Effectiveness.* Society of Mining Engineers of AIME, Transaction Vol. 274-2001. 1984.

40. Lane, D.D. *Controlling Dust on Unpaved Roads*. The Rural Transportation Fact Sheet, No. 84-02. T^2 Program, University of Kansas Transportation Center, Lawrence, Kansas. 1984.

41. La Touché, D.E. “Soil Stabilization with Lignosol.” *Roads & Engineering Construction 97*(12). 1959.

42. McCarthy, D.F. *Essentials of Soil Mechanics and Foundations: Basic Geotechnics.* Prentice Hall, New Jersey. 1993.

43. Mitchell, J.K. *Fundamentals of Soil Behavior*. John Wiley and Sons, New York. 1993.

44. Mckee, J.E. and H.W. Wolf. *Water Quality Criteria* 2nd Ed. State Quality Control Board, Sacramento California. 1963.

45. Mertens, E.W. and J.R. Wright. "*Cationic Asphalt Emulsion: How They Differ from Conventional Emulsions in Theory and Practice*. Proceedings Highway Research Bd. Volume 38. 1959.

46. National Technical Advisory Committee to the Secretary of Interior. *Water Quality Criteria*. U.S. Govt. Printing Office, Washington, D.C. 1968.

47. Paterson, W.D.O. *Road Deterioration and Maintenance Effects – Models for Planning and Management.* Baltimore, MD: The John Hopkins University Press. 1987.

48. Personal Communication. Larimer County Roads and Bridges Office. 1993.

49. Pollock, S.J., and L.G. Toler. *Effects of Highway Deicing Salts on Groundwater and Water Supplies in Massachusetts*. Highway Research Board, No. 425 17-21. 1973.

50. Ross, S.S., and K.B. Woods. *Highway Design Reference Guide*. McGraw-Hill. 1988.

51. Sanders, T.G. and J.Q. Addo. "Experimental Road Dust Measurement Device." Journal of Transportation Engineering, ASCE. 2000.

52. Sanders, T.G., J.Q. Addo, A. Ariniello, and W.F. Heiden. "Relative Effectiveness of Road Dust Suppressants." *Journal of Transportation Engineering*, ASCE. 1997.

53. Sawyer, C.N. *Chemistry for Sanitary Engineers*. McGraw-Hill. 1960.

54. Schraufnagel, F.H. *Chlorides*. Commission on Water Pollution, Madison, Wisconsin. 1965.

55. Shepard, J.M., J. Pickett, and M. Kienzle. *Full-Depth Reclamation with Calcium Chloride*. Transportation Research Record 1295. National Academy of Sciences – National Research Council Washington D.C. 1991.

56. Snoeyink, V.L. and D. Jenkins. *Water Chemistry*. John Wiley & Sons, Inc., New York. 1980.

57. Squier, L.D. *Evaluation of Chemically Stabilized Secondary Roads*. Unpublished M.S. Thesis, Iowa State University, Ames Iowa. 1974.

58. American Public Health Association *Standard Methods for the Examination of Water and Wastewater*, 16th ed. Washington, D.C. 1985.

59. Strong, F.C. *A Study of Calcium Chloride Injury to Roadside Trees*. Michigan Agr. Exp. Station, Quarterly Bulletin, 27:209-224. 1944.

60. Sultan, H.A. *Chemical Stabilization for Control of Dust and Traffic Erosion.* Transportation Research Record 593. National Academy of Sciences – National Research Council Washington D.C. 1976.

61. The Asphalt Institute, *The Asphalt Handbook*. Manual Series 4. College Park Maryland. 1987.

62. The Rural Transportation Fact Sheet No. 84-02. *“Controlling Dust on Unpaved Roads.”* Transportation Center, University of Kansa Lawrence, Kansas. 1984.

63. Traaen, A.E. *Injury to Norway Spruce Caused by Calcium Chloride Used Against Dust on Road.* Proceedings International Botanical Congress 7: 185-186. 1950.

64. Transportation Research Board. *Earthwork Compaction*. Transportation Research Record 897. 1982.

65. U.S. Department of Transportation. *America’s Highways, 1776-1976*, Federal Highway Administration Washington. 1976.

66. U.S. Environmental Protection Agency. *Compilation of Air Pollutant Emission Factors; 4th Edition*. U.S. EPA Publication No. AP-42, including Supplements A&B. 1988.

67. Woods, K.B. *Highway Engineering Handbook*, First Edition McGraw-Hill. 1960.

7. APPENDICES

A. Suppressants and Their Characteristics

B. Dust Measurement Data

Appendix A. Suppressants and Their Characteristics

	Calcium Chloride	Sodium Chloride
ATTRIBUTES	Starts to absorb water from air at 29 percent relative humidity (77°F) • Reduces rate of evaporation 3.4 times (vapor pressure of saturated solution at 77°F is 7 mm Hg). Note: the lower the vapor pressure, the greater the ability to resist evaporation. • Significantly increases surface tension of water film between particles, helping to slow evaporation and further tighten compacted soil as drying progresses. • Lowers the freezing point of water solution to -60°F, minimizing frost heave (30% solution). Freezing of treated road not only begins at lower temperature but is gradual and seldom completed. • Treated road can be regraded and recompacted with less concern for losing moisture and density.	• Starts to absorb water from air at 76 percent relative humidity (77°F). • Reduces rate of evaporation 1.3 times (vapor pressure of saturated solution at 77°F is 18 mm Hg) • Increases surface tension slightly less than calcium chloride. • Lowers freezing point of water solution to -6°F (25 % solution). • When mixed into road base, effectively improves mechanical stability. • Costs the least of any chloride salt.
LIMITATIONS	• Slightly corrosive to steel, highly corrosive to aluminum and its alloys; attracts moisture, thereby prolonging active period for corrosion. • Rainwater tends to infiltrate and leach out highly soluble chlorides, but if road has proper crown, most water is deflected sideways into ditches. • During dry periods, upward capillary action may cause chlorides to crystalize near road surface, where they can be leached away by sudden rain. • No cementing action; effective control only with well-graded, stable road mixes. • Exothermic: releases heat as it dissolves, enough to be a safety hazard to workers mixing the dry form in water. • Spills of concentrate may kill or burn vegetation; reasonable care in handling required. • Should not be spread over bridge decks; spills must be cleaned quickly to prevent slick spots.	• Moderately corrosive to steel in dilute solutions, but no worse than water in concentrated solutions; attracts moisture, thereby prolonging active period of corrosion. • As it becomes diluted or leaches out, disperses clay which shrinks on drying and becomes more susceptible to blowing. • If over applied, poses threat to plant and animal life as well as possible ground water contamination. • Not an effective dustproofer; thus typically used to stabilize road base and topped with calcium chloride to control dust.
APPLICATIONS	Typically 2 treatments/year: Initial: Flake.......... 1.0 to 1.5 lb./sq. yd. Pellet.......... 0.8 to 1.3 lb./sq. yd 35% solution .... .2 to 0.3 gal./sq. yd. Followup: ½ to ⅔ in initial dosage Can be stored in buildings, hoppers, silos, or covered piles. Must be airtight and protected from wet, humid conditions. Storage floor at ground level should be paved asphalt or treated concrete. Gravity feed systems required 45 degrees for flakes to flow, 35 degrees for pellets. Spread by tank trucks with pressure distributors and spinner disk or positive-displacement units.	Generally higher dosages than calcium chloride treatment.
SOURCES	By-product brine from manufacture of sodium carbonate by ammonia-soda process and of bromine from natural brines. Three forms: Flake, or Type 1: (77 to 80 % conc. 100# bags) Pellets, or Type 2: (94 to 97 % conc. 80# bags) Clear Liquid (32 / 35 / 38 % conc. tankers) Some brand names: LIQUIDOW DOW FLAKE PEADOW SUPERFLAKE	Occurs naturally as rock salt (mined mechanically or hydraulically) and brines (refined or evaporated). Some brand names: MORTON SALT DIAMOND SALT

Adapted from Colorado Transportation Information Bull. # 3 (1989).

	Lignin Derivatives	Road Fabric
ATTRIBUTES	• Greatly increase dry strength of soil; under dry conditions, outperforms bituminous binders. • During rain, disperses clay which in turn swells and plugs pores, reducing water penetration. • Tends to remain slightly plastic, permitting reshaping and additional traffic compaction. • With addition of calcium carbonate slurry to counteract corrosive effects, solubility is reduced, thereby prolonging dust-laying capability. • Ammonium-base sulfonates are superior to sugar-free calcium-base sulfides for aggregate binding. • Material cost comparable to that of inorganic chemicals.	• Flexible, durable, water permeable, and highly resistant to soil chemicals. • Used as a separator, prevents intermixing of subgrade material and base course, thereby preserving drainage systems and load transfer capability. Structural section life is prolong and maintenance costs reduced. • In tension, reduces localized loads over a large area of subgrade, thereby improving the support properties of the system. • Can reduce the amount of aggregate required in the initial design of unpaved structural sections. • If buried, can be expected to function indefinitely. • By preventing subgrade fines from "pumping" up into the aggregate, serves to control dust production.
LIMITATIONS	• Control depends on well-graded soil-aggregate mix, loosened to a depth of 1 to 2 inches prior to initial application; wearing surface silt and clay content needs to be 4 to 8 %. • May cause corrosion of aluminum and its alloys. • Surface binding action may be reduced or completely destroyed by heavy rain, owing to solubility of solids content in water. • Become slippery when wet, brittle when dry.	• High material cost, though installation cost is low. • Material degradation may result from exposure to ultraviolet rays (sunlight).
APPLICATIONS	Generally 1 to 2 treatments/year: 10 to 25 % solution .... 0.5 to 1.0 gal./sq. yd. Powder .... 1.0 to 2.0 lb./sq. yd. Application methods same as for chlorides.	Placed during road construction; no special equipment required.
SOURCES	Water liquor of papermaking industry; contains lignin and carbohydrates in solution (lignin is natural cement that binds fibers of woods). Composition depends on raw materials (mainly wood pulp) and chemicals used to extract cellulose; active constituent is neutralized lignin sulphonic acid containing sugar. Common names: sulfite liquor, black or green liquor, sulfite lye, ammonium lignin sulfonate, calcium lignosulfonate. Some brand names: LIGNOSOL NORLIG RAY BINDER	Manufactured from manmade fibers, typically polypropylene, mechanically interlocked by needlepunching and heat bonding. Available in various weights and widths, by the roll. Some brand names: SUPAC MIRAFI TYPAR TREVIRA

Adapted from Colorado Transportation Information Bull. # 3 (1989)

	Water	Bitumens and Tars or Resinous Adhesives
ATTRIBUTES	• Poses no threat to the environment • Normally, readily available	• Binds soils because of asphalt's adhesive properties. • Serves to waterproof roads • May be adapted to suit wide range of soils, gravel and traffic conditions.
LIMITATIONS	• Evaporates readily, controlling dust generally for less than a day. • Costs more than other inorganic chemical suppressants because of repeated applications needed to achieve same level of dust control (labor intensive).	• Under dry conditions, some may not maintain resilience; can form a crust and fragment under traffic loads. • Waste oil subject to state regulations for handling and disposing of hazardous substances. • Use of cutback asphalt or products with cutback asphalt as a primary ingredient limited by the Colorado Department of Health. • Material cost significantly higher than for other chemical suppressants.
APPLICATIONS	Frequency of treatments depends on temperature and humidity.	Generally 1 to 2 treatments/year: 0.1 to 1.0 gal. /sq. yd. depending on road surface condition and dilution. Material sprayed using many types of equipment, from hand-held hoses to asphalt distributors.
SOURCES		Tars (residues from coal) and bitumens (residues from crude oil) combined with lighter fractions of distillate; wide range of viscosities. Liquid asphalt: Grade SC - 70, SC - 250 Bituminous emulsions: Grade SS-1, SS1h, CSS-1, or CSS-1h mixes with 5 + parts water by volume.

Adopted from Colorado Transportation Information Bull. # 3 (1989)

	Sodium Chloride and Calcium Chloride Mix	Magnesium Chloride
ATTRIBUTES	• Combines stabilizing action of sodium chloride with dust control of calcium chloride. • Compared to calcium chloride used alone, reduces cost 20 % while losing less than 5% in dust control.	• Starts to absorb water from air at 32 % relative humidity (77°F). • Reduces rate of evaporation 3.1 times (vapor pressure of saturated solution at 77°F is 7.6 mm Hg). • More effective than calcium chloride solution for increasing surface tension, resulting in a very hard road surface. • Lowers freezing point of water solution to -27°F (22% solution). Freezing of treated road not only begins at lower temperature but is gradual and seldom completed. • Treated road can be regraded and recompacted with less concern for losing moisture and density.
LIMITATIONS	• Same limitations as for these salts used individually.	• In concentrated solutions, very corrosive to steel, attracts moisture, thereby prolonging active period of corrosion. (Note: corrosive action of seawater on steel attributed to $MgCl_2$ content.) Some products may contain a corrosion-inhibiting additive. • Rainwater tends to infiltrate and leach out highly soluble chlorides, but if road has proper crown, most water is deflected sideways into ditches. • During dry periods, upward capillary action may cause chlorides to crystallize near road surface, were they can be leached away by sudden rain.
APPLICATIONS	Typically 2 treatments / year: Initial: 1 lb. mix/sq. yd. Followup: ½ initial dosage	Typically 2 treatments/year: Initial: 30% solution ....0.5 gal./sq. yd. Followup: ½ initial dosage Storage and handling same as for liquid calcium chloride. Applied preferably with pressure spray bars (splash bars produce uneven applications).
SOURCES	Salts mixed before applying: equal parts by weight of Cc-grade rock or evaporated salt with flake calcium chloride (if pellet, use 100# salt/80# pellet). Not available premixed.	Occurs naturally as brine (evaporated); also byproduct of potash production. Usually liquid form, 25 to 35 % solution. Some brand names: DUSTGUARD DUS-TOP

Adapted from Colorado Transportation Information Bull. # 3 (1989)

Appendix B. Dust Measurement Data

Section #		6/8/2000	7/3/2000	7/13/2000	7/27/2000	8/8/2000	8/21/2000	9/16/2000	10/8/2000	5/17/2001	5/31/2001	6/21/2001	6/28/2001	7/18/2001
1	Filter #1	4.45	4.39	4.49	4.43	4.37	4.36	4.31	4.16	4.62	4.67	4.34	4.33	4.31
1	Bag #1	3.88	3.70	3.37	3.37	3.37	7.71	7.66	7.47	3.11	3.19	3.47	3.45	3.58
1	Total	11.32	10.81	12.43	13.14	12.11	9.89	11.91	10.40	10.47	10.93	10.52	9.03	10.45
1	Dust	2.99	2.72	4.57	5.34	4.37	2.18	4.25	2.93	2.74	3.07	2.71	1.25	2.56
1	Filter #2	4.46	4.41	4.50	4.42	4.30	4.37	4.35	4.16	4.61	4.67	4.34	4.34	4.32
1	Bag #2	3.70	3.85	3.32	3.33	3.37	7.69	7.71	7.52	3.10	3.23	3.44	3.37	3.53
1	Total	12.29	10.80	12.32	13.06	12.05	10.15	12.13	10.92	10.19	10.50	10.42	9.08	10.76
1	Dust	4.13	2.54	4.50	5.31	4.38	2.46	4.42	3.40	2.48	2.60	2.64	1.37	2.91
1	Filter #3	4.44	4.43	4.49	4.41	4.32	4.39	4.28	4.16	4.61	4.66	4.37	4.35	4.32
1	Bag #3	4.20	3.53	3.28	3.37	3.30	7.75	7.66	7.42	3.09	3.19	3.40	3.66	3.47
1	Total	10.87	10.45	12.08	13.01	12.01	10.52	12.19	10.43	10.28	10.08	10.92	9.16	10.41
1	Dust	2.23	2.49	4.31	5.23	4.39	2.77	4.53	3.01	2.58	2.23	3.15	1.15	2.62
2	Filter #4	4.56	4.42	4.49	4.40	4.33	4.37	4.35	4.14	4.60	4.66	4.31	4.35	4.36
2	Bag #4	4.39	3.38	3.30	3.37	3.17	7.72	7.69	7.43	3.11	3.14	3.41	3.52	3.43
2	Total	9.16	10.36	9.53	9.00	9.08	10.48	9.16	10.25	9.34	10.85	10.66	9.92	10.55
2	Dust	0.21	2.56	1.74	1.23	1.58	2.76	1.47	2.82	1.63	3.05	2.94	2.05	2.76
2	Filter #5	4.41	4.43	4.52	4.35	4.34	4.33	4.37	4.16	4.60	4.65	4.32	4.31	4.34
2	Bag #5	3.88	3.33	3.23	3.35	3.32	7.66	7.76	7.36	3.11	3.10	3.42	3.47	3.43
2	Total	10.21	8.89	9.16	8.63	8.83	10.21	9.16	9.56	9.43	10.86	10.73	9.77	10.31
2	Dust	1.92	1.13	1.41	0.93	1.17	2.55	1.40	2.20	1.72	3.11	2.99	1.99	2.54
2	Filter #6	4.49	4.43	4.48	4.33	4.32	4.33	4.32	4.15	4.63	4.64	4.33	4.33	4.33
2	Bag #6	3.78	3.60	3.31	3.32	3.29	7.72	7.66	7.42	3.12	3.10	3.34	3.46	3.45
2	Total	9.63	10.74	9.11	8.48	8.54	10.14	9.04	9.69	9.31	11.07	9.91	9.81	10.33
2	Dust	1.36	2.71	1.32	0.83	0.93	2.42	1.38	2.27	1.56	3.33	2.24	2.02	2.55
3	Filter #7	4.34	4.41	4.52	4.35	4.36	4.38	4.34	4.15	4.59	4.65	4.34	4.33	4.37
3	Bag #7	3.58	3.57	3.27	3.35	3.59	7.74	7.73	7.39	3.13	3.15	3.40	3.51	3.35

Section #		6/8/2000	7/3/2000	7/13/2000	7/27/2000	8/8/2000	8/21/2000	9/16/2000	10/8/2000	5/17/2001	5/31/2001	6/21/2001	6/28/2001	7/18/2001
3	Total	8.91	9.61	8.68	8.26	8.26	9.75	9.21	9.02	8.72	9.09	9.04	9.71	8.79
3	Dust	0.99	1.63	0.89	0.56	0.31	2.01	1.48	1.63	1.00	1.29	1.30	1.87	1.07
3	Filter #8	4.28	4.40	4.48	4.32	4.32	4.32	4.39	4.15	4.60	4.66	4.35	4.32	4.32
3	Bag #8	3.56	3.30	3.30	3.36	3.22	7.69	7.75	7.37	3.14	3.09	3.34	3.50	3.46
3	Total	8.72	9.50	8.90	8.16	8.11	9.62	9.17	8.62	8.79	8.72	8.80	9.34	9.12
3	Dust	0.88	1.80	1.12	0.48	0.57	1.93	1.42	1.25	1.05	0.97	1.11	1.52	1.34
3	Filter #9	4.26	4.40	4.49	4.31	4.32	4.36	4.36	4.16	4.62	4.64	4.31	4.34	4.34
3	Bag #9	3.33	3.38	3.44	3.36	3.21	7.83	7.79	7.40	3.14	3.61	3.40	3.51	3.42
3	Total	8.43	9.59	8.96	8.23	8.23	9.43	9.25	8.23	8.65	9.50	8.64	9.10	8.86
3	Dust	0.84	1.81	1.03	0.56	0.70	1.60	1.46	0.83	0.89	1.25	0.93	1.25	1.10
4	Filter #10	4.28	4.41	4.49	4.34	4.36	4.32	4.34	4.16	4.63	4.63	4.36	4.34	4.32
4	Bag #10	3.35	3.47	3.31	3.36	3.30	7.69	7.68	7.40	3.15	3.31	3.31	3.25	3.45
4	Total	8.61	8.62	9.14	8.16	8.24	9.12	9.42	8.10	8.55	9.18	9.49	8.02	8.81
4	Dust	0.98	0.74	1.34	0.46	0.58	1.43	1.74	0.70	0.77	1.24	1.82	0.43	1.04
4	Filter #11	4.22	4.41	4.40	4.34	4.33	4.32	4.30	4.15	4.61	4.66	4.34	4.35	4.28
4	Bag #11	3.58	3.49	3.27	3.33	3.29	7.73	7.55	7.38	3.15	3.57	3.37	3.48	3.52
4	Total	8.30	8.63	8.63	8.10	8.27	8.78	9.25	8.07	8.52	9.92	9.02	8.52	9.04
4	Dust	0.50	0.73	0.96	0.43	0.65	1.05	1.70	0.69	0.76	1.69	1.31	0.69	1.24
4	Filter #12	4.20	4.43	4.37	4.37	4.30	4.36	4.30	4.14	4.64	4.62	4.33	4.37	4.34
4	Bag #12	3.39	3.58	3.25	3.33	3.27	7.72	7.63	7.35	3.17	3.35	3.50	3.43	3.52
4	Total	8.22	8.46	8.72	8.29	8.27	8.94	9.64	7.88	8.53	9.54	9.76	8.50	9.09
4	Dust	0.63	0.45	1.10	0.59	0.70	1.22	2.01	0.53	0.72	1.57	1.93	0.70	1.23

Section #		6/8/2000	7/3/2000	7/13/2000	7/27/2000	8/8/2000	8/21/2000	9/16/2000	10/8/2000	5/17/2001	5/31/2001	6/21/2001	6/28/2001	7/18/2001
7	Filter #19	4.21	4.44	4.38	4.35	4.38	4.33	4.20	4.64	4.62	4.70	4.35	4.34	4.39
7	Bag #19	3.53	3.53	3.42	3.33	3.36	7.61	7.69	7.95	3.09	3.33	3.28	3.35	3.54
7	Total	13.37	12.27	12.71	13.84	12.96	11.58	12.81	12.04	11.98	10.95	13.38	10.82	14.04
7	Dust	5.63	4.30	4.91	6.16	5.22	3.97	5.12	4.09	4.27	2.92	5.75	3.13	6.11
7	Filter #20	4.23	4.41	4.41	4.38	4.36	4.30	4.19	4.66	4.64	4.67	4.37	4.32	4.32
7	Bag #20	3.26	4.22	3.48	3.48	3.24	7.63	7.60	7.90	3.13	3.31	3.30	3.36	3.53
7	Total	13.69	12.48	12.40	13.88	13.51	10.96	12.53	11.42	12.25	10.94	13.36	10.77	13.43
7	Dust	6.20	3.85	4.51	6.02	5.91	3.33	4.93	3.52	4.48	2.96	5.69	3.09	5.58
7	Filter #21	4.22	4.45	4.44	4.36	4.41	4.35	4.16	4.64	4.64	4.67	4.36	4.33	4.33
7	Bag #21	3.32	3.27	3.38	3.28	3.22	7.64	7.41	7.88	3.13	3.28	3.30	3.40	3.34
7	Total	13.60	12.14	12.46	13.58	13.82	10.83	11.71	11.58	12.36	10.87	12.21	11.26	14.19
7	Dust	6.06	4.42	4.64	5.94	6.19	3.19	4.30	3.70	4.59	2.92	4.55	3.53	6.52
8	Filter #22	4.22	4.42	4.39	4.37	4.38	4.30	4.17	4.63	4.66	4.69	4.39	4.37	4.32
8	Bag #22	3.72	3.39	3.39	3.36	3.38	7.60	7.41	7.95	3.13	3.39	3.26	3.39	3.35
8	Total	9.20	11.35	9.65	9.55	8.82	8.99	9.65	9.76	9.15	9.25	9.19	10.09	10.97
8	Dust	1.26	3.54	1.87	1.82	1.06	1.39	2.24	1.81	1.36	1.17	1.54	2.33	3.30
8	Filter #23	4.24	4.42	4.42	4.38	4.30	4.34	4.15	4.65	4.65	4.71	4.37	4.33	4.35
8	Bag #23	3.30	3.20	3.40	3.45	3.24	7.62	7.58	7.97	3.14	3.54	3.36	3.42	3.36
8	Total	8.77	11.69	9.05	9.66	8.55	8.93	9.74	9.86	8.85	9.18	9.86	10.41	10.64
8	Dust	1.23	4.07	1.23	1.83	1.01	1.31	2.16	1.89	1.06	0.93	2.13	2.66	2.93
8	Filter #24	4.15	4.46	4.40	4.36	4.33	4.34	4.15	4.64	4.62	4.72	4.37	4.33	4.33
8	Bag #24	3.35	3.14	3.36	3.51	3.29	7.56	7.48	7.91	3.14	3.47	3.34	3.40	3.36
8	Total	8.61	12.10	9.06	9.49	8.63	8.94	10.03	9.47	9.00	9.13	9.74	10.28	10.59
8	Dust	1.11	4.50	1.30	1.62	1.01	1.38	2.55	1.56	1.24	0.94	2.03	2.55	2.90
9	Filter #25	4.23	4.44	4.42	4.38	4.32	4.31	4.20	4.66	4.61	4.73	4.35	4.34	4.35
9	Bag #25	3.50	3.11	3.35	3.58	3.27	7.63	7.59	7.89	3.20	3.41	3.34	3.34	3.29
9	Total	8.29	12.81	9.97	9.20	9.34	9.20	11.23	9.59	9.74	9.90	11.10	10.58	11.27
9	Dust	0.56	5.26	2.20	1.24	1.75	1.57	3.64	1.70	1.93	1.76	3.41	2.90	3.63

Section #		6/8/2000	7/3/2000	7/13/2000	7/27/2000	8/8/2000	8/21/2000	9/16/2000	10/8/2000	5/17/2001	5/31/2001	6/21/2001	6/28/2001	7/18/2001
9	Filter #26	4.21	4.46	4.40	4.36	4.30	4.35	4.36	4.63	4.63	4.70	4.34	4.36	4.35
9	Bag #26	3.47	3.12	3.37	3.59	3.30	7.70	7.73	7.86	3.24	3.51	3.29	3.51	3.31
9	Total	8.31	12.72	9.86	9.33	9.36	9.06	11.25	9.85	9.73	9.79	10.69	10.67	11.57
9	Dust	0.63	5.14	2.09	1.38	1.76	1.36	3.52	1.99	1.86	1.58	3.06	2.80	3.91
9	Filter #27	4.17	4.48	4.40	4.41	4.34	4.34	4.20	4.63	4.68	4.70	4.38	4.37	4.35
9	Bag #27	3.56	3.26	3.30	3.60	3.20	7.67	7.71	7.83	3.24	3.55	3.32	3.56	3.35
9	Total	8.37	13.06	9.80	9.14	9.71	8.73	10.77	10.08	10.08	10.37	10.39	10.72	12.59
9	Dust	0.64	5.32	2.10	1.13	2.17	1.06	3.06	2.25	2.16	2.12	2.69	2.79	4.89
10	Filter #28	4.22	4.47	4.42	4.35	4.36	4.31	4.17	4.60	4.66	4.67	4.34	4.33	4.38
10	Bag #28	3.45	3.36	3.25	3.45	3.23	7.67	7.44	7.76	3.22	3.54	3.29	3.65	3.42
10	Total	8.74	12.13	10.80	8.89	9.94	8.78	11.97	10.06	9.34	10.52	11.47	10.60	11.85
10	Dust	1.07	4.30	3.13	1.09	2.35	1.11	4.53	2.30	1.46	2.31	3.84	2.62	4.05
10	Filter #29	4.25	4.49	4.35	4.32	4.32	4.34	4.15	4.61	4.66	4.66	4.35	4.38	4.35
10	Bag #29	3.44	3.45	3.29	3.42	3.25	7.73	7.35	7.78	3.23	3.55	3.43	3.52	3.41
10	Total	8.69	12.24	11.40	9.04	9.94	9.14	11.76	9.84	9.30	10.52	11.63	10.37	11.92
10	Dust	1.00	4.30	3.76	1.30	2.37	1.41	4.41	2.06	1.41	2.31	3.85	2.47	4.16
10	Filter #30	4.26	4.48	4.40	4.32	4.35	4.31	4.17	4.61	4.65	4.67	4.35	4.33	4.36
10	Bag #30	3.34	3.51	3.25	3.41	3.28	7.73	7.44	7.75	3.24	3.62	3.50	3.43	3.44
10	Total	8.73	11.90	10.99	9.25	9.81	9.07	11.44	9.77	9.48	10.65	11.76	10.07	12.10
10	Dust	1.13	3.91	3.34	1.52	2.18	1.34	4.00	2.02	1.59	2.36	3.91	2.31	4.30