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Evaluation of Dust Suppressants for Gravel Roads: Methods Development and Efficiency Studies

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ABSTRACT

Approximately 75 percent (300 000 km) of the total Swedish road network and 20 percent (20 000 km) of the national road network consists of gravel roads. One of the most significant problems associated with gravel roads is traffic-generated dust emission, which contributes to the deterioration of the road surface and acts as a major source of particulate matter released into the atmosphere, thereby involving public economics, road safety, human health, and environmental quality. In order to bind the fine granular material, which is prone to rise into the air, dust suppressants are applied on roads on a yearly basis.

Methods for evaluating the efficiency of dust suppressants will facilitate in the selection of the most appropriate product and its optimal application rate. For example, methods for supervision of residual dust suppressant concentration are valuable tools for estimating longevity and optimal application rates, and, consequently, effectiveness of different products.

Application of the proper dust suppressant to a gravel road ensures road safety and riding comfort as well as creating a cleaner and healthier environment for residents in buildings adjacent to the road. It also reduces the need and cost for vehicle repair, road maintenance activities, and aggregate supplementation.

Both field-based and laboratory research were performed to evaluate the efficiency of various suppressants and the influence such factors as product concentration, leaching, and fine material content have on the efficiency of different products. Within the field-based research, a newly developed mobile methodology was used to measure dust emission on numerous test sections treated with various dust suppressants. In general, all dust suppressants tested, except a polysaccharide (sugar) and products, which form a brittle surface crust, i.e. lignosulphonate and bitumen emulsion, showed acceptable dust reduction.

Test sections treated with a magnesium- or calcium chloride solution were the most effectively dust suppressed. The application of solutions instead of a solid salts achieves a more uniform product distribution and, therefore, probably a more efficient performance. By applying a calcium- or magnesium chloride solution instead of traditionally used solids, the cost for annual dust control, as well as the environmental impact from the release of these chemicals in the environment, can be reduced by 50 percent.

A significant problem when using dust suppressants is their tendency to leach during rainfall due to their soluble properties. Residual chloride could be detected in the gravel wearing course over a longer period of time than lignosulphonate and, therefore, showed more effective long-term performance. Optimal percentages of fine material for minimal lignosulphonate and chloride leaching were found to be 15 percent by weight and 10-16 percent by weight, respectively. Ions of calcium chloride seemed to initiate flocculation of clay particles, thereby preventing them from leaching. Still, the fine material in gravel wearing courses has to be

replenished regularly as indicated by studies of the longevity of fine material. Loss up to 80 percent was found after two years.

Toxicity tests show that dust suppressant application for dust control purposes, at traditionally used application rates, does not constitute a threat to sensitive aquatic life. Tests on subsoil water samples indicated elevated chloride levels, which possibly could cause corrosion to pipes, but not high enough to flavour drinking water.

Keywords: Gravel road, dust, particulate matter, PM_{10}, horizontal dust diffusion, deteriorations, maintenance, dust control, dust suppressants, efficiency, application rate, leaching, residual concentration, seasonal variations, salt solution, solid salt, calcium chloride, magnesium chloride, lignosulphonate, polysaccharide (sugar), bitumen emulsion, rape oil, starch, surfactant, mesa, clay, fine material content.

SAMMANFATTNING

Denna doktorsavhandling behandlar trafikgenererat damm på grusvägar, effektiviteten av olika dammbindningsmedel och olika metoder för att utvärdera dessa. Ungefär 75 procent (300 000 km) av hela det svenska vägnätet och 20 procent (20 000 km) av det statliga vägnätet består av grusvägar. Trafikgenererat damm på dessa vägar kan vara en trafiksäkerhetsrisk eftersom det bidrar till nedsatt sikt. Dammpartiklarna kan också vara hälsovådliga om de kommer ner i luftvägarna. Dessutom bidrar dammet till ökad nedsmutsning och besvär för människor, som bor bredvid en grusväg. Det finmaterial i vägen som dammar bort innebär också ekonomisk förlust, i synnerhet då processen leder till att även grövre material binds sämre till vägen, vilket i sin tur med tiden kräver att nytt grus tillsätts.

För att minimera dammbildningen behöver vägen dammbindas årligen. Exempel på traditionellt använda dammbindningsmedel är kalcium- och magnesiumklorid (salt), lignosulfonat (lut) och bitumenemulsion. Inom detta projekt har också mindre konventionella produkter såsom stärkelse, socker och vegetabilisk olja undersökts. Kunskapen är otillräcklig vad gäller olika medels dammbindningsförmåga, effekt vid olika koncentrationer, lämplighet vid olika finmaterialhalter hos slitlagret, livslängd, kostnader samt miljöpåverkan.

Studier har genomförts såväl i fält som i laboratoriemiljö. I fält har också dammbildning och spridning respektive avklingning efter fordonspassage vid sidan av grusvägen, analyserats. Resultaten visar att partikelhalten minskar linjärt med avståndet från vägen. De minsta partiklarna, med förmåga att ansamlas i luftvägarna, tycks i princip inte spridas längre än 45 m från vägen i vindriktningen. Resultaten jämfördes sedan med maximalt tillåtna partikelhalter enligt rådande EU-direktiv. Risken att överträda direktivets gränsvärden tycks vara liten på grusvägar vid de låga trafikmängder som normalt förekommer.

Dammbindningsmedlens livslängd studerades, liksom dammbindningsmedlens effektivitet som funktion av tillsatt mängd och spridningsmetod. Optimal finjordshalt för att minimera urlakningen av dammbindningsmedel samt finjordens benägenhet att försvinna från vägen genom damning eller urlakning studerades också. I viss mån undersöktes även dammbindningsmedlens påverkan på miljön. Metoder för utvärdering av faktorer som påverkar olika dammbindningsmedels effektivitet utvecklades under projektets gång.

På fyra olika grusvägar i Sverige belägna i Umeå, Rättvik, Hagfors och Halmstad, testades olika dammbindningsmedel på 1 km långa, teststräckor under tre säsonger. Generellt visade resultaten att samtliga utprovade produkter band dammet tillfredställande, med undantag för socker och produkterna som efter applicering och upptorkning bildar en hård yta; lignosulfonat och bitumenemulsion. De sistnämnda nöttes relativt snabbt bort av fordonstrafiken. Lignosulfonat, liksom de flesta andra undersökta dammbindningsmedel, tvättas också relativt lätt bort vid nederbörd. Salter (klorider) uppvisade emellertid länge livslängd än lignosulfonat. Av testade

dammbindningsmedel var salterna de mest effektiva. Resultaten visar att man genom att använda saltlösning istället för salt i fast form kan reducera mängden dammbindningsmedel till ungefär hälften och ändå uppnå jämförbara resultat. På enbart det statliga grusvägnätet skulle detta kunna medföra en årlig kostnadsbesparing på ca.15 MKr.

Den optimala finjordshalten i slitlagret för minimering av urlakning av dammbindningsmedlet konstaterades vara 15 viktsprocent för lignosulfonat och 10-16 viktsprocent för salt. Tillsats av kalciumklorid tycks initiera sammanklumpning av lerpartiklar, vilket försvårar urlakningen av partiklarna. Studier av materialförlust av finjorden tyder på att finjordshalten i grusslitlagret trots detta behöver kompletteras regelbundet. Förlusten två år efter tillsats var 60-80 procent.

Genomförda toxicitetsstudier visar att dammbindning, vid de koncentrationer som normalt används, inte utgör ett hot mot känsliga vattenorganismer. Grundvattenprover uppvisade förhöjda halter klorid, vilket skulle kunna leda till korrosion på ledningar, men inte tillräckligt höga halter för att ge smak åt dricksvatten eller visa på någon toxicitet.

Sammanfattningsvis kan sägas att resultaten från dessa studier bidragit med utvecklad metodik för analys av material i grusvägar och underlag till nya tekniska beskrivningar för förstärkning och underhåll av grusvägar. Resultaten har också bidragit till minskade livscykelkostnader och bättre miljö genom minskad dammbildning och mindre utsläpp av kemikalier i naturen.

PREFACE

This doctoral thesis is based on a research co-operation between the Royal Institute of Technology (KTH), Dalarna University (HDa), the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU), the Research Centre Road Technology (RT), and the Swedish Road Administration (SRA).

All the accomplishments achieved during this Ph.D. work were made possible thanks to the direct and indirect contribution of many people. Even though not mentioned here by name, I am very grateful for their valuable contribution. However, some people I would like especially thank.

First I would like to thank my supervisors: Rolf Magnusson, for good scientific guidance, for his support, enthusiasm and ideas, for adding structure to this project, and for endless reading of infinite numbers of drafts; and Ulf Isacsson, for always being there when needed, offering his time to review my manuscripts, and provide valuable scientific advice and structure to this project.

I also thank members of my project steering committee for being an endless source of ideas and for sharing their knowledge with me: Hossein Alzubaidi, Håkan Arljung, Ronny Bengtsson, Björn Birgisson, Hans Cedermark, Kent Enkell, Pontus Gruhs, Lars-Erik Holmström, Rolf Löfvenholm, Robert Karlsson, and Håkan Westerlund.

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Thanks also to my co-authors, Alf Gustafsson and Jonas Ekblad.

To my past and present colleagues at Högskolan Dalarna: thanks for creating such a cheerful and inspiring atmosphere. Special thanks to Åsa for library assistance, to Yngve, Daniel, Mikaela, Susanne, and Jenny at the chemistry department for invaluable consultations and excellent technical support in the laboratory, and to Hawzheen, Catherine, and Emmi for creating a good Ph.D. student environment, for all help, and for all enjoyable discussions.

The Swedish Road Administration (Vägverket) through the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU) are gratefully acknowledged for financial support.

Last, but certainly not least, I would like to thank my parents for their unreserved love and support and for always being there, and my husband, Jörgen, for his patience and love and for all help with computer-based issues.

Karin Edvardsson
Borlänge, January 2010

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LIST OF APPENDED PAPERS

This doctoral thesis is based on the following five publications, referred to in the text by their Roman numerals (I-V):

I. Karin Edvardsson. *Gravel Roads and Dust Suppression. State-of-the-Art.* This copyrighted review article is reprinted with kind permission of the publisher and may not be copied or redistributed without the permission of the Journal. Originally published in Road Materials and Pavement Design, vol. 10 (3), 2009, pp. 439-469.

II. Karin Edvardsson and Rolf Magnusson. *Monitoring of Dust Emission on Gravel Roads. Development of a Mobile Methodology and Examination of Horizontal Diffusion.* This copyrighted research article is reprinted with kind permission of the publisher and may not be copied or redistributed without the permission of the Journal. Originally published in Atmospheric Environment, vol. 43 (4), February 2009, pp. 889-896.

III. Karin Edvardsson, Jonas Ekblad, and Rolf Magnusson. *Methods for Quantification of Lignosulphonate and Chloride in Gravel Wearing Courses.* Accepted for publication in Road Materials and Pavement Design. In press No. 1/2010.

IV. Karin Edvardsson, Alf Gustafsson, and Rolf Magnusson. *Dust Suppressants Efficiency Study: In-Situ Measurements of Dust Generation on Gravel Roads.* Submitted to the International Journal of Pavement Engineering.

V. Karin Edvardsson and Rolf Magnusson. *Transport of Dust Suppressants in Gravel Road Wearing Courses Related to Fine Material Content.* Submitted to the Journal of Materials in Civil Engineering, ASCE.

The vocabulary concerning operation and maintenance of gravel roads varies in the literature. The study is also related to several fields of science. To avoid confusion, a list of abbreviations and definitions, used in this thesis, has been assembled and can be found following the bibliography list.

THE AUTHOR'S CONTRIBUTION TO THE PAPERS

Most of the experimental work and analyses described in the enclosed papers were done by me. Methods were, with kind contribution from numerous people, developed and evaluated by me, if not otherwise stated. Manuscripts were written by me but were revised by the co-authors. In paper III, the co-author Jonas Ekblad contributed by developing and evaluating the analytical method for quantifying lignosulphonate dissolved from an authentic gravel road sample.

In paper IV, the co-author Alf Gustafsson contributed by compiling results from visual assessments made every 14th day by the road contractor's crew. He was also responsible for-, and kept a record of dust suppressant application rates, aggregate supplementation, and required resources. Cost analysis for the dust suppressants that were evaluated were performed by the field study project leader Göran Gabrielsson and the environmental studies of dust suppressants were performed by a consultant.

My supervisor and paper co-author, Professor Rolf Magnusson, has apart from reading and suggesting improvements to the manuscripts, participated in the experimental design and discussions regarding any research problems that arose.

1. INTRODUCTION

1.1 Background

Nearly 90 percent of road networks worldwide are unpaved (Kuennen, 2005). In Sweden, about 20 percent of the 100,000 km national road network consists of gravel roads (Vägverket, 2005a). In total, the Swedish gravel road network is roughly estimated to be 300,000 km, or about 75 percent of the total road network (Enkell, 2003). A considerable problem on these roads is dust generation from vehicle passage, most commonly observed as a dust cloud behind vehicles travelling on the road.

The main consequences of dust include discomfort for road-users and inhabitants of buildings adjacent to the gravel road (Jones, 1999). Visibility for following and passing other vehicles is greatly reduced, thus creating a safety hazard. A badly dust suppressed and, therefore, uneven gravel road surface also contributes to increased fuel costs, travelling times, riding discomfort, and vehicle wear (Carlsson, 1986). Other important negative effects of dusting include health hazards, reduced agricultural yields, pollution, and loss of road construction material.

Most particle measurements have focused on particulate matter of sizes up to 10 μm in diameter (PM_{10}) because of the health hazard posed by these particles in the atmosphere (Addo and Sanders, 1995). Gottschalk (1994) reports that PM_{10} can be retained in the human respiratory system. Increased PM_{10} concentrations, regardless of particle composition, have through several medical studies been shown to increase the mortality rate from heart and lung diseases (Gustafsson, 2005). Particle pollution has been linked to decreased lung function, aggravated asthma, development of chronic bronchitis, and irregular heartbeat (Kuennen, 2006). Concerns have been raised whether the maximum allowed concentration of particulate matter (PM_{10}), according to the European Council Directive 1999/30/EC, is violated in the vicinity of a gravel road, which could create a threat to inhabitants of buildings adjacent to the road.

Application of a proper dust suppressant to a gravel road is necessary to ensure road safety and riding comfort while creating a cleaner and healthier environment for residents alongside the gravel road and reducing the need and cost of road maintenance activities and aggregate supplementation. Dust control treatments with lignosulphonate, calcium chloride, or magnesium chloride may reduce dusting by up to 90 percent (Addo and Sanders, 1995) and total aggregate loss by 55-67 percent (Monlux and Mitchell, 2007) compared to untreated, reference roads.

However, dust control is associated with a significant expense. The degree of this expense is dependent on the type of dust suppressant, the amount used, and the number of required treatments, which, in turn, is dependent on the amount of suppressant loss and variables such as traffic and precipitation (U.S. Department of Transportation, 2001; Powers, 2007; Zilioniene et

al., 2007). By applying the proper application rate of a dust suppressant, the annual cost of dust control as well as the environmental impact, from the release of these chemicals in the environment, can be significantly reduced.

Presumably, the efficiency of a dust suppressant is dependent on a series of different factors. In addition to the type of dust suppressant used, its concentration in terms of both application rate and residual concentration during the season, which in turn is dependent on the degree of leaching, is assumed to have an influence on its efficiency as well as the dust suppressant's transportation upwards with capillary water rise within the roadway (Slesser, 1943). Since there is no known method in use for quantifying the residual concentration of dust suppressants within a solid matrix, such as gravel wearing course materials, there is a need to develop such a method.

Another factor assumed to influence the efficiency of a dust suppressant is the content of fine material (i.e. particles < 0.075 mm) within the gravel wearing course, since the applied dust suppressant often adheres to this fraction (U.S. Department of Transportation, 2001). Because of this fine material, dust adhesion on the road surface is improved and possible leaching of dust suppressant prevented. Therefore, it is desirable to determine and specify optimal fine material content for different dust suppressants. Studies showing to what degree and rate this fine material is subjected to loss from dusting and leaching is also important for a more complete overview.

Introduction of suitable quantification methods for evaluating dust suppressant efficiency will facilitate the selection of the most appropriate dust suppressant and its optimal application rate. The customary used methodology for estimating dust generation from gravel roads is classification by visual assessments. However, such evaluations are always subjective, resulting in inconsistent results (van der Gryp and van Zyl, 2007). Therefore, it is desirable to develop a fast, mobile, reliable, and quantitative methodology for measuring dust generation.

The efficiency of control methods for reducing dust generation from gravel roads has not been adequately measured or documented (Gillies et al., 1999). No comprehensive and systematic investigation of dust emissions within the road environment and its influence on the type of suppressant used, its application rate, the rate of seasonal loss due to leaching, and gravel gradation, has been found in literature until now.

1.2 Objectives and Delimitations

The purpose of this PhD project is to give a comprehensive evaluation of the performance of a variety of dust suppressants as well as the various properties and factors influencing their performance. A second purpose is to develop suitable quantitative methods for evaluating the efficiency of dust suppressants, particularly with respect to their dust suppressing ability and residual concentrations within the gravel material.

More specific objectives are to:

- Compile previously published studies concerning control methods for reducing dust generation from gravel roads and comment on this literature with regards to agreement between various sources as well as practical experiences (Paper I).
- Study the horizontal transportation of PM_{10} from a gravel road and examine if the concentration of these particles found at the roadside exceed the limit specified by the European Council Directive (Paper II).
- Develop and evaluate a reliable, mobile, and relatively rapid methodology for quantitative and relative measurements of dust emission which offers a continuous series of measurement (Paper II).
- Identify methods for quantitative analyses of lignosulphonate and chloride, develop and adapt these methods for application on a gravel matrix, and validate these methods using samples collected *in-situ* (Paper III).
- Compare the dust suppressing efficiency of different suppressants and product combinations and study the influence of application rates (Paper IV).
- Identify the minimum quantity of dust suppressant required to achieve desired performance (Paper IV).
- To some extent, examine dust suppressants with consideration to purchase cost and environmental impact (Paper IV).
- Study how the seasonal variation of residual dust suppressant concentrations depends on the type of dust suppressant used, application rate, and amount of precipitation and examine how residual concentrations affect dust emission (Paper IV).
- Find an optimal fine material percentage, which results in minimal dust suppressant leaching (Paper V).
- Examine if leaching of clay is prevented due to a salt's presence in gravel wearing course material and if a high concentration of clay and fine material prevents salt from leaching (Paper V).
- Develop a method for estimating the relative content of mesa within the gravel wearing course based on samples collected *in-situ* and study the gradual loss, from leaching and dust emission, over time. In this respect, mesa is considered as a marker for fine material in general. (Paper V).

The results are anticipated to yield reduced lifecycle costs for gravel roads, better methods for analyses of materials for gravel roads, a basis for new technical specifications for maintenance of gravel roads, as well as to contribute to environmental gains by virtue of reducing the amount of dust emitted into the atmosphere and of chemicals released in nature.

The number of dust suppressants tested was limited based on the number of product distributors willing to have their product tested free of charge. Limiting factors of the experimental design, especially regarding studies performed *in-situ*, were the climate and weather conditions during the test seasons as well as the length and condition of the test roads, such as the existing gravel wearing course size gradation, traffic volume, average vehicle speed, and topography. Studies were limited to be valid for Nordic climate and design practises, aggregate materials, and maintenance traditions. In spite of these restrictions, there are reasons to believe that the results are valid for gravel roads in general worldwide.

1.3 Study description

To define the outline of the study and gather existing knowledge within the area, a literature review was performed (Paper I). Results from the literature review are briefly presented in the next chapter, but also in the papers included, when relevant. To examine to what degree people living in the vicinity of a gravel road are subjected to particles up to 10 µm in diameter (PM_{10}), which are considered detrimental to health, studies of horizontal diffusion of these particles downwind from a road were performed (Paper II).

After examining, for this thesis, the extent of research trials done and studying dust emission by examining horizontal downwind dust diffusion, it became clear that objective methods for studying the efficiency of dust control treatments were lacking. Therefore, a part of this project concerns method development. For continuous and mobile measurements of dust emission *in*-situ, a quantitative methodology based on an onboard, photometric, particle sensor measuring PM_{10} was developed (Paper II). To the author's knowledge there exists no widely used method to quantify residual concentrations of dust suppressant within the gravel road surface. Therefore, methods for quantifying the residual concentration of lignosulphonate and chloride, respectively, in a gravel matrix were developed to use on samples collected *in-situ* (Paper III). In addition, a method for analysing the relative residual content of mesa (calcium carbonate) in gravel wearing courses was developed (Paper V). In this thesis, the description of procedures used when developing these methods is presented in the Materials and Experimental Design chapter and the resulting methods and their precision in the Results and Analyses chapter.

The studies of dust suppressants efficiency comprise three different elements of this thesis: the influence of type and amount of dust suppressant on dust emission, leaching resistance of dust suppressants, and durability of fine material addition. To analyse efficiency and service life of various dust suppressants, field-based studies examining dust emission rates and suppressant loss were performed (Paper IV). Analyses of costs, optimal application rates, and environmental impact were also done. A laboratory study was performed to examine how the content of fine material influences leaching of dust suppressants (Paper V). During the study, there were

indications that the presence of salt in gravel wearing course samples might prevent fine material loss, i.e. clay particles from leaching. This was investigated further by examining samples in detail using an electron microscope (Paper V). Finally, the durability of mesa addition, used as a general marker for fine material was studied by analysing its loss over time in a gravel wearing course (Paper V).

2. LITERATURE REVIEW

2.1 Design of Gravel Roads

Gravel roads may be used where the annual daily traffic (ADT) < 250 (Giummarra et al., 1997; Vägverket, 2005b; Vägverket, 2007). However, for gravel roads with adjacent development an ADT of 125 is, in Sweden, considered a maximum (Vägverket, 2005b). For roads with a higher traffic volume, paving the road is more cost effective than spending financial resources on gravel road maintenance in order to keep an acceptable standard regarding dust emission and driving comfort.

Newly constructed gravel roads should be built up of two to four layers of gravel material according to specifications in the Swedish National Guidelines (Vägverket, 2007). These are, from surface to ground: the gravel wearing course (50-90 mm), the basecourse (~100 mm), and occasionally the sub-base and protective layer. Limits for variations in grain size distributions for these layers are also specified. Most gravel roads are old and were constructed before this specification existed. Therefore, the gravel material layer is often thinner than specified and any difference between the gravel wearing course and basecourse is usually difficult to distinguish (Johansson, 2005).

Gravel wearing courses typically consist of graded and compacted 0-16 mm crushed rock material (Vägverket, 2007). The fine material fraction makes up between 8 and 15 percent of the total mass of a well-graded wearing course. Gradations that have less fine material cannot achieve a maximum cohesive effect whereas gradations that have more fine material tend to retain too much moisture, develop ruts, and become soft, instable, and slippery when wet (U.S. Department of Transportation, 2001). Traditionally, certain amounts of clay have been added to wearing courses in order to add cohesion to the aggregate and, thereby, prevent dust emission and ravelling (Thompson and Visser, 2007). Basecourse material for gravel roads should be slightly denser and contain more fine material than basecourse materials for paved roads in order to prevent too rapid drainage and drying of the wearing course (Vägverket, 2007).

Gravel demand for road construction, i.e. both paved and gravel roads, represents a large part of the total worldwide demand for gravel material today (Al-Awadhi, 2001). Frequent aggregate supplementation is unsustainable as natural resources are being depleted (Jones and Ventura,

2003). Both naturally found gravel and crushed rock are used as gravel material in Sweden, but crushed rock is used in increasing proportions due to more stringent restrictions regarding usage of naturally found gravel (Johansson, 2005).

2.2 Deterioration and Maintenance

When conditions on the road reaches the lowest acceptable standards, maintenance activities are required to bring it back up to standard. Maintenance activities for a gravel road usually include aggregate supplementation, blading, dust control, ditching, and clearing of ambient vegetation. These activities repair damage to the driving lane by correcting its geometry as well as drainage and visibility. Maintenance blading may be required once, twice, or several times during the period when the ground is free from snow. Blading is performed on a wet road surface to reduce wear on the gravel material. Good drainage of a gravel road is obtained by making the crossfall about 4 percent (Vägverket, 2007) and the depths of the ditches about 0.8 m below the road surface (Johansson, 2005). Visibility, and consequently the road safety, is reduced if the surrounding vegetation is not cleared. Less vegetation also leads to faster drying of the road.

The most significant deterioration mechanisms are caused by traffic action and either excess or lack of water. Large amounts of precipitation wash away fine material and accelerate the formation of potholes and an accumulation of water on the surface softens the road and reduces its bearing capacity. Therefore, good drainage and, thus, passability in wet weather is important (van Veelen and Visser, 2007). In contrast, low moisture content within the road surface material may result in dust emission. The finest grain size fractions, i.e. particles less than 100 μm in diameter (Boulter, 2005), become airborne due to the mechanical wear and tear of rolling tyres as well as the turbulent airflow around passing vehicles (Thompson and Visser, 2007).

Most of the particles emitted from a gravel road have been found to move horizontally with the dominant wind direction (Gillies et al., 1999). Gillies et al. also report that downwind dust concentration decreases exponentially with distance. Docx et al. (2007) reports that particle emission decay returns to background levels about 30 m downwind from the roadside whereas Gillies et al. (1999) report 100 m.

Dust generation eventually leads to a deficiency of fine material, which in turn may cause ravelling, corrugations, and potholes. Ravelling is when coarser gravel material is torn loose and usually accumulates along the middle and edges of the road. The continuous loss of both fine and coarser gravel material eventually leads to an incorrect gradation of the gravel wearing course material. For that reason, gravel wearing courses usually have an excess of sand fractions.

Corrugations are mainly caused by traffic action where an initial unevenness on the road makes the vehicles oscillate and load the road surface dynamically. The resulting wave peaks

consist mainly of sand, since the fine material is resuspended and the coarse grains roll down into the wave troughs and are transported away by mechanical action. These wave-like patterns are typically formed where traffic accelerates or brakes, mainly in curves and uphill or downhill slopes (Beskow, 1932). To correct corrugations, the road is bladed all the way down to the bottom of these wave troughs. Otherwise they would soon return on the same spot. Long-term improvement is probably best achieved by correcting the size gradation in accordance with specifications in the national guidelines.

Potholes are typically formed in the wave troughs of corrugations due to accumulation of water which washes out fine material (Beskow, 1932). The fine material, suspended in water, is then splashed off the road by vehicle tyres. To correct potholes, the road requires blading all the way down to the bottom of the holes. Long-term improvement is best achieved by securing a sufficient crossfall, and, consequently, drainage.

Dust generation varies due to many different factors, including: traffic intensity, vehicle weight, vehicle speed, composition of the gravel wearing course, surface moisture, and topography. Numerous published studies indicate that the amount of dust generated by a vehicle traversing a gravel road is directly related to the vehicle speed (Lindh, 1981; Jones T.E., 1984; Nicholson et al., 1989; Kuhns et al., 2001; Addo and Sanders, 1995; Gillies et al., 2005; Monlux and Mitchell, 2007; Powers, 2007). Reducing vehicle speed will generally reduce the amount of dust generated. Improving visibility with effective dust control treatments often results in an increase in the highest possible speed. However, there are strong indications that there exists a threshold speed for dust generation, where a lower speed do not necessarily reduce the amount of dust generated (Nicholson et al., 1989; Powers, 2007). This threshold speed seems to be somewhere between 25–35 km/h. However, there are variations in the amount of dust generated from different kinds of vehicles, travelling at the same speed (Jones T. E., 1984).

2.3 Dust Control

A dust suppressant functions either by attracting moisture from the surrounding air, which in turn holds the dust, or by adhering particles together. Salts (chlorides) depend on the former principle whereas most organic suppressants, such as lignosulphonate and vegetable oils, primarily rely on the latter one.

The first part of a dust control operation is prewetting and blading. Prewetting brings the gravel material to near optimum moisture content, which assists in blading to remove ruts, corrugations, potholes, and loose gravel. It also reduces the surface tension, which allows for maximum penetration of the dust suppressant and ensures a uniform application of the dust suppressant over the whole treated area (Armstrong, 1987). Where liquid products are used, the amount of water used for prewetting should be reduced compared to the amount used for the

application of solid products to avoid exceeding an optimum moisture level (Monlux and Mitchell, 2007).

The best time to apply dust suppressants is early spring when the moisture content of the road surfaces is high (Monlux and Mitchell, 2007). Dust suppressants are usually applied topically. Procedures where the product is mixed-in with the aggregate are probably more effective, but the lower application rate and shorter preparation time for topical applications warrant their use (Rushing and Tingle, 2007). The maintenance crew normally allows traffic to flow during the entire dust control operation, which presents additional challenges to the work process (Powers, 2007). Compaction, other than from regular vehicular traffic, is generally not performed, since there are no indications that this has any long-term performance benefits (Monlux and Mitchell, 2007). When road deteriorations eventually develop, the maintenance crew must reblade the road surface and possibly apply supplementary dust suppressant material.

Salts used for dust control purposes, i.e. magnesium chloride or calcium chloride, probably provide the most satisfactory combination of ease of application, durability, cost, and dust control (Mulholland, 1972; Foley et al., 1996; U.S. Department of Transportation, 2001). Salt can be applied in two forms: as solid flakes or as a solution. When applied as a solid, Reyier (1972) indicates that 18 percent by weight more magnesium chloride than calcium chloride is needed to achieve an equal level of dust control for an equal length of time, while Enkell (2003) even suggests up to 50 percent by weight.

According to Thenoux and Vera (2003), the main causes of deterioration on salt-treated surfaces are:

- Loosening of saturated fine material by rainwater resulting in slippery road surfaces,
- Cracking of dry gravel road surfaces, and
- The presence of loose gravel on the road surface.

The major disadvantages of a salt are the corrosivity to most metals and the negative effect on road-side vegetation and the local water system (Foley et al., 1996; U.S. Department of Transportation, 2001). Salt is also highly water soluble and tends to leach and migrate downwards through the roadway. Slesser (1943) found that salt showed minimal horizontal movement. However, certain weather conditions and the groundwater table could trigger vertical movement. Warm, dry, windy days, together with low groundwater tables, favoured retention of chloride in the upper soil layers, whereas cold, wet, calm days, together with high groundwater tables, favoured loss of chloride to the subgrade.

Lignosulphonate is also called sulphite lye or lignin. Lignin is a major component in wood, i.e. 33-40 percent of its dry weight is lignin. It works as nature's own adhesive and binds the wood fibres together (McDougall, 1986). Lignosulphonate is obtained as a waste product from the boiling of wood for paper pulp production. Its composition varies depending on the feed and

pulping process used in the sulphite pulping industry (Thompson and Visser, 2007). This product adheres to the fine material in the wearing course, creates a surface crust, and prevents dust formation (Lindh, 1981). A primary concern regarding lignosulphonate, which is highly water soluble, is its tendency to leach out from the roadbed during heavy rains, making frequent reapplication necessary (Jones, 1999; U.S. Department of Transportation, 2001). An advantage to the using of this product is its counteracting of corrosive attacks on iron, thanks to the ability of lignin to bind oxygen and, consequently, prevent its contact with iron (Glänneskog and Skog, 1994).

2.4 Dust Suppressant Efficiency

Several studies related to the efficiency of dust suppressants have been reported by researchers (Mulholland, 1972; Addo and Sanders, 1995; Rushing et al., 2006; Zilioniene et al., 2007; Rushing and Tingle, 2007; Monlux and Mitchell, 2007; Surdahl et al., 2007). However, results vary and tests often involve a limited number of suppressants tested during a short period, i.e. typically one season.

Considering the environmental, economic, and safety aspects, dust suppressant application rates and frequencies have to be adjusted to the minimum possible amounts, while still providing an acceptable road surface in terms of dust control (Langdon and Williamson, 1983; U.S. Department of Transportation, 2001; Jones, 2003; Kaarela, 2003). Dust control failures are usually ascribed to loss of dust suppressant during rainfall. However, traffic, dust suppressant type and quantity used, blading frequency, composition of the wearing course material and grain size gradation will also affect the life-span of the treatment (Slesser, 1943; Mulholland, 1972; Chunhua, 1992; Si and Herrera, 2007). The life expectancy of dust suppressants decreases with increasing traffic intensity (Chunhua, 1992). This is particularly true for products forming a hard surface crust, which is subject to breaking. Dust suppressants also tend to wear-out or deteriorate more rapidly in areas where vehicles repeatedly stop or accelerate and in curves (Powers, 2007). Therefore, these areas may require more frequent applications of dust suppressants than a straight stretch of road (Langdon and Williamson, 1983). The effectiveness of a dust control treatment also depends on the uniformity of the suppressant application (Si and Herrera, 2007). Variations in the concentration of a dust suppressant within the gravel material cause the dustiness of gravel roads to vary in places (Zilioniene et al., 2007).

Dust suppressants which form a hard surface crust, such as lignosulphonate and vegetable oils, often become hard and brittle. Treatments that resist brittle failure of the surface have the greatest potential to create long-term dust reductions (Gillies et al., 1999). Experience has shown that traffic quickly degrades the surface crust, especially at road bends and edges (Mulholland, 1972; Bolander, 1997). Once ravelling starts, general deterioration is rapid indicating that it is

probably more effective to use a dust suppressant with a stronger penetrating effect on roads with a high traffic volume (Chunhua, 1992).

Lignosulphonate performance failure often occurs following rains due to loss of suppressant (McDougall, 1986; Acres International Limited, 1988). However, its strength and water resistance increases with an increase in the length of air curing time as well as by compaction of the road surface after adding the suppressant (Acres International Limited, 1988; Addo and Sanders, 1995; van Veelen and Visser, 2007). Neither lignosulphonate nor salt can be relied upon to provide satisfactory dust control for a second year (Mulholland, 1972; Foley et al., 1996). However, Bolander (1997) as well as product distributors claim that, even though lignosulphonate is subjected to leaching, it can be applied at one-half the initial application rate in successive years, since some residual material remains on the surface.

In wearing courses with poor size gradation, dust suppressants do not work effectively nor aid in forming a compacted and stable surface (Thompson and Visser, 2007). Ideally, the size gradation should be rehabilitated and a dust suppressant should be applied at the same time to maximize efficiency and minimize initial costs. It seems as though grain size gradation is especially important when lignosulphonate is used. Lignosulphonate is regarded as most effective when the total percentage of fine material exceeds eight but is below 20 percent by weight (Hallberg, 1989; U.S. Department of Transportation, 2001), since the product act as a dispersing agent for clay (Addo and Sanders, 1995). Apart from increasing the cementing effect of lignosulphonate, the addition of fine material, e.g. clay or mesa, will result in less leaching of lignosulphonate during rainfall (Statens Väginstitut, 1940; Svensson, 1997; Bolander, 1997). Mesa (also called lime mud) is a fine grained waste product obtained from paper factories, consisting of mainly calcium carbonate.

3. MATERIALS AND EXPERIMENTAL DESIGN

Field-based testing is time-consuming, costly but also difficult to fully control due to varying parameters such as weather conditions and traffic. Road-based studies often require long test periods, especially for establishing general models, which means an associated risk of test sections requiring maintenance activities before the test program is completed. Dust emission might also vary naturally over different sections of the road due to differences in topography, geometry, level of groundwater table, ambient vegetation, fine material content, etc.

Laboratory experiments are generally the fastest, simplest, and cheapest way to study road material properties. Most parameters can be controlled, e.g. precipitation, moisture content, curing period, temperature, load, and wear. Furthermore, some laboratory investigations simply aim to make chemical or physical analyses of material collected at a test site. However, the

influence of traffic and climate is difficult to realistically simulate in a laboratory. Nonetheless, laboratory tests are valuable as complement to field-based studies.

The most commonly used method for evaluating the amount of dust generated from vehicle passage on a gravel road is visual assessment. This subjective and not very measurement-intensive method is used by many gravel road agencies for quick, comparative evaluations of dust control strategies (Monlux and Mitchell, 2007; Thompson and Visser, 2007). Besides the degree of dust generation, defects such as corrugations, potholes, ruts, and loose gravel (ravelling) can be evaluated simultaneously. These defects are typically rated on a scale of 1-4 where 1 is good and 4 is bad (Alzubaidi, 2002; Vägverket, 2005c). However, this type of evaluation technique is too dependent upon the person carrying out the assessments and, therefore, can often lead to variable results (van der Gryp and van Zyl, 2007). Surdahl et al. (2007) conclude that this methodology is acceptable for comparing product performance at a single point in time but less suitable for comparing product performance over time.

Quantitative measurements of dust generation often include static dust collectors or mobile measuring devices. Static dust collection is considered too sensitive to changing wind conditions at a sampling site to be reliable (Brown and Elton, 1994). In addition, this method generally requires sampling over prolonged time intervals in order to collect measurable quantities of dust. Nevertheless, several previous field-based research programs have used this dust sedimentation method (Jones T. E., 1984; Rushing et al., 2006; Docx et al., 2007). The main advantage of the method is the possibility of further analyses of collected material.

Mobile measurement results may be affected by vehicle aerodynamics, speed variations, and road roughness. Most mobile measurement programs for evaluating dust generation, performed by different researchers, have used onboard, photometric, particle sensors to measure particles up to 10 µm in diameter (Etyemezian et al., 2003; Fitz and Bufalino, 2002; Gillies et al., 2005; Moosmüller et al., 2005; Thenoux et al., 2007). Photometric techniques are based on light scattering or absorption properties of particles, since particles of all sizes may reduce visibility by absorbing light (Addo and Sanders, 1995). Since particles up to 10 µm in diameter pose the greatest risk to human health, several types of measuring instruments are already on the market for measuring such particles. However, measurements of fine particles could give unrepresentative results, since it is not evident that the amount of PM_{10} directly corresponds to the amount of particles up to 0.1 mm (Boulter, 2005), which impair driving visibility on the road and, thereby, negatively affect road safety.

Numerous attempts have been made to develop a mobile and automatic system for registering relative dust emissions, which would offer objective evaluations with good precision. However, such a methodology could possibly make tests more time-consuming due to such physical limitations as the speed of the test vehicle. A mobile methodology should allow for: (a) measurements of dust generated by moving vehicles, (b) evaluation of the relative efficiency of

different dust suppressants, (c) determination of the optimum application rates of dust suppressants, and (d) introduction of a complementary objective tool for gravel road maintenance management. The influence of several variables during testing might make it difficult to accurately quantify the results. Measuring vehicle generated dust is extremely sensitive to the conditions under which sampling is performed. Among those conditions, the test speed normally shows a greater influence than any other factor (Thenoux et al., 2007).

One of the PM_{10} samplers used by researchers worldwide is the TSI DustTrak Aerosol Monitor (Fitz and Bufalino, 2002; Etyemezian *et al.*, 2003). A pump within the sampler draws the sample through a PM_{10} filter into an optical chamber where a 90º light scattering diode sensor in real time determines the mass concentration of aerosol particles, ranging in size from 0.1 to 10 µm in diameter (Hitchins et al., 2000; Wu et al., 2002; Veranth et al., 2003). Earlier mobile measuring methods usually required additional vehicle equipment, such as a trailer, or a permanent mounting or fixture on the test vehicle, which caused some physical disturbance.

Together with dust emission measurements, methods for supervising relative variations in residual dust suppressant concentrations in gravel wearing courses are valuable tools for estimating the life-span, optimal application rates, and, consequently, the efficiency of different products. There are several possible analytical methods for quantifying the concentration of salt. All these methods require the salt in solution.

Conductometry, where the conductivity of the solution is measured is a relatively fast and simple method commonly used. A disadvantage of this method is poor selectivity for chloride ions, which in turn means continuous calibration. An ion selective electrode, in this case for chloride, is another alternative. It is fast and selective but has to be calibrated for interfering ions, such as other halogens (i.e. fluorine, bromine, or iodine), and matrix effects. However, other halogens are usually not present within a gravel wearing course. Titration methods can also be used but are often time-consuming and more laborious. Chemicals for generating precipitation, e.g. silver nitrate, are often relatively expensive. Using a spectrophotometer is a relatively simple, fast, and cheap method, considering the fact that most laboratories already have such equipment or that simpler alternatives can be purchased. A colour staining reagent for chloride can be used for quantification.

Lignin absorbs light at a wavelength of 280 nm (Uprichard and Benfell, 2004). However, similarly to the quantification of residual chloride, there is no known methodology for quantifying residual lignosulphonate in a gravel wearing course. Methods for purifying lignosulphonate and chloride, respectively, from the gravel matrix could solve this problem.

Because road contractors are paid for handling the paper and pulp industry's waste product called mesa, it is more advantageous than clay for increasing the fine material content in gravel wearing courses. However, it is unknown to what degree basic mesa is lost over time due to leaching, dust emission, or degradation from acid precipitation. Consequently, there is need for a

method for quantifying residual content of mesa. Since mesa is not very soluble in water, a dry rather than wet method is more convenient. A relatively easy way of estimating fine material loss is by taking gravel wearing course samples and determining the fine material percentage, by sieve analysis, over time. However, this method does not allow for differentiating between mesa and other fine material present. A non-destructive method, such as X-ray analysis, is a better alternative.

3.1 Dust diffusion

PM_{10} samplers, i.e. TSI DustTrak Aerosol Monitors, were placed at 5, 10, 15, 20, 25, and 30 m downwind from a gravel road with severe dust problems. Particle inlets were placed at 1.3 m above ground level. Average wind velocity during the test was 2.7 m/sec. The PM_{10} values were used to estimate to what degree, in a worst-case scenario, people living in the vicinity of a gravel road are subjected to health damaging particles of up to 10 μm in diameter and examine if the concentration of these particles alongside the road exceed the limit specified by the current European Council Directive (1999/30/EC). According to this legislation, the average daily concentration of PM_{10} should not exceed 50 $\mu g/m^3$ for more than seven days a year. The 150 m long test section was located in an open environment with fields on both sides. About two months before the test this section was treated with 1.0 kg dry calcium chloride per running metre but was, at the time of testing, very prone to excess dust which, during a visual assessment, was classified as a class 4, the worst class according to Swedish National Regulations. The duration of the test was approximately 12 minutes, during which traffic intensity was slightly less than one vehicle per minute, corresponding to an ADT well above 1000. The average vehicle speed was between 55 and 60 km/h, which is considered a typical average speed on a Swedish gravel road.

3.2 Development of methods

3.2.1 Quantitative mobile methodology for measuring relative dust emission

PM_{10} samplers, TSI DustTrak Aerosol Monitors, were mounted on the roof-rack of an estate vehicle (Fig. 1). Four different estate vehicles were used (with GVW 1820-2100 kg). One sampler, with inlet tubing on the left rear-view mirror, was set to register background particulate matter. Another sampler, with inlet tubing taped to the back windscreen wiper, registered particulate matter generated by the test vehicle. However, background concentrations were low and constant for all sampling occasions. Therefore, it was considered adequate to only use the

sampler registering PM_{10} concentrations behind the vehicle. Bends in the tubing were avoided to minimize particle loss on the walls and the length of the tubing was kept constant.

Figure 1. *Montage of PM_{10} samplers on test vehicle.*

The sampling inlet is needed to be attached (a) in the well-mixed turbulent wake behind the vehicle and (b) high enough above the road surface to collect actual airborne material but (c) close enough to the surface to collect adequate sample mass. A sampling intake height of 1.1 m was selected because this height corresponds to a height where dust impairs visibility and also because this height is representative of the peak PM_{10} exposure (i.e. 1 m) according to Muleski et al. (2003).

The DustTrak was set to record average PM_{10} concentrations with second resolution to work with a level of detail of approximately 10 m road length using a constant vehicle speed of 40 km/h. A Personal Digital Assistant connected to a Geographic Positioning System was programmed to register time, geographic position, and speed of travel with 1-second resolution. This data was then combined with data from the PM_{10} sampler.

The precision of the methodology was evaluated on 13 different test sections in Halmstad (see Chapter 3.3). The test vehicle was driven three times in the same direction. To investigate the validity of measuring PM_{10}, while assuming this particle fraction to be representative of the whole dust fraction which impairs visibility, PM_{100}, sampling data was compared to the mass of dust collected by sedimentation in two air permeable filters, with openings of 16 mm in diameter, mounted about 400 mm behind the test vehicle. In addition, visual classifications, made in accordance with the SRA-method for assessment of gravel road condition (Vägverket, 2005c), were compared to the results recorded with the mobile methodology.

3.2.2 Quantitative methods for analyses of residual concentrations

Gravel wearing course samples of 150 mm x 150 mm x the total depth of the gravel wearing course, were collected for residual quantification of dust suppressant concentration. Some of the test sections constructed to study the efficiency of different dust suppressants were also used in this study. These test sections are presented in Chapter 3.3. All test sections treated with chloride and lignosulphonate, in Hagfors and Halmstad, were used. Samples were taken in the middle of each test section, from the same wheel track. The section middle was marked with a post placed beside the road (Fig. 2) For the second sampling, the sample was taken approximately 0.5 m behind the first sample spot and the third sampling a further 0.5 m behind and so on. In this manner, the risk of analysing replaced material was kept at a minimum, while there was a good chance that all samples were similar regarding dust suppressant distribution and environmental conditions.

To evaluate the importance of sampling at approximately the same site and also study the uniformity of the chloride distribution based on a liquid or solid salt application, gravel wearing course samples were collected from five different spots within each test section: the right wheel track 200 m in front of the section middle post, the right and left wheel track as well as in the middle of the road at the section middle post, and the right wheel track 200 m after the post (Fig. 2). The samples were collected about ten days after dust suppressant application on four sections treated with solid calcium chloride, solid magnesium chloride, a calcium chloride solution, and a magnesium chloride solution, respectively.

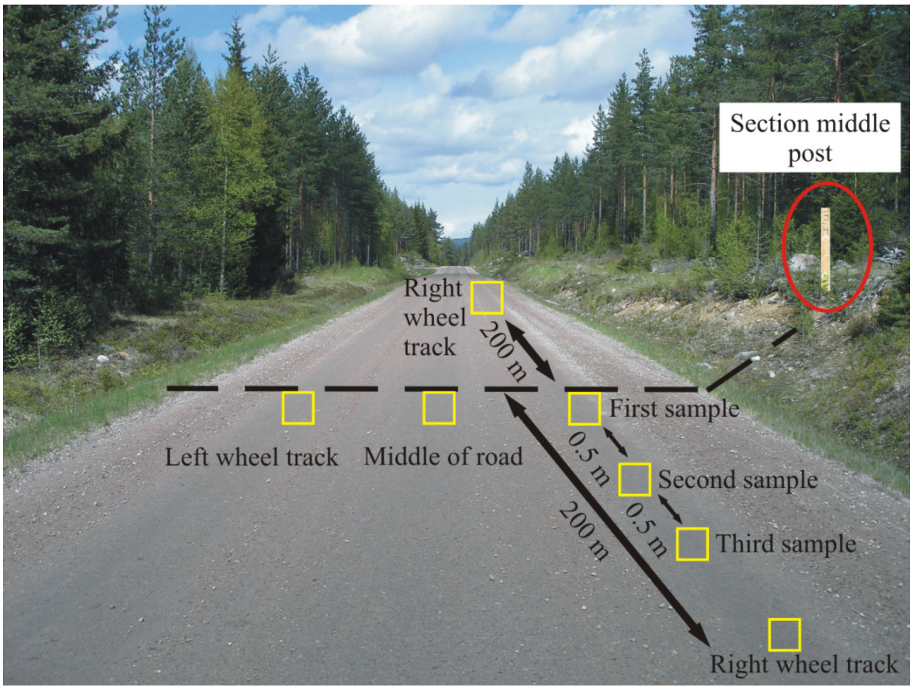

Figure 2. *Sampling procedure. Sample squares are 150 x 150 mm.*

Sample preparation, i.e. dissolving and purifying residual lignosulphonate and chloride, respectively, from the gravel matrix, before quantification, is shown in Figure 3. To a sample of 50 g gravel wearing course material, containing residual dust suppressant, 50 mL deionised water was added. To avoid incorporation of the largest grains, which would add substantially to the total weight, the 50 g sample had to be hand-picked. The water-soaked samples were then placed in an ultrasonic water bath for 10 minutes to dissolve the residuals. A standard filter paper (125 mm in diameter, Schleicher & Schuell, No. 311611) was folded and inserted into a funnel. The solution, taken from the ultrasonic bath, was decanted into the funnel and placed on top of a clean glass beaker. To avoid eventual background contamination from very fine soil particles which could have passed through the filter paper pores during filtration, each lignosulphonate containing sample was filtered once more with a 0.45 μm PTFE-membrane coupled to a 5 mL syringe with a Luer-connection. Each chloride containing filtrate was centrifuged with the same purpose. Two 1.5 mL samples of the chloride filtrate were put into Eppendorph tubes which were centrifuged at 10,000 rpm (or 13,000 times the G-force) for 10 minutes to sediment fine particles.

Lignosulphonate concentrations were determined by measuring absorbance, with a uv/vis-spectrophotometer, at 280 nm, since absorbance is linearly related to concentration according to the Beer-Lambert law. Chloride concentrations were determined with a water analysis kit, Hanna Instruments HI-3815, and an ion specific photometer, Hanna Instruments HI-93753, using a wavelength of 470 nm. All samples were diluted to obtain a concentration within the detectable limits of the spectrophotometers.

Energy-dispersive X-ray spectroscopy (EDS) was used for quantification of mesa in gravel wearing course samples. A sample of pure mesa, obtained from a distributor, a sample taken from each test section before the addition of mesa, and samples collected over time from two mesa test sections (in Rättvik) were analysed for chemical composition using this method. The road samples were collected using the same sampling procedure as described above. The test material was sieved using a 0.5 mm sieve to obtain a more homogenous sample. A sample holder, 10 mm in diameter, covered with carbon tape was randomly dipped into the sieved soil sample for EDS-analysis at 500 times magnification, 10 kV acceleration voltage, and a working distance of 25 mm.

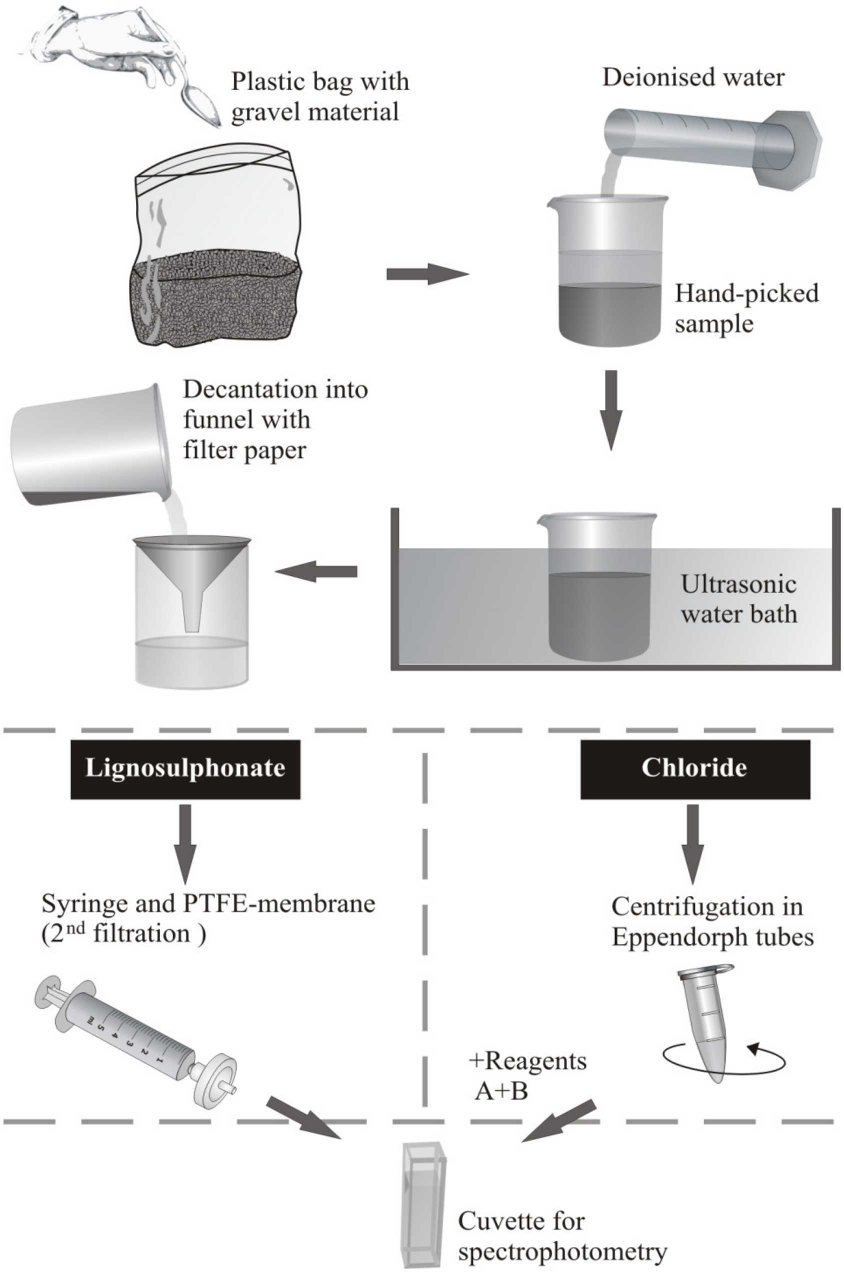

Figure 3. *Sample preparation for residual dust suppressant quantification of samples collected in-situ.*

3.3 Efficiency of dust suppressants

Four different test sites, in Umeå, Rättvik, Hagfors, and Halmstad, were used for field-based testing of dust suppressants (Fig. 4). The field-based research study started in June 2005 and continued during three subsequent summers until September 2007. However, in 2007, the gravel road in Rättvik was excluded from the test, since it received another contractor. At each test site meteorological data for the test period was received from the closest weather station with the road weather monitoring system (VViS) run by the Swedish Road Administration. At each test site a gravel road was further divided into 13–16 different 1 km long test sections, to which different dust suppressants were applied. The test roads were chosen based on their homogeneity with regards to traffic, road width, surface course thickness, topography, and alignment as well as having an adequate length to accommodate the test sections. However, at the Umeå site, the 16 test sections had to be split onto two roads: sections 1-8 on road one and section 9-16 on road two.

Figure 4. *Geographic position of the four test sites, from north to south: Umeå, Rättvik, Hagfors, and Halmstad.*

All test sites except those in Umeå had existing gravel wearing course gradations with an excess of sand fraction. To study the importance of adequate gradation, all test sections in Halmstad received supplementation of deficient aggregate fractions prior to the dust control operation in 2007. Supplementary quantities of fine material and 8-16 mm material were chosen with consideration to the deficient fractions in the existing gravel wearing course, determined from gradation analyses. By this way, it was assumed that an acceptable gradation had been obtained, even though no new samples were collected to confirm the assumption.

The dust suppressant test program was designed to compare product performance. Application rates were varied in an attempt to identify the minimum material quantity needed to attain the desired effect (Table 1). A magnesium chloride ($MgCl_2$) solution, a calcium chloride ($CaCl_2$) solution, $MgCl_2$ flakes, $CaCl_2$ flakes, calcium lignosulphonate, as well as a solution of starch were used at all test sites. The mixing proportions used for making the starch solution was 250 kg starch powder dissolved in 2m^3 hot water, followed by heavy stirring to prevent clumping, and, finally, addition of 3 m^3 cold water. Calcium and magnesium chloride solutions (32 percent by weight) were either bought as ready-to-use solutions or prepared from solid flakes on site. According to the contractor crew, about half the amount of time was spent dissolving calcium chloride compared to magnesium chloride, probably due to a stronger exothermic reaction.

Table 1. *Applied concentrations of tested dust suppressants.*

Tested dust suppressant	Halmstad			Hagfors			Umeå			Rättvik	
	2005 (kg/m²)	2006 (kg/m²)	2007 (kg/m²)	2005 (kg/m²)	2006 (kg/m²)	2007 (kg/m²)	2005 (kg/m²)	2006 (kg/m²)	2007 (kg/m²)	2005 (kg/m²)	2006 (kg/m²)
$MgCl_2$ solution (0.6 L/m) + mesa	-	0.11	0.10	0.05	0.11	0.11	0.07	0.13	0.11	0.06	0.06
$CaCl_2$ solution (0.6 L/m) + mesa	-	0.07	0.07	0.07	0.07	0.11	0.23	0.09	0.08	0.08	0.04
$CaCl_2$ solution (1.2 L/m)	0.25	0.14	0.14	0.12	0.15	0.22	0.17	0.16	0.17	0.16	0.09
$MgCl_2$ solution (1.2 L/m)	0.28	0.22	0.20	0.09	0.21	0.22	0.14	0.24	0.20	0.11	0.14
$CaCl_2$, 0.7 kg/m	0.18	0.22[d]	0.13	0.12	0.12	0.12	0.16	0.11	0.11	0.12	0.11
$CaCl_2$, 1.0 kg/m	0.27	0.17	0.19	0.17	0.17	0.17	0.20	0.17	0.19	0.17	0.18
$MgCl_2$, 1.0 kg/m	0.22	0.17	0.19	0.17	0.17	0.17	0.20	0.18	0.20	0.17	0.18
$MgCl_2$, 1.3 kg/m	0.29	0.22	0.25	0.22	0.23	0.22	0.26	0.22	0.26	0.21	0.22
$MgCl_2$ solution (1.0 L/m)	-	-	-	-	-	0.19	-	-	-	-	-
$MgCl_2$ solution (0.8 L/m)	-	-	0.16	-	-	0.15	-	-	-	-	-
$MgCl_2$ solution (0.6 L/m)	-	-	0.11	-	-	-	-	-	-	-	-
$CaCl_2$ solution (0.8 L/m)	-	-	0.10	-	-	-	-	-	-	-	-
$MgCl_2$ solution (0.8 L/m) + 1% surfactant	-	-	-	-	-	0.18	-	-	0.20	-	-
$MgCl_2$ solution (0.8 L/m) + 0.5% surfactant	-	-	-	-	-	0.16	-	-	0.20	-	-
Lignosulphonate[a, b]	1.2 (20%)	1.2 (20%)	0.89 (20%)	1.3 (20%)	1.15 (20%)	-	0.96 (30%)	0.96 (30%)	1.1 (30%)	1.5 (25%)	0.97 (25%)
Lignosulphonate[a] + mesa	-	1.2 (20%)	-	1.5 (20%)	1.08 (20%)	1.1 (20%)	0.87 (30%)	0.89 (30%)	0.93 (30%)	0.98 (25%)	0.76 (25%)
Lignosulphonate[a] + $CaCl_2$	1.2 (10%) + 0.10	0.96 (10%) + 0.11	-	1.2 (10%) + 0.09	1.2 (10%) + 0.11	-	0.53 (15%) + 0.13	1.1 (15%) + 0.11	0.53 (15%) + 0.11	1.1 (12%) + 0.09	1.0 (12%) + 0.11
Starch solution	0.05	0.06	0.06	0.05	0.10	0.05	0.07	0.06	0.09	0.05	0.05
Rape oil[a]	1.1	1.1	-	-	-	-	-	-	-	-	-
Bitumen emulsion[a]	-	-	-	-	1.14	-	-	-	-	-	-
Asphalt granulate	-	-	34.2	-	-	-	-	-	-	-	-
Polysaccharide solution[a]	-	-	-	-	0.68	-	-	-	-	-	-
Silt[c] + $CaCl_2$	-	-	-	-	-	-	-	-	13 + 0.11	-	-
Slaked lime[c] ($CaOH_2$) + $CaCl_2$	-	-	-	-	-	-	-	-	8 + 0.08	-	-

[a] Unit: L/m²

[b] % by weight of applied lignosulphonate solution in brackets.

[c] Unit: m³.

[d] Higher application rate than planned, in Halmstad 2006, due to incorrect instructions.

At all test sites, mesa was added to three different test sections, in combination with $MgCl_2$ solution, $CaCl_2$ solution, and lignosulphonate, respectively. Sections to which mesa was added received a lower application rate of dust suppressant. Other products tested were rape oil, bitumen emulsion, and polysaccharide (sugar). These products were only tested at one test site. Surfactant was tested at two sites, in combination with a solution of either $MgCl_2$ or $CaCl_2$, with the objective of decreasing surface tension and, thereby, facilitate soil permeation. Contamination of dust suppressants between different test sections was regarded as negligible, as the first and last 100 m of each test section were excluded when measuring dust emission and when taking material samples.

Dust suppressant applications were preceded by wetting and blading the gravel wearing courses, after which the suppressants were applied topically without mixing. Regular traffic was relied on for compaction of the dust suppressed sections. As the only exception, bitumen emulsion was mixed with the surface material and subjected to rolling. Lignosulphonate was applied by the product supplier according to their standard topical procedure, which does not include rolling. The machinery used for dust suppressant application is presented in Table 2.

Table 2. *Machinery used for application of the various dust suppressants and fine material additives tested.*

Material	Machinery
Chlorides (dry flakes)	Sand or salt distributor
Chlorides (solutions)	Salt distributor or lorry with solution cistern, pressure pump and ramp
Lignosulphonate (solution)	Solution cistern, pressure pump and ramp
Starch (solution)	Solution cistern or water barrel, pressure pump and ramp
Rape oil	Tractor with dung cistern
Bitumen emulsion	Salvaco® truck
Polysaccharide	Tractor with dung cistern
Mesa	Lorry with platform
Clay	Lorry with Forshaga® platform applicator

3.3.1 Relative dust emission and dust suppressant toxicity

Measurements of dust emission from the different test sections were performed using the mobile measuring methodology described in Chapter 3.2.1. Three different estate vehicles, with GVW varying from 1960 to 2100 kg, were utilized during different years. To the greatest extent possible, the driving pattern was restricted to the existing wheel tracks on the road. Two samplings in one direction on each test section, using a 1-s interval of registration, provided a

basis for analysis of variance. This gave a more reliable identification of dust suppressants with statistically different performances and a reliable basis for dust suppressant selection. To avoid contamination between different test sections, the first and last 100 m of each test section were excluded from the analyses. Results from the statistical calculations are based on more than 40,000 sampling values from 22 different observations. Within the field-based study, each test section was also rated on the basis of visually perceived dust generation according to the contracted method described by the Swedish Road Administration (Vägverket, 2005c). This rating ranged from 1 (no dust) to 4 (critically reduced visibility).

An environmental study of the toxicity of dust suppressants on aquatic life was performed by the chemical consultant companies Pelagia Environmental Consultant and AnalyCen on subsoil water collected beside and leaching water samples collected, at Hagfors in 2006, on test sections containing calcium chloride, magnesium chloride, lignosulphonate, starch, or bitumen emulsion. Algal growth inhibition tests were performed on *Selenastrum capricornutrum*, according to Guideline 201 OECD and ISO-standard 8692, and *Lemna minor*, Duckweed, according to OECD Guideline 221. Toxicity tests to *Daphnia magna* (representative for zooplankton), according to ISO 6341:1982, was also performed. Chloride concentration in subsoil water samples was measured according to SS 028113.

3.3.2 Leaching resistance of dust suppressants

At the same time as the dust emission sampling was done, gravel wearing course samples were collected from test sections treated with either chloride or lignosulphonate, at various application rates, for analyses of seasonal variations in residual concentrations. Samples were collected from the test road in Rättvik and Hagfors and were collected over time from April until September, 2006. The sampling, preparation, and analysis procedures used were as described in Chapter 3.2.2.

The influence of fine material content on dust suppressant leaching resistance was studied by means of laboratory tests. Plastic measuring cylinders, with a diameter of 48 mm, a height of 167 mm, with forty 2 mm holes in the bottom, were used. Cylinders were filled with 300 g of 0-16 mm gravel course material, collected from a nearby gravel pit belonging to a certified distributor. The holes were covered with Para-film from underneath to prevent gravel material from escaping during the filling process. To find optimum fine material content for minimal leaching, clay was added in increasing proportions. As the percentage of clay was increased in steps of 1-2 percent by weight, the corresponding percentage of 8-16 mm gravel material fraction was removed. A dust suppressant consisting of 20 mL of either 10 percent by weight lignosulphonate or a 22 g/L calcium chloride solution was used. The samples were allowed to cure, untouched, over night at room temperature. Each cylinder was then placed on top of a

glass beaker to collect the leachate obtained after adding 25 mL deionised water. The leachate was analysed by means of the quantitative methods described in Chapter 3.2.2. The spectrophotometrically recorded concentrations were multiplied with the volume of the leachate collected in order to obtain comparative results.

3.3.3 Durability of fine material addition

During sample preparations for quantification of residual chloride concentration in gravel wearing courses collected *in*-situ, it was noticed that the filtrates of the samples collected before salt application, which should have a low chloride concentration, were turbid whereas the filtrates from the samples collected after salt application, which should have a high chloride concentration, were clear. This observation made it interesting for further research into salt's ability to flocculate, and, consequently, prevent leaching, of clay particles. One representative sample, collected before and one after calcium chloride application, respectively, were chosen for a more careful examination in a Scanning Electron Microscope (SEM). Spot samples of filter paper with its pores content, filter retentate, and filtrate were placed on sample holders, covered with carbon tape, for SEM- and EDS- analysis.

To further investigate whether the addition of mesa (calcium carbonate), as a typical fine material, tends to disappear with time from gravel wearing courses, two test sections containing mesa were examined for residual contents. Both sections were 1 km in length and 6 m in width, with a gravel wearing course thickness of 25 mm. Section 1 received 10 m^3 of mesa and 40 m^3 of 4-16 mm gravel material while Section 2 received 10 m^3 of mesa and 50 m^3 of 4-16 mm gravel material. These amounts were determined based on sieve analyses of the wearing course. The addition of coarser material was necessary to keep the fine material content of the new wearing course gradation around 15 percent by weight, in accordance with Swedish National Guidelines (Vägverket, 2007). Sampling was done according to the procedure described in Chapter 3.2.2. Residual quantification of mesa was performed according to the method described in Chapter 3.2.2 and 4.2.2. On the 16th of June 2006, samples were collected from five different spots within each test section to study mesa content variation.

4. RESULTS AND ANALYSES

4.1 Dust diffusion

The study of horizontal particle diffusion from the gravel road indicated a linear decay in PM_{10} concentration with respect to the downwind distance from the road edge (Fig. 5). By extrapolating, it was found that the particles essentially did not travel more than 45 m from the

road, provided downwind velocities of 0-7 m/sec. It seems unlikely that larger particles would diffuse further. Assuming the general validity of the result and proportionality between traffic intensity and PM_{10} concentration, the maximum allowed ADT to comply with the EC-directive can be calculated based on the highest particle concentrations recorded and the traffic intensity in the study. According to such calculations, based on a highest observed particle concentration of 566 µg/m^3 at a distance of 5 m from the road edge, there is no immediate risk of exceeding the maximum allowed PM_{10} concentration in the ambient air, established by the EC-directive, which provides for an ADT ≤ 125. As mentioned in Chapter 2.1., an ADT of 125 is already stated by the Swedish Road Administration as the maximum allowed traffic intensity for gravel roads with nearby development (Vägverket, 2005b). Roads with an ADT greater than 125 should be paved.

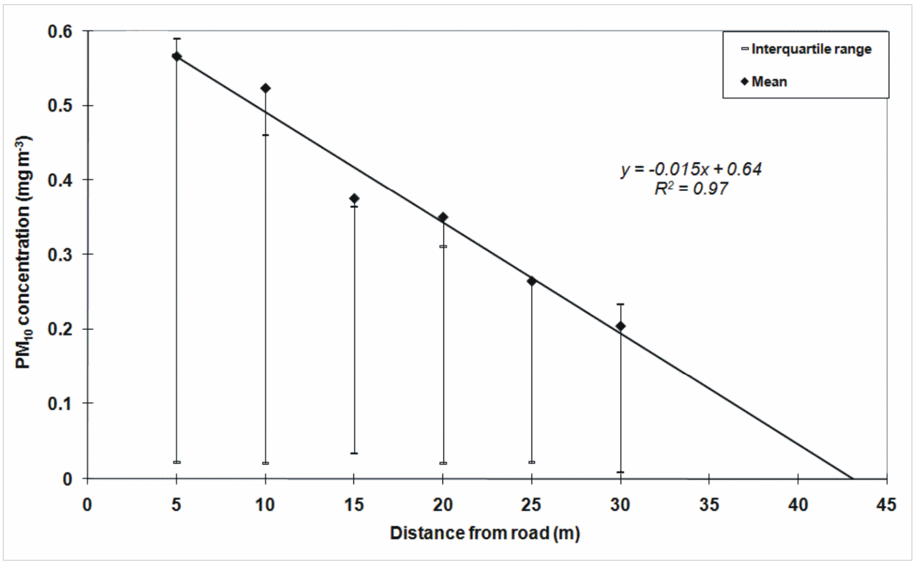

Figure 5. *PM_{10} concentration as a function of distance downwind from the road. Each point represents the average of about 700 observations over 12 min (i.e. the time resolution is every second) with a traffic intensity of one vehicle per minute and an average vehicle speed of 55-60 km/h.*

4.2 Development of methods

4.2.1 Quantitative mobile methodology for measuring relative dust emission

Over each 1000 m long test section there was considerable variation in 1-s PM_{10} concentration recordings. The coefficient of variation (standard deviation / mean value) around the common average from three consecutive, averaged passes was between 2 percent and 19 percent. To study the validity of the method, visual assessments by experienced personnel were compared to the automatic mobile PM_{10} samplings on the same test sections, despite the obvious problems with variations associated with subjective visual assessments. This resulted in a coefficient of determination, R^2, of 0.61. The results indicated that relative measurements of dust mass collected in filters, placed in the aerosol plume behind the vehicle, were in agreement with PM_{10} measurements behind a test vehicle, $R^2 = 0.73$. Both methodologies provided results that correlated with the subjective visual observations made by the crew of the road contractor. According to a laser granulometric (Cilas Granulometer 715) gradation analysis of the filter fraction, 99 percent by weight of the collected material was smaller than 128 μm and 97 percent by weight was smaller than 96 μm.

4.2.2 Quantitative methods for analyses of residual concentrations

Repeatability was determined according to guidelines given in SS-ISO 5725-2. Repeatability statistics were calculated from 45 different concentration levels regarding lignosulphonate analysis and 192 different concentration levels regarding chloride analysis. Each level comprised 4 replicates. The determined repeatability variances were found to be dependent on a mean level in a linear way, thus, repeatability is expressed as the ratio of repeatability standard deviation (SD) to mean value, i.e. coefficient of variation. Repeatability limits, r, were calculated by multiplying with the factor $1.96\sqrt{2}$ (SS-ISO 5725-6): r = 23 percent for lignosulphonate analysis and 30 percent for chloride analysis, respectively. Under repeatability conditions, r will be exceeded not more than once in 20 cases.

The concentration variations within a specific section were significant, especially on the sections treated with solid chloride. The coefficient of variation, calculated from residual concentrations of samples collected from five different sites within each test section, was about 30 percent for test sections treated with chloride solution. The corresponding coefficient of variation for sections treated with solid chloride was up to 80 percent. These results show that samplings from approximately the same site within a test section are of utmost importance.

The relative content of mesa can be calculated as:

I_{Ca} / I_K,

where I_{Ca} and I_K are the atomic percentages of calcium and potassium, respectively, obtained from the total sample EDS spectrum.

The calcium to potassium ratio was used to manage potential variations in the amount of sample particles analysed. The large quantity of calcium in mesa makes it a suitable trace element for analysis of mesa content. The gravel material only showed low levels of calcium. The amount of potassium in the gravel material is assumed relatively constant over time. The amount of potassium in mesa was very small.

4.3 Efficiency of dust suppressants

4.3.1 Relative dust emission and dust suppressant toxicity

The results from the field-based study of dust suppressant efficiency are shown in Figure 6 and Appendix Tables I-V as PM_{10} emission on test sections with the same kind of dust suppressant, averaged from all measurements at all test sites. In these tables, the efficiency of various dust suppressants is expressed as the test section average PM_{10} concentration divided by the average PM_{10} concentration of the section dust suppressed with 1.0 kg $CaCl_2$ per running metre. No significant difference in efficiency of tested products was found between the different geographical test sites. Even though test sites were located in different climatic zones, the differences in the amount of precipitation received were not pronounced.

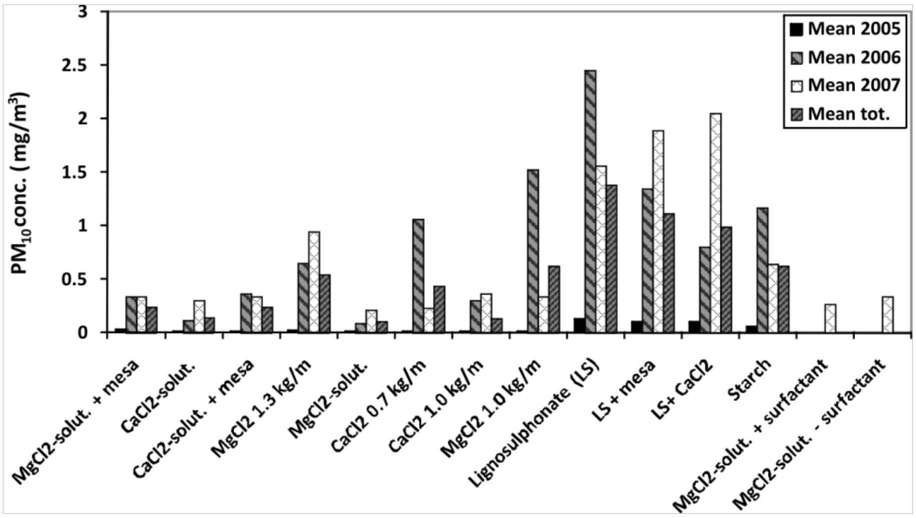

Figure 6. *Averaged PM_{10} emissions from all test occasions and sites (except from Halmstad in 2007 for reasons described in the Discussion).*

The application rate of chloride seemed correlative to dust reduction efficiency, with higher concentrations suppressing dust more efficiently. Chloride solutions demonstrated the best performance in nearly all evaluations, followed by solid salt. Also visual assessments concluded that chloride solutions were the most efficient. However, solution application did appear to cause some moderate ravelling. Solid calcium chloride seemed more efficient than solid magnesium chloride, even at an equivalent percentage of chloride. Regarding salt solutions, magnesium chloride was at least as efficient as calcium chloride provided equivalent salt concentrations. The minimum application rate for a chloride solution (32 percent by weight) was estimated to be 0.8 m^3/km.

Test sections treated with one percent by weight surfactants were more efficiently dust suppressed than references without or with a lower concentration of the surfactant, but the differences were so small that surfactant addition can hardly be economically justified. A higher chloride application rate seemed more effective than surfactant addition. Rape oil demonstrated excellent performance until rupturing in the late summer. However, the high cost of this product makes it less interesting for gravel road dust control.

The polysaccharide solution was the least effective material tested. Bitumen emulsion was after the first season also regarded as not economically feasible and was, therefore, withdrawn from further testing. Its performance from the first season was poor. On average, all products except polysaccharide, bitumen emulsion, and pure lignosulphonate showed acceptable dust reduction

efficiency. The performance of lignosulphonate increased significantly in combination with mesa addition. However, rehabilitation of the wearing course gradation by aggregate supplementation, at Halmstad in 2007, resulted in significantly more dust emission on all test sections that year.

The environmental tests showed that dust suppressant application, using conventionally application rates, does not constitute a threat to the growth of green algae, *Selenastrum capricornutum*, or Duckweed, *Lemna minor*, and are not toxic to *Daphnia magna*. Tests on subsoil water samples indicated elevated chloride levels, which could possibly cause corrosion to pipes, but not high enough to influence toxicity tests or flavour drinking water.

4.3.2 Leaching resistance of dust suppressants

Sections treated with solid calcium chloride showed residual chloride concentrations corresponding to amounts on sections treated with a 30 percent by weight higher application rate of solid magnesium chloride. Sections treated with solutions of these salts showed the lowest values of PM_{10} particle emission over the test period (Fig. 7a). Even so, these sections showed the lowest residual concentrations during the same period (Fig. 7b). Test sections treated with lignosulphonate showed a rapid reduction in residual concentration, and the results from PM_{10} particle emission measurements revealed that the lignosulphonate test sections were amongst those sections showing the most severe dust generation.

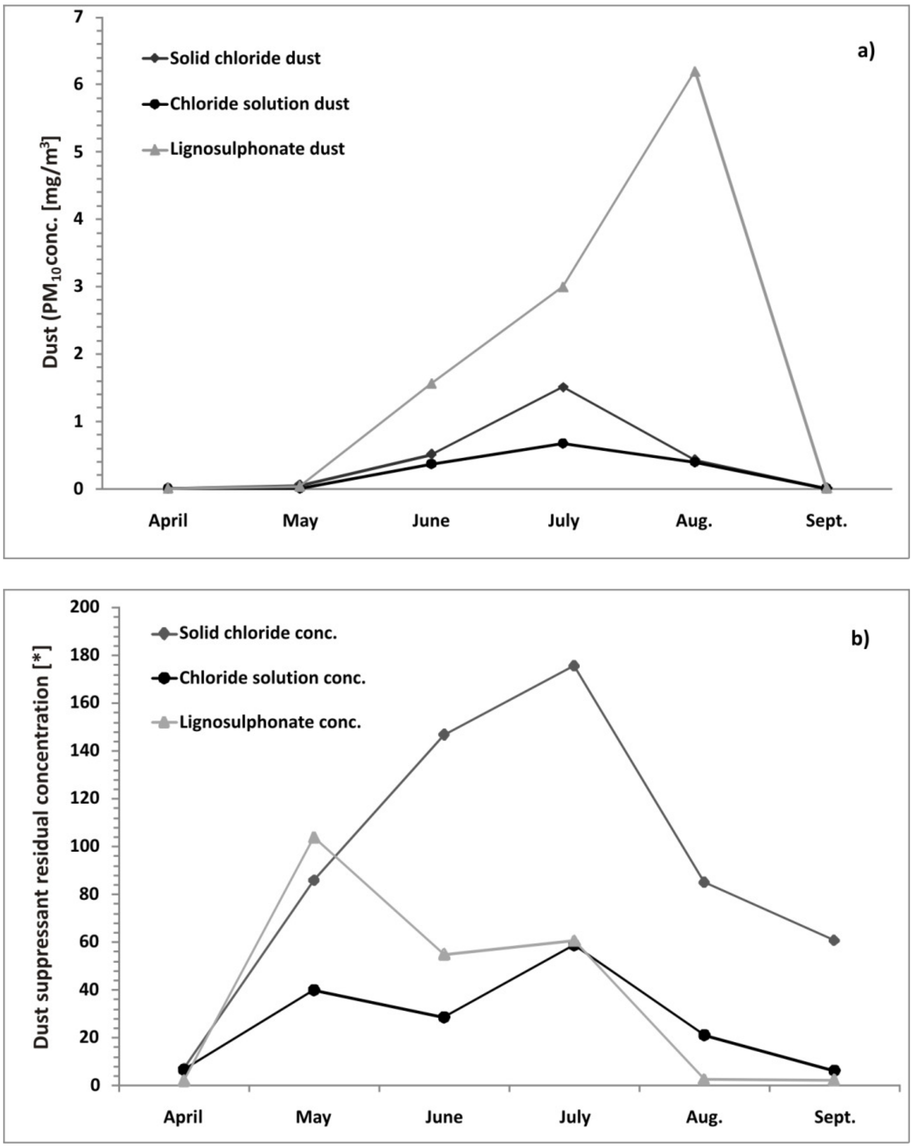

Figure 7 a-b. *A typical example of seasonal variation of dust generation (a) and dust suppressant residual concentration (b) within the gravel wearing course. Data were obtained in 2006 from road sections treated with solid chloride (both calcium- and magnesium chloride), chloride solutions, and lignosulphonate, respectively. *Chloride residual concentration in mg per 50 g gravel wearing course material. Lignosulphonate residual concentration expressed as absorbance at 280 nm x 4 x dilution factor (in order to receive a comparative scale).*

Results from the analysis of residual concentrations in chloride treated test sections indicated that the chloride concentration actually increased initially for a period and then began to decrease about one month after application. This pattern was evident on practically all chloride treated sections in Rättvik. Due to severe rainfall following the application at Hagfors, residual concentrations were low during the whole test period. In general, the residual concentration quickly decreased in the gravel wearing course during periods with a lot of precipitation, whereas the reduction in residual concentration was less during periods with little precipitation. The solid chlorides increased significantly.

The results from the study where clay was added in increasing proportions, to define the optimal fine material content for minimal leaching, indicated that an addition of about seven percent by weight clay, or approximately 15 percent by weight fine material, was optimal for preventing lignosulphonate water leaching (cf. Fig. 8a). There were statistical significant differences, at the 0.05 level, amongst all means except between five and six percent as well as seven and eight percent by weight added clay. Regarding chloride leaching, the optimal percentage of fine material was found to be 10-16 percent by weight (cf. Fig. 8b). There were no significant differences, at the 0.05 level, amongst the means of samples of two to eight percent by weight added clay, except between two and six as well as two and seven percent. The coefficient of variation for leaching amounts of both chloride and lignosulphonate was below 25 percent for all percentages of clay added.

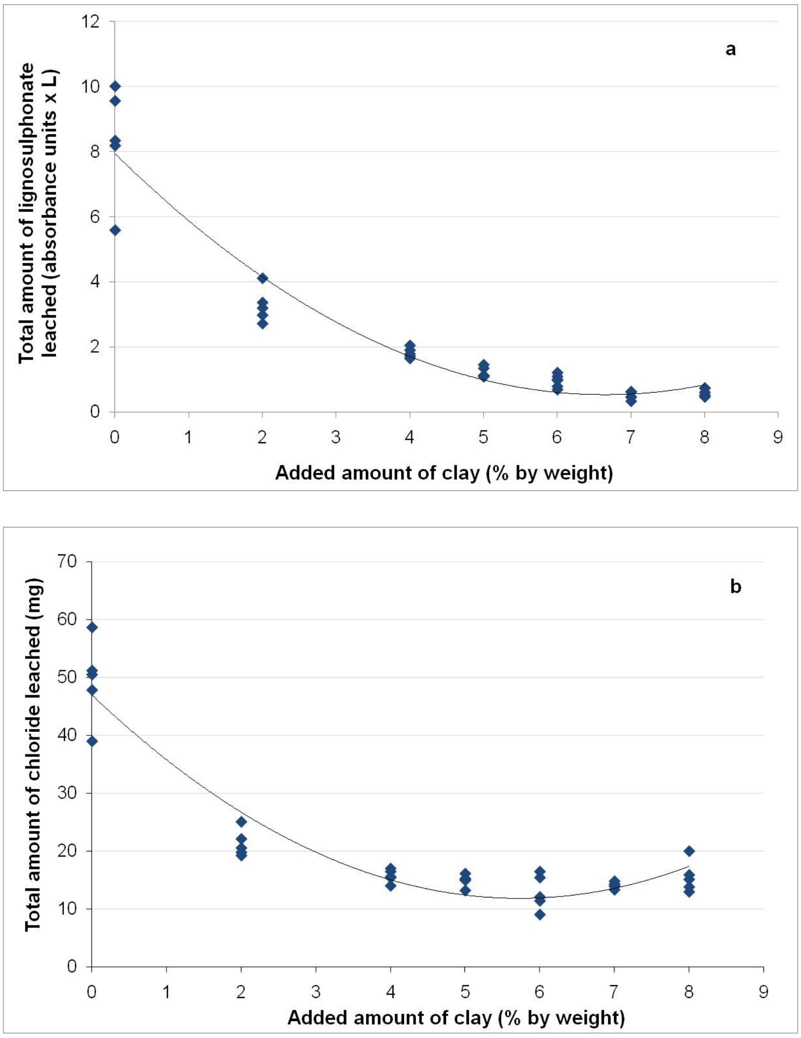

Figure 8 a-b. *Leaching of lignosulphonate (a) and chloride (b), respectively, as a function of the added amount of clay to gravel material. initially containing 8 percent by weight of material smaller than 0.075 mm. The fine material content of the clay was approximately 85 percent by weight and the clay content approximately 50 percent by weight. The amount of lignosulphonate leached, from the addition of 25 mL deionised water, is expressed in relative numbers as the amount of leachate obtained in litres multiplied by the leachate absorbance obtained at 280 nm and the dilution factor used to obtain an absorbance within the detection limit of 0-2 absorbance units. The amount of chloride leached is expressed in grams as the amount of leachate obtained in litres multiplied by the leachate chloride concentration in gram per litre.*

4.3.3 Durability of fine material addition

Since the filter adherent solid retentate from the sample collected before calcium chloride application contained smaller particles (cf. Fig. 9a) than the filter retentate from the sample collected after the application (cf. Fig 9b), it seems as though the addition of salt causes clay particles to flocculate and, consequently, prevent them from leaching. This is supported by the fact that the filtrate from the sample collected after calcium chloride application was clear and contained very little silicon, i.e. soil, but a higher content of calcium and chloride, whereas the filtrate from the sample collected before calcium chloride application was turbid and contained a high silicon content, but no calcium or chloride (Table 3). Neither calcium nor chloride was present in elevated amounts within the filter adherent solid retentate according to the EDS analysis. These results indicate that the flocculation process might be initiated by the presence of salt but does not prevent the salt from leaching.

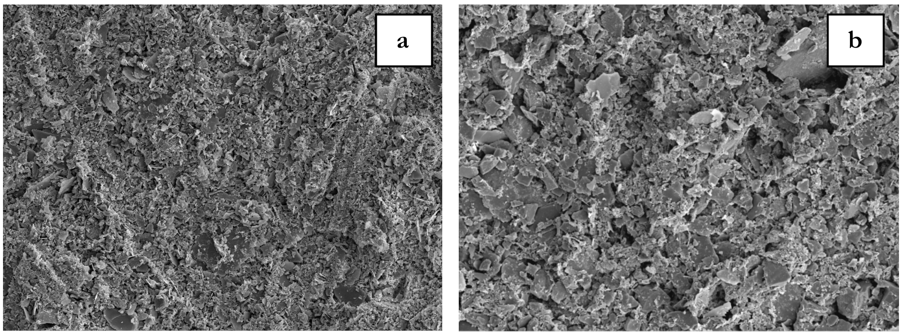

Figure 9 a-b. *Surface morphology of filter retentates collected before (a) and after (b) calcium chloride application, respectively. Frame width 0.6 mm.*

Table 3. *EDS analysis of filter retentate, filter paper, and filtrate, respectively, obtained after water addition and filtration of an in-situ collected gravel wearing course sample. 10 kV, 100 x magnification. (Atomic-% = percentage of specific atom relative to a total number of atoms in sample).*

Sampling	Element	Filter retentate (atomic-%)	Filter paper (atomic-%)	Filtrate (atomic-%)
Before $CaCl_2$ application	Si	22.9	14.3	19.8
	Cl	-	0.02	-
	Ca	0.6	0.4	0.7
After $CaCl_2$ application	Si	21.5	6.9	1.3
	Cl	-	0.05	30.3
	Ca	0.5	0.3	15.9

From the results of the residual quantification of mesa in gravel wearing course samples collected from May 2006 until June 2007, it is apparent that mesa disappeared from the road with time (Fig. 10). Results are presented as the difference between I_{Ca}/I_K at a given time and before application, respectively. Two summers after the mesa application, only 20-40 percent of the initial content remained. Coefficient of variation for samples collected at five different spots within the same section was 49 percent for Section 1 and 22 percent for Section 2, respectively.

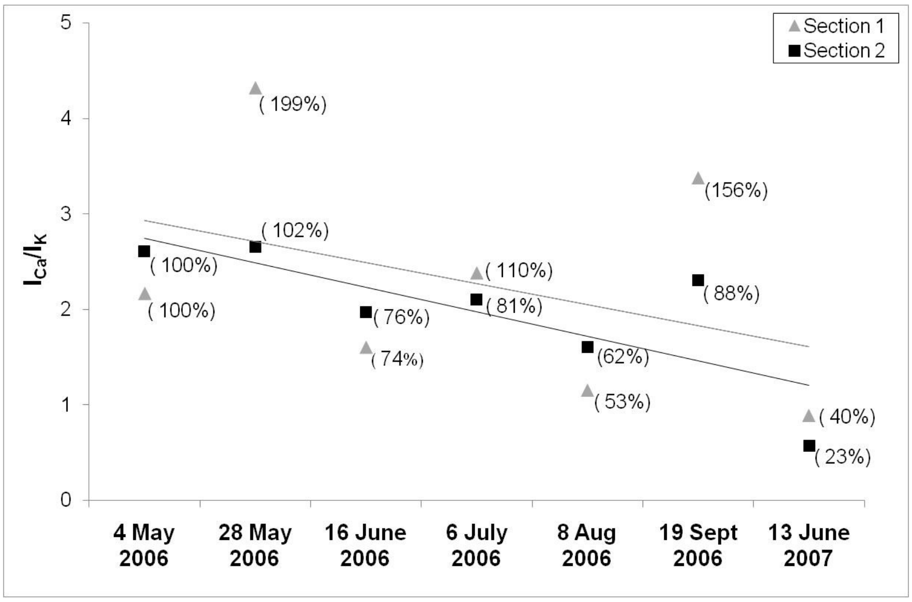

Figure 10. *Relative residual content of mesa, from samplings performed during the period May 2006 – June 2007, within gravel wearing courses of test sections treated with mesa in May 2005. Percentages represent I_{Ca}/I_K divided by I_{Ca}/I_K from the sampling made on the 4th of May 2006. Sampling on the 19th of September was made after the road sections had been bladed.*

5. DISCUSSION

Results presented in this thesis, indicating that dust particles do not diffuse downwind further than 45 m from the gravel road, can be compared to Docx et al.'s (2007) report of concentrations returning to background levels 30 m downwind from the road and Gillies et al.'s (1999) report of particle concentration being less than 0.01 percent of the initial concentration 100 m downwind from the road (at equivalent wind velocities).

The coefficient of variation for the developed mobile dust emission measurement methodology (2-19 percent) was remarkably small considering the fact that the gravel road actually changes slightly between each vehicle pass, since the driving pattern can never be exactly the same and large differences in dust emission within each test section exist. However, the maximum coefficient of variation for the developed mobile measuring methodology is somewhat higher compared to result reported by Thenoux et al. (2007), who reported $PM_{2.5}$ coefficient of variation between 3 and 12 percent at a travelling speed of 50 km/h. The Environmental Protection Agency (EPA) requires a coefficient of variation below 40 percent

for three or more emission measurements (EPA, 2001). This indicates that PM_{10} emission values can be used for relative estimations of dust emissions, which impair visibility on gravel roads. The validity of Boulter's (2005) definition of dust as an aerosol of particles up to 100 µm in diameter was confirmed by the laser granulometric gradation analysis of the dust fraction collected on filters placed in the aerosol plume behind the test vehicle. The developed mobile PM_{10} measurement methodology offers fast, high resolution evaluations, at comparably low cost. This methodology also provides continuous sequence of data, mobility, and easy handling.

The similarity of the repeatability limits, r, for the lignosulphonate and chloride residual concentration analysis methods reveals that method error is associated with the sampling procedure rather than sample preparation and spectrophotometric analyses. The lignosulphonate and chloride methods showed r-values of 23 and 30 percent, respectively. The repeatability of these methods is considering good when taking sampling problems into account. Sampling from approximately the same site is of utmost importance in order to follow seasonal variations on residual concentrations, since variations within a specific section are significant (coefficient of variation up to 80 percent for solid chloride was registered). However, if the test surface is restricted to a small area, variations are reduced.

From the analysis of residual chloride concentration over time, it was observed that, as a rule, the chloride concentration varied in the same manner during the test period on all test sections. This was the case for magnesium chloride as well as calcium chloride, for solutions as well as solids, as well as for different application rates. The results strongly suggest acceptable method reliability and sampling and sample preparation procedures.

During periods of dry weather, chlorides migrate towards the road surface by means of capillary rise (Slesser, 1943). This could cause chlorides to accumulate at the road, as also indicated by the fact that the residual concentrations within the wearing course increased during some weeks after the dust control operation. However, dusting was most severe in the middle of the summer even though residual concentrations were high at the same time (Fig. 7). Lignosulphonate did not seem to be transported by capillary action in the same manner as chloride.

I_{Ca}/I_K is considered a suitable parameter for relative residual content quantification of mesa within gravel material. By only using material less than 0.5 mm in size for the analysis, a more homogenous sample was obtained. A sample containing many small particles is also better suited for EDS analyses, due to the relatively small surface area which is analysed using this technique.

Residual dust suppressant concentration supervision gives indications of leaching behaviour and, consequently, a basis for determination of requirements in terms of time of renewed application as well as environmental exposure. However, test sections probably need to be

examined for a longer period, with different prerequisites, to get a more complete analysis and, if possible, a model for estimating suppressant concentration.

From the results of the residual dust suppressant concentration quantification, it may be concluded that there are very low levels of suppressant (i.e. chloride or lignosulphonate) left in the gravel wearing course one year after the application. Therefore, annually renewed dust suppressant application is probably required. This is supported by previously reported results by Mullholland (1972).

Sections treated with solid calcium chloride showed residual chloride concentrations which corresponded with those on sections treated with a 30 percent by weight higher application rate of solid magnesium chloride. In principle, these two types of salt treated sections have the same application rate of chloride owing to the higher chloride concentration of calcium chloride compared to magnesium chloride. This indicates that about 30 percent by weight more solid magnesium chloride than solid calcium chloride is required to attain an equal level of dust control for an equal length of time. This result can be compared to 18 percent by weight and up to 50 percent by weight indicated by Reyier (1972) and Enkell (2003), respectively. The field-based evaluation of dust suppressing efficiency gave results which agreed more with the latter.

The test sections treated with chloride solutions were the most efficiently dust suppressed test sections, even though they showed the lowest amount of residual chloride concentration (Fig. 6). Permeability is believed to be improved by dissolving the chlorides in water. Application by solution attained a more uniform product distribution than application of solids, as indicated by the smaller coefficient of variation obtained with samples collected within sections treated with a chloride solution (30 percent) compared to sections treated with solid chloride (80 percent). Since, according to Si and Herrera (2007), the efficiency of dust suppressants depends on the uniformity of application, this parameter probably explains the better performance observed for solutions. The solutions were applied with a cistern lorry carrying spray nozzles (Table 1). The pressure generated, when the solution hits the road surface, might have caused a washing effect on stones, rinsing the fine material downwards into the roadbed. This washing effect could in turn have caused the moderate ravelling seen on some chloride solution treated sections. This problem could be solved by either reducing the pressure, by spraying the solutions slightly backwards instead of forwards or straight down, or by blading the road subsequent to application, even though this results in increased labour. Mounting the spray nozzles further from the road surface would also reduce the pressure.

Comparable to the results presented by Gillies et al. (1999), products forming a brittle surface skin, i.e. lignosulphonate, rape oil, and bitumen emulsion, generally failed to create effective long-term dust reductions. According to Rushing and Tingle (2007), vehicles tend to break the bonds at the road surface and dislodge aggregate through abrasive action. The rupturing process seemed to start from the road edges and work its way towards the middle. Lignosulphonate loss

through leaching also seemed substantial. Polysaccharide was so ineffective that it had to be withdrawn from the test program, whereas starch solutions showed fairly good dust reduction.

By comparing dust suppressing efficiency of chloride solutions and solid chlorides at equivalent concentrations, it is clear that dissolving the solid salt and applying it as a solution leads to significant efficiency profit (Fig. 6). In other words, it is possible to reduce the application rates of chloride solutions and still achieve good dust control results, and, at the same time, reduce costs and environmental impacts.

Chloride solutions were regarded as the most efficient by visual assessments as well, but several test sections did not receive any criticism. It seems possible to use alternative products, i.e. more environmentally sound products such as starch, or to further reduce application rates. The objective must be to make a careful adjustment between reducing the quantity of applied chemicals, while still keeping dust formation at a minimum, in such way that road safety, comfort, and the health of people living alongside gravel roads are not threatened.

On average, magnesium chloride showed slightly better dust control efficiency than calcium chloride when applied as a solution, even though both salts showed good or even excellent performance. Magnesium chloride was at the time of the field-based study 26 percent less expensive per unit weight. However, this is counterbalanced by the demands of 33 percent by weight less calcium chloride than magnesium chloride to attain the same volume of an equivalent 32 percent by weight salt solution. Therefore, a calcium chloride solution seems the most cost effective dust suppressant with current pricing.

Gravel roads, which annually receive some form of dust control, have traditionally received 1,000 kg solid calcium chloride or about 1,300 kg solid magnesium chloride per running kilometre in Sweden. As was previously stated, the length of the national Swedish gravel road network amounts to approximately 20,000 km. The purchase price of salt varies somewhat depending on location but was, at the time of the field-based study, 1,550 SEK/tonne for calcium chloride and 1,150 SEK/tonne for magnesium chloride. This gives a total yearly cost for dust control of about 30 MSEK. By using solution, the application rate can be reduced to 0.8 m^3/km, which is equivalent to about 450 kg solid calcium chloride per km or 660 kg solid magnesium chloride per km. This corresponds to a yearly cost savings of approximately 50 percent or about 15 MSEK for the Swedish national gravel road network alone and a 50 percent reduction in quantity of chemicals released in nature. At sheltered road segments, with, for example, surrounding vegetation, which offers protection from sun and wind, application rates could be reduced even further. The mobile dust measuring methodology for scanning gravel roads would aid in recognising favourable or problematic areas.

All sections in Halmstad were supplemented with 8-16 mm aggregate and clay prior to the 2007 test season. In the average PM_{10} emission results on test sections treated with various dust suppressants (Fig. 6), the 2007 seasonal data from this site have been excluded, since the

addition of this fine material resulted in significantly heightened dust emissions as compared to previous years, as well as to other test sites. Clay is said by distributors to show the best results during its second and third years. Since the field-based research study was terminated the year following the addition of clay, this could not be investigated. However, during a year of clay addition it might be wise to increase the application rate of a dust suppressant.

The test sections in Umeå, which were the only sections with an initial gradation satisfying the specifications of the Swedish National Guidelines (Vägverket, 2007), were, initially, the most efficiently dust suppressed. In 2006, the lignosulphonate sections also showed good performance at this site. This could indicate that composition of the gravel wearing course is highly significant for the performance of dust suppressants. However, aggregate supplementation, compensating for deficient fractions, resulted in increased particle loadings on test sections in Halmstad in 2007, which is in conflict with this theory. The only product, which seemed to gain an advantage by a higher percentage of fine material, i.e. mesa addition, was lignosulphonate. In no other case could a correlation between dust suppressant efficiency and size gradation of the gravel wearing course be established. This is in agreement with results presented by Monlux and Mitchell (2007). A correct size gradation could be more important for avoiding ravelling and formation of potholes and corrugations, as indicated by visual assessments reported by the contractor crew.

Based on the results from the laboratory study of optimal clay addition for minimal dust suppressant leaching, the fine material content should not be below 10 percent by weight (Fig. 8). No studies examining the influence of clay (<0.002 mm) content, which might require specification, were performed. Until further studies are performed, the fine material content may be specified as 10-16 percent by weight. The existing specification in the Swedish National Guidelines cites 8-15 percent by weight (Vägverket, 2007). Optimal fine material content seems, according to this study, to be 15 percent by weight for lignosulphonate and 14 percent by weight for chloride, even though the fine material content seems to have a more decisive influence on lignosulphonate. A higher fine material content than 16 percent by weight was not considered, since it is well known that an excessive percentage of clay prevents water drainage and makes the road surface wet and slippery (Addo and Sanders, 1995; Bolander, 1997; U.S. Department of Transportation, 2001).

A soil sample containing calcium chloride seemed to contain larger particles compared to a corresponding soil material sample without calcium chloride (Fig. 9). The filtrate containing calcium and chloride showed low levels of silicon, i.e. soil particles, and was clear, whereas the filtrate lacking calcium and chloride showed high levels of silicon and was turbid. Since salt ions were absent from the filter adherent solid retentate, it seems that ions of the salt molecule flocculate the soil particles and, thereby, preventing them from passing through the filter paper pores. Hypothetically, calcium ions produce electrostatic bindings or neutralise repulsive

bindings between the clay mineral itself, bindings that remain when the salt has leached away. In conclusion, salt seems to aid in fine material retention both in dry and wet road conditions. In dry conditions, it serves as a hygroscopic dust suppressant. In wet conditions, it flocculates the fine material particles, making it more difficult for them to pass the framework of larger gravel wearing course particles and, thus, prevents them from leaching.

Mesa disappeared from the road over time due to leaching and dust emission (Fig. 10). This is probably true for fine material in general, even though it also is replenished to some degree by traffic induced wear. Aggregate supplementation is, therefore, required on a regular basis. Mesa Section 1 was located in the beginning/end of the gravel road and, therefore, was subjected to more vehicle acceleration and breaking, which could possibly explain some of the larger variations in mesa content observed over time. This large variation in mesa content might also indicate an inhomogeneous distribution. These sections were bladed once, on the 9th of August 2006, which explains the suddenly elevated mesa content on the 19th of September 2006 (cf. Fig. 10).

6. CONCLUSIONS

- There is a relatively rapid linear reduction in particle concentration as a function of distance from a gravel road. The results do not indicate any immediate risk of exceeding the maximum allowed PM_{10} concentration in the ambient air according to the European Council Directive provided an ADT $\leq$ 125.
- The mobile PM_{10} sampling method developed offers relative measurements of dust emission with good resolution, reliability, and economy. PM_{10} measurements can be used to estimate the severity of vehicle generated dust plumes, which impair visibility on gravel roads. The method may replace traditional visual assessments.
- Methods developed for examination of relative variations in residual concentrations in dust suppressed gravel wearing courses are considered to offer acceptable repeatability and reliability.
- In general, all tested dust suppressants except polysaccharide and products forming a brittle surface crust, i.e. lignosulphonate and bitumen emulsion, showed efficient dust reduction.
- Chloride-treated sections were, by quantitative as well as qualitative evaluations, found to be the most efficiently dust suppressed. The application rate for chlorides is very important for dust control efficiency, with higher rates suppressing dust more efficiently. Solid calcium chloride is more effective than solid magnesium chloride at equivalent percentages by weight of chloride. However, a magnesium chloride solution is at least as effective as a calcium chloride solution, provided a concentration of 32 percent by weight for both salt solutions.

- Toxicity and growth inhibition tests show that chloride application for dust control purposes, at conventionally used application rates, does not constitute a threat to the environment.
- By applying either magnesium chloride or calcium chloride as solutions instead of solids, it is possible to reduce the application rate and still obtain satisfactory dust control. This will result in reduced chemical usage, environmental impact, and community cost. Application of solutions instead of solids accomplishes a more uniform product distribution and, therefore, more efficient performance.
- An application rate, of a 32 percent by weight salt solution, of 0.8 m^3/km is optimal for dust control purposes, at least considering Nordic gravel road prerequisites. This concentration corresponds to an application rate reduction and cost saving of about 50 percent, or about 15 MSEK per year for the Swedish national gravel road network alone, compared to conventionally applied rates of solid salt. A corresponding 50 percent reduction in the quantity of chemicals released in the environment represents a considerable environmental argument for its implementation.
- Both chlorides and lignosulphonate are highly water soluble and, therefore, tend to leach with precipitation. The reduction in residual concentration due to leaching means that both chlorides and lignosulphonate require renewed application at least annually. However, chlorides seem to remain on the road and, therefore, show effective performance for a longer period compared to lignosulphonate. Chlorides are favoured by their ability to transport upwards through the soil by capillary forces.
- It is crucial that a fine material content of about 15 percent by weight is ascertained when lignosulphonate is used. This will minimize leaching. The optimal percentage of fine material for minimal chloride leaching is within the interval of 10-16 percent by weight.
- Ions of salt seem to initiate clay mineral flocculation, which, in turn, seems to prevent loss of clay particles due to leaching.
- The large quantity of calcium in mesa makes this element suitable as a trace element for analyses of fine material loss. Mesa addition, or fine material in general, cannot be expected to last on the road more than a couple of years due to loss over time from leaching and dusting.

7. FUTURE STUDIES

Starch seems to be an interesting substance to include in further studies, since it showed fairly good dust suppressing ability. It is regarded as a more environmentally friendly product than salt, since it is non-toxic and does not promote corrosion. It is also easily biodegradable but might result in rapid degradation on the road or even inside storage tanks. However, there were

no apparent signs of mould growth, caused by micro-organisms, neither on the road nor on the application equipment from the starch treatment. The starch tested, extracted from corn, is not a domestic product and might be questionable because of cost and environmental aspects. This product also claims land for its cultivation and releases carbon dioxide during degradation. Still, it would be interesting to investigate other starches, extracted from domestic products such as potatoes, rye, oats, wheat, or barley. Due to the high surface tension of the product, it might be favourable to add surfactant to the solution before application onto the road, which, hypothetically, would decrease surface tension and, consequently, aid in soil permeation.

A second proposal for future studies is to perform tests to see if it is possible to further reduce salt solution application rates in more sun- and wind sheltered road areas and still receive a well dust suppressed and uniform road. By scanning the gravel road network using the mobile methodology developed for continuous dust emission measurements, it would be possible to identify critical areas prone to dusting and, therefore, in need of high application rates and *vice versa*.

It would also be interesting to evaluate the mobile dust measuring methodology for use on paved roads. Another interesting task would be to develop a universal "gravel road test vehicle", which automatically and continuously offers objective measurements of the degree of dust, ravelling, crossfall, and unevenness, when passing over gravel roads.

Initially, development of a handheld laboratory device for estimating dust generation from a test surface was one of the main objectives with this Ph.D. project. Such equipment would to some extent reduce the need for costly, time consuming, and laborious field-based evaluations of dust suppressants regarding application rates, gravel material gradations, etc. A handheld laboratory device, with high-pressure air for generating dust on a test surface and filters for collecting the suspended particles, has been constructed, but the repeatability of the results has so far been poor. Some reconstruction suggestions for its improvement have come to mind and would be interesting to implement in future studies.

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Abbreviations

ADT – Annual Daily Traffic
$CaCl_2$ – Calcium chloride
EC – European Council
EDS – Energy-dispersive X-ray spectroscopy
GVW – Gross vehicle weight
$MgCl_2$ – Magnesium chloride
MSEK – Million Swedish kronor
Ph.D. – Doctor of Philosophy
PM – Particulate matter
$PM_{2.5}$ – Particulate matter with an aerodynamic diameter less than 2.5 μm
PM_{10} – Particulate matter with an aerodynamic diameter less than 10 μm.
Rpm – Rotations per minute
SD – Standard Deviation
SEM – Scanning Electron Microscope
SMHI – The Swedish Meteorological and Hydrological Institute
SRA – The Swedish Road Administration
UV/VIS – Ultraviolet/ visible
VViS – The Road Weather Information System of the SRA

Definitions

Aggregate – A mix of stone, sand, and fine-sized particles used on a road.

Annual Daily Traffic, ADT – The average traffic volume per day in both directions on a particular road during a particular year.

Atomic-percent – Percentage of specific atom relative to a total number of atoms in a sample.

Bitumen emulsion – An emulsion is a chemical system, containing two different liquids that do not dissolve in each other, such that one of them exists as small dispersed spheres (the disperse- or inner phase) in the other liquid (the dispersion medium). In a bitumen emulsion, bitumen represents the disperse phase and water represents the dispersion medium.

Blading – Re-shaping of the gravel wearing course by usage of a grader.

Capillary forces – Surface tension causing the water column to transport upwards when the adhesive intermolecular forces between water and soil are stronger than the cohesive intermolecular forces within the water.

Clay – Mineral particles less than 0.002 mm in size.

Coefficient of variation – Ratio repeatability standard deviation (SD) to mean value.

Compaction – Soil compaction (reducing the pore space between the particles), usually exerted by regular traffic or rollers.

Corrugation – A series of ridges and depressions in a wave-like pattern across the road surface (washboard effect).

Crossfall – The transversal gradient of a road surface. A gravel road should have an "A-shaped crown" (four percent crossfall) to drain off excess water from the surface.

Dust – An aerosol of particles of solid minerals, with particle size less than 100 μm (microns) in diameter, originating from the gravel material.

Dust control – Every attempt of preventing dust emission into the environment, if this is done as the main purpose.

Dust suppressant – Substance used for the purpose of suppressing dust.

Fine material – The general term for gravel fractions of silt and clay, i.e. particles passing through a 0.063 mm sieve according to the specification of the Swedish Road Administration. In American literature fine material most often refers to material fractions passing through a 0.075 mm or 200 mesh sieve.

Grader – Any device either self-propelled or mounted on another machine used for final shaping and maintenance of gravel surfaces.

Gravel – See Aggregate.

Gravel wearing course material – The gravel material in the uppermost layer of a gravel road with specifications according to VVTBT "Obundna lager" (Vägverket, 2007).

Gravel road – An unpaved road with natural gravel or crushed rock, not intended to be paved later. A gravel road is an engineered road, built up of a gravel wearing course (50-90 mm), a basecourse (~100 mm), and, occasionally, a sub-base and protective layer, with specifications for grain size distributions (gradations). Gravel roads are normally used for low volume traffic roads.

Groundwater table – The depth at which soil pore spaces become water-saturated with subsoil water.

Leaching – The process during which the dust suppressant is washed away from the gravel material by water.

Lignosulphonate – Lignosulphonate, also called sulphite lye or lignin, is a waste product obtained during the boiling of wood for paper pulp production.

Maintenance – Refers to the efforts necessary to maintain an adequate gravel road condition. The most important maintenance activities on gravel roads are dust control, re-gravelling, and blading.

Mesa –A residual product from the paper and pulp industry, consisting mainly of calcium carbonate, used as an alternative to clay for increasing the amount of fine material in the gravel wearing course.

Moisture content – The proportion of the total weight of a material that contains water.

Paved road – Any road that has a permanent surface laid on it such as asphalt or concrete.

PM_{10} – Any particle with a diameter less than or equal to 10 microns.

Potholes – Depressions or voids in the road surface.

Ravelling – Loose gravel on the road surface due to deficiency of fines and excess of coarse gravel.

Salt – An ionic compound composed of positively charged cations and negatively charged anions, resulting in a product without a net charge (neutral). Generally, salt refers to sodium chloride which is used during de-icing and cooking etc. Regarding dust suppressants for gravel roads, salt refers to calcium chloride or magnesium chloride.

Sand – Aggregate fraction 0.06 - 2 mm.

Subsoil water – Water located beneath the ground surface in soil pore spaces.

Surfactant – A surface active agent (surfactant) is a wetting agent that can greatly reduce the surface tension of water even when used in very low concentrations.

Supplementation – Aggregate/gravel supplementation or re-gravelling is done to obtain a grain size distribution in accordance with specification (In Sweden by the SRA (Vägverket, 2007)). Gravel wearing courses often become deficient in fines, < 0.063 mm, as well as fractions 5–64 mm. Supplementary gravel is mixed-in with the existing material using a grader.

Swedish Road Administration, SRA – The authority responsible for road planning, construction, operation, and maintenance of the Swedish road network.

Unevenness – Gravel road surface damage which includes both corrugations and potholes.

Appendix

Table I. *Dust suppressants efficiency – Mean PM_{10} value for test sections in relation to mean PM_{10} value for reference section treated with 1.0 kg $CaCl_2$/m.*

Dust suppressant	Efficiency[a, b]	Number of test seasons
$MgCl_2$ solution	0.81	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$CaCl_2$, 1.0 kg/m	1.00	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$CaCl_2$, solution	1.10	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$MgCl_2$, solution + mesa	1.84	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$CaCl_2$, solution + mesa	1.85	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$CaCl_2$, 0.7 kg/m	3.43	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$MgCl_2$, 1.3 kg/m	4.22	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
Starch solution	4.89	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
$MgCl_2$, 1.0 kg/m	4.92	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
Lignosulphonate + $CaCl_2$	7.74	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
Lignosulphonate + mesa	8.74	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
Lignosulphonate	10.87	3 at Hagfors & Umeå + 2 at Rättvik & Halmstad
Rape oil	1.08	2 seasons (2005/ 2006) at Halmstad
Bitumen emulsion	24.34	1 season (2006) at Hagfors
Polysaccharide	41.21	1 season (2006) at Hagfors
Silt + $CaCl_2$	3.38	1 season (2007) at Umeå
Slaked lime + $CaCl_2$	1.66	1 season (2007) at Umeå
$MgCl_2$ solution (0.8 L/m) + surfactant	2.09	1 season (2007) at Hagfors & Umeå
$MgCl_2$ solution (0.8 L/m)	2.61	1 season (2007) at Hagfors & Umeå

[a] Mean PM_{10} value of test section divided by mean PM_{10} value of reference section.

[b] Efficiency data was collected from on average 2-3 occasions per season.

Table II. *Dust suppressants efficiency at Umeå – Mean PM_{10} value for test sections in relation to mean PM_{10} value for reference section treated with 1.0 kg $CaCl_2$/m. Overall annual ranking is shown between brackets.*

UMEÅ *Dust suppressant*	**2005**[a] *Efficiency*[b] *(rank.)*	**2006**[a] *Efficiency*[b] *(rank.)*	**2007**[a] *Efficiency*[b] *(rank.)*	**Tot. 2005-2007** *Efficiency*[b] *(mean rank.)*
$MgCl_2$ solution (0.8 L/m)			0.34 **(1)**	
$MgCl_2$ solution (1.2 L/m)	0.46 **(6)**	45.23[d]	-	0.4 **(3.5)**[c]
Slaked lime + $CaCl_2$			0.52 **(2)**	-
$CaCl_2$, 0.7 kg/m	0.40 **(4)**	0.79 **(1)**	0.75 **(5)**	0.65 **(3.3)**
$MgCl_2$ solution (0.8 L/m) + 1% surfactant			0.72 **(3)**	-
$MgCl_2$ solution (0.8 L/m) + 0.5% surfactant			0.80 **(6)**	-
$CaCl_2$ solution (1.2 L/m)	0.37 **(3)**	1.41 **(3)**	0.92 **(7)**	0.90 **(4.3)**
$CaCl_2$, 1.0 kg/m	1.00 **(8)**	1.00 **(2)**	1.00 **(9)**	1.00 **(5.7)**
Silt + $CaCl_2$			1.07 **(10)**	-
$CaCl_2$ solution + mesa	0.30 **(1)**	4.35 **(5)**	1.07 **(10)**	1.91 **(5.3)**
$MgCl_2$ solution + mesa	0.30 **(1)**	5.00 **(6)**	0.74 **(4)**	2.01 **(3.7)**
$MgCl_2$, 1.0 kg/m	0.75 **(7)**	5.15 **(7)**	0.98 **(8)**	2.29 **(7.3)**
$MgCl_2$, 1.3 kg/m	0.40 **(4)**	8.37 **(9)**	1.30 **(12)**	3.36 **(8.3)**
Lignosulphonate + $CaCl_2$	4.38 **(10)**	2.45 **(4)**	5.09 **(15)**	3.97 **(9.7)**
Starch solution	1.40 **(9)**	12.54 **(10)**	1.74 **(13)**	5.23 **(10.7)**
Lignosulphonate + mesa	5.01 **(11)**	5.72 **(8)**	5.44 **(16)**	5.39 **(11.7)**
Lignosulphonate	10.29 **(12)**	14.35 **(11)**	3.88 **(14)**	9.51 **(12.3)**

[a] Data collected on one occasion in 2005, two occasions in 2006, and two occasions in 2007.

[b] Mean PM_{10} value of test section divided by mean PM_{10} value of reference section.

[c] Mean value calculated from concentrations (0.8 L/m) and (1.2 L/m).

[d] Outlier; not included in the calculation of total mean for 2005-2007.

Table III. *Dust suppressants efficiency at Rättvik - Mean PM_{10} value for test sections in relation to mean PM_{10} value for reference section treated with 1.0 kg $CaCl_2$/m. Overall annual ranking is shown between brackets.*

Rättvik *Dust suppressant*	**2005**[a] *Efficiency*[b] *(rank.)*	**2006**[a] *Efficiency*[b] *(rank.)*	**Tot. 2005-2006** *Efficiency*[b] *(mean rank.)*
$MgCl_2$ solution	0.93 **(1)**	1.03 **(2)**	0.98 **(1.5)**
$CaCl_2$, 1.0 kg/m	1.00 **(2)**	1.00 **(1)**	1.00 **(1.5)**
$MgCl_2$, 1.3 kg/m	1.20 **(4)**	1.45 **(3)**	1.33 **(3.5)**
$CaCl_2$, 0.7 kg/m	1.57 **(7)**	99.41[c]	-
$CaCl_2$ solution	1.19 **(3)**	2.08 **(4)**	1.64 **(3.5)**
$CaCl_2$ solution + mesa	1.27 **(5)**	2.89 **(5)**	2.08 **(5.0)**
$MgCl_2$ solution + mesa	5.07 **(10)**	3.52 **(6)**	4.30 **(8.0)**
Lignosulphonate + $CaCl_2$	2.29 **(8)**	14.58 **(7)**	8.44 **(7.5)**
$MgCl_2$, 1.0 kg/m	1.49 **(6)**	20.40 **(9)**	10.95 **(7.5)**
Starch solution	4.71 **(9)**	18.69 **(8)**	11.70 **(8.5)**
Lignosulphonate	7.04 **(12)**	30.25 **(10)**	18.65 **(11.0)**
Lignosulphonate + mesa	6.60 **(11)**	44.31 **(11)**	25.46 **(11.0)**

[a] Data collected on two occasions in 2005 and three occasions in 2006.

[b] Mean PM_{10} value of test section divided by mean PM_{10} value of reference section.

[c] Outlier; not included in the calculation of total mean for 2005-2006.

Table IV. *Dust suppressants efficiency at Hagfors – Mean PM_{10} value for test sections in relation to mean PM_{10} value for reference section treated with 1.0 kg $CaCl_2$/m. Overall annual ranking is shown between brackets.*

Hagfors *Dust suppressant*	**2005**[a] *Efficiency*[b] *(rank.)*	**2006**[a] *Efficiency*[b] *(rank.)*	**2007**[a] *Efficiency*[b] *(rank.)*	**Tot. 2005-2007** *Efficiency*[b] *(mean rank.)*
$MgCl_2$ solution (1.2 L/m)	0.45 **(3)**	0.17 **(1)**	0.63 **(2)**	0.42 **(2.0)**
$CaCl_2$ solution (1.2 L/m)	0.41 **(1)**	0.25 **(2)**	0.70 **(3)**	0.45 **(2.0)**
$CaCl_2$ solution + mesa	0.77 **(5)**	0.91 **(4)**	0.71 **(4)**	0.80 **(4.3)**
$MgCl_2$ solution (0.8 L/m) + 1% surfactant			0.93 **(7)**	-
$CaCl_2$, 0.7 kg/m	1.18 **(7)**	1.27 **(6)**	0.50 **(1)**	0.98 **(4.7)**
$MgCl_2$ solution (0.8 L/m)			0.74 **(5)**	-
$CaCl_2$, 1.0 kg/m	1.00 **(6)**	1.00 **(5)**	1.00 **(8)**	1.00 **(6.3)**
Lignosulphonate + $CaCl_2$	1.46 **(8)**	1.72 **(7)**	-	1.59 **(7.5)**
$MgCl_2$ solution (0.8 L/m) + 0.5% surfactant			1.61 **(9)**	-
$MgCl_2$, 1.0 kg/m	0.57 **(4)**	4.87 **(12)**	0.86 **(6)**	2.10 **(7.3)**
$MgCl_2$ solution + mesa	2.37 **(10)**	0.83 **(3)**	4.06 **(11)**	2.42 **(8.0)**
$MgCl_2$, 1.3 kg/m	1.64 **(9)**	1.81 **(8)**	4.17 **(12)**	2.54 **(9.7)**
Starch solution	5.15 **(11)**	2.36 **(10)**	1.79 **(10)**	3.10 **(10.3)**
Lignosulphonate	0.41 **(1)**	5.96 **(13)**	-	3.19 **(7.0)**
Bitumen emulsion		3.54 **(11)**	-	-
Lignosulphonate + mesa	6.42 **(12)**	3.34 **(9)**	4.85 **(13)**	4.87 **(11.3)**
Polysaccharide		5.99 **(14)**	-	-

[a] Data collected on two occasions in 2005, three occasions in 2006, and two occasions in 2007.

[b] Mean PM_{10} value of test section divided by mean PM_{10} value of reference section.

Table V. *Dust suppressants efficiency at Halmstad – Mean PM_{10} value for test sections in relation to mean PM_{10} value for reference section treated with 1.0 kg $CaCl_2$/m. Overall annual ranking is shown between brackets.*

Halmstad *Dust suppressant*	**2005**[a] *Efficiency*[b] *(rank.)*	**2006**[a] *Efficiency*[b] *(rank.)*	**Tot. 2005-2006** *Efficiency*[b] *(mean rank.)*	**2007**[a] *Efficiency*[b] *(rank.)*
$MgCl_2$ solution + mesa	-	0.18 **(1)**	-	13.14 **(12)**
$CaCl_2$ solution	0.54 **(2)**	0.24 **(2)**	0.39 **(2.0)**	1.66 **(4)**
$MgCl_2$ solution	0.78 **(3)**	0.44 **(3)**	0.61 **(3.0)**	1.90 **(5)**
$CaCl_2$ solution + mesa	-	0.81 **(5)**	-	11.49 **(11)**
Rape oil	0.53 **(1)**	1.31 **(7)**	0.92 **(4.0)**	-
$CaCl_2$, 1.0 kg/m	1.00 **(4)**	1.00 **(6)**	1.00 **(5.0)**	1.00 **(1)**
$MgCl_2$, 1.3 kg/m	1.68 **(8)**	0.63 **(4)**	1.16 **(6.0)**	1.28 **(2)**
$CaCl_2$, 0.7 kg/m	1.06 **(5)**	1.36 **(8)**	1.21 **(6.5)**	1.55 **(3)**
$MgCl_2$, 1.0 kg/m	1.49 **(7)**	4.55 **(9)**	3.02 **(8.0)**	3.20 **(7)**
Starch solution	1.36 **(6)**	4.84 **(10)**	3.10 **(8.0)**	6.50 **(8)**
Lignosulphonate + mesa	-	9.33 **(12)**	-	-
Lignosulphonate + $CaCl_2$	17.12 **(9)**	5.65 **(11)**	11.39 **(10.0)**	-
Lignosulphonate	17.42 **(10)**	12.70 **(13)**	15.06 **(11.5)**	11.01 **(10)**

[a] Data collected on two occasions in 2005, three occasions in 2006, and two occasions in 2007.

[b] Mean PM_{10} value of test section divided by mean PM_{10} value of reference section.

[C] Data from 2007 is not included in the total mean ranking because the fine material addition resulted in significantly heightened dust emissions compared to previous years as well as other test sites.