EFFECTIVENESS AND ENVIRONMENTAL IMPACT OF ROAD DUST SUPPRESSANTS

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16. Abstract

This report describes a research project conducted at Colorado State University to evaluate the relative effectiveness and environmental impact of road dust suppressants. The objectives were to develop a device that would provide a standard, quantitative and precise method of measuring dust from unpaved road surfaces; to evaluate the relative effectiveness of the different dust suppressants in common use and to assess the environmental impact in terms of possible water quality effects resulting from the use of the different dust suppressants.

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PREFACE

This report describes a research project conducted at Colorado State University to evaluate the relative effectiveness and environmental impact of road dust suppressants. The objectives of the study were to 1) develop a device that would provide a standard, quantitative and precise method of measuring dust from unpaved road surfaces, 2) evaluate the relative effectiveness of the different dust suppressants in common use and 3) assess the environmental impact in terms of possible water quality effects resulting from the use of the different dust suppressants. The study was primarily a field based research project, and was done between the periods of spring to fall, 1993 and 1994. During the first year study (1993) five test sections were evaluated — four treated with different dust suppressants and one untreated. The dust suppressants used include 1) calcium lignosulfate, 2) calcium chloride, 3) magnesium chloride, and 4) calcium chloride-special. In the second year study (1994), four test sections were evaluated — three treated with three different dust suppressants and one untreated serving as the control. The dust suppressants include 1) lignosulfonate, 2) calcium chloride and 3) magnesium chloride.

The principal findings of this research are that 1) the dust-measuring device developed in this research, Colorado State University Dustometer, was found too extremely precise and inexpensive, 2) the use of road dust suppressants significantly reduces the emissions of fugitive dust and loss of fines from unpaved road surfaces, 3) aggregate pullout and periodic maintenance of unpaved roads are lower with the use of dust suppressants when compared to untreated roads and 4) surface runoff from the treated test sections show significant dust suppressant concentrations although the mass entering the environment is small. The information contained in this report can be used by managers of unpaved roads to evaluate dust suppressing techniques.

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EXECUTIVE SUMMARY

The research project entitled "Effectiveness and Environmental Impact of Road Dust Suppressants" was undertaken at Colorado State University in cooperation with the Larimer County Department of Roads and Bridges. The project was sponsored by the Department of Transportation through the Mountain Plains Consortium.

Low-volume unpaved roads are known to form a large part of the road network in the United States. Their use contributes substantially to the particulate loading in atmospheric air pollution. In addition, fugitive dust from unpaved roads means loss of essential fines from the road surface. The fines act as the binder that holds the surface of unpaved roads together. When fines are lost in the form of dust, road surfaces become unstable, increasing aggregate loss, harming drainage properties and dramatically increasing maintenance costs. To minimize the loss of fines and the associated problems, dust suppressants are used. Dust suppressants may be classified as 1) water (fresh and sea), 2) deliquescent and hygroscopic chemicals, 3) organic non-bituminous binders and 4) resinous adhesives. Of these classes, deliquescent and hygroscopic chemicals (which are chiefly chloride compounds) are the most widely used. The chloride compounds calcium, magnesium and sodium are also widely used as road deicers because of their additional property of lowering the freezing point of water. Their use as deicers has been noted to have adverse effects on water quality and roadside vegetation. Of the organic binders, lignin and its derivatives are widely used. Lignin has the disadvantage of being biodegradable and, like the chloride compounds, is also water soluble.

The objectives for this research project are 1) to develop a device that will provide a standard, quantitative and precise method of measuring dust from unpaved road surfaces, 2) to evaluate the relative effectiveness of the different dust suppressants in common use and 3) to assess the environmental impact in terms of possible water quality effects resulting from the use of the different dust suppressants. To meet the objectives set in this research, the Colorado State University Dustometer — a moving dust sampler —

was developed and used for the comparative dust studies of the research. The device provided a standard, quantitative, portable and precise method for measuring fugitive dust from the test sections. It has a potential for future dust studies. Road test sections were constructed in the Loveland area of Larimer County on county road (CR) 12/29. Three of the test sections were treated with different commercially available dust suppressants, namely, lignosulfonate, calcium chloride, and magnesium chloride. One control test section which was untreated was also constructed to help assess the relative effectiveness of the different treatments. Extensive traffic survey to determine the volume and type of traffic using the test sections was done. Comparative dust measurement and total aggregate loss measurement from each test section was carried out. A cost analysis for each test section was performed based on cost figures provided by Larimer County road officials. Surface runoff from the test sections were collected and analyzed during the study period to determine the amount of dust suppressants being washed off into the environment. A few of the conclusions and summaries from the research project are listed below:

1. The generation of vehicular dust from an unpaved road is significantly reduced by the application of dust suppressants.
2. The Colorado State University Dustometer, a dust-measuring device, developed and used in the comparative dust studies, is a portable, quantitative and precise research tool which can be used in future dust studies.
3. The amount of dust production measured using the Colorado State University Dustometer is linearly related to the velocity of the vehicle travelling the unpaved road.
4. Under the prevailing field conditions, the lignin-treated test section produced less dust than the chloride-compound-treated test sections during the test period.
5. There is an estimated 30-46 percent cost savings in treating the test sections with the different dust suppressants. The magnesium chloride-treated test section was found to be the most cost effective.
6. Water quality analyses indicate significant dust suppressant concentrations in runoff samples from treated test sections.

INTRODUCTION

Background and Statement of Problem

Out of the 3.8 million miles of road in the continental U.S., it is estimated that approximately 65 percent are aggregate and earth surfaced roads (Eaton, et al., 1988). The percentage of unpaved road networks varies between 30 and 70 percent in different parts of the country. For example, in Colorado approximately 65 percent of public roads are unpaved (Colorado Transpr. Info. Center. #5, 1989). Most of the unpaved roads are classified as low-volume secondary roads and are located in the rural and forest areas. While unpaved roads carry a small portion of the nation's traffic, they provide a vital first link in the nation's economy.

One major and obvious problem associated with all unpaved roads is fugitive dust. Airborne dust can penetrate homes, causing a nuisance and health problems, such as hay fever and allergies, to residents living along unpaved roads Dust can also be a conveyor of other diseases (United Nations, 1979). Fine suspended dust particles contribute significantly to the particulate loading in the atmosphere, making road dust a major source of air pollution. The dust cloud formed when vehicles use unpaved roads can impair the visibility of motorists, leading to accidents and other road hazards. The fine abrasive particles can also greatly increase the wear and tear on the moving parts of vehicles. The dust can also pollute nearby surface waters and stunt crop growth by shading and clogging the pores of the plants (Colorado Transpr. Info. Center. #3, 1989).

Besides polluting the environment, the generation of dust means road degradation as a result of loss of fines which act as road surface binder. The loss of fines represents a significant material and economic loss. The severity of the dust problem is determined primarily by the type and speed of vehicles, the abrasive resistance of the road aggregates and the amount of fines in the initial aggregate mix (Colorado Transpr. Info. Center. #3, 1989). The volume of traffic and the climatic condition of the region are also important parameters affecting road dust production. Long dry spells in semiarid and arid regions can also aggravate the road dustiness.

The loss of fines from the road surface as dust leads to the coarser aggregates becoming loose, so they can be more easily thrown or washed away from the road surface. The resulting road is one that is full of corrugations and potholes that require costly maintenance. The amount of dust from an untreated unpaved road can be appreciable: "For every vehicle traveling one mile of unpaved roadway once a day, every day for a year, one ton of dust is deposited along a 1,000-foot corridor centered on the road" (USDA Forest Service, 1983). The high maintenance cost in terms of aggregate replacement, increased public awareness of pollution problems and increased road user cost, has lead highway agencies to have a renewed interest in dust control measures. The frequently used dust control methods include reduction of vehicular speed, application of water and the use of dust-suppressing chemicals.

Although dust control has been practiced for decades, quantitative studies on the effectiveness of the various dust suppressing methods and their environmental impact have been virtually nonexistent. The purpose of this research project, therefore, is to evaluate, under field conditions, the effectiveness of some of the commonly used road dust suppressants, and to investigate water quality effects resulting from their use.

Objectives

The primary goal of dust control is to stabilize the road surface, thus reducing the rate of aggregate loss and the money spent annually in aggregate replacement. In recent times, another goal has been to diminish dust emission to maintain acceptable air quality, particularly in urban centers. Both goals are complementary, making the achievement of dust reduction an interest of both environmentalist and the road departments. Methods for dust suppressing range from the use of dust-suppressing chemicals, chiefly chloride compounds and resinous adhesives, to the utilization of geotextiles in the road surface during construction. There are a number of these dust suppressants on the market now. Notable among them are lignin derivatives — waste from paper production operations; calcium, magnesium, and sodium chlorides — deliquescent and hygroscopic by nature; Cohorex — a proprietary product; bitumens/tars, and many others. So far, many claims as to the effectiveness of these chemicals have been made, but quantitative assessments of these claims have been scarce. This may have been due to the fact that there was not an easy and inexpensive method to measure dust production in the field. Therefore, the objectives identified for this research project are to:

1) Develop a device that would provide a standard, quantitative and reproducible method of measuring dust from unpaved road surfaces.
2) Evaluate the relative effectiveness of the different dust suppressants in controlling dust clouding, taking into consideration the prevailing climatic condition as well as field conditions.
3) Assess the environmental impact of using dust suppressants on water quality.

Tasks

The specific tasks of study include:

1. Review of the pertinent literature.
2. Development and construction of a dust sampling device attached to the rear of a vehicle.
3. Construction of test sections which include Lignosulfonate, calcium and magnesium chloride treated test sections and an untreated test section serving as the control.
4. Conducting a traffic survey to determine the volume and type of traffic using the test sections.
5. Measuring dust production from each test section.
6. Measuring aggregate loss from each test section.
7. Collecting and analyzing runoff from surfaces of test sections to assess water quality effects from the use of suppressants.
8. Analyzing the results.
9. Documenting and writing final report.

LITERATURE REVIEW

Problem of Road Dustiness

Nearly 65 percent of America's roads are unpaved (Eaton, et al., 1988), besides an even larger percentage of private roads and parking lots. In Colorado approximately 65 percent of the public roads and over 70 percent of local roads are unpaved (Colorado Transpr. Info. Center. #5, 1989). These unpaved roads are located in the agricultural and forest areas and in cities, town and villages. Although they are low-volume and low-load-bearing roads, they are a vital first link in the local economy.

An unpaved road can be said to consist of a mixture of gravel, sand and fines (silt and clay) in the proportions of 40-80 percent stone or gravel, 20-60 percent sand and 8-15 percent fines (Woods, 1960). The aggregates are blended and compacted into a strong dense surface crust hard enough to resist breaking down under traffic. A crown is provided at the center of the road and ditches are provided at the shoulders to facilitate drainage. The problem associated with unpaved roads is traffic-generated dust which facilitates the deterioration of the road surface and acts as a major source of particulate in the air. This involves public economics and environmental quality and is also a nuisance to the public (Hoover, et al., 1981). But dust from unpaved roads is more than just a nuisance:

1. It obscures the vision of drivers, so is a traffic hazard.
2. Dust particulates can be carried several hundred feet, penetrating nearby homes and covering crops, stunting growth due to the shading effect and the clogging of the plant's pores.
3. Dust is a common cause of allergies and hay fever and a conveyor of diseases, according to a United Nation study (United Nations, 1979).
4. The fine dust particles can be abrasive, increasing wear of moving parts of vehicles.
5. The loss of fines (road binder) as dust represents a significant material and economic loss (Colorado Transpr. Info. Center. #3, 1989).

6. The fine dust particles are washed off during precipitation and carried into streams, creeks and lakes, increasing their respective particulate loadings.

7. Fugitive dust from unpaved roads is a major non-point source contributor to the particulate loading in atmospheric air pollution (AQMCP, 1985).

The severity of a dust problem from unpaved road is determined primarily by the velocity, type and amount of traffic on the unpaved road. The condition can be aggravated by long dry spells, softer road aggregates and initially excessive soil binder in the road surface material (Colorado Transpr. Info. Center. #3, 1989). Without binder material (enough fines) and adequate moisture, the coarser material will be thrown and washed away from the road surface. When that happens the road begins to ravel, rut and washboard, leading to deterioration and costly repairs. Ultimately local governments end up spending enormous sums of money in aggregate replacement and maintenance. For example, in Larimer County, Colorado, during the 1994 fiscal year, out of the total budget of $10 million for county roads, over 12 percent was spent on aggregate replacement alone and another 18 percent on unpaved road maintenance (personal comm., 1993).

The problem of road dustiness has been around for a long time, and in the United States as early as 1909 the "Office of Public Roads" suggested clay-bound stones as the surfacing for unpaved roads to alleviate dusting and raveling (U.S. Dept. of Transportation, 1976). Mckee (1969) showed that evidence existed that suspended particulates have the potential to alter weather patterns. Dust is an air pollutant; studies show that particulate matter (PM) from unpaved roads is one of the major contributors to the micron and sub micron size (PM_{10}) emissions from non-point sources on a national basis. In a study conducted under the Air Quality Monitoring and Control Plan (AQMCP) for the city of Fort Collins, Colorado, fugitive dust emission from unpaved roads was estimated as 65 percent of the total source emission inventory (AQMCP, 1985).

Hoover, et al. (1973) showed that the concentration of silt-sized particles in the air behind a car moving at 35 mph on a moderately dusty unpaved road is about 100 times the pollution concentration in the air of an industrial city. A study commissioned by the American Petroleum Institute estimated that soil dust from agricultural tillage and unpaved roads contributed approximately 10 percent of the annual total particulate emissions on a global scale (Robinson, et al., 1971). Governmental regulations in recent years have accelerated the rate of air quality monitoring and control. For example, here in Colorado the Clean Air Act of 1982 (Title 25) specifically section III.D.2.a(i.)(B) of Regulation 1 states in the general requirement that: "Any owner or operator responsible for construction or maintenance of any (existing or new) unpaved roadway which has vehicle traffic exceeding 200 vehicles per day in attainment areas or 150 vehicles per day in non-attainment areas (averaged over any consecutive 3-day period) from which fugitive particulate emissions will be emitted shall be required to use all available practical methods which are technologically feasible and economically reasonable in order to minimize emissions resulting from the use of such roadway." Regulations like this and the general public's perception about air pollution can have a considerable impact on local government's maintenance and/or construction procedures for unpaved roads.

Type of Dust Suppressants

In relation to unpaved roads, dust suppressing and road surface stabilization go hand-in-hand. Dust suppressing, which involves incorporating a dust suppressing chemical into the road surface by spraying, prevents the loss of fines, thus stabilizing the road surface material. Road surface stabilization, on the other hand, involves incorporating a binding material into the road surface by mechanically mixing the binder with the road material. This causes the finer materials to be firmly bound to the coarse material, thus preventing the loss of fines.

Presently, many proprietary products are available for dust palliation. They range from organic and inorganic chemical mixes to synthetic fabrics which are used to physically contain the road material. Dust suppressants may be classified under the following headings:

1) Water (fresh and sea)
2) Deliquescent and hygroscopic chemicals
3) Organic, non-bituminous binders
4) Resinous adhesives

Water (fresh and sea)

Water for the most part is readily available but suppresses dust only temporarily: maybe for a few hours. It requires frequent applications due to evaporation depending on weather conditions. As suggested in Compendium 12 (1980), several light applications should be carried out instead of one heavy application to prevent the excess water from turning the dust into soft mud, washing away fines or even penetrating the road to the subgrade, resulting in road failure. Seawater is said to be generally more effective in controlling dust than fresh water due to the presence of small amounts of deliquescent chemicals — chiefly magnesium chloride (Compendium 12, 1980). Under sufficiently humid conditions, the salts will hold the water they absorb and the road surface will remain damp for a longer time than if fresh water is used. Brine resulting from the production of salt from seawater can also be used as dust suppressant with favorable results.

Deliquescent and Hygroscopic Chemicals

These are mainly chloride compounds. Calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), sodium chloride (NaCl) and mixtures of calcium and sodium chlorides are principally used. $CaCl_2$ and $MgCl_2$ possess both deliquescent and hygroscopic properties and therefore have a high affinity for water. Deliquescence is the property of dissolving and becoming a liquid by attracting and absorbing moisture from the air. This property is influenced by the vapor pressure and solubility of the substance. The vapor pressures of salt solutions are usually less than those of water in the atmosphere at the same temperature. Hygroscopicity is the property of readily absorbing and retaining moisture. It depends on the exposed surface area of the substance: more moisture is absorbed when the substance is finely divided (Compendium 12, 1980). These properties are closely related to relative humidity and air temperature (Hogentogler, 1938). Sodium chloride does not possess these properties at the levels of $CaCl_2$ and $MgCl_2$.

$CaCl_2$ is obtained as a byproduct of the ammonia-soda (Solvary) process and also as a joint product from natural salt brine (Lowenheim, et al., 1975). $CaCl_2$ is 36.1 percent calcium and 63.9 percent chloride and forms several stable hydrates.

$MgCl_2$ is prepared from magnesium ammonium chloride hexahydrate in the presence of hydrochloric acid (HCl), according to the Merck Index (1989). $MgCl_2$ is 25.4 percent magnesium and 74.5 percent chloride.

NaCl, known as common salt, occurs in nature as the mineral halite. It is produced by mining rock salt as well as by the evaporation of brine from underground salt deposits. It can also be produced from seawater by solar evaporation (Lowenheim, et al., 1975). NaCl is 60.6 percent chloride and 39.4 percent sodium.

$CaCl_2$, $MgCl_2$ and NaCl all depress the freezing point of aqueous solutions in relation to their concentration. This effect is more pronounced in $CaCl_2$ and $MgCl_2$ than in NaCl. As reported in Woods (1960), a 30 percent $CaCl_2$ solution would freeze at approximately -51°C (-60°F), a 22 percent $MgCl_2$ solution would freeze at about -33°C (-27°F) while a 25 percent NaCl solution would freeze at -21°C (-6°F). In chloride-treated roads this property minimizes frost heave and reduces freeze-thaw cycles. It also makes these chloride compounds effective road deicers (Hanes, et al., 1970).

Studies done on the effect of relative humidity on chloride compounds reveal that $CaCl_2$ ceases to absorb moisture when the relative humidity falls below 30 to 40 percent depending on its purity (Compendium 12, 1980). $MgCl_2$ is said to start absorbing water at 32 percent relative humidity (Hansen, USFS). NaCl on the hand can only absorb water when the humidity exceeds 75 percent (Compendium 12, 1980). Hogentogler (1938) studying $CaCl_2$ deliquescence reported the relative humidity at which $CaCl_2$

will dissolve for a given temperature (Table 1.1). Data from Brudal (1941) on the subject is illustrated in Figure 1.1. The inability of these chloride compounds to attract and absorb water at low relative humidity could have an effect on their ability to suppress dust on unpaved roads in the semiarid and arid regions of the country.

Table 1.1 Deliquescence of Calcium Chloride

Relative Humidity	Temp. (°F)
20	100
30	74
40	44
43	32

Adapted from Hogentogler (1938)

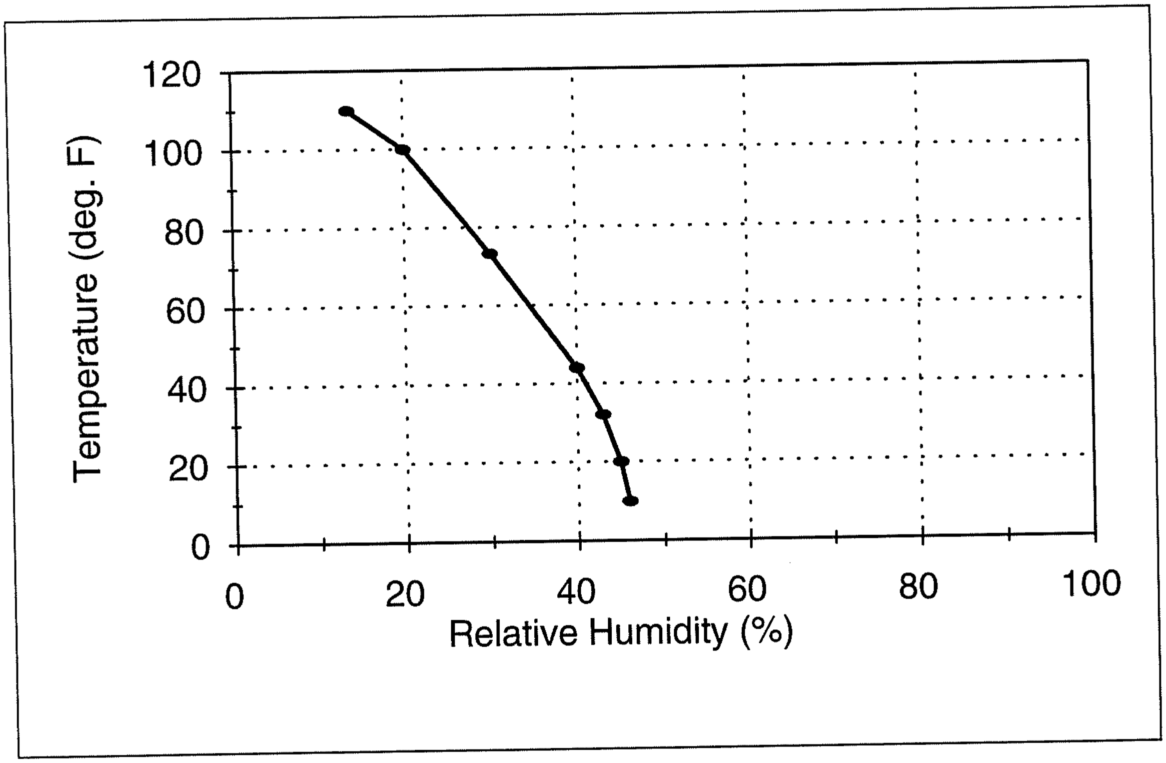


Figure 1.1 Relative Humidity at which Calcium Chloride is Effective at given Temp.
Adapted from Brudal (1941)

In areas where the temperature and relative humidity are in the zone to the left of the curve (Figure 1.1), $CaCl_2$ will not absorb sufficient moisture for it to be effective as a dust suppressant, although the evaporation of water from the road surface would be greatly reduced because of the lower vapor pressure of $CaCl_2$.

Chloride compounds are noted to significantly increase the surface tension of water molecules between soil particles when used in soil stabilization or dust suppressing. This property helps to slow evaporation and further increase the compacted density of the road as drying progresses (Colorado Transpr. Info. #3, 1989). $MgCl_2$ is reported to possess this property more than $CaCl_2$, with NaCl increasing surface tension slightly less than $CaCl_2$. These compounds are also noted to cause dispersion of clay in soil-aggregate mixture. The benefit of this is that when there is leaching out of the compound due to 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 stabilizer (Squier, 1974).

Deliquescent and hygroscopic dust suppressants can be applied either in aqueous solution or in solid form as flakes. As reported in Compendium 12 (1980), the latter is generally preferred, especially when heavy applications are to be made. The major problem with these types of suppressants is that they are water soluble and they also tend to migrate downward through the road (Slesser, 1941). As a result they are easily washed away by rain and therefore more than one treatment a year is usually required for them to be effective. Other noted disadvantages are that they are very corrosive to most metals. Their corrosiveness depends on the air temperature, humidity and concentration. Their storage is also a problem since the presence of moisture would make them damp and thus difficult to handle.

The method of application of chloride compounds depends on whether mixed-in-place application or topically sprayed application is desired. For topically sprayed application, power sprayers are used, while flakes are spread. In case of mix-in-place application the road surface is scarified, after which the suppressant is spread at appropriate rate and thoroughly mixed with the road material. The rate of application varies and usually depends on the field conditions as well as the level of dustiness. Other inorganic salts such as sodium and potassium silicates (Woods, 1960) are also used as dust suppressants. Their use is limited because they are not available in large quantities and hence are expensive.

Organic Non-Bituminous Binders

Organic non-bituminous binders have been in use as dust suppressants for several years. These suppressants include a variety of industrial waste products, animal fats and vegetable oils. Industrial by-products, with the exception of spent sulfite liquor, have not been investigated very thoroughly. Denny (1973) and Squier (1974) investigated a few of these binders in the laboratory, but only to a limited extent. Of the industrial by-products, lignin derivatives and molasses are the most important. One main concern with all organic non-bituminous binders is that they are very liable to oxidation which leads to their gradual degradation.

Lignin Derivatives

The lignin type dust suppressant is a waste product from the paper making industry. It contains lignin and carbohydrates in solution; however its specific composition depends on the chemicals and processes used to extract the cellulose. Lignin is said to be the natural cement that binds the fibers of wood together in plants (Brauns, 1952). Consequently, the lignin polymer and wood sugars act as a glue that binds soil particles together when used in road treatment. The most common process used in extracting lignin from pulping liquor is the sulphite process. The lignin obtained is called "lignosulfonate" and is water soluble. The term Spent Sulfite Liquor (SSL) is often used in place of lignosulfonate. From the digester the waste liquor contains approximately 8 percent solids. This is usually concentrated to 46-50 percent solids (Smith, 1954). Complete drying and pulverizing produces the powered form of lignin.

SSL has been used for successful treatment of unpaved roads in Europe, North America, and in Canada since the 1920s (Harmon, 1957; La Touche, 1959; Brudal, 1941). Initially, the aim of SSL treatment was simply dust abatement, which was accomplished by spraying light applications of dilute raw SSL onto dirt roads. The method gained importance when concentrated SSL was shown in various studies (La Touche, 1959; Harmon, 1957) to promote the stabilization and consolidation of roadway mixtures. According to Woods (1960), the lignosulfonate acts essentially as clay dispersant, making the clay more plastic at lower moisture content which, after compression, leads to a denser, firmer road surface. For this reason, fines are an important component of the road surface material and a prerequisite for successful road binding with SSL (Brudal, 1941; Statens Vaginstitut, 1940).

The method of application is usually mixed-in-place, which approaches the process of soil stabilization. Primary disadvantages are water solubility and biodegradability. The surface binding action may be reduced or completely destroyed by heavy rain and therefore additional treatment may be necessary to maintain effectiveness.

SSL is noted to be corrosive to aluminum and its alloys due to the presence of caustic compounds used in the extraction process (Compendium 12, 1980). As reported by Schotte (1958), the corrosive effect of lignosulfonate can be reduced by the addition of a calcium carbonate slurry. The carbonate is also noted to reduce the solubility of the compound and thus prolong the dust suppressing effect. Calcium lignosulfonate has been reported as a dispersing agent with beneficial effects on soil properties (Lambe, 1954). The addition of bichromate to SSL in a chrome-lignin soil stabilization study revealed that the mixture formed a gel and acted as a waterproofing agent (Hough, 1951). An increase in stability of the soil was also reported .

Molasses Residues

These are a byproduct of the sugar industry. They have been used as dust suppressants in a 50 percent solution in water, where they are sprayed on the road surface and then blended with sand (Compendium 12, 1980). Like most water-soluble compounds, additional treatment is needed during the year, particularly after heavy rain as the molasses dissolves. The addition of slake lime and charcoal to molasses is reported to yield a very good dust suppressant (Compendium 12, 1980).

Vegetable Oils, Animal Fats and Greases

These include linseed and cotton seed oils and wool grease derivatives. They are usually available in very small quantities and when used as dust suppressants they have little binding power and are therefore considered ineffective.

Resinous Adhesives

Waste oils, tars, bitumens and by-products from the plastic industry are considered under this class of dust suppressants. Waste oils such as engine oils and ship bunker oils have been used as surface treatment with sands and fine grain soils (Compendium 12, 1980). They possess very little binding power and therefore their effectiveness can only be prolonged with frequent treatment. Recently their use has been but all eliminated due to environmental concerns over the presence of certain heavy metals in the oils.

The present day production of tars (distillation of coal) and bitumens (distillation of crude oil) is a very carefully controlled process. The heavier grades of the residue are combined with the lighter fractions of the distillate to produce products with a wide range of viscosities (Compendium 12, 1980). The use of these products has lead to varying degrees of success in soil stabilization and road surface water proofing. The commonly used asphaltic products for dust suppressing are cutback asphalt and asphalt emulsions, with the latter being the most widely used (Hoover, et al., 1973).

Asphalt is a highly complex material, composed primarily of various hydrocarbon compounds (Schweyer, 1958; The Asphalt Handbook, 1965; Ritter, et al., 1967). Cutback asphalts are formed by adding various amounts and types of solvents to asphalt cement. The type of solvent used determines the type of cutback produced. Highly volatile solvents (gasoline or napthal) produces rapid curing (RC) cutback. Kerosene produces medium curing (MC) cutbacks and light volatile solvents produce slow curing (SC) cutbacks.

Asphalt emulsions on the other hand are relatively new in road surfacing in the U.S. with anionic emulsions first introduced in 1930 and cationic emulsions in 1958 (Mertens, 1959). Emulsions in general contain asphalt dispersed as small droplets in a water medium. The dispersion of the asphalt is maintained by the addition of emulsifying agent during formulation of the emulsion. Three classes of emulsions are generally available for highway purposes; rapid setting (RS), medium setting (MS) and slow setting (SS). The formulation and properties of emulsions are different from that of cutbacks; for detailed discussion see (Sumner, 1954; Bennett, 1968). Specification on the use of these bituminous materials are set by the Asphalt Institute, American Society of Testing Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHO) standard testing methods.

As dust suppressants, bitumen binders are usually applied at ambient air temperature and at rates which depend on the type of road surface material and the depth to be treated. For surface treatment, rates between 0.55 and 1.35 l/m^2 (0.1 and 0.25 gal/yd^2) are generally used. Mixed-in-place treatment application rate may be up to 5.5 l/m^2 (1 gal/yd^2) (Compendium 12 1980). On the whole, resinous adhesives provide the most durable dust-free surfacing due to their adhesive properties and insolubility in water. Their use may be adapted to suit a wide range of soils/gravels and traffic conditions.

Common to the success of all the above-mentioned dust suppressants is the structure and composition of the road surface material. As Squier stated (1974), "the road should have good mechanical stability in itself, since chlorides are not strong binders." Of lignin derivatives it is said that clay is a very important component of a good road soil (Hallberg, 1936). For bitumens and tars it is stated that the structure and composition of the aggregates is one of the most important factors that affect adhesion in an aggregate-asphalt system (Mertens, 1959; Day, 1965; Zvejnieks, 1958). For treated unpaved roads to provide the best results in terms of a dense, smooth-riding, dust-free surface that is strong enough to support even the heaviest vehicles, the road surface material must by themselves be mechanically stable.

Although dust suppressing is a very important maintenance operation due to the loss of aggregate and environmental concern with fugitive dust, the use of dust suppressants can be justified when:

1) the traffic is low

2) paving is not feasible because of budget constraint

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

4) when stage construction is planned.

As stated in Colorado Transpr. Info. #3, (1989) "the selection of a dust suppressant should not depend solely on its performance characteristics but also on the type and volume of traffic, roadway condition, climate, and product cost to achieve the desired level of dust control." In summary, the attribute, limitation, typical application rates and sources of the various dust suppressants discussed are noted in the charts in appendix A.

Effectiveness of Dust Suppressants

Numerous factors related to the effectiveness of dust suppressants have been reported by various researchers. Notable among the factors are the suppressant application method, moisture content of road surface material during application of suppressant, hydrological conditions, mechanical stability of road surface aggregate and the percent of fines in the aggregate mix, to mention a few (Hoover, et al., 1981; Lane, et al., 1984). There are two primary methods of incorporating suppressants into the road surfaces; 1) surface or topically sprayed application and 2) mixed-in-place or in-depth application.

Surface or topically sprayed application involves spraying the suppressant on the road after the road surface has been maintained (bladed and shaped with an "A crown"). The method is simple and fast (Woods, 1960). Suppressants applied by this method turn out to be effective for short periods of time, resulting in the need for repeated application in a single dust-production season. $CaCl_2$, NaCl, $MgCl_2$, lignin and cutback asphalt are usually applied using this method (Compendium 12, 1980).

Mixed-in-place application, which approaches the process of soil stabilization, involves the addition of the suppressant to the road surface material in-situ (Woods, 1960). This in-depth treatment is achieved by mechanically mixing the suppressant with the aggregate after the road surface has been scarified. 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 future higher type pavements.

Laboratory methods as well as on-site testing have been done in various studies to quantify dust suppressants' effectiveness. In one such study Lane, et al. (1984), used laboratory methods to quantify dust suppressant effectiveness. The methods included an unconfined compression test and a wet sieve analysis test. Three different commercially available suppressants were tested; a) an emulsified petroleum residue, b) a processed chemical derived from petroleum residues and c) calcium lignosulfonate. The unconfined compression test (ASTM test No. C-39) was used as an indication of the dust suppressant's cohesive strength under different drying conditions since the aggregate used had no cohesion. The wet sieve analysis was used as an indicator of the dust suppressant's ability to resist wash out during intense rainfall and thunderstorms since this is crucial to the longevity of the suppressant on the road surface.

Results indicated that each product tested varies in cohesive strength with a range of 34-300 kpa (5-44 psi). The calcium lignosulfonate at each of the initial aggregate moisture contents (4, 6 and 8 percent) showed a higher compressive strength than both of the petroleum base suppressants while the petroleum base suppressants resisted water stripping better than the lignin under air-dry conditions. The researchers concluded that, in general, chemical dust suppressant efficiency depends on the aggregate moisture content at the time of suppressant application.

The Quebec Department of Roads conducted laboratory tests comparing the engineering properties of lignin treated aggregate with that of raw aggregate and clay stabilized gravel (Hurtubise, 1953). It was reported that the bearing capacity of the aggregate treated with 1.2 percent lignin was higher than that of the raw aggregate and the clay stabilized aggregate. Compressive strength increased with the addition of only 2 percent of 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 increase in length of air curing.

Hoover, et al. (1981), in a mission-oriented project designed to quantify and evaluate dust control and surface improvement processes for unpaved roads tested various suppressants including $CaCl_2$ and ammonia lignosulfonate. Based on dust fall measurements (bucket method) and analytical techniques, Hoover recommended that for a dust suppressant to be judged as effective, a dust amount of not more than 1.7 g/m^2/day/100 vehicles (15 lbs/acre/day /100 vehicles) should be measured within a distance of 30.5 to 45.7 m (100 to 150 ft) from the centerline of the unpaved roadway. The $CaCl_2$ and ammonia lignosulfonate were found to be comparatively cost-effective as dust palliative.

Hoover, et al.(1973), in a highway research project (HR-151) tested several dust suppressants and road surface improvement agents. Of the twenty-two tested in laboratory experiments, six were selected and placed in test sections in Poweshiek, Linn, and Clinton Counties in Iowa for controlled experimentation. The chemicals tested were a MC-800 cutback asphalt, a cationic asphalt emulsion, lignin, lignin plus alum, lignin plus lime and a by-product from the Chemplex Plastic Co, Clinton, Iowa. The experiments, both laboratory and field showed approximately 30 to 80 percent reduction in dust from the treated roads as compared to the untreated with the amount of dust reduction depending on the method of treatment: surface application or mixed-in-place application. Aggregate pullout from the treated test section surfaces were found to be approximately 25-75 percent less than that of the untreated test sections.

HR-151 project demonstrated that indeed the use of dust suppressants and road surface improvement agents can control dust from unpaved roads while reducing the annual aggregate replacement by a factor of 2 to 4, the latter alone saving thousands of dollars in road maintenance cost. The project also showed that the effectiveness of suppressants depends largely on the method of application. Aggregate loss data from several surface application test sections and mixed-in-place application test sections (sections had lignin as suppressant) showed that the best mixed-in-place test section lost aggregate at the rate of 3.3 kg/km/vpd/year, while the worst surface application section lost 2185 kg/km/vpd/year or more than 600 times difference (Hover, et al., 1973; Handy, et al., 1975).

Squier (1974) in a cooperative research project with chemical stabilization agent producers evaluated the performance of fifteen chemicals in Linn County, Iowa. Volumetric dust measurements were made on six test sections. Test sections included lignin, lignin plus pramitol, two cationic emulsions, and a proprietary chemical called Kelpak in a mixed-in-place application and $CaCl_2$ in a surface sprayed application. Dust measurements were made using a volumetric dust sampling device mounted at the rear of a vehicle and driven at constant speed of 50 kph (30 mph). The two lignin based agents and the two cationic asphalt emulsions test sections produced less than 160 g and 48 g of dust /10^3 m^3 of air, respectively, as compared to over 881 g/10^3 m^3 measured prior to construction of the test sections. The proprietary chemical produced 104 g/10^3 m^3 with its control (untreated test section) producing 208 g/10^3 m^3 (13 lb/10^6 ft^3) of air. Dust measurements a year later showed that the lignin and the emulsions still produced significantly less dust, while the Kelpak produced as much dust as its control. Initial data from the $CaCl_2$ treatment showed 192 g of dust/10^3 m^3 of air and 432 g of dust/10^3 m^3 of air for the control. Approximately three weeks later after a dry spell the control was producing about 897 g while the treated section produced only 224 g. In less than a year later both treated and untreated were producing identical amounts of dust, confirming the need for more than one treatment per year for certain suppressants in order to maintain their effectiveness.

In a cost benefit study on roads conducted in the Seattle Industrial Valley, Robert (1975) reported that dust emissions from 30.6 km of gravel road and 177 km of paved but dusty roads contributed an estimated 2,455 metric tons/year of particulate matter into the atmosphere. Of this, 636 metric tons were of particle size of less than 10 microns (0.01 mm). It was suggested that paving roads having an average daily traffic (ADT) over 15 was the least costly method for controlling dust and a good investment when the traffic exceeded 100 ADT. Paving the road was estimated to produce benefits of nearly $3.9 million annually in household cleaning, health care, vehicle operation, sewer and road maintenance costs, coupled with increased property value.

Conclusion

Hoover, et al. (1981), writing about dust suppressants effectiveness stated "they must significantly increase the physico- and surface-activity of the road surface material in order for the fine material to remain in an aggregate form under adverse conditions of both weather and traffic." It is apparent that treating unpaved roads with some form of dust suppressant does indeed suppress dust and reduce the total aggregate loss from the road surface. The amount of dust emission reduction depends on the type of suppressant used, the method of application and the ambient weather conditions. Some suppressants such as lignosulfonate applied mixed-in-place were noted to be effective the whole year, whereas other suppressants such as $CaCl_2$ applied topically required more than one treatment to be effective the whole year.

The methods of dust measurement employed varied from research to research, making the comparison of dust data difficult. This underscored the need for a standard, inexpensive, reliable and precise method of measuring dust from unpaved roads.

Dust Measurement Techniques

Most of the research done in dust measurement has been in the area of air pollution. The focus of the atmospheric scientists has largely been on aerosol size particulate measurement; the contribution of dust from unpaved roads to the total particulate loading in the atmosphere has also been of interest. In the area of dust measurement, the studies have focused mainly on two categories: 1) atmospheric modeling and prediction and 2) field measurement and quantifications (Hoover, et al., 1981).

Methods of air sampling used in the area of atmospheric pollution can be classified as sedimentation technique, filtration technique and photometric technique. The sedimentation technique is a simple sampling method used for measuring particulate fallout or dust fallout in community atmosphere. The method involves the use of open-top collectors which are usually glass jars, metal or plastic containers having a height about two to three times its diameter. After an exposure period, usually a month, the amount of particulates collected is expressed in terms of weight per unit area per 30 days. Sedimentation methods depend on gravitational force and are therefore limited to particle sizes of about 2 microns or greater. The details of the procedure are outlined in the manual of the American Society of Testing Materials (ASTM -D 1739).

The filtration method involves the suction of air over a filter medium. The choice of filter medium and sampling instrument is governed largely by the type of test to be performed and the information that is sought. For example, in the determination of mass concentration per unit volume of air, the primary objective is to collect a weighable quantity of aerosol within a reasonable period by means of a high-efficiency filter that has comparatively low resistance to high air flow rate. The high volumetric sampler is an example of a device that employs filtration technique (ASTM -D2928-71). The photometric method is based on the light scattering or absorption properties of particles. Particles of all sizes may reduce visibility by absorbing light. The amount of light scattered depends upon the concentration, size, refractive index, shape and color of the suspended particles (ASTM-D1899-61T). Most particle measurements have been on particle sizes of 10 micron (PM_{10}) or less because of the health hazard posed by that size particulate matter in the atmosphere.

Gottschalk (1994) reported that particulate matter of sizes 10 microns (PM_{10}) or less can be retained in the human respiratory system. Depending on which region of the respiratory system (nasopharynx, tracheobronchial and pulmonary) particle deposition occurs, it can take minutes to several weeks for the body to clear the particles. Although the human body has an immune response mechanism for the protection of the respiratory tract, serious health effects can result depending on the elemental constituents of the depositional particles and respiratory exposure time.

The need to improve predictions of particulate matter emission from unpaved roads has lead to many quantitative dust studies: several of these studies have proposed mathematical models for the generation and distribution of particulate emission from various source (Robinson, et al., 1971; Becker, 1978). Becker (1978) applied a Guassian plane model to dust generation from unpaved roads in Iowa and Kansas and concluded that dust levels of 60 mg/m^3 of air drawn using high volumetric sampler were not exceeded at approximately 6 m (20-ft) from either side of unpaved roads. Hoover, et al., (1973) using stationary collectors placed adjacent to unpaved roads measured dust levels in the range of 0.67 to 12.3 mg/m^2/day (6 to 110 lbs/acre/day). Also, the Environmental Protection Agency (EPA) in its attempt to have an estimate of the amount of dust generated from unpaved roads, published a formula (AP-42) which can be used to estimate unpaved road dust amounts. The empirical equation is based on the properties of the road surface material and the number of passing vehicles as well as their speed. It predicts the emissions of particle sizes in the range of 10 micron (PM_{10}) or less (U.S EPA, 1988). The equation is defined as follows:

$$E=5.9K\left(\frac{S}{12}\right)\left(\frac{V}{30}\right)\left(\frac{W}{3}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{d}{365}\right) \qquad \textbf{(1)}$$

Where: E = emission factor (lbs/vehicle-mile) of PM_{10} particles.

K = proportionality constant specific to the aerosol size range of emitted particles (0.45 for PM_{10}).

S = silt content of the road surface material, in percent of sizes smaller than 75 micron.

V = vehicle speed in miles per hour.

W = vehicle weight in tons.

w = number of wheels on the vehicle.

d = number of dry days per year with less than 0.01 inches of rain.

While the above equation has been used with success, recent field studies suggest that the AP-42 equation could both under- and overestimate the dust emissions from unpaved roads (William, et al., 1988; Muleski, et al., 1989).

The devices and techniques developed for road dust measurement employed one or more of the three particulate sampling techniques mentioned earlier, namely, sedimentation, filtration and photometric techniques. Hoover, et al. (1981), using a sedimentation technique involving cups installed by the side of unpaved roads provided data on the nature of dust generation and distribution. Wellman and Barraclough (1972) used visible light (photometric method) to measure dust concentration at a point along an aggregate surface road. Langdon (1984), using a filtration technique, built a portable cyclone dust collector and mounted it at the rear of a dust generation vehicle to measure the road dust over a section of the road instead of at a point. More recently Irwin, et al. (1986), in a cooperative study between Cornell University and USDA Forest Service, developed a device that measured the road dust in terms of air opacity using photometric technique. The above mentioned dust measurement studies are reviewed in detail below.

Studies by Iowa State University

In a dust control and road surface improvement study Hoover, et al. (1981), collected dust fallout from aggregate surfaced roads during the spring and fall months of 1978-80. The dust collection was done in order to assess the effectiveness of the various dust control and surface improvement processes being field tested. The dust collectors consisted of 6-inch (15.2 cm) diameter by 7-inch (19 cm) deep semi-rigid plastic containers, mounted 3 feet (91.4 cm) above ground level in accordance with ASTM D-1739. The dust data was analyzed by plotting on a log-log scale, the quantity of the depositional dust in lbs/acre/day/100 vehicles versus the distance from the centerline of the roadway. Kittleman (1973), Eaton (1964) and Lutenegger (1979) had all concluded that the deposition of particulates due to sedimentation varied logarithmically with distance from the source of generation. However, during the Iowa project it was observed that dust fall in any of the directions considered did not follow a perfect log-log relationship. It was noted that dust quantities during any period of the measurement were affected by the direction and velocity of the of the prevailing wind, topography of the road, trees, vegetation, moisture content of the roadway surface, type of roadway surfacing, humidity and other factors.

Dust measurement by ASTM - D 1739 is not without problems. Besides the time-consuming laboratory work of sample drying, removal of foreign matter and weighing of dust samples, the amount of dust collected can only quantify the road dustiness at a specific point along the stretch of road. As a result, due to the natural variations on the roadway (upgrades, downgrades, curves, etc.) the level of dust measured at a single point can not justifiably be used to characterize the degree of dustiness for an entire road section. This requires the use of many stationary collectors. In addition, the time required to generate a single data point could be as long as 30 days.

Photoelectric Dust Densitometer

In a USDA Forest Service research project during the summer of 1970 and 1971, Wellman and Barraclough (1972) observed and measured the amount of dust generated by logging, recreation and construction traffic on several types of aggregate-surfaced roads in the Winema National Forest. The dust measurement technique employed both photometric and sedimentation methods. A photoelectric densitometer was used to measure the dust density (opacity). The setup was stationary and the device consisted of a twelve-volt, 100-watt aircraft landing light used for illuminating the dust cloud produced by the passing vehicles. It had a recorder that recorded the percent of light transmitted through the dust cloud. Dust fallout was also collected using buckets in accordance with ASTM -D 1739. The photoelectric device used in the experiment is shown in Figure 1.2, while Figure 1.3 shows the setup of the test. Flashboxes were used to determine vehicular speed. Many factors influenced the procedure. These included temperature, humidity, sunlight and wind velocity/direction.

Although the photoelectric densitometer quantified the dust measurement directly in the field without any laboratory measurement, it provided a measurement valid for only a specific point along the road since the setup was stationary. The study concluded that the amount of dust generated by vehicle traversing an unpaved road is related to the vehicle's speed, gross weight, number of wheels, and its load shape factor, which influences the degree of turbulence created by the vehicle. The study also showed that there was a good correlation between the dust density measurement and the dust fall measurement.

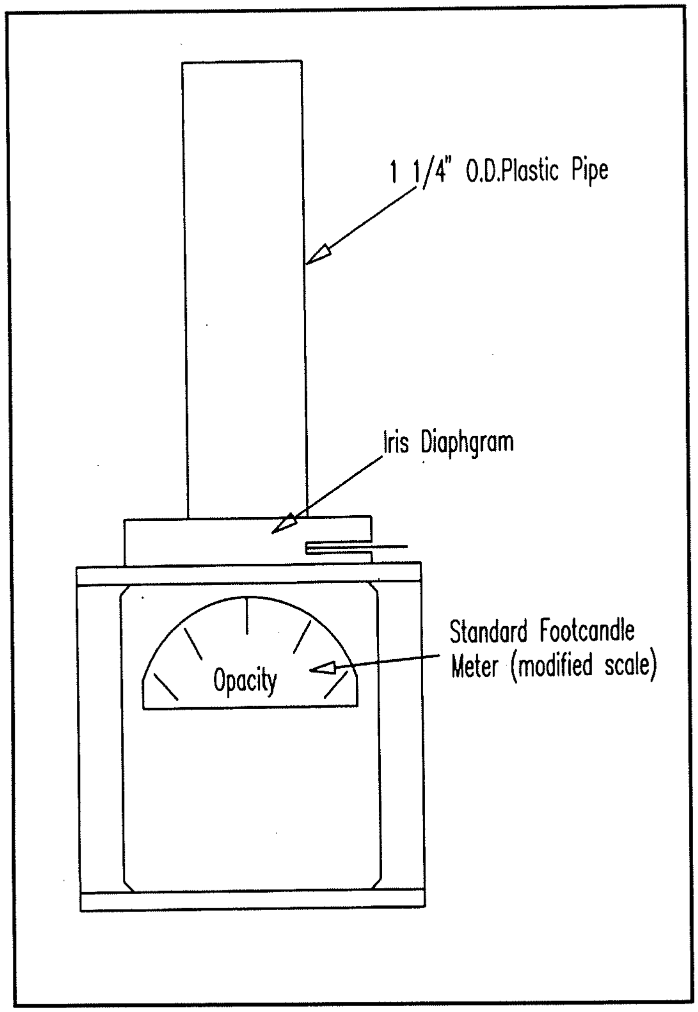


Figure 1.2 Photoelectric Dust Densitometer
(Adapted from Wellman and Barraclough, 1972)

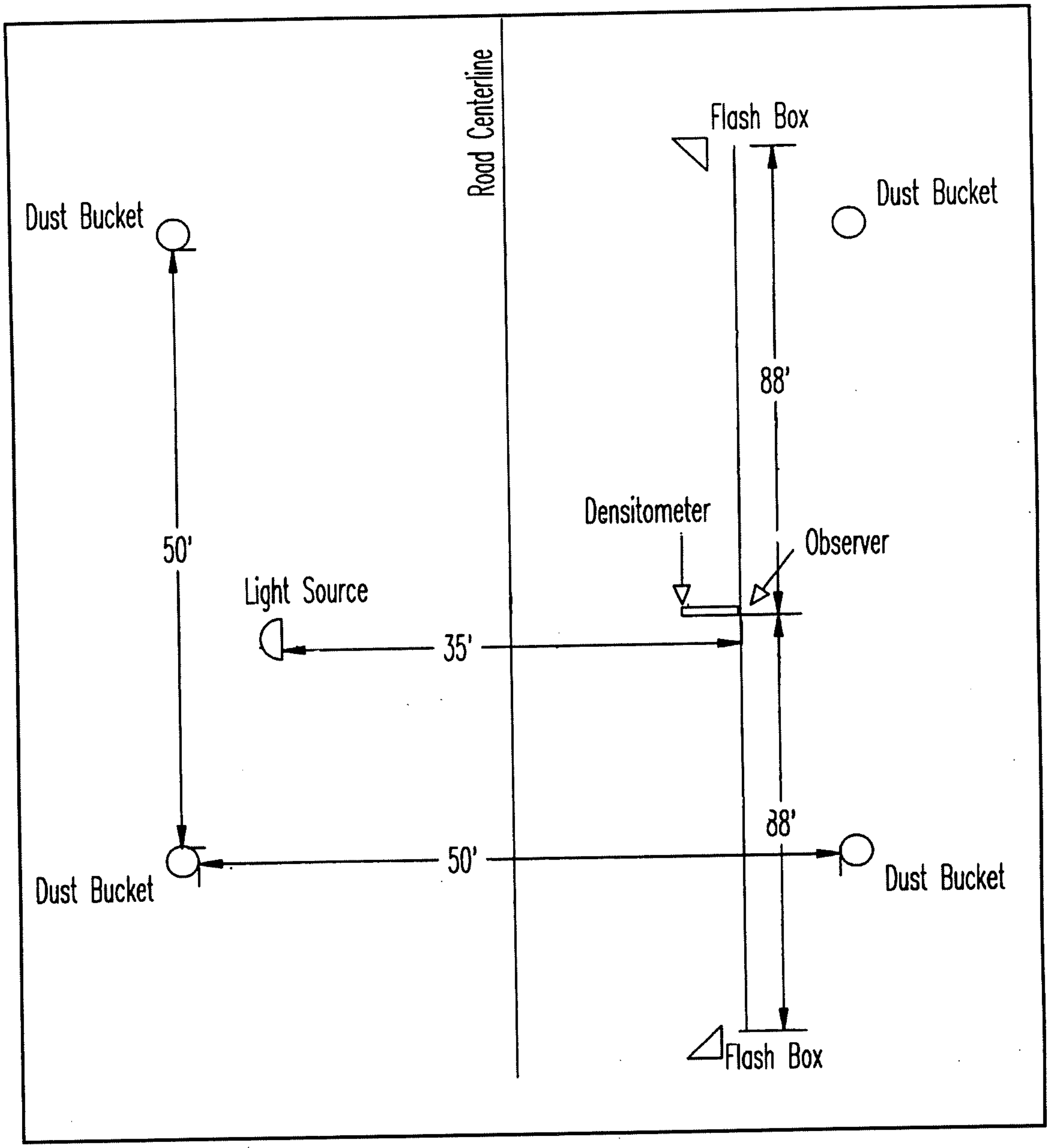


Figure 1.3 Flashboxes and Set-up of Photoelectric Densitometer

(Adapted from Wellman and Barraclough, (1972)

Dust Volume Sampler

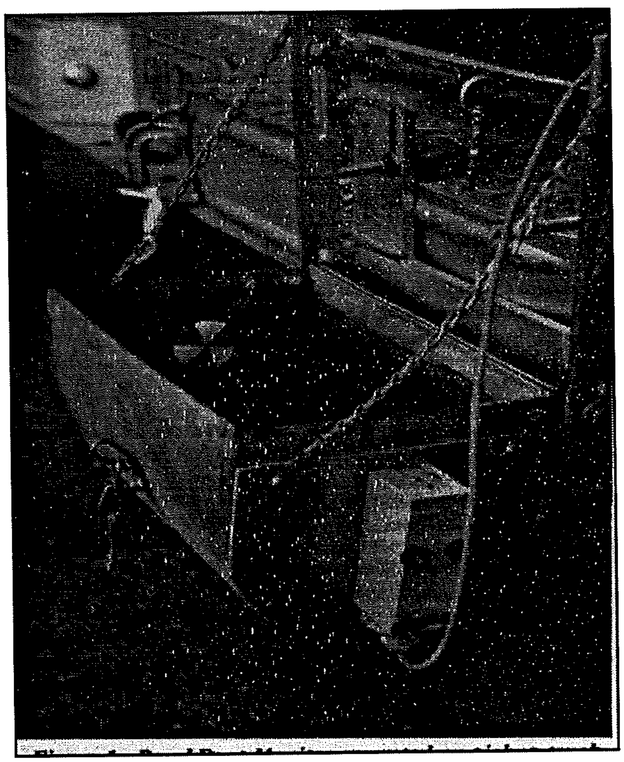
In a USDA Forest Service dust abatement study, Langdon (1984) measured dust over a section of roadway instead of at a particular point along the section. A section descriptor instead of a point descriptor was used for the dust quantification in order to take into account the characteristics of a road section (upgrades, downgrades, curves, variation in road surface material, moisture content, shading of the roadway by trees, etc.) which may influence the variability of dust generation from the section of the roadway.

Using the filtration sampling technique, Langdon put together a device consisting of a cyclone dust collector mounted behind the driver's side rear wheel of 3/4 ton pickup truck. As the test truck drives along the test section, dust kicked up by the left wheel enters the cyclone dust collector and at the end of the run the dust collected is quantified by weight. Driving the truck at a speed of 25 mi/hr the amount of dust collected ranged from 0 to 2.5 grams per 5000-ft of roadway.

Road Dust Monitor (RDM)

In a cooperative study by the Cornell University Local Roads Program and the USDA Forest Service, Irwin, et al. (1986), developed and field tested a device based on the photometric principle called the Road Dust Monitor (RDM). The idea behind the RDM was to provide a standard, repeatable and quantitative method of monitoring dust production from unpaved roads and also to provide Forest Service road managers with a more reliable and repeatable approach to deciding when to maintain an unpaved road rather than the qualitative method which is based entirely on human judgement and experience. The RDM consisted of an 8-in by 12-in (20.32 cm by 30.48 cm) galvanized sheet metal duct, and an instrument package with an indicating meter. The duct, which has a transducer system mounted in it, is positioned behind the driver's side rear wheel of a 1/2 ton pickup truck (Figure 1.4).

Dust kicked up by the truck as it moves along the roadway enters and passes through the duct. The transducer contains a light source and a photoelectric sensor. The light beam shines onto a reflector and the reflected light is detected by the sensor. Dust passing through the duct scatters or absorbs the light beam reducing the amount of light reflected back to the sensor. The sensor measures the reflected light and converts it to a voltage which is displayed on an indicating meter position in the cab of the truck (Figure 1.5).



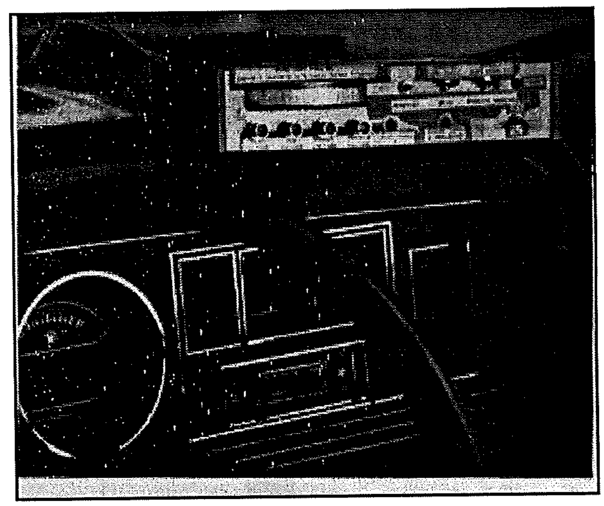


Figure 1.5 Voltage Meter Display mounted on Pickup Truck Dashboard

Figure 1.4 Road Dust Monitor mounted on Pickup Truck (Adapted from Irwin, et al., 1986)

The RDM measures the opacity of the air as the test truck travels the unpaved road. Figure 1.6 shows a typical instrument response curve. The measured air opacity varies as the vehicle moves along the roadway. The variations in the instantaneous dust reading were explained to be due to spotted sunlight which gave a higher reading than the shaded spots, higher readings on curves and lower readings on upgrades. These inherent road variations, along with changes in types of surface material according to

Irwin, et al. (1986), make it difficult to use a point response as a valid measure of road dust levels. As a result of the variation in road dust levels a section descriptor rather than a point descriptor is used to quantify the road dustiness in the RDM procedure. From the response curve (Figure 1.6) it appears that the area under the curve would be indicative of the cumulative dust generated as the test vehicle traverse the roadway.

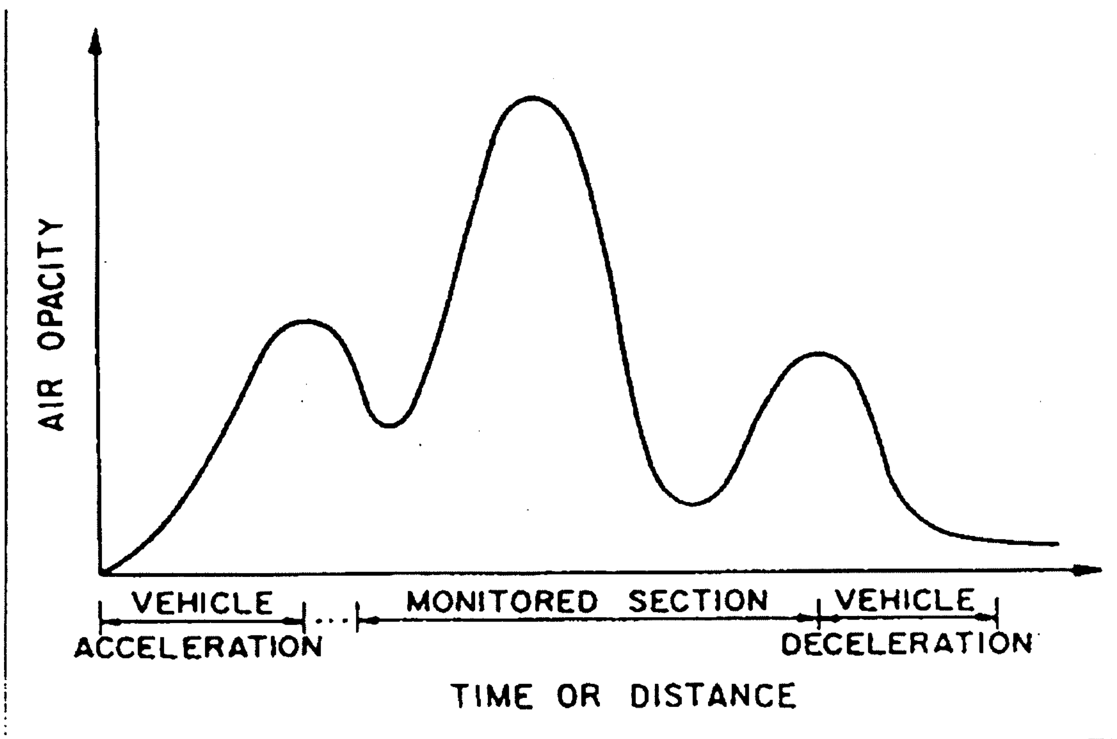


Figure 1.6 Road Dust Monitor Response Curve
(Adapted from Irwin et al., 1986)

Environmental Impact

Similar to road deicing, the liberal use of road dust suppressants could result in water quality degradation as well as air quality degradation. Although road dust suppressants have been in use since the beginning of the century, the review of the current state of knowledge reveals very sketchy direct information on their environmental impact as it relates to effects on water quality, roadside vegetation and animal life. The reasons 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 the rural areas, and thus can easily be ignored.
2. Some of the most commonly used compounds for dust suppressing, namely, calcium chloride, magnesium chloride and sodium chloride, 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.

Since the compounds used for dust suppressing are the same compounds used for road deicing, the literature review presented here is based on studies done on the effects of deicing salts on water quality, plant and animal biota. A review of the effect of deicers on roadside vegetation and soils is presented because of the profound effects salts have on the physiology and morphology of plants.

Effect of Deicing Salts on Water Quality

The use of salts for deicing or dust suppressing can contribute substantial amounts of the chloride ion to runoff from surface of roads treated with these compounds. Chloride in any body of water can come from many sources — seawater, natural brines, rain, surface runoff, sewage plant effluent, industrial wastes and agricultural chemicals. Table 1.2 lists some chloride sources and their average content.

Table 1.2 Chloride Content of Various Waters

Type of Water	**Chloride Content (mg/l)**
Rain water	2
Upland surface water	12
Unpolluted river water	up to 15
Spring water	25
Deep well water	50
Weak sewage	70
Medium sewage	100
Strong sewage	up to 500
Drinking water	10-20, but vary
Urine	4,500-5,000
Sea water	20,000

Adapted from Klein (1959)

Tidal water may contain a few mg/l up to 20,000 mg/l of chloride depending on the amount of seawater present. Streams that pass through salt-bearing strata can also contain high amounts of chloride. Natural brines in the Arkansas-Red River Basins have been reported to range in chloride concentration from 20,000 to 190,000 mg/l (Division of Water Supply and Pollution Control, U.S. Public Health Service, 1964).

Petroleum, natural gas and other mining activities produce tremendous amounts of chlorides that contaminate water. For every barrel of oil produced, about 100 barrels of salt water with chloride concentration ranging from a few thousands to about 20,000 mg/l may be released (Texas Water

Commission and Pollution Control Board, 1963). Sewage contains relatively high chlorides content (Table 1.2) and sewage treatment does not alter the chloride concentration in the effluent significantly. Human excreta, especially urine, has a high chloride composition. The average person according to (Sawyer, 1960) excretes nearly 6 grams of chloride daily, which adds about 15 mg/l of chloride to the average sewage flow. Varying amounts of chloride are also present in rain water.

Roadside Drainage

In studies done in Wisconsin to measure chloride concentration in roadside runoff from salt treated roads, Schraufnagel (1965) reported up to 10,250 mg/l chloride concentration measurement in the Chippewa Falls area during the winter although surface runoff during the same period had chloride concentrations of only 4.5 mg/l. The decrease was attributed to dilution. Measurement in the summer showed up to 16 mg/l chloride concentration in roadside runoff while streams 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 sodium and chloride concentrations of water samples taken daily over a 60-day period during March - April from a culvert that carried runoff from about a mile of Interstate Highway 95. The chloride concentration ranged from 38 to 84.5 mg/l with a mean of 57 mg/l whereas the sodium concentration ranged from 70 to 265 mg/l, with a mean of 168 mg/l. The Massachusetts Department of Public Works and the Water Resources Division of the U.S. Geological Survey in a study of groundwater from wells close to several highways in Massachusetts measured chloride concentrations of up to 250 mg/l in most of the samples. The highways ranged from newly built to 20 years old to give a variation in the number of years of salt application. They concluded that salt application to streets and highways for ice and snow removal may be affecting groundwater quality ("Side Effects of Salting for Ice Control," 1965).

Water samples extracted from soils 30 cm deep at edges of roads in Maine in April of 1967 revealed high concentrations of chloride and sodium (Hutchinson, 1967). The sodium values ranged from

66 to 725 mg/l and the chloride values from 40 to 130 mg/l. These values show that soils at the edges of roadways receiving deicing salts are becoming polluted. The high chloride content of roadside runoff especially in the winter months is due to the large amount of salt applications over a limited area with small water volume. This could post a potential danger of chloride contamination to nearby wells, ponds, and even streams with low flow rates.

Wells

The liberal use of deicing salt has lead to complaints to highway authorities in certain parts of the U.S. of suspected well pollution especially wells within the vicinity of roadways. During the period 1983-1990, Massachusetts Department of Public Works received complaints of salt contamination of public and private water supplies from about 100 of the 351 municipalities in Massachusetts (Pollock, 1992). Hutchinson (1966), in a study of the contribution of chlorides from deicing, sampled 20 wells in Maine. Of the 20 wells sampled, three that were not close to any road had less than 1.0 mg/l of chloride. Of the rest which were located close to roads, five contained about 100 mg/l of chloride with the highest containing 461 mg/l of chloride. This exceeds the maximum contaminant level (MCL) of 250 mg/l.

Followup research in 1967 by Hutchinson (1967) on another 20 randomly selected private wells all located near salt treated roads revealed that nearly 50 percent of the samples contain chloride concentrations of 250 mg/l at one time of the year. Most of the highly polluted wells were noted to be hand-dug and shallow, whereas those with low chloride concentrations were drilled and encased. The chloride concentrations were found to be seasonal and high in April (Hutchinson, 1967). Tthe study also found that repeated salting of the highways increased the chloride content not only of wells but of ponds near treated highways.

Lakes

In 1962 a study was done by the Wisconsin River and Lakes Commission to understand the effects of deicing chemicals on lakes in the Madison region. The results in terms of chloride concentrations are listed in Table 1.3. Five lakes were monitored during the research, which compared 1962 values to 1940-47 period values.

Table 1.3 Chloride Content of Lakes in the Madison Wisconsin Region

Lake	**Cl^- content (mg/l)** 1940 - 47 range Yearly Average	1962 range Indiv. samples
Mendota	2-3	5-10
Wingra	4-5	6-14
Monoma	6-12	13-15
Kegonsa	29-38	10
Waubesa	34-57	14

Adapted from Rivers & Lake Commission (1962)

Three lakes, Mendota, Wingra and Monoma, showed an increase in the chloride concentrations, while Kegonsa and Waubesa showed a decrease. The decrease in chloride concentration in the two lakes was attributed to the result of a diversion of Madison's sewage treatment plant effluent around these two lakes beginning in 1958. The commission concluded that although the use of chemicals had increased the chloride concentration in the lakes, the levels were of no threat to aquatic life (River and Lakes Commission, 1962). Schraufnagel (1965) sampled the outlet of lake Wingra on May 21st, June 9th and July 1st and measured chloride concentrations of 43, 41 and 40.5 mg/l respectively. It could be seen that during the summer months when the use of deicing salts have ceased, the chloride concentration decreases. Comparing Shraufnagel (1965) data with lake Wingra data in Table 1.3 it is interesting to note that there is a four-fold increase in the 1962 value and a eight fold-increase since the 1940-47 period. However the 1965 chloride concentrations are still considered insignificant as far as water use is concerned.

The concern over possible contamination of water resources by deicing compounds in certain regions of the U.S. does not end only with groundwater, ponds and lakes, but affects rivers and public water supplies as well. Although chloride concentrations in these public water supplies are still below the stipulated Drinking Water Standards, certain industrial consumers find the water undesirable (Karalekas, 1967).

Rivers

Hutchinson (1966,67) analyzed major rivers in the Maine area for sodium and chloride levels during the salt application period. The concentration of these ions rose from 1 to 2 mg/l in a month in sections of the rivers where road density was highest. Analyses of two waterways that fed into Kenduskeag stream yielded an average chloride concentration of about 57 mg/l for a 60-day period. The chloride concentrations in the waterways were higher than that of the receiving stream. Since there is very little industrial pollution within this area, Hutchinson concluded that road salts contamination was significant in these waters. Analyses of the Kenduskeag stream before it entered the city of Bangor yielded an average sodium and chloride concentration of 4 and 6.5 mg/l respectively. In the center of the city, after the stream had received water containing roadside drainage, the mean sodium concentration measured 5.3 mg/l and that of the chloride measured 10 mg/l (Hutchinson, 1966). Comparing the upstream and downstream figures it is apparent that the sodium and chloride concentrations of the stream are affected by the drainage water that entered it. However, due to the large dilution factor, the concentrations of these ions are still low. Having analyzed the rivers in the Maine region Hutchinson (1967) stated: " It can be concluded from the results obtained in the first two years of this research that sodium and chloride ion concentrations in rivers of Maine are not being seriously affected by deicing salts. In no instance is the concentrations of these ions sufficient to pose a health hazard for men or other animals."

Effect of Deicing Salts on Animal Biota

Humans

The Drinking Water Standards set forth by the Environmental Protection Agency (EPA) and supported by the American Water Works Association (AWWA) states that the maximum chloride concentration of water for domestic use should be 250 mg/l. However, in certain documents a desirable limit of less than 25 mg/l is recommended. This restriction is base solely on taste and palatability rather than health. In certain states, especially those in the arid and semiarid region where the water supplies naturally have mineral concentrations well in excess of the recommended values, the use of these waters have proven adequate. Sawyer (1960) reported that water containing chloride concentrations as high as 2,000 mg/l has been used without any adverse effects once the human system has adjusted to it.

One of the major adverse effects of the chloride ion in water is taste. A salty taste can be produced by as little as 100 mg/l chloride concentration in some waters whereas in others as much as 700 mg/l would not affect the taste (Standard Methods', 16th ed., 1985). In research done on the amount of sodium and calcium chlorides that can affect water taste, Moore (1950) reported a range of 200-900 mg/l for sodium chloride and a range of 150-350 mg/l for calcium chloride. Lockhart, et al.(1985), reported that the threshold amount of sodium chloride in water that would affect the taste of brewed coffee is 345 mg/l: an equivalent of 135 mg/l sodium and 210 mg/l chloride. That of calcium chloride was reported as 347 mg/l which is equivalent to 125 mg/l of calcium and 222 mg/l of chloride. Calcium concentration as high as 1,800 mg/l in water has been reported harmless to man (Ohio River Valley Water Sanitation Commission, 1950).

Hardness in water is caused by the presence of multivalent cations. Thus the objection to calcium and magnesium in water supplies is their adverse effect of producing hard water. Hardness of more than 100 mg/l has been noted to increase soap consumption and incrustation of utensils (Phelps, 1984). Hard water form scales in hot water heaters/boilers, pipes, and utensils, thereby decreasing their useful life.

In human health, excessive chloride concentration is noted to be harmful to some people with heart and kidney diseases (Mckee and Wolf, 1963). It has also been well documented in medical science that excessive amounts of salt can aggravate high blood pressure and related effects such as hypertension (Payne and Callahan, 1983). Health hazards from deicing salts entering domestic water supplies can at best be speculative. There have been reports of increase sodium, calcium, and chloride ions concentrations in water supplies of which some are due directly to deicing chemicals (Donahue, 1965). However, the concentrations at which these ions which are detrimental to humans differ with each situation and individual. Schraufnagel (1965) stated that the concentration of calcium and sodium chlorides found in water thus far are relatively harmless and far below those values considered as having adverse effects on water consumption.

Animals

Humans are noted to have less tolerance for water with high salinity than animals. The California State Water Quality Control Board (Mckee and Wolf, 1963) has indicated that water having a chloride concentration of 1,500 mg/l would be suitable for livestock and wildlife. In states such as Colorado and Montana in the semiarid region water supplies with chloride concentration of about 2,000 mg/l are acceptable. In Western Australia, water containing up to 5,000 mg/l of salt are allowed to be continuously used by livestock. The upper safe limit allowed are 2,860 mg/l for poultry, 4,290 mg/l for pigs, 6,435 mg/l for horses, 10,000 mg/l for cattle beef and 12,900 mg/l for adult dry sheep (Officers of the Dept. of Agriculture and Government Chemical Laboratories, 1950). Peirce (1966) found that water containing 2 percent salt was very toxic to sheep, 1.5 percent was harmful to some sheep by lowering their food intake and therefore suggested 1.3 percent sodium chloride (13,000 mg/l) as the safe upper limit. Heller (1932) studying the effect of calcium chloride on rats reported; 10,000 mg/l interfered with the production of normal litters, 15,000 mg/l reduced the growth rate, 20,000 mg/l affected lactation and 25,000 mg/l caused death. Similar to humans there could be health effects in animals as the result of excessive salt use. The

National Technical Advisory Committee to the Secretary of the Interior (1968) stated that "salinity may have 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 with the use of deicing salts according to Donahue (1965) is that widelife would be attracted to the highways due to " salt craving," which could create traffic hazard to both motorist and animals.

Fish

The tolerance of fish to various concentration of salts has been well documented and their mortality is undoubtedly attributed to osmotic phenomenon related to salting. Ellis (1973) stated that any effluent with an osmotic pressure above 6 atmosphers will kill fresh-water fish. Marine fish are noted to survive better in fresh water than vice versa and here in North America it has been found that for every fresh water fish that went into the ocean, nine species of marine fish came into fresh waters (Ellis, 1973).

A study was done on a brine-polluted stream with an upstream and downstream chloride concentrations of 20,000 and 100 mg/l respectively. Fish life was found to be nonexistent in the stream where the chloride content exceeded 1,000 mg/l (Clemens, et al., 1955). Ellis (1973) reported that a concentration of 227 mg/l calcium chloride ($CaCl_2$) in distilled water did not harm minnows exposed for over 5-7 week period. The threshold of $CaCl_2$ concentration has been reported as 12,060 mg/l for pickerel and 22,080 mg/l for white fish (Ohio River Valley Water Sanitation Commission, 1950). In a research done using lake Erie water, the addition of 920 mg/l $CaCl_2$ immobilized Daphnia and the addition of 1,830 mg/l $CaCl_2$ killed the Daphnia and other aquatic crustacean fish organisms within only 2 days (Anderson, 1984).

Effect of Salts on Plant Biota

Salts applied to roads and streets for deicing or dust suppressing can be carried by surface runoff into streams and waterways or they can infiltrate soils bordering the treated roadways. When soil infiltration occurs, ions of the salts can flow with drainage or groundwater, remain in soil solution or become absorbed by the soil. The presence of salts can increase the salinity (the total salt concentration) of water, thereby rendering the water unpotable. The infiltrate with high salt concentration can cause soils to lose its ability to support desirable plant growth.

Methods and techniques used in ascertaining water quality in relationship to salt content and its effect on plants have been established by various agriculture agencies. For detailed reference refer to Agriculture Handbooks, Allison (1964) and others. The water property most commonly used to determine water suitability for plant use is the total soluble salts, referred to as salinity and expressed as the Electrical or Specific Conductance (EC) in millimhos per centimeter. To measure the effect of salinity on plants, analyses of soil-water extract and plant tissue should be performed (Allison, 1964).

Plants and vegetation growth are physiologically and morphologically affected by the accumulation of soluble salts in the root medium. 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 (ion balance in soils and tissues), and 3) accumulating specific ions to toxic concentrations in the plants. The osmotic pressure (OP) of a soil solution can be estimated using the relation established by Cambell et al. (1949).

$$OP = 0.36 x EC x 10^3 \quad \textbf{(2)}$$

Where: OP = Osmotic Pressure (atm)

EC = Electrical or Specific Conductance (mmhos)

The accumulation of salts in soil solutions leads to the increase in osmotic pressure. The effect of high osmotic pressure on growth inhibition is explained by the classical osmotic theory in terms of a decreased diffusion gradient between the soil medium and the plant. This causes severe moisture stress which limits the plant's water supply (Allison, 1964). When osmotic pressure is the predominant factor limiting plant growth, as observed by Lunin, et al. (1961, 1965), Berstein (1961), there is usually a progressive decline in growth, with an increase of salt concentration in plant tissues and sap. For grasses and other nonwoody vegetation, this principle applies along highways where deicing salts were used (Hanes, et al., 1976). The increased osmotic concentration due to the use of road salts would influence plants more during dry as compared to wet periods. This mode of salt effect on plants would also be more prevalent in the arid and semiarid regions.

Growth reduction and plant injury are also attributed to salt-induced toxicity and nutritional disorders. According to Hanes, et al. (1970), "nutrition problems arise when the introduction of certain salts causes imbalance of ions in soils, which upsets the mineral intake and composition of plants." As pointed out by Lunin, et al. (1942), increasing the $CaCl_2$ and NaCl in bean plants caused a marked decrease in the percentage of total nitrogen and nitrate nitrogen in the plant. Although the high concentration of one or more ions can interfere with the uptake of other nutrient ions in a plant, the degree of nutritional response depends on the type of plant.

The specific toxicity effects of salts are due to the accumulation of harmful concentrations of toxic ions in plant tissue. Usually this mode of salt effects in plants is referred to as salt injury. Such injuries are common in fruit, nut, shade and ornamental trees and shrubs (Bernstein, 1965). Allison (1964) stated that chloride accumulation of 1-2 percent of dry weight of leaves would cause marginal burn leading ultimately to leaf drop, twig dieback, and even death of plant. Such amount of ion concentration in leaves could occur with chloride concentrations of 700 to 1,500 mg/l in soil solution. In addition to the uptake of salts through roots, plants can absorb salt through foliage. Strong (1944) observed that trees along a roadside where $CaCl_2$ was sprayed to suppress dust were frequently injured. The injury was mostly leaf scorch. In one of the few studies investigating the effect of dust suppressants on plant life, Traaen (1950) found that the spraying of $CaCl_2$ to control dust on roads caused injuries to Norway Spruce trees. He explained that the salt-coated dust particles accumulated on the leaves absorbed moisture from the air and the resulting salt solution was in turn absorbed by the leaves.

Hanes, et al. (1970, 1976) under a National Cooperative Highway Research Program did a comprehensive study on the effects of deicing salts on the environment. The study was done in two phases. Phase one involved a thorough literature review of the effects salts have on water quality and biota. Phase two involved experimental work investigating the effect of deicing salts on plant biota and soil. Roadside and other environments coupled with laboratory and greenhouse research were used in the experimental phase. The research was done on the two most commonly used deicing salts which also happens to be frequently used road dust suppressants, namely, NaCl and $CaCl_2$. The following is a brief summary of some of their findings.

1. Investigations along a highway showed that deicing practices increased the concentrations of sodium and chloride ions and also the specific conductance in the roadside soils especially along the low side of the highway.
2. Silver Maple trees along the low side of the highway suffered extensive decline and death. Meanwhile along the opposite side (high side) of the highway, trees were healthy and soil had low specific conductivity and low salt content.
3. Eighteen woody species and grasses treated with the deicing salts under greenhouse conditions showed different and varying tolerance to treatment (see Table 1.4).
4. Plants tolerances to deicing salts tended to increase with age and size.
5. Fertilization minimized the harmful effect of deicing salts on plants.

Table 1.4 Salt Tolerance of Plant Biota

Plant Biota	Salt Tolerance
Deciduous Trees:	
Honey Locust	Good
Redbud, Sugar Maple, White Birch	Moderate
Tulip Poplar, Green Ash	Poor
Deciduous Shrubs:	
Honeysuckle, Privet	Good
Weigela, Forsythia	Moderate
Rose, Spirea	Poor
Evergreen Trees and Shrubs:	
Creeping Juniper, Adam's Needle	Good
Pfitzer Juniper	Moderate
Norway Spruce, White Pine, Hemlock	Poor
Temperate Perennial Grasses:	
Kentucky 31 tall Fescue	Good
Bromegrass, Red Fescue	Moderate
Kentucky Bluegrass	Poor

Adapted from Hanes, et al. (1976)

Lignosulfonate Concentration in Surface Runoff

Although the literature does not report any thorough study done on runoff quality analysis from lignosulfonate treated roads, Hoover, et al. (1973), reported calculations done on lignin solids concentration in surface runoff. The calculations showed that even under most severe conditions, the lignin solids concentration does not approach the 4 percent maximum concentration permitted by the Food and Drug Administration for animal ingestion (CFR 12.234). The calculation considered a 2 percent lignosulfonate solids on a dry soil weight basis, as well as a 100 percent dissolution of the lignin from the top one-quarter inch of the roadway. For an inch rainfall, a concentration of 1 percent solids is computed to be wash off. This did not consider a dilution factor due to runoff from adjacent land area and yet the calculation showed an expected lignosulfonate concentration well below the allowable FDA 4 percent concentration.

Summary

The use of chloride compounds, namely, sodium, calcium and magnesium chlorides for road deicing, as documented by various researches, does indeed have an impact on environment (water quality, plant or animal biota). The levels of impact, though subjective, are noted to be significant or not significant based upon the variables of the particular research. In all the studies a change of state was noted in the systems evaluated. The reported increase in chloride concentrations in wells in Massachussetts, the decline and death of Silver Maple trees along highways receiving deicing treatments are few of the typical examples.

Salts used for road deicing are the same salts commonly used as road dust suppressants. This is so because chloride compounds possess the properties of deliquescency, hygroscopicity and low freezing point. They abound naturally and in large quantities, making them less expensive. Studies on the environmental impact of chloride compounds as dust suppressant are practically nonexistent. In one of the rare studies, the spraying of $CaCl_2$ to control dust on an unpaved road was noted to cause injuries to Norway Spruce trees. In view of the lack of research in this area, the environmental impact of road dust suppressants can only be extrapolated from the documented environmental impact studies done on road deicers. Thus, one of the objectives of this research project was to assess the water quality effects resulting from the use of the different road dust suppressants.

EXPERIMENTAL DESIGN

This section of the report describes the procedure followed in the construction of the test sections as well as the materials used. The location of the test sections are also described. Larimer County Roads and Bridges Department, partners of this research project, constructed the test sections using the county's personnel and equipment. Prior to the start of the project in the spring of 1993, the county had ongoing stage construction program for some of its unpaved roads, one of which happened to be the test site for this project. The road had received a magnesium chloride treatment once a year for two years before the start of the project. The treatments evaluated in the research project are the third and fourth in succession of the road stabilization program that started four years ago. In the first year (1993) of the project five test sections were evaluated. Four of the test sections were treated with four different dust suppressants and one was untreated which served as the control. The dust suppressants used were calcium lignosulfate, calcium chloride, magnesium chloride and calcium chloride-special. In the second year (1994) four test sections treated with lignosulfonate, calcium chloride, magnesium chloride and an untreated test section were evaluated.

Procedure

The construction of the treated test sections followed the procedures recommended in most of the highway engineering literature and that of the dust suppressant suppliers. Important application techniques for many dust suppressants and road surface stabilizers include:

a) road surface scarification,

b) adequate grading and smoothing of the road surface,

c) application of the dust suppressant in quantities sufficient for effective dust control,

d) proper road finishing procedures that include the forming of the surface crown, optimum compaction of the road surface and proper drainage (Rural Transportation Fact sheet # 84-02, 1984).

A specific description of the methods used for constructing each test section is presented below. Preconstruction of the test sections for both the first and second year evaluations consisted primarily of blade dressing of the road shoulders and ditchline as well as reclaiming of aggregate pullout. In the first year evaluation, the existing road surface material was used without the addition of any new gravel material.

Lignin test section (first year): The road surface was watered down to soften it while scarification and pulveralization took place. The surface was scarified to a depth of about 6 in (15.24cm). The material was further watered to the necessary optimum moisture content for compaction. The lignin dust suppressant was sprayed into the pulverized material by the supply truck at the supplier's recommended application rate of 2.3 l/m^2 (1/2 gal/yd^2). The grader then mixed the lignin with the surface material by windrowing the mixture from one side of the road to the other. The road was shaped to crown as the grader finished blading. It was then rolled and compacted using a steel drum compactor.

Calcium Chloride test section (first year): The road surface was sprayed with water to soften it and also control fugitive dust during subsequent grader operations. The graders scarified the road surface removing all irregularities including potholes. The loose material was windrowed while the water trucks continued watering to achieve the necessary optimum moisture content for compaction. The road was then shaped to crown after which it was rolled and compacted. Finally, the compacted road surface was sprayed with water followed by the spraying of the calcium chloride dust suppressant at the supplier's recommended application rate of 1.14 l/m^2 (1/4 gal/yd^2).

Magnesium Chloride test section (first year): The construction procedure and suppressant application rate was identical to that of the calcium chloride.

Calcium Chloride-Special test section (first year): The construction procedure and suppressant application rate was identical to that of the calcium chloride.

Untreated test section (first year): After the preconstruction of reshaping the ditch line and reclaiming pullout aggregate, the road surface was watered and bladed. The loose material was windrowed to shape the road surface to crown while the water trucks continued to water the material to the necessary moisture content for compaction. The shaped road surface was then rolled and compacted to a firm wearing course.

The second year test sections construction was similar to that of the first year's with few exceptions. Instead of utilizing the existing road surface material, about 4 in (10.16 cm) of new gravel material was laid on top of the existing road surface, thus the wearing course was constructed entirely from a fresh gravel. The calcium chloride-special test section did not receive any treatment during the second year evaluation. Instead, that test section became the untreated test section. The suppressants application rates were the same at 2.3 l/m^2 (1/2 gal/yd^2) of road surface.

Materials

The road surface material used for the first year evaluation was the existing road surface material. No specific tests were performed to determine the engineering properties of the material. Information obtained from the county engineer's office indicated that the material used for all the test sections was from the same gravel pit. Based on visual examination of the material, their assessment is that the material should fall under AASHO classification A-1-a, rated as excellent to good subgrade material.

A new or virgin gravel material was used for the construction of the surface course in the second-year evaluation. The material was thoroughly analyzed to determined its engineering properties. Tests performed include sieve analysis, Atterberg limit, Los Angeles abrasion, soundness and specific gravity. The sieve analysis was performed on the aggregate according to ASTM Test No. C-136. The results of the analysis are shown in Table 2.1 and Figure 2.1. The quantity of material passing the No. 40 (425-μm) standard sieve referred to as fine sand/silt is 9.6 percent. The fine sand/silt fraction is directly related to the amount of dust emission from road surfaces. The Los Angeles abrasion test (ASTM C-131) was performed to determined how resistant the aggregate would be to abrasion under vehicular activity since a significant contribution of unpaved road dustiness can be attributed to the abrasion of road surface material. A loss of 30 percent was measured: a moderate wear factor compared to the recommended value for surface aggregate of 27 percent or less (Wood, 1960). The rest of the material property results are summarized in Table 2.2. From the results of the sieve analysis and the Atterberg limits, the material can be classified as A-1-a under the AASHO classification system and a poorly graded gravel (GP) under the Unified Soil Classification System (USCS).

Table 2.1 Aggregate Particle Size Distribution

Sieve	Particle Size (mm)	Percent Passing (%)
1.0 inch	25.400	100.00
¾ inch	19.100	95.70
½ inch	12.700	82.30
⅜ inch	9.510	73.35
¼ inch	6.350	63.60
#4	4.750	57.15
#10	2.000	41.15
#18	1.000	27.45
#40	0.425	9.60
#100	0.125	1.50
#200	0.075	0.40
#400	0.037	0.15

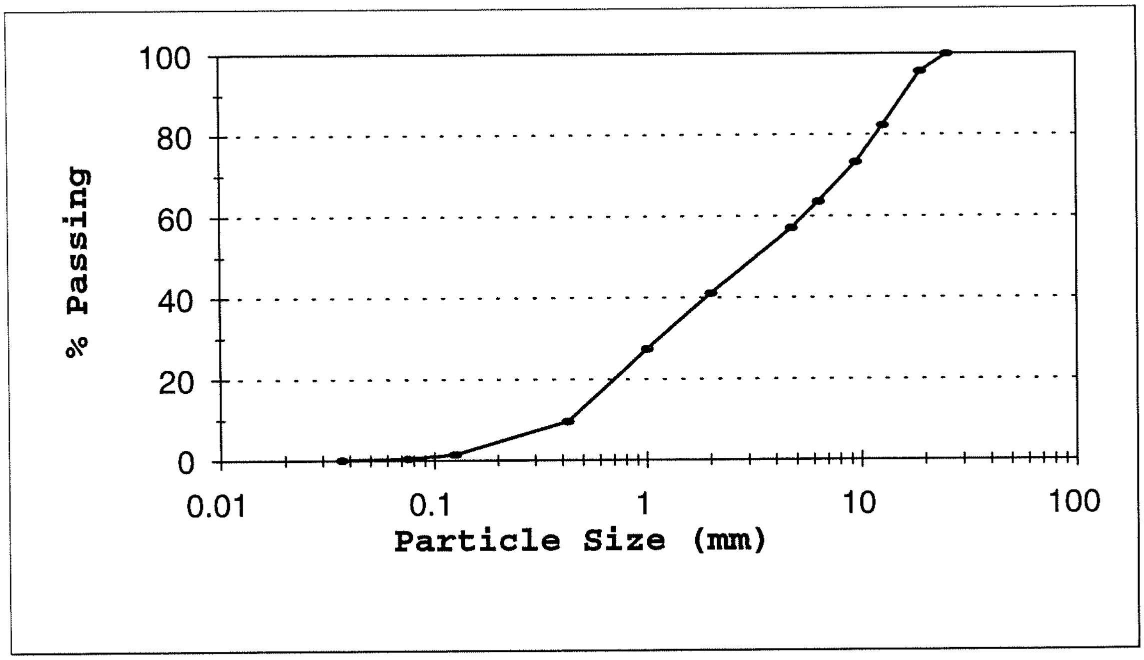


Figure 2.1 Cumulative Distribution of Aggregate Particle Size

Table 2.2 Aggregate Property Results

Test	Results
Atterburg Limits (ASTM No. D-423 & D-424)	Nonplastic and no cohesion
Los Angeles Abrasion Test (ASTM No. C-131	30%
Soundness (ASTM No. C-88)	N.D.
Specific Gravity (ASTM No. D-845)	2.6

In comparing the aggregate particle size distribution with the recommended aggregate mix to achieve a good surface course (Table 2.3), it is apparent that the aggregate used for the test sections do not have a sufficient portion of fines. The recommended aggregate particle size distribution percent passing No. 40 (425-µm) and No. 20 (75-µm) standard sieves are between 25-45 percent and 10-25 percent respectively. The material used had only 9.6 percent and 0.4 percent passing the No.40 and No. 20 respectively.

Table 2.3 Suggested Aggregate Mix

	% Passing Sieve	
Designation	**Surface Course**	**Base Course**
1.0 inch	100	100
¾ inch	85-100	70-100
⅜ inch	65-100	50-80
#4	55-85	32-65
#10	40-70	25-50
#40	25-45	15-15
#200	10-25	5-15

Adapted from Horwell (1993)

Without sufficient fines the larger size aggregates cannot bind together into a tight matrix, and thus aggregate pullout is easier. This results into rapid road surface deterioration in the form of ravelling, washboarding and potholing as vehicular traffic activity increases. The lack of fines which serves as a binder to the coarser aggregate also means more driving hazard to approaching vehicles passing each other as loose aggregate picked by the tires of the vehicles are thrown around, leading to the breaking of windshields and possible injuries. Insufficient fines also means reduction in the total surface area available for ions in the dust suppressant, especially chloride compounds to attach themselves. As stated in Compendium 12 (1980), the greater the surface area the more moisture can be attracted to keep the road surface wet.

In the first year evaluation, four commercially available dust suppressants were used. They are:

1) Calcium Lignosulfate

A by-product of the paper pulp industry, this form of lignosulfate was supplied by Georgia Pacific Corporation. The application rate was 2.3 l/m^2 (1/2 gal/yd^2) - supplier's recommendation.

2) Calcium Chloride (35 percent $CaCl_2$ in solution)

A deliquescent and hygroscopic by nature. The compound was supplied by Hill Brothers Chemical Company. The application rate was 1.14 l/m^2 (1/4 gal/yd^2) - supplier's recommendation.

3) Magnesium Chloride (32 percent $MgCl_2$ in solution)

A deliquescent and hygroscopic by nature. The compound was supplied by Envirotech Services, Inc. The application rate was 1.14 l/m^2 (1/4 gal/yd^2) - supplier's recommendation.

4) Calcium Chloride-Special

A $CaCl_2$ based compound. According to the suppliers, the $CaCl_2$-special brand contains no magnesium whereas the $CaCl_2$ brand contains small amount of magnesium. The compound was supplied by Hill Brothers Chemical Company. The application rate was 1.14 l/m^2 (1/4 gal/yd^2) - supplier's recommendation.

In the second year evaluation only three of the suppressants were evaluated. They are:

1) Lignosulfonate

A by-product of the paper pulb industry. This type did not contain any calcium as did the first year's. The compound was supplied by Envirotech Services Inc. The application rate was 2.3 l/m^2 (1/2 gal/yd^2) - supplier's recommendation.

2) Calcium Chloride (35 percent $CaCl_2$ in solution)

A deliquescent and hygroscopic by nature. The compound was supplied by Hill Brothers Chemical Company. The application rate was 2.3 l/m^2 (1/2 gal/yd^2) - supplier's recommendation.

3) Magnesium Chloride (32 percent $MgCl_2$ in solution)

A deliquescent and hygroscopic by nature. The compound was supplied by Envirotech Services, Inc. The application rate was 2.3 l/m^2 (1/2 gal/yd^2) - supplier's recommendation.

Location

The test sections evaluated in this project were all located in Larimer County, Colorado. They are part of a five-mile stretch of unpaved road in the Loveland area of the county. The stretch is county road (CR) 12 which changes into county road (CR) 29 at about halfway towards the north. The CR-12/29 is located in the foothills and has about two-thirds of its stretch lying in a flat area with hills on both far sides. The other one-third of the stretch lies in the open, flat plains. The road links two paved roads in the area, namely, CR-23 to the southeast and CR-18 and 29 to the north. Figure 2.2 shows portion of the map of Larimer county with the location of the test site highlighted.

CR-12/29 serves a rural community of livestock owners as well as a recreational area - Carter lake. The climatic condition in this region is semiarid with annual precipitation in the test site area being approximately 14 inches/year (35.6 cm/year). The generalized soil/aggregate characteristics in the test site area can be termed as glacial till/some silty clay/sand/gravel. The average daily high temperature during the dust production season late May through October is approximately 27°C (80°F) with an average relative humidity of about 25 percent.

During the first year evaluation only four of the five test sections were constructed on CR-12/29 due to lack of space. The fifth which is the untreated test section was located on CR-40 in the Fort Collins area of the county. CR-12/29 and CR-40 are within 30-miles radius of each other. During the second year evaluation all the four test sections; three treated and one untreated were located on CR-12/29. The length of each test section was 1.25 miles long.

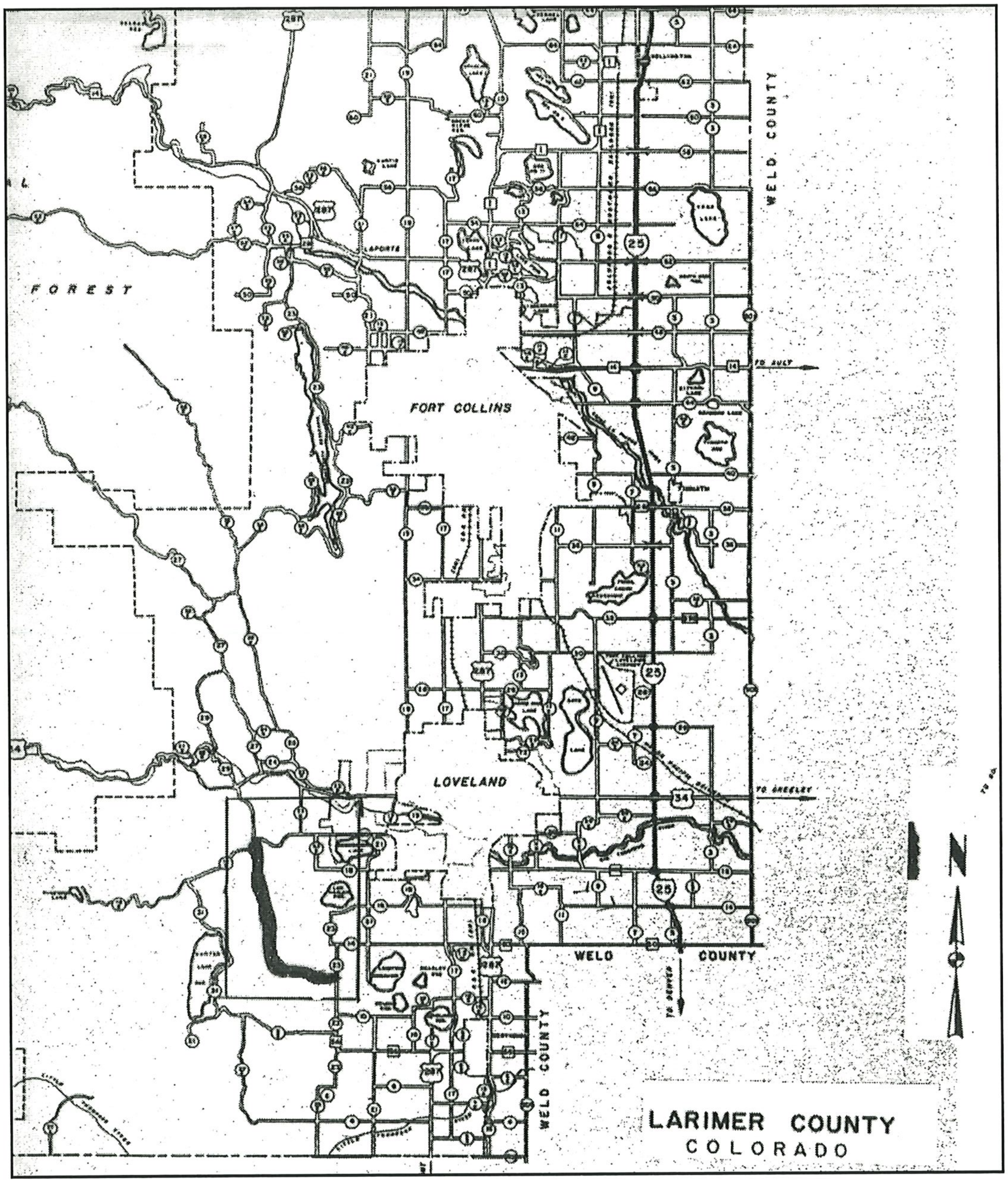


Figure 2.2 Map of Larimer County - Colorado

Figure 2.3 shows a detailed drawing of CR-12/29 and the position of each test section on the road for both the first year and second year evaluations. Table 2.4 describes the features in the terrain of each test section. The number of curves, uphills/downhills and their steepness, the drainage condition of a particular test section, as well as the type and volume of traffic are factors that determine how well a treatment holds up.

Table 2.4 Test Sections Features

Test Sections (CR-12/29)		**Features in Terrain**
A. Calcium Lignosulfate Lignosufonate	(1st yr.) (2nd yr.)	• flat for most part • one main curve • excellent drainage
B. Calcium Chloride	(1st/2nd yr.)	• moderate slopes • two hills • one main curve • good drainage
C. Magnesium Chloride	(1st/2nd yr.)	• gentle slopes • two hills • one main curve • good drainage
D. Cal. Chloride- Special Untreated	(1st yr.) (2nd yr.)	• gentle slopes • one curve • excellent drainage

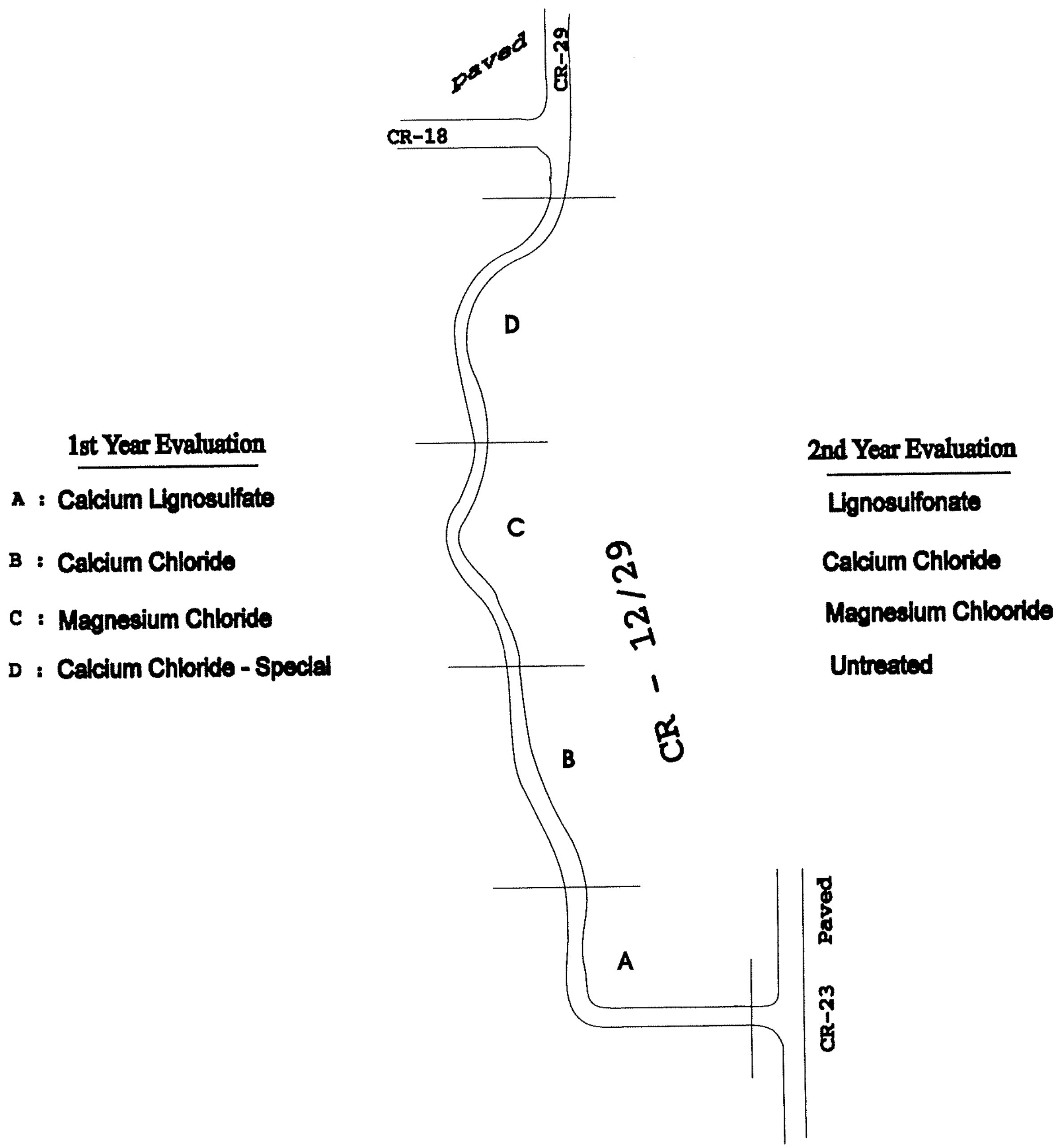


Figure 2.3 CR-12/29 Showing the Location of each Test Section

RESEARCH DESIGN

The improvement of the engineering properties of soils treated with stabilizing agents and dust suppressants has been proven in various laboratory studies by Lane, et al. (1984), Davidson, et al. (1960) and Hoover, et al. (1973). Field evaluation of the various dust suppressants has also been carried out in the much more humid regions, e.g. Iowa (Hoover, et al., 1973, 1981). However, field performance data on the dust suppressants in the semiarid and arid regions is nonexistent. For this reason, the performance evaluation of the dust suppressants studied in this research was done using solely field measurements. The field measurements used include traffic survey, dust measurement and aggregate loss measurement.

Traffic Survey

The five-mile long test section serves a rural community of livestock owners. Carter lake a recreational area within a 15-mile radius of CR-12/29 has most of its traffic using this road. There are a number of rock quarry companies located within the foothills and the products from these quarries are often transported over this road. The composition of traffic on this road varied from horsedrawn wagons, cars, trucks to heavy tandem-axle vehicles. From field observations it appears that about half of the vehicles using the road are pickup trucks. They range in all sizes from small to full size. The tandem axle vehicles also constitute a substantial portion of the traffic volume; they range from the normal ten wheelers to the large eighteen wheelers. Most of them carry very heavy quarry products in the form of large stone slaps and crushed stone aggregate. Figure 2.4 to Figure 2.7 shows some of the type of vehicles using the test sections.

The type and number of vehicles using a road have a direct effect on the degradation of the roadway. In the case of unpaved roads, the amount of degradation is measured in terms of fines loss and aggregate pullout. The total aggregate loss from the road surface equals the aggregate replacement during annual maintenance of the roadway. To assess the cost associated with the operation and periodic maintenance of the test sections evaluated, a traffic survey was done yielding a cost per vehicle per year.

Figure 2.4 Small Size Truck

Figure 2.5 Eighteen Wheel Tandem-Axle Vehicle

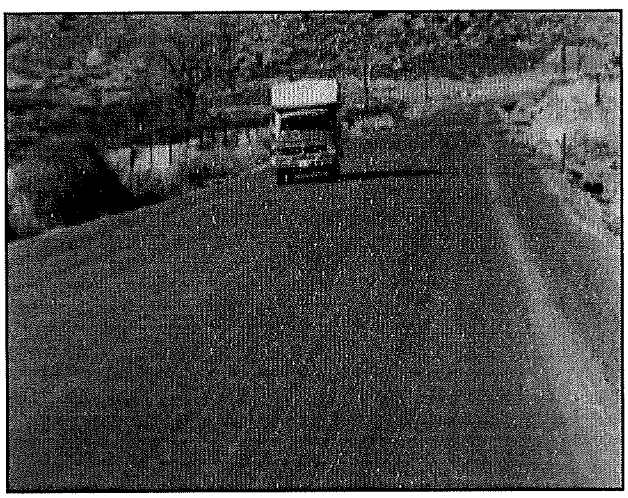


Figure 2.6 Full Size Pickup Truck

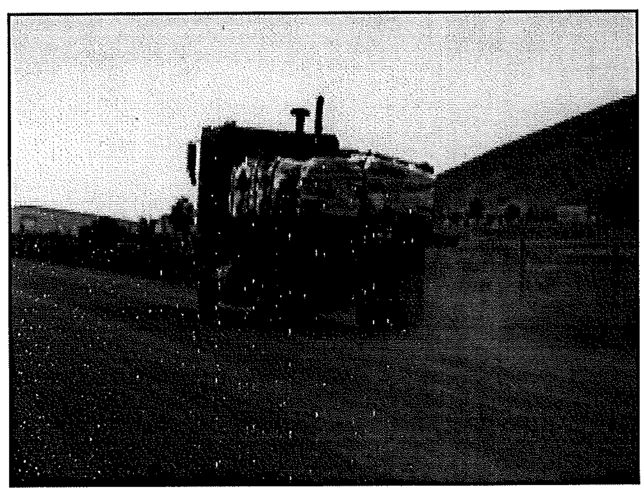


Figure 2.7 Six Wheel Vehicle

To count the number of vehicles using the test sections, traffic counters were installed at the beginning and end of each test section. Figure 2.8 is a schematic of CR-12/29 showing the position of the counters relative to each test section. During the first year evaluation the counters were installed for only one week (14th - 21st) in the month of June 1993 in order to determined the ADT. Table 2.5 shows the results of that measurement.

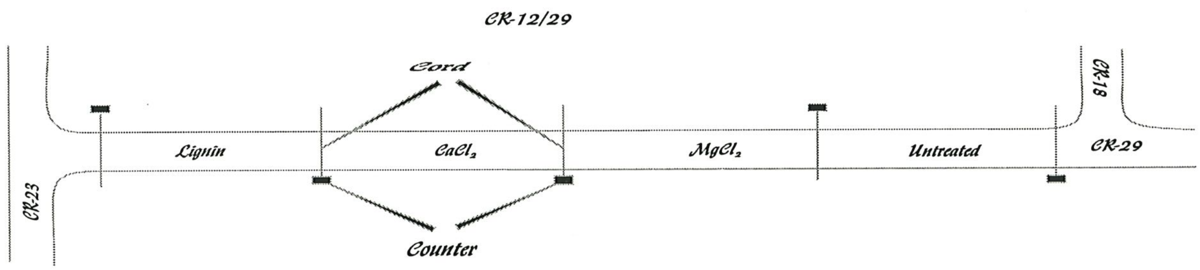


Figure 2.8 Position of Traffic Counters Relative to Test Sections (2nd yr. Evaluation)

Table 2.5 Traffic Survey on Test Sections (1st Year Data)

Test Sections	**Weekday ADT**	**Weekend ADT**	**Weeklong ADT**
Beginning of Lignin	515	541	515
Lignin/$CaCl_2$ split	389	451	416
$CaCl_2$/$MgCl_2$ split	322	381	347
$MgCl_2$/$CaCl_2$ (Spec) Split	423	510	460
End of $CaCl_2$ (Spec)	437	503	465

The first year untreated test section ADT was estimated as 200
(personal communication with Larimer county road engineer).

The lignin test section had the most traffic, with an average weeklong ADT of 466 followed by the $CaCl_2$-special treatment with 463. The $CaCl_2$ test section showed the least traffic, with a weeklong measurement of 382 ADT while the $MgCl_2$ section had a 404 ADT. The untreated test section ADT was estimated at 200 (personal comm. 1993). In the second-year evaluation the traffic counters were kept on the road throughout the duration of the field measurement, i.e. from May 25th to October 10th (1994). This was done in order to measure as accurately as possible the total number of vehicles using the test sections during the dust production season so that a cost comparison of the different treatments can be made. The results of the measurement are presented in Table 2.6 and Figures 2.9 and 2.10.

Table 2.6 Traffic Survey on Test Sections (2nd Year Data)

Total traffic count over duration of field measurement
Starting date: 05/25/94
Finished date: 10/13/94
Duration: 141 days (app. 4.5 months)

Test Section	**Beginning** --------	**End (# of Veh.)**	**Average** --------	**ADT**
Lignin	85,326	59,746	72,536	515
CaCl2	59,746	58,659	59,203	421
MgCl2	58,659	67,680	63,170	448
Untreated	67,680	83,895	75,788	538

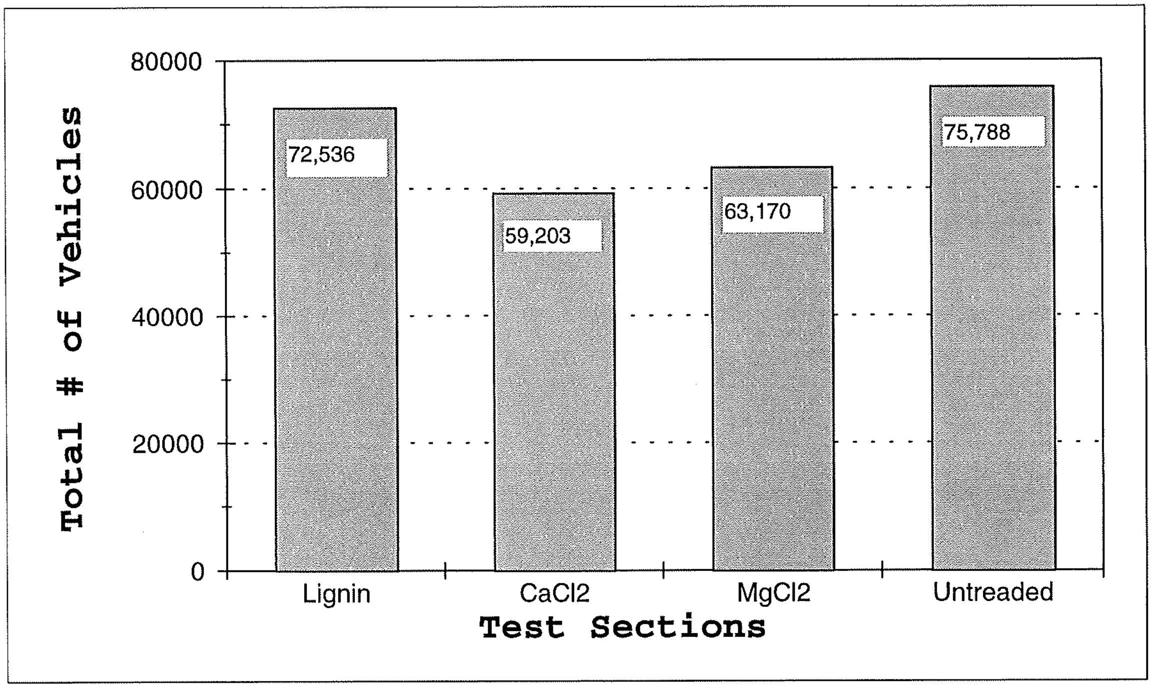


Figure 2.9 Total number of Vehicle in 4.50 months

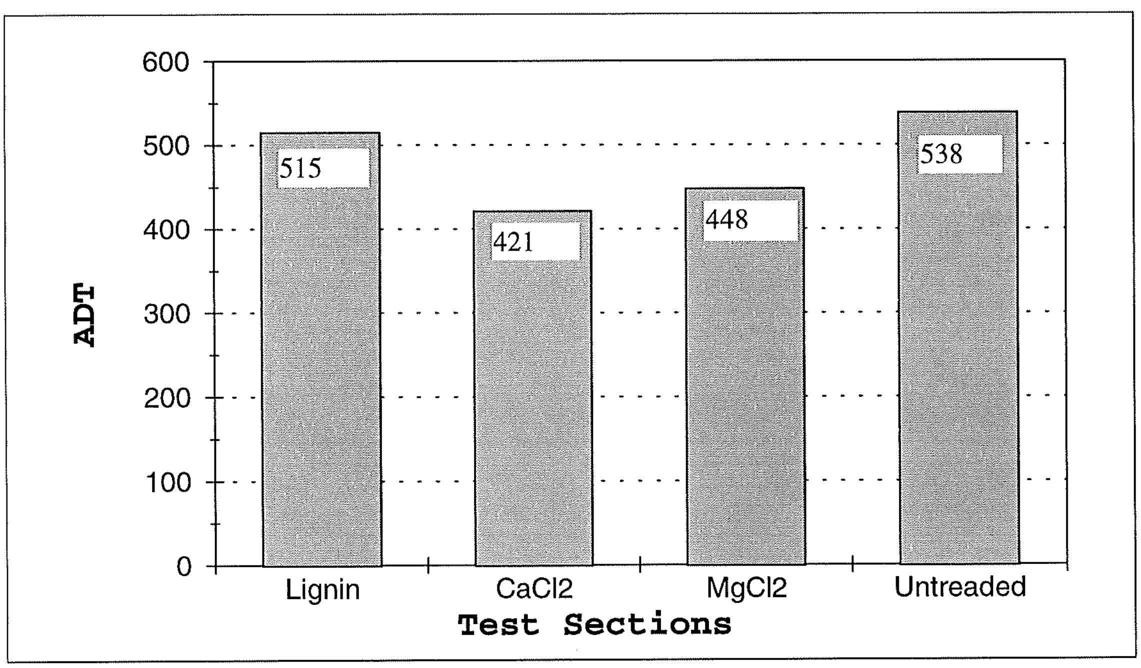


Figure 2.10 Daily Average Traffic (2nd Yr. Data)

From the survey in the second-year test, it is apparent that the test sections at the beginning and end of the roadway — namely, the lignin and the untreated test sections — experienced more traffic than the $CaCl_2$ and $MgCl_2$ test sections located in the middle portion of the road. The lignin and the untreated test sections had an average total traffic count of 72,536 and 75,788, respectively, compared to 58,659 and 67,680, respectively, for the $CaCl_2$ and $MgCl_2$. Note that more vehicles entered/exited the lignin test section from the southeast end than entered/exited at lignin/$CaCl_2$ split, which is the north end (a difference of 25,580 vehicles). This trend is also true for both the $CaCl_2$ and $MgCl_2$ test sections. The untreated section, unlike the others, had more vehicles entering/exiting from its north end than at the $MgCl_2$/untreated split (a difference of 16,215 vehicles). From this extensive survey it can be said that over 59,000 vehicles drove through all the test sections in the 4.50 month period, yielding an average daily traffic (ADT) of about 420, a rather high figure for an unpaved road.

Dust Measurement and Quantification

Although road dust research has been going on for several decades, it is apparent from the review of previous works that despite all the money and time invested, quantitative measurements of dust from unpaved roads have been practically nil. Without any uniform, quantitative dust measurement procedure, it is difficult if not impossible to assess the economics and lasting value of dust palliation methods, or to compare data from different projects and regions of the country. With the aforementioned problem in mind, one of the objectives of this research project became to develop a dust monitoring method/device that would be quantitative, reproducible, portable, cost-effective and easy to operate.

From the literature review it was apparent that various attempts have been made by a number of individuals to develop devices and procedures that would measure road dust. Notable among them are Schultz (1983), Wellman and Barraclough (1972), Hoover et al. (1973), Langdon (1984) and Irwin et al. (1986), as mentioned previously in the report. Some of the measuring techniques used stationary devices which characterize road dustiness at a particular point while others used moving devices which provided a dust measurements that describe a section of road. The dust quantification method common among all the previous works was either the weighing of the collected dust or the measurement of air opacity using visible light.

In this research project, early attempts to use the dust collecting bucket method according to ASTM D-1739 (see Figure 3.1) in the summer and fall of 1992 proved to be ineffective and inefficient. The reasons were that 1) it was difficult to obtain permission from the land owners to setup the dust collectors, 2) the land along the test sections are grazing pastures and there was the problem of livestock continually tampering with the dust collectors, 3) the method requires so many vehicles to drive by the buckets before a substantial amount of dust can be collected for quantification, 4) it was assumed that at least a month would be required to collect a reasonable amount of dust for measurement, 5) contamination by insects and foreign matter proved to be a problem and 6) the prevailing wind speed and direction were contributing factors influencing how much of the dust fallout entered the buckets when a vehicle passes by.

Figure 3.1 Dust Collecting Buckets after ASTM D - 1739

Because of these problems, a decision was made to develop a device and procedure that would measure the dust production from the test sections in-situ and on a real time basis. Instead of getting one data point a month, many data could be generated daily. Considering the inherent variability associated with road dust, the method should measure dust along a section of road rather than at a single point. The method should also be quantitative and precise. Modeling a device and procedure after Langdon (1984) who used a portable cyclone dust collector mounted behind a dust generating vehicle, the Colorado State University Dustometer, which is basically a moving dust sampler was developed, field tested and used in this research.

The moving dust sampler is illustrated in Figure 3.2. The device consists of 1) a quarter-ton pickup truck, 2) a 3,000 watt electric generator, 3) a standard high volumetric suction pump borrowed from the Atmospheric Science Department at Colorado State University who used it for sampling atmospheric particulate, 4) a fabricated metal box that contains a 10 in by 8 in (25.40 cm by 20.32 cm) glass fiber filter paper, 5) a metal bracket attached to the bumper of the truck, and 6) a 2-in (5.08 cm) internal diameter flexible tube for connecting the suction pump to the filter box. The combined weight of vehicle, equipment and driver is 3,880 lb.

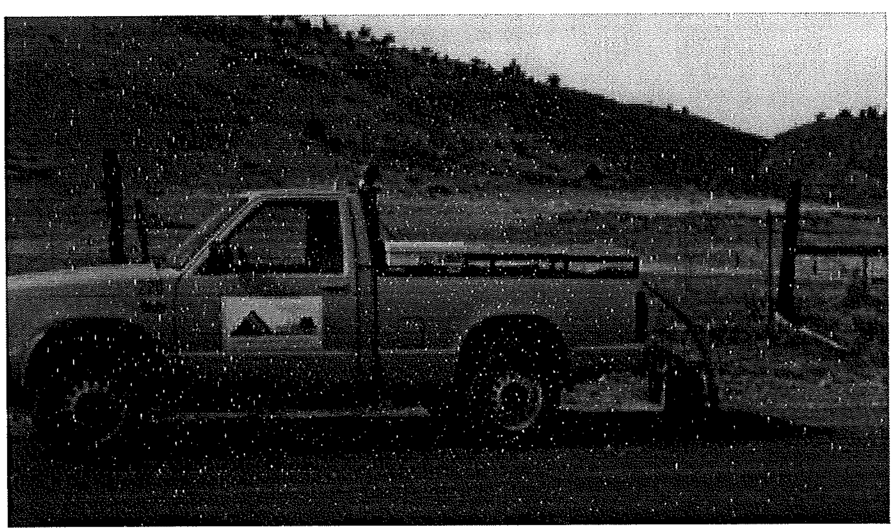


Figure 3.2 Colorado State Dustometer (Moving Dust Sampler)

The filter box is rigidly secured to the bumper by way of the bracket behind the left rear tire of the quarter-ton pickup truck. The generator and the high volumetric sampler are secure in the bed of the truck (Figures 3.3).

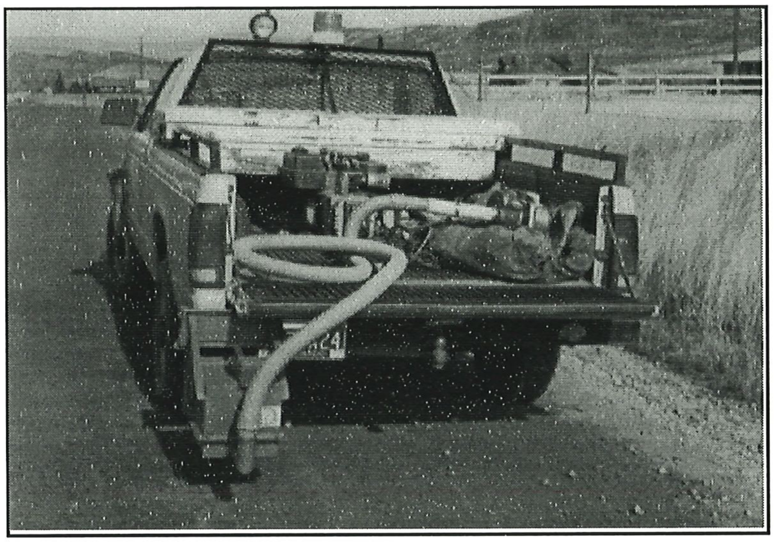


Figure 3.3 Electric Generator and High Volumetric Suction Pump in the Bed of Truck

The filter box when mounted behind the truck is horizontally aligned with the left rear tire (drivers side) and the distance from the center of the tire to the front of the box is 3.0 ft (0.9 m). There is a vertical clearance of 1.0 ft (0.3 m) between the bottom of the filter box and the road surface as shown in Figure 3.4.

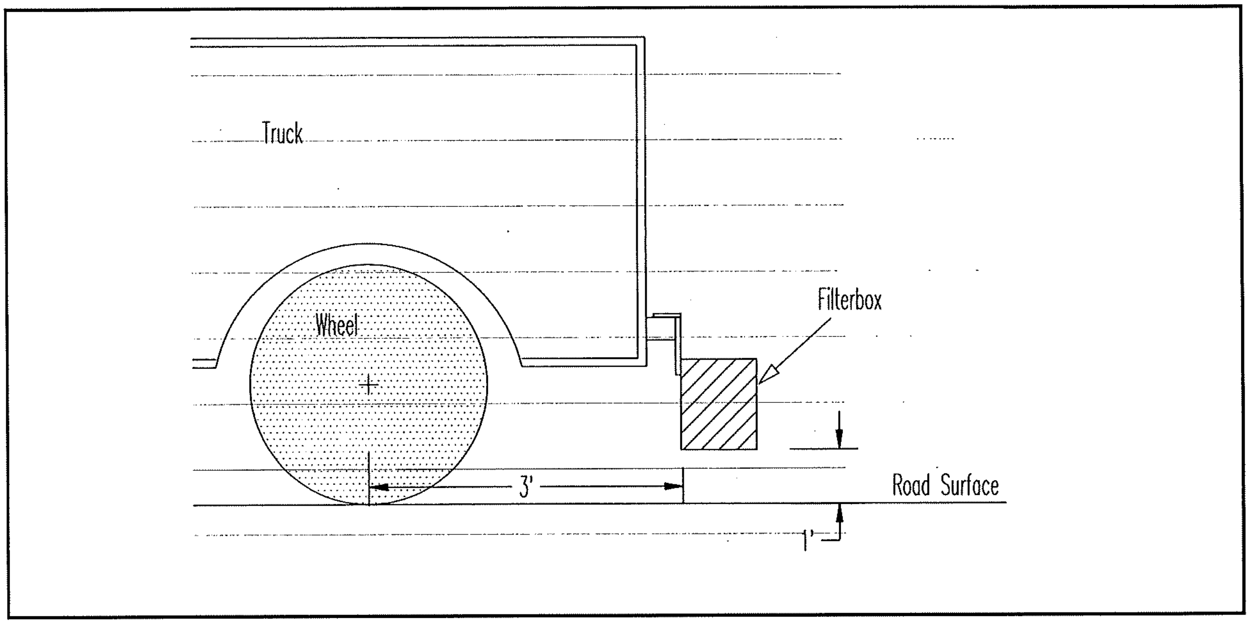


Figure 3.4 Schematic of the Colorado State University Dustometer Position

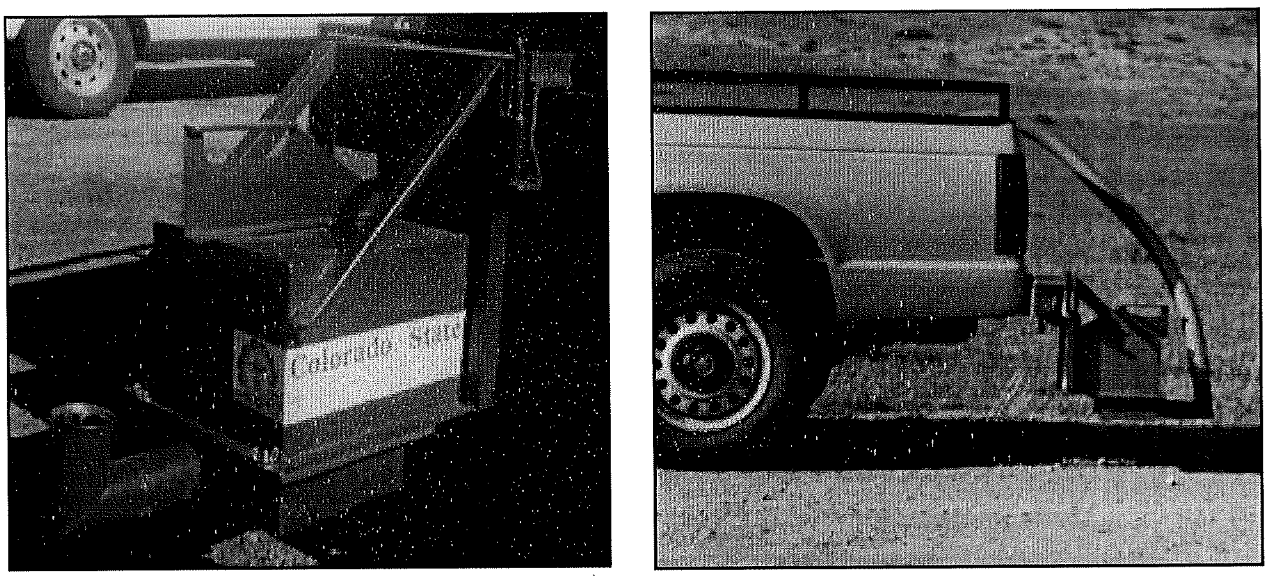
The design of the box and bracket system is such that although the box is rigidly secured to the bumper of the truck after the setup, it can be mounted and dismounted with relative ease. Appendix B shows the detail technical drawing of the filter box. The bracket is made out of 1/4-in (6.4 mm) thick, 6-in by 6-in (15.24 by 15.24 cm) steel angle treated with a rust-proof paint. It is fixed to the bumper by bolts as shown in Figure 3.5. The filter box is fabricated out of a steel sheet. It has a 12-in by 12-in (30.48 by 30.48 cm) opening that is covered with a 450 micron mesh sieve which faces the tire. The 450 micron sieve prevents any nondust particles from being drawn onto the filter during dust measurement. The bottom part of the box contains a sieve that supports the filter paper. The box is designed to allow for easy replacement of the filter paper.

Figure 3.5 Mounting Bracket Bolted to Bumper of Truck.

Experimental Procedure

To run a typical dust measurement test, the filter box is fitted with a glass fiber filter paper 10 in by 8 in (25.40 cm by 20.32 cm) and attached to the mounting bracket as shown in Figure 3.6a. The flexible tube is used in connecting the high volume suction pump to the filter box (Figure 3.6b).

The beginning and end points of test section (one mile) are clearly demarcated on each test segment. The generator is started and the truck is driven at the stipulated speed of 45 mph (72.58 kph). At the beginning of the mile mark, the suction pump is turned on by the driver with the aid of a switch in the cab of the truck. A portion of the dust kicked up by the left rear tire is drawn onto the filter as the truck traverses the road. At the end of the mile run the pump is turned off and the truck is brought to a stop. The filter box is dismounted from the bracket and taken into the cab of the truck out of the wind, where the dust-laden filter paper is removed and put in a very thin plastic bag. All of the operations are carried out very carefully to prevent any loss of dust. After the removal of the filter paper, the filter box is fitted with a new paper and another dust sampling run is carried out as described above. Three runs are made in the same driving lane for each test section. At the end of the runs, the dust laden filters are taken to the laboratory and weighed. The average of the three measurements for each test section are compared to assess the relative effectiveness of the different treatments, in controlling fugitive dust emission from the test sections.



(a) (b)

Figure 3.6 a) Filter Box Mounted to Bumper of Truck,

b) Flexible Tube Connecting Pump to Filter Box.

To establish a uniform base for evaluating the different dust suppressants tested, certain protocols were followed during the dust monitoring. These protocols are:

1. The dust sampling should be done once a week when the weather and field conditions permit.
2. The dust sampling should be done at the time of day when the temperature is highest and relative humidity is lowest. Since most of the suppressants being evaluated are deliquescent and hygroscopic, it is only then that their true ability to suppress dust can be evaluated.
3. After rainfall events, sufficient dry days should be allowed before dust sampling.

4. Every dust sampling run should be done at 45 mph (72.58 kph), the stipulated driving speed for the road.

5. For each test section, three sampling runs, in the same direction, in the same driving lane and by the same driver should be performed. The average of the three sampling runs would be used as a data point.

Results

To demonstrate the precision in the dust measurements made using the Colorado State University Dustometer, nine replicate samples were taken on the untreated test section at a speed of 45 mph (72.58 kph). Table 3.1 shows the data and its distribution. A mean of 2.74 grams was obtained with a standard deviation of 0.21 grams and a variance of 0.04 grams. From the distribution of the data and the fact that this is measuring dust in the field as the test truck traverses the roadway, one can conclude that the Colorado State University Dustometer is a precise road dust measuring device. Note that there are numerous factors that could affect the amount of dust sampled by the Dustometer. This may include the total weight of test vehicle, the size/width of tire, the suction power of high volumetric pump, efficiency of filter paper, air flow rate across filter paper, amount of fines in road surface material mix, maintenance history of roadway and others. All these variables were kept constant throughout this research.

Table 3.1 Typical Dust Measurement Data

Speed : 45 mi/hr
Length of Run : 1.00 mile
Test Section : Untreated

Sample #	**Weight (g)**
1	2.85
2	2.60
3	2.83
4	2.86
5	2.87
6	2.47
7	2.62
8	2.48
9	3.09

Mean = 2.74 g Standard Deviation = 0.21 g Variance = 0.04 g

It is obvious from visual observations that the speed of a vehicle is a very important factor in dust generation from unpaved roads. The faster the vehicle travels, the more dust is generated. To help quantify this phenomenon, dust measurements at various speeds were made using the Colorado State University Dustometer. Figure 3.7 shows the amount of dust sampled at speeds of 20, 30, 40 and 50 mph (32.25, 48.39, 64.52 and 80.65 kph) from the untreated test section. As stated earlier, the dust measurement technique employed in this research involves the suction of dust as it is generated and hence the volume of dust cloud drawn is related to how long the suction pump is allowed to run. This means that for the 1.0 mile run, the amount of dust drawn is different at each test speed. To make the data in Figure 3.7 comparable, the amounts of dust were adjusted for a three minute run to make the dust collection time equal for all the speeds. Figure 3.8a shows the adjusted data. Surprisingly, Figure 3.8a shows a linear relationship between the speed and amount of dust generated. The coefficient of linear regression r^2 for the plot is 0.98.

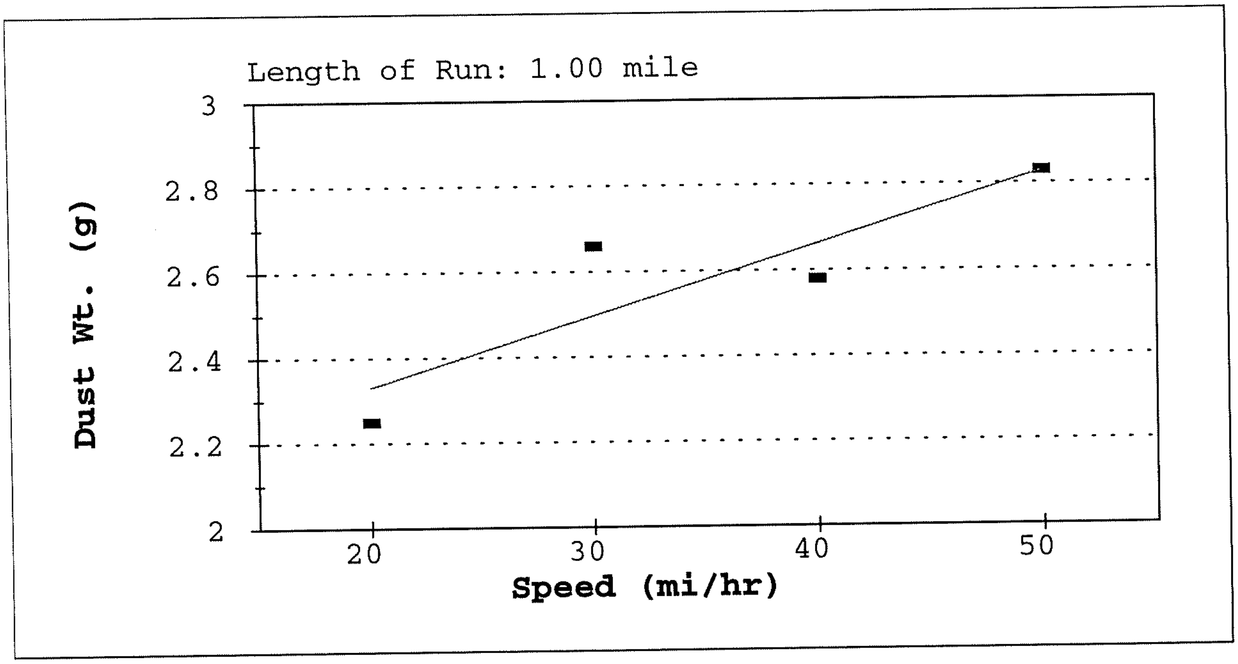


Figure 3.7 Dust Generation as a Function of Speed

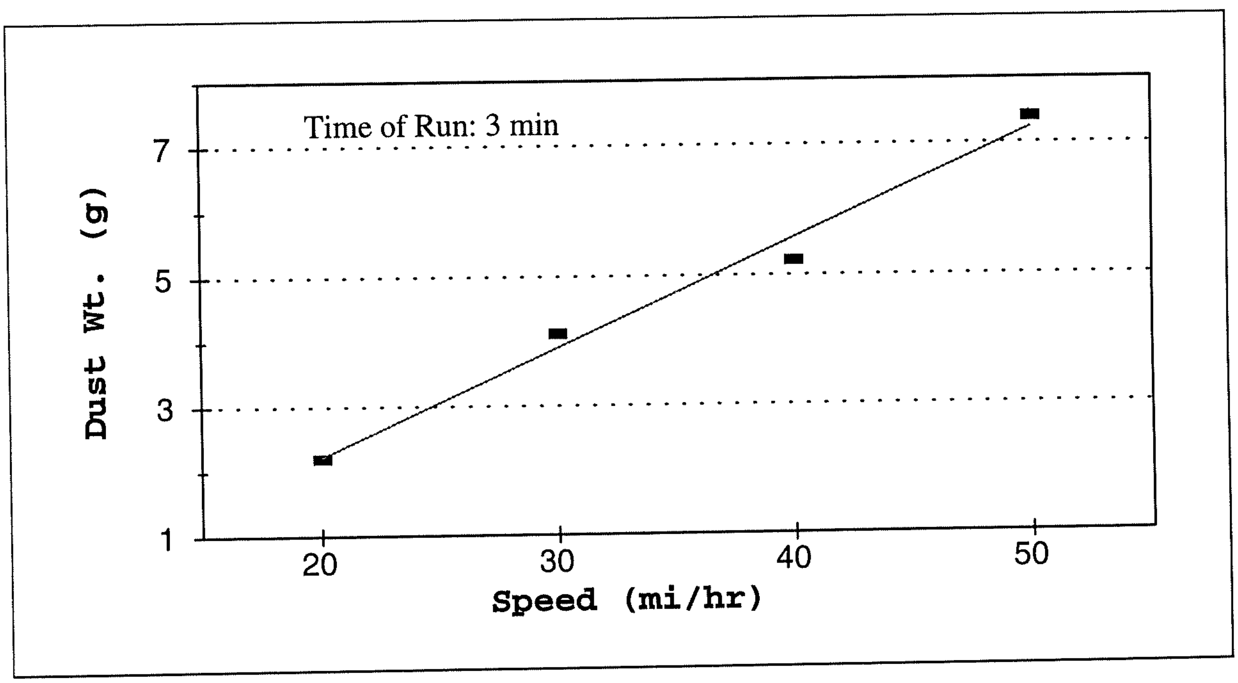


Figure 3.8a Dust Generation as a Function of Speed

Additional dust data was collected several days later for speeds of 25, 35 and 45 mph (40.32, 56.45 and 72.58 kph). Adding these data points to the plot did not change the linear relationship as shown in Figure 3.8b. The coefficient of linear regression r^2 for the plot is 0.95. Approximately, 2.3 grams of dust was measured at a speed of 20 mph (32.26 kph) while about 7.3 grams of dust was measured at 50 mph (80.65 kph), indicating a more than three-fold increase.

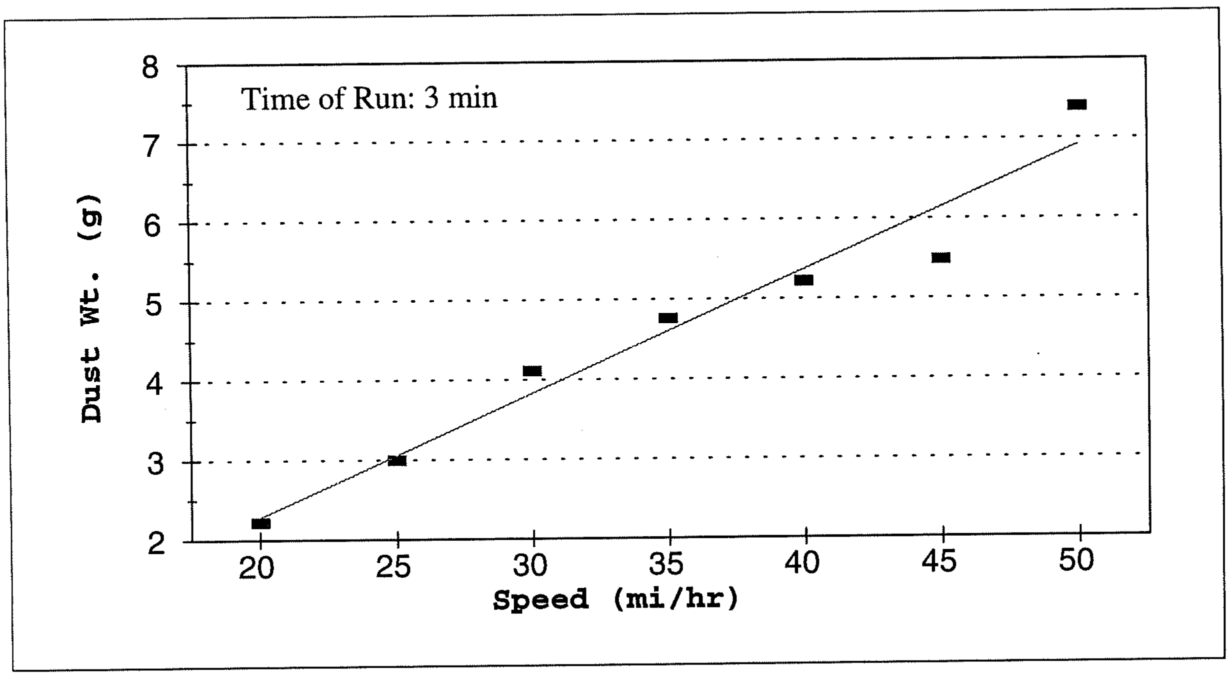


Figure 3.8b Dust Generation as a Function of Speed

During the first-year evaluation the dust monitoring was carried out from spring to early fall 1993, the time of year when dust generation is severe in Larimer County. The construction of the test sections were done on May 10th, but it was not until 42 days later before the dust measurements started. This was because the treated test sections were virtually dust free in the early days of the research. Much precipitation in the spring kept the road surface wet thereby making dust sampling inappropriate.

In all, fourteen data points were measured for each test section during the research period. The results of the first year dust measurements are presented in Table 3.2 and Figure 3.9. The prevailing temperatures at the time of the dust measurements were in the 80s (°F) while the relative humidity was in the 20s (percent). The average temperature during the season was approximately 84°F and the average relative humidity was about 24 percent.

The amount of dust sampled from the lignin test section ranged from a low of 0.05 grams to a high of over 0.3 grams. The low value occurring at a time when the treatment was fresh, and the high value occurring at a time shortly before the periodic maintenance of the road. Before the maintenance of the test sections, they had all developed potholes, ravels and corrugations to the extent that driving comfort was poor. The dust measured from the $CaCl_2$ treatment unlike the lignin was higher. It had a low value of 0.3 grams and a high of about 2.0 grams. The $MgCl_2$ and $CaCl_2$-Special treatments showed dust amounts that were slightly lower than the $CaCl_2$'s but more than the lignin's. The measurement from the untreated test section clearly distinguished itself as considerably high with an average of 2.5 grams of dust being sampled each sampling time, although the traffic count on the untreated test section was about one-half that of the treated test sections. The untreated test section also received three periodic maintenances during the research period. Periodic maintenance involved blading to cut off all irregularities on the road surface, watering, shaping to crown and compacting of the roadway to a hard wearing surface. The last two measurements on the 140th and 147th days after initial treatment were taken after the periodic maintenance of the test sections. Figures 3.10 - 3.14 shows the plots of the amount of dust sampled versus age of the initial treatment for each of the test sections. The vertical lines drawn at day 127 on Figures 3.9 - 3.14 shows when the periodic maintenance occurred. From the dust measurements data there is a strong indication that as the treatment ages, the dust generation increases.

Table 3.2 Dust Measurement (1st Year Data)

Dust weight = average of three measurements
Passes are run in the same driving lane
Length of run for each test section = 1.00 mile
Dust measurement done at an average speed of 45 mi/hr
Test Sections completed on 05/10/93

Notes	Sampling Date	Days after treatment	Temp. (°F)	Relative Humidity (%)	Test Sections				
					Lignin (g)	$CaCl_2$ (g)	$MgCl_2$ (g)	$CaCl_2$-Spec (g)	Untreated (g)
	06/21/93	42	84	21	0.2832	1.2530	0.8528	0.9295	2.0777
	06/28/93	49	86	24	0.1298	0.3899	0.2937	0.2371	2.3805
	07/08/93	59	85	25	0.0634	0.5582	0.2982	0.3815	2.4352
	07/16/93	67	87	28	0.1697	1.8521	1.2837	0.9700	2.4673
	07/23/93	74	86	27	0.1658	1.7273	1.6020	1.1395	2.8310
	07/29/93	80	88	27	0.2540	1.9030	1.0337	1.2265	3.2498
	08/09/93	91	87	23	0.1830	1.7636	1.4437	1.5455	1.6039
	08/13/93	95	80	30	0.3713	1.8050	1.6532	1.7106	2.1326
	08/16/93	98	85	26	0.3690	1.9227	1.8313	1.5717	2.0215
	08/23/93	105	87	25	0.3371	1.9783	1.7554	1.7523	2.6074
	09/01/93	114	88	21	0.3627	2.1132	1.7526	1.6895	3.2319
	09/11/93	124	85	17	0.3497	1.8049	1.4730	1.4920	2.3324
*	09/27/93	140	82	21	0.1213	0.6331	0.3064	0.3500	2.1495
	10/04/93	147	84	23	0.1431	0.8702	0.4423	0.4246	3.0917

* Dust measurement after Periodic Maintenance of Test Sections (done on 09/14/93).
Periodic Maintenance involves blading, watering and compacting of test sections.

PM: Time of Periodic Maintenance

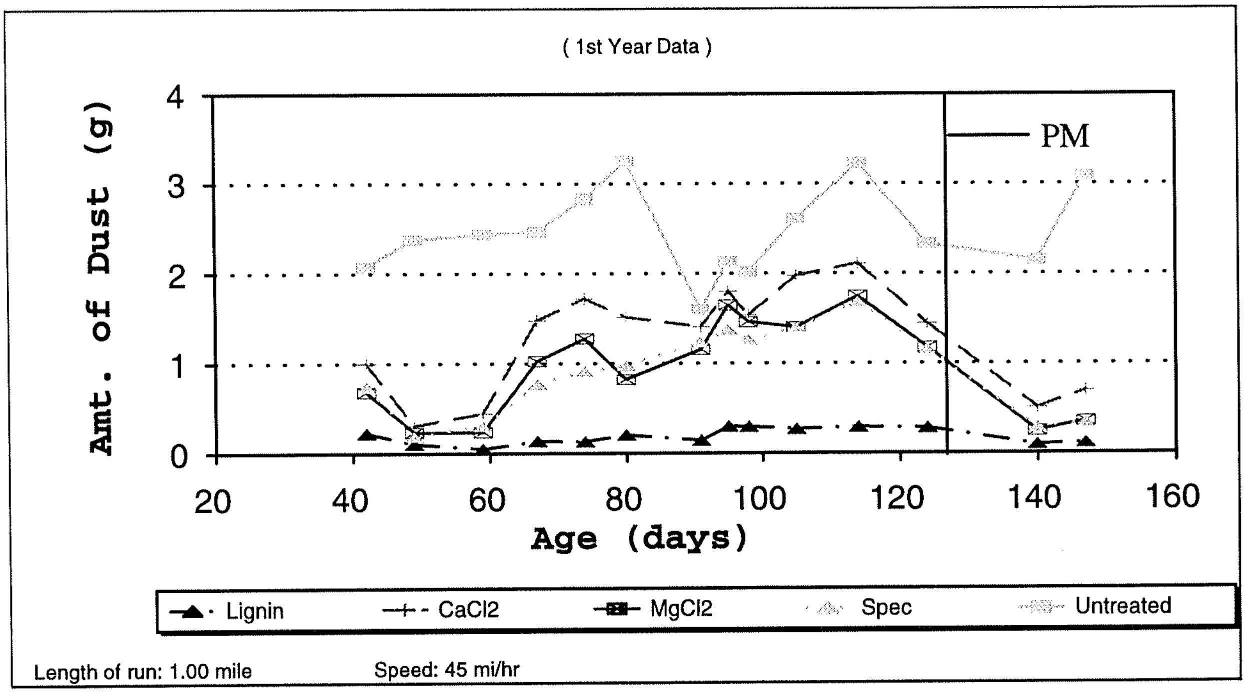


Figure 3.9 Dust Measurement from Test Sections

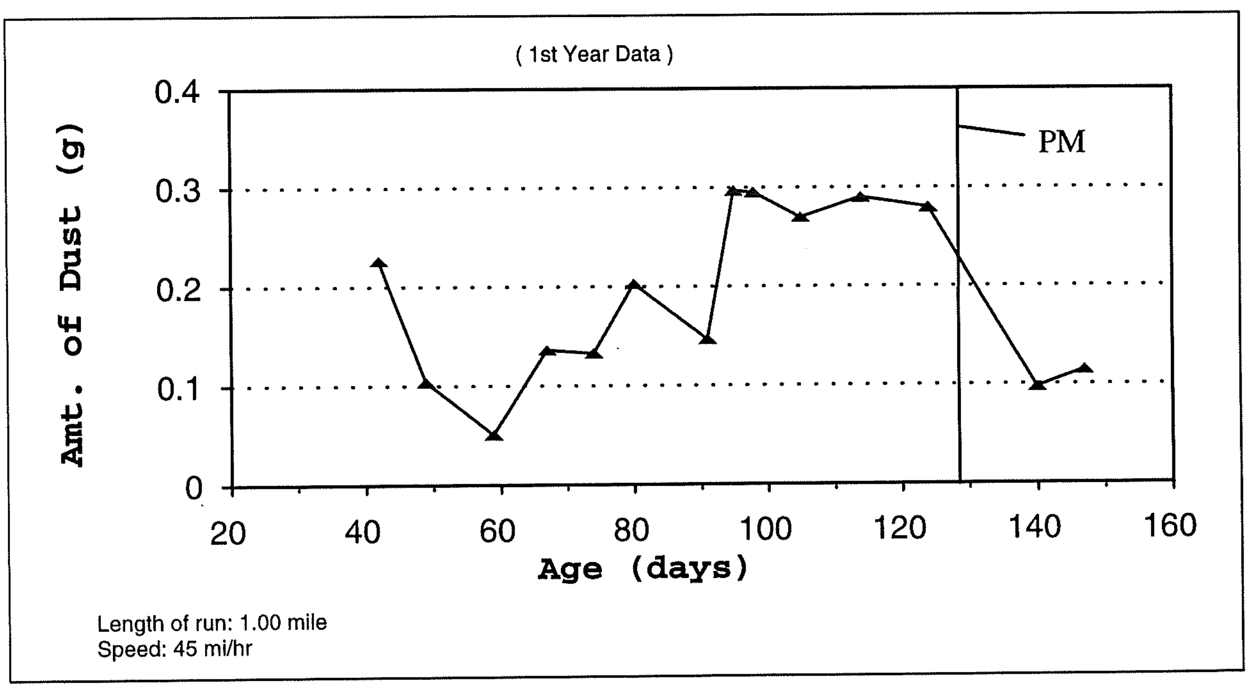


Figure 3.10 Dust Measurement from Lignin Test Section

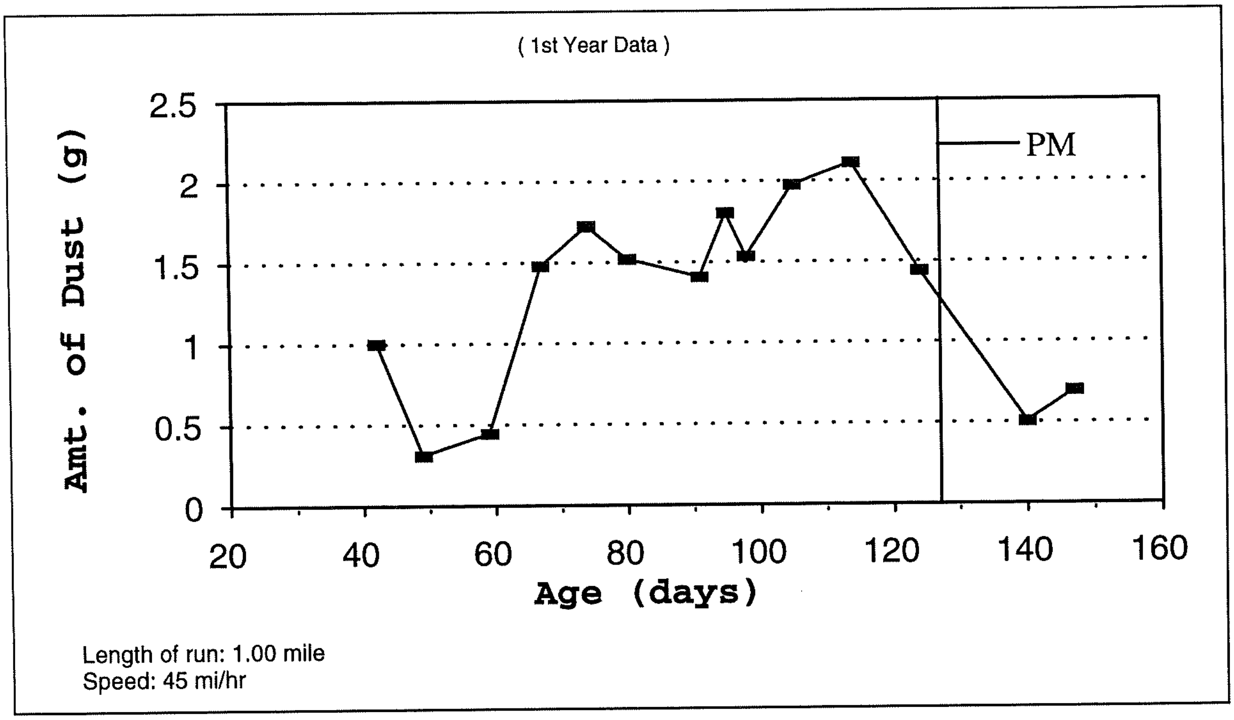


Figure 3.11 Dust Measurement from Calcium Chloride Test Section

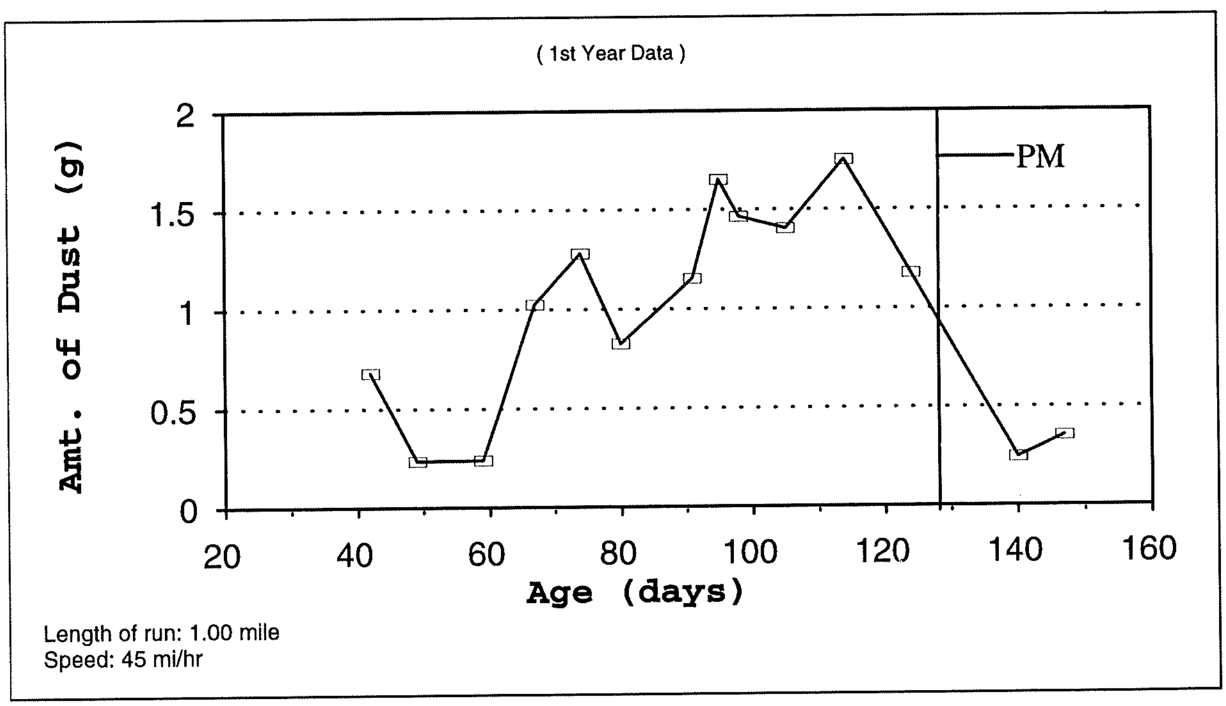


Figure 3.12 Dust Measurement from Magnesium Chloride Test Section

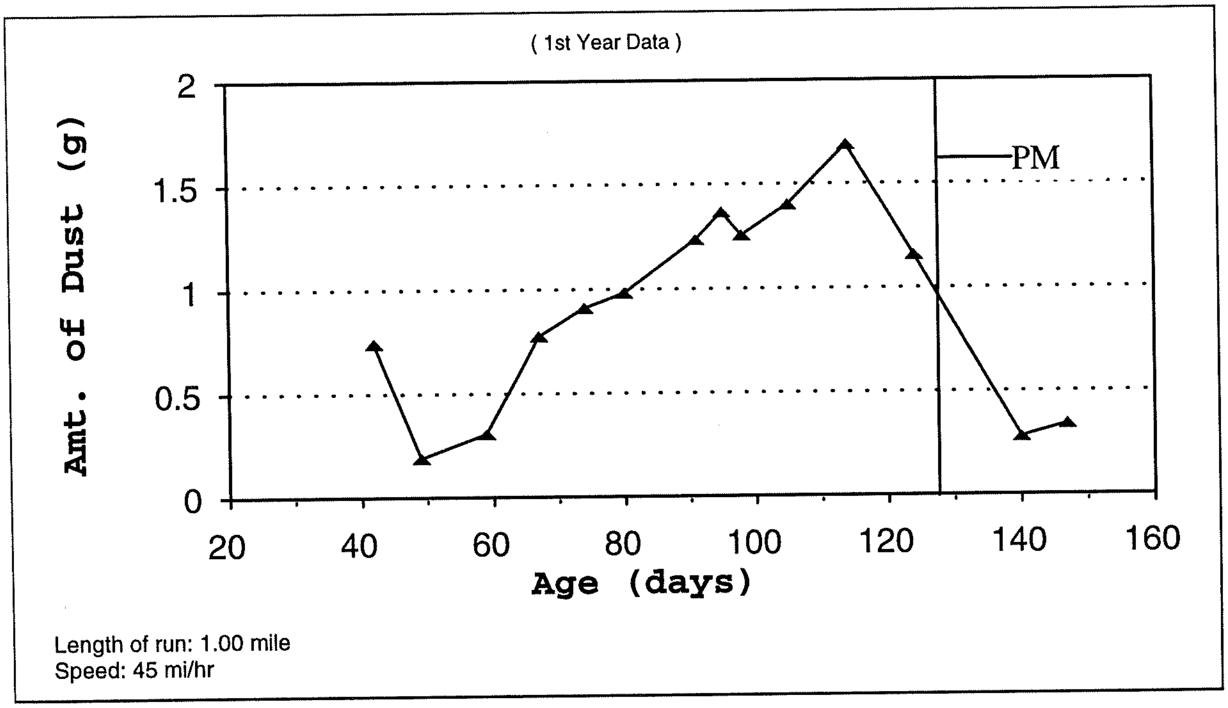


Figure 3.13 Dust Measurement from Calcium Chloride-Special Test Section

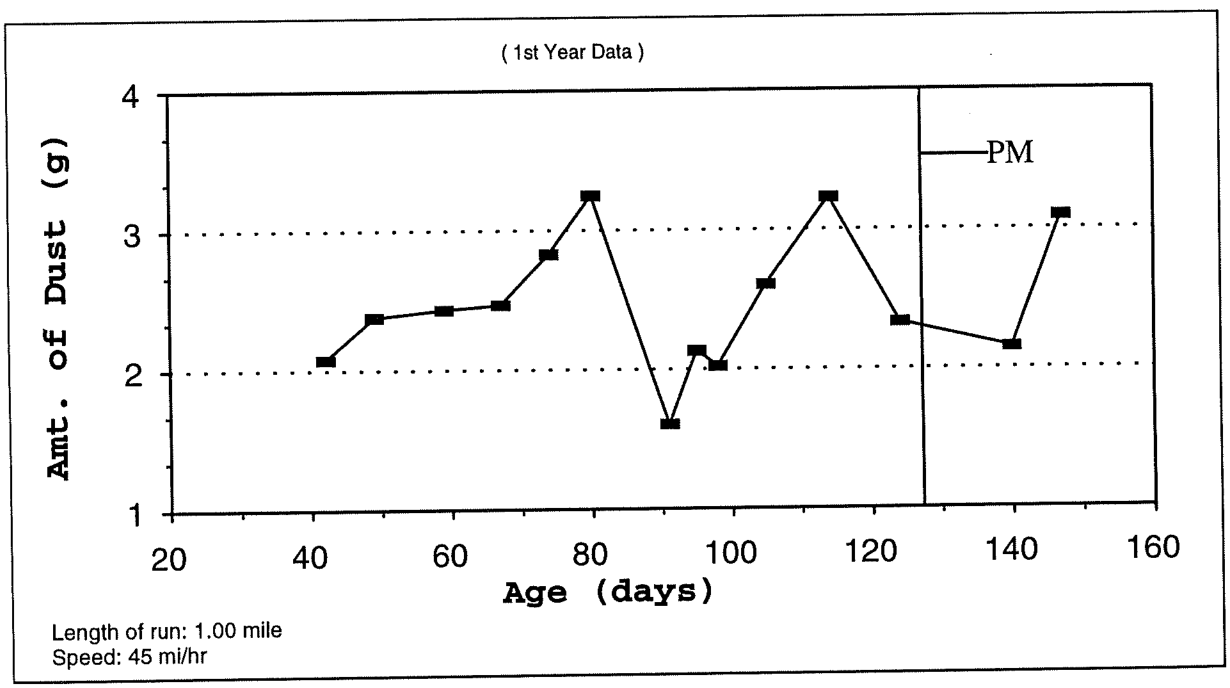


Figure 3.14 Dust Measurement from Untreated Test Section

The dust monitoring data as exhibited in Table 3.2 and Figure 3.9 - 3.14 indicates that indeed treating an unpaved road with dust suppressants does reduce the loss of fines in the form of dust from the surface of the roadway. Under the prevailing field conditions of high temperature and low relative humidity, the amount of dust sampled from the lignin test section is approximately one-eighth that of the untreated test section. The $MgCl_2$ and $CaCl_2$-special dust amounts are about one-third that of the untreated while the $CaCl_2$'s is nearly one-fourth of the untreated test section's. Within the dust measurement period it appears that the lignin suppressant performs better than the chloride base compounds in suppressing dust.

In the second-year evaluation the dust measurements followed the first year's procedure with the exception that the test sections were built using 4 in (10.16 cm) of additional virgin gravel material. As stated earlier, all the test sections were located on CR-12/29 and were four in number compared to five in the first year's evaluation. This was done in order to subject both observed and control test sections to nearly the same field conditions. The untreated test section took the place of the $CaCl_2$-Special test section and all the test sections were subjected to nearly the same amount of traffic.

The construction of the test sections were completed on May 15th 1994 and the dust sampling started 16 days later. Table 3.3 and Figure 3.15 represent the results of the fifteen measurements made during the research period. The treated test sections did not receive any maintenance until after the dust measurements were completed. The untreated test section received two periodic maintenances in the course of the study. The average temperature and relative humidity were computed as approximately 88°F and 24 percent respectively. The amount of dust sampled from the lignin test section varied from a low of 0.05 gram measured when the treatment was fresh to a high of nearly 0.60 gram measured towards the end of the season. The $CaCl_2$ treatment started with a about 0.30 gram of dust and had a high of about 0.90 gram. The $MgCl_2$ gave off dust as low as 0.08 gram and a high of approximately 0.70 gram. Despite the high traffic volume, the untreated test section averaged about 1.00 gram of dust per sample. Figure 3.16 to

3.19 show the individual test sections dust measurements. Note the ordinates scales vary for each of the individual plots.

Table 3.3 Dust Measurement (2nd Year Data)

Dust weight = average of 3 measurements
Passes are run in the same driving lane
Length of run for each test section = 1.00 mile
Dust measurement done at an average speed of 45 mi/hr
Test Sections completed on 05/25/94

Notes	Sampling Date	Days after treatment	Temp. (°F)	Relative Humidity (%)	Test Sections			
					Lignin (g)	$CaCl_2$ (g)	$MgCl_2$ (g)	Untreated (g)
	06/10/94	16	90	20	0.0501	0.3874	0.0805	0.5067
	06/17/94	23	87	30	0.1055	0.4523	0.0907	0.6159
	06/24/94	30	93	18	0.3137	0.5662	0.4581	0.9660
	07/06/94	42	92	20	0.1122	0.5935	0.1361	1.4412
	07/13/94	49	82	35	0.1080	0.3409	0.1635	0.7893
	07/22/94	58	96	15	0.1218	0.4872	0.1537	0.7618
	08/01/94	68	84	35	0.2604	0.4825	0.2635	0.7597
*	08/10/94	77	90	22	0.3370	0.6495	0.3506	0.7565
	08/17/94	84	93	20	0.5312	0.8893	0.7402	1.7325
	08/25/94	92	92	20	0.3663	0.9077	0.5783	1.6729
	09/04/94	102	90	20	0.4940	0.5546	0.4656	0.7707
**	09/10/94	108	86	25	0.3697	0.4516	0.3388	1.1443
	09/20/94	118	80	30	0.5764	0.7903	0.7358	1.4870
	09/27/94	125	82	32	0.5255	0.5278	0.4284	0.6315
	10/09/94	137	85	25	0.5340	0.6780	0.5980	0.8245

* Dust measurement after Periodic Maintenance of Untreated Test Section (done on 08/03/94)

** Dust measurement after Periodic Maintenance of Untreated Test Section (done on 09/08/94)

PM: Periodic Maintenance involves blading, watering and compacting of test section.

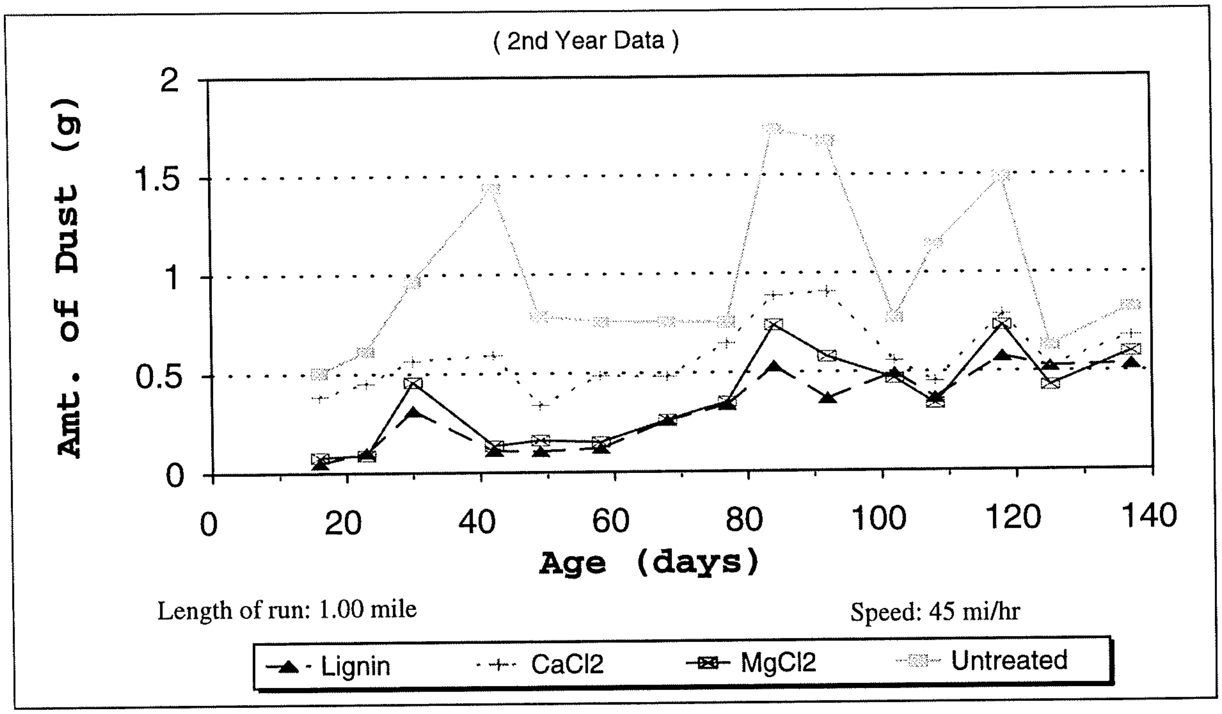


Figure 3.15 Dust Measurement from Test Sections

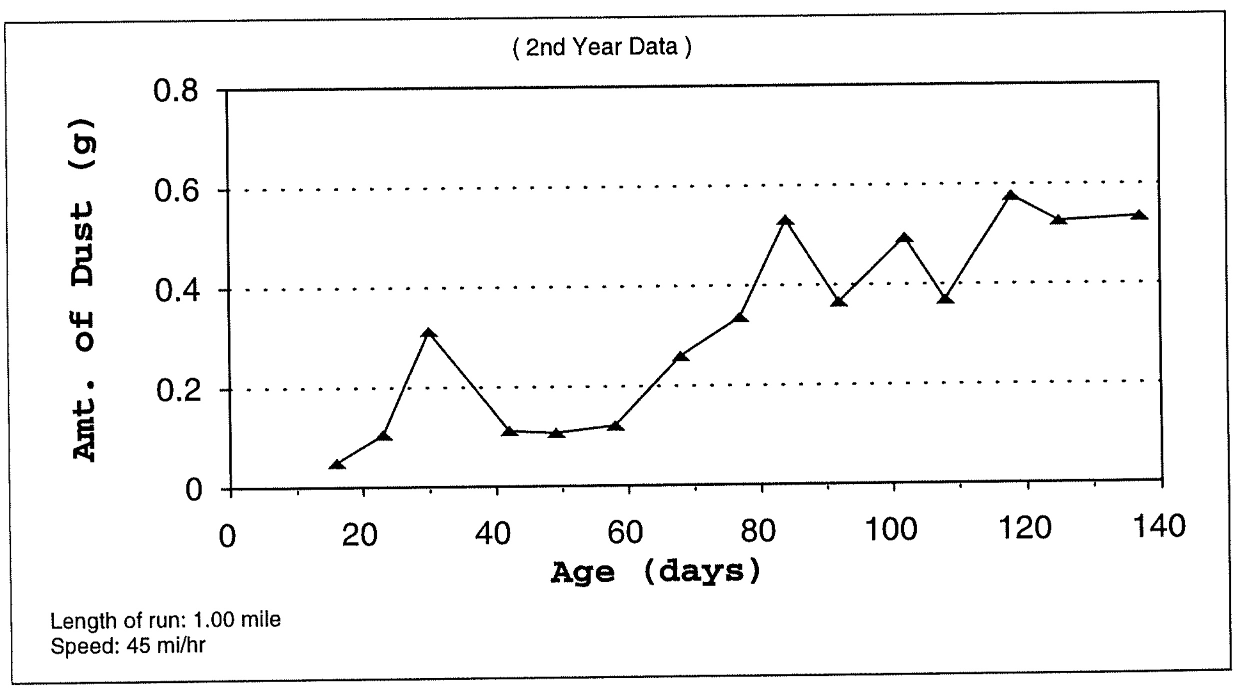


Figure 3.16 Dust Measurement from Lignin Test Section

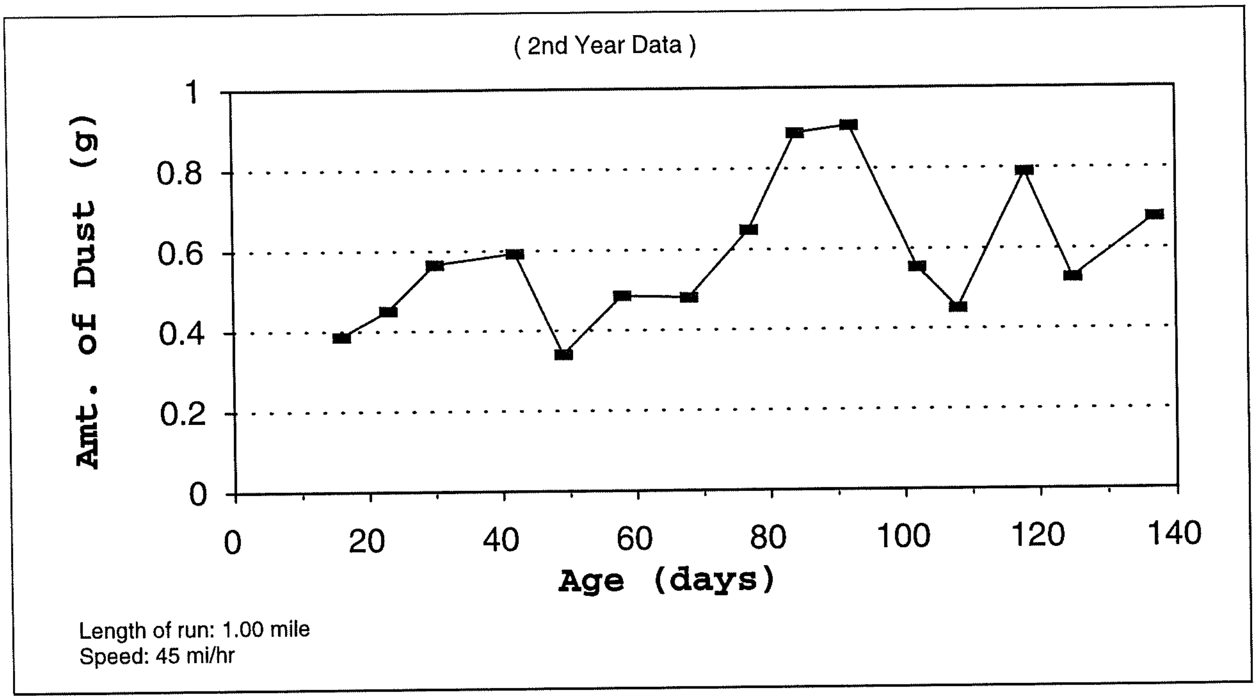


Figure 3.17 Dust Measurement from Calcium Chloride Test Section

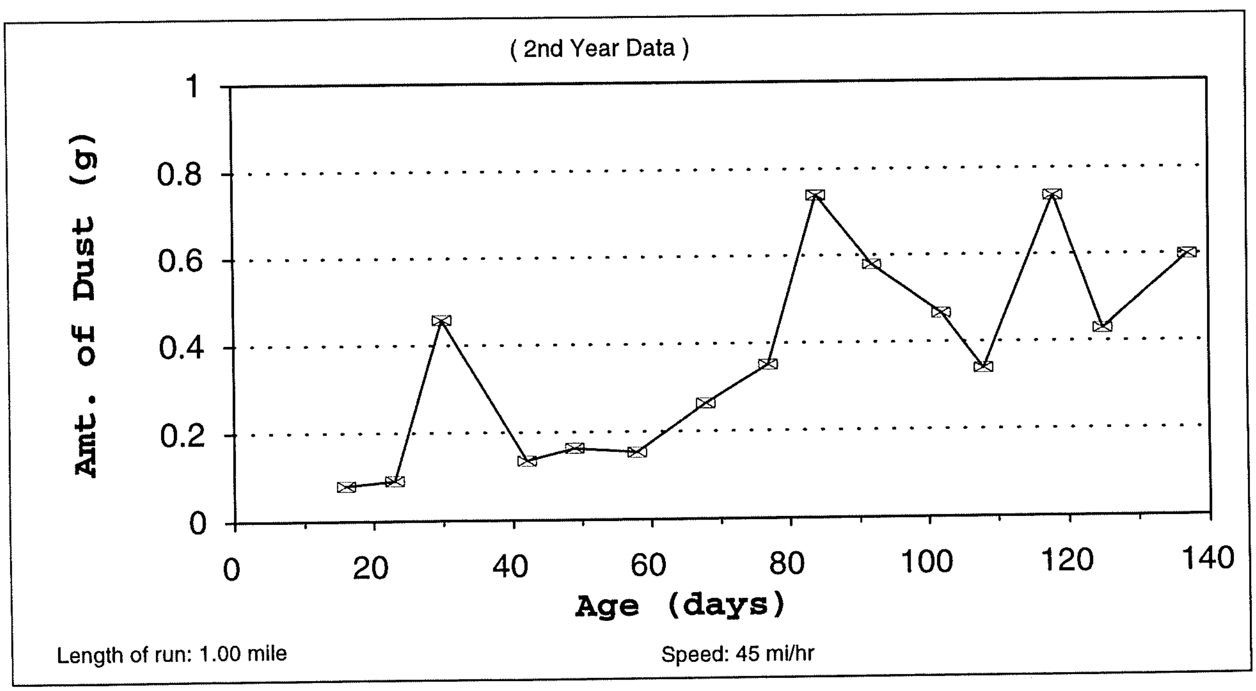


Figure 3.18 Dust Measurement from Magnesium Chloride Test Section

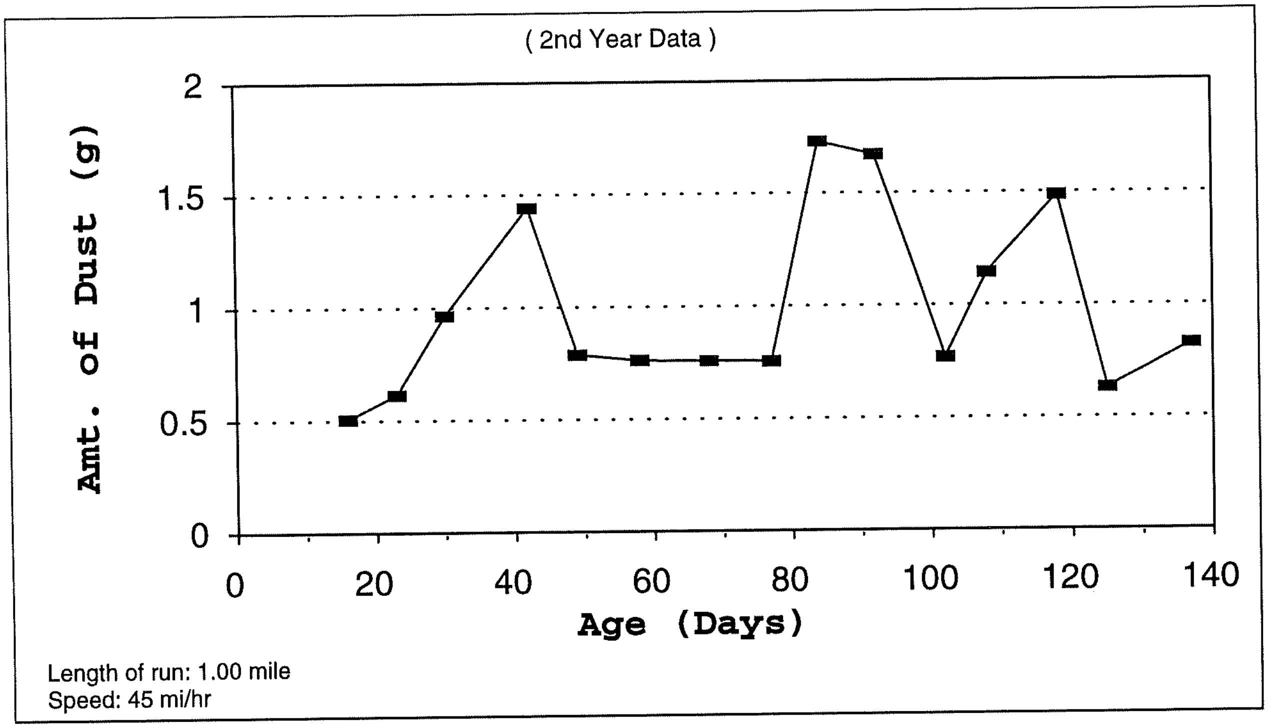


Figure 3.19 Dust Measurement from Untreated Test Section

As noted by various researchers, the amount of vehicular generated dust from unpaved roadway is influenced by numerous factors such as speed of vehicle, degree of turbulence created by vehicle, characteristics of roadway, prevailing field conditions, shading of roadway by trees, and environmental factors. The aforementioned dust production data (Table 3.3 and Figures 3.15-3.19) showed variations in the amount of dust sampled as the test sections aged. The high and low points on the plots could be due to many factors. Significant among them is the rainfall pattern during the test period. Depending on the amount of rainfall and the weather conditions prior to a dust measurement, higher or lower dust amounts could be measured. Rainfalls that did not produce runoff but gave the road surface just enough moisture to help vehicular compaction of the road surface and the rejuvenation of the dust suppressing chemicals in the case of the treated test sections, had subsequent dust measurements been low. For example there were a number of light showers between the 45th and 75th days during the test period, and from Figures 3.15-3.19 it could be seen that the dust measurements were lower.

On the other hand, rainfalls that produced substantial runoff were noted to have washed off the dust suppressant in the immediate top portion of the road surface, allowing the fines in the top portion of the road surface to be lost in the form of dust. For example, there were rainfalls on the 26th day and the 77th day during the test period that produced measurable runoff and from the above plots it could be seen that the subsequent dust measurements on the 30th and 84th days showed higher dust measurements. In addition, in the case of the untreated test section, two periodic maintenances were done during the test period (70th and 106th days). From Figure 3.19 it could be seen that the subsequent dust measurements on the 77th and 108th days were lower.

The dust measurement data (Table 3.3 and Figure 3.15) show that the use of road dust suppressants does indeed reduce the amount of traffic generated dust on unpaved roads. The lignin and $MgCl_2$ test sections produced one-third as much dust as the untreated test section. Dust measurements from the $CaCl_2$ test section were one-half as much as that of the untreated. Within the dust measurement period, the lignin and $MgCl_2$ suppressants performed comparably and both performances were slightly better than the $CaCl_2$ suppressant's. The amounts of dust sampled from the untreated, $MgCl_2$ and the $CaCl_2$ test sections were less than the first year's. This difference can be attributed to the portion of fines (material passing the No. 4 sieve) in the road surface material: the second-year material had a very small portion of fines compared to the first year's material. This confirms the fact that the amount of fines in the road surface material does influence the amount of traffic-generated dust. From all the dust measurements it is apparent that as the road ages the amount of dust generated increases.

AGGREGATE LOSS MEASUREMENT

Aggregate replacement on unpaved roads is noted as one of the most costly expenditures in the road maintenance budgets of most agencies in charge of unpaved roads. The loss of fines from unpaved road surface in the form of dust sets off a chain effect of road surface degradation. Since the fines serve as a binder for the coarse aggregate, their loss as dust allows the large particles to break loose from the road surface resulting in rapid road deterioration. In addition, the loose particles have much of their surface area exposed to traffic action which leads to their rapid degradation. More fines are produced as a result, some of which are eventually lost in the form of more dust or washed off the road surface by erosion.

Experimental Procedure

To assess the longlasting effectiveness of road dust suppressants it is imperative that some form of aggregate loss quantification should be done. As part of the second-year evaluation the task of measuring the aggregate loss from each test section was undertaken. To accomplish this task the mile-long test sections were divided into one-quarter mile sections. Metal posts were used to mark the sections as illustrated in Figures 4.1 and 4.2. Each one-quarter mile cross section was divided into 3 ft (0.9 m) intervals as shown in Figure 4.2. The starting point of the 3 ft (0.9 m) intervals at each one-quarter mile section was marked with a small wooden stake driven into the road surface at the edge. The horizontal distance from the starting point to the metal post markers was also recorded for future reference.

Using a leveling instrument (Dumpy Level) a local datum was established for each of the five cross sections in each test section. Levels were then taken at the 3 ft (0.9 m) interval markings and recorded. The initial levels were taken on May 28th 1994 two days after the test sections were completed. The average width of the road is 33 ft (10 m); in all, an average of twelve levels were taken for each cross section, giving a total of 240 levels taken to document the initial level of the roadway. After 4.50-months of use, the test sections were given a periodic maintenance without additional aggregate. The periodic maintenance was started on October 10th and completed on October 12th.

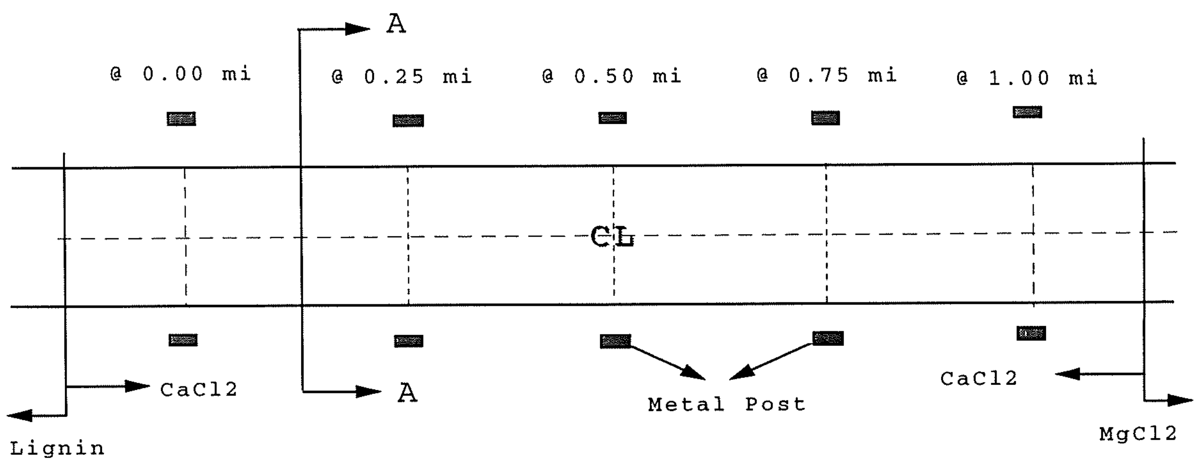


Figure 4.1 Division of Test Section into Quarter-Mile Sections

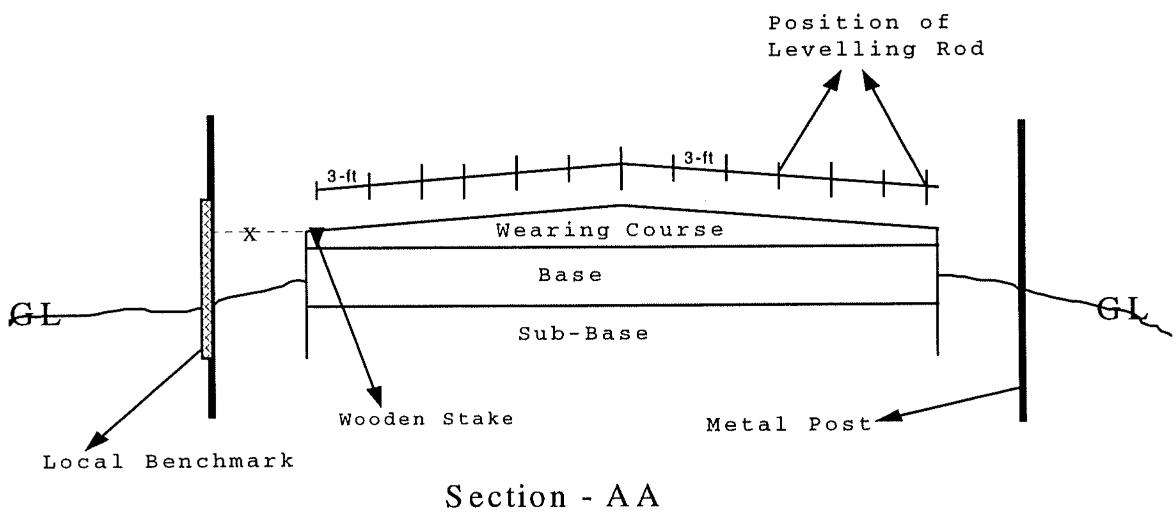


Figure 4.2 Cross Section showing Positions of Staff at 3-ft Intervals

Following the same procedure used in taking the initial levels, the final levels were taken. All the levels were then reduced and the initial reduced levels were compared with the final reduced levels (appendix C contains the initial and final reduced levels). The final reduced levels were subtracted from the initial reduced levels at each of the five cross sections namely, at 0.00-mile, at 0.25-mile, at 0.50-mile, at 0.75-mile and at 1.00-mile (see appendix C). This was done for each test section. If an initial reduced level minus a final reduced level was positive, it was recorded as loss of aggregate, and if negative it was recorded as gain of aggregate. All the losses and gains were added and averaged to give the average loss or gain for that particular cross section. All the losses or gains for each of the five cross sections in each test section were then summed up and averaged to give the overall average aggregate loss for each test section.

Results of Aggregate Loss Measurement

Table 4.1 and Figure 4.3 show the measured aggregate loss for each of the test sections over the 4.50-month period in which the study was done. Table 4.1 also contains the estimated annual loss based on the measured loss.

Table 4.1 Aggregate Loss Measurement

Date at which initial levels were taken: 05/28/94
Date at which final levels were taken: 10/13/94

Test Section	Aggregate Loss			Estimated Year Loss
	(mm)	(inches)	(ft)	(inches)
Lignin	5.80	0.228	0.019	0.604
$CaCl_2$	7.01	0.276	0.023	0.731
$MgCl_2$	5.18	0.204	0.017	0.541
Untreated	15.55	0.612	0.051	1.622

Initial thickness of wearing course: app. 4.00 inches (102 mm)

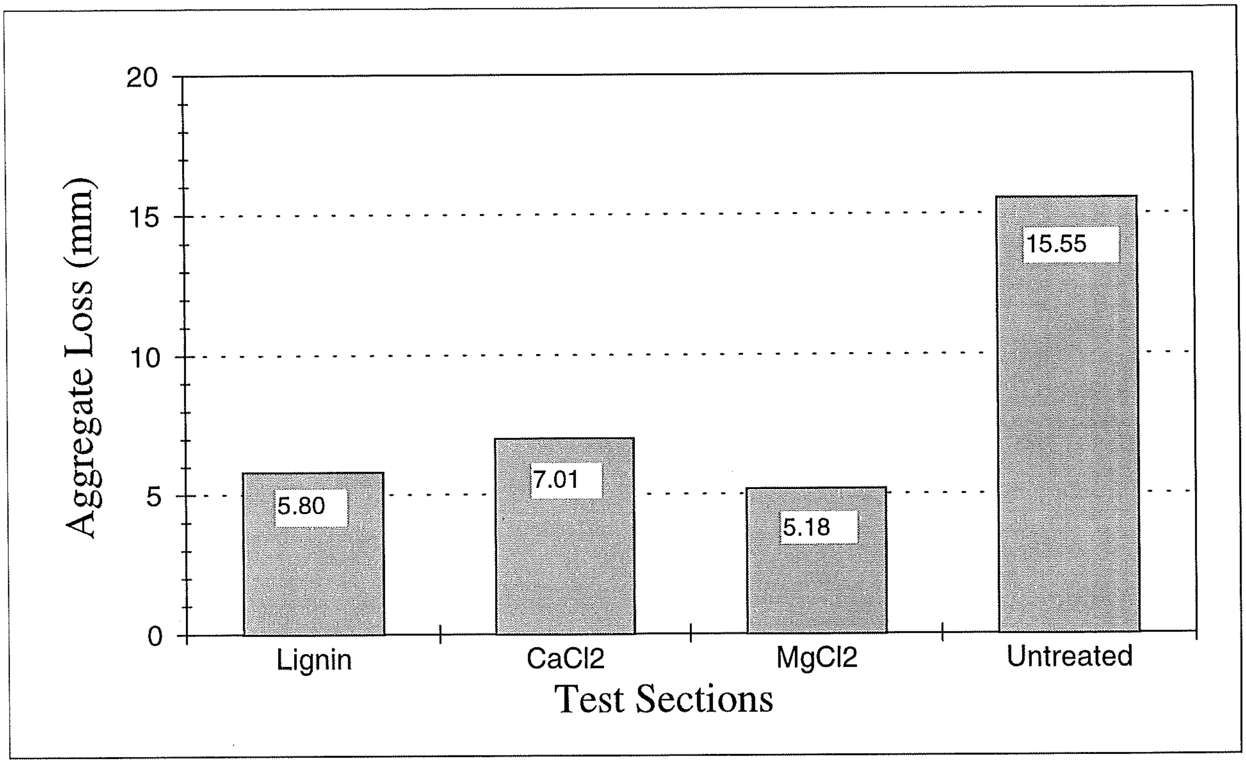


Figure 4.3 Bar Chart showing the Measured Aggregate Lost

The aggregate loss for the lignin treated test section was estimated to be 5.80 mm. These of the $CaCl_2$ and $MgCl_2$ treated test sections were estimated to be 7.01 mm and 5.18 mm respectively. The untreated test section lost an estimated 15.55 mm, which is approximately 3 times more than that of the $MgCl_2$ treated test section. The lost is about 2.7 times more and 2 times more than that of the $CaCl_2$ and lignin treated test sections, respectively. This is consistent with results of other researches. Hoover, et al. (1973), reported aggregate pullout from treated unpaved road surface as approximately 25-75 percent of that of untreated test section. This research showed percentages of 33-45 percent.

The lost of aggregate from unpaved road surface is due to primarily to vehicular activities and therefore the volume of traffic using the road test sections would determine the total aggregate lost from the test sections within a given time. Since the ADT's for the test sections are different, Table 4.2 and Figure 4.4 represent the estimated total aggregate lost from each of the test sections in tons/mile/year/ADT.

The estimated loses were computed considering a 33 ft wide roadway with a compactive density of 1.6 tons/yd^3.

Table 4.2 Estimated Total Aggregate Lost

Length of test section: 1.00 mi (5280 ft)
Width of test section: 33 ft
Compacted density: 1.6 tons/yd^3

Test Sections	ADT	Measured Aggregate Lost/ mi/4.5 months (ft)	Estimated Aggregate Lost/ mi/year (ft)	Estimated Aggregate Lost/ mi/year (ton)	Estimated Aggregate Lost/ mi/year/ADT (ton)
Lignin	515	0.019	0.050	519.88	1.01
$CaCl_2$	421	0.023	0.061	629.33	1.49
$MgCl_2$	448	0.017	0.045	465.16	1.04
Untreated	538	0.051	0.135	1,395.47	2.59

A total aggregate lost of 1.01 tons/mile/year/ADT is estimated for the lignin treated test section. The estimated loses for the $CaCl_2$ and $MgCl_2$ treated test sections are 1.49 and 1.04 tons/mile/year/ADT, respectively. The untreated test section, on the other hand, lost an estimated total aggregate of 2.59 tons/mi/year/ADT, 42-61 percent more than the treated test sections. Note that the estimated loses include loss of fines in the form of vehicular-generated-dust and loses to due erosion (wind and rainfall).

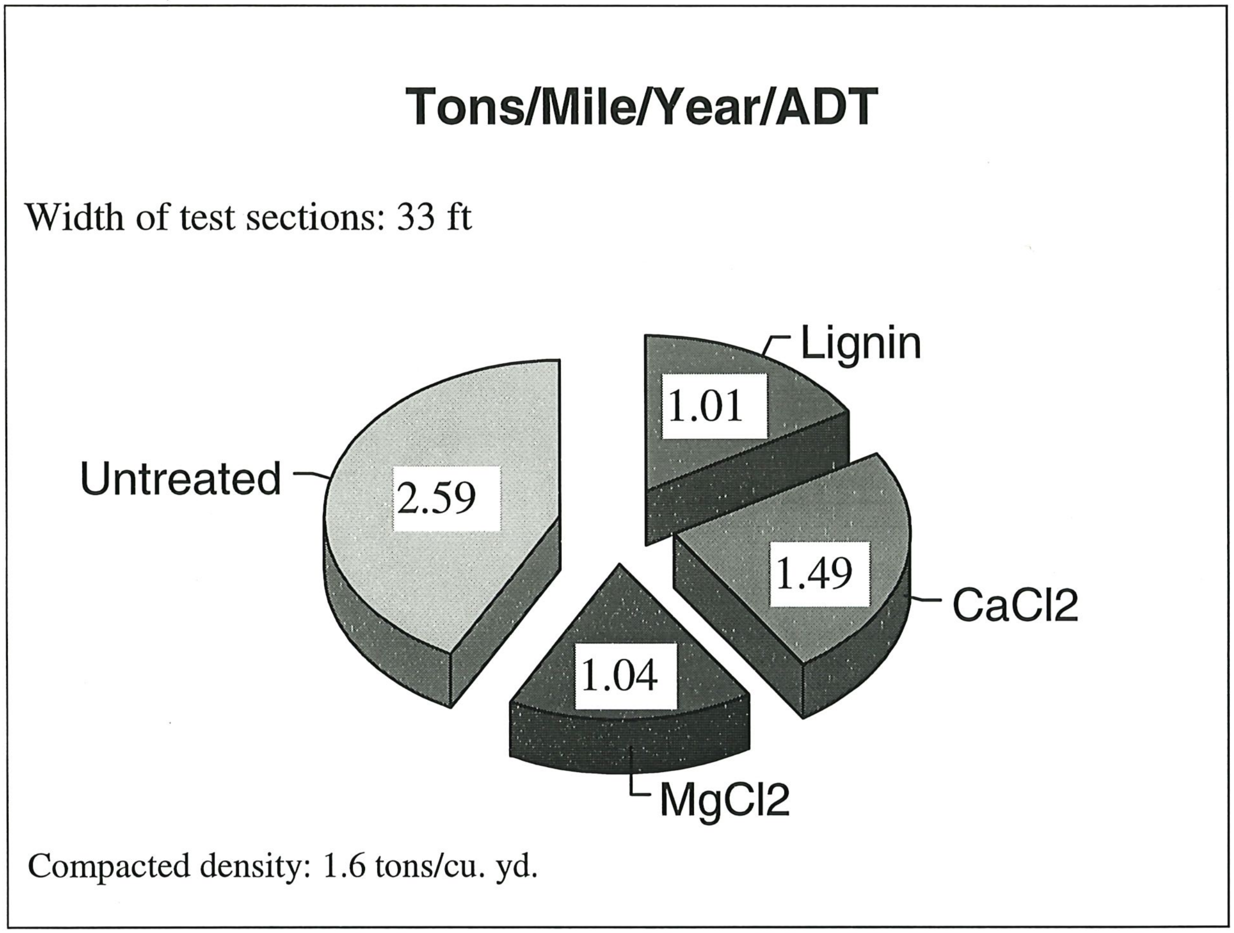


Figure 4.4 Estimated Total Aggregate Lost

COST ANALYSIS

As stated earlier some of the major problems associated with unpaved roads are aggregate replacement cost and periodic maintenance cost. With nearly 65 percent of roads in Colorado unpaved, the pressure from the public to keep these roads in good shape in terms of trafficability has put strains on the budgets of local governments. In Larimer County, for example, there are over 1100 miles of roads under the jurisdiction of the county. Out of this, over 700 miles (65 percent) are unpaved. The cost of maintenance of the unpaved roads runs into millions of dollars a year. Based on 1994 budget figures $1,041,130 (12% of total budget) was spent on aggregate replacement alone and another $1,476,368 (17% of total budget) on periodic maintenance of the unpaved roads.

The main objective of dust suppressing on unpaved roads is to prevent the loss of aggregate in the form of dust and fines as well as to reduce the number of periodic maintenances required to the keep the road in good shape. Protecting the environment by decreasing the atmospheric particulate loading is a positive benefit but not the primary reason in the past for dust suppressant activities. In order for the relative effectiveness of the dust suppressants evaluated in this research to be ascertained, a cost accounting for each test section has to be done. Because of the lack of aggregate loss data from the first year evaluation, the cost analysis presented in this section of the report is based on the second-year evaluation only.

The application rate of each treatment namely, lignosulfonate, $CaCl_2$ and $MgCl_2$, was the same at 2.3 l/m^2 (½ gal/yd^2) of road surface. The price at which they were delivered was also the same at $0.285/gal. Figures provided by the county engineer's office indicate that the total costs of material (suppressants), labor and equipment for placing the treatments were $3528.32/mile for the lignin and $2767.67/mile each for the chloride compounds. The lignin treatment cost $760.65 more in labor and equipment than the $CaCl_2$ or the $MgCl_2$ treatments. This difference was due to the method of application between the lignin and the chloride compounds. The lignin was mixed in place while the chlorides were topically sprayed. The cost of periodic maintenance, which included the use of a water truck and compactor, was reported as \$529/mile.

Under the assumption that the amount of aggregate loss would be replaced by the same amount, Table 4.3 was developed. Table 4.3 shows the cost analysis of each test section evaluated in the project. From the aggregate loss measurement over the 4.50 months (see Table 4.1), a loss for the year was estimated. Based on a compactive density of 1.60 tons/yd^3, the aggregate loss or replacement in tons was calculated. With the cost of gravel given at \$11.57/ton in place, the cost to replace the loss aggregate is computed. The treated test sections are expected to receive two periodic maintenances in a year, while eight periodic maintenances would be required for the untreated test section in the same period.

From the cost of aggregate replacement, cost of material/ labor/equipment and cost of periodic maintenance, the total cost of each test section is calculated (Figure 4.5). Because of the variation in ADT for the test sections, the total cost is transformed to cost per ADT as shown in Table 4.3 and Figure 4.6. The cost of \$20.59/ADT is computed for the lignin treated test section, \$26.38/ADT and \$20.55/ADT for the $CaCl_2$ and $MgCl_2$ treated test section, respectively. The untreated test section cost \$37.88/ADT. This analysis indicates a 30-46 percent cost savings in the treated sections over the untreated test section. The slight differences between the treated test sections costs could be just random and therefore is of less importance. What is of importance is the fact that the use of road dust suppressants reduces the overall total aggregate pullout from the road surface as well as the number of periodic maintenance required to keep the road in good shape. These would always result in substantial cost savings, as demonstrated by this research project, especially when the ADT on an unpaved road is high.

Table 4.3 Cost Analysis (2nd year Evaluation)

Length of test section : 1.00 mi (5280 ft)
Width of test section : 33 ft
Compacted density : 1.6 ton/cu yd
Cost of gravel : $11.57/ton in place
ADT : Average Daily Traffic
PM : Periodic Maintenance
M+L+E : Cost of Material (suppressant), Labor and Equipment
Actual Total Cost : include cost of M+L+E, cost of PM and cost of Aggregate replacement
Cost of Suppressants per gallon are the same for all three compounds.
The Lignin treatment cost $760.65 more in Labor and Equipment than the CaCl2 and MgCl2 treatments.

Test Section	ADT # veh.	Measured Aggregate Loss/ mi/4.5 months (ft)	Estimated Aggregate Loss/ mi/yr (ft)	Estimated Aggregate Loss/ mi/yr (ton)	Cost of Test Sections						
					Aggregate Loss/ mi/yr (dollars)	(M+L+E)/mi/yr (dollars)	PM/mi (dollars)	* PM/yr	Actual Total Cost/mi/yr (dollars)	Actual Total Cost/mi/yr/ADT (dollars)	@ ADT of 100 (dollars)
Lignin	515	0.019	0.050	519.88	$6,015.02	$3,528.32	$529.00	2	$10,601.34	$20.59	$2,058.51
CaCl2	421	0.023	0.061	629.33	$7,281.34	$2,767.67	$529.00	2	$11,107.01	$26.38	$2,638.24
MgCl2	448	0.017	0.045	465.16	$5,381.86	$2,767.67	$529.00	2	$9,207.53	$20.55	$2,055.25
Untreated	538	0.051	0.135	1,395.47	$16,145.57	$0.00	$529.00	8	$20,377.57	$37.88	$3,787.65

*** The Periodic Maintenance performed is with a Water Truck and Compactor.**
If this were being performed without these tools, we anticipate that the Periodic Maintenance would have to be done weekly.

* Duration of Study is 4.50 months

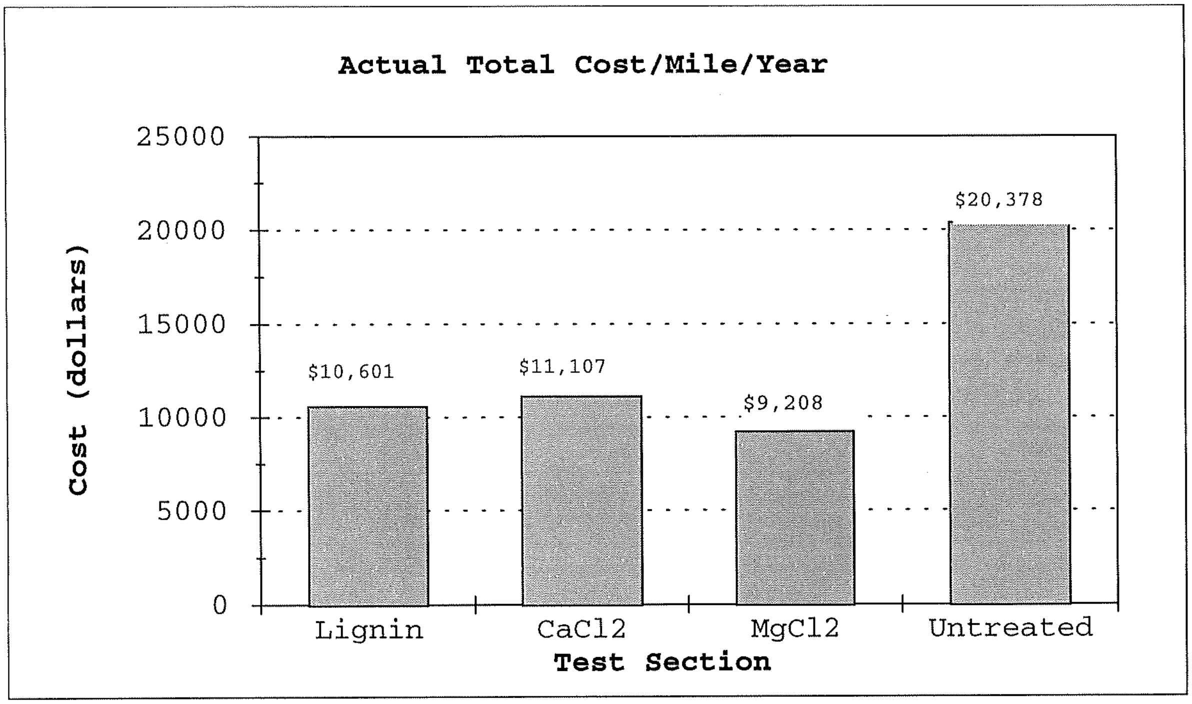


Figure 4.5 Total Cost of each Test Section

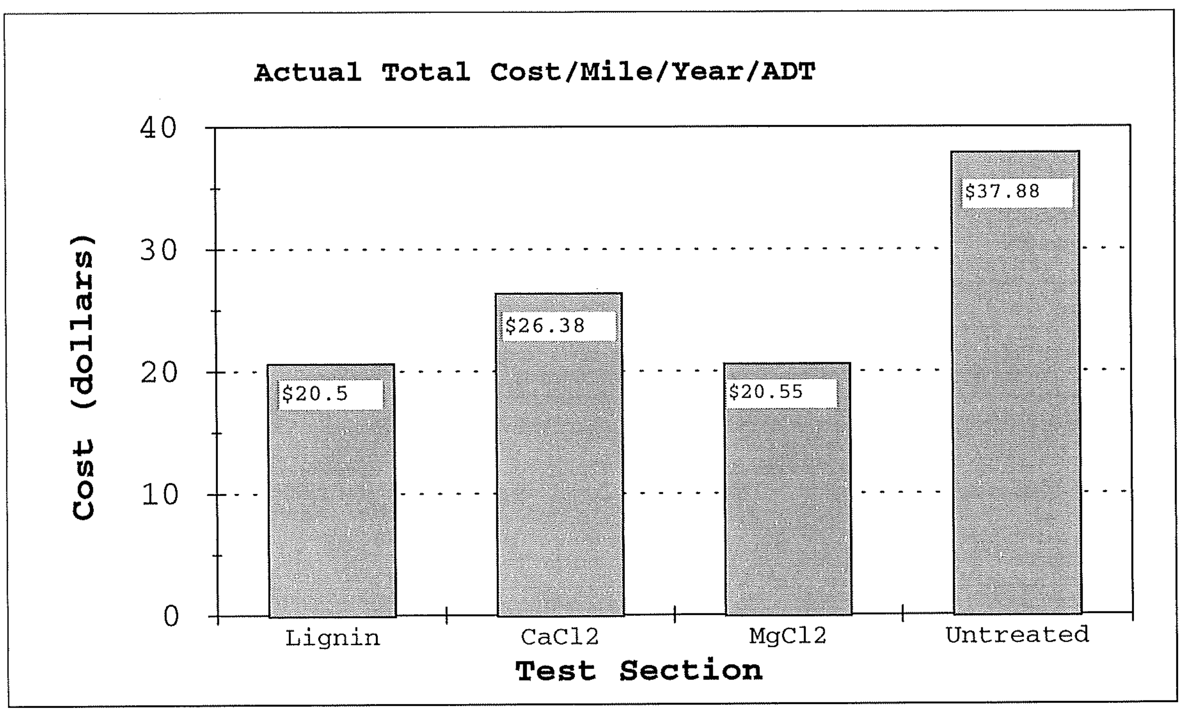


Figure 4.6 Cost per ADT for each Test Section

Because of the high initial cost (material, labor and equipment) involved in applying dust suppressants, the question of what minimum ADT would dust suppressing be feasible was posed. The answer may be influenced by a few factors, of which the most important is cost of aggregate in place. Based on the aggregate loss measurement and cost figures for the different treatments in this research, Figure 4.6 was developed. The cost of aggregate in place was given as $11.57/ton, the initial cost per mile of roadway per year in material (suppressant), labor and equipment for placing each treatment was given as $3,528.32 for the lignin test section, $2,767.67 each for $CaCl_2$ and $MgCl_2$ test sections and $529.00 for the untreated test section (y-intercept, Figure 4.7). The cost of periodic maintenance for each test section was given as $529.00. Two periodic maintenances per year were estimated for the treated test sections and eight per year for the untreated test section. Based on the traffic count in this research, the cost of aggregate in place and periodic maintenance cost the slope of each curve was established.

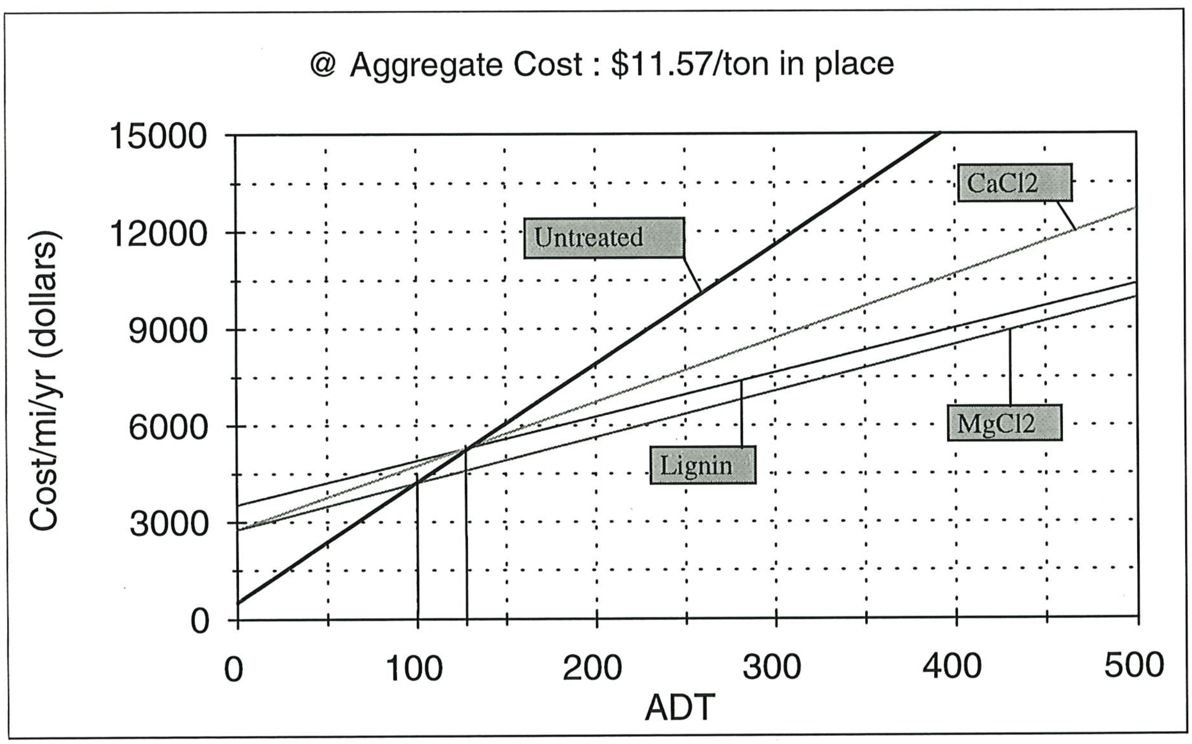


Figure 4.7 Cost of Treatment versus ADT

From the Figure 4.7, it is obvious that at low ADT is it more economical to leave the unpaved road untreated. As the ADT increases, the cost of keeping the road untreated increases. The point where a treated test section curve crosses the untreated test section curve (indicated with vertical lines on Figure 4.7) is the minimum ADT at which a particular treatment is economically feasible.

Since the cost of aggregate in place is such an important variable influencing the economics of this exercise, the minimum ADT at which treatment is feasible is determined at different aggregate costs. Table 4.4 shows the results.

Table 4.4 Minimum ADT at which Treatment is Feasible

	Lignin	$CaCl_2$	$MgCl_2$
Cost of Agg./ton	ADT	ADT	ADT
$5.00	232	225	180
$7.50	180	180	140
$11.57	130	130	100
$15.00	105	105	80

The procedure followed in establishing the minimum ADT's for the different aggregate cost is the same as described above. The minimum ADT's at $5.00/ton, $7.50/ton and $15.00/ton in addition to the $11.57/ton were determined. From the economic analysis and the results (Table 4.4) one can conclude that as the cost of aggregate in place increases the minimum ADT at which the use of dust suppressants become economically feasible decreases. Note: this analysis does not include the improvement of the base when the roadway is ungraded to a chip and seal, asphalt or concrete road.

RUNOFF SAMPLING AND ANALYSIS

Similar to the problems associated with road deicing, there may be possible environmental problems of water quality degradation in both surface and subsurface due to the long term use of road dust suppressants. The suppressants evaluated in this research, namely, the chloride compounds and the lignin derivatives, are water soluble and therefore can be leached out into the environment by precipitation.

During the first-year evaluation limited analyses were done on the runoff collected from the test sections. In the second-year evaluation however, a comprehensive analysis was done on the runoff collected and the data reported herein are from the second-year evaluation. Five measurable rainfall events occurred during the test period — late May to October — although there were many more showers that occurred.

Experimental Procedure

To help answer the question of how much of the suppressants are being washed out during rainfall events, surface runoff from the test sections were collected and analyzed during the test period. Because of the difficulty of being at the test site during rainfall events, a sampling technique was employed. The technique involved the use of plastic containers installed on the shoulders of the test sections. The containers had their lids perforated with small slits and holes. The perforations allowed only the runoff with some small amount of sediment to enter the containers while preventing the washed road surface material from entering and filling the container up. Figure 4.8 shows an installed container on the shoulder of a test section. The locations selected for the installation of the containers were such that during a rainfall event with adequate runoff from the road surface, some amount of the runoff would enter the containers. An average of four containers were installed per each test section. After a rainfall event, all the containers were inspected and emptied if runoff were collected. The sampling containers were reinstalled and the samples were sent to the Soil, Water and Plant laboratory at Colorado State University for analysis.

Figure 4.8 Runoff Sampling Container installed on shoulder of Test Section.

The water quality variables analyzed for in the runoff samples included the known constituents of the suppressants, namely, calcium (Ca), magnesium (Mg), chloride (Cl), sodium (Na), potassium (K) and others. Metal such as iron (Fe), aluminum (Al), copper (Cu), zinc (Zn), nickel (Ni) and others were also analyzed. The variables are listed in Table 4.5. In all, twenty-one variables were analyzed. The hardness of $CaCO_3$ and the total dissolved solids (TDS) were calculated. The TDS was calculated using the relationship:

$$TDS = 0.67 x EC \qquad (3)$$

Where: TDS = Total Dissolved Solids (mg/l)

EC = Electrical or Specific Conductance (μmhos/cm)

The 0.67 was derived from the measurement of TDS and EC on the runoff samples using the conductivity meter.

The total hardness was calculated as calcium plus magnesium (Snoeyin and Jenkins, 1980).

Table 4.5 List of Water Quality Variables

1. pH	9. B	17. Mo
2. EC	10. P	18. Cd
3. TDS	11. Al	19. Cr
4. Ca	12. Fe	20. Ba
5. Mg	13. Mn	21. Pb
6. Cl	14. Cu	22. SO_4
7. Na	15. Zn	23. Hardness as $CaCO_3$
8. K	16. Ni	

Results of Water Quality Analysis

Samples of the suppressants used for the test sections were analyzed to ascertain the original amounts of the variables present. The results of the analysis are presented in appendix D. It includes the analyses of the lignosulfonate, calcium chloride and magnesium chloride compounds. Appendix D also contains the results of the runoff analysis from the rainfall events on May 31st, June 20th, July 22 nd, August 10 th, and September 22nd 1994. Common to all the results are the analysis of the runoffs of the untreated test section which was done in order to provide background data.

The amount of rainfall recorded varied from test section to test section. An average of 0.42 inches (10.75 mm) was recorded for May 31st rainfall, 1.04 inches (26.50 mm) - June 20th rainfall, 0.42 inches (10.75 mm) - July 22nd rainfall, 2.85 inches (72.39 mm) - August 10th rainfall, and 0.28 inches (7.00 mm) - September 22 nd rainfall. The average total rainfall recorded for the five events of 5.01 inches (127.25 mm) is about a third of the yearly average precipitation of 14 inches (355.60 mm) in the test site area of the county.

Taking into account the dilution factor from the amount of rainfall, it appears that the runoff from the rainfalls occurring shortly after the treatments have more dissolved constituents than the subsequent ones. This is expected since the highly concentrated compounds used for the treatments would enter into solution more easily at the early age of the treatment. But as the suppressants settle into the road surface and curing occurs, the amount of suppressants available in the top part of the road surface reduces, leading to a reduction in the concentration of the constituents in the runoff. Figure 4.9 shows the total hardness measured in the runoff samples from all the test sections and illustrates the aforementioned phenomenon. For example, the hardness in the May 31st runoff sample from the $CaCl_2$ treated test section is 10,473 mg/l compared to the July 22nd sample of 4,248 mg/l. Other variables such as the TDS also exhibited the same trend a drop of about 50 percent between the June 20th $CaCl_2$ treated section sample and that of the July 22nd sample.

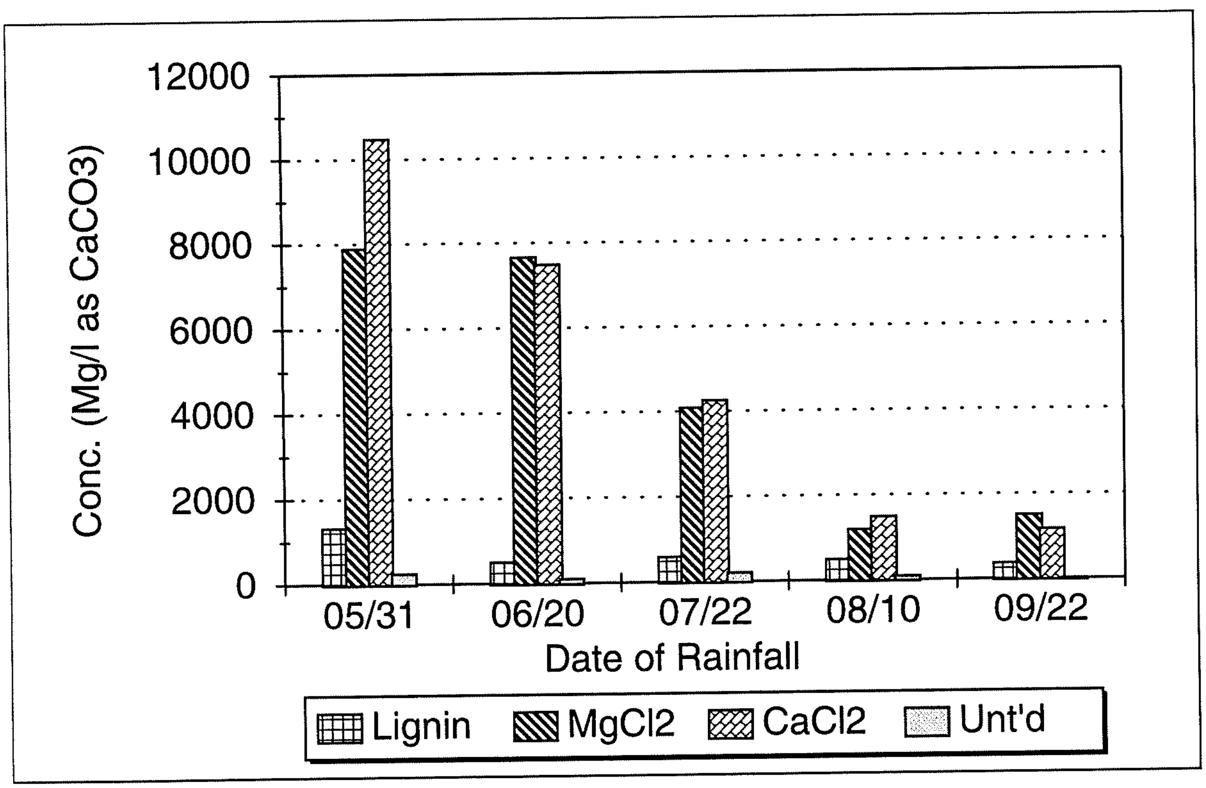


Figure 4.9 Total Hardness Measured in Runoff from Test Sections

The presence of most of the metals analyzed are nonexistent in the stock solution (see appendix D) and this is reflected in the runoff analysis as well. Some of the metals, if present at all, were in such trace amounts that they do not exceed the amounts found in the surface water and groundwater in Colorado. Considering that the runoff samples collected were directly from the road surface and therefore have not been diluted by the non-road surface runoff from the adjacent land areas, one can conclude that the metals analyzed for do not pose any immediate environmental danger.

Lignin as a compound is biodegradable, especially under aerobic conditions, and therefore its presence in the environment is nonthreatening. The amounts of its constituents in the runoff samples (appendix D) make one wonder if there are any water quality concerns from their use as road dust suppressant. The chloride compounds, on the other hand, when used as road deicers are noted to harm certain trees and plants receiving drainage water from the treated roads (Hanes, 1972; 1980). Although the concentration of chloride ions in the stock solutions is high, the combined amount measured in all the five runoffs constituted less than 9 percent of the amount used for the treatment in case of the $MgCl_2$ test section and less than 8 percent in case of of the $CaCl_2$ test section. The average TDS in the untreated test section runoffs is 220 mg/l. This is slightly more than the average of 200 mg/l measured in the surface waters and considerably less than the 670 mg/l measured in the groundwater of Colorado (USGS,1991). It should be noted that the 200 mg/l and 670 mg/l are average values of samples taken in the months of July and August of 1991. Although the concentrations of the major constituents of the dust suppressants in the runoff are high, it is the total mass concentrations that enters the environment that should be of concern, not the point concentrations.

SUMMARY OF RESULTS

The research documented herein attempts to quantify and evaluate under field conditions the effectiveness of chloride compounds and lignin derivatives as road dust suppressants. The study also assesses water quality effects from the use of the suppressants by analyzing surface runoff from test sections treated with the dust suppressants. At the beginning it became apparent that in order to undertake the proposed research it would be necessary to develop a dust measuring device, hence making this a major thrust of the research as well.

The study was conducted from the periods of late May to early October in both 1993 and 1994. The dry nature of this region (semiarid) makes dust one of the major nuisances to the public at large. As stated earlier, nearly 65 percent of roads in Colorado are unpaved. In Larimer County, where the study was conducted, there are approximately 1100 miles of road under the county's jurisdiction. Of these only 387 miles are paved; besides, nearly all private roads in the area are unpaved as well. Aside from the few rainy and snowy days in a year, it is dry and dusty year-round. The following summarizes the results of the research:

1. The Colorado State University Dustometer developed and utilized for the comparative dust studies proved to be a very precise inexpensive dust-measuring device. The Dustometer driven at a speed of 25 mph collected an average of 2.54 grams of dust per mile of unpaved roadway. This compares favorably with the reported 0 to 2.5 grams of dust collected per 5000 ft of unpaved roadway by the Dust Volume Sampler developed by Langdon (1984).
2. Using the Colorado State University Dustometer, the relationship between the velocity of a vehicle and the amount of dust generated on an unpaved road was found to be linear which had been reported in other research. The EPA model (AP-42) EQ. 1 in the text shows a linear relationship between velocity and amount of dust generated.

3. The lignin treated test section in both the first- and second-year evaluations produced less dust during the test period than any of the other treatments.

4. With exception of the lignin treatment, all the test sections showed higher dust measurements in the first year's evaluation than in the second year's. The $CaCl_2$ test section measured from 0.3 to 2.0 grams in the first year, compared to 0.3 to 0.9 grams in the second year. The $MgCl_2$ test section measured from 0.24 to 1.75 grams in the first year, compared to 0.08 to 0.7 grams in the second year. The lignin test section measured from 0.05 to 0.3 grams in the first year, compared to 0.05 to 0.6 grams in the second year. The untreated test section averaged approximately 2.5 grams of dust in the first year, compared to 1.0 gram in the second year. This could be due to the fact that the second-year road surface material had a very small portion of fines in the mix.

5. There was, on average, a 50-70 percent reduction in dust emissions from the treated test sections versus the untreated test section in both years of the study. As a result, there are less particulate emissions into the atmosphere and less aggregate loss from the road surface.

6. Aggregate loss measurement over a 4.50 month period during the second-year evaluation showed that the $MgCl_2$ treated section lost less aggregate overall, followed by the lignin treated section and then the $CaCl_2$ treated section. The untreated test section on the other hand lost 55-67 percent more total aggregate than the treated test sections.

7. Calculations indicate an estimated total aggregate lost of 1.01 ton/mile/year/ADT from the lignin test section, 1.49 tons/mile/year/ADT from the $CaCl_2$ test section, 1.04 tons/mile/year/ADT from the $MgCl_2$ test section and 2.59 tons/mile/yr/ADT from the untreated test section. Note that the estimated losses include loss of fines in the form of vehicular-generated-dust and loses due to erosion (wind and rainfall). The aforementioned estimates compare favorably with the estimated 1 ton of dust deposited along a 1,000-foot corridor centered on the road by every vehicle traveling a

mile of an unpaved road, once a day, every day for a year (USDA Forest Service, 1983; Hoover, et al., 1973).

8. Cost analyses show that there is a cost savings of 30-46 percent when the unpaved road is treated with lignosulfonate or the chloride compounds, compared to the untreated road. The cost per mile per year per ADT was \$20.55 for the $MgCl_2$ test section, \$20.59 for the lignin test section, \$26.38 for the $CaCl_2$ test section and \$37.88 for the untreated test section.

9. The ADT (Average Daily Traffic) for the test sections was 515 for the lignin test section, 421 for the $CaCl_2$ test section, 448 for the $MgCl_2$ test section and 538 for the untreated test section.

10. The total concentrations of the major constituents in the runoff samples from the five rainfall events constituted less than 10 percent of the concentration of the major constituents in the stock solutions. Some of the metals and ions analyzed for were neither present in the stock solutions nor the runoff.

11. Extensive traffic survey on the test sections show that the daily average traffic (ADT) varied considerably from test section to test section, although all the test sections were part of the same stretch of road. The test sections at the ends of the roadway experienced more traffic than those in the middle portion of the roadway, a difference of about 90 ADT was found in the second year study. The overall average ADT is nearly 480.

CONCLUSIONS

The research project entitled "Effectiveness and Environmental Impact of Road Dust Suppressants" was conducted at Colorado State University in cooperation with the Larimer County Department of Roads and Bridges. The study which was mostly field-based research conducted between the periods of spring to fall, 1993 and 1994. During the first-year study (1993) five test sections of road each 1.25 miles in length were evaluated — four treated with different dust suppressants and one untreated serving as the control. The dust suppressants include 1) Calcium Lignosulfate, 2) Calcium Chloride, 3) Magnesium Chloride and 4) Calcium Chloride-Special. In the second-year study (1994), four test sections were evaluated — three treated with different dust suppressants and one untreated serving as the control. The dust suppressants used include 1) Lignosulfonate, 2) Calcium Chloride and 3) Magnesium Chloride. The following conclusions can be made:

1. The Colorado State University Dustometer, a dust measuring device, developed and used in this comparative dust study is a portable, inexpensive, quantitative and a precise research tool which can be used in future dust studies.
2. Dust measurement data from both study years indicate that there is a substantial reduction in dust generation with application of suppressants.
3. Dust production was found to be linearly related to vehicular velocity.
4. Under the high temperature and low relative humidity conditions, the lignin suppressant treated test sections (in both years), appear to produce less dust than the test sections treated with chloride compounds during the test period. However, field observations after the research was completed showed that the lignin test section produced equal or more dust than the chloride compounds. The driving comfort on the lignin test section was also found to be considerably less than on the chloride test sections, mainly because of pothole formations on the lignin test section.

5. Aggregate loss measurements showed that there is a 55-67 percent reduction in total aggregate loss when unpaved roads are treated with Lignin, $CaCl_2$ or $MgCl_2$ dust suppressants.
6. There is an estimated total aggregate loss of 1.01 ton/mile/year/ADT from the lignin treated test section, 1.49 tons/mile/year/ADT from the $CaCl_2$ treated test section, 1.04 tons/mile/year/ADT from the $MgCl_2$ treated test section and 2.59 tons/mile/year/ADT from the untreated test section.
7. Cost analysis shows a 30-46 percent reduction in total annual maintenance cost for treated test sections over the untreated test section.
8. At an ADT of over 120, the use of any of the dust suppressants evaluated proved to be cost effective.
9. Water quality analysis indicates significant dust suppressant concentrations in runoff samples from treated test sections, but that the total mass going into the environment is small.

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APPENDICES

A: Types of Dust Suppressants

B: Blue Print of Dustometer

C: Initial and Final Reduced Levels

D: Runoff Quality Analysis

Appendix A

	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)

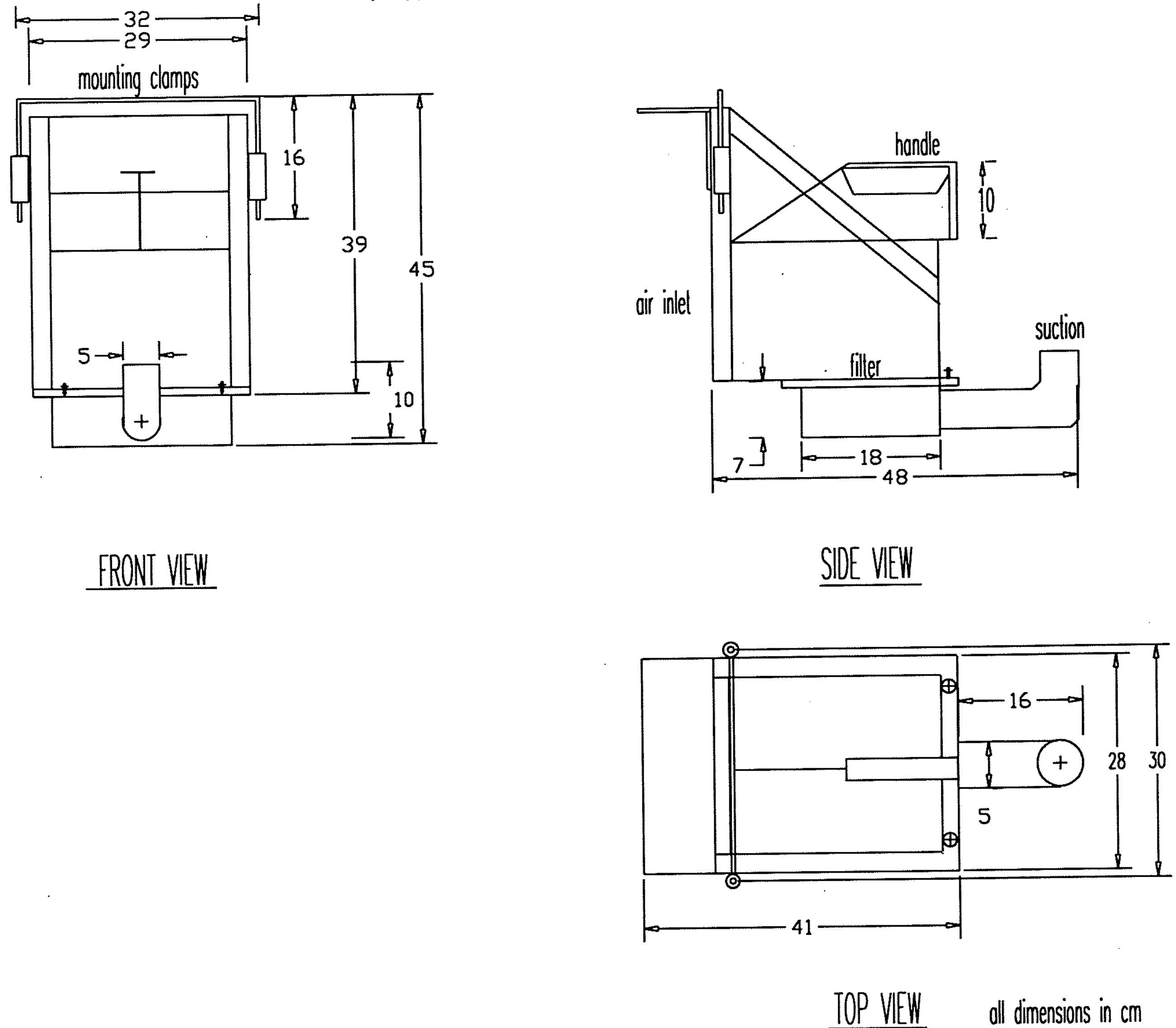
	Water	Bitumens and Tars or Resinous Adhesives
ATTRIBUTES	• Poses no threat to the environment • Normally, readily available	• Binds soils because of asphalt's adhesive properties. • Serves to waterproof roads • May be adapted to suit wide range of soils, gravel and traffic conditions.
LIMITATIONS	• Evaporates 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



COLORADO STATE UNIVERSITY DUSTOMETER

Appendix C

Difference between reduced levels; Initial - Final

Date at which initial levels were taken: 05/28/94
Date at which final levels were taken: 10/13/94
Intervals at which levels were taken: 3.00 ft

(+) = lost & (-) = gain

Test Section: Lignin

	@ 0.00 mi			@ 0.25 mi			@ 0.50 mi			@ 0.75 mi			@ 1.00 mi		
	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.
1	0.330	0.290	0.040	-0.335	-0.340	0.005	0.710	0.700	0.010	-0.020	-0.020	0.000	-0.305	-0.290	-0.015
2	0.405	0.360	0.045	-0.255	-0.250	-0.005	0.815	0.770	0.045	0.210	0.155	0.055	-0.110	-0.150	0.040
3	0.475	0.450	0.025	0.035	-0.165	0.200	0.920	0.860	0.060	0.275	0.215	0.060	-0.040	-0.055	0.015
4	0.560	0.535	0.025	0.010	-0.080	0.090	0.985	0.915	0.070	0.305	0.300	0.005	0.025	0.015	0.010
5	0.650	0.650	0.000	0.070	0.000	0.070	1.035	0.965	0.070	0.395	0.365	0.030	0.100	0.055	0.045
6	0.730	0.745	-0.015	0.100	0.095	0.005	1.100	1.030	0.070	0.435	0.455	-0.020	0.170	0.135	0.035
7	0.805	0.790	0.015	0.135	0.085	0.050	1.105	1.040	0.065	0.525	0.565	-0.040	0.210	0.170	0.040
8	0.700	0.715	-0.015	0.070	0.010	0.060	1.000	0.995	0.005	0.460	0.480	-0.020	0.115	0.105	0.010
9	0.620	0.620	0.000	0.010	-0.040	0.050	0.950	0.935	0.015	0.275	0.270	0.005	0.050	0.050	0.000
10	0.545	0.570	-0.025	-0.115	-0.115	0.000	0.880	0.935	-0.055	0.290	0.220	0.070	-0.040	-0.020	-0.020
11	0.505	0.510	-0.005	-0.180	-0.160	-0.020	0.820	0.845	-0.025	0.175	0.140	0.035	-0.150	-0.130	-0.020
12	0.390	0.430	-0.040	-0.300	-0.230	-0.070	0.685	0.700	-0.015	0.080	0.060	0.020	-0.230	-0.245	0.015
Average			0.004			0.036			0.026			0.017			0.013

Overall Average (estimated aggregate lost) 0.019 (0.228 inches or 5.8 mm)

Test Section: CaCl2

	@ 0.00 mi			@ 0.25 mi			@ 0.50 mi			@ 0.75 mi			@ 1.00 mi		
	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.
1	-0.770	-0.930	0.160	-2.900	-3.000	0.100	-0.740	-0.760	0.020	-0.510	-0.590	0.080	0.635	0.500	0.135
2	-0.680	-0.730	0.050	-2.860	-2.880	0.020	-0.675	-0.665	-0.010	-0.420	-0.500	0.080	0.785	0.630	0.155
3	-0.575	-0.630	0.055	-2.690	-2.810	0.120	-0.575	-0.585	0.010	-0.415	-0.425	0.010	0.875	0.745	0.130
4	-0.515	-0.550	0.035	-2.565	-2.710	0.145	-0.470	-0.525	0.055	-0.360	-0.375	0.015	0.900	0.830	0.070
5	-0.485	-0.495	0.010	-2.465	-2.610	0.145	-0.425	-0.470	0.045	-0.315	-0.315	0.000	1.025	0.910	0.115
6	-0.415	-0.425	0.010	-2.385	-2.525	0.140	-0.355	-0.385	0.030	-0.215	-0.210	-0.005	1.045	1.020	0.025
7	-0.345	-0.360	0.015	-2.475	-2.505	0.030	-0.305	-0.335	0.030	-0.225	-0.210	-0.015	1.110	1.065	0.045
8	-0.435	-0.410	-0.025	-2.515	-2.540	0.025	-0.375	-0.385	0.010	-0.315	-0.310	-0.005	1.035	1.010	0.025
9	-0.515	-0.480	-0.035	-2.565	-2.545	-0.020	-0.415	-0.430	0.015	-0.410	-0.380	-0.030	0.970	0.960	0.010
10	-0.640	-0.570	-0.070	-2.590	-2.570	-0.020	-0.465	-0.470	0.005	-0.475	-0.420	-0.055	0.905	0.895	0.010
11	-0.670	-0.620	-0.050	-2.740	-2.615	-0.125	-0.505	-0.540	0.035	-0.540	-0.475	-0.065	0.845	0.830	0.015
12	-0.765	-0.695	-0.070	-2.870	-2.675	-0.195	-0.590	-0.595	0.005	-0.640	-0.550	-0.090	0.790	0.755	0.035
Average			0.007			0.030			0.021			-0.007			0.064

Overall Average (estimated aggregate lost) 0.023 (0.276 inches or 7.01 mm)

Difference between reduced levels; Initial - Final

Date at which initial levels were taken: 05/28/94
Date at which final levels were taken: 10/13/94
Intervals at which levels were taken: 3.00 ft

(+) = lost & (-) = gain

Test Section: MgCl2

	@ 0.00 mi			@ 0.25 mi			@ 0.50 mi			@ 0.75 mi			@ 1.00 mi		
	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.
1	-1.900	-1.935	0.035	-0.720	-0.755	0.035	0.815	0.750	0.065	-0.235	-0.240	0.005	-2.170	-2.360	0.190
2	-1.810	-1.855	0.045	-0.660	-0.680	0.020	0.900	0.855	0.045	-0.155	-0.160	0.005	-2.205	-2.330	0.125
3	-1.735	-1.780	0.045	-0.595	-0.610	0.015	0.955	0.960	-0.005	-0.110	-0.140	0.030	-2.405	-2.320	-0.085
4	-1.680	-1.710	0.030	-0.505	-0.540	0.035	1.040	1.025	0.015	-0.060	-0.065	0.005	-2.305	-2.330	0.025
5	-1.615	-1.645	0.030	-0.480	-0.530	0.050	1.090	1.095	-0.005	0.045	0.030	0.015	-2.345	-2.290	-0.055
6	-1.540	-1.575	0.035	-0.455	-0.510	0.055	1.170	1.175	-0.005	0.160	0.125	0.035	-2.380	-2.340	-0.040
7	-1.485	-1.495	0.010	-0.470	-0.480	0.010	1.120	1.115	0.005	0.145	0.155	-0.010	-2.435	-2.395	-0.040
8	-1.585	-1.595	0.010	-0.530	-0.530	0.000	1.045	1.035	0.010	0.040	0.030	0.010	-2.450	-2.455	0.005
9	-1.690	-1.675	-0.015	-0.590	-0.580	-0.010	0.985	0.960	0.025	-0.080	-0.110	0.030	-2.535	-2.540	0.005
10	-1.760	-1.760	0.000	-0.675	-0.655	-0.020	0.935	0.905	0.030	-0.185	-0.210	0.025	-2.590	-2:590	0.000
11	-1.805	-1.840	0.035	-0.770	-0.725	-0.045	0.885	0.835	0.050	-0.260	-0.280	0.020			
12	-1.875	-1.945	0.070	-0.845	-0.800	-0.045	0.775	0.700	0.075	-0.335	-0.370	0.035			
Average			0.028			0.008			0.021			0.017			0.013

Overall Average (estimated aggregate lost) 0.017 (0.204 inches or 5.18 mm)

Test Section: Untreated

	@ 0.00 mi			@ 0.25 mi			@ 0.50 mi			@ 0.75 mi			@ 1.00 mi		
	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.	Initial	Final (ft)	Diff.
1	0.310	0.285	0.025	-0.015	0.025	-0.040	0.240	0.315	-0.075	0.135	0.220	-0.085	0.580	0.540	0.040
2	0.340	0.395	-0.055	0.060	0.100	-0.040	0.380	0.400	-0.020	0.205	0.280	-0.075	0.700	0.600	0.100
3	0.430	0.495	-0.065	0.155	0.195	-0.040	0.445	0.480	-0.035	0.285	0.340	-0.055	0.810	0.625	0.185
4	0.505	0.615	-0.110	0.260	0.260	0.000	0.520	0.555	-0.035	0.335	0.405	-0.070	0.945	0.715	0.230
5	0.610	0.700	-0.090	0.345	0.340	0.005	0.620	0.635	-0.015	0.440	0.440	0.000	1.055	0.790	0.265
6	0.705	0.785	-0.080	0.440	0.410	0.030	0.785	0.710	0.075	0.510	0.445	0.065	1.125	0.855	0.270
7	0.730	0.845	-0.115	0.505	0.455	0.050	0.860	0.720	0.140	0.585	0.520	0.065	1.235	0.905	0.330
8	0.690	0.785	-0.095	0.415	0.355	0.060	0.790	0.705	0.085	0.505	0.430	0.075	1.335	0.980	0.355
9	0.620	0.735	-0.115	0.310	0.290	0.020	0.760	0.655	0.105	0.430	0.380	0.050	1.435	1.045	0.390
10	0.560	0.675	-0.115	0.220	0.225	-0.005	0.725	0.595	0.130	0.310	0.310	0.000	1.565	1.115	0.450
11	0.520	0.615	-0.095	0.105	0.155	-0.050	0.670	0.545	0.125	0.320	0.290	0.030	1.685	1.135	0.550
12	0.420	0.540	-0.120	0.055	0.075	-0.020	0.610	0.470	0.140	0.255	0.210	0.045			
Average			-0.086			-0.003			0.052			0.004			0.288

Overall Average (estimated aggregate lost) 0.051 (0.612 inches or 15.55 mm)

Appendix D

Stock Solution Analysis Data

Lignin and $MgCl_2$ supplied by Environ Tech Services Inc. (Dust Suppressant Suppliers)
$CaCl_2$ supplied by Hill Brothers Inc. (Dust Suppressant Suppliers)

Variables		**Stock Solution**		
		Lignin	**$CaCl_2$**	**$MgCl_2$**
pH		5.80	5.20	5.80
E.C	μmhos/cm	278,000.00	864,850.00	412,780.00
TDS	mg/l	186,260.00	579,449.50	276,562.60
Ca	mg/l	846.90	95,933.00	4,209.00
Mg	mg/l	2,276.90	1,779.80	74,587.00
Cl	mg/l	6,961.00	203,464.50	259,972.50
Na	mg/l	845.40	2,200.20	1,623.20
K	mg/l	N.D	N.D	N.D
B	mg/l	<0.01	9.99	635.40
P	mg/l	75.30	<0.10	175.30
Al	mg/l	<0.10	<0.10	<0.10
Fe	mg/l	932.97	52.50	70.00
Mn	mg/l	71.30	5.29	2.84
Cu	mg/l	15.27	<0.01	<0.01
Zn	mg/l	25.57	<0.01	9.49
Ni	mg/l	<0.01	<0.01	10.94
Mo	mg/l	1.05	<0.01	1.20
Cd	mg/l	<0.01	<0.01	<0.01
Cr	mg/l	<0.01	5.85	3.95
Ba	mg/l	52.13	<0.01	12.80
Pb	mg/l	<0.05	<0.05	<0.05
SO_4	mg/l	27,591.00	N.D	12,508.00
Hardness as $CaCO_3$	mg/l	11,604.33	247,248.33	321,301.60

N.D: Not Determined

Test Sections Surface Runoff Analysis (05/31/94)

Date of Rain: 05/31/94
Rainfall amt. av. = 0.42 in (10.75 mm)

Variables		Test Sections			
		Lignin	**$CaCl_2$**	**$MgCl_2$**	**Untreated**
pH		N.D	N.D	N.D	N.D
E.C.	µmhos	N.D	N.D	N.D	N.D
TDS	|	N.D	N.D	N.D	N.D
Ca	|	258.80	4,080.00	95.60	68.10
Mg	|	159.70	65.60	1,835.00	17.60
Cl	|	575.60	6,400.00	6,220.00	76.50
Na	|	26.40	88.40	45.00	9.90
K	|	16.40	11.90	14.10	1.30
B	|	0.90	0.64	13.95	0.17
P	|	0.60	0.70	1.30	<0.10
Al	|	2.80	0.50	0.60	<0.10
Fe	|	31.04	0.55	0.11	0.04
Mn	mg/l	5.30	1.22	0.12	0.01
Cu	|	0.07	0.02	<0.01	<0.01
Zn	|	0.05	0.02	0.07	<0.01
Ni	|	0.16	0.03	0.17	<0.01
Mo	|	0.03	0.02	0.10	0.02
Cd	|	<0.01	0.01	0.01	<0.01
Cr	|	0.06	0.14	0.11	<0.01
Ba	|	N.D	1.34	0.34	N.D
Pb	|	<0.05	0.12	0.18	<0.05
SO_4	|	53.30	1,440.70	N.D	25.20
Hardness as $CaCO_3$	|	1,310.40	10,473.30	7,884.83	243.30

N.D : Not Determined

Test Sections Surface Runoff Analysis (06/20/94)

Date of Rain: 06/20/94
Rainfall amt. av. =1.04 in (26.50 mm)

Variables		**Test Sections**			
		Lignin	**$CaCl_2$**	**$MgCl_2$**	**Untreated**
pH		5.63	6.60	6.90	7.47
E.C.	μmhos	1,219.00	15,125.00	14,713.30	253.00
TDS	|	816.73	10,133.80	9,857.90	169.51
Ca	|	114.50	2,764.75	191.20	28.03
Mg	|	54.28	138.10	1,725.67	7.63
Cl	|	234.23	4,498.75	6,581.67	35.73
Na	|	14.23	137.48	92.00	12.20
K	|	10.43	12.30	10.90	1.43
B	|	0.32	0.38	6.12	1.60
P	|	0.38	0.63	1.07	0.40
Al	|	1.28	0.30	0.47	0.47
Fe	|	8.05	0.33	0.28	0.30
Mn	mg/l	1.97	1.46	0.49	0.02
Cu	|	0.03	0.01	0.01	0.01
Zn	|	0.11	0.09	0.25	0.24
Ni	|	0.05	0.04	0.12	0.05
Mo	|	0.02	0.02	0.07	0.03
Cd	|	<0.01	<0.01	<0.01	<0.01
Cr	|	0.02	0.01	0.12	0.03
Ba	|	0.21	0.78	0.71	0.11
Pb	|	<0.05	<0.05	<0.05	<0.05
SO_4	|	64.68	637.40	564.63	18.53
Hardness as $CaCO_3$	|	512.40	7,487.29	7,668.28	101.89

N.D : Not Determined

Test Sections Surface Runoff Analysis (07/22/94)

Date of Rain: 07/22/94
Rainfall amt. av. = 0.42 in (10.75 mm)

Variables		**Test Sections**			
		Lignin	**$CaCl_2$**	**$MgCl_2$**	**Untreated**
pH		6.05	6.28	6.98	7.20
E.C.	μmhos	1,428.75	8,517.50	7,655.00	485.75
TDS	|	957.26	5,706.73	5,128.85	325.45
Ca	|	239.30	1,538.50	90.73	52.75
Mg	|	58.00	96.53	926.25	18.55
Cl	|	267.18	2,725.75	3,728.48	83.58
Na	|	16.55	33.70	20.83	5.78
K	|	9.70	6.18	6.45	0.63
B	|	0.40	0.26	4.45	0.11
P	|	0.25	0.33	4.38	0.10
Al	|	0.83	0.25	0.90	0.15
Fe	|	9.73	0.26	0.28	0.07
Mn	mg/l	3.09	0.88	0.10	0.03
Cu	|	0.06	0.01	0.19	0.01
Zn	|	0.10	0.15	0.01	0.12
Ni	|	0.09	0.02	0.11	0.02
Mo	|	0.02	0.02	0.06	0.02
Cd	|	<0.01	<0.01	<0.01	<0.01
Cr	|	0.04	0.09	0.07	0.01
Ba	|	0.26	0.70	0.23	0.05
Pb	|	<0.05	<0.05	0.11	<0.05
SO_4	|	129.10	486.93	455.80	44.45
Hardness as $CaCO_3$	|	589.92	4,248.44	4,086.19	209.17

N.D : Not Determined

Test Sections Surface Runoff Analysis (08/10/94)

Date of Rain: 08/10/94
Rainfall amt. av. = 2.85 in (72.39 mm)

Variables		**Test Sections**			
		Lignin	**$CaCl_2$**	**$MgCl_2$**	**Untreated**
pH		6.43	6.37	6.75	7.10
E.C.	µmhos	1,077.00	3,580.00	3,050.00	239.00
TDS	|	721.59	2,398.60	2,043.50	160.13
Ca	|	110.53	529.13	64.35	21.80
Mg	|	52.40	38.38	246.90	7.10
Cl	|	213.80	958.27	920.10	103.50
Na	|	28.10	25.00	18.70	16.00
K	|	<0.10	<0.10	<0.10	<0.10
B	|	<0.01	<0.01	<0.01	<0.01
P	|	<0.10	<0.10	<0.10	<0.10
Al	|	<0.10	<0.10	<0.10	<0.10
Fe	|	5.81	<0.01	<0.01	<0.01
Mn	mg/l	1.87	0.41	0.04	<0.10
Cu	|	0.17	<0.01	<0.01	<0.01
Zn	|	<0.01	<0.01	<0.01	<0.01
Ni	|	<0.01	<0.01	<0.01	<0.01
Mo	|	<0.01	<0.01	<0.01	<0.01
Cd	|	<0.01	<0.01	<0.01	<0.01
Cr	|	<0.01	<0.01	<0.01	<0.01
Ba	|	0.13	0.27	0.08	<0.10
Pb	|	<0.05	<0.05	<0.05	<0.05
SO_4	|	69.00	22.87	92.35	14.60
Hardness as $CaCO_3$	|	494.67	1,482.69	1,189.63	84.08

N.D : Not Determined

Test Sections Surface Runoff Analysis (09/22/94)

Date of Rain: 09/22/94
Rainfall amt. av. = 0.28 in (7.00 mm)

Variables		**Test Sections**			
		Lignin	**$CaCl_2$**	**$MgCl_2$**	**Untreated**
pH		6.50	6.75	6.80	N.D
E.C.	µmhos	1,385.00	3,400.00	3,800.00	N.D
TDS	|	927.95	2,278.00	2,546.00	N.D
Ca	|	70.30	372.00	132.60	N.D
Mg	|	45.55	58.05	279.90	N.D
Cl	|	511.65	1,81380	2,332.50	N.D
Na	|	2.90	<0.10	<0.10	N.D
K	|	<0.50	<0.50	<0.50	N.D
B	|	<0.01	<0.01	0.96	N.D
P	|	<0.10	<0.10	<0.10	N.D
Al	|	<0.10	4.60	<0.10	N.D
Fe	|	0.91	7.28	0.88	N.D
Mn	mg/l	0.75	0.43	0.07	N.D
Cu	|	<0.01	<0.01	<0.01	N.D
Zn	|	0.04	0.06	0.08	N.D
Ni	|	<0.01	<0.01	<0.01	N.D
Mo	|	<0.01	<0.01	<0.01	N.D
Cd	|	<0.01	<0.01	<0.01	N.D
Cr	|	<0.01	<0.01	<0.01	N.D
Ba	|	0.03	0.27	0.09	N.D
Pb	|	<0.05	<0.05	<0.05	N.D
SO_4	|	N.D	N.D	N.D	N.D
Hardness as $CaCO_3$	|	365.54	1,171.88	1,497.75	N.D

N.D : Not Determined