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Brynhild Snilsberg

Pavement wear and airborne dust pollution in Norway

Characterization of the physical and chemical properties of dust particles

NTNU
Norwegian University of
Science and Technology

Doctoral Thesis

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Thesis for the degree of
doktor ingeniør
Faculty of Engineering Science and Technology
Department of Geology and Mineral Resources Engineering

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To my family

The committee for appraisal of this thesis was comprised of the following members:

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Department of Geology and Mineral Resources Engineering,

Norwegian University of Science and Technology

Senior engineer, **Nils Uthus**

Norwegian Public Roads Administration

Preface

The work presented in this doctoral thesis has been conducted at the Department of Geology and Mineral Resources Engineering at the Norwegian University of Science and Technology in Trondheim during the period 2005-2008. This dr.ing study was financed by the Norwegian Public Roads Administration through the four-year R&D project called “Environmentally friendly pavements - dust and noise properties of pavements” and has been conducted in close collaboration with the Norwegian University of Science and Technology. The focus in “Environmentally friendly pavements” was to develop low noise, wear resistant and durable pavements adapted to Norwegian climatic and traffic conditions, and the project lasted from 2004 to 2008. The dr.ing study started in 2005 and was a part of this project, aiming at characterizing dust from pavement wear.

The study was initiated by Professor Tom Myran at the Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, who saw a lack of knowledge regarding characterization of ambient suspended matter. Tom Myran has also been the main supervisor for the work and a major resource on the subject.

Senior engineer Nils Uthus at the Norwegian Public Roads Administration has been co-adviser for the study and responsible for activities connected to the dust aspect in “Environmentally friendly pavements”.

From this study five research papers have been written, and they are the main work in this study. Three of these papers have been presented at different international conferences and published in proceedings and international journals; the other two has not yet been published. Each of the research papers is an independent unit which can be read separately.

Acknowledgements

This thesis is a result of four years of study where many people have been crucial for the result.

First of all I would like to thank my supervisors; Tom Myran and Nils Uthus for giving me this opportunity, always being there when I needed advice and encouragement. My colleagues at the Norwegian Public Roads Administration have also given me much input through useful dialogues and discussions, and I would like to mention Rabbira Garba Saba, Joralf Aurstad and Jostein Aksnes in particular.

This study would not have been possible without the full financial support by the Norwegian Public Roads Administration, and I am really thankful for the solid frames around my project, giving me the opportunity to perform the testing which was necessary.

I would also like to mention the staffs at the laboratory at the Department of Civil and Transport Engineering and at the Department of Geology and Mineral Resources Engineering, NTNU, who have been helpful through this study. I would especially acknowledge Tore Menne for prioritizing and helping me when it was needed.

Finally, I am grateful for having a loving family and caring friends, who have encouraged me through this period in my life, giving me input from other things in daily life. There is a life outside a dr.ing study! A special thought goes to Inge, my dear partner, for his patience and for his firm belief that I would finish this study.

Brynhild Snilsberg

Brynhild Snilsberg, Trondheim, February 2008

Summary

In several large cities in Norway the traffic volume is high. The use of studded tires and other friction enhancing measures during winter leads to significant pavement wear, which in turn leads to an increase in the amount of airborne particulate matter, often exceeding the limits set in the ambient air regulation. This represents a nuisance or health risk for people being exposed to the pollution. According to regulations set by the European Union particulate matter is measured and regulated through mass concentration of particles less than 10 µm in diameter (PM10). However, studies of health effects related to exposure to particulate matter have shown that particle properties like morphology and composition are essential regarding toxicity and in considering risk of developing disease. There seems to be a more complex relationship between dust pollution and health effects, which cannot be explained with just the mass concentration alone. This makes it necessary to characterize the physical and chemical properties of the road dust. Characterization of road dust particles is important to provide basis for a better understanding of the pavement wear and production of road dust and its influence on human health in urban areas. The overall purpose of this study has been to characterize particles generated from pavement wear qualitatively and quantitatively.

Five papers are included in the thesis. Paper I and II present field investigations of road dust sampled in the vertical direction close to an urban road in Trondheim, Norway. In Paper III different laboratory methods have been used for simulation of pavement wear and road dust generation by studded tires. Paper IV and V describe how aggregate size, driving speeds and vehicle tires affect pavement wear and particle properties.

The main conclusions from the study are:

Studded tires used in the winter season in Norway are the main cause for generation of road dust from pavement wear. If studded tires were not used, there would be much less suspended particulate matter originating from wear of pavements in urban air. Studded tires produce much more dust particles from wear of pavements compared to non-

studded tires. For instance, at 60 km/h studded tires produce 30-40 times more TSP compared to non-studded tires on an SMA 8 pavement measured in an indoor test facility. The airborne road dust is composed of almost 90 % by weight of mineral particles under winter conditions, and approximately 50 % of the particles have size smaller than 25 μm (D50). Based on all samples analyzed, D10 is 3 μm and D90 is 60 μm. However, agglomeration of particles seems to make the measured particle size distribution coarser than it really is. Studded tires generate dust with finer particle size distribution than non-studded tires. The main fraction of the particles can be described as rounded particles, with average roundness value around 0.6. The specific surface area of the sample is dependent on the amount of organic material present in the sample and the particle size distribution. In general, field samples have higher specific surface area than dust particles generated in laboratory because of higher organic content. However, finely ground particles produced in laboratory may exhibit even higher surface area than field samples of road dust because of finer particle size distribution. Surface area is an important factor in health considerations since the reactivity of particles increase with increasing surface area.

Other factors affecting the generation of particles from pavement wear are the driving speed and type of rock material used in the pavement. Test results show that the PM10 concentration measured under laboratory conditions is reduced by 32-49 % when reducing the driving speed from 70 to 50 km/h, 52-83 % when reducing the driving speed from 50 to 30 km/h, and 76-89 % when reducing the driving speed from 70 to 30 km/h. The driving speed affects the particle size and the particle shape distributions. Increasing driving speed generate particles with finer particle size distribution and more irregular particles. The rock material used in the pavement affect the amount of dust generated, the composition, the particle size distribution, the shape distribution, and the specific surface area. Some mineral types are regarded harmful to health, for example quartz and asbestos which are classified as carcinogenic. The total amount of airborne dust (TSP) and PM10 can be very different; a high TSP does not necessarily lead to a high PM10 concentration and vice versa.

This study has shown that it is possible to produce dust comparable to studded tire wear by use of simple laboratory techniques. This has significance with regard to cost because it is not necessary to build expensive test sections when the purpose is to generate and characterize the dust from pavement wear. The small scale asphalt testing procedures, Prall and Tröger, are the methods best suited to give fine material which is comparable to particles generated from the Pavement testing machine (PTM). It also seems that one can test the aggregate alone to get reasonably good samples for analysis of dust from wear by studded tires. Among the aggregate testing procedures, the Los Angeles (LA) method gives the best correlation with the PTM. The dust produced by Tröger and Prall is more similar to the dust produced in the field because the dust is generated from asphalt mixtures, while the dust produced by LA, Nordic ball mill (KM) and micro-Deval (MD) comes from the aggregate only. However, none of these methods include/simulate the effect of the car tire, only the studs.

The results have shown that apart from the use of studded tires, the rock material used in the pavement has a significant influence on the airborne dust generated. It is therefore important to carefully select the rock materials for use in urban road pavements. The aggregate type affects both the amount of dust generated and the particle properties. Existing knowledge shows that the finer the particles, the greater will be their potential effects on health. Since driving speed influences both the amounts of road dust generated and the particle size distribution, one may have to consider the use of speed restrictions in urban areas in winter time to reduce the potentially hazardous effects of road dust. However, this has to be balanced against other traffic conditions such as congestion.

Sammendrag (in Norwegian)

Trafikkmengden er høy i store byer i Norge. Bruk av piggdekk og andre friksjonsforbedrende tiltak om vinteren medfører stor asfaltslitasje, som fører til en økning i mengde svevestøv i byer og tettsteder som ofte overskrider luftkvalitetskriteriet for uteluft. Dette utgjør en plage eller helserisiko for befolkningen som eksponeres for denne type forurensning. I følge krav satt av den Europeiske Union blir partikulært materiale målt og regulert gjennom massekonsentrasjon av partikler mindre enn 10 μm i diameter (PM10). Studier av helseeffekter relatert til eksponering for partikulært materiale viser imidlertid at partikkelegenskaper som morfologi og sammensetning er viktige for giftighet og for vurdering av risiko for utvikling av sykdom. Det ser ut til at sammenhengen mellom partikulær forurensning og helseeffekter er kompleks, og den kan ikke forklares ut ifra massekonsentrasjonen alene. Dette betyr at det er viktig å karakterisere vegstøvpartikler med hensyn på fysiske og kjemiske egenskaper. Karakterisering av vegstøvpartikler er viktig med tanke på å gi et grunnlag for bedre å forstå vegslitasjen og produksjon av vegstøv, og hvordan dette påvirker menneskers helse i urbane områder. Hovedmålsettingen med dette studiet var å karakterisere partikler generert fra vegslitasje kvalitativt og kvantitativt.

Fem artikler er inkludert i avhandlingen. Paper I og II presenterer feltmålinger av vegstøv som ble prøvetatt i vertikal retning rett ved en trafikkert veg i Trondheim, Norge. I Paper III ble forskjellige laboratoriemetoder brukt for å simulere vegslitasje og produsere vegstøv fra piggdekk. Paper IV og V beskriver hvordan tilslagets størrelse, kjørehastighet og type bildekk påvirker vegslitasjen og partikkelegenskapene.

Hovedkonklusjonene fra studiet er:

Piggdekk brukt i vinterhalvåret i Norge er hovedårsaken til produksjon av støv fra vegslitasje. Hvis piggdekk ikke ble brukt, ville det være mye mindre svevestøv i urbane områder på grunn av vegslitasje. Piggdekk produserer mye mer svevestøv enn piggfrie dekk. For eksempel ga piggdekk i laboratorieforsøk 30-40 ganger større mengde slitasjepartikler ved 60 km/h på et SMA 8 asfaltdekke sammenlignet med piggfrie dekk.

Vegstøvet består av nesten 90 vekt % mineralpartikler om vinteren, og ca. 50 % av partiklene har en størrelse mindre enn 25 µm (D50). Basert på alle prøver som ble undersøkt var D10 på 3 µm og D90 på 60 µm. Agglomerering av partiklene gir imidlertid en grovere partikkelstørrelsesfordeling enn det virkelig er. Piggdekk gir støv med finere partikkelstørrelsesfordeling enn piggfrie dekk. Hovedandelen av partiklene kan beskrives som avrundete partikler, med gjennomsnittlig rundhet på rundt 0.6. Det spesifikke overflatearealet til prøven er avhengig av mengde organisk materiale til stede i prøven, samt partikkelstørrelsesfordelingen. Generelt sett har feltprøver høyere overflateareal enn prøver produsert i laboratoriet på grunn av høyere organisk innhold. Men for prøver hvor partiklene har høy nedmalingsgrad, kan prøver produsert i laboratoriet gi høyere spesifikk overflate på grunn av finere partikkelstørrelsesfordeling. Spesifikt overflateareal er viktig for vurdering av helserisiko siden reaktiviteten til partikler øker med økende overflateareal.

Andre faktorer som påvirker produksjon av slitasjepartikler er kjørehastighet og type steinmateriale brukt i asfalten. Testresultater viser at PM10 konsentrasjonen målt under laboratorieforhold går ned med 32-49 % når hastigheten reduseres fra 70 til 50 km/h, 52-83 % når hastigheten reduseres fra 50 til 30 km/h, og 76-89 % når hastigheten reduseres fra 70 til 30 km/h. Kjørehastigheten påvirker også fordelingen til partikkelstørrelsen og partikkelformen. Steinmaterialet i asfalten påvirker mengde støv generert, sammensetningen, partikkelstørrelsesfordelingen, partikkelformen og det spesifikke overflatearealet. Noen mineraltyper er skadelige for menneskers helse, for eksempel kvarts og asbest som er klassifisert som kreftfremkallende. Totalmengde støv (TSP) og PM10 kan være veldig forskjellige; høy TSP medfører ikke nødvendigvis høy PM10 konsentrasjon og omvendt.

Metoder brukt for å studere asfaltslitasje og støvproduksjon i laboratoriet viser at det er mulig å generere støv sammenlignbart med støv generert fra piggdekk ved bruk av enkle laboratorium metoder. Dette er viktig med tanke på kostnader forbundet med bygging av kostbare teststrekninger i felt for å generere og karakterisere støv fra vegslitasje. Småskala slitasjetesting av asfalt i laboratoriet, Prall og Tröger, er metodene som er best egnet til å produsere støv sammenlignet med Pavement testing machine (PTM). Man kan også teste steinmaterialet alene og få noenlunde gode prøver av støv fra piggdekk. Blant steinmaterialtestene er det Los Angeles (LA) metoden som best kan sammenlignes med PTM. Støv produsert med Tröger og Prall er mer sammenlignbart med støv generert i felt siden støvet er produsert fra en asfaltmasse, mens støv produsert med LA, kulemølle (KM) og micro-Deval (MD) bare er fra steinmaterialet. Ingen av disse metodene inkluderer effekten av et bildekk.

Resultatene viser at foruten bruk av piggdekk er steinmaterialet som brukes i asfalten av største viktighet for støvet som genereres. Det er derfor viktig å velge steinmateriale med omhu når det skal brukes til vegdekke i urbane strøk. Steinmaterialet påvirker både mengde støv generert og egenskaper til partiklene. Dagens kunnskap viser at jo finere partiklene er, jo høyere er den potensielle helserisikoen. Siden kjørehastigheten påvirker både mengde støv generert og partikkelstørrelsesfordelingen, bør man vurdere redusert kjørehastighet i urbane områder vinterstid for å redusere de potensielle farlige effektene av vegstøv. Dette må balanseres med andre trafikale effekter, som for eksempel trafikkflyt.

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Appendix

Paper overview

The following papers are included in the second part of the thesis.

Paper I

Snilsberg, B., Myran, T. and Saba, R. G. (2006). *Analysis of dust emission from pavement abrasion in Trondheim, Norway*. Proceedings. 1st Transport Research Arena Europe 2006, TRA 2006. Göteborg, Sweden.

Paper II

Snilsberg, B., Myran, T. Uthus, N. and Erichsen, E. (2007). *Characterization of road dust in Trondheim, Norway*. Symposium Proceedings. The 8th International Symposium on Cold Region Development, ISCORD. Tampere, Finland.

Paper III

Snilsberg, B., Myran, T. Uthus, N. and Aurstad, J. (2008). *Evaluation of different laboratory methods for simulation of pavement wear and road dust generation from studded tires*. International Journal of Road Materials and Pavement Design. 3rd European Asphalt Technology Association Conference, EATA08. Lyon, France.

Paper IV

Snilsberg, B., Myran, T. Uthus, N. (unpublished A). *Asphalt pavement wear and road dust generation – Effects of different aggregate grading, vehicle tires and driving speed.*

Paper V

Snilsberg, B., Myran, T. and Uthus, N. (unpublished B). *The influence of driving speeds and tires on road dust properties*.

Contributions to the papers

The second part of the thesis consists of five papers where the author of this thesis is the main author. The main supervisor of this thesis has been Professor Tom Myran at the Norwegian University of Science and Technology (NTNU), while Senior engineer Nils Uthus at the Norwegian Public Roads Administration has been co-supervisor. The main work in the five papers has been performed by the author of this thesis, including planning, experimental work, evaluation of results and writing of the actual paper.

I Analysis of dust emission from pavement abrasion in Trondheim, Norway

Brynhild Snilsberg, Tom Myran, Rabbira Garba Saba

Snilsberg planned and performed the experimental and analytical work and wrote the paper. Myran and Saba gave advice on the structure of the paper and the analysis of the results.

II Characterization of road dust in Trondheim, Norway

Brynhild Snilsberg, Tom Myran, Nils Uthus, Eyolf Erichsen

Snilsberg planned and performed the experimental work, evaluated the results and wrote the paper. Myran and Uthus gave some input on discussion of the result in the paper. Erichsen gave input on evaluation of mineral composition of the samples.

III Evaluation of different laboratory methods for simulation of pavement wear and road dust generation from studded tires

Brynhild Snilsberg, Tom Myran, Nils Uthus, Joralf Aurstad

The main author planned the work, evaluated the results and wrote the paper. Asphalt samples were tested in an indoor Pavement testing machine at the Swedish National

Road and Transport Research Institute (VTI), with Tröger and Prall at NTNU, while the unbound aggregates were tested in Los Angeles abrasion machine, Nordic ball mill and micro-Deval at NTNU. Particle characterization was performed at NTNU. The co-authors contributed with advice and discussions.

IV Asphalt pavement wear and road dust generation – Effects of different aggregate grading, vehicle tires and driving speed

Brynhild Snilsberg, Tom Myran, Nils Uthus

The main author planned the work, evaluated the results and wrote the paper. Production of dust was performed at VTI (Pavement testing machine) and NTNU (Tröger), and dust analysis was performed at NTNU. The co-authors gave input on evaluation of the results in the paper.

V The influence of driving speeds and tires on road dust properties

Brynhild Snilsberg, Tom Myran, Nils Uthus

Snilsberg planned and performed the experimental and analytical work, evaluated the results and wrote the paper. Myran and Uthus provided input on discussion and results in the paper.

List of abbreviations

AC	Asphalt concrete
BET	Brunauer-Emmett-Teller (measure of specific surface area, 0-100m^2)
CEN	European Committee for Standardisation
D_{max}	Maximum aggregate size
D_P , d_P	Particle diameter
ICP-MS	Inductively coupled plasma mass spectroscopy
KM	Nordic ball mill (in Norwegian: Kulemølle)
LA	Los Angeles mill
MD	micro-Deval
NTNU	Norwegian University of Science and Technology
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PM10	Particulate matter with particle size < 10 µm (1 µm = 0.001 mm)
PM10-2.5	Coarse fraction, particles with size 2.5-10 µm
PM2.5	Fine fraction, particles with size < 2.5 µm
PTM	Pavement testing machine
SEM	Scanning electron microscopy
SMA	Stone mastic asphalt
TSP	Total suspended particulates
VTI	Swedish National Road and Transport Research Institute
XRD	X-ray diffraction

1. Introduction

1.1 Project background and founding

This PhD study has been a part of a large R&D project administrated and financed by the Norwegian Public Roads Administration; called “Environmentally friendly pavements - dust and noise properties of pavements”. The project has been conducted by the Norwegian Public Roads Administration in close cooperation with research institutions and the road industry. The project focuses on optimizing the properties of road surfacing in order to reduce the environmental impact on surroundings, and thereby contribute to achieving the environmental targets set for levels of dust and noise. The project has been conducted over a four-year period; 2004-2008.

1.2 Problem statement

In several large cities in Norway the traffic volume is high. The use of studded tires and other friction enhancing measures during winter leads to significant pavement wear, which in turn leads to an increase in the amount of airborne particulate matter, often exceeding the limits set in the ambient air regulation. This represents a nuisance or health risk for people being exposed to the pollution. According to regulations set by the European Union, particulate matter is measured and regulated through mass concentration of particles less than 10 µm in diameter (PM10). However, studies of health effects related to exposure to particulate matter have shown that particle properties like morphology and composition are essential regarding toxicity and in considering risk of developing disease. There seems to be a more complex relationship between dust pollution and health effects, which cannot be explained with just the mass concentration alone. This makes it necessary to characterize the physical and chemical properties of the road dust. Characterization of road dust particles is important to provide basis for a better understanding of the pavement wear and production of road dust and its influence on human health in urban areas.

1.3 Objective of the study

The main goal of this study was to characterize particles generated from pavement wear qualitatively and quantitatively. The specific objectives were to:

- Review available literature on effects of dust particles on health.
- Characterize airborne particles sampled in field and laboratory.
- Study and evaluate methods for accelerated pavement wear in the laboratory.
- Study the effects of tire type, driving speed, aggregate size and aggregate type on dust generation and pavement wear.
- Evaluate the effect of measured dust particle properties on health.

Wear particles from both asphalt pavements in the field and laboratory samples were characterized and analyzed to determine their physical and chemical properties. The focus was on characterization of dust particles to evaluate their potential health effects.

1.4 Methodology

The methodology adopted to meet the objectives of this study includes review of literature, and field and laboratory investigations.

The literature review has been conducted to identify health risks related to particle exposure in urban areas, and to gain knowledge about wear of pavements and particle characterization.

Field measurements of road dust were performed using standardized dust downfall samplers (particulate fallout collectors). The collected samples were characterized at the Norwegian University of Science and Technology (NTNU) using gravimetric analysis, annealing furnace for determination of % inorganic material, X-ray diffraction (XRD) to find the mineralogical composition, inductively coupled plasma mass spectroscopy (ICP-MS) for determining elemental composition, Brunauer-Emmett-Teller (BET) to measure specific surface area, helium pycnometer to determine density, and laser diffraction to determine particle size distributions. Scanning electron microscopy (SEM) was used for imaging purposes.

The laboratory investigation included both accelerated large scale testing of asphalt and small scale testing of asphalt cores and aggregate. Accelerated laboratory testing of asphalt was performed at the Swedish National Road and Transport Research Institute (VTI) with the indoor Pavement testing machine (PTM) to investigate wear as function of different tires and speeds. Small scale laboratory testing at NTNU was conducted using two types of asphalt wear testing equipment; Tröger and Prall, and three equipments for aggregate testing; Los Angeles mill, Nordic ball mill and micro-Deval mill. Based on the results of these tests, effects of aggregate size on pavement wear and methods for generating road dust were investigated.

1.5 Structure of the thesis

This thesis is divided into two parts.

Part one consists of 8 chapters where chapter 1 gives a short introduction and objective of the study. Chapter 2 and 3 reviews the problem related to pavement wear and production of road dust, and its effects on human health. Chapter 4 describes the testing, materials and experimental procedures used in the study. In chapter 5 summaries of all papers are given, and in chapter 6 the findings of the papers are discussed. Main conclusions and further recommendations are given in chapter 7, and in chapter 8 the references are listed.

Part two of this thesis presents the scientific work of the study. It includes five research papers which have been the main work in this dr.ing study. The author of this thesis has been the main author of all the papers. In addition, the appendix gives some additional data which are not described in the papers.

2. The problem of pavement wear and dust generation in Norway

2.1 Introduction

About 850 000 people in Norway experience daily nuisance because of air pollution (Totlandsdal et al. 2007). Most of these people live in cities or urban areas. Road traffic is an important source of particulate matter (PM) emission to the ambient air. Since the beginning of the 1990s airborne PM from roads has been given much attention in Norway. This is because increased particulate air pollution shows a significant potential for adverse health effects.

High concentrations of PM are found mainly in urban and urban-influenced regions and are, to a large extent, attributed to increased traffic density in the last decades. The most important sources of airborne PM in Norway in urban air today are combustion of fuel in vehicles, wood burning and pavement wear.

The main focus in this chapter is on particles from pavement abrasion caused by the use of studded tires during the winter season in Norway. Use of studded tires is the most important factor affecting the pavement wear in Norway. The following sections describe studded tires, pavement wear, road dust suspension time and ambient air quality.

THE CONQUEST OF ROAD-DUST

"It is satisfactory to learn from a notice sent to the county councils by the Secretary of the Road Board that the tar-painting of the roads throughout the country is proceeding apace and that already much useful work has been done. Indeed, a writer in the *Times* says that without indulging in any undue optimism we are within measurable distance of seeing all the main roads of England rendered dustless. If that is to be a near consummation, then we agree with the writer that "motorists, travelers of every kind, owners of wayside property, pedestrians, and ratepayers will be considerable gainers and the public health must also improve as well." Road-dust has probably been the most evil nuisance which the motor-car has thrust upon us, widespread mischief up and down the great roads of the country has been done, and it is fortunate that a remedy has so comparatively quickly been found and that public authorities have been so ready to apply it. The credit of pioneer in this work belongs to the Kent county council, whose officers have been hard engaged for some years upon practical inquiry into the several methods which have been brought forward. Tar-painting of roads is not without its drawbacks. It has caused damage to private horse vehicles and to personal clothing, but it must be admitted, we allow, that these incidents are trifling compared with the far-reaching mischief of the motor dust-storm. Moreover, tar-painting must preserve the road surface itself, and the sucking out of its binding material must be prevented by it. The possible poisoning of fishes in our rivers and streams is, however, a serious matter, It has been stated that where rain-water sweeping over a tar-painted surface has drained into a river the effect upon fishes has been fatal, and in one instance the poisoning of hundreds of trout has been reported. It is to be hoped that some steps will be taken to prevent this most undesirable destruction of fish life."

The Lancet, July 30, 1910

2.2 Studded tires

In northern countries like Sweden, Finland and Norway, parts of Denmark (Greenland), USA (Alaska) and Iceland, airborne particulate matter from wear of pavements caused by use of studded winter tires and other friction enhancing measures affects the air quality in urban areas significantly. Regulations control the use of studded winter tires, and these tires are allowed in Norway only from 1st November to 1st Sunday after Easter for the mid and southern region and from 16 October to 30 April for the northern region (Lovdata, 1990). Studies show five times higher PM10 concentrations during winter conditions compared to summer conditions (Johansson, 2007).

The development of studded tires in Norway (Skoglund and Uthus 1994, Haakenaasen 1995, Bakløkk 1997, Bakløkk et al. 1997) can be summarized as follows:

In the beginning of the 1960's there was no regulation or restriction in the use of studded tires, and the pavements were not designed for wear from studded tires. The use of studded tires in Norway started in the 1960's after the sale of cars was released, and an increase of pavement wear was observed.

In the 1970's the traffic volume was growing rapidly leading to considerable pavement wear. Research was started to find the factors contributing to this wear. Results showed that use of larger maximum aggregate size (D_{max}) in the asphalt reduced the wear. In 1970, restriction in the length of the studded tire season was introduced (from 15 October to 1 May), in 1972 it was prohibited to use tube stud, and regulations in number, weight, overhang and force of the studs were set. In 1979 a reduction in weight of studs for passenger cars was set.

In the 1980's lighter studs and stone mastic asphalt (SMA) were introduced, but there was still an increasing problem with wear and dust due to increase in the traffic volume. In 1988 a new restriction was set on the length of the studded tire season (from 1 November to 1st Sunday after Easter).

The focus changed in the 1990's to environmental issues, and non-studded winter tires were developed. A political decision was made to raise the share of non-studded winter tires to 80 % in the largest cities in Norway (Krokeborg, 1998), and research on the problem of dust pollution began. Salting of the roads was introduced to maintain satisfactory friction (to keep them ice free). In 1992 additional weight reduction of studs for passenger cars was enforced; from 1.8 to 1.1 g for passenger cars and from 8.0 to 3.0 g for trucks. Passenger cars with these light weight studs were shown to wear the pavement only half as much as the old steel studs (Juneholm, 2007).

In 2000 restrictions in use of studded tires was tightened and focus on environment and friction was enhanced. Fees for driving with studded tires were introduced.

Use of non-studded winter tires reduces the pavement wear substantially. The use of non-studded winter tires in urban areas of Oslo and Trondheim, and in rural areas of Norway is shown in Figure 2-1. From the winter season 1999/2000 in Oslo and 2001/2002 in Trondheim a fee was introduced for use of studded winter tires. This was done to stimulate citizens to choose non-studded winter tires, and this clearly had an effect. In 1999 the share of non-studded winter tires was about 30 % in Trondheim and has increased to about 70 % in 2007. A rapid decrease in the share of non-studded winter tires was observed in Oslo after the fee was taken away in 2001 when the 80 % goal was achieved. A new goal of 90 % non-studded winter tires in Oslo has recently been introduced.

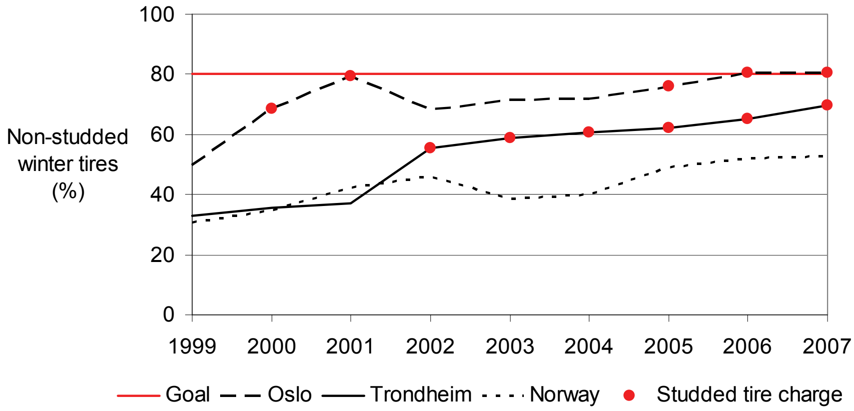


Figure 2-1. Share of non-studded winter tires (Norwegian Public Roads Administration)

Heavy vehicles cause more wear of the pavements than passenger cars. Data from 1997 showed that passenger cars with studded tires wear 0.3 g per driven km compared to

1.5 g per driven km for heavy vehicles with studded tires, measured as PM10 (Johansson et al. 2004).

The effect of studded tires on emission of PM10 has been studied both in field and in laboratory. By reducing the studded tire usage by 10 %, the annual PM10 value can be reduced by 1 μg/m^3 (Bartonova et al. 2002) and the daily PM10 value can be reduced by 10 μg/m^3 (Johansson et al. 2004).

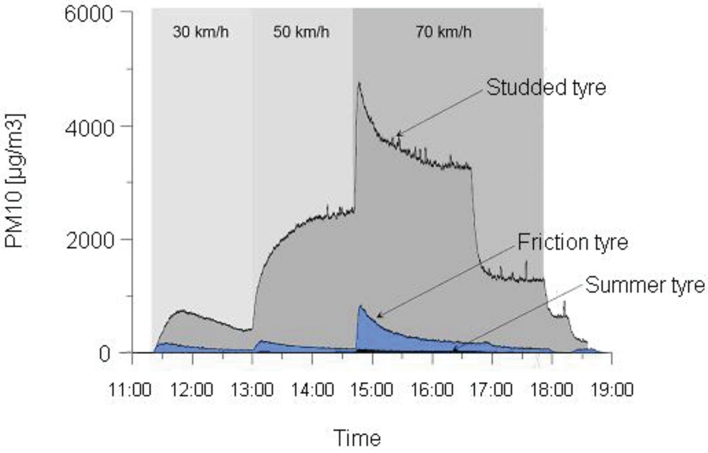


Figure 2-2. PM10 concentrations with different tires and speeds (Gustafsson et al. 2008 A)

Figure 2-2 shows PM10 concentrations as a function of different tires and driving speeds. Clearly studded tires generate more PM10 than non-studded tires. According to Johansson (2007) laboratory measurements from Sweden and Finland show that studded tires give respectively 50-100 and 2-9 times higher PM10 values compared to non-studded winter tires. On the other hand, field studies in Sweden found 2-6.4 times higher emission of PM10 from studded tires compared to non-studded tires (Hussein et al. 2007), while Finnish field studies suggest higher emissions from non-studded tires because of the suction pad effect caused by the lamellas (Johansson, 2007). The total emissions of PM from pavements include both accumulated material on the road (resuspension) and the generation of particles because of pavement wear from tires. For studded tires the resuspension was measured to 16-43 % of the total emission, while for the non-studded tires the resuspension was > 87 % (Johansson, 2007).

2.3 Pavement wear

The phenomenon of wear is defined as the progressive loss of material from the operating surface of a body occurring as a result of relative motion at its surface (Williams, 2005). In this case it is a mechanical wear caused by a car tire on an asphalt pavement surface (abrasion).

Airborne particulate matter from abrasion of pavements represents environmental, economical and health related problems in Norway. The mechanical wear takes place mainly during the winter due to the use of studded winter tires. This is indicated by the high concentrations of minerals in the dust; 70-80 % mineral dust in the winter, 15-25 % in the summer (Bakløkk et al. 1997, Låg et al. 2004). The content of inorganic matter is large because of the pavement wear, and because asphalt is composed mainly of aggregates. The composition of a typical asphalt surfacing material is shown in Figure 2-3. These particles can affect human health and cause both pulmonary and cardiovascular diseases. Studded tires have been identified as the most important source for particles in urban air, 17 % of the total emitted particles to air in Norway was caused by studded tires (Krokeborg, 1998). An emission factor of 0.6 gram/vehicle km for 100 % studded tires has been found from the indoor pavement testing machine at the Swedish National Road and Transport Research Institute (Juneholm, 2007). In field measurements emission factors of 0.43 gram/vehicle km (40 % studded tires) and 0.2-0.4 gram/vehicle km (30 % studded tires) were found for the southern part of Sweden (Juneholm, 2007).

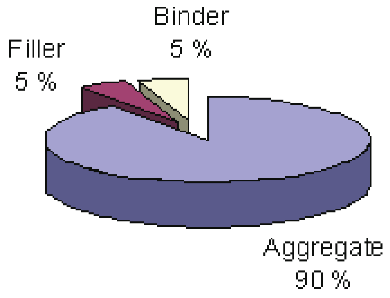


Figure 2-3. Asphalt composition

The main sources of particulate air pollution in urban areas during the winter is road traffic (30-47 %) and heating by wood burning (47 %) (Låg et al. 2004). According to a report made by Statistics Norway in 1997 about 39 % of the suspended particulate matter in Norway is related to road traffic, and 15 % of this is from asphalt pavements. In 2001, the total contribution from road traffic (exhaust, abrasion of pavements etc.) was estimated to 7 % of the total emission of PM10 in Norway (Finstad et al. 2003). Ormstad and Løvik (2002) reports that 10-20 % of the annual mean PM10 values in Oslo (adjusted for exposed inhabitants) is caused by wear of pavements due to the use of studded tires.

The connection between abrasion on pavements, accumulation of dust and suspended particulate matter is complex. Episodes with high concentrations of airborne particulate matter occur, sometimes dominated by particles from pavement abrasion and other times by particles from wood burning (Norwegian Institute of Public Health, 2005). Over longer time periods (yearly basis) pavement particles make only a small contribution compared to exhaust particles (Norwegian Institute of Public Health, 2005), and even particles from wood burning have a limited season. Long distance transported particles from other countries and continents will make a considerable pollution many places on a yearly basis (Norwegian Institute of Public Health 2005, Ormstad and Løvik 2002).

Rutting caused by studded tire wear and deformations is the most important trigger factor for repaving on Norwegian roads (Skoglund and Uthus, 1994). Around 250 000 - 300 000 tons of asphalt are worn off Norwegian roads every year (Bakløkk et al. 1997, Ormstad and Løvik 2002). The rutting is dominant for roads with annual daily traffic above 3000 vehicles per day, and about 90 % of the wear happens on 10 % of the road network where the amount of traffic is high (Låg et al. 2004, Ormstad and Løvik 2002). The authorities in Norway decided to increase the share of non-studded winter tires to 80 % in the largest cities because the studded tires caused considerable problems with urban air quality and pavement wear (Krokeborg, 1998).

The production of dust is dependent on several factors. Skoglund and Uthus (1994), Bakløkk (1997), Gustafsson (2001) and Gustafsson et al. (2006) mention factors such as type of stud (metal/plastic/weight), amount of traffic, design/shape of the streets/roads, cleaning of the pavements, vehicle type, driving speed, weather, driving conditions and maintenance measures, quality of pavement and type of aggregate in the pavement. Finnish studies have shown that asphalt wear is affected both by studded winter tires and anti-skid sand on pavement surface. This effect was named the "sandpaper effect" (Kupiainen et al. 2003, Kupiainen et al. 2005, Tervahattu et al. 2006). The sandpaper effect takes place when tires (both studded and non-studded tires) and anti-skid aggregates wear the pavement and create fine-grained material. This material is an effective abrasive material, especially when the road surface is wet. The pavement wear increases 2-6 times when the pavement is wet (Bakløkk et al. 1997).

The emission from abrasion of road pavements has however decreased steadily the last 30 years. According to Finstad et al. (2003) the emission factor for pavement abrasion in 1973 was 0.40 g/km for light vehicles using studded tires, and in 2001 the factor was reduced to 0.25 because of development of more durable pavements and lower weight of the studs in the tires. They also report reduction from 2.01 g/km in 1973 to 1.27 in 2001 for heavy vehicles.

2.4 Road dust suspension time

Hinds (1999) and Seinfeld and Pandis (2006) define dust as an aerosol of solid particles produced by mechanical disintegration of a material such as crushing or grinding. The particles range in size from sub micrometer to more than 100 µm and are usually of irregular shape. An aerosol is generally referred to as a suspension of airborne particles, whether liquid droplets or solids (Hinds, 1999). The aerosol term includes both the particles and the suspending gas.

The falling velocity of particles is important for evaluating the retention time of particles in the air. According to Stokes law the falling velocity (v_{Stokes}) in stagnant air for a spherical particle is described by (Sandvik et al. 1999, Hinds 1999):

$$v_{Stokes} = d^2 g(\rho_{particle} - \rho_{air})/18\eta_{air} \qquad [2\text{-}1]$$

Where:

d = diameter of the particle

g = gravitational constant (9.80665 m/s^2)

ρ = density

η = viscosity (18.6 µPa s for air)

Stoke's law can be used to estimate the time needed by particles of different size to fall one meter. The following particle densities are employed:

$\rho_{particle}$ = 2.65 g/cm^3 for quartz (Prestvik, 1992)

$\rho_{particle}$ = 1.1-1.2 g/cm^3 for diesel exhaust particles (Virtanen et al. 2002)

ρ_{air} = 0.0012 g/cm^3 (Hinds, 1999)

Specific densities measured in Pittsburg, Pennsylvania, in 1967-68 were 1.8±0.2 g/cm^3 and 2.1±0.5 g/cm^3 for dust in spring and winter conditions, respectively (Corn et al. 1971). These values are similar to values found for the dust downfall samples in Trondheim, Norway, from 2005 (Appendix A):

$\rho_{particle}$ = 2.12 g/cm^3 for dust downfall in March-April 2005

$\rho_{particle}$ = 1.71 g/cm^3 for dust downfall in April-May 2005

The estimated time for particles to fall one meter is shown in Figure 2-4. The result from the calculation shows that the ultrafine and fine fractions of the dust take significantly longer time to fall down and settle even in stagnant air. However, in urban areas the air is turbulent most of the time, and suspension time of particles will be even longer.

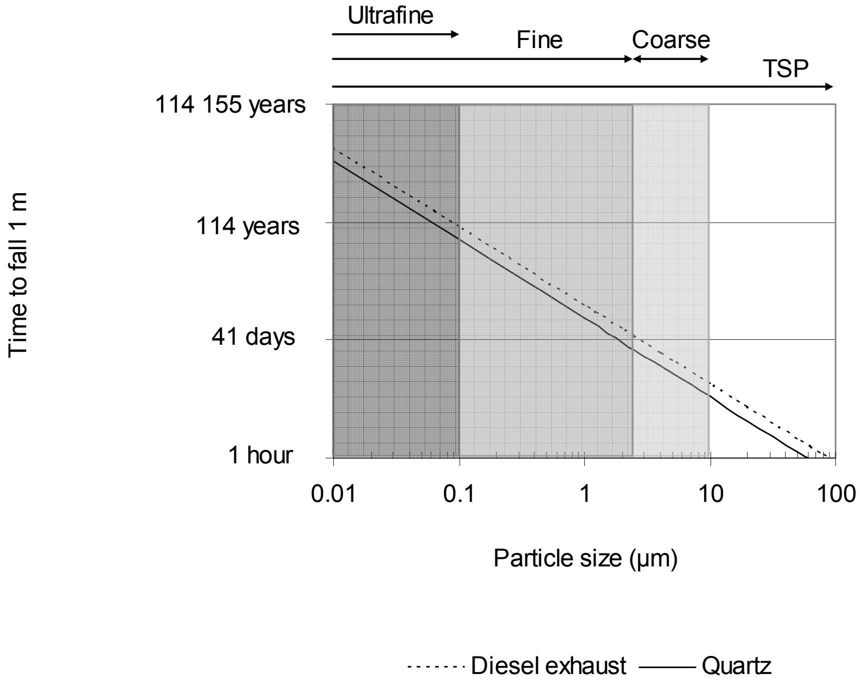


Figure 2-4. Calculated time for particles to fall 1 m in stagnant air as a function of its size and origin

Composition of urban air in large cities consist mostly of organic particles from combustion processes, but in northern European countries like Norway, Sweden and Finland, large amounts of inorganic material are present because of pavement wear from studded tires and other friction enhancing measures. Sizes of wear particles from pavements are around 10-2.5 μm (coarse fraction), while combustion particles are below 2.5 μm (fine and ultrafine fraction) (Refsnes et al. 2004, Johansson 2007). TSP is the total amount of particles in the air.

2.5 Ambient air quality

The quality of ambient air is regulated through a European Union (EU) directive. According to the EU directive (European Council Directive 1999/30/EC) the daily averages of PM10 should not exceed 50 μg/m^3 for more than 35 days during each year, and the annual average PM10 concentration should not exceed 40 μg/m^3.

Monitoring of the ambient air quality in Trondheim started in 1990 (Berg, 1991). In

Trondheim in 1993 the public attention to ambient air pollution was raised when amphibole minerals were found in the road dust, and it was alleged in media that it was asbestos. This attracted attention of the public since asbestos is known as being carcinogenic. Trondheim municipality has since been a pioneer with regard to particulate matter in the ambient air in Norway.

Monitoring of air quality in Norway show that there are too many days on which the daily limit value is exceeded (Oslo kommune and Statens vegvesen Region øst 2004, Berthelsen et al. 2005, Statens vegvesen 2005b). Close to high traffic roads, the content of particles below 10 µm can become 3-4 times above the air quality requirements, especially with dry and cold weather conditions (Ormstad and Løvik, 2002). Resuspension processes (particles settled on the ground becoming airborne again) are important in this regard (Sternbeck et al. 2002, Gertler et al. 2006). According to Ormstad and Løvik (2002) about 80 % of the dust at high particle exposure episodes is related to resuspension processes. Most of these traffic related particles when measuring by mass concentration are coarse particles (size 2.5-10 µm).

Measurements done by Trondheim Municipality and Norwegian Public Roads Administration show that the dust concentration in Trondheim has been reduced in the last few years. A decreasing trend is observed when considering PM10 values for the worst months of the year (February, March, April, November and December) for the years 1994-2007, as shown in Figure 2.5. There are fewer extreme high values although it is difficult to keep the level below the daily average limit value of 50 µg/m^3. Reasons for the reduction in dust level is development of more durable pavements, reduction in the number of vehicles using studded tires, implementation of measures for reduction of suspended matter, changes in the climate from year to year etc. To fulfill the requirement of maximum 35 days on which the limit value is exceeded, Trondheim needs to reduce the pavement wear and the resuspension of dust (Berthelsen et al. 2005). Figure 2-6 shows the number of days in the period 1994-2007 where the daily limit value was exceeded in Trondheim, while Figure 2-7 shows which periods of the year the daily limit value is exceeded. Figure 2-8 shows the yearly average PM10 concentration measured in Trondheim.

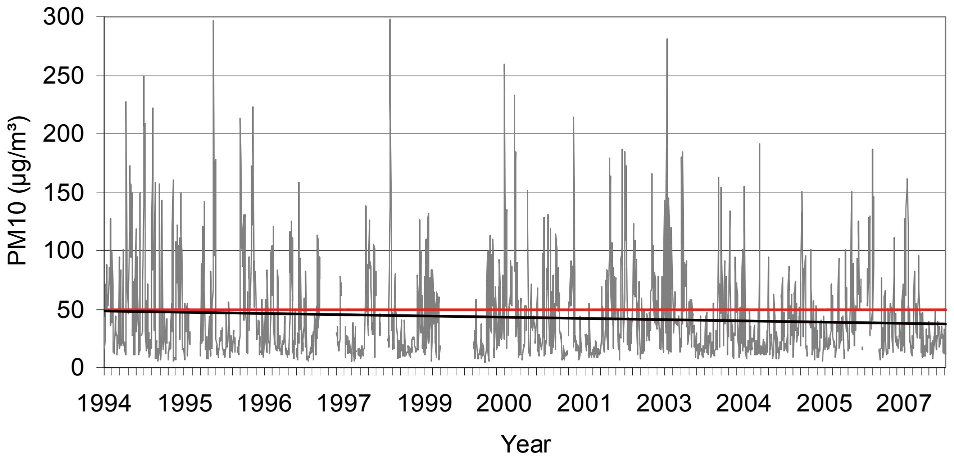


Figure 2-5. PM10 daily values for February, March, April, November and December in the years 1994-2007 for Elgeseter Street in Trondheim, Norway (data obtained from www.luftkvalitet.info*). The red line indicates the limit value, and the black line indicates the trend line.*

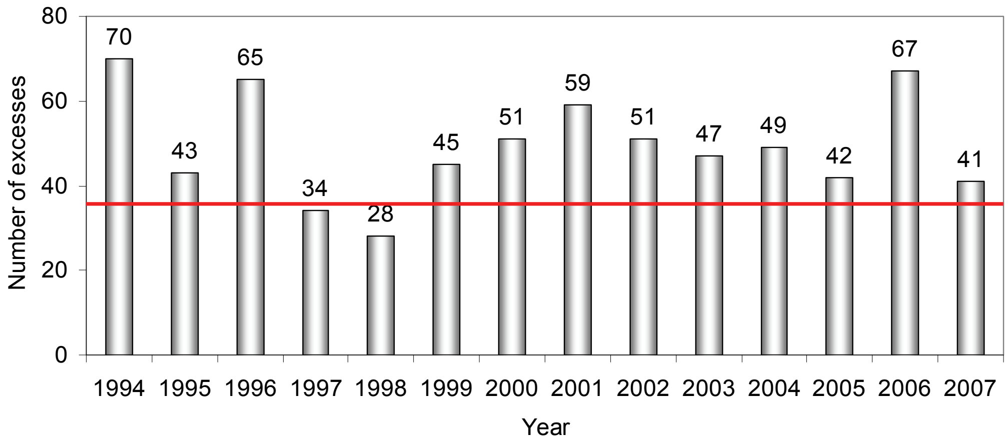


Figure 2-6. Number of days with PM10 levels exceeding the daily limit value in Elgeseter Street in Trondheim, Norway (data obtained from www.luftkvalitet.info*). The red line indicates the maximum number of excesses allowed.*

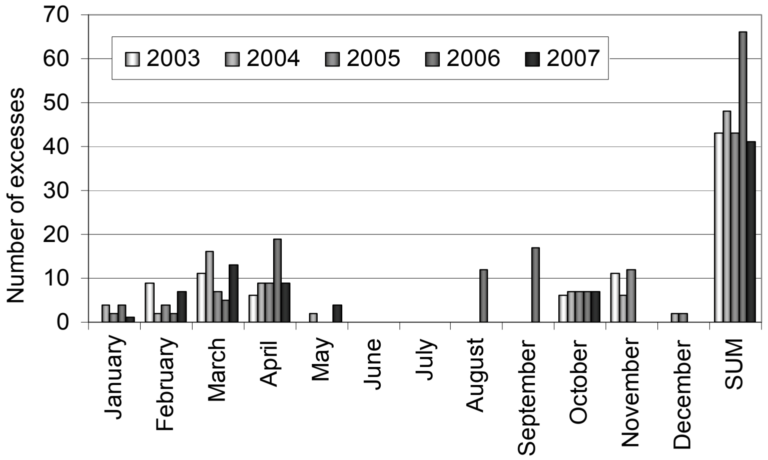


Figure 2-7. Periods of the year with PM10 levels exceeding the daily limit value in Elgeseter Street in Trondheim, Norway (data obtained from www.luftkvalitet.info*)*

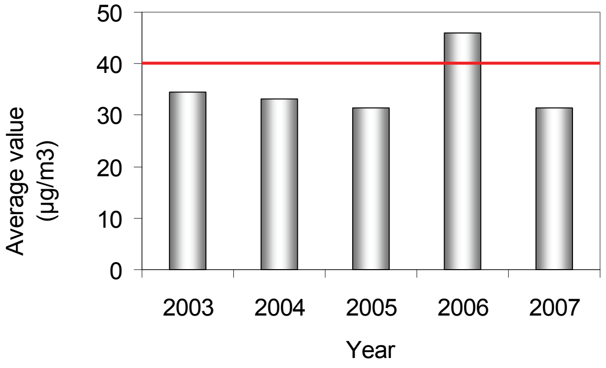


Figure 2-8. Annual average values for PM10 in Elgeseter Street in Trondheim, Norway (data obtained from www.luftkvalitet.info*). The red line indicates the limit value.*

Due to seasonal variations in the concentration of particulate matter in the air, there usually are few problems with too high concentrations of PM10 in the summer time. The worst months of the year regarding PM10 are in early winter when the winter tires are put on (October, November), and early spring around the time when the winter tires are taken off (March, April). The reason for this is a combination of use of studded winter tires, heating with wood, and dry and ice/snow free roads in addition to weather conditions with little wind and poor dispersion of the air pollution. Emission factors tend to decrease significantly from late spring to early summer by as much as a factor of 4 (Gertler et al. 2006).

Climatic conditions are also important for the amount of dust in the air. When the pavement is wet, the dust is bound by the water. Rain and melting water from ice and snow can flow onto the pavement and bind the dust. But when the pavement dries, dust is raised by vehicles and wind and will then be dispersed in the air. Salt has a similar effect as water, and is often used as a dust binding measure to prevent high concentrations of dust in the air. Hygroscopic properties of the salt will contribute to keep the pavement wet when the pavement is salted, the temperature is higher than -4°C and the relative humidity is above 80 %. However, salting to prevent dust in the air can lead to more wear of the pavement and enhanced need for cleaning since a moist pavement is worn 2-6 times faster than a dry pavement (Bakløkk, 1997).

The air humidity is often low in the springtime. Heat from the sun and wind will rapidly dry the pavement. Accumulated dust including dust from salt and newly produced dust can then be raised and resuspended. The different parameters will affect each other, for instance the air temperature will influence the relative air humidity. Relative humidity increases when the temperature drops.

It is important to note that there is a big difference between total emissions of pollutants and local air quality. In calculation of concentrations, the amount of particles available for inhalation is considered and the altitude for emission is essential (i.e. particles from wood burning for heating purposes are more diluted when they reach inhalation altitude since they are emitted higher up than e.g. exhaust from vehicles). Road traffic contributes to emissions affecting local air quality and concentrations of airborne PM.

3. Health effects of dust

3.1 Introduction

Health effects of air pollutants is an old issue in cities and urban areas around the world, but became evident during severe air pollution episodes in the first part of the 20th century. In particular “The Big Smoke” in London the winter 1952/53 with extreme high levels of air pollution lead to 12 000 deaths (Refsnes et al. 2004). This resulted in abatement policies to reduce air pollution concentrations substantially during the 1960’s and until today.

Airborne particulate matter affects human health in different ways and it is important to identify how and why these particles can be harmful.

According to Furuseth and Myran (1992) four factors affect the toxicity of PM and hence the risk of developing disease:

1) Amount of dust retained in the lung
2) Duration and intensity of exposure
3) Individual sensitivity
4) The properties of the dust

These factors are described in the next sections, with focus on mineral particles.

3.2 Amount of dust retained in the lung

The amount of dust retained in the lung depends on chemical and physical properties of the dust (particle size, shape, density and solubility) and where in the respiratory tract the particles are deposited (Schwarze et al. 2004). Figure 3-1 presents the structure of the human respiratory tract. The way of breathing (nasal/oral, breathing frequency and volume), physical activity, possible existing diseases and particle properties determine the location in the respiratory system where the particles will be deposited (Schwarze et al. 2004). The potential for health risk depends on if, how and how fast the particles are removed from the respiratory system.

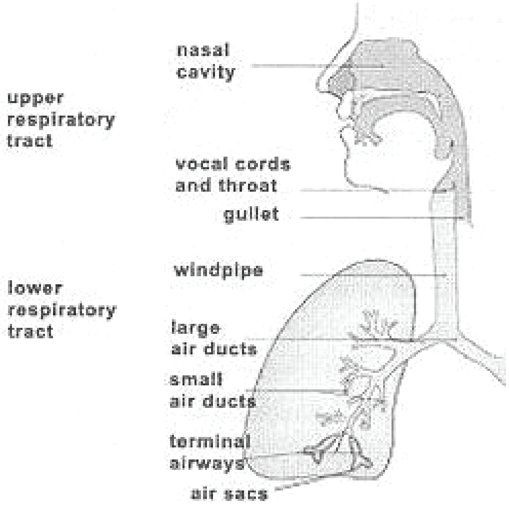


Figure 3-1: Human respiratory tract (Dybing et al. 2005)

The human respiratory tract can be considered as a series of filters starting with the nose or mouth, via the various diameters of airways to the alveoli; Figure 3-2 presents deposition efficiency in the airways as a function of particle diameter. The efficiency is related to particle mass inhaled.

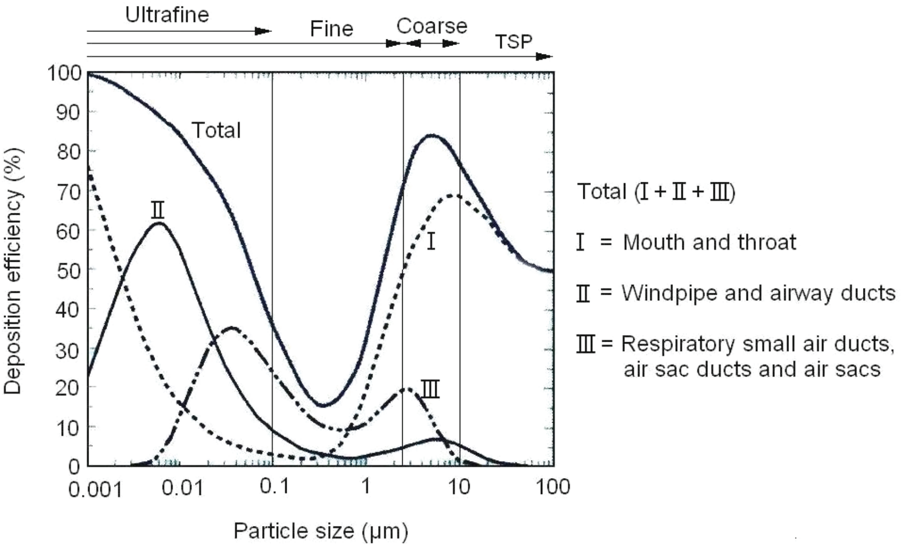


Figure 3-2. Deposition of particles in the airways (Schwarze et al. 2004)

According to Dybing et al. (2005) three mechanisms determine deposition in the respiratory tract: (1) sedimentation by gravitational forces acting on particles > 0.5 µm in aerodynamic diameter; (2) impaction caused by their inertial mass in branching airways acting on particles > 1.5 µm; and (3) diffusional motion of particles < 0.5 µm by thermal motion of air molecules. They also suggest that these mechanisms work through three important components during breathing: (a) particle dynamics including the size and shape and its possible dynamic change during breathing; (b) geometry of the branching airways and the alveolar structures; and (c) breathing pattern determining the airflow velocity and the residence time in the respiratory tract, including breathing through the nose in comparison to breathing through the mouth.

Different cells with various properties exist in our respiratory system and air sacs (Schwarze et al. 2004):

- Some cells produce mucus and secrete compounds to counteract effects of particles and other foreign matter. The thickness of the mucus layer (lining fluid) is smallest in the deep lung (air sacs, terminal airways and small air ducts), and if sufficient foreign matter reaches the lungs, cells will send out signaling substances which summon other cells (i.e. different types of leucocytes such as granulocytes and lymphocytes) that create inflammation to render the foreign matter harmless. Inflammation is important to block infections by destroying the foreign matter, but can also result in injury to the tissue around. Strong and persistent inflammatory reaction may lead to cell damage and create areas sensitive to illness in the lungs.

- Other cells are covered with cilium and are involved in the transport of the mucus to the gullet. In this way, particles, microbes and other foreign matter can be transported away from the respiratory system.
- Specialized cells (macrophages) take up and break down foreign matter in the gas exchange area in the air sacs.

Particles can be divided into three categories depending on their solubility (Schwarze et al. 2004); soluble, partly soluble and low solubility. The main part of urban airborne PM is partly soluble. The particle size is important for removal of the low solubility fraction. Particles of different size are removed in different ways and the place of deposition also determines in what way the particles are removed. Particles deposited in the upper and middle part of the respiratory tract are removed relatively fast (hours, days), while it may take a considerable longer time (months, years) for particles deposited in the lower part. Deposited particles are removed in different ways depending on solubility and where they are deposited in the respiratory tract (Schwarze et al. 2004):

- Soluble particles or components are removed fast. A protecting liquid layer covers the surface of the respiratory system and has different composition in different parts of the respiratory tract. Soluble particles or components attached can be partly or completely dissolved, and the components may reach the blood vessels often via the lymphatic system. This may cause effects far away from the place they where deposited.
- Coarse low solubility particles > 5 μm which are deposited in the upper part of the respiratory tract are removed by coughing, sneezing or by muccociliary clearance to

the gullet where the particles can reach the gastrointestinal tract. They are either secreted with excrements or taken up in the gut. The muccociliary transport is slower the further down in the respiratory tract the particles are deposited. Low solubility particles with size between 5 µm and 0.1 µm can be taken up by macrophages. Ultrafine particles (< 0.1 µm) can cross to the blood stream and reach other organs, but the effect of these particles is not yet established.

The activation state of the target lung in terms of the response to particle exposure reflects an important issue. Differences in the activation state of the macrophages dictate the extent of their pro-inflammatory response (Donaldson and Tran, 2002). The sequence of effects in lungs after exposure to low solubility particles is inflammation, fibrosis, and then cancer (Muhle and Mangelsdorf, 2003). Inflammation is crucial to the development of adverse health effects associated with particle exposure.

There are several implications for health connected to inhalation of airborne PM. The particles can affect the heart and blood vessel system. The heart is the organ that receives the blood stream from the respiratory system first and according to Dybing et al. (2005), air pollution may result in diminished oxygen supply, increased blood coagulation and possible clot formation in the vessels supplying the heart muscle, deleterious hearth rhythm effects etc. Ultrafine particles can be found in liver, spleen, kidneys, brain and nerves (Dybing et al. 2005). Lung inflammation, heart variability, changes in blood viscosity and oxygen deprivation can result in exacerbating the symptoms of pre-existing lung disease such as asthma, as well as heart and blood vessel disease and probably induction of lung cancer (Dybing et al. 2005, Katsouyanni et al. 2005).

3.3 Duration and intensity of exposure

The length and intensity of exposure to PM air pollution are important factors that influence the effect on health. Both short-term (hours, days) and long-term (weeks, months, years) exposure to air pollution can enhance existing disease in the population. Long-term exposure can directly contribute to the development of disease and subjects living in cities with higher long-term average PM10/PM2.5 concentrations die earlier than subjects living in cities with low air pollution. Short-term exposure has been linked to increased daily mortality and number of hospitalization due to respiratory and cardiovascular diseases (Katsouyanni et al. 2005, Totlandsdal et al. 2007). Relatively few studies have documented effect of long-term exposure on local air pollution on health (Totlandsdal et al. 2007), but it is documented that the relative risk due to long term exposure is greater than that of short term exposure (The Norwegian Institute of Public Health 2005, Totlandsdal et al. 2007).

Studies on effects of outdoor air pollutants on human health have included both epidemiological and toxicological studies. Toxicology aims to understand the processes of how pollutants affect people's health and to identify the factors influencing those processes, while epidemiology identifies disease by studying its occurrence in a population and employs statistical methods to assess whether exposure and disease are related to one another. The AIRNET network project on air pollution and health (2002-2005) founded by the European Union (EU), has tried to help create a foundation for public health policy that can improve European air quality (Dybing et al. 2005, Katsouyanni et al. 2005), and has collected extensive material on the subject to improve present knowledge.

Epidemiological studies show a connection between short term exposure to PM10 and acute health effects. An increase in PM10 of 10 $\mu g/m^3$ resulted in an increase in relative risk of 0.6 % for all causes of death, and 0.9 % and 1.3 % for death by cardiovascular and respiratory diseases, respectively (Totlandsdal et al. 2007). There is also evidence of cardiac infarction at very short changes (hours) in PM10 concentration. It is difficult to separate health effects of PM10 from short and long term exposures. However, for long term exposure an increase in PM2.5 of 10 $\mu g/m^3$ resulted in an increase in relative risk of 4 % for all causes of death, and 6 % and 8 % for death by cardiovascular disease and lung cancer, respectively (Totlandsdal et al. 2007).

The risk for developing health effects increases linearly even at very low concentrations of air pollution in general and PM in particular, and it was not possible to establish a level of concentration beyond which there is no health effect (Refsnes et al. 2004). There are different opinions on whether a threshold level for exposure to airborne PM exists (Totlandsdal et al. 2007). Donaldson and Tran (2002) assume all particles have a threshold effect level where the lung can deal with them, while Dybing et al. (2005), Katsouyanni et al. (2005) and de Kok et al. (2006) report no support for general thresholds for PM-induced adverse health effects at a population level, even though general toxicology understanding makes thresholds for individuals biologically plausible.

3.4 Individual sensitivity

Individual sensitivity towards the actual dust is important for evaluation of health effects from PM air pollution. Risk or susceptibility is dependent on the specific health end point being evaluated and the level and length of exposure (Pope and Dockery, 2006).

Some groups of the population are particularly susceptible to PM. Fetus, children, elderly people and groups with chronic diseases (respiratory disorders like asthma, allergy and chronic obstructive pulmonary disorder (COPD), cardiovascular disease, cancer and diabetes) respond more intensely than healthy people (Schwarze et al. 2004, Refsnes et al. 2004, Norwegian Institute of Public Health 2005, Næss et al. 2006, Pope and Dockery 2006, Totlandsdal et al. 2007). There is also evidence of increased infant mortality rate and various birth outcomes because of particle exposure (Norwegian Institute of Public Health 2005, Pope and Dockery 2006). In addition, risk for worsening of asthma and allergy because of air pollution is larger for children than adults (Norwegian Institute of Public Health, 2005).

Age is an important factor when evaluating individual sensitivity. Children have narrower bronchia and different breathing pattern compared to adults, which may result in different places of deposition for inhaled particles. Increased sensitivity with elderly people may be caused by diseases as a consequence of age and not the age itself.

Characteristics that have been shown to influence susceptibility include (Pope and Dockery, 2006) pre-existing respiratory or cardiovascular disease, diabetes, medication use, age, gender, race, socioeconomic status and health care availability, educational attainment, housing characteristics and genetic differences. But still there are gaps in the knowledge about who is most at risk or susceptible to PM.

It must be mentioned that the number of those susceptible to less serious health effects may be larger than risk of dying or hospitalization. For most people those effects are likely to be small, transient and largely unnoticed (Pope and Dockery, 2006).

The Norwegian Institute of Public Health (2005) has proposed an equation, which estimates the change in number of incidents of health damage for the population in a given area if the concentration of airborne particulate matter changes as a result of different measures. The equation is expressed as follows:

$$PM = D_0 * \Delta RR * \Delta E_x / 10\ \mu g/m^3 \qquad [3\text{-}1]$$

Where:

PM = Number of incidents caused by an increase in concentration of PM10

D_0 = Total number of incidents per year/area

ΔRR = Increase in relative risk

ΔE_x = Increase ($\mu g/m^3$) in PM10

3.5 The properties of the dust

Particles can be defined by different properties. It is not possible to fully characterize a given particle by a single parameter. Several studies (Oberdörster et al. 1994, Fubini 1997, Hetland et al. 2000, Hetland et al. 2001, Skaug 2001, Muhle and Mangelsdorf 2003, Låg et al. 2004, Moreno et al. 2004, Nygaard et al. 2004, Refsnes et al. 2004, Brunekreef and Forsberg 2005, Dybing et al. 2005, Øvrevik et al. 2005) indicate that the most important characteristics of particles are particle size, shape, composition, substances attached, solubility, surface area and number of particles. In this section particle properties and their relation to health effects of dust are discussed.

3.5.1 Particle size

Particles found in the air we breathe vary greatly in size. For example, pollen can be as small as 10 micrometers (µm), clay particles in soil as small as 0.02 µm, tobacco smoke as small as 0.01 µm, and smog (primarily resulting from automobile combustion) as small as 0.001 µm.

The particle size distribution of total suspended particles (TSP) is trimodal including coarse particles (comminution mode), fine particles (accumulation mode) and ultrafine (nucleation mode) particles as illustrated in Figure 3-3. Over time some particles can increase in size in the air when colliding with other particles, while other particles increase in contact with humidity (e.g. acidic particles containing sulphate or nitrate). Also the fact that the particles tend to stick together (coagulation); the smaller ones covering the larger ones because of surface charges, may somehow distort particle size measurements (Fubini et al. 1995, Ormstad and Løvik 2002). Fine and coarse particles may overlap in the intermodal region between 1-3 µm (Wilson and Suh, 1997).

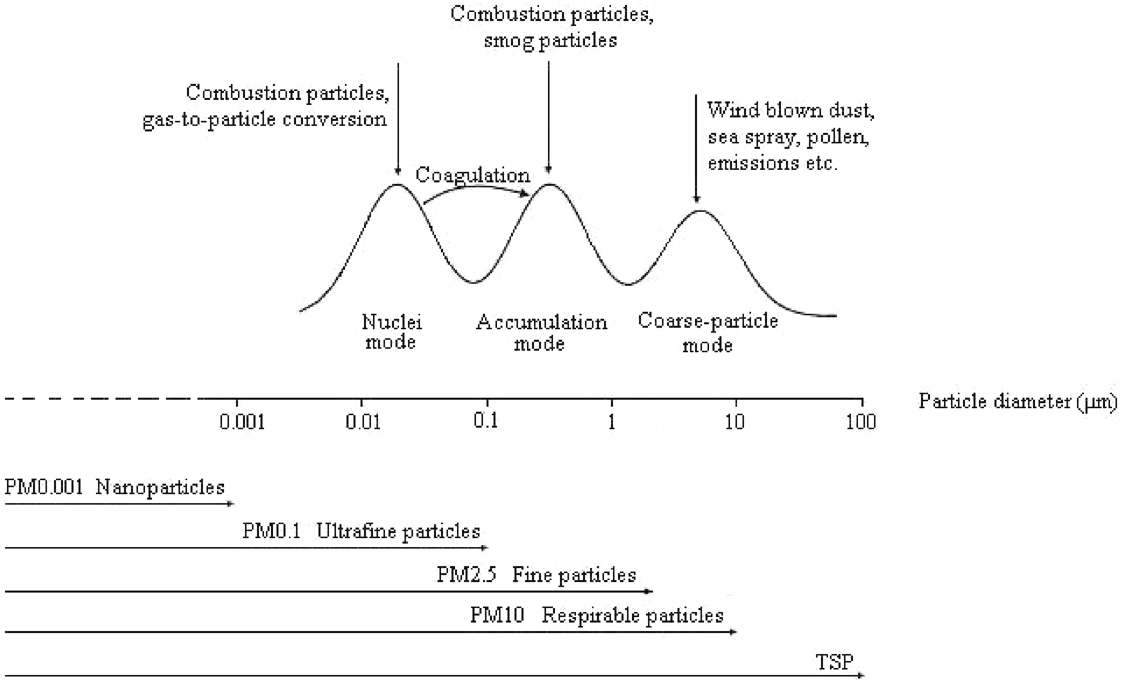


Figure 3-3. Particle size and origin (based on Wilson and Suh 1997 and Hinds 1999)

Particle size is not defined uniquely. In general, particle diameter implies a diameter of a sphere, but for non-spherical particles, there is no unique diameter. According to Matsuyama and Yamamoto (2004) a certain basis will be defined and on that basis some reading relating to particle size will be measured. Particle size is often defined by the aerodynamic diameter. Aerodynamic diameter is determined by the actual particle size, the particle density, and an aerodynamic shape factor. The aerodynamic diameter is a theoretical diameter to a spherical particle with density of 1 g/cm^3, which will have the same falling velocity in air as the real particle (Stein et al. 1969, Ormstad and Løvik 2002, DeCarlo et al. 2004). It is somewhat different from the geometric diameter; different densities give different aerodynamic diameters of particles which are alike geometrically. For comparison of deposition probabilities for particles with various sizes, shapes and densities, the aerodynamic diameter is used (Skaug, 2001).

Airborne particles are defined based on their size as particulate matter, PM (Skaug 2001, Schwarze et al. 2004):

- Total amount of airborne particles (TSP) is defined as the part of the dust which can be suspended in the air for a longer period of time as shown in Figure 2-4, and are particles with aerodynamic diameter < 75-100 µm. Particles above this size are named dust downfall because they will sediment relatively fast (i.e close to the source).The TSP was defined by the design of the high volume sampler (Wilson and Suh, 1997).
- PM10 represents the standard measure for respirable (thoracic) particles used to describe ambient air particulates. It is the mass of particles having a 50 % cut-off for particles with an aerodynamic diameter of 10 µm. Respirable dust is airborne particulate matter which can penetrate to the gas-exchange region in the lungs (alveoli). In occupational settings it is defined as PM4 which is the mass of particles present in the air having a 50 % cut-off for particles with an aerodynamic diameter of 4 µm. Particles larger than 4 µm impact onto the surface of the upper respiratory tract and cannot reach the lungs. It is usually meant PM10 when ambient airborne particles is referred to since this is the fraction for which limit values are set in connection to requirements for ambient air quality. Approximately 9-10 % of the

TSP is below 10 µm (Ormstad and Løvik 2002, Låg et al. 2004).

- The coarse part, PM10-2.5, contains mainly mechanically generated particles (Schwartz et al. 1996). According to Wilson and Suh (1997) “fine and coarse particles are separate classes of pollutants and should be measured separately in research”. Some say the coarse mode are particles > 1 µm (Wilson and Suh 1997, Claiborn et al. 2000).
- The fine mode PM2.5 is formed mainly by chemical reactions predominantly from combustion processes, nucleation, and condensation of gases and coagulation of smaller particles, and is the mass of particles having a 50 % cut-off for particles with an aerodynamic diameter of 2.5 µm. These particles are very numerous and represent large surface areas compared to mass. Fine particles produced by combustion processes are usually < 1 µm (Schwartz et al. 1996), and Claiborn et al. (2000) therefore propose that the cut point should be at 1 µm to avoid bias during wind blown dust storms.
- Ultrafine particles (PM0.1) are particles less than 0.1 µm. The number of particles and total surface area are large compared to mass. Ultrafine particles are mainly produced by combustion processes (Dybing et al. 2005), and the probability for production of ultrafine particles by road abrasion is very low (Låg et al. 2004). The atmospheric lifetime of these particles in high concentrations is very short according to Katsouyanni et al. (2005), but in concentrations observed in urban air it can be a few hours. This makes exposure assessment for them more demanding than for accumulation mode particles.
- Nanoparticles (PM0.001) are particles less than 0.001 µm = 1 nm, and they are generated mostly from combustion processes (road traffic). Some of these particles are likely to originate from the rubber in the tires (Dahl et al. 2006).

Humans inhale airborne particulate matter while breathing. An adult breathe about 10 000 liters of air every day, and the quality of the air is therefore important for the human health. Figure 3-4 illustrates inhalability of particles as a function of particle size. From this figure it can be seen that about 75 % of particles with size 10 µm can be inhaled, and about 90 % of particles with size 2.5 µm are inhalable. Particle size affects particle motion and the probabilities for physical phenomena such as coagulation, dispersion, sedimentation, and impaction onto surfaces.

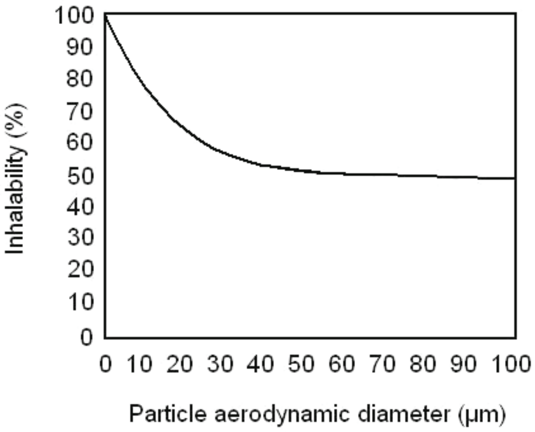


Figure 3-4: Inhalability as a function of particle size (Schwarze et al. 2004)

The size of the particles in the air is an important parameter with regard to health. Particle size affects the distribution and deposition in the lung, and is of importance in generating health effects (Ormstad and Løvik 2002, Norwegian Institute of Public Health 2005). Figure 3-2 shown earlier illustrates deposition of particles in the airways as a function of particle size. Daily mortality was more strongly associated with concentrations of PM2.5 than with concentrations of larger particles in six U.S. cities (Schwartz et al. 1996). This study was reanalyzed and supported by Klemm et al. (2000).

According to Katsouyanni et al. (2005), coarse particles are more likely to deposit in the bronchial region, while fine particles are more likely to be deposited in the periphery of the lung, in particular in the respiratory bronchioles and alveoli. Particles < 1 µm are able to reach the alveoli, and their deposition in the alveoli increases until they reach a size of 20 nm. These very small particles are likely to be particularly important for heart and blood vessel effects, as they may penetrate the lung epithelial membrane and enter into the blood vessels (Dybing et al. 2005). According to Dybing et al. (2005) the toxicity associated with pollutant particles is not limited to one size range. Recent evidence incriminates ultrafine particles for the induction of some health effects (especially blood and heart vessel disease). Other evidence suggests that larger particles may also have a serious health effect. Ormstad and Løvik (2002) report that negative health effects are more highly connected to the fine fraction than the coarse fraction, and that some data indicate a relationship between the amount of ultrafine particles and lung function, cardiovascular effects and mortality.

3.5.2 Particle shape

The particle shape is an important factor with regard to particle motion and deposition probabilities. It is often assumed that the particles are spherical, but ambient air particles are seldom so. Urban particles have large daily variations in the frequency of occurrence of different particle shapes (Stein et al. 1969).

Particle shape has recently been found to be more important than particle size for phagocytosis (Champion et al. 2007). Earlier it was believed that the ability of a macrophage to process a particle through phagocytosis was dependent solely on its size. Phagocytosis is a key part of the body's innate immune system, and depends on macrophages - the cell's clean-up crew. The macrophages find and frequently remove particles from the body.

Three different but related properties determine particle shape: form, roundness, and surface texture. Particle form is the overall shape of particles, typically defined in terms of the relative lengths of the longest, shortest, and intermediate axes. Particles can be cubical, spherical, elliptical, elongated, flat, tubular, platy and needle shaped (Dodds, 2003). The global shape, or form, of a particle is determined during formation, and is later affected by weathering. Weathering mechanisms are related to cleavage. Weathering changes roundness and roughness. Roundness or angularity is a measure of the large scale smoothness of particles, while surface texture defines the local roughness features (Barrett, 1980). The roughness of the particle is environmentally determined as specific surface textures are characteristic of specific environments (Dodds, 2003). Particle shape is illustrated in Figure 3-5. Fourier analysis is often used for defining particle shape since it captures the shape of a particle at many different scales.

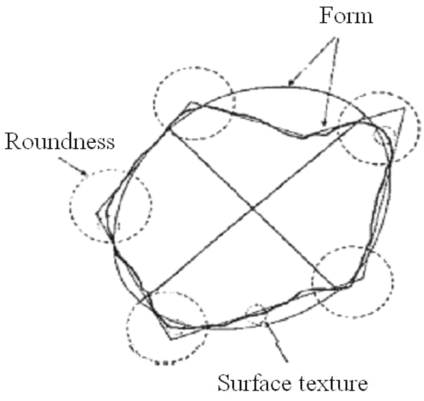


Figure 3-5. Particle shape (Bowman et al. 2000)

Freshly crushed mineral particles are more angular with a rougher surface texture and usually flakier and more elongated compared to particles which have been eroded for some considerable time. The roundness of rock particles normally increases through abrasion, and can change greatly without much effect on form (Barrett, 1980). The hardness, microcracks and mineral structure of the minerals will influence the particle shape after crushing. The fracture strength and the specific fracture energy of most minerals increase with the decrease of their size in the range of about 10 µm to 120 mm, however, under about 10 µm, the fracture strength decreases with decreasing particle size (Ryu and Saito, 1991). However, more and more energy is required to break particles into smaller units, which establishes a lower limit of 1 µm for coarse particles (mechanically generated) (Wilson and Suh, 1997).

Silica is one of the most common minerals on earth. It is a stable mineral with high mechanical strength and is resistant to chemical and mechanical weathering (Prestvik, 1992). Single silica particles have sharp and protruding edges, and the mineral has been recognized to inflict injury on human lungs in occupational settings after prolonged exposure. Silicosis is a disabling, non-reversible and sometimes fatal lung disease caused by overexposure to respirable crystalline silica.

Fibrous materials have been reported to be more active in pathogenicity than their non-fibrous counterparts (Fubini, 1997). Asbestos is a generic name given to the asbestiform fibrous varieties of six naturally occurring minerals in the serpentine (chrysotile) and amphibole groups (crocidolite, amosite, anthophyllite, tremolite and actinolite) which are made up of fiber bundles. These bundles are composed of extremely long and thin fibers that can be easily separated from one another. The aerodynamic properties of fibers are such that fibers as long as 50 µm or as big as 3 µm in diameter can reach the alveolar region and are considered respirable (Hinds, 1999). The fibers can reach the alveolus because they align themselves with the streamlines and "snake" their way through the narrow airways. Large asbestos fibers cannot be removed by normal clearance mechanisms once they have entered the alveolus, and the length of the fibers is therefore important in health risk assessments (Donaldson and Tran, 2002). Exposure to asbestos may lead to the lung disease asbestosis and cancer in the pleura (mesothelioma).

3.5.3 Particle composition

The ambient air will always contain particles, and the airborne PM in Norwegian cities can possess very different compositions and consist of different components. Epidemiological studies have demonstrated associations between effects on health and particles from a wide range of sources. There is no clear evidence that associations with effects on health are restricted to specific types of particles. Particle composition can be investigated in terms of inorganic/organic content, mineral composition or elemental composition. In this section mineral composition is in focus.

Urban dust samples generally show more health effects than rurally-collected dusts, with some evidence for a traffic-sourced contribution (Dybing et al. 2005). There is evidence that combustion particles are more important than particles of geologic origin (wind blown dust), and that emissions produced by motor vehicles appear to be most dangerous to human health based on several epidemiological studies (Katsouyanni et al. 2005). In urban air the fine fraction (< 2.5 µm) mainly consist of organic components like sulphur aerosols and soot particles, while the coarse fraction (2.5-10 µm) is predominantly composed of inorganic mineral matter such as silicates (Granum et al. 2001).

Various types of rock material and minerals can induce pulmonary diseases. Much attention has been and will still be paid to silica particles. In regulations for work environment the occupational exposure limits are set according to the total content in the airborne PM based on 8 hours exposure, and silica is here an important parameter. Threshold limit value (TLV) is set to 0.1 mg/m^3 for α-quartz (inhalable fraction) (Arbeidstilsynet, 2007), but the EU has proposed that this value should be reduced to 0.05 mg/m^3 (Myran, 2005, personal communication). It is a known fact that many miners get silicosis, and it may progress to disability and death even if the individuals are removed from further dust exposure (Furuseth and Myran, 1992). Silicosis may appear many years or shortly after exposure. According to Muhle and Mangelsdorf (2003), various national and international organizations have classified crystalline silica dust inhaled from occupational sources as a human carcinogen.

Mineral particles can be divided into crystalline and non-crystalline (amorphous) forms. In crystalline phases, the molecules make a three-dimensional repeating pattern forming the mineral structure (Prestvik, 1992). Amorphous minerals have no such pattern; the molecules are arranged randomly. Crystallinity seems to be an important factor to the toxicity of mineral particles (Øvrevik, 2004).

Several studies have been conducted on quartz. Fubini et al. (1995) studied the effect of grinding on different types of quartz. Freshly ground silica has shown a higher degree of toxicity ascribed to the reactivity on newly created surfaces. Donaldson and Borm (1998) and Donaldson and Tran (2002) also found a difference in the response to natural or composed dust with significantly more toxicity measured in rats exposed to artificially composed dust. According to Hetland et al. (2000), Muhle and Mangelsdorf (2003) and Øvrevik (2004) crystalline particles seem to be more potent in inflammatory reactions than amorphous (non-crystalline) particles with identical chemical composition (i.e. amorphous and crystalline quartz). It was found that genotoxic effects only appeared after exposure to crystalline but not amorphous silica, despite a high degree of inflammation cell response to both types of silica.

It is currently not possible to determine whether quartz is a primary carcinogen or whether it acts indirectly, e.g. by indirect pathways like reactive oxygen species (Muhle and Mangelsdorf, 2003). When silica is heated, surface radicals are healed and disappear, while silanols are condensed into siloxanes and the hydrophilic surface is progressively converted into a relatively hydrophobic one. Etching may attack the silica framework, and the chemicals destroy the external surface layers and progressively eliminate surface radicals. Etching also eliminates impurities which modulate silica toxicity. Donaldson and Borm (1998) propose that the hazard posed by quartz is not a constant entity, but one that may vary dramatically depending on the origin of the silica sample or its contact with other chemicals/minerals within its complex constitution. Also the fact that the quartz hazard depends on the species under test complicates the matter since rats, other rodents and humans all respond differently to quartz in terms of their tendency to mount an inflammatory response and a tumor response (Donaldson and Borm 1998, Donaldson and Tran 2002, Muhle and Mangelsdorf 2003). The same holds true for other particles.

Another important solid matter in this aspect is asbestosis. A connection between lung cancer and asbestosis has been established (Furuseth and Myran, 1992), and an increased mortality and death rate in lung cancer has been observed in the asbestos manufacturing industries. Asbestos has been classified as carcinogenic to humans by the International Agency for Research on Cancer (www.iarc.fr).

Little is known about the potential health effects of mineral particles other than asbestos and quartz. According to Låg et al. (2004) few epidemiological studies indicate that mineral particles from traffic and road abrasion cause harmful effects to health, but effects from mineral particles in general are well known in the work environment (occupational health). Especially exposure to quartz and asbestos has been investigated. Interaction of a mineral particle with living matter depends on its form (crystal structure, size, shape and micro morphology) and surface reactivity (surface arrangement or site liable to react at the liquid-solid or air-solid interface) (Fubini et al. 1995). However, Låg et al. (2004) and Øvrevik et al. (2005) studied in vitro the effect of nine different rock samples, and the results indicate that stone particles with a high content of plagioclase had a low inflammatory response and that none of the other minerals (potassium feldspar, quartz, pyroxene, chlorite, epidote, amphibole, mica, calcite and garnet) could be identified as responsible for a strong inflammatory response. The study concludes that analyzing mineral and element content alone is insufficient to predict stone particle bioactivity, and that biological testing is necessary. Airborne PM can also act as reactants or carriers to deliver toxicants to the deep lung (Dybing et al. 2005).

3.5.4 Substances attached to particles

The mineral particle itself needs not to be harmful to human health, but may act as a transporter of other substances into the body via inhalation. These substances attached on the mineral particles can be endotoxins, metals and other substances like polycyclic aromatic hydrocarbons (PAH) from combustion processes, pollen and fungi.

The chemical composition of the coarse PM is likely to vary from place to place and season to season in addition to climate and time of the day (Refsnes et al. 2004, Brunekreef and Forsberg 2005). Both the particle core, organic and inorganic substances on the particles, particle composition and biosolubility have shown to affect allergic sensitization (Nygaard et al. 2004). Specific chemicals present in PM such as metals and polycyclic aromatic hydrocarbons (PAH) and their derivates determine to a large extent the toxic potency of PM (de Kok et al. 2006).

Bacterial endotoxins are more often found on the coarse fraction of the ambient air particles compared to the fine fraction (Nygaard et al. 2004, Brunekreef and Forsberg 2005, Totlandsdal et al. 2007). The content of bacterial endotoxins has been recognized to produce inflammatory responses. Bacterial endotoxin is a lipopolysaccharide-protein complex (LPS) derived from the outer membrane of Gram-negative bacteria, and is known to cause symptoms involving airway inflammation, fever, and lung function decline in occupational settings (Heinrich et al. 2003). A study by Heinrich et al. (2003) found 10 times higher endotoxin content in the coarse fraction (PM10-2.5) compared to the fine fraction (PM2.5).

Airborne particles are also recognized as important carriers of metals, and in urban areas road traffic is an important source both for particles and certain metals (Sternbeck et al. 2002, de Kok et al. 2006). The vehicle itself (e.g. wear products from brake linings, tires, coach, and combustion products from fuel and oil) and the pavement wear contribute to the composition. Resuspension processes have a major effect on the presence of many metals and larger particles in air close to roads (Sternbeck et al. 2002). Transition metals have been shown to contribute to particle-induced reactive oxygen species (ROS) through the Fenton reaction (Hetland 2001, Øvrevik 2004).

3.5.5 Particle solubility

A specific characteristic of many mineral particles is the low solubility of the dust components involving potential accumulation in the lungs (Muhle and Mangelsdorf, 2003). However, some of the particles, or substances attached to the particles, may be soluble. Particle solubility was also discussed in section *3.2*.

Particles entering the respiratory tract will first come in contact with the mucus, and the fate of these particles will depend on their solubility. Therefore, as discussed earlier, it can be important to distinguish between: (1) soluble particles; (2) partly soluble particles; and (3) poorly soluble particles (Dybing et al. 2005, Schwarze et al. 2004). Soluble particle compounds will be dissolved and often metabolized in the lining fluid, and will eventually be transferred to the blood, undergoing further metabolism. In this way they have the potential to reach any organ and produce toxic effects far from their site of entry into the lungs. Within 1-2 days slower-dissolving and insoluble particles deposited in the airway wall will be mostly moved by action of ciliated cells with the mucus or by coughing to the throat, where they are swallowed. Slower-dissolving and insoluble particles deposited in the alveolar region will be taken up and digested by specialized defense cells (macrophages) in the alveoli within a few hours after deposition, but this particle removal may be impaired especially in children and elderly people with diseased lungs. Macrophages are also less able to take up ultrafine particles even in healthy lungs. The particles that are soluble will not contribute to dose as much as the non-soluble particles, but the exception is if the soluble particle releases compounds and elements that have some intrinsic toxicity, for example heavy metals (Granum et al. 2001, Donaldson and Tran 2002). In this case, dissolution may be a factor that contributes to toxicity. According to Ormstad and Løvik (2002) the boundary between solid and liquid is not clear when the particles are sufficiently small.

Particle biopersistence, solubility, and direct or indirect epithelial cell cytotoxicity might be key factors in the induction of either mutagenic events or target cell death. Biopersistence is a function of the potential of particles to dissolve or lose elements, break, or to be mechanically cleared from the lungs by macrophages (Donaldson and Tran, 2002).

3.5.6 Particle surface area and number of particles

Fine particles have a much higher total surface area compared to coarser particles at a given dose in mass. Biological effects of particles are thought to be dependent on how much of the particles are in direct contact with the human cells (Hetland et al. 2001, Låg et al. 2004).

Some particles are smooth and the geometric surface area can be calculated from the size distribution. With indented particles the true exposed surface may be evaluated only by means of physical adsorption of gases (BET). Findings indicate that toxic effects of particles have a higher correlation with the particle number or surface area concentration than with the mass concentration (Granum et al. 2000, Katsouyanni et al. 2005).

Particle exposure has traditionally been monitored as mass concentration of PM10. However, the mass concentration is strongly influenced by the large particles. Therefore mass concentration is a poor measure for characterizing the fine, and possibly more biologically potent particles (Nygaard et al. 2004). Studies in Sweden show that 70-80 % of the total particle number concentration in a large city is caused by local sources compared to only 30-40 % for PM10 (mass concentration) (Johansson et al. 2007). Johansson et al. (2007) also found that particle number concentration is highly correlated to vehicle exhaust particles.

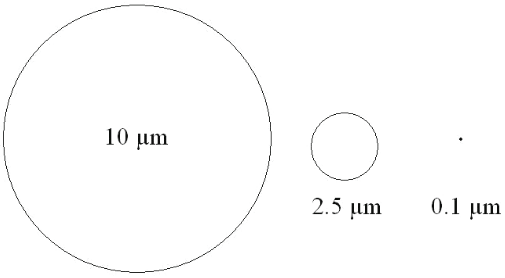


Figure 3-6. Ratio between a particle with diameter 0.1 µm (e.g. a diesel particle), 2.5 µm and 10 µm (e.g. mineral particle)

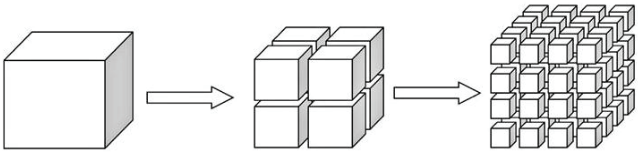


Figure 3-7. Illustration of surface area and number of particles with same total mass

Figure 3-6 illustrates the ratio between a coarse, fine and ultrafine particle, and Table 3-1 shows relative surface area and relative number of particles for a given mass of spherical particles. There is an enormous difference in the total number of particles (1 mill ultrafine compared to 1 coarse for the same mass), but also the relative surface area is much larger for small particles. This is illustrated in Figure 3-7. On the surface, especially for particles with large specific surface area such as carbon particles from combustion processes, more or less soluble components e.g. metals, organic compounds (PAH, nitrogen and sulphur compounds), allergic agents, gases, fungi spores and endotoxins are usually attached (Schwarze et al. 2004, Norwegian Institute of Public Health 2005). These compounds can take part in the triggering effects, but the available knowledge on these processes is insufficient. The human cells will not recognize what is inside an insoluble particle, but only react with the molecules according to their structure at the particle surface. Donaldson and Borm (1998) and Fubini et al. (1995) have studied impurities on silica particles, especially iron and aluminum which is the most commonly found metal ion contaminants on these specimens. These impurities can enhance or decrease the intensity of pathogenic responses, and the reactive surface can be inactivated by various common minerals e.g. aluminum salts.

Table 3-1. Relative surface area and number of particles for a given mass of spherical particles with different diameter (Ormstad and Løvik, 2002)

Particle diameter	Mass	Relative surface area	Relative number
0.1	1	100	1 000 000
1.0	1	10	1 000
2.5	1	4	64
10.0	1	1	1

Aerosols have integral properties that depend upon the concentration and size distribution of the particles. In Figure 3-8 some of the important integral properties are shown:

- Number concentration, which is the total number of airborne particles per unit volume of air, without distinction as to their sizes.
- Surface concentration, which is the total external surface area of all the particles in the aerosol, may be of interest when surface catalysis or gas adsorption processes are of concern. Aerosol surface is one factor affecting light-scatter and atmospheric-visibility reductions.
- Mass concentration, which is the total mass of all the particles in the aerosol, is frequently of interest. The mass of a particle is the product of its volume and density. If all particles have the same density, the total mass concentration is simply the volume concentration times the density. In some cases, such as respirable, thoracic, and inhalable dust sampling, the parameter of interest is the mass concentration over a restricted range of particle size.

According to Nygaard et al. (2004) the particle number concentration mainly reflects the amount of ultrafine particles (< 0.1 µm), the surface area best reflects the particles between 0.1-1 µm, whereas the particle mass reflects particles > 0.1 µm.

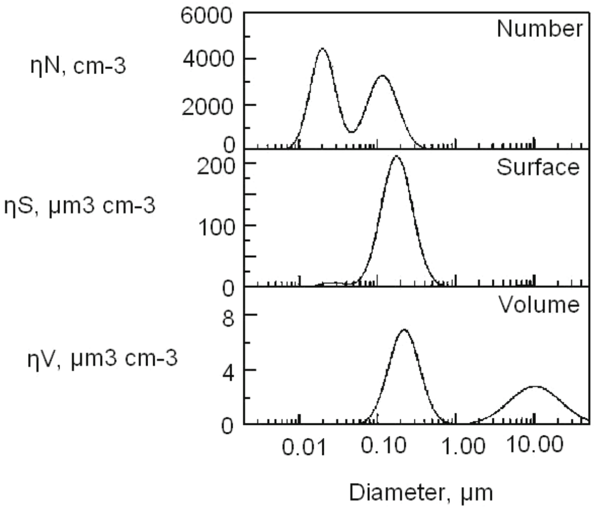


Figure 3-8. Typical urban aerosol number, surface and volume distributions (Seinfeld and Pandis, 2006)

Small particles have a larger total surface area compared to the same volume of larger particles. This means that more substances can adhere themselves to the particles and can be transported into the human body. A high volume of particles inside macrophages, blockading further phagocytosis and allowing particles to interact with the epithelium, was thought to be the mechanism of overload (Oberdörster et al. 1994, Donaldson and Tran 2002), but more recently, work has been conducted to emphasize the role of particle surface area in the initiation of overload. By in vivo experiments on rats one can confirm this by testing same mass deposition of different particulate substances in the lungs with respect to adjustment to same surface area of the particles deposited (Donaldson and Tran, 2002). A single response to surface area was seen, while the inflammatory response was different for the substances. Donaldson and Tran (2002) conclude therefore, based on experiments given above, that a mass burden of ultrafine particles is more likely to cause overload than the same mass burden of larger particles of the same material. The lower the particle size, the lower the mass of particles needed to initiate overload. Cardiovascular causes and lung cancer seemed to have threshold effects, while chronic obstructive pulmonary disorder (COPD) appeared to have linear effects (Næss et al. 2006).

Studies of mineral particles have demonstrated that the toxic and carcinogenic effects are, in some cases, related to the surface area of inhaled particles and their surface activity (Oberdorster et al. 1994, Fubini 1997). Particle surface characteristics are considered to be key factors in the generation of free radicals and reactive oxygen species formation and in the development of fibrosis and cancer by quartz (crystalline silica) (Fubini, 1997).

Particles are capable of generating or inducing generation of free radicals in humans, thereby leading to an increase in oxidative stress (Sørensen et al. 2003). Oxidative stress may damage cells and important molecules, and is caused by chemical reactions in the body involving the production of harmful oxygen radical molecules (Donaldson and Tran 2002, Dybing et al. 2005). Reactive quartz is known for its silanol (SiOH) groups (Øvrevik et al. 2005). Donaldson and Borm (1998) and Øvrevik et al. (2005) emphasize the ability of quartz to generate free radicals and causing oxidative stress, and the fact that this could be modified by a range of substances that affect the quartz surface. Transition metals have been shown to contribute to this reactive oxygen species generation through the Fenton reaction, thus enhancing particle toxicity (Øvrevik et al. 2005). In an experiment on human epithelial lung cells, Hetland et al. (2000) report that the most potent particle samples exhibited a relatively high content of transition metals, such as iron. In this study the size distribution on different materials was the same, but the mineral content and metal composition differed. In the same experiment it was concluded that exposure to identical masses or surface areas resulted in the same order of potency among the different particle samples. Donaldson and Borm (1998) argue that it is only the surface layer, a molecule or so thick, that interacts with lung cells and fluids. A change in the chemical makeup of this layer could alter the reactivity of the particle, but might impact only minimally on the bulk chemistry of the quartz. Experiments with external agents not in the dust have shown that such agents may coat the surface of quartz and decrease its toxicity (Donaldson and Borm, 1998). Metals need only to be present in trace amounts to generate inflammation via receptor-mediated cell activation or via oxidative stress pathways (Donaldson and Tran, 2002).

4. Experimental work - Description of methods used in the study

In this chapter sampling and specimen preparation, methods used for experimental dust generation, particle characterization and asphalt rutting studies are described. Some of the information can also be found in the papers in Part two of the thesis.

4.1 Sampling and specimen preparation

The different papers include the following samples:

- Paper I describes a study on particles sampled in field (2005) from dust downfall in Trondheim, Norway.
- Paper II describes particles sampled in field (2005 and 2006) from dust downfall in Trondheim, Norway, and particles generated from Tröger test on asphalt cores taken

from the pavement at the dust downfall sampling spot in Trondheim (Elgeseter street, SMA 11).

- Paper III evaluates particles generated in laboratory (Pavement testing machine, Tröger, Prall, Los Angeles mill, Nordic ball mill, and micro-Deval mill) from asphalt and aggregate materials. The asphalt material (SMA 11) was produced in laboratory for the Pavement testing machine, and the aggregate testing was conducted on the same rock material as was used in the asphalt.
- Paper IV deals with particles sampled in laboratory (Pavement testing machine and Tröger). For the Pavement testing machine asphalt material was produced in laboratory (SMA 11). For the Tröger test asphalt cores samples were taken from a test section right outside Trondheim (Trolla) with pavement types AC and SMA with maximum aggregate size of 6, 8 and 11 mm.
- Paper V also deals with particles sampled in laboratory (Pavement testing machine). The asphalt material was produced in laboratory (in this case SMA 8).

4.1.1 Field sampling

The sampling in the field for Papers I and II was performed according to NS 4852:1981 (Norwegian Standards Association, 1981) using standardized particulate fallout collectors as shown in Figure 4-1. Dust downfall includes particles which are large enough to sediment because of specific gravity, particles which are deposited on the inside of the sampler walls and particles which are brought down with precipitation (Norwegian Standards Association, 1981). The exposure time is one month (30±2 days), and the result is expressed as amount of dust downfall per unit of area per 30 days. The particulate fallout collectors used for sampling is made of high density polyethylene with a diameter of the collecting surface of 200 mm and collector height of 400 mm (ISO standard).

Samples of dust downfall were collected in Holtermanns vei 1 close to the E6 main road in Trondheim, Norway. The samples were collected on a high building façade about 30 m in horizontal distance from the road. The collectors were mounted on banisters and were directed towards the road on every second floor starting from the 3rd floor (which was 7 m above ground level) and up to the 13th floor (which was 37 m above ground level), with two parallel collectors at each height.

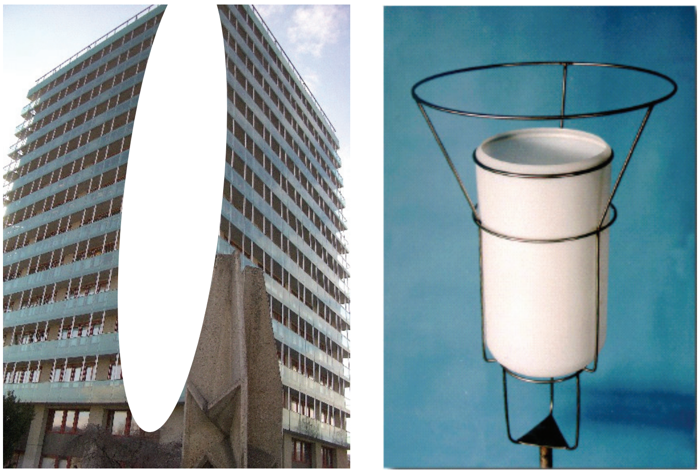


Figure 4-1. Sampling of dust downfall (Photos by Brynhild Snilsberg)

4.1.2 Laboratory sampling

A wet vacuum cleaner (Kärcher NT 361 Eco) with de-ionized and distilled water was used for sampling of particles from SMA 11 in the Tröger and in the Pavement testing machine (PTM). Sampling from the Tröger equipment is shown in Figure 4-5. Samples of dust from the PTM were collected during driving (60 km/h) with the inlet mounted behind one of the tires. The PTM is shown in Figure 4-3.

A dry cyclone (Michelin Dyson DC 19) was used for sampling from SMA 8 in the Pavement testing machine (PTM). It collects particles down to 0.1 µm. Sampling was performed at driving speeds 20, 30, 40, 50, 60 and 70 km/h.

Samples of dust from Prall are collected in the cooling water which flushes through the chamber while running the experiment as shown in Figure 4-6. This sludge is collected and dried.

Fine material produced by milling in Los Angeles mill, Nordic ball mill, and micro-Deval mill was sieved to obtain material less than 63 µm in diameter.

4.1.3 Specimen preparation

Dust downfall samples from 2005 were filtered through an ash free Millipore filter (filter mesh 0.8 µm) and dried in an exsiccator with silica-gel as shown in Figure 4-2. Equipment used for analyzing water-insoluble matter includes sedimentation columns (with 6 filter holders), vacuum pump, funnel, filter holder and suction bulb of type Millipore. Dust downfall samples from 2006 were not filtrated; they were only dried in a cabinet without fan and temperature around 50 ºC.

The other dust samples containing water were dried in cabinets without fan and temperature around 50 ºC. This includes mixture of water and particles collected in the wet vacuum cleaner from PTM and Tröger, the sludge from Prall and samples from wet grinding in the mills.

Figure 4-2. Filtration column and exsiccator (Photos by Brynhild Snilsberg)

Asphalt cores tested in Tröger where conditioned in room temperature, while asphalt cores tested in Prall where conditioned in water at 5 ºC.

Asphalt plates for the PTM were made in the laboratory at VTI under controlled conditions, and these plates were glued to the circular track.

4.2 Methods for experimental dust generation

Methods used for experimental dust generation in laboratory are described in this section. The methods include the Pavement testing machine, Tröger, Prall, Los Angeles mill, Nordic ball mill and micro-Deval mill. These methods are also described in Papers III and IV.

4.2.1 Pavement testing machine (PTM)

The PTM at the Swedish National Road and Transport Research Institute (VTI) was used to simulate pavement wear. The method is described by EN 13863-4:2004 (CEN, 2004 B). The machine has an electrically powered rotating axle with four wheels and adjustable rotating speed (Figure 4-3). The axle system is tuned to move sideways. The diameter of the test ring is ca. 6 m, and the machine is located in a closed room with controlled ventilation. In this machine particles from wear of pavement and tires can be studied separately, without interference of particles from exhaust and other sources (Gustafsson et al. 2005). The machine also accelerates the study, and pavement types, car tires, friction materials, driving speeds and temperatures can be varied. Studies at VTI have shown very good correlation between the studded tire wear on the road and in the machine (Wågberg et al. 2003). Jacobson (1995) reported a correlation factor of R^2=0.96-0.98.

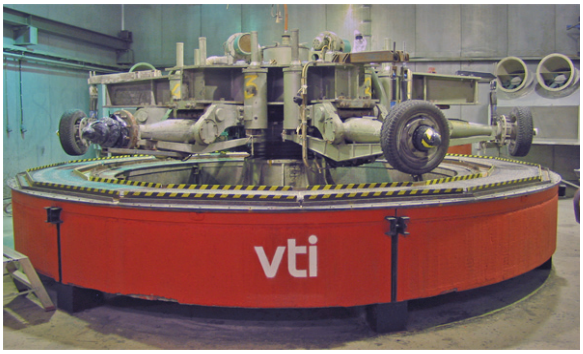


Figure 4-3. Pavement testing machine (Photo by VTI)

Tire types used during testing were studded tires (Nokian Hakkapeliitta 4), non-studded winter tires (Nokian Hakkapeliitta RSi) and summer tires (Nokian NRHi Ecosport). The different tires are shown in Figure 4-4. The rubber in the winter tires is designed to stay soft at low temperatures, while the rubber in summer tires is harder (Gustafsson et al., 2008 B).

Figure 4-4. Studded tire, non-studded winter tire and summer tire used in the study (www.nokiantires.com)

4.2.2 Tröger

Tröger is described by EN 1871:2000 Annex K (CEN, 2000) and Statens vegvesen (2005a). This method was originally designed for testing abrasion properties of road marking materials, but has also been used to determine the resistance of asphalt pavements to wear caused by studded tires (Hveding et al. 1986, Skoglund and Uthus 1994, Horvli 2004). The apparatus is shown in Figure 4-5.

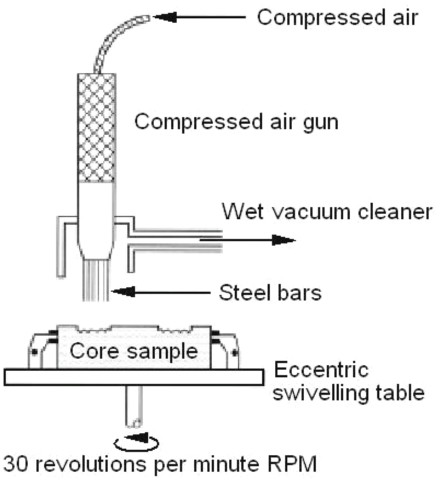


Figure 4-5. Tröger apparatus (adopted from Statens vegvesen, 2005a)

The dry and cooled (4 °C) pavement sample (height 30 mm and diameter 100 mm) is mounted on an eccentric rotating table (30 rotations per minute). Steel needles (52 needles, each 2 mm in diameter) hammer the sample driven by a compressed air gun (5 bar), simulating the hammering and scratching influence of the tire studs (Lerfald, 2007). Particles torn loose from the sample can be collected by a modified wet vacuum cleaner (with de-ionized and distilled water). The dust produced in such a way can then be dried and analyzed. Studies at VTI have shown a correlation between the studded tire wear on the road and Tröger test of R^2=0.68-0.99 (Jacobson, 1995). A disadvantage with the method is poor reproducibility (Skoglund and Uthus, 1994).

4.2.3 Prall

The Prall method is described by EN 12697-16:2004 (CEN, 2004 A). It was first developed to determine wear resistance of asphalt concrete, but has also been used for other asphalt mixtures. The apparatus is shown in Figure 4-6. The pavement sample (height 30 mm and diameter 100 mm, conditioned in water at 4-5ºC) is placed in a test chamber with 40 steel balls (12 mm in diameter). The steel balls hammer the sample driven by a stay rod which moves with 950 rotations per minute, and cooling water is flushed through the chamber (2 liters/minute). Particles torn loose from the sample are washed out by the cooling water into a collector. The dust produced can then be dried and analyzed. Studies at VTI have shown a correlation between the studded tire wear on the road and Prall test of R^2=0.89-0.96 (Jacobson 1995, Raitanen 2005).

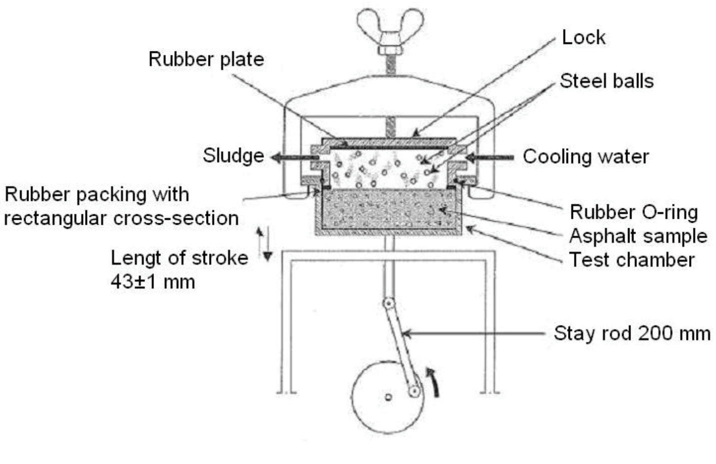


Figure 4-6. Prall apparatus (adopted from EN 12697-16:2004 (CEN, 2004 A))

4.2.4 Los Angeles mill

The Los Angeles method is described by EN 1097-2:1998 (CEN, 1998 A), and determines the resistance to fragmentation of an aggregate. The apparatus is shown in Figure 4-7. The test was originally developed in USA; it was adopted as an ASTM method in 1938. The CEN version of the test method is similar to the ASTM method. The most significant difference between the CEN and ASTM methods is that in the CEN method masses and dimensions are specified in metric units, whereas in the ASTM method they are specified in U.S. units.

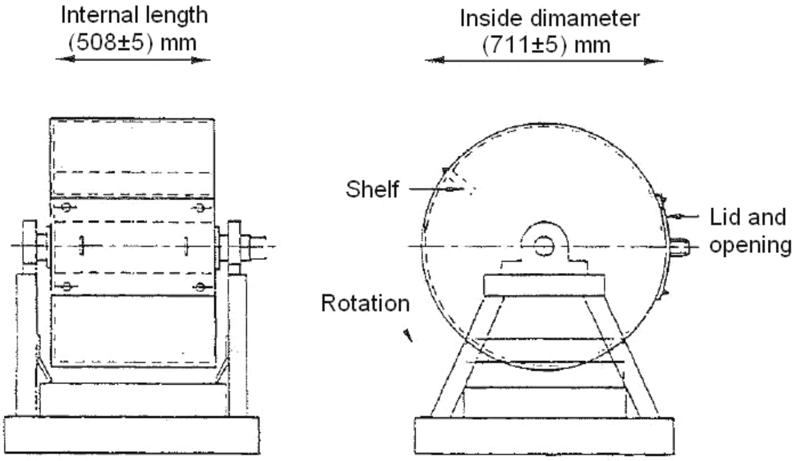


Figure 4-7. Los Angeles mill (adopted from EN 1097-2:1998 (CEN, 1998 A))

The standard fraction tested is 5 kg (65 % 10.0-12.5 mm and 35 % 12.5-14.0 mm) (Statens vegvesen, 2005a). The test is run dry with 11 steel balls (45-49 mm in diameter) for 500 rotations with 31-33 RPM. Inside the mill a shelf (width 90 mm and thickness 25 mm) is installed which lifts both the aggregate and the steel balls during rotation. This causes fragmentation of the aggregate when it drops from the shelf together with the steel balls. The weight loss, defined by amount of material below 1.6 mm which is determined by sieving after testing, relates to the resistance to fragmentation for the material tested.

4.2.5 Nordic ball mill

The Nordic ball mill test determines the resistance to wear by abrasion from studded tires, and is described by EN 1097-9:1998 (CEN, 1998 B). The apparatus is shown in

Figure 4-8. Inside the drum there are three ribs which will turn, lift and drop the aggregate when rotating. This results in a small influence of fragmentation in addition to the dominant abrasive effect. The test was originally developed in Sweden by Pete Höbeda.

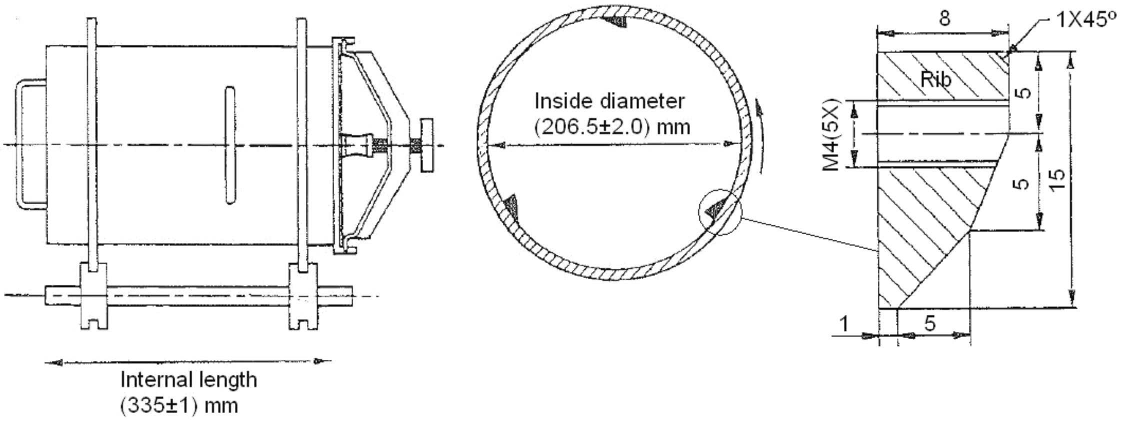


Figure 4-8. Nordic ball mill (adopted from EN 1097-9:1998 (CEN, 1998 B))

The standard test is performed dry or wet with aggregate fraction 11.2-16.0 mm. The aggregate is drummed together with steel balls (15 mm diameter, 7000 gram) with or without water (2 liters) for 5400±10 rotations at 90±3 RPM (about one hour). The weight loss (material below 2 mm) relates to the studded tire abrasion resistance.

According to Horvli and Værnes (2006) the Nordic ball mill gives a ranking of rock materials with regard to the resistance to wear by studded tires. Studies at VTI have shown a correlation between the studded tire wear on the road and the wet Nordic ball mill test of R^2=0.93-0.94 (Jacobson, 1995).

4.2.6 Micro-Deval mill

The micro-Deval test is described by EN 1097-1:1996 (CEN, 1996), and determines the resistance to wear of a sample of aggregate during rolling. The apparatus is shown in Figure 4-9. The test is usually performed wet (reference method), but can also be performed under dry conditions. The test method was originally developed in France, and as opposed to the Los Angeles and Nordic ball mill, it is close to a pure abrasive method.

Steel balls (10 mm in diameter, 500 gram) and aggregate fraction 10-14 mm (2 kg) are milled with or without water (2.5 liters) for 12 000 revolutions (100 RPM). It is possible to run four samples at the same time.

The weight loss (material below 1.6 mm) determines the micro-Deval coefficient (M_{DE}).

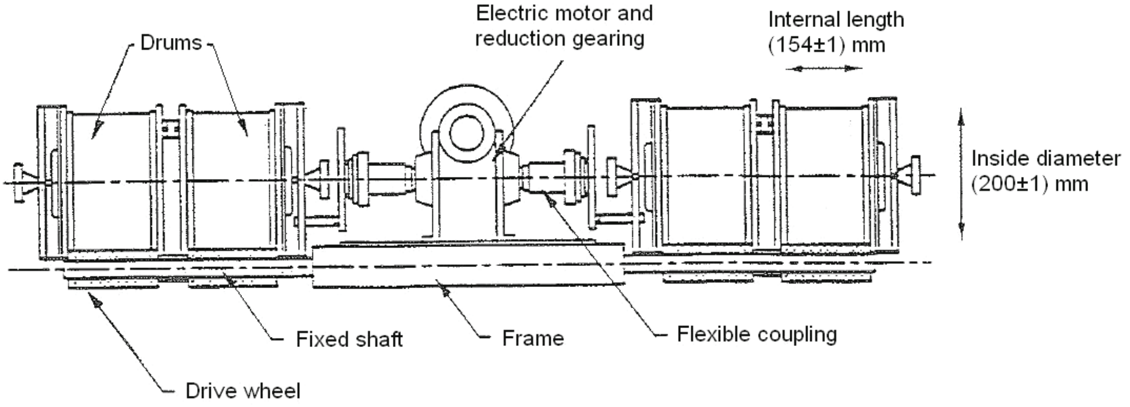


Figure 4-9. Micro-Deval mill (adopted from EN 1097-1:1996 (CEN, 1996))

4.3 Methods for characterization of dust

Particle characterization was conducted at NTNU using gravimetric analysis, annealing furnace for determination of % inorganic material, X-ray diffraction (XRD) to find the mineralogical composition, inductively coupled plasma mass spectroscopy (ICP-MS) for determining elemental composition, Brunauer-Emmett-Teller (BET) to measure specific surface area, laser diffraction to get particle size distributions by Coulter LS230, image analysis to get the particle shape (roundness) by Pharma Vision 830, density measurement with Accupyc 1330, and scanning electron microscopy (SEM) with Zeiss Ultra 55 Limited Edition for particle image analysis.

4.3.1 Gravimetric analysis

Gravimetric analysis is a method used for quantitative determination of the mass of a sample. The samples in this study were either filtrated and dried or only dried before weighing. Gravimetric analysis of the dust samples were performed with a Mettler AT261 Delta Range with accuracy 1/100 mg. The apparatus is shown in Figure 4-10.

Figure 4-10. Mettler AT261 Delta (Photo by Brynhild Snilsberg)

4.3.2 Particle size distribution

Particle size distribution was determined with laser diffraction (a light scattering system) using Coulter LS 230 Laser Diffraction Particle Sizer. The apparatus is shown in Figure 4-11. This is an indirect method where the particles in the sample are illuminated with a monochromatic laser beam, and the light is diffracted when the laser beam passes through a dispersion of particles. The angle of diffraction increases as particle size decreases. The distribution pattern is characteristic for the particle size, and by measuring this, the particle size can be calculated. Coulter LS 230 measures particle size distribution in the range 0.04-2000 µm (in fluid).

Figure 4-11. Coulter LS 230 Laser Diffraction Sizer (Photo by Brynhild Snilsberg)

The samples were put in ultrasonic bath with a dispersing agent (Calgon) before analysis to minimize problems with agglomeration. Agglomeration means a collection of particles that are held together by both weak and strong forces, including van der Waals and electrostatic forces, and sintered bonds. The analysis was run repeatedly to further remove the agglomeration.

A disadvantage with the method is that the light scattering may be sensitive to small changes in refractive index, scattering angle, particle size or shape, which can lead to confusing or misleading results (Hinds, 1999).

Many different techniques are used to determine size of particles and the particle shape affects each technique differently. The differences are often accentuated at the tails of the distribution; the D10 and D90 more than at the median D50 (Bumiller et al. 2002). Consider the example of needle shaped particles (e.g. asbestos) measured by laser diffraction. Depending on both the aspect ratio and the size of the longest dimension, the fibers will often tumble through the laser beam at random orientations to the light source. At times the laser sees the maximum projected area, at other times the minimum projected area (essentially a sphere with a diameter equal to the thickness of the needle) and every orientation in-between. Therefore the distribution recorded by this technique could be a broader distribution than results measured by sieves, microscopy or other techniques.

4.3.3 Particle shape - Image analysis

Image analysis to get the particle shape (roundness) was performed using Pharma Vision 830 (5-2000 µm). The apparatus is shown in Figure 4-12. Roundness is a measure of the length/width relationship, with values between 0-1. A perfect circle has roundness 1.0, while a needle shaped object has roundness close to 0. For all samples 10 000 particles were characterized which give a good statistical result for the bulk sample.

Figure 4-12. Pharma Vision 830 (right) with preparation device (left) (Photo by Brynhild Snilsberg)

The instrument is used for characterization of particle size and particle shape in the range 5-2000 µm, and is based on standard microscopy and automated image processing techniques. The sample is dispersed on a microscope slide by using the sample preparation device. The preparation device uses compressed air to disperse the sample and to break up agglomerates by forming a particle cloud in a sealed chamber. The cloud settles on the microscope slide in a few seconds, and the whole procedure takes only a few minutes to perform. The sample is placed on a sample tray under a video camera. A linear actuator moves the camera across the sample tray and the camera takes digitized video images. These are segmented into individual particles, whereupon the software makes direct measurements of physical properties such as length, width, volume, roundness, and convexity. Results are presented as morphological distribution on the screen. The system can perform analysis of 20 000 particles in less than 15 minutes.

4.3.4 Specific surface area

The surface area is determined by the size and shape of the particle. Small particles exhibit specific surface area much higher than larger particles (Ormstad and Løvik 2002, Hetland et al. 2001), as described in section 3.5.6. Specific surface area was measured by physical adsorption of gas molecules on the particles surface according to the BET theory by using FlowSorb II (DIN 66131). The apparatus is shown in Figure 4-13.

Figure 4-13. FlowSorb II (Photo by Brynhild Snilsberg)

The surface area of granulated and powdered solids or porous materials is measured by determining the quantity of a gas that adsorbs as a single layer of molecules, a so-called monomolecular layer, on a sample. This adsorption is done at or near the boiling point of the adsorbate gas. Under this condition, the area covered by each gas molecule is known within relatively narrow limits. The area of the sample is thus calculable directly from the number of adsorbed molecules, which is derived from the gas quantity at the prescribed conditions, and the area occupied by each. This method measures the surface of fine structures and deep texture on the particles, and is expressed as surface area divided by mass (m^2/g).

BET consists of the initials of the family names of Stephen Brunauer, Paul Hugh Emmet and Edward Teller who published an article about the BET theory in 1938 (Brunauer et al, 1938). The Brunauer-Emmett-Teller (BET) was used to measure specific surface area in the range 0-100 m^2 with Flowsorb II 2300 using a gas mixture of 70 % He and 30 % N.

4.3.5 Analysis of composition

Inorganic/organic content - Annealing furnace

Annealing furnace was used for determination of % inorganic material. The apparatus is shown in Figure 4-14.

Figure 4-14. Annealing furnace (Photo by Brynhild Snilsberg)

Annealing (at 710 °C) will burn off the ash free filter and the organic fraction (ignition loss). The remaining material is mainly inorganic matter. However, the organic matter is not ash free, and the remaining material can be influenced by the organic fraction if it constitutes a large part of the total dust downfall. Another factor is that some rock types and minerals may lose mass during annealing, i.e. calcareous rocks will produce CO_2 during annealing which will lead to loss of mass.

Mineral composition - X-ray diffraction (XRD)

X-ray powder diffraction (XRD) was used to find the mineralogical composition of the samples. The equipment used was Philips PW 1830. The apparatus is shown in Figure 4-15.

Figure 4-15. Phillips PW 1830 (Photo by Brynhild Snilsberg)

XRD is a qualitative and semi-quantitative method. The method is based on dissimilar diffraction of the X-ray beam because of different lattice spacing for different minerals and was formulated by Bragg and Bragg in 1912 (Braggs law) (Skoog et al. 1998). About 95 % of all solid materials can be described as crystalline. When X-rays interact with a crystalline substance, a diffraction pattern is obtained. When the diffraction pattern is recorded, it shows concentric rings of scattering peaks corresponding to the various lattice spacing in the crystal lattice. The positions and the intensities of the peaks are used for identifying the underlying structure (or phase) of the material. The X-ray diffraction pattern of a pure substance is like a fingerprint of the substance. The powder diffraction method is thus ideally suited for characterization and identification of polycrystalline phases. The sample is in a powdery form (the crystalline domains are randomly oriented in the sample) consisting of fine grains of single crystalline material to be studied.

A disadvantage of XRD is that it is limited to crystalline materials (since amorphous materials do not diffract). It is more of a qualitative technique and it does not provide accurate information about quantities. The concentration estimate may be in error by a factor of two or more (Skoog et al, 1998). Inversion of the measured intensities to find the structure is more difficult and less reliable.

Elemental composition - Inductively coupled plasma mass spectroscopy (ICP-MS)

Inductively coupled plasma mass spectroscopy (ICP-MS) was used for determining elemental composition of the samples using PerkinElmer SCIEX ELAN DRC II. The apparatus is shown in Figure 4-16.

Figure 4-16. PerkinElmer SCIEX ELAN DRC II (Photo by Brynhild Snilsberg)

ICP-MS is based on coupling together inductively coupled plasma as a method of producing ions (ionization) with a mass spectrometer as a method of separating and detecting the ions. The instrument is capable of detecting substances at concentrations below one part in 10^{12}. It determines the composition by counting the number of ions at a certain mass of the element. The ICP-MS instrument measures most of the elements in the periodic table. It can determine accurately how much of a specific element is concentrated in the material analyzed. Standards are analyzed to generate a calibration curve and the signals from unknown samples are compared against the calibration curve to determine the concentration of each element in the sample.

4.3.6 Density measurement

Density measurements were performed using AccuPyc 1330. The apparatus is shown in Figure 4-17. This is a helium pycnometer which measures absolute density 0-20 g/cm^3. A pycnometer is a vessel with a precisely known volume. Although a pycnometer is used to determine density (ρ) or specific gravity, it measures volume (V); a balance is used to determine mass (m) (Webb, 2001). Density is calculated by $\rho = m/V$.

Figure 4-17. AccuPyc 1330 (Photo by Brynhild Snilsberg)

Measurements of volume of materials are difficult because the material contains surface irregularities, small fractures, fissures, and pores that both communicate with the surface and that are isolated within the structure. The AccuPyc 1330 works by measuring the amount of displaced gas. The pressures observed upon filling the sample chamber and then discharging it into a second empty chamber allow computation of the sample solid phase volume. Gas molecules rapidly fill the tiniest pores of the sample; only the truly solid phase of the sample displaces the gas. The instrument achieves high repeatability, and automatically purges water and volatiles from the sample and then repeats the analysis until successive measurements converge upon a consistent result.

Density, volume, and porosity are physical characteristics of solid materials that can be determined by a variety of experimental techniques. However, the value obtained is very likely to be dependent on the technique. This is largely because of the way the measurement technique treats volume with respect to the degree of exclusion of void spaces associated with the sample material. Various definitions of density and volume are used to differentiate these values in terms of what void volumes are included with the overall volume determination. An analyst must understand the type of volume or density sought in order to select the appropriate measurement technique (Webb, 2001).

4.3.7 Scanning electron microscopy (SEM)

The resolution for optical microscopes is limited by the wave nature of the light, while electrons which are accelerated through a field will result in shorter wavelength and much higher resolution for the electron microscopes. Scanning electron microscopy (SEM) is a useful method for characterization of heterogeneous materials in nano- and micrometer scale. It has most frequently been used to obtain topographic images, but has much more applicability. In the SEM a thin electron beam is focused and can be stationary or scan a raster over the material which is being examined. The electron beam will give rise to several different signals which give information about the sample (morphology, topography, chemical composition, crystallography, atomic number etc.) (Hjelen, 1989). The signals that can be detected in a SEM and the resolution are illustrated in Figure 4-18. The different signals are more closely described in the next sections.

In SEM the primary electron beam (energy ranging from a few hundred eV to 100 keV) is focused by one or two condenser lenses into a beam with a very fine focal spot sized 1 nm to 5 nm. The beam passes through pairs of scanning coils in the objective lens, which deflect the beam horizontally and vertically so that it scans a raster over a defined area of the sample surface. When the primary electron beam interacts with the sample, the electrons lose energy by repeated scattering and absorption within a teardrop-shaped volume of the sample (interaction volume), which extends from less than 100 nm to around 5 µm into the surface. The size of the interaction volume depends on the beam accelerating voltage, the atomic number and density of the sample. The energy exchange between the electron beam and the sample results in different signals which can be detected. Type of signals that are produced from interaction between the electron beam and the sample are secondary electrons, backscattered electrons, X-rays and photons which can be used to investigate several properties of the sample (Hjelen 1989, Goldstein et al. 2003).

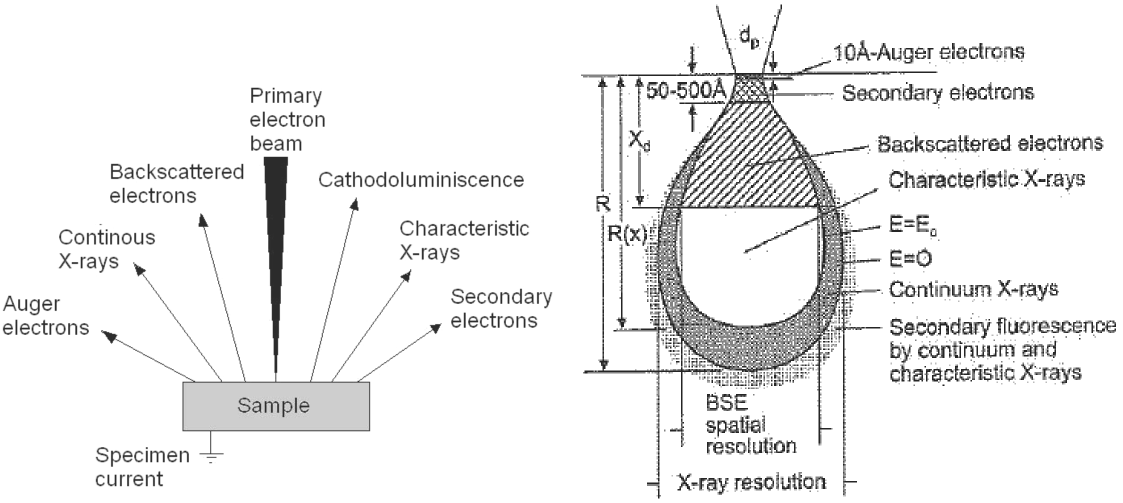


Figure 4-18. Signals and resolution which can be detected in SEM (adopted from Hjelen, 1989)

A field emission scanning electron microscope (FE-SEM) at the Norwegian University of Science and Technology (Zeiss Ultra 55 Limited Edition), Department of Materials Technology, was used in the study. The equipment is shown in Figure 4-19. In the FE-SEM more electron current can be concentrated into a smaller beam spot compared to regular SEM (thermionic sources), and an effective improvement in resolution can be obtained (Goldstein et al. 2003).

Figure 4-19. Zeiss Ultra 55 Limited Edition (Photo by Brynhild Snilsberg)

Secondary electrons (SE)

SE are electrons which are knocked loose from the outer shell electrons from the atoms in the sample by the incoming primary electrons or the outgoing backscatter electrons (Hjelen, 1989). SE are low energetic and defined by their kinetic energy; all electrons < 50 eV are by definition SE (Goldstein et al. 2003). If SE are produced close to the surface of the sample and the energy is above the surface barrier (2-6 eV), the probability of escaping the sample is high. Because of this the SE gives mostly information about the samples surface properties, and are valuable for imaging purposes.

Backscattered electrons (BSE)

BSE consist of high-energy electrons originating from the electron beam that are reflected or back-scattered out of the sample interaction volume (Hjelen, 1989). The BSE are elastically scattered by either single or multiple scattering events, and is valuable for imaging. BSE may be used to detect contrast between areas with different chemical compositions, especially when the average atomic number of the various regions is different, since the brightness of the BSE image tends to increase with the atomic number. BSE can also be used to form electron backscatter diffraction (EBSD) image. This image can be used to determine the crystallographic structure of the sample.

The information depth is about 100 times larger for BSE compared to SE (Hjelen, 1989).

Characteristic and continuous X-rays

X-ray photons are generated by the primary electron beam in the beam-sample interaction volume beneath the sample surface. X-ray photons emerging from the sample have energies specific to the elements in the sample, while other photons have no relationship to the sample elements (Goldstein et al. 2003).

Characteristic X-rays are a result of interaction between the primary electrons and the sample's inner shell electrons. The electrons of the sample's atom is found on discrete energy levels (K-, L-, M-shell) given by the quant numbers of the atom. If the primary electrons have large enough energy, they can knock out electrons and ionize the atom. The atom relaxes to its ground state when electrons from an outer shell fill in the inner vacancy, and the energy balance is maintained by either photons or Auger electrons being emitted. Since the electrons have discrete energy levels in the atom, the emitted photons will have discrete energy levels equal to the difference between initial and final level in the atom. This difference is specific for atoms with different atomic number. That is why the wavelength of the characteristic radiation is specific for atoms at a given atomic number, and can be used to determine the chemical composition both qualitatively and quantitatively (Hjelen, 1989).

Continuous X-rays (Bremsstrahlung) are photons emitted when primary electrons are decelerated by inelastic scattering with the Coulombic field of the sample's atoms (Hjelen, 1989, Goldstein et al. 2003). This is unwanted background radiation which reduces determination of the chemical composition of the sample.

Cathodoluminescence (CL)

CL is emission of light when atoms excited by high-energy electrons return to their ground state, and is the color of visible light produced by the interaction of the electron probe with the sample (Goldstein et al. 2003).

Auger electrons

When an electron is removed from a core level of an atom, leaving a vacancy, an electron from a higher energy level may fall into the vacancy, resulting in a release of energy. Although sometimes this energy is released in the form of an emitted photon, the energy can also be transferred to another electron, which is ejected from the atom. This second ejected electron is called an Auger electron, and has a characteristic energy (Hjelen, 1989).

4.4 Methods for measurement of rutting

4.4.1 Field measurement of rutting

Rutting in field was measured with ALFRED (Automatisk Linjal For REgistrering av Dekketilstand). The rut measurement device mounted in front of the vehicle is shown in Figure 4-20. ALFRED measures rut depth, width and area, cross fall, macrotexture, horizontal radius of curvature and roughness index IRI (International Roughness Index) with laser-/ultrasound sensors, gyros, mileage recorder and digital camera. Rutting in field is caused both by deformation and wear.

Figure 4-20. ALFRED rut measurement device mounted in front of vehicle (Photo by Statens vegvesen)

4.4.2 Measurement of rutting in the laboratory

The Wheel tracking test was used to measure rutting in the laboratory. The standard test procedure is described by EN 12697-22:2003 (CEN, 2003), and determines the susceptibility of bituminous materials to deform under load This is assessed by measuring the rut depth formed by repeated passes of a loaded wheel at constant temperature; 50 °C and 10 000 load cycles where each load cycle includes two passes (outward and return) of the loaded wheel. The apparatus is shown in Figure 4-21. A small size device was used, and the conditioning of specimens was performed in air at 50 °C. The device consists of a loaded wheel made of solid rubber (diameter 200-205 mm, width 50±5 mm) that bears on the sample held securely on a table. The wheel moves to and fro, and a device monitors the rate at which a rut develops in the top of the test specimen. The thickness of asphalt sample was 25 mm for mixtures with $D_{max} < 8$ mm, and 40 mm for mixtures with $D_{max} \geq 8$ mm and $D_{max} < 16$ mm. For each mixture 2 parallel samples were tested.

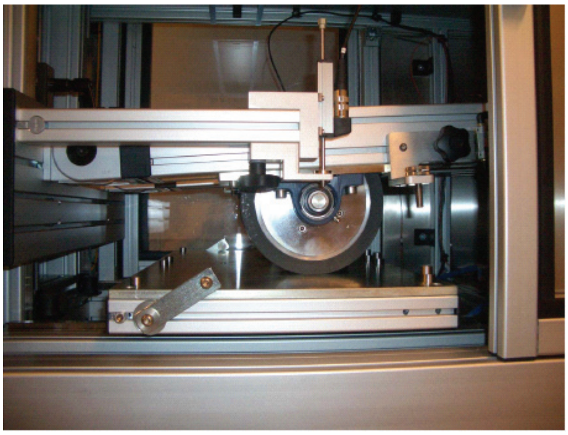


Figure 4-21. Wheel-track equipment for measuring rut depth of asphalt samples in the laboratory (Photo by Sintef)

5. Summary of the papers

In this chapter a short summary of the papers in Part two of this thesis is given. The summary includes a short description of objectives, materials, methods and results for each paper. Table 5-1 shows the relationship between the papers and the different factors characterizing road dust.

Table 5-1. The link between the papers and the different factors describing road dust

Paper	Type of study	Characterization
I	Field (dust downfall)	Amount, composition, dispersion
II	Field (dust downfall)	Amount, size, composition, surface area, dispersion
III	Lab (PTM / Tröger / Prall / LA / KM / MD)	Amount, size, shape, composition
IV	Lab (PTM / Tröger)	Amount, size, shape, composition
		Dmax, amount of coarse aggregate, driving speed, tire type
V	Lab (PTM)	Amount, size, shape, composition, imaging
		Driving speed, tire type

5.1 Paper I: Analysis of dust emission from pavement abrasion in Trondheim, Norway

Paper I presents a study on characterization of road dust sampled as dust downfall close to a heavily trafficked urban street in Trondheim, Norway. Two time periods were selected for sample collection; 17 March-18 April and 18 April-18 May 2005. The sampling periods were at the end of the studded tire season, and one of the aims of the study was to see if there was a difference in the amount and composition of the dust before and after the end of the studded tire season. The sampling was performed in the vertical direction (7-37 m above ground level) 30 m from the road, as shown on Figure 4-1. The material sampled was annealed to find the amount of mineral and organic matter. In this paper factors relevant to air born particles in urban conditions were studied and discussed. The paper focuses on dispersion of dust downfall and distribution of organic and inorganic matter, analytical procedures, climatic factors, pavement condition, and factors affecting abrasion of pavements. Amounts of material sampled, mineral and organic content and distribution of dust in the vertical direction were determined. Results from the study showed small differences between amounts of material sampled in the two sampling periods. This might be because they both are transitional periods between winter and summer where the dust concentration is high. The portion of inorganic material was about the same for both periods (87 %). (Snilsberg et al. 2006)

5.2 Paper II: Characterization of road dust in Trondheim, Norway

Paper II is a follow up of Paper I. Annealing of mineral matter can alter some properties of the samples, i.e. the procedure can impede further characterization of the particles. The sampling in 2006 was performed in the same way and around the same time of year as in 2005 (24 March-24 April and 24 April-24 May 2006). In addition, core samples from the asphalt pavement were taken and particles were produced in the laboratory using the Tröger equipment which simulates the wear of studded tires on pavements. This was done to be able to compare the mineralogical composition in the pavement to the composition of the dust downfall samples. The samples were analyzed with regard to amounts, particle size distribution, composition (organic/inorganic part, minerals and elements) and specific surface area. Results from the study showed that more than 90 % of the dust downfall is < 75 µm, i.e. suspended matter. The Tröger test gave a similar size distribution as the field samples. All the minerals found in the field samples are also found both in the laboratory produced samples and in the asphalt aggregate. Heavy metals concentrate in the fine fractions, and most of these elements from field samples exceed the background values (norm) for Norwegian soil. Particles produced in the laboratory have a much smaller specific surface area than field samples investigated. This is probably due to the presence of organic matter in the field samples. The specific surface area for the laboratory produced particles was found to be about 1/5th of the field samples. (Snilsberg et al. 2007)

5.3 Paper III: Evaluation of different laboratory methods for simulation of pavement wear and road dust generation from studded tires

Paper III describes a study on different laboratory methods for studded tire pavement wear simulation and road dust generation. Testing in laboratory is less resource demanding and less time consuming compared to large scale testing. The indoor Pavement testing machine at the Swedish National Road and Transport Research Institute was used as the reference because it has shown very good correlation between the studded tire wear on the road and in the machine. A stone mastic asphalt with maximum aggregate size of 11 mm was tested at 60 km/h with studded tires. Asphalt laboratory testing was performed on the same material with Tröger and Prall, while aggregate laboratory testing was performed with Los Angeles mill, Nordic ball mill and micro Deval on different size fractions of the aggregate (8-11 mm, 4-11 mm and 0-11 mm without the filler). Tröger was performed under dry conditions, while Prall was performed under wet conditions. Los Angeles tests were performed under dry conditions, while the Nordic ball mill and micro-Deval tests were performed under both dry and wet conditions. Samples of fine material were collected from each test and analyzed for particle size distribution, particle shape and mineralogical composition.

Results from the study show that it is possible to produce dust comparable to studded tire wear by use of simple laboratory techniques. Tröger and Prall are the methods best suited for pavement wear simulation and road dust generation. However, the test methods for aggregates may also be used, and of these methods Los Angeles mill was found to be the method best suited for dust generation. (Snilsberg et al. 2008)

5.4 Paper IV: Asphalt pavement wear and road dust generation – Effects of different aggregate grading, vehicle tires and driving speed

Paper IV presents a study in two parts; part one includes laboratory testing of asphalt with different aggregate grading. Asphalt concrete and stone mastic asphalt with maximum aggregate size of 6, 8 and 11 mm were tested with Tröger equipment. The asphalt mixes were compared based on the amount of dust material produced and the particle size distribution. The asphalt cores were taken from a test section in Trondheim and the rutting on the test sections was evaluated. Results from this study show that the aggregate size does not affect the amount of dust generated significantly; however, the amount of coarse aggregate (> 2 mm) appears to be important for resistance against pavement wear from studded tires. Asphalt concrete produced more dust than stone mastic asphalt.

Part two include large scale testing of a stone mastic asphalt with maximum aggregate size of 11 mm with different tire configurations (0-100 % studded tires and non-studded winter tires) and different speeds (30-70 km/h) in the indoor Pavement testing machine at the Swedish National Road and Transport Research Institute. Amounts, particle size, shape and composition was determined. Results from the study show that the share (%) of studded tires and driving speed are important for pavement wear and road dust generation. There is a significant increase in pavement wear when the driving speed is increased. The effect of speed is not as evident for a change from 50 to 70 km/h as it is for a change from 30 to 50 km/h. Studded tires produce 122 % more dust compared to non-studded winter tires. (Snilsberg et al. unpublished A)

5.5 Paper V: The influence of driving speeds and tires on road dust properties

Paper V includes further development of material presented in Paper IV. It consists of two parts; part one describes the effect of different driving speeds with studded tires on road dust properties. Stone mastic asphalt with maximum aggregate size of 8 mm was tested in the indoor Pavement testing machine at the Swedish National Road and Transport Research Institute using studded tires only. Dust generated was sampled at different driving speeds (20-70 km/h) and analyzed for particle size distribution, particle shape and particle composition. In addition, PM10 concentration in the room was monitored during testing. Results from the study show that the driving speed affects both amount of dust generated, and size and shape of the particles. The PM10 concentration increases with increasing driving speed, the particles decreases in size with increasing driving speed, and the particles become more irregular with increasing driving speed.

Part two presents effects of different car tires on particle characteristics. Tires used in the study were studded tires, non-studded winter tires and summer tires. The indoor Pavement testing machine was used for dust generation. Samples of dust were collected behind the different tires while testing at 70 km/h. Characterization of the samples show that studded tires generate large amounts of dust with finer particle size distribution compared to non-studded winter tires and summer tires. The rubber in the summer tires seem to be more worn compared to the wear of studded and non-studded winter tires. (Snilsberg et al. unpublished B)

6. Discussion

In this chapter the findings of the papers in Part two of this thesis are discussed. The discussion is based on pavement wear and suspension of dust as contributors to airborne PM on one hand and their effects on health on the other. The focus of the investigation has been on the direct tire induced pavement wear. However, resuspension of dust is an important factor, especially with regard to airborne dust sampling in field.

6.1 Amounts of road dust

Amounts of road dust produced have been investigated in all of the papers (Paper I, II, III, IV and V). Both amounts of airborne dust sampled in field with particulate fallout collectors (Paper I and II) and amounts sampled in laboratory (Paper III, IV and V) from the Pavement testing machine, Tröger, Prall, Los Angeles mill, Nordic ball mill and micro-Deval are determined.

Collection of road dust in field as a function of height above ground (7-37 m) is described in Paper I and II. These studies show that the concentration of suspended PM in urban air is kept high even relatively far above and away from the source (pavement). "Canyon-like" conditions in cities with high buildings on the sides of the road can prevent air ventilation and dilution of particles generated and resuspended from pavement wear. The dilution factor is between 24-39 % related to height for the four sampling periods as shown in Figure 2 in Paper II. The reduction is significant, but still the values exceed the proposed regulation of 5 g/m^2 per 30 days for mineral dust.

Paper III deals with particles produced by different laboratory methods for asphalt and aggregate testing (dust generation). The laboratory methods applied are more intense compared to the wear from tires on the real pavement, which means that the wear in the laboratory is accelerated. The natural disintegration of asphalt materials outdoors (especially the binder degradation as a function of time, temperature, radiation, oxidation etc.) is not included in these methods.

The generation of road dust as a function of maximum aggregate size (D_{max}) and pavement type/composition (stone mastic asphalt, SMA, and asphalt concrete, AC) has been studied in Paper IV. The study shows that the maximum aggregate size does not affect the dust generation significantly. On the other hand, Prall testing point out that asphalt mixtures with 6 mm maximum aggregate size are less resistant against wear by studded tires compared to asphalt mixtures with 8 mm and 11 mm maximum aggregate size (Appendix B). The pavement type/composition is more important than the D_{max}; AC pavements generate more dust (TSP) than SMA pavements (see Figure 6 in Paper IV). This is probably because of higher amount of coarse aggregate (> 2 mm) in SMA pavements compared to AC pavements. Studies in Sweden support this theory; they show that the D_{max} is not as important for generation of PM10 as the aggregate type (Gustafsson et al. 2007). This is also supported by results from the Finnish VIEME-project "Studies on the impact of road surfaces and tyres on noise and dust emission and transmission" (Kupiainen, 2007, personal communication). Earlier, rutting was assumed to be caused mainly by wear from studded tires. Today we know that deformation is an increasing contributor to the rutting measured in field, while the wear on pavements has been reduced because of reduction in number, weight, overhang and force of the studs. Horvli and Værnes (2006) concluded that the rutting measured in field is dependent on the amount of aggregate material > 4 mm. Additional Wheel track testing of asphalt types used in Paper IV has been performed to find the relative deformation values. Based on results from field measurements of rutting (Paper IV) and laboratory testing of permanent deformation with Wheel track (Appendix B), no connection between maximum aggregate size and deformation properties of the asphalt is found.

The aggregate type seems to be more important for the dust generation than the aggregate size. Dust particles generated as a function of aggregate type was investigated by use of the Nordic ball mill. The testing consisted of six different aggregate types frequently used in high volume roads in Norway. This study shows that the aggregate type is important for the amount of particles produced (see Figure C-1 in Appendix C), both for TSP and PM10. The TSP was ranging from 180-239 gram, while the amount of PM10 varied between 38-54 % of the TSP. Quartzite gave high amounts of TSP, but low amounts of PM10.

Dust generation as a function of driving speed and tire type has been studied in Paper IV and V. The driving speed and tire type is important for pavement wear and road dust generation as shown in Figure 10, 13 and 14 in Paper IV, Figure 4 and Table 4 in Paper V and discussed in Chapter 2 (Figure 2-2). Studded tires were found to generate 30-40 times more dust compared to non-studded winter tires and summer tires in Paper V. The PM10 concentration increases proportionally with increasing driving speed when using studded tires.

These results show that the use of studded tires is the most important factor affecting wear of asphalt pavements and generation of road dust. This means that a reduction in use of studded tires is more important for air quality in Norwegian cities than other factors like driving speed, amount of coarse aggregate and aggregate type.

6.2 Particle size of road dust

Particle size distribution of road dust has been investigated as described in Paper II, III, IV and V. Both laboratory produced samples (Paper III, IV and V) and material sampled in field (Paper II) have been analyzed. The results show that most of the dust particles are 20-30 μm in size. However, particles with size range of 0.4-1000 μm can be found. If we assume that the particles have the same density, 20-40 weight % of the TSP are below 10 μm (PM10) and 5-10 weight % are below 2.5 μm (PM2.5). Figure 6 in Paper II and Figure 7 in Paper III show particle size distributions for field samples and laboratory produced samples (Pavement testing machine (PTM), Tröger, Prall, Los Angeles mill (LA), Nordic ball mill (KM), micro-Deval mill (MD)).

Particle size distribution was determined with laser diffraction. The laser method, based on Fraunhofer diffraction, is one of the most widely used methods for particle size analysis because it is easy and quick to use and has a good reproducibility (Matsuyama and Yamamoto, 2004). Although, this method has some disadvantages as discussed in Chapter 4. Especially the shape of the particles will distort the results, and the mineral particles are often irregular. One reason why light scattering systems are affected by particle shape is the fact that particles moving through the optical system in turbulent flow typically arrange themselves in random orientation to the light source and detection system. This “tumbling” effect results in particles exposing their minimum and maximum projected areas to the instrument optics, along with every other conceivable orientation. This random orientation broadens the reported size distribution (Bumiller et al. 2002), and will affect D90 and D10. The “real” particle size distribution might be narrower than displayed, with lower amount of PM2.5 and possibly higher amount of PM10 than measured.

Agglomeration of dust particles may also cause problems when determining particle size of bulk samples. Especially the smallest particles stick together, and might be attached to larger particles as shown in Figure 9, 10 and 11 in Paper V.

Particle size as a function of driving speed and tire type has been investigated in Paper V. It was found that increasing driving speed gave higher amount of finer particles (Figure 5 and Table 1 in Paper V), and that studded tires generated wear particles with finer particle size compared to non-studded winter tires and summer tires (Table 4 and Figure 7 in Paper V).

Particle size as a function of type of aggregate material has been investigated by use of the Nordic ball mill (Appendix C). This study showed that the particle size of mineral dust varied, as shown in Figure C-2 in Appendix C. The PM10 content varied from 38-54 %. Most of the particles have sizes within the range of 2-50 µm.

The coarse fraction with size range of 2.5-10 µm is the dominant part of PM10 generated by pavement wear when particle mass is considered. This means that most of the particle mass that might be inhaled will be deposited in the upper respiratory tract. However, if number of particles or surface area is considered, the dominant part will be within the fine fraction (< 2.5 µm) which might be deposited in the lower respiratory tract when inhaled.

6.3 Particle shape of road dust

Particle shape distribution was measured from two-dimensional images of particles. The roundness is expressed by comparing the outline of the two-dimensional projection of the particle to a circle (length-width relationship). A perfect circle has roundness 1.0, while a needle shaped object has roundness close to 0. The two-dimensional particle shape is generally considered to be a function of attrition and weathering, while the three-dimensional shape is more related to particle lithology (Powers, 1953). Image analysis is often required to automate the complex task of assigning shape values to large numbers of particles. The apparatus used for particle roundness analyses has an operating range from 5-2000 µm, and was set to characterize 10 000 particles, which gives a good statistical result.

Particle shape of road dust has been investigated in Paper III, IV and V. Roundness was chosen as shape parameter since it describes a large scale smoothness of particles which is important for effects on human cells, and it changes through abrasion while the overall shape does not (Barrett, 1980). Powers (1953) developed classes for evaluating roundness of two-dimensional particle shape: well rounded 1.00-0.70, rounded 0.70-0.49, sub-rounded 0.49-0.35, sub-angular 0.35-0.25, angular 0.25-0.17, and very angular 0.17-0.12. The class between 0.12-0.00 is excluded because natural particles generally have roundness values greater than 0.12.

The roundness of particles was determined for dust samples produced in laboratory from asphalt with the PTM, Tröger and Prall, and from aggregate with the LA, KM and MD. Mean values for roundness based on all samples analyzed were in the range 0.598-0.739, with an average of 0.640. According to Powers scale of roundness this equals rounded particles. However, the shape of the particles varies from well rounded to very angular. This indicates that some of the particles are more worn than others (resuspended particles) and that different minerals are worn differently depending on crystal structure and hardness.

Results reported in Paper III show that mineral particles obtain a higher degree of roundness with increasing milling time; i.e. freshly crushed mineral particles are more angular, whereas after some time, under mechanical influence, the sharp edges of the particles are worn off (Barrett, 1980). Figure 8 in Paper III shows roundness distribution for particles generated from different laboratory equipment (PTM, Tröger, Prall, LA, KM and MD). Increasing driving speed was shown to generate more irregular particles in Paper V.

Particle shape as a factor of tire type (studded and non-studded winter tires) was described in Paper IV and V. In these studies it was not found any significant differences between mechanically generated particles by studded tires, non-studded winter tires and summer tires.

The particle shape analysis has shown that the main fraction of asphalt wear particles can be described as rounded particles. Increasing roundness of dust particles is positive in a health aspect; sharp and fibrous particles are identified to cause injury on human lungs. However, agglomeration of particles may distort the particle shape measurements. The agglomeration may result in higher roundness when the mineral particles are kneaded into the organic material and lower roundness when the mineral particles cover the organic material, as shown in Figure 10 and 11 in Paper V.

6.4 Road dust surface area

Surface area is a measure of the exposed surface of a solid sample on the molecular scale. Particle surface area is inversely proportional to particle size, which means the total surface area increases as the particle size decreases for a constant mass of particles. The reactivity of particles increases with increasing surface area. The BET (Brunauer, Emmet, and Teller) theory is a frequently used model to determine the surface area. The surface of the airborne particles will tend to adsorb materials from the air. One implication of larger surface area is that far more adsorbed material then will be carried by inhaled particles to their deposition sites. The adsorbed material can be toxic even if the particles are not. A second implication of the larger surface area is that the dissolution of the particles will be accelerated.

Surface area of road dust has been investigated in Paper II. Both laboratory samples (Tröger) and material sampled in field (dust downfall) at different elevations were analyzed. Specific surface area of laboratory produced dust was 0.21 m^2/g, while the field samples displayed about five times higher values. Road dust samples from March-April had specific surface areas of 0.73-1.03 m^2/g with an average of 0.92 m^2/g, while April-May showed some higher values of 0.90-1.31 m^2/g with an average of 1.15 m^2/g.

Road dust produced in laboratory from asphalt samples contains, as described in Chapter 2 and 3, 95 % mineral matter. However, field samples of road dust are influenced by other sources like combustion products and biological components which will influence the specific surface area largely. Road dust sampled in field will therefore give a higher specific surface value compared to laboratory produced particles.

Testing of six types of aggregate material in the Nordic ball mill gave values of specific surface area ranging from 3.05-4.24 m^2/g (see Figure C-3 in Appendix C). It might not be logical that pure mineral particles exhibit larger surface area than samples influenced by organic substances (field samples). But if we consider the particle size of these dust samples, KM give higher amount of small particles in proportion to Tröger and the PTM because of high milling time (as shown in Figure 7 in Paper III). In addition, Myran and Horvli (1998) found specific surface area ranging from 3.96-18.06 m^2/g for different rock types tested in the Nordic ball mill, which is in accordance with the results in Appendix C.

The specific surface area of airborne road dust sampled in field is about five times higher than for particles produced in the laboratory with Tröger from the same asphalt pavement material. This is probably caused by organic matter in the field samples. However, dust particles produced by KM have a specific surface area four times higher than road dust sampled in field and about 20 times higher than Tröger produced dust. This is because the KM generates particles with smaller particle size compared to pavement wear and Tröger.

6.5 Road dust composition

Composition of road dust has been described in all papers, but focus has been varying between inorganic content, mineral and elemental composition.

6.5.1 Inorganic and organic content

Traditionally, inorganic compounds are considered to be of mineral origin. The content of inorganic matter (i.e. mineral particles) in road dust has been described in Paper I and II. Of airborne road dust sampled in field, in average 87 % of the material were mineral particles. This implies that the main part of the airborne PM close to high traffic roads in the spring period (March-May) comes from pavement wear and suspension of road dust.

The car tires are also worn while interacting with the pavement as discussed in Paper IV and V. Non-studded winter tires seem to generate 4 % more rubber particles compared to studded tires as shown in Figure 15 in Paper IV and Table 4 in Paper V. Summer tires seem to give 16 % more rubber particles compared to studded tires as shown in Table 4 in Paper V. The relative high proportion of organic particles in dust generated from summer tires seem to enhance agglomeration of particles as shown in Figure 9 in Paper V.

6.5.2 Mineral composition

A mineral is defined as a naturally occurring inorganic crystalline solid with a narrowly defined chemical composition and characteristic physical properties such as density, color and hardness (Monroe and Wicander, 1994). Crystalline means it has a regular internal structure. Most rocks are solid aggregates composed of one or more minerals, and thus minerals are the building blocks of rocks.

Mineral composition has been investigated in Paper II, III, IV and V. Mineral composition was found by X-ray diffraction (XRD) which is a qualitative and a semi-quantitative method. This means that the type of principal minerals present is determined, while the amount of each mineral is not accurate. Only principal minerals are determined (mainly minerals which are present with 0.5 % or more). As a result, the XRD method is difficult to apply for quantitative determination of each mineral present in the sample, and can only be looked upon as an indication. This was tried in Paper II, as shown in Figure 8B, for road dust sampled in field and compared to dust particles produced in the laboratory with Tröger.

Minerals found in the samples are, of course, dependent on minerals present in the aggregate materials. However, some minerals (silicates) are more abundant than others in the Earth's continental crust. In Norway feldspar, mica and quartz are abundant minerals, and typical rock types used in aggregate production are gneiss (17 %), granite (13 %), gabbros (10 %), syenite (10 %) and gneissic granite (10 %) (Neeb, 1992).

The samples investigated in Paper II, III, IV and V contained quartz (≈ 30 %), plagioclase (≈ 40-50 %), potassium feldspar, chlorite, calcite, epidote, amphibole, mica and some other minerals. Quartz and plagioclase are the dominant minerals. Quartz is a hard mineral (H=7) with density 2.65 (Prestvik, 1992). It is classified as a human carcinogen. Plagioclase has a hardness of 5-7 and a density around 2.63-2.76 (Prestvik, 1992). According to Øvrevik (2004) and Låg et al. (2004) high plagioclase content shows strong negative correlation with ability to induce inflammatory reactions in lung cells. It was further shown that the feldspar content (plagioclase and potassium feldspar) displayed an even stronger negative correlation to induce inflammatory reactions. This may suggest that feldspar minerals in general have low biological reactivity, which is valuable information since they are the most common minerals and make up almost half of the Earth's crust.

6.5.3 Elemental composition

Elemental composition of road dust has been investigated in Paper II. The results show that most of the heavy metal elements from the field samples exceed the norm value for Norwegian soil, and that the concentrations of some elements decrease with increasing height as shown in Table 4 in Paper II.

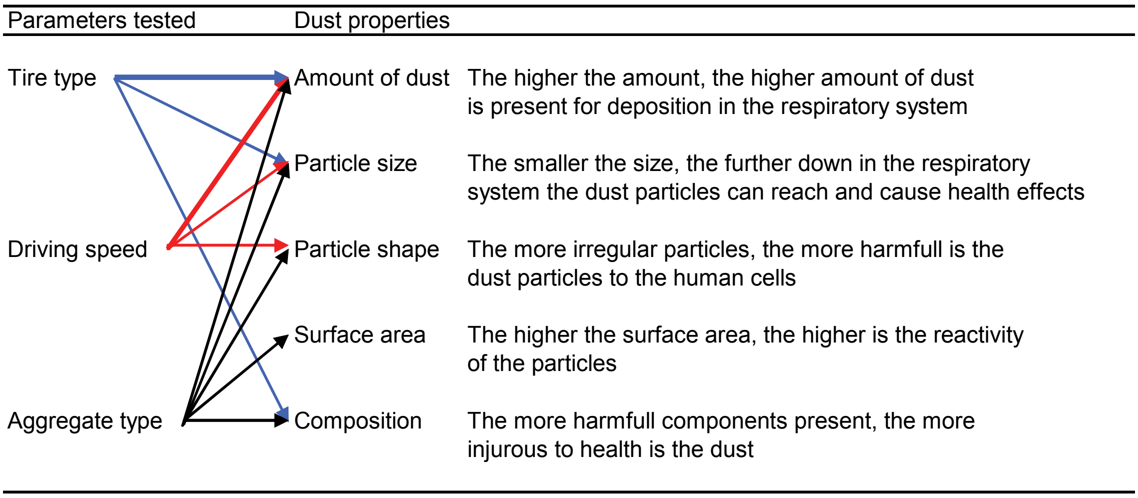
Elemental composition of particles can be used to interpret the major sources in the surroundings for supply of PM in urban air, i.e. fuel combustion products, wear of the vehicles, pavement wear, salt, wood burning, long distance pollution etc. In addition, health effects of particles may depend on the composition. Elements relevant to traffic and urban environment are aluminum (Al), calcium (Ca), iron (Fe), manganese (Mn) and titanium (Ti) which have road dust as source, sodium (Na), Ca, magnesium (Mg) and potassium (K) from road salt, K from heating with wood, copper (Cu), zinc (Zn), cadmium (Cd), antimony (Sb), barium (Ba) and lead (Pb) from wear of brakes etc., and Al, Ca, Fe, Mn, Ti, Cu, Zn, Cd, Sb, Ba, Pb, molybdenum (Mo), strontium (Sr), chromium (Cr) and nickel (Ni) from diesel (Hagen et al. 2005).

6.6 Methods utilized for accelerated dust generation

Methods utilized for accelerated studded tire wear in the laboratory are presented in Paper III. The methods include a large scale indoor Pavement testing machine (PTM), two small scale laboratory asphalt testing equipments; Tröger and Prall, and three small scale laboratory aggregate testing equipments; Los Angeles mill (LA), Nordic ball mill (KM) and micro-Deval (MD). The PTM is regarded as the best method for road dust generation since it is similar to real conditions outdoors, an asphalt pavement is loaded with a real tire, but without influence from tail-pipe emissions and low contamination from surrounding sources (Gustafsson et al., 2008 B). The Tröger and Prall methods also use real asphalt samples, but are not worn by a real tire. In the LA, KM and MD only the aggregate are being tested, without the influence of a real tire. Table 3 in Paper III gives a simple comparison of the different methods.

6.7 Concluding remarks

Figure 6-1 show the interaction between tire type, driving speed, aggregate type and the dust properties investigated.



Dust properties	
Amount of dust	The higher the amount, the higher amount of dust is present for deposition in the respiratory system
Particle size	The smaller the size, the further down in the respiratory system the dust particles can reach and cause health effects
Particle shape	The more irregular particles, the more harmfull is the dust particles to the human cells
Surface area	The higher the surface area, the higher is the reactivity of the particles
Composition	The more harmfull components present, the more injurous to health is the dust

Figure 6-1. Relation between parameters tested and dust properties investigated

This study clearly shows that the type of tires largely affect the quantities of dust generated from pavement wear; studded tires generate high amounts compared to non-studded tires. In addition, the particle size is affected by the type of tire; studded tires generate dust with finer particle size distribution compared to non-studded tires. The tire type also affects the rubber content in the dust.

The driving speed is important for dust generation and suspension into the air; the higher the driving speed, the higher is the amount of dust generated and suspended. In addition, the driving speed affects the particle size distribution and particle shape; increasing driving speed generates finer particles with more irregular shape.

The maximum aggregate size used in the pavement does not seem to affect any of the examined dust properties significantly. However, the aggregate type used in the pavement seems to affect all examined properties.

6.8 Remarks on health effects

Most of the investigations and expertise on airborne PM and health effects are based on European and North-American studies. The knowledge of health effects from airborne PM produced under Nordic conditions is limited. Some studies on particles from road pavement abrasion indicate a similar effect as from combustion particles on pulmonary cells. Knowledge about health effects associated with mineral particle exposure is mostly limited to studies on quartz and asbestos (Øvrevik et al. 2005).

During laboratory experiments, a single constituent is generally tested. However, the ambient air is a complex mixture of different particles, which may have undergone different atmospheric reactions which can result in interactive effects (Dybing et al. 2005). Muhle and Mangelsdorf (2003) report that mixed fibrous and non-fibrous dust exposures lead to an aggravation of effects. Synergetic interaction of multiple components is difficult to estimate. Synergetic interaction means the effect of exposure is larger than the sum of each effect separately.

Particle mass concentration (e.g. $\mu g/m^3$) is used for measurement of airborne particulate matter in urban air. This mass concentration overestimates large particles in the coarse fraction and basically neglects ultrafine particles < 100 nm in size. Some components, which contribute significantly to the total mass of airborne PM, appear to have low toxicity. Particle mass concentration is not the measuring unit of choice if the component that causes the response is linked to the total surface area, the reactive surface area or metal component released from the surface (Donaldson and Tran, 2002). According to Øvrevik et al. (2005), the surface reactivity of stone particles appears to induce high levels of chemokine release from epithelial lung cells. No consistent relation with the mass concentration has been observed, and there seems to be a more complex relationship than with just the mass concentration alone (Dybing et al. 2005, de Kok et al. 2006). The limitations of this mass concentration unit may also be illustrated by the water-solubility of ambient airborne particles, which may vary from

20-80 % of particle mass (Dybing et al. 2005). Other measurements (such as the particle number and surface area) need to be taken into account, depending on whether ultrafine or larger particles are to be considered. The number of deposited particles per unit surface area or dose to a specific cell may determine the response for specific regions of the human body. This means that the metric depends on the specific question posed, requiring specifically defined measures.

Adverse health effects of airborne particulate matter can not be linked only to particles of a certain size or chemical composition (Dybing et al. 2005, Donaldson and Tran 2002). Particle size does not seem to be an important factor in the ability to induce chemokines, and one must therefore assume that qualitative particle characteristics are of greater importance (Øvrevik et al. 2005). According to Dybing et al. (2005) the amount of knowledge on how particle size, surface property or chemical composition is related to toxicity is rapidly growing. The concept of “specific particle surface activity” means a small surface area of a reactive surface may be equivalent in ability to cause inflammation to a large surface area of low reactivity. It was introduced by Donaldson and Tran (2002), and can be an appropriate way to characterize airborne particulate matter. Solubility of particles is an important parameter in the particle-lung interaction. The large amount of reactive molecular species located only on the surface of insoluble particles and on core particles (remaining after dissolution of the soluble components), may be the ultimate metric determining adverse outcomes, although this molecule may only add a small fraction to the particle mass (Dybing et al. 2005). In toxicology studies mass, particle number, surface area and durability are important properties in clearance mechanisms and health outcomes (Dybing et al. 2005). But the existing evidence still does not provide an adequate basis for quantitatively relating the effects of airborne particulate matter to any specific measure of exposure.

7. Conclusions and recommendations

This chapter presents the overall conclusions from this doctoral thesis based on the conclusions drawn in the research papers and the discussion section. Recommendations for further research are also given.

7.1 Conclusions

Studded tires used in the winter season in Norway are the main cause for generation of road dust from pavement wear. If studded tires were not used, there would be much less suspended particulate matter originating from wear of pavements in urban air. Studded tires produce much more dust particles from wear of pavements compared to non-studded tires. For instance, at 60 km/h studded tires produce 30-40 times more TSP compared to non-studded tires on an SMA 8 pavement measured in an indoor test facility. The airborne road dust is composed of almost 90 % by weight of mineral particles under winter conditions, and approximately 50 % of the particles have size smaller than 25 µm (D50). Based on all samples analyzed, D10 is 3 µm and D90 is 60 µm. However, agglomeration of particles seems to make the measured particle size distribution coarser than it really is. Studded tires generate dust with finer particle size distribution than non-studded tires. The main fraction of the particles can be described as rounded particles, with average roundness value around 0.6. The specific surface area of the sample is dependent on the amount of organic material present in the sample and the particle size distribution. In general, field samples have higher specific surface area than dust particles generated in laboratory because of higher organic content. However, finely ground particles produced in laboratory may exhibit even higher surface area than field samples of road dust because of finer particle size distribution. Surface area is an important factor in health considerations since the reactivity of particles increase with increasing surface area.

Other factors affecting the generation of particles from pavement wear are the driving speed and type of rock material used in the pavement. Test results show that the PM10 concentration measured under laboratory conditions is reduced by 32-49 % when reducing the driving speed from 70 to 50 km/h, 52-83 % when reducing the driving speed from 50 to 30 km/h, and 76-89 % when reducing the driving speed from 70 to 30 km/h. The driving speed affects the particle size and the particle shape distributions. Increasing driving speed generate particles with finer particle size distribution and more irregular particles. The rock material used in the pavement affect the amount of dust generated, the composition, the particle size distribution, the shape distribution, and the specific surface area. Some mineral types are regarded harmful to health, for example quartz and asbestos which are classified as carcinogenic. The total amount of airborne dust (TSP) and PM10 can be very different; a high TSP does not necessarily lead to a high PM10 concentration and vice versa.

This study has shown that it is possible to produce dust comparable to studded tire wear by use of simple laboratory techniques. This has significance with regard to cost because it is not necessary to build expensive test sections when the purpose is to generate and characterize the dust from pavement wear. The small scale asphalt testing procedures, Prall and Tröger, are the methods best suited to give fine material which is comparable to particles generated from the Pavement testing machine (PTM). It also seems that one can test the aggregate alone to get reasonably good samples for analysis of dust from wear by studded tires. Among the aggregate testing procedures, the Los Angeles (LA) method gives the best correlation with the PTM. The dust produced by Tröger and Prall is more similar to the dust produced in the field because the dust is generated from asphalt mixtures, while the dust produced by LA, Nordic ball mill (KM) and micro-Deval (MD) comes from the aggregate only. However, none of these methods include/simulate the effect of the car tire, only the studs.

The results have shown that apart from the use of studded tires, the rock material used in the pavement has a significant influence on the airborne dust generated. It is therefore important to carefully select the rock materials for use in urban road pavements. The aggregate type affects both the amount of dust generated and the particle properties. Existing knowledge shows that the finer the particles, the greater will be their potential effects on health. Since driving speed influences both the amounts of road dust generated and the particle size distribution, one may have to consider the use of speed restrictions in urban areas in winter time to reduce the potentially hazardous effects of road dust. However, this has to be balanced against other traffic conditions such as congestion.

7.2 Recommendations for further research

The present study has contributed to new and interesting knowledge concerning physical and chemical characterization of dust particles from pavement wear by studded tires, and indicates which of the parameters are important in the analysis of road dust. Nevertheless, further work is required to give a more complete understanding of the subject for a wider range of particle properties. Factors considered by the author to be important and relevant to health effects from exposure to road dust particles, which were not investigated in this study, are solubility, surface charge (Zeta-potential), number of particles and components attached to the mineral particles. It is therefore recommended to do further study on these properties of road dust and their potential negative effect on health.

SEM is a useful technique which has been tried with success in this doctoral project, but it was not enough time to further investigate the wide application potential of the equipment. However, an enormous possibility lies in the technique, especially descriptions of particle size, shape, surface properties and composition, agglomeration, number of particles and for imaging purposes.

Organic particles were not the main topic in this study. Regarding rubber particles from tire wear, only the total amount was examined. The size and composition of these particles might be of importance in a health aspect, and should be looked further into. The type of binder used in the asphalt pavement will also affect the composition of the dust. Both the rubber and binder might contain components and particle sizes far more injurious to health than the mineral particles. However, the dominant part of road dust in a mass perspective is inorganic material and thus organic material will only constitute a small part. As long as the regulation for ambient air PM only considers the mass of particles, these organic particles will only constitute a small part of road dust in Nordic countries where studded tires are used. In the years 2008-2010 the PM2.5 level in European cities will be monitored. A 25 % reduction in PM2.5 concentration is aimed at in the period 2018-2020 compared to the period 2008-2010 (Rosland, 2008, personal communication). This show that there is a growing concern regarding airborne PM generated from tail-pipe emissions in urban areas.

The choice of rock material used in a pavement seems to be one of the most important parameters governing amount of particles generated, but also affecting particle properties. Therefore, resistance to mechanical degradation of different types of mineral particles due to wear from studded tires should be surveyed.

The best way to establish relationship between different particle properties and health effects is to isolate different particle properties and do in vitro studies in laboratory or in vivo studies for instance on rodents. However, these are expensive and complicated experiments which are performed by scientists with medical background. A thorough description of particle properties should therefore be done in advance with particle technology to verify the variation in each property, and collaboration between medicine and particle technology is therefore crucial.

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PART II

PAPER I

Analysis of dust emission from pavement abrasion in Trondheim, Norway

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Abstract

Suspended particulate matter that is emitted from road traffic is a heterogeneous mixture of particles with regard to size and type, and is composed of mineral matter, asphalt, soil and exhaust. In this paper factors relevant to air born particles in urban conditions have been studied and discussed. The paper focuses on dispersion of dust downfall and distribution of organic and inorganic matter, analytical procedures, climatic factors, pavement condition, and factors affecting abrasion of pavements.

Samples from dust downfall have been collected close to the E6 main road in Norway's third largest city, Trondheim. The traffic level at the sampling spot is about 35 000 vehicles/day, with a speed limit of 50 km/h. Survey of the traffic in the winter season 2004/2005 showed that 38 % of the vehicles use studded tires. In comparison, 25 % of the traffic in Oslo uses studded tires, and the average portion of traffic using studded tires for Norway excluding the cities is 55 %.

Samples investigated where collected in 12 Particulate Fallout Collectors on a high building façade about 30 m in horizontal distance from the road. The collectors were mounted on banisters and were directed towards the road on every second floor starting from the 3 floor (7 m above ground level) and up to the 13 floor (37 m above ground level), with two parallel collectors in each spot. The samples were analyzed according to NS 4852 at the Norwegian University of Science and Technology.

Two time periods were selected for sample collection; 17 March-18 April and 18

April-18 May 2005. The selected periods for sampling are based on the fact that in the spring times the pavements are dry and bare, and the dust produced will be blown and raised by vehicles and wind. The climate is considered to be very important in this regard.

1. Introduction

The Norwegian Public Roads Administration has a responsibility to minimize and prevent risk on human health caused by increasing road traffic. Dust in suspension caused by abrasion of pavements in Norway is mainly a problem during winter because of the use of studded tires. This is indicated by the high concentrations of minerals in the dust; 70-80 % mineral dust in the winter, as compared to 15-25 % in the summer (Bakløkk et al., 1997, Låg et al., 2004).

Trondheim is Norway's third largest city with a population of 170 000 inhabitants (Trondheim Municipality, 2005). However, the population density is high and emissions from road traffic and wood burning for heating purposes influence the air quality considerably from time to time. Especially during the dry and cold periods in the winter/spring time, high amounts of particles are measured in the ambient air. Use of friction enhancing measures (like studded tires, chains, friction sand, salt) lead to increased wear of road pavements.

Suspended particulate matter from road traffic is a heterogeneous mixture of particles in regard to size and type, and is composed of mineral matter, asphalt, soil and exhaust. The road pavement consists of about 95 % rock material (90 % aggregate and 5 % filler) and only about 5 % bitumen. The main component of the dust from mechanical abrasion of the pavement will therefore be mineral particles. Close to highly trafficked roads, the proportion of particles with size below 10 µm (1 µm = 1/1000 mm) can become 3-4 times above the air quality requirements (50 $\mu g/m^3$ on daily mean concentration), especially on dry and cold weather conditions (Ormstad and Løvik, 2002). According to Ormstad and Løvik (2002) about 80 % of the dust at high particle exposure episodes is related to resuspension processes.

Total suspended particulates is defined as the part of the dust which can be suspended in the air for a longer period of time (Schwarze et al., 2004), and are particles with aerodynamic diameter < 75 µm. Dust downfall includes particles which are large enough to sediment because of specific gravity, particles which are deposited on the inside of the sampler walls and particles which are brought down with precipitation. Most of these particles are larger than 75 µm (The Norwegian Standards Association, 1981), while 9-10 % is below 10 µm and 2-3 % is below 2.5 µm (Låg et al., 2004, Ormstad and Løvik, 2002, Hedalen and Myran, 1994). Dust downfall is measured using standardized sampling buckets with exposure time of one month, and the result is expressed as amount of dust downfall per unit of area per 30 days. It is divided into an inorganic and organic part. Inorganic material consists mainly of minerals, while the organic part is composed of carbon and other combustion products, parts of plants and insects, spores and pollen, fibres etc. (Myran, 2004a, Myran, 2004b).

The proportion of vehicles using studded tires in Trondheim was 40 % for winter (2004/2005). The production of dust is dependent on several factors. Skoglund and Uthus (1994) and Bakløkk (1997) mention factors such as type of stud (metal/plastic/weight), amount of traffic, design/shape of the streets/roads, cleaning of the pavements, vehicle type, driving speed, weather, driving conditions and maintenance measures, quality of pavement and type of aggregate in pavement as primary factors influencing dust production. Around 250 000 -300 000 tons of asphalt is worn off our roads every year (Bakløkk et al., 1997, Ormstad and Løvik, 2002). This represents an environmental problem and a potential health problem in and around Norwegian cities. About 90 % of the wear happens on 10 % of the road network where the traffic amount is high (Låg et al., 2004, Ormstad and Løvik, 2002). According to Låg et al. (2004) the main sources to particulate air pollution during the winter is road traffic (30-47 %) and heating (47 %). In a report made by Statistics Norway in 1997 about 39 % of the suspended particulate matter in Norway is related to road traffic, and 15 % of this is from asphalt pavements. In 2001 the total contribution from road traffic (exhaust, abrasion of pavements etc.) was estimated to 7 % of the total emission of PM_{10} in Norway (Finstad et al., 2003). Ormstad and Løvik (2002) reported that 10-20 % of the annual mean SPM values in Oslo (adjusted for exposed inhabitants) come from wear on pavements from studded tires.

Several studies have been done on dust downfall in Trondheim. Factors that have been studied include the deposition alongside roads (Myran and Hedalen, 1994, Statens vegvesen, 1993, Berg, 1993), particle size distribution of the dust (Myran and Horvli, 1998, Bakløkk et al., 1997, Hedalen and Myran, 1994), chemical and mineralogical composition (Erichsen et al., 2004, Hedalen and Myran, 1994) and organic content (Myran and Horvli, 1998). Figure 1 illustrate dispersion of total dust downfall in horizontal distance from roads and how the amount of dust changes with varying annual mean traffic and distance from the shoulder of the road.

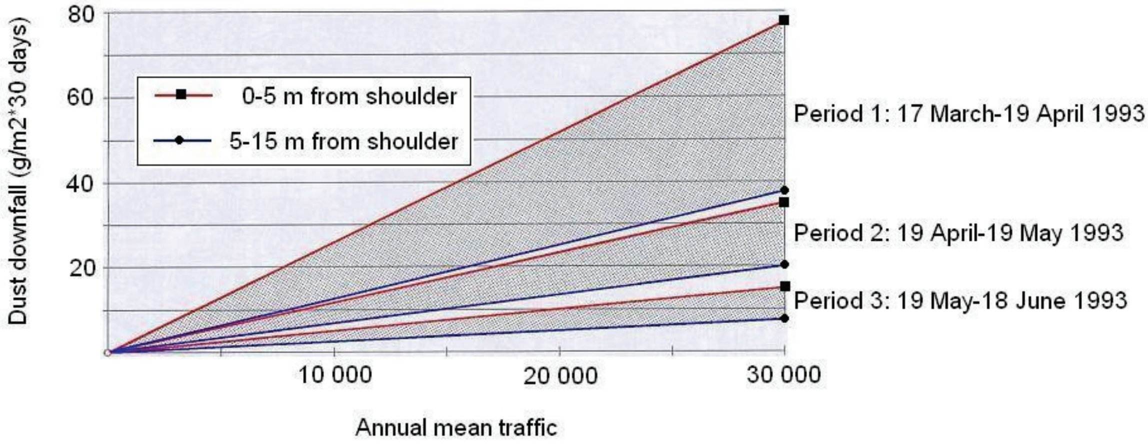


Figure 1. Dust downfall as a function of traffic (Statens vegvesen, 1993)

Research has shown that the amount of dust decreases logarithmically with the distance from the shoulder of the road (Bakløkk et al., 1997). Most of the road dust is found within a distance of 10-12 m from the road, and about 50 % of the dust is within 2 m. Myran and Hedalen (1994) reported that the content of dust from roads decreases exponentially in horizontal direction from the road. Figure 2 illustrates the horizontal deposition alongside roads. Most of the dust will be deposited within 20 m form the road, but some components can be found several hundreds of meters from the road.

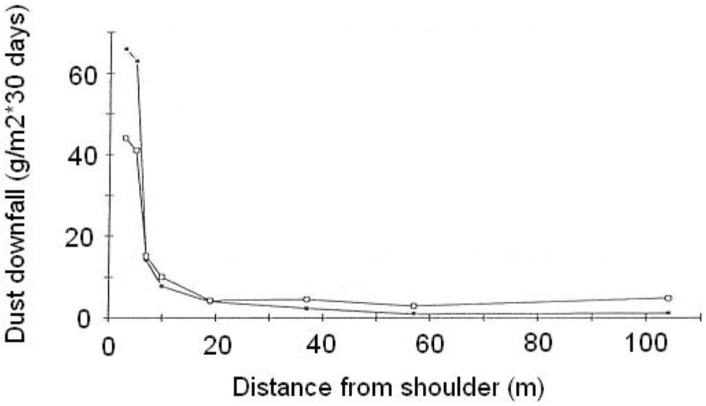


Figure 2. Deposition of dust alongside roads (Myran and Hedalen, 1994)

Measurement of dust downfall in Trondheim (2.5 m above ground level) has demonstrated that the dust is more fine-grained at low concentrations (Figure 3), and the organic matter content is relatively low at high dust concentrations (Figure 4). Hedalen and Myran (1994) report that the organic content decreases with lower particle size of the dust downfall, though increasing below 10 µm. Two samples show an organic content of 5-15 % of the material below 10 µm. This implies that particles from the rock material in the pavement are the dominant part of the dust at high dust concentrations. The amount of organic matter (weight %) in road dust was measured at four different sampling locations in Trondheim during winter (Figure 4). The pavement at one of the sampling points was made of concrete, while the pavement at the other three sampling points was asphalt pavement. The content of organic matter from the concrete pavement was not different from that of the other sampling points, indicating that the organic part of the dust downfall in the winter time is dominated by other sources than wear of bitumen. The average particle size distribution from 22 samples of dust deposit in Trondheim is plotted in Figure 5. About 70 % of the material was larger than 75 µm (Figure 5A) for all the material, while for the material < 74 µm 30 % of the particles are below 10 µm (Figure 5B).

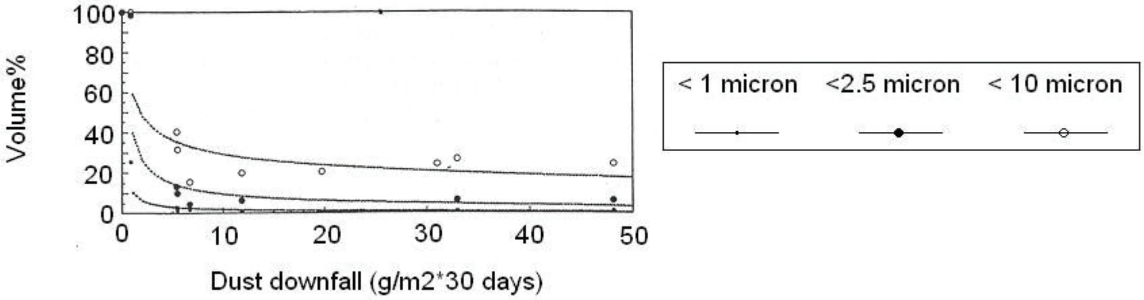


Figure 3. Distribution of dust downfall (Myran and Horvli, 1998)

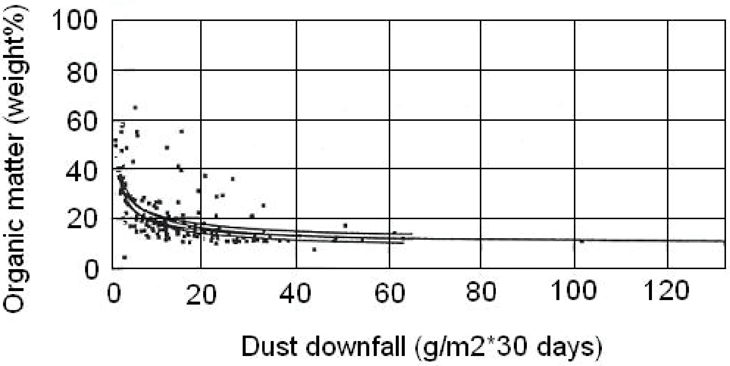


Figure 4. Organic content in dust downfall (Myran and Horvli, 1998)

In this study it was attempted to collect dust downfall from wear of pavement from the E6 main road through the city of Trondheim (Elgeseter Street). This street has high concentrations of particles in the air. Two air quality measuring units were near this street; one is measuring background levels and one measuring levels close to the road. The air quality in Norway can be viewed at www.luftkvalitet.info.

The purpose of the study was to measure and analyze dust downfall in the vertical direction close to a busy road to observe the distribution of particles at different altitudes from pavement wear. This is important because of propagation of particles from pavement wear. Distribution of organic and inorganic matter was also determined.

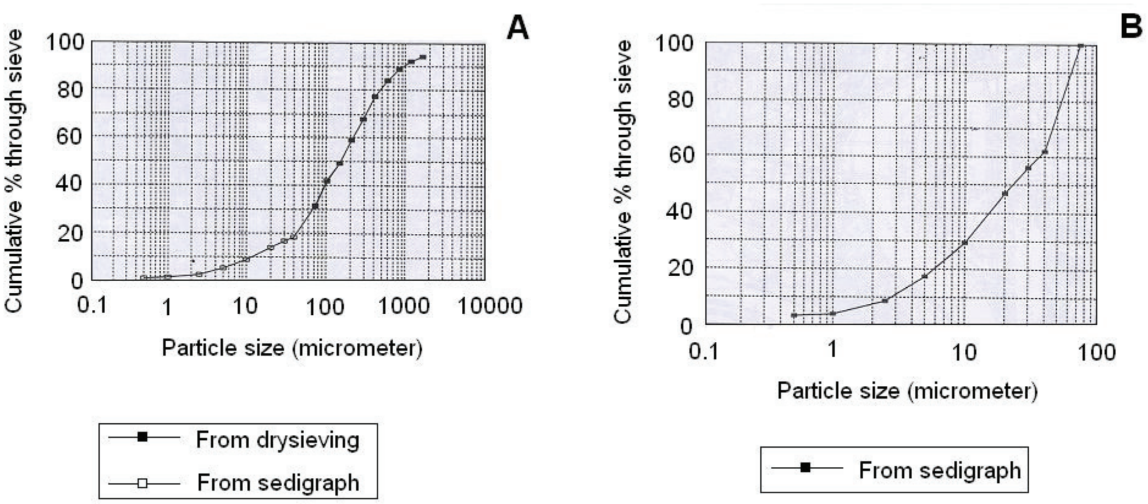


Figure 5. Particle size distribution of dust downfall in Trondheim. A: Average particle size distribution of 22 samples. B: Average particle size distribution of the material < 74 µm (Hedalen and Myran, 1994)

2. Methods, results and discussion

The sampling procedure was based on the Norwegian standard NS 4852 (The Norwegian Standards Association, 1981). Dust downfall was collected with standardized particulate fallout collectors with diameter 200 mm and height 400 mm (ISO standard) supplied by Norwegian Institute for Air Research (NILU). These collectors were mounted on the façade of a tall building which was located 30 meters in horizontal distance from the main road (Elgeseter street) entering the city of Trondheim from the south. The collectors were mounted on banisters in north/east direction facing the road on every other floor starting on the 3 floor (7 m above ground level) and up to the 13 floor (37 m above ground level), with two parallel collectors in each spot. The speed limit at the location is 50 km/h, and the traffic load is about 35 000 vehicles/day (around 10 % heavy vehicles). Two time periods were selected for sampling; 17 March-18 April and 18 April-18 May 2005, the first period represents a winter condition while the second period represents a summer condition. These periods were chosen because experience has shown that the proportion of mineral particles in the dust emission in the proximity of main streets in Trondheim is quite high at this time of year. Resuspension processes are important in this regard, (but also the fact that many people is waiting to change to summer tires a couple of weeks later even though it is not allowed). The studded tires are by law illegal to use in the time period from the first Sunday after Easter holidays (3 April in 2005) to 31 October (if not the driving conditions makes it necessary) for the Trondheim area.

The samples were analyzed according to NS 4852 at the Norwegian University of Science and Technology (NTNU). Equipment used for analyzing water-insoluble matter include sedimentation columns (with 6 filter holders) of type Millipore and Solberg & Andersen, vacuum pump, funnel, filter holder and suction bulb. Exsiccation was used to condition filters before and after sampling, and a radioactive source was used to discharge electrostatic charge in the filter. The samples were annealed at 710 °C to find the proportions of organic and inorganic materials. A Mettler AT261 Delta Range scale (with accuracy 1/100 mg) was used for all weighing.

Results show that the amount of dust downfall increases with decreasing height above the ground. The change in mass as a function of altitude can be described as a polynomial function of second degree:

$$DDF = 0.0041x^2 - 0.2581x + 8.9862 \qquad (R^2 = 93\ \%) \qquad (1)$$

$$DDF = 0.0047x^2 - 0.2786x + 8.4332 \qquad (R^2 = 99\ \%) \qquad (2)$$

where DDF is dust down fall and x is height above ground. Equation 1 applies to period 1 (17 March – 18 April 2005) while equation 2 applies to period 2 (18 April – 18 May 2005).

At the time being there are no official guidelines for evaluation of dust downfall in Norway. NILU has proposed a basis of assessment which is comparable with values used in Nordic countries and Germany, see Table 1. At the moment it looks like a proposed regulation of 5 g/m^2 and 30 days for mineral dust will be agreed upon.

Table 1. Basis of assessment for dust downfall (g/m^2 and 30 days) (Myran, 2004a)

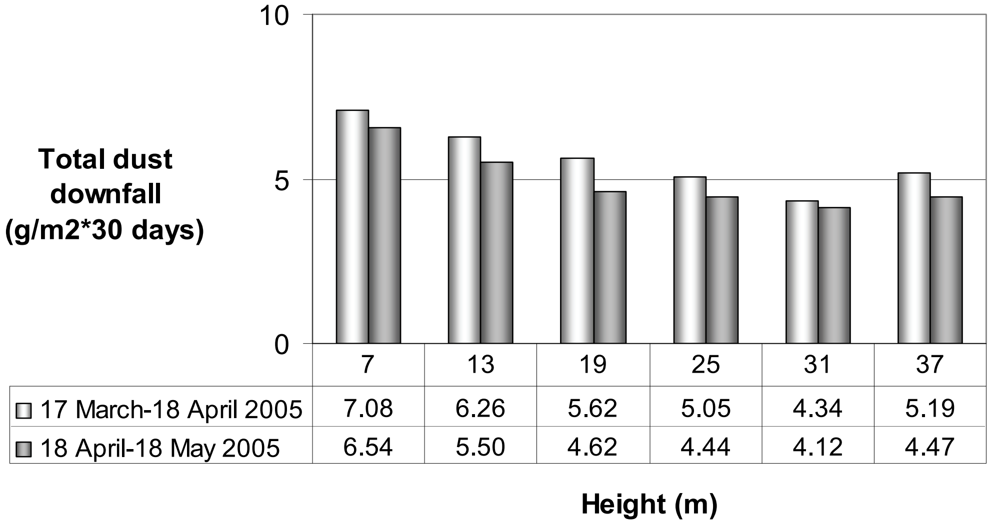
Low	≤ 3	High	8-13
Moderate	3-8	Very high	≥ 13

The dust downfall measurements done in this study are around the proposed regulations of 5 g/m^2 and 30 days for mineral dust. Table 2 give the inorganic part of the dust downfall, and Figure 6 give values for total dust downfall for both sampling periods. Values for both inorganic and total dust downfall are moderate according to Table 1. Table 2 show that four samples exceeds the proposed regulation of 5 g/m^2 and 30 days for mineral dust. However, this proposed regulation is based on sampling at an elevation about 1.8 m above ground level. The importance of distance from the source will be discussed later. If the functions (1) and (2) describing the change in dust downfall are used, the total dust downfall at 1.8 m altitude would be 8.53 and 7.95 g/m^2 for period 1 and 2 respectively. This is above the proposed regulations. Period 1 had higher amount of total dust downfall than period 2, this was as expected (see Figure 6). The reduction was 0.55, 0.78, 1.03, 0.63, 0.23 and 0.74 g (in average 0.66 g) for sampling spots at elevation 7, 13, 19, 25, 31 and 37 m respectively above ground level. This is mainly due to the effect of pavement cleaning and removal of studded tires. In the period March-May, the reduction in total dust downfall was 1.93 and 2.12 g for period 1 and 2 respectively from 7 to 37 m above ground level. This is a reduction of about 27-34 % for an altitude difference of 30 m. The total amount of dust sampled was 1053.8 mg and 932.6 mg for period 1 and 2 respectively. One remarkable result is that the amount of dust downfall increases slightly in the topmost sampler compared to the one below. This was the case for both sampling periods. One explanation for this might be that these samplers were located close to the top of the building, and that the flow pattern of the air changes dramatically. Near the top of the building, the shielding effect of the building decreases, and there is more turbulence leading to less sedimentation. But also sedimented particles on top of the building might get suspended and affect the topmost sampler more than the lower samplers.

Table 2. Inorganic dust downfall ($g/m^2 * 30$ days) for each sampling point

Height (m)	7	13	19	25	31	37	Average	Total
Period 1	6.42	5.75	5.20	4.48	3.85	4.36	5.01	30.06
Period 2	5.91	4.92	4.12	3.95	3.73	4.04	4.45	26.67

A higher amount of organic matter was expected for the second period compared to the first since it was meant to represent a summer condition. This was found not to be the case. The portion of organic material was about the same for both periods (average of 12.8 % in period 1 and 12.4 % in period 2). The total amount of organic material was 134.4 mg and 115.3 mg for period 1 and 2 respectively (Table 3). Mineral particles dominate therefore the samples from all floors. The samplers from period 1 were stored about one month longer than the samplers from period 2 which was analyzed only one week after they were taken down. Large organic parts as insects might therefore have been partly dissolved and the amount of dust downfall measured would then be somewhat overestimated for period 1.



	7	13	19	25	31	37
☐ 17 March-18 April 2005	7.08	6.26	5.62	5.05	4.34	5.19
▨ 18 April-18 May 2005	6.54	5.50	4.62	4.44	4.12	4.47

Figure 6. Dust downfall measurements

Table 3. Organic content (%) for each sampling point

Height (m)	7	13	19	25	31	37	Average	Total (mg)
Period 1	11.7	10.4	9.9	13.5	13.5	18.1	12.8	134.4
Period 2	12.0	12.7	13.0	13.2	11.7	11.8	12.4	115.3

The amount of dust downfall measured in this study was moderate, and around the proposed regulation for mineral dust (5 g/m^2*30 days). However, these values should be discussed, especially when one takes into account the mounting of the samplers. The height above the ground, but also effect from the façade of the building might be important. The source, amount and direction of dust downfall can vary with e.g. the dominant wind direction, tunneling effects because of tall buildings around the road and temperature gradients in the air (especially temperature inversion). The horizontal distance from the road is of course also important which in this case was 30 m. According to Figure 1 the reduction in dust downfall is 40-50 % in a distance from 0-5 m to 5-15 m from the shoulder in the period March-May in 1993 in Trondheim. In a horizontal distance of 30 m the reduction would be much higher. Also Figure 2 indicates a rapid reduction alongside roads. And as mentioned earlier Bakløkk et al. (1997) report a logarithmic decrease of amount of dust with the distance from the road, while Myran and Hedalen (1994) report an exponential decrease. The vertical distance from the road is also important, and the purpose of the sampling in this study was to investigate this effect. The sampling was performed at higher elevation compared to what is usual and standard. According to the standard (The Norwegian Standards Association, 1981) the opening of the sampler should be 1.8±0.2 m above the ground or surface. The first two samplers were placed 7 m above the ground and the other samplers every second floor above these (about 6 m distance in between). This will result in even higher dilution of particles. In addition the samplers were mounted along a façade of a tall building where the conditions are different compared to an open area. Factors like turbulence and shielding from wind and precipitation will affect the results since dust downfall is particulate matter accumulated by sedimentation, turbulent deposition or by precipitation. The standard recommends at least 5 m distance to the closest object near to the sampler.

Pavement condition is also important for the amount of dust in the air. When the pavement is wet, the dust is bound by the water. Rain and melting water from ice and snow can flow onto the pavement and bind the dust. But when the pavement dries, dust is raised by vehicles and wind and will then be dispersed in the air. Salt has a similar effect as water, and is often used as a dust binding measure to prevent high concentrations of dust in the air. Hygroscopic properties of the salt will contribute to keep the pavement wet when the pavement is salted, the temperature is higher than -4°C and the relative humidity is above 80 %. The air humidity is often low in March-April, in addition the sun and wind rapidly dries the pavement. Accumulated dust inclusive dust from salt and newly produced dust can then be raised. However, a moist pavement is worn 2-6 times more than a dry pavement (Bakløkk, 1997), therefore salting to prevent dust in the air can lead to more wear of the pavement and enhanced need for cleaning. The different parameters will affect each other, for instance the air temperature will influence the relative air humidity. Relative humidity increases when the temperature drops. From a climatic viewpoint the spring 2005 has been humid with vast amounts of precipitation and relatively high humidity, especially compared to both 2004 and 2003 when the pavements were dry for longer periods of time already from mid February. Particularly April 2005 was humid. This climate favour low concentration of particles in the air and result in few crossings of the ambient air quality requirements. The wind direction is also important for the amount of particles transported from the pavement and how much will be deposited in the samplers. Dominant wind direction in the sampling period is therefore essential for placing of the samplers, and they should be placed downwind to the road to receive particles from the wear of pavement.

The two selected sampling periods were not that different in regard to total amount of dust downfall, vertical concentration and organic content as expected. As a matter of fact the two periods are very similar, maybe because they both are transitional periods between winter and summer where the dust concentration is high. Few measures were taken in the spring 2005 to reduce high episodes of dust to see what effects cleaning and dust reducing measures have on the dust concentration in the city. According to Trondheim Municipality only five actions were performed to reduce dust in the sampling period (all five in period 1), and this is a cause for stable high particle concentrations. The air quality requirement on daily average 50 µg/m^3 was exceeded 12 times (9 times in period 1 and 3 times in period 2) during the sampling period. Measurements done by Trondheim Municipality and Norwegian Public Roads Administration show that the dust concentration in Trondheim has been reduced in the last few years. The trend line is decreasing when we use values from the worst months of the year (February, March, April, November and December) from 1994-2005. There are fewer extreme high values, but still it is difficult to keep below the daily average limit value 50 µg/m^3. Reasons for the reduction in dust level can be development of more durable pavements, reduction in the number of vehicles using studded tires, implementation of actions to decrease suspended matter, changes in the climate from year to year, etc.

3. Conclusion

The results from this study point out the importance of doing these kinds of measurements. It is an easy and cheap method to investigate amount of mineral particles from mechanical abrasion of pavements. The findings in this study strengthen the evidence of high amount of inorganic particulate matter in urban air in March-May from pavements. Another study could investigate the particle size distribution at different elevations, and correlate the composition of inorganic matter to the mineral content in the pavement.

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PAPER II

Characterization of road dust in Trondheim, Norway

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Summary

In this study field samples and laboratory produced road dust has been investigated. The paper discusses properties of particles from field measurements and compares these to properties of particles produced in the laboratory. These properties are particle size distribution, composition and specific surface area. Different analytical methods have been applied to characterize road dust (Coulter, annealing furnace, XRD, ICP-MS and BET). Field samples have been collected close to the European road number 6 in Norway's third largest city, Trondheim. The samples investigated where collected at a horizontal distance of about 30 m from the road. The elevations of sampling points varied between 7 m and 37 m above ground level. Sampling periods were between March-May in the years 2005 and 2006. In addition core samples from the pavement were taken in 2006 from which particles were produced in the laboratory using the Tröger equipment. The samples were analyzed at the Norwegian University of Science and Technology. Results from this study show that the field samples are mostly suspended matter; about 90 % of which are smaller than 75 µm. All the minerals found in the field samples are also found both in the laboratory produced samples and in the pavement. The composition is dominated by inorganic material (87 %) and specific surface area is about 1/5th part for particles produced in the laboratory compared to the field samples investigated.

Keywords: Road dust, mineral particles, studded tires, suspended matter, Tröger

1. Introduction

Road dust due to the use of studded tires represents demanding environmental challenges for several Norwegian cities. The requirements for air quality set by the World Health Organisation and European Union are often exceeded. The city of Trondheim has been regarded as one of the worst cities in Norway on suspended particulate matter from road traffic during winter seasons. A four-year research and development project was therefore started in 2004 to develop pavements resistant to dust production adapted to Norwegian climatic and traffic loading. This study is a part of this project aiming at characterizing road dust from pavement wear.

In this study dust downfall was sampled, characterized and compared to the mineral content in the pavement below. Dust downfall includes particles which are large enough to sediment because of specific gravity, particles which are deposited on the inside of the sampler walls and particles which are brought down with precipitation [1]. It is measured using standardized sampling buckets with exposure time of 30±2 days, and the result is expressed as amount of dust downfall per unit of area per 30 days (gram/m^2 and 30 days). Dust downfall is usually in the size range 75-300 μm (1 μm = 1000 mm), while 9-10 % is below 10 μm and 2-3 % is below 2.5 μm [2, 3, 4]. The total amount of particles in the air is called total dust, and regulations regarding air quality and particulate matter are set only for particles below 10 μm (PM10).

Suspended particulate matter emitted from road traffic is a heterogeneous mixture of particles with regard to size and type. It is composed of mineral matter, asphalt, soil and exhaust. The characterization of road dust from pavement wear was done by describing size, compositions and surface area of field samples and laboratory produced dust from pavement samples.

2. Material and methods

Samples of dust downfall were collected close to the E6 main road in Trondheim, Norway. The samples where collected in 12 Particulate Fallout Collectors on a high building façade about 30 m in horizontal distance from the road. The collectors were mounted on banisters and were directed towards the road on every second floor starting from the 3 floor (which is 7 m above ground level) and up to the 13 floor (which is 37 m above ground level), with two parallel collectors in each spot.

Periods selected for sample collection were 17 March-18 April and 18 April-18 May 2005, and 24 March-24 April and 24 April-24 May 2006. The time periods selected for sampling has background in the studded tire season. The studded tires are by law illegal to use in the time period from the first Sunday after Easter holidays (3 April in 2005, 23 April in 2006) to 31 October for the Trondheim area if the driving conditions do not make it necessary. The March-April period represents a winter condition while the April-May period represents a summer condition. At this time of year the pavements are often dry and bare, and the dust produced will be blown and raised by vehicles and wind.

The traffic level at the sampling spot is about 35 000 vehicles/day with a speed limit of 50 km/h. Survey of the traffic in the winter season 2004/05 and 2005/06 showed that respectively 38 % and 35 % of the vehicles use studded winter tires in Trondheim. In comparison, 19-24 % of the traffic in Oslo uses studded winter tires, and the average portion of traffic using studded winter tires for Norway excluding the cities is 54 % for the same time period.

The samples from 2005 were sampled and analyzed based on the Norwegian standard on dust downfall (NS 4852). The samples were analyzed at the Norwegian University of Science and Technology (NTNU). The procedure includes filtration of non water-soluble part through an ash free filter, drying, weighing and annealing at 710 °C (ignition loss) to find the total dust downfall and proportion of organic and inorganic material in the dust downfall.

A different analytical technique was applied in 2006. Annealing of the samples at 710 °C can alter some properties of the samples (like specific surface area and composition) meaning the procedure according to NS 4852 can impede further characterization of the particles. The samples from 2006 were dried and analyzed at NTNU/SINTEF using Flowsorb II 2300 to find the specific surface area (Brunauer-Emmett-Teller (BET) 0-

100m^2), Coulter LS 230 to get the particle size distribution (laser diffraction 0.04-2000 µm), x-ray diffraction (XRD) to find the mineralogical composition (semi quantitative mineral analysis) and inductively coupled plasma mass spectroscopy (ICP-MS) to get the elemental composition. Some of the samples from 2005 were analysed using Coulter LS 230 to find the particle size distribution and ICP-MS to find the elemental composition. Annealing at 710 °C alters these properties very little. Table 1 describes the analytical work.

Table 1. Characterization matrix for the different samples

Year		2005												
Period		March-April						April-May						Tröger
Height (m)		7	13	19	25	31	37	7	13	19	25	31	37	0
Sample		1a	2a	3a	4a	5a	6a	1b	2b	3b	4b	5b	6b	
Method	NS-4852	x	x	x	x	x	x	x	x	x	x	x	x	
	CoulterLS230	x		x	x		x	x		x	x		x	
	ICP-MS	x		x	x		x	x		x	x		x	
Year		2006												
Sample		1c	2c	3c	4c	5c	6c	1d	2d	3d	4d	5d	6d	e
Method	BET	x	x	x	x	x	x	x	x	x	x	x	x	x
	CoulterLS230	x	x	x	x	x	x	x	x	x	x	x	x	x
	XRD	x	x	x	x	x	x	x	x	x	x	x	x	x
	ICP-MS	x	x	x	x	x	x	x	x	x	x	x	x	x

In addition to characterizing mineral particles from dust downfall measurements an attempt was made to correlate the composition of inorganic matter to the mineral content of the aggregate in the pavement. Samples of the asphalt pavement outside the building were taken (core samples), and particles were produced in laboratory by the Tröger test. Tröger is a simple laboratory test who simulates the wear of studded tires on pavements (Figure 1). The standard test is developed so it is possible to collect loose particles during the test. The pavement sample is mounted on an eccentric swiveling table which rotates with 30 revolutions per minute while steel bars are hammering on the sample by the compressed air gun. Particles that are torn loose from the sample are sampled by a modified wet vacuum cleaner with deionized and distilled water. The Tröger produced dust was then characterized in the same way as the dust downfall samples from 2006 including BET, Coulter LS 230, XRD and ICP-MS, se Table 1.

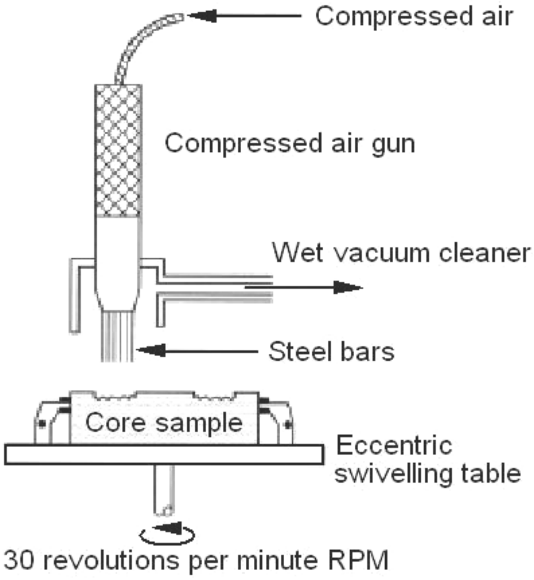

Figure 1. Tröger apparatus [5, 6]

3. Results and discussion

3.1. Amounts sampled in field

In this study dust downfall was collected from the E6 main road through the city of Trondheim (Elgeseter Street). This street has high concentrations of particles in the air mainly because of traffic. Two air quality measuring units are near this street; one is measuring background levels and one measuring levels close to the road. The air quality can be viewed at www.luftkvalitet.info.

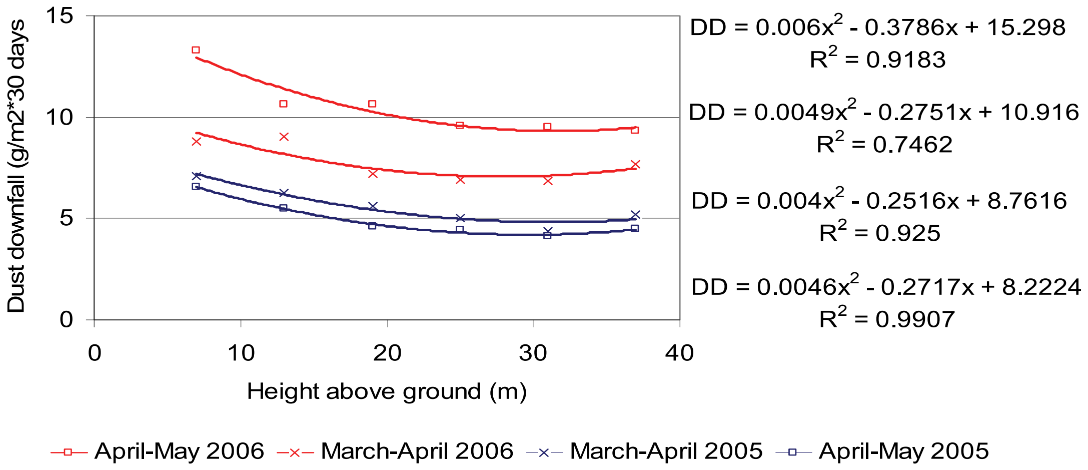

Figure 2. Dust downfall for each sampling period (g/m^2 and 30 days)

The amount of dust downfall in the different sampling periods for 2005 and 2006 is illustrated in Figure 2. The figure illustrates the dust downfall (g/m^2 and 30 days) with height above ground (m). April-May 2006 was the worst period for dust downfall amounts followed by March-April 2006, March-April 2005 and April-May 2005. Some of this dust may be caused by nearby building activity.

At the time being there are no official guidelines for evaluation of dust downfall in Norway. Norwegian Institute for Air Research (NILU) has proposed a basis of assessment which is comparable with values used in Nordic countries and Germany, see Table 2. At the moment it looks like a proposed regulation of 5 g/m^2 and 30 days for mineral dust will be agreed upon. This value will be the upper limit for "low polluted" conditions.

Table 2. Guidance for evaluation of dust downfall (g/m^2 and 30 days) [7]

Level	Very high	High	Medium	Low
g/m^2*30 days	> 15	10-15	5-10	< 5

The dust downfall values are quite high when you take into consideration the horizontal distance from the road which is 30 m. Research has shown that the amount of dust downfall decreases logarithmically with the distance from the shoulder of the road [8, 9]. Most of the road dust is deposited within a distance of 10-20 m from the road, and about 50 % of the dust is within 2 m. Some components can be found several hundreds of meters away.

The vertical distance from the source is also important. According to NS 4852 [1] the sampling should be done 1.8±0.2 m above ground level. In this case the sampling was from 7 to 37 m above ground level. Therefore the Norwegian guidance levels for dust downfall (Table 2) are difficult to apply in this case, however the level can be said to be medium according to Table 2. This type of sampling was chosen because the method is simple to perform and is less resource demanding than other types of dust measurements. It has also a very long sampling period and gives large amounts of material for further characterization.

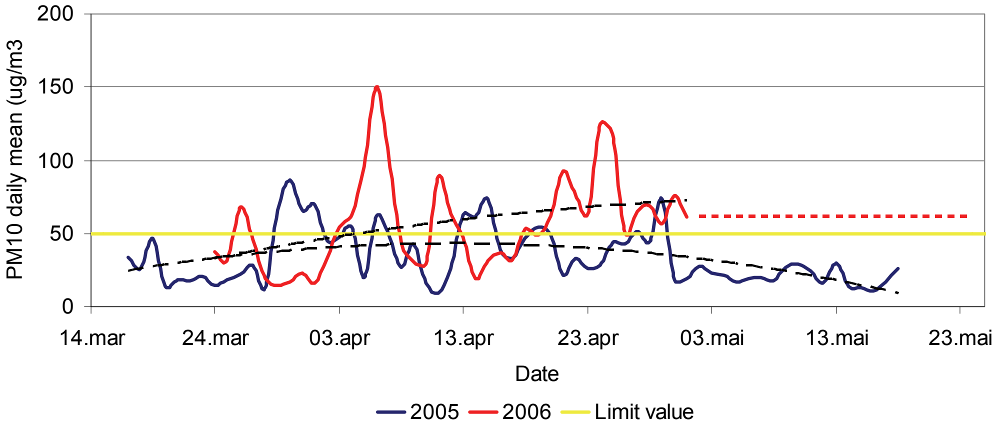

Figure 3. Daily mean values for PM10 (µg/m^3) www.luftkvalitet.info

The daily mean values for PM10 measured at an air quality station (Elgeseter Street) are shown in Figure 3. The measuring station is close to the sampling point (620 m in north direction) and can give an explanation for the higher amount of dust downfall for 2006 compared to 2005. The recorded values were much higher in 2006 (Figure 3), and the trend line (black dotted line) for 2005 is descending while for 2006 it is increasing. The limit value is marked as a yellow line. All the air quality measuring stations in Trondheim were however taken down for calibration 1 May 2006 and measurements to the end of the last sampling period (24 May 2006) is therefore missing. During the sample period in 2005, 12 days exceeds the limit value, while 21 days were above the limit in the sample period in 2006 where 23 days were not monitored. According to the EU directive (1999/30/EG) the daily averages of PM10 should not exceed 50 µg/m^3 for more than 35 days during each year.

A correlation between dust downfall and PM10 was established in 1995/96 for Elgeseter Street in Trondheim [10]. The model is traffic related and is based on situations with relatively high traffic amounts. It can estimate PM10 concentrations which are expected from dust downfall measurements. The conversion from measured dust downfall with height above ground to theoretical PM10 concentrations is shown in Table 3.

Table 3. Conversion from dust downfall to PM10 [10]

Dust downfall (g/m^2 * 30 days) from Figure 2		PM10 ($\mu g/m^3$)	
March-April 2005:	$DD = 0.004x^2 - 0.2516x + 8.7616$	Upper limit	4.7*DD+13.3
April-May 2005:	$DD = 0.0046x^2 - 0.2717x + 8.2224$	Average	2.5*DD+7.8
Marc-April 2006:	$DD = 0.0049x^2 - 0.2751x + 10.916$	Lower limit	0.7*DD+7.8
April-May 2006:	$DD = 0.006x^2 - 0.3786x + 15.298$		

The calculated PM10 concentration from the dust downfall samples of heights 7 m to 37 m above ground level is illustrated in Figure 4. The limit value of 50 µm is marked as a red dotted line, and the average PM10 concentration measured at the air quality station in Elgeseter Street for the sampling period is marked as a square blue dot at 2.5 meters above ground level. The sampling periods from 2005 and 2006 seem to follow the model relatively well since the PM10 concentration will increase closer to the ground.

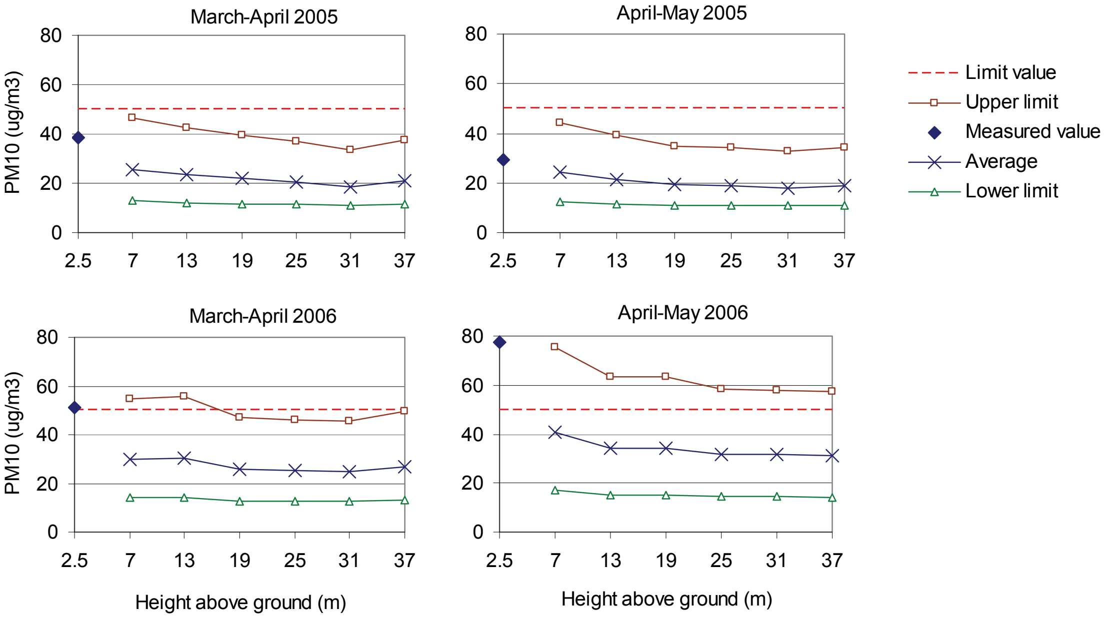

Figure 4. Estimated PM10 concentrations (µg/m^3) for each height

3.2. Size distribution

Size distribution of field and laboratory produced samples are very similar; Tröger produced particles have just a bit finer grading up to 20 µm and a hunch coarser above 20 µm compared to the field samples. Field samples from different sampling periods and different heights above ground level seem also to have almost identical curves. Figure 5 gives the size distributions for each elevation (7, 13, 19, 25 31 and 37 meters above ground level) based on dust downfall samples from 2005 and 2006 and Tröger analyzed by Coulter LS 230. Figure 6 gives average volume frequencies (%) and cumulative volumes (%) for each height and Tröger dust.

Total suspended particulates are defined as the part of the dust which can be suspended in the air for a longer period of time [11]. In this study the average size distributions (Figure 6) show that about 90 % of the field samples and laboratory samples are below 75 µm. The volume frequencies show that most of the particles are around 25 µm in size.

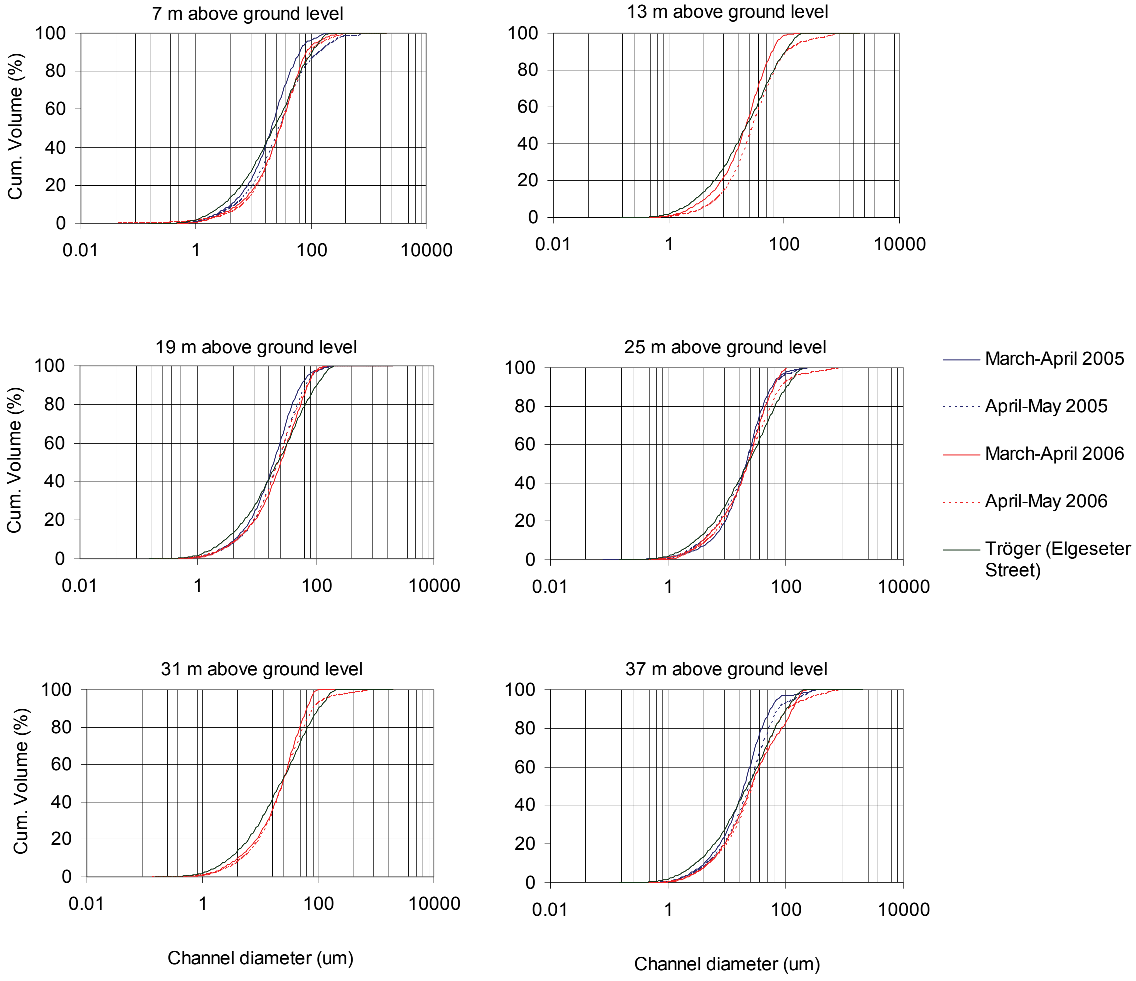

Figure 5. Size distributions (cumulative volume, %)

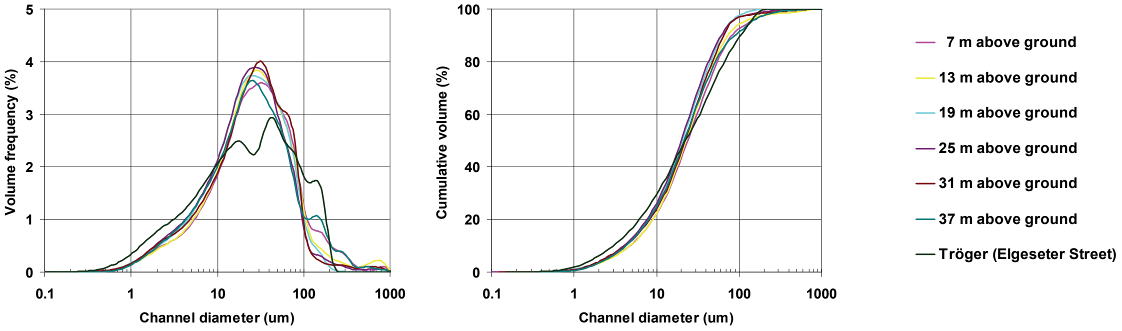

Figure 6. Average volume frequencies (%) and cumulative volumes (%) for each height

3.3. Composition

3.3.1. Inorganic material

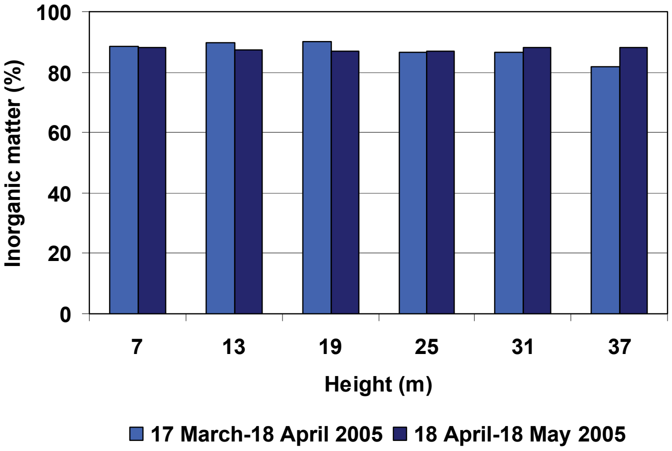

Figure 7. Inorganic content (%) in field samples [12]

Dust downfall is described by dividing into an inorganic and organic part [1] by annealing. Inorganic material consists mainly of mineral particles, while the organic part is composed of carbon and other combustion products, parts of plants and insects, spores and pollen, textile fibres etc. [9, 10]. The inorganic part is very high for the sampling period March-May 2005. The study from 2005 [12] showed that the inorganic content in average was 87 %, Figure 7 give the inorganic content (%) for each elevation for the sampling periods in 2005.

3.3.2. Mineral composition

The pavement at the sampling point is a stone mastic asphalt with maximum aggregate size 11 mm with 47 % Ottersbo (mylonite) 8-11 mm, 29 % Lia (greenstone) 0-11 mm, 17 % Ekle (glaciofluvial deposit) 0-8 mm, 7 % limefiller 0-1 mm, and binder B85. Mineralogical composition of the pavement (named Potential (NGU)) has been estimated by the Geological Survey of Norway (NGU) based on the composition of each deposit of the aggregate in the pavement [13, 14] and is illustrated in Figure 8B. The uncertainty in connection with estimating the amounts of each mineral in field samples and Tröger sample from XRD analysis is large, and values can only be looked upon as indications. Semi quantitative mineral analyses (XRD) of the field samples from 2006 and Tröger produced dust give quartz, feldspar, chlorite, calcite, amphibole and small amounts of other minerals (mostly mica and epidote). The quantity of each mineral differs between each height, and between the sampling periods, Tröger and Potential (NGU) composition. The field samples are most likely contaminated by calcite. Renovation work with plasterboards inside the building where the samplers were mounted may have caused high concentration of calcite in the field samples. The average values for March-April 2006 and April-May 2006 in Figure 8A was therefore recalculated with 7 % calcite content as the pavement contain 7 % lime filler, and is shown in Figure 8B. In general the Tröger produced sample contained more quartz and calcite, and less chlorite, while the Potential (NGU) contains more amphibole and other minerals, and less quartz compared to the adjusted field samples. The amount of feldspar is almost similar for all samples.

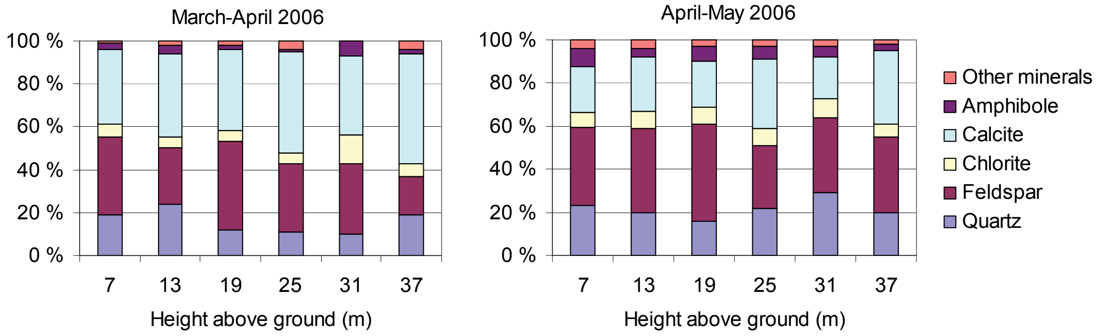

Figure 8A. Mineral compositions (%)

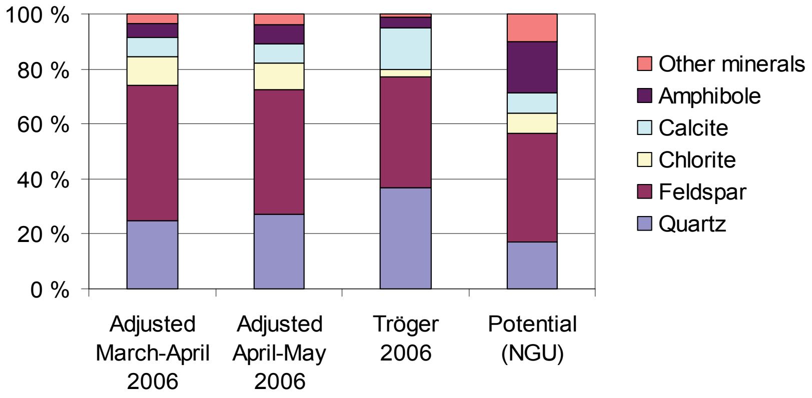

Figure 8B. Mineral compositions (%)

The XRD analysis can give different values for different particle size categories for the same sample. This is because the composition of the particles is dependent of the crushing method; weak and strong minerals are differently crushed [15] and some minerals can therefore be concentrated in some sizes [4]. The Tröger apparatus is a very hard test method for studded tires in regard to the type of studs we use in Norway nowadays. Today light-weight studs are used compared to the steel studs that were allowed earlier. This might be one of the reasons for the high amount of quartz produced in laboratory compared to field samples.

Different types of aggregate (especially jaspis), are used in pavements in Trondheim city, and therefore it is difficult to compare the asphalt recipe at the sampling location directly to the composition of the field samples. Also other sources will affect the dust downfall composition like building activity, trucks hauling aggregate materials to and from construction sites, industry etc.

3.3.3. Elemental composition

The elemental analysis (ICP-MS) includes 58 elements, 7 of these elements are presented in Table 4 together with the background values (norm) for Norwegian soil [16]. These elements are chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd) and lead (Pb). The samples were dissolved in concentrated nitric acid for 45 minutes at 180 ºC before analysis.

Most of the heavy metal elements from field samples in Table 4 exceed the norm value, only Pb is below. Especially Cr, Cu, Zn and As have values high above the norm value. Field samples 1a-6a and 1b-6b from 2005 was annealed which result in lower total mass and higher concentrations compared to the field samples 1c-6c and 1d-6d from 2006 which was only dried. No general trend is observed, but some elements decrease in concentration with increasing height.

Earlier studies have investigated the content of heavy metals in the PM10 fraction of road dust [13, 17] and topsoil [18] in Trondheim. Heavy metals tend to concentrate at low particle size [4], and PM2.5 has higher concentrations of heavy metals than the PM10 fraction [17]. Median values for concentrations of heavy metals in topsoil close to the sampling point for the dust downfall measurements are: Cr 63.2 mg/kg, Ni 38.2 mg/kg, Cu 35.3 mg/kg, Zn 156 mg/kg, As 2.8 mg/kg, Cd 0.20 mg/kg, and Pb 58 mg/kg [18].

Table 4. Elemental analysis (mg/kg)

Sample	Cr	Ni	Cu	Zn	As	Cd	Pb
1a	6330	3570	180	1420	195	9.19	34
2a	106	81	181	1680	8	3.47	32
3a	106	80	376	2970	1770	3.96	29
4a	89	77	333	6030	12	3.84	35
5a	106	79	243	2090	261	2.84	48
6a	103	82	604	4720	6	2.48	64
1b	101	77	181	1070	4	10.90	59
2b	106	74	307	902	9	2.33	48
3b	98	77	613	1180	10	1.63	37
4b	103	74	249	1120	23	2.38	33
5b	103	78	277	1850	9	2.74	34
6b	108	82	473	2486	612	3.76	44
1c	81	62	229	719	71	15.80	30
2c	55	51	257	966	23	6.93	34
3c	55	48	307	670	3	5.20	20
4c	47	48	337	663	7	2.05	18
5c	45	42	429	782	89	2.79	22
6c	41	41	589	2370	7	2.73	39
1d	62	60	214	583	4	2.45	23
2d	600	410	292	667	38	2.61	29
3d	63	65	234	549	24	2.38	24
4d	72	54	288	605	0	2.08	20
5d	53	51	320	865	0	1.50	28
6d	652	485	455	1190	59	2.03	30
e	46	46	69	124	nd	0.78	18
NORM	25	50	100	100	2	3.00	60

3.4. Specific surface area

The specific surface area (m^2/g) for field samples from 2006 and Tröger sample is shown in Figure 9. Figure 9 give the specific surface area (m^2/g) for each elevation (meters above ground level) based on dust downfall samples from 2006 and from Tröger analyzed by BET. The field samples have about five times larger surface area compared to the Tröger sample. The reason for this might be the presence of organic substances mentioned earlier in the paper. Even though the inorganic content by weight is about 87 % [12], the number of organic particles and relative surface area can be large.

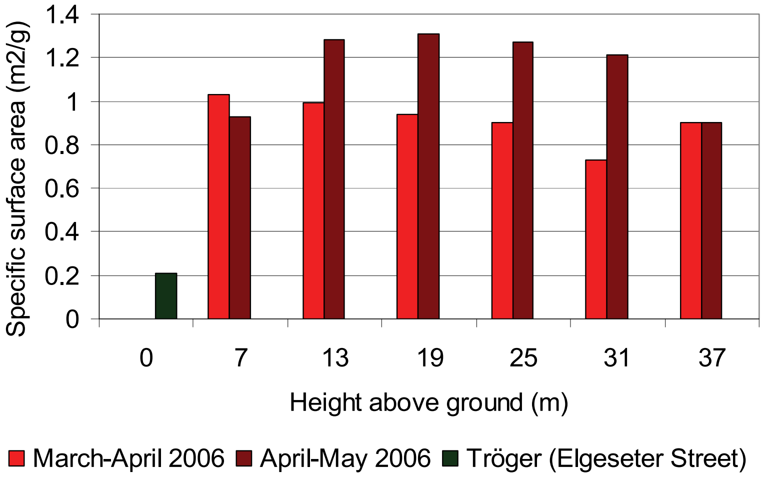

Figure 9. Specific surface area (m^2/g)

Table 5 might explain this effect; it shows the relative surface area and number of particles for a given mass of spherical particles with different diameter. Earlier studies has shown that carbon black, which can be found in road dust from exhaust and other combustion processes, has a specific surface area of 90-100 m^2/g [19]. The same study found a specific surface area of 1.5 m^2/g for dust sampled in a tunnel, and 3-18 m^2/g for dust from rock samples produced with different methods (ball mill, Los Angeles mill, boring dust and industry production). Further it is found values of 3.88-7.10 m^2/g for PM10 samples and 9.42-14.99 m^2/g for PM2.5 samples from 9 different rock materials [2].

Table 5. Particle size vs. surface area and number [3]

Diameter (μm)	Relative surface area	Relative number
0.1	100	1 000 000
1.0	10	1 000
2.5	4	64
10.0	1	1

The laboratory produced sample is not exposed to the traffic and outdoor environment, and will therefore lack organic particles from these sources. Only organic particles caused by the binder will be present.There is also a trend showing larger specific surface area for the period April-May compared to March-April. In average March-April has a specific surface area of 0.915 m^2/g, while April-May has a bit higher value of 1.15 m^2/g. A possible explanation for this is the organic content which is larger closer to the summer, and organic particles in traffic environments are often smaller and have a much larger surface area than inorganic particles [3, 20].

Specific surface area reveals the potential for the particles to attaché other substances to their surface; the larger the surface area the more substances can be attached. On the surface, especially for particles with large specific surface area such as carbon particles from combustion processes, more or less soluble components e.g. metals, organic compounds, allergic agents, gases, fungi spores and endotoxins are usually attached [11, 21].

4. Conclusion

Determination of size distributions reveals that the field samples collected in the period March-May 2005 and 2006 are mostly suspended matter; about 90 % of which are smaller than 75 µm. Most of the particles are around 25 µm in size. Samples from field investigations have very similar size distribution as laboratory (Tröger) produced particles. The size distribution of all particles are similar for field samples collected at different heights, different sampling periods and for laboratory produced samples.

There are large amounts of suspended matter at this time of year (March-May), and inorganic material dominates the composition. The inorganic content was in average 87 %. All the minerals found in the field samples are also found both in the laboratory produced samples and in the pavement. Heavy metals concentrate in the fine fractions, and most of these elements from field samples exceed the background values (norm) for Norwegian soil.

Particles produced in the laboratory have a much smaller specific surface area than field samples investigated probably because of organic matter in the field samples. The specific surface area for laboratory produced particles is about 1/5th of the field samples.

5. Acknowledgement

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PAPER III

Evaluation of different laboratory methods for simulation of pavement wear and road dust generation from studded tires

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Abstract

The study presented in this paper investigated the possibility of simulating wear by studded tires in the laboratory. Samples of suspended matter were produced by use of various laboratory wear equipment and compared to dust collected during indoor large-scale tests conducted in a Pavement Testing Machine at the Swedish National Road and Transport Research Institute. The project included studies on dust samples collected from asphalt using Tröger and Prall apparatus as well as samples collected from aggregates using the Nordic Ball mill, Los Angeles mill and micro-Deval mill. The dust samples were analyzed at the Norwegian University of Science and Technology with regard to composition, particle shape and particle size distribution. The project has clearly shown that simulation of wear due to studded tires in the laboratory is less time consuming and less resource demanding than full scale testing of pavements, and is useful for investigation of different pavements with regard to wear and dust generation.

Keywords: Pavement wear, Studded tires, Pavement Testing Machine, Tröger, Prall, Nordic Ball mill, Los Angeles mill, Micro-Deval, Road dust characterization.

1. Introduction

Suspended matter from road traffic is generated from wearing of the pavement, and wear of and emission from the vehicle. In northern European countries, especially Finland, Sweden and Norway, the mechanical wear of asphalt pavements is significant, mainly caused by extensive use of studded tires during winter. In Norway, about 47 % of the vehicles use studded tires (Norwegian Public Roads Administration, 2007). This leads to substantial problems with air quality in urban areas (Johansson, 2006). Measurements show that the mineral part in the dust is about 70-80 % in the winter, compared to only 15-25 % in the summer (Bakløkk et al., 1997, Låg et al., 2004). A study from 2005 showed 87 % inorganic material in dust downfall samples collected in the period March-May close to a heavily trafficked road in Trondheim, Norway (Snilsberg et al., 2006). Asphalt pavements consist of about 95 % rock material (90 % aggregate and 5 % filler), and about 5 % bitumen. The main component in the dust from wear of asphalt pavements will, therefore, be mineral particles. In periods during winter, the contribution from road traffic of suspended matter in the air can be more than 90 % in urban areas (Berthelsen et al., 2005). This is because the road traffic has different characteristics compared with other emitters; the emission takes place close to the grounds where people live, travel and stay, and emitted suspended matter will be whirled up by vehicles and wind over and over again.

Air quality regulations are specified for particles below 10 μm i.e. PM10 and are based on particle mass concentration. According to the European Community (EC) Directive, 1999/30/EC (European Communities, 1999), the daily PM10 average should not exceed 50 $\mu g/m^3$ for more than 35 days per year. The EC Directive regulates the total mass of all particles less than 10 μm irrespective of size, morphology and chemistry, and also irrespective of their health effects. It is, therefore, important to characterize particles generated from wear of pavements using studded tires.

The composition of dust in northern European countries is very different from the rest of Europe. In the rest of Europe, organic particles from exhaust are predominant. These particles are much smaller in size and have lower density than inorganic particles.

The sizes of exhaust particles are usually between 0.1-1 µm, while the dominant part of inorganic particles has sizes ranging from 0.3-100 µm (Myran, 1985). Mineral particles have also a higher density than organic particles, and will, therefore, entirely dominate the measured particle mass concentration. But if number of particles or relative surface area is counted, the organic fraction will dominate.

The wear caused by studded tires can be divided into wear due to abrasive forces and wear due to fragmentation. The driving speed is an important factor; higher driving speeds increase the wear. The wear is 20 % higher for 90 km/h compared to 75 km/h, and 20 % higher for 75 km/h compared to 50 km/h (Bakløkk et al., 1997, Bakløkk, 1997). Swedish tests have shown 44 % higher wear for 85 km/h compared to 60 km/h for lightweight studs (Haakenaasen, 1995). At low driving speed, the abrasion effect dominates, while fragmentation increases at higher driving speeds (Skoglund and Uthus, 1994).

The methods described in this study try to simulate the abrasive and fragmentation effects, and the purpose has been to find simple laboratory techniques to simulate studded tires wear on asphalt pavements. Characterization of generated dust has been performed to compare the different methods and to find the method which agrees best with particles generated from the Pavement Testing Machine (PTM) at the Swedish National Road and Transport Research Institute (VTI).

Particles can in general be characterized based on physical properties, e.g. number, size and shape, and chemical properties, e.g. composition and solubility. The shape and size of mineral particles are important for the interaction with living matter (Furuseth and Myran, 1992, Fubini et al., 1995, Dybing et al., 2005). However, qualitative particle characteristics are also important in regard to the health aspect (Øvrevik et al., 2004). During this study, extensive work has been performed to generate road dust particles from mechanical wear of both asphalt pavements and aggregates. Characterization of the produced road dust particles was done with focus on amount, particle size, particle shape and composition.

2. Materials and methods

The asphalt pavement material tested was stone mastic asphalt (SMA) with 11 mm maximum aggregate size (SMA 11). The use of SMA has reduced the pavement wear by up to 20 % in some parts of Norway (Bakløkk, 1997), and given about 40 % longer service life (Skoglund and Uthus, 1994). The SMA 11 composition was 52 % 8-11 mm, 20 % 2-4 mm and 16 % 0-2 mm Durasplitt/mylonite, 5 % 0-9 mm Lyngås gravel and 7 % Breivik lime filler with bitumen 70/100 and fiber. The rock material used in the SMA was Durasplitt, which is a wear resistant rock material frequently used in Norway on pavements with high traffic volumes. The mylonite aggregate has fine/moderate mineral texture, abrasion value of 0.38, Sa-value of 1.66 and Mv of 6.1 (Myran and Horvli, 1998). The Sa-value is an old Norwegian value used to describe a rock materials resistance against wear by studded tires, and Mv is a value described by EN 1097-9:1998 giving the resistance to wear by abrasion from studded tires of a rock material.

Both asphalt samples and aggregates were tested during the project. Asphalt samples were tested in an indoor PTM, Tröger and Prall, while the unbound aggregates were tested in Los Angeles Abrasion machine, Nordic Ball mill and micro-Deval mill. These methods were also used to produce dust samples, which again were compared to the PTM. In this study the PTM was the reference test method for studded tires on asphalt pavements, and the other methods were compared to this method.

All dust samples were analyzed at the Norwegian University of Science and Technology (NTNU) for particle size distribution, particle shape and mineralogical composition.

2.1. Pavement Testing Machine (PTM)

The PTM at VTI was used to simulate the pavement wear. The method is described by EN 13863-4:2004. The machine has an electrically powered rotating axle with four wheels and adjustable rotating speed (Figure 1). The axel system is tuned to move sideways. The diameter of the test ring is ca. 6 m, and the machine is located in a closed room with controlled ventilation. In this machine particles from wear of pavement and tires can be studied separately, without interference of particles from exhaust and other sources (Gustafsson et al., 2005). The machine also accelerates the study, and pavement types, car tires, friction materials, driving speeds and temperatures can be varied. Asphalt plate samples are made in the laboratory under controlled conditions, and these plates are glued to the circular track. Earlier studies at VTI have shown very good correlation between the studded tire wear on the road and in the machine (Wågberg et al., 2003). Jacobson (1995) reported a correlation factor of R^2=0.96-0.98.

One of the limitations of PTM is the lateral movement of the wheels which creates more wear and possibly more resuspension of the dust compared to real road conditions. In addition all the produced dust will accumulate in the room, while in field conditions; the dust will be blown away by wind and vehicles. This may lead to higher dust concentration in laboratory as compared real field conditions.

The sampling was performed at a speed of 60 km/h with studded tires (Nokian Hakkapelitta 4), relative humidity 79.2-86.0 % and temperature between -6 and 6 ºC, in the room to represent the temperature in winter conditions (Gustafsson, 2007). Samples of dust were collected during driving using a wet vacuum cleaner filled with deionized and distilled water, with the inlet mounted behind one of the studded tires for half an hour. The dust was then dried and characterized.

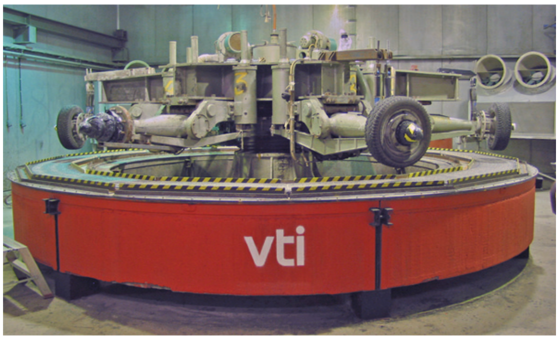

Figure 1. Pavement Testing Machine (VTI)

2.2. Other methods for simulating pavement wear

SMA 11 core samples were tested using two methods that simulate the wear of pavements due to studded tires; Tröger and Prall. These tests are described in the next sections.

2.2.1. Tröger

Tröger is described by EN 1871:2000 Annex K and Norwegian Public Roads Administration (2005). This method was originally designed for testing abrasion of road marking materials, but has also been used to determine the resistance of asphalt pavements to wear caused by studded tires (Hveding et al., 1986, Skoglund and Uthus, 1994, Horvli, 2004). The apparatus is shown in Figure 2. The dry an cooled pavement sample with temperature 4 °C, height 30 mm and diameter 100 mm is mounted on an eccentric swiveling and rotating table with 30 rotations per minute (RPM). The 52 steel needles, which are 2 mm in diameter, hammer the sample driven by a compressed air gun at 5 bars, simulating the hammering and scratching influence of the tire studs (Lerfald, 2007). Particles torn loose from the sample can be collected by a modified wet vacuum cleaner filled with deionized and distilled water. The Tröger produced dust can then be dried and characterized. Studies at VTI have shown a correlation between the studded tire wear on the road and Tröger test of R^2=0.68-0.99 (Jacobson, 1995). A disadvantage with the method is poor reproducibility (Skoglund and Uthus, 1994).The wear, W, is expressed as:

$$W = (M_i - M_s)/\rho \qquad [1]$$

where M_i = mass of original test specimen (g)

M_s = mass of test specimen after testing (g)

ρ = density of tested material (g/cm^3)

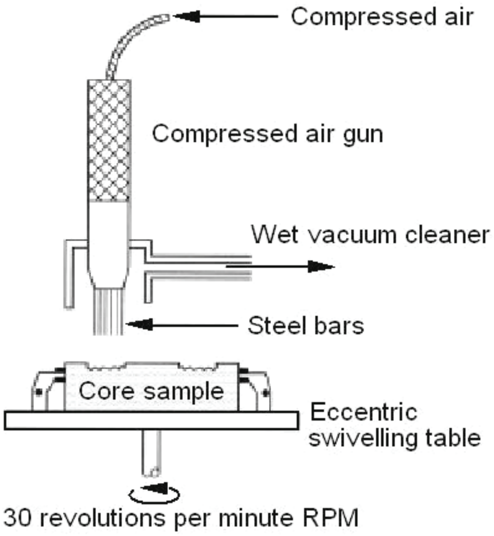

Figure 2. Tröger apparatus (adopted from Norwegian Public Roads Administration, 2005)

2.2.2. Prall

The Prall method is described by EN 12697-16:2004. It was developed to determine wear resistance of asphalt concrete, but has also been used for other asphalt mixtures. The apparatus is shown in Figure 3. The pavement sample with height 30 mm and diameter 100 mm is conditioned in water at 4-5ºC, before it is put in a test chamber with 40 steel balls. The steel balls, which are 12 mm in diameter, hammer the sample driven by a stay rod which rotates with 950 RPM, and cooling water is flushed through the chamber with efficiency 2 liter per minute. Particles torn loose from the sample are washed out by the cooling water into a collector. The Prall-produced dust can then be dried and characterized. The abrasion value, Abr_A, is expressed as:

$$Abr_A = (M1-M2)/\rho_{bssd} \qquad [2]$$

where M1 = mass of water stored specimen (surface dry) before abrasion (g)

M2 = mass of water stored specimen (surface dry) after abrasion (g)

ρ_{bssd} = bulk density of specimen (g/ml)

Earlier studies at VTI have shown a correlation between the studded tire wear on the road and Prall test of R^2=0.89-0.96 (Jacobson, 1995, Raitanen, 2005).

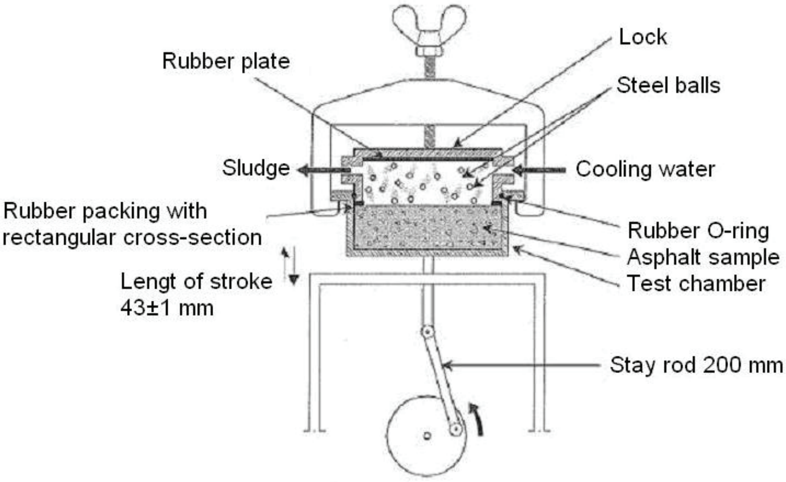

Figure 3. Prall apparatus (adopted from EN 12697-16:2004)

2.2.3. Pavement wearing ratio (PWR)

The PWR method was not used in this study. The method, described by EN 12697-16:2004, originates from Finnish experience and correlates with abrasion in field. The side of the core sample, with diameter 100 mm and height 50 mm, is tested with three small rotating studded tires at 520 RPM for 2 hours. The temperature of the sample is 5 ºC. During the test the sample is rinsed with water. The method is used for estimating the wearing properties of the asphalt surfaces when studded tires are used.

2.3. Methods for simulating aggregate wear

Three fractions of the aggregate in the SMA 11 pavement were tested: 8.0-11.2 mm Durasplitt; 4.0-11.2 mm Durasplitt; and 0-11.2 mm Durasplitt and Lyngås gravel, without filler. The testing procedures are described in the next sections. Los Angeles test was performed under dry conditions, while the Nordic Ball mill and micro-Deval tests were performed under both dry and wet conditions.

2.3.1. Los Angeles mill (LA)

The Los Angeles method, described by EN 1097-2:1998, is used to determine the resistance to fragmentation of an aggregate. The apparatus is shown in Figure 4. The test was originally developed in USA; it was adopted as an ASTM method in 1938. The CEN version of the test method is similar to the ASTM method. The most significant difference between the CEN and ASTM methods is that in the CEN method masses and dimensions are specified in metric units, whereas in the ASTM method they are specified in imperial units.

The standard fraction tested is 5 kg where 65 % is 10.0-12.5 mm and 35 % is 12.5-14.0 mm (Norwegian Public Roads Administration, 2005). The test is run dry with 11 steel balls which are 45-49 mm in diameter for 500 rotations with 31-33 RPM. Inside the mill a shelf with width 90 mm and thickness 25 mm is installed. The shelf will lift both the aggregate and the steel balls during rotation. This will result in fragmentation of the aggregate. The weight loss, defined by amount of material below 1.6 mm, relates to the resistance to fragmentation for the material tested. The Los Angeles coefficient, LA_C, is estimated as follows:

$$LA_C = 100*(5000-m)/5000 \qquad [3]$$

where m = material above 1.6 mm (in gram), after testing

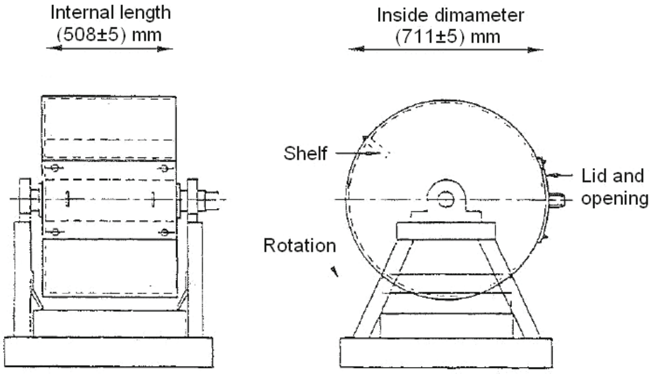

Figure 4. Los Angeles mill (adopted from EN 1097-2:1998)

2.3.2. Nordic Ball mill (KM)

The Nordic Ball mill test determines the resistance to wear by abrasion from studded tires, and is described by EN 1097-9:1998. The apparatus is shown in Figure 5. Inside the drum there are three ribs which will turn and lift the aggregate when rotating. This results in a small influence of fragmentation in addition to the dominant abrasive effect.

The standard test is performed dry or wet with aggregate fraction 11.2-16.0 mm. The aggregate is drummed together with 7000 gram of steel balls which are 15 mm in diameter, with or without 2 liter of water for 5400±10 rotations at 90±3 RPM for about one hour. The weight loss, defined by amount of material below 2 mm, relates to the studded tire abrasion resistance. The mill value, A_N, is estimated as follows:

$$A_N = 100*(m1-m2)/m1 \qquad [4]$$

where m1 = dry weight of sample before testing

m2 = dry weight of sample (> 2 mm) after testing

According to Horvli and Vaernes (2006), the KM gives a ranking of rock materials with regard to the resistance to wear by studded tires. Studies at VTI have shown a correlation between the studded tire wear on the road and the wet Nordic Ball mill test of R^2=0.93-0.94 (Jacobson, 1995).

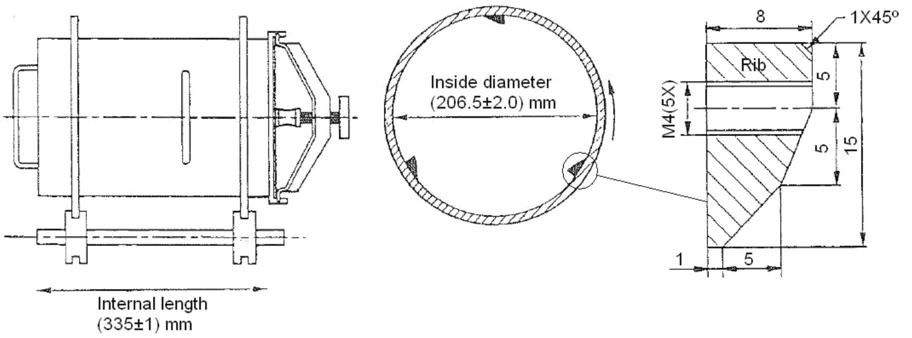

Figure 5. Nordic Ball mill (adopted from EN 1097-9:1998)

2.3.3. Micro-Deval mill (MD)

The micro-Deval test, described by EN 1097-1:1996, is used to determine the resistance to wear of a sample of aggregate during rolling. The apparatus is shown in Figure 6. The test is usually performed wet which is the reference method, but can also be performed under dry conditions. The test method was originally developed in France and, in contrast to the Los Angeles and Nordic Ball mill, is close to a pure abrasive method.

The 500 gram of steel balls 10 mm in diameter, and 2 kg of aggregate fraction 10-14 mm are milled with or without 2.5 liter of water for 12 000 revolutions at 100 RPM. It is possible to run four samples at the same time.

The weight loss, defined by amount of material below 1.6 mm, determines the micro-

Deval coefficient, M_{DE}:

$M_{DE} = 100*(500\text{-}m)/500$ (wet condition) [5]

where m = mass (in gram) of oversize fraction (> 1.6 mm) after testing

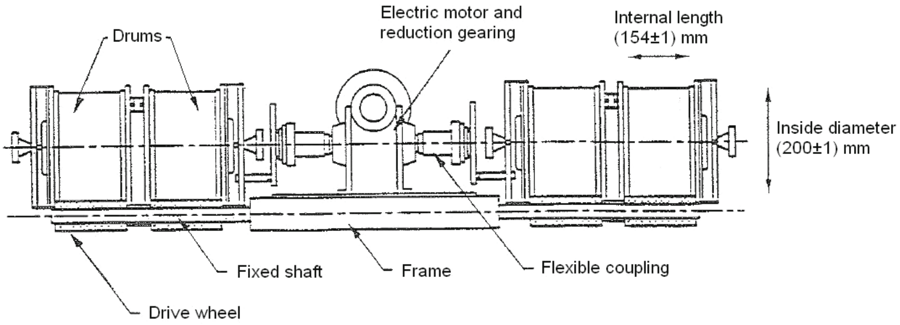

Figure 6. Micro-Deval mill (adopted from EN 1097-1:1996)

2.4. Particle characterization

Methods used for particle characterization were laser diffraction to get particle size distributions by Coulter LS 230 in the size range 0.04-2000 µm, image analysis to get the particle shape as roundness by Pharma Vision 830 in the size range 5-2000 µm, and x-ray diffraction (XRD) by Philips PW 1830 to find the mineralogical composition.

Fines are defined as particles below 63 µm (EN 13043:2002) and dust samples from laboratory aggregate wear were therefore sieved at 63 µm to have the same basis for particle characterization. Dust samples from the PTM, Tröger and Prall were not sieved because of small amounts of material collected.

Before XRD analysis the samples were sieved through a 10 µm sieve to see if there were differences in composition between fractions larger and smaller than 10 µm. This was done because regulations regarding particulate matter and air quality (European Communities, 1999) are set for the fraction below 10 µm.

3. Results and discussions

Results from the characterization of fines generated using the different methods are described in the next sections. The characterization involved the determination of quantities, particle size, particle shape and composition. The PTM was the reference test method in the study.

3.1. Quantities

Table 1 and 2 give the amounts of fine material produced by pavement and aggregate wear methods, respectively. The amounts of fine material produced in the different methods vary by a factor of 500. This is due to different wear durations and procedures of the methods, as described in section *2 Materials and methods* and section *3.5 Evaluation of wear methods/procedures*. LA is the method which produces most fines per minute. Fine materials studied from both LA and MD are fractions below 1.6 mm, while it was the fraction below 2 mm for the KM. For PTM, Prall and Tröger all fine materials produced were collected for further characterization.

Table 1. Fine material produced in the pavement wear test methods

Method	Material fraction used	Time (min)	Amount	
			Total (g)	g/min
PTM	All	30	10	0.33
Prall	All	5	17	3.40
Tröger	All	5	18	3.60

Table 2. Fine material produced in the aggregate wear test methods

Method	Material fraction used	Time (min)	Amount			
			Total (g)	> 63 um	< 63 um	g/min
LA 8-11 Dry	< 1.6 mm	15	630	39 %	61 %	42.00
LA 4-11 Dry	< 1.6 mm	15	739	33 %	67 %	49.29
LA 0-11 Dry	< 1.6 mm	15	1448	28 %	72 %	96.51
KM 8-11 Dry	< 2 mm	60	57	88 %	12 %	0.94
KM 4-11 Dry	< 2 mm	60	183	94 %	6 %	3.04
KM 0-11 Dry	< 2 mm	60	443	98 %	2 %	7.39
KM 8-11 Wet	< 2 mm	60	94	86 %	14 %	1.57
KM 4-11 Wet	< 2 mm	60	209	98 %	2 %	3.48
KM 0-11 Wet	< 2 mm	60	471	98 %	2 %	7.85
MD 8-11 Dry	< 1.6 mm	120	3	89 %	11 %	0.02
MD 4-11 Dry	< 1.6 mm	120	19	88 %	12 %	0.16
MD 0-11 Dry	< 1.6 mm	120	273	97 %	3 %	2.27
MD 8-11 Wet	< 1.6 mm	120	55	99 %	1 %	0.45
MD 4-11 Wet	< 1.6 mm	120	77	100 %	0 %	0.64
MD 0-11 Wet	< 1.6 mm	120	312	96 %	4 %	2.60

The LA, KM and MD samples were sieved through a 63 µm sieve to have the same basis for assessment and further characterization. For the LA method, 60-70 % of the fine material was smaller than 63 µm. For KM and MD, the amounts of fines smaller than 63 µm were 2-14 % and up to 12 %, respectively.

3.2. Particle size

The size distributions determined by Coulter LS 230 apparatus are shown in Figure 7, both as Volume frequencies (%) and Cumulative volumes (%). Only particles < 63 µm are displayed.

The particle size distribution of particles generated by Tröger and Prall agree well with those produced by PTM (Tröger slightly better than Prall).

For aggregate wear, the LA is comparable to Tröger and Prall, while KM and MD produced more fine grained material. MD gives finer grading than KM. This could be improved by shortening the mill time. The mill time of LA is 15 minutes; MD is 120 minutes, while KM has a mill time of 60 minutes. Wet grinding gives finer particles compared to dry grinding for KM and MD.

Earlier studies have shown that the LA test may give a representative size distribution compared to field measurements (Myran and Horvli, 1998).

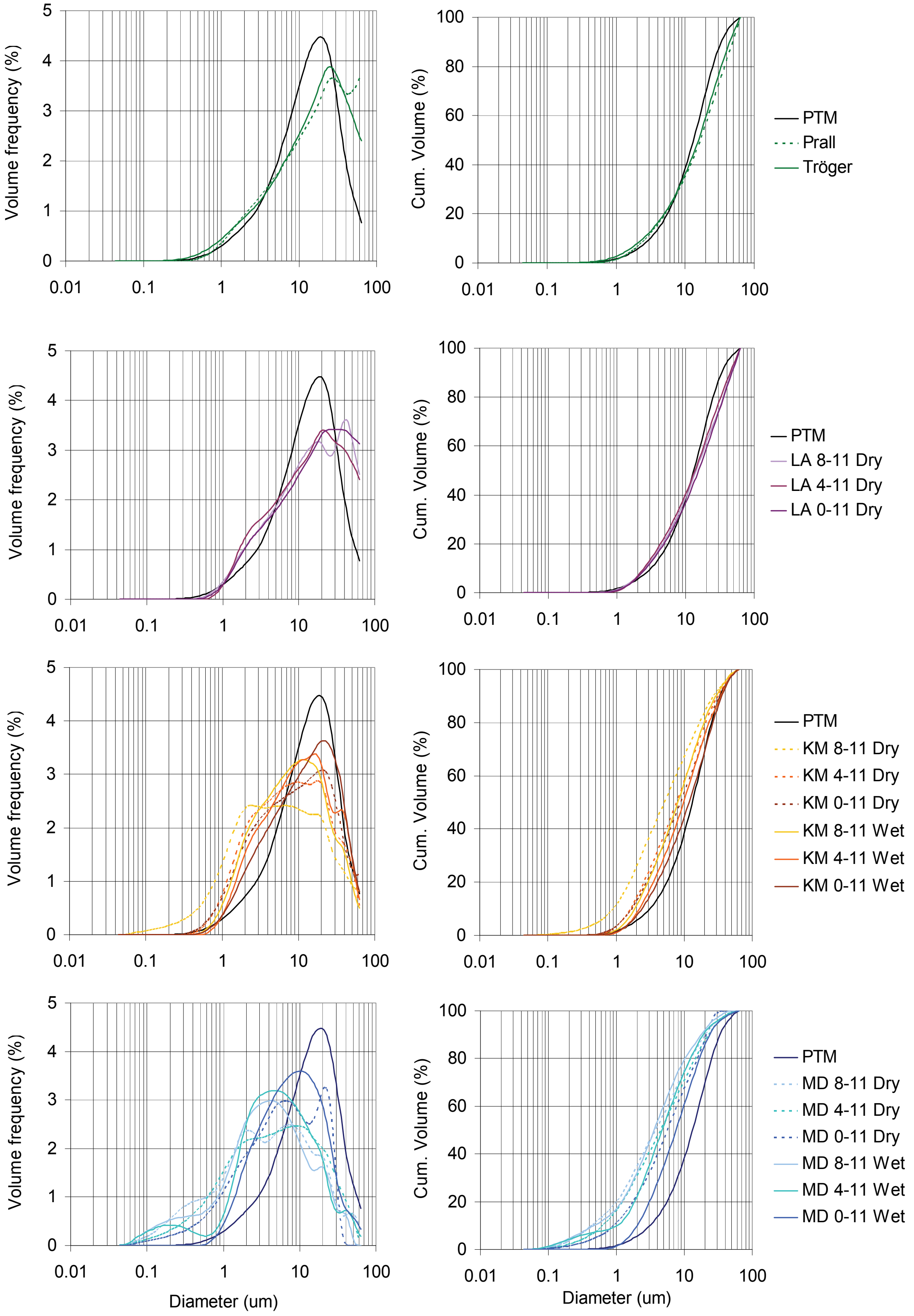

Figure 7. Size distributions as volume frequencies (%) and cumulative volumes (%)

3.3. Particle shape

The particle shape analysis was performed with an automated imaging technique, giving the roundness of the different samples. Roundness is a measure of the length/width relationship, with values between 0-1. A perfect circle has roundness 1.0, while a needle shaped object has roundness close to 0. For each sample 10 000 particles were characterized.

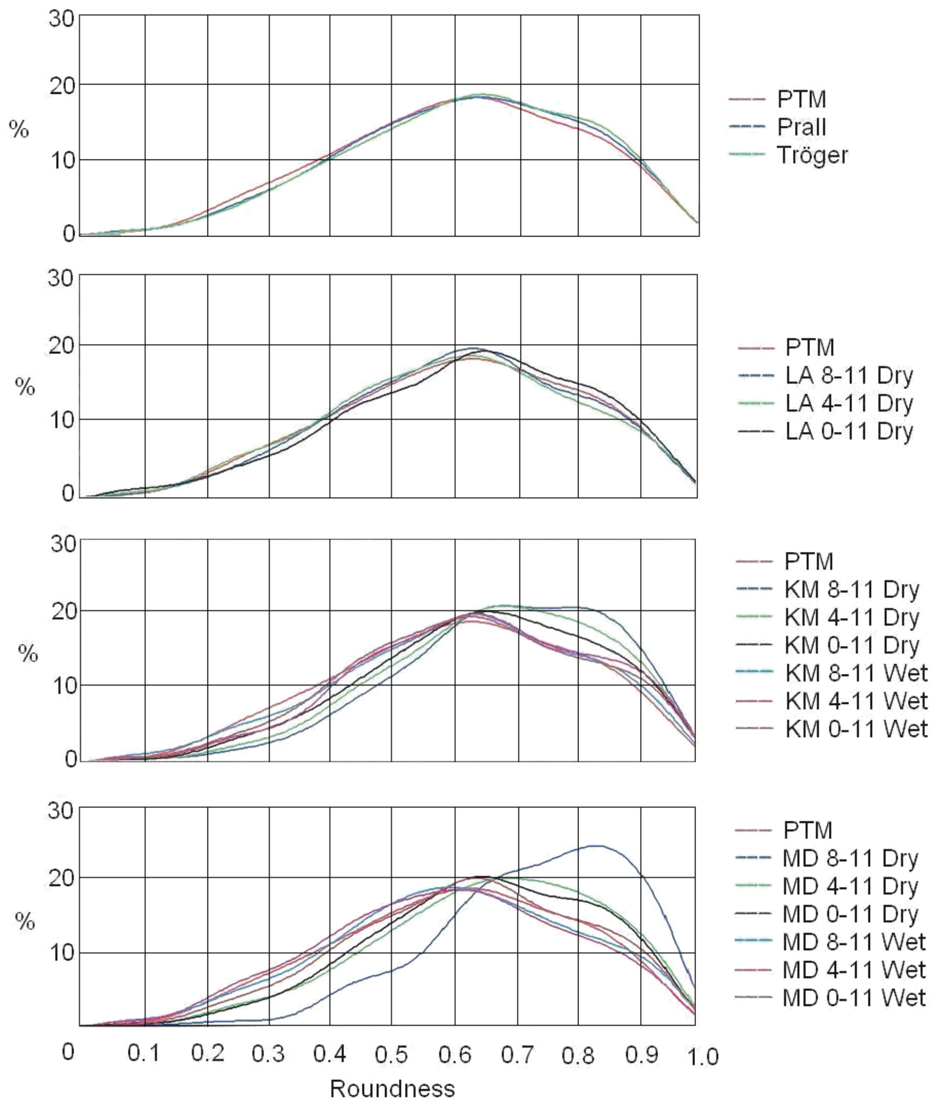

Figure 8. Roundness distribution by number (%)

The particle shape analysis shows that Prall and Tröger seem to be the methods best suited to simulate wear from studded tires. Both methods have roundness almost similar to the curve of a sample from the PTM.

Regarding the “mill methods”, the LA turns out best, while KM and MD are not as suited, especially the dry grinding procedure. Dry grinding requires more energy to break a grain compared to wet grinding and will cut the edges of the grains. This is in agreement with the dry grinding with KM and MD which produce fines with higher roundness than the other methods. Of the aggregate fractions tested, the 8-11 mm fits best with the shape curve for PTM, and 0-11 mm least.

Sample MD 8-11 Dry was sieved with different equipment than the rest of the samples, which probably gave a different roundness.

3.4. Mineralogical composition

The mineralogical composition was determined with XRD which is a qualitative and semi-quantitative method. The method is based on dissimilar diffraction of the x-ray beam because of different lattice spacing for different minerals. The concentration estimate may be in error by a factor of two or more (Skoog et al, 1998). The mineralogical composition is given in Figure 9.

The analysis was performed on sieved samples both for material larger and smaller than 10 µm. Minerals found in all samples were quartz, plagioclase, mica, chlorite, calcite and epidote. The amount of each mineral varies somewhat from sample to sample; with plagioclase around 50 %, quartz around 30 % and epidote around 10 %. No clear difference was found in mineral distribution between materials larger and smaller than 10 µm, which means that none of the methods is better than the others in simulation of wear by studded tires.

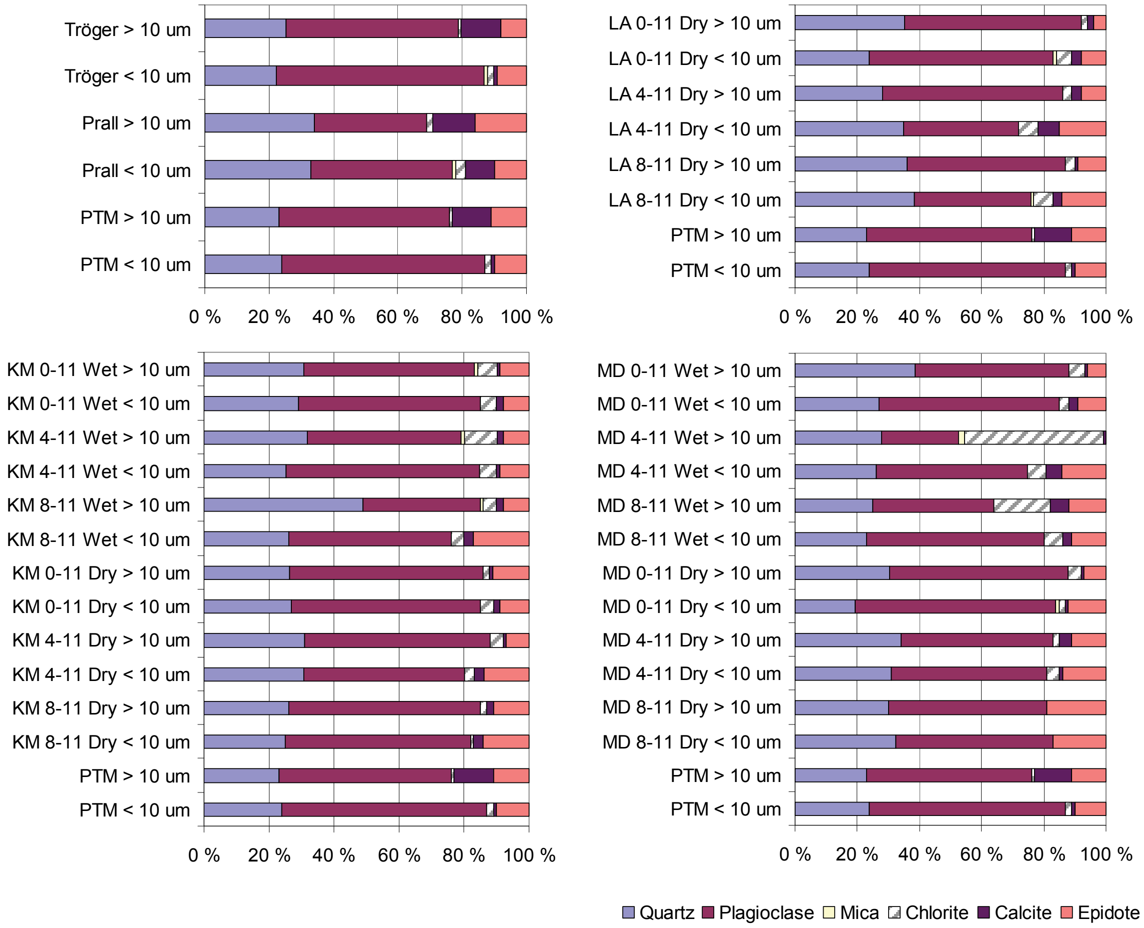

Figure 9. Mineralogical composition (%)

3.5. Evaluation of wear methods/procedures

The methods that have been considered in this study are different, but comparable with regard to simulating wear from studded tires. Table 3 gives some characteristics for the different methods. All methods can be changed in different ways. The LA, KM and MD can be modified according to milling time, speed, amount and size of balls, input etc., which would give different results. In this study they were performed close to standard procedures. Four of the methods use steel balls (Prall, LA, KM and MD), while Tröger uses steel needles and PTM use studded tires. The PTM, Tröger and LA were run under dry conditions, Prall can only be run with water, KM and MD can be performed both wet and dry (with or without water). LA has larger steel balls and 3.5 times larger diameter of the drum compared to KM and MD. The LA causes mainly fragmentation forces on the aggregate material, while MD causes mainly abrasive forces on the material. KM is something in between, but close to MD.

Table 3. Comparison of the methods used

Method	Dry	Wet	Input			Wear method	Time
				Sample (g)	Water (l)		(min)
PTM	x		Asphalt		-	Studded tire, 60 km/h, 110 studs each 1.1 g, 1.2 mm overhang	30
Prall		x	Asphalt	600	10	40 steel balls, d=12 mm, 950 rpm	5
Tröger	x		Asphalt	600	-	52 hardened steelneedles, 2 mm in diameter, 500 kPa	15
LA	x		Aggregate	5000	-	Steel balls, d=45-49 mm, total 4762 g, 32 rpm, 500 rotations, L=508, D=711	15
KM	x	x	Aggregate	1000	2	Steel balls, d=15 mm, total 7000 g, 90 rpm, 5400 rotations, L=335, D=206	60
MD	x	x	Aggregate	500/1000*	2	Steel balls, d=10 mm, total 5000 g, 100 rpm, 12000 rotations, L=154, D=200	120

d=dimeter of steel balls, L=Length of drum, D=Diameter of drum, * 500g for 8-11, 1000 g for 4-11 and 0-11

In this study the "reference PTM studded tire wear" was collected while driving at 60 km/h. If other speeds were chosen, the particle characterization might have given other results. The reproducibility of dust production for each method and quantity variance should be found through systematic testing which was not a task in this project.

The dust produced by Tröger and Prall is more similar to the dust produced in the field because the dust is generated from asphalt mixtures, while the dust produced by LA, KM and MD comes from the aggregate only. In addition, none of these methods include the effect of car tire.

4. Conclusion

It is possible to produce dust comparable to studded tire wear by use of simple laboratory techniques. According to this study, Prall and Tröger are the methods best suited to give fine material which comply with particles generated from the PTM (60 km/h, SMA 11). It also seems that one can test the aggregate alone to get reasonably good samples for analysis of dust from wear by studded tires. Among the aggregate testing procedures, the LA method give best correlation with the PTM. This has significance with regard to cost in that one can avoid building test sections to generate and characterize the dust from pavement wear.

5. Acknowledgements

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PAPER IV

Asphalt pavement wear and road dust generation – Effects of different aggregate grading, vehicle tires and driving speed

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Abstract

Studded tires cause mechanical wear of asphalt pavements in the northern European countries which leads to substantial problems with air quality in urban areas. Experience show that the pavements wear resistance is among other factors dependent on amount and size (D_{max}) of the coarse aggregate. To reduce noise from pavements, one measure is to reduce the aggregate size (D_{max}) in the pavements. However, this can increase the production of suspended matter from pavement wear. In this study two similar pavement types with different aggregate size (D_{max}) have been investigated with regard to dust production using the Tröger equipment. The effect of speed and studded tires versus non-studded tires are evaluated using an indoor large scale Pavement testing machine applied at the Swedish National Road and Transport Research Institute. The share of studded tires varied between 0-100 %, and the traffic speed between 30-70 km/h. Samples of dust were collected and characterized. The study has clearly shown that amount of studded tires and driving speed is important for pavement wear and road dust generation. Aggregate size does not affect the dust generation in the same regard.

Keywords: Pavement wear, studded tires, non-studded winter tires, aggregate size, driving speed, Pavement testing machine, Tröger, road dust characterization

1. Introduction

Studded tires cause mechanical wear of asphalt pavements in the northern European countries which leads to substantial problems with air quality in urban areas. Experience show that the pavements wear resistance is among other factors dependent on amount and size (D_{max}) of the coarse aggregate. Pavements with reduced aggregate size (D_{max} < 16 mm) are becoming more and more popular in Norway. The aggregate size D_{max} is defined as the upper limit for the aggregate grading; however, oversize materials are accepted within certain limits (Statens vegvesen, 2005 B). Earlier pavements with D_{max} of 16 mm were used because of good wear resistance against studded tires. The use of studded tires is decreasing. Today D_{max} of 11 mm is used, and also pavements with D_{max} of 8 mm and even 6 mm are being tested. To minimize noise from pavements, one measure is to reduce the aggregate size (D_{max}) in the pavements. Measurements show reduced rolling noise in accordance with reduced D_{max}. However, the reduction in D_{max} can lead to increased rutting and dust generation from the pavements.

In this study two similar pavement types with different aggregate size (D_{max}) have been investigated with regard to dust production using the Tröger equipment at The Norwegian University of Science and Technology (NTNU). The Tröger was used on core samples of asphalt concrete (AC) and stone mastic asphalt (SMA) with D_{max} of 6, 8 and 11 mm. AC and SMA are pavement types mainly used on roads with heavy traffic (> 5000 vehicles per day). SMA is a wear resistant pavement with SPSV around 2-4, while AC has SPSV around 6-8 (Horvli, 1996). SMA consists of a coarse aggregate skeleton bound with a mastic consisting of crushed rock fines, filler and bitumen. The essential requirement for a successful SMA is the gap grading with high amount of coarse aggregate (> 2 mm). The stone to stone contact of the coarse aggregate ensures a very durable matrix capable of high resistance to deformation. The AC has a more continuous aggregate grading, with relatively high amount of material < 2 mm which gives a stable aggregate skeleton. It can be expected that the deformation resistance of SMA is higher than that of AC.

The effect of driving speed and studded tires versus non-studded winter tires on pavement wear and dust generation has been investigated in a large scale indoor Pavement testing machine (PTM) applied at the Swedish National Road and Transport Research Institute (VTI). The PTM tests were run with a SMA with D_{max} of 11 mm, different driving speeds and different shares of studded tires.

Several studies (Lindland, 1986, Uthus, 1993, Skoglund and Uthus, 1994, Jacobson, 1995, Bakløkk, 1997, Bakløkk et al., 1997, Wågberg et al., 2003, Horvli and Værnes, 2006) have shown that D_{max}, amount and mechanical strength of the coarse aggregate, driving speed, studded tires and voids are the most important factors for pavement wear. These factors are more closely described in the next sections.

1.1. Aggregate size and mechanical strength

Requirements for mechanical and physical properties for aggregate in asphalt pavements are set by European standards; EN 1097-9:1998 (CEN, 1998 B) determining a rock materials resistance to abrasion by studded tires (Nordic ball mill), EN 12697-16:2004 (CEN, 2004 A) determining bituminous mixtures studded tires abrasion resistance (Prall), EN 1097-2:1998 (CEN, 1998 A) determining a rock materials resistance to fragmentation (Los Angeles) and EN 1097-1:1996 (CEN, 1996) determining a rock materials resistance to wear (micro-Deval).

In Norway, specific studded tire wear is estimated in two ways; SPS and SPSV. SPS (specific studded tire wear) is defined as amount of worn mass for a passenger car with studded tires (g/km). Heavy vehicles are assumed to equal 5 passenger cars. SPS is estimated on basis of measured worn out area (rutting) and adjusted for traffic level, amount of vehicles using studded tires and chains, and length of the studded tire season (Skoglund and Uthus, 1994).

SPSV (specific studded tire wear in volume) is defined as volume of worn mass for a passenger car with studded tires (cm^3/km), and is calculated from the SPS value (Trøan, 2000):

$$SPSV = SPS / \rho_{pavement} \qquad [1]$$

where $\rho_{pavement}$ = density of the asphalt pavement

Recent studies have shown that reduction in D_{max} and aggregate quality result in significant higher wear from studded tires. Thus, the properties of the mortar become more important when D_{max} is reduced. One study (Horvli and Vaernes, 2006) gave twice as high rutting for pavements with D_{max} of 8 mm compared to 11 mm.

A wear parameter has been defined as (Uthus, 1993):

$$\text{Wear parameter} = 100 * (\text{Aggregate quality}) * (\text{Void}) / (\text{Aggregate size}) \qquad [2]$$

where Aggregate quality = Abrasion value*√(Aggregate crushing value)

Void = 1 when void > 4.5 %

$= [(\text{Void}-4.5)/10]^2$ for void < 4.5 %

Aggregate size = % material > 8 mm

High void content in asphalt pavements increases the rutting. The rutting will increase when the void content in dense asphalt types exceed 4.5-5 % (Bakløkk et al., 1997, Bakløkk, 1997). The same effect is not experienced for porous (open graded) asphalt types. In most literature rutting is referred to as wear, even if the substantial part of the rutting was caused by deformations.

According to Jacobson (1995) wearing resistance increases with increased coarse aggregate content above 8 mm, and also with increasing D_{max}. SMA 16 is worn approximately half as much as SMA 8. The difference between SMA 12 and SMA 16 is 25 % (Jacobson, 1995).

Equation [2] shows high correlation with wear measured on pavements in field, and it has later been modified to be valid for the Nordic ball mill and material > 4 mm (Horvli and Værnes, 2006):

$$\begin{aligned}\text{Wear parameter} &= 100 * (\text{Aggregate quality}) / (\text{Aggregate amount}) \\ &= 100 * (\text{Mill value}) / (\%\ \text{material} > 4\ \text{mm}) \qquad [3]\end{aligned}$$

1.2. Studded tires

Pavement wear from studded tires and rutting is the most important cause for repaving on Norwegian roads (Skoglund and Uthus, 1994). A maximum of 25 mm rutting is accepted on a road section in Norway before maintenance measures must be activated (Statens vegvesen, 2003). The wear is dominant for roads with traffic amount above 3000 vehicles per day. About 250 000-300 000 tons of asphalt is worn off Norwegian roads every year, but the tendency is decreasing (Bakløkk, 1997). The specific wear is reduced to one third of what it was 30 years ago because of more wear resistant pavements and development in studded tires (Bakløkk, 1997). Jacobson (1995) reports that a light weight stud wears only half as much compared to a heavier steel stud on the same tire.

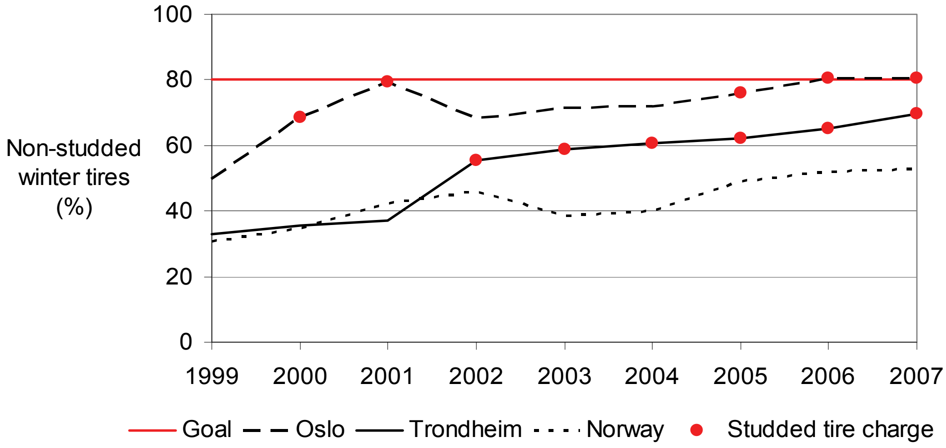

Figure 1. Amount of non-studded winter tires (Statens vegvesen, www.luftkvalitet.info)

The authorities in Norway have decided on a goal of 80 % non-studded winter tires in the largest cities in Norway (Krokeborg, 1998). The use of non-studded winter tires has increased from 1999 until today for Oslo, Trondheim and Norway, as shown in Figure 1. From the winter season 1999/2000 in Oslo and 2001/02 in Trondheim a charge for using studded tires was introduced to stimulate citizens to choose non-studded winter tires. This charge has had a substantial effect. In 1999 the amount of non-studded winter tires was about 30 % in Trondheim and has increased to about 65 % in 2006. A small amount of studded tires is still desirable to prevent polishing of the pavements.

1.3. Driving speed

The driving speed is an important factor for wear of asphalt pavements as shown in Figure 2. Higher driving speed increase the wear (Johansson et al., 2004), i.e. the wear is 20 % higher for 90 km/h compared to 75 km/h, and 20 % higher for 75 km/h compared to 50 km/h (Bakløkk et al., 1997, Bakløkk, 1997). Swedish tests showed 44 % higher wear for 85 km/h compared to 60 km/h for light weight studs (Haakenaasen, 1995). Swedish tests in the PTM indicate a factor of 2.5 when the speed increases from 30 to 50 km/h, and a factor of 4 from 30 to 70 km/h for the emission of PM10 (particles < 10 μm in size).

The effect of studded tires can be divided into wear because of abrasive forces and fragmentation. At low driving speed the abrasion effect dominates, while fragmentation forces increases at higher driving speeds (Skoglund and Uthus, 1994).

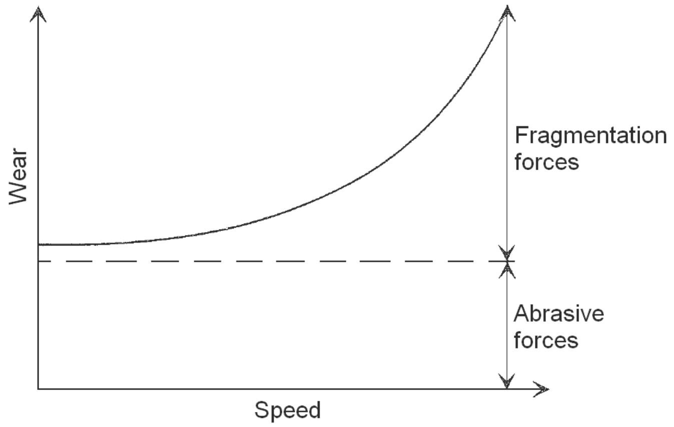

Figure 2. Pavement wear as a function of speed (Skoglund and Uthus, 1994)

The driving speed also has large influence on the turbulence vehicles cause, and this is important for resuspension of particles. Higher driving speed gives higher turbulence. Experiment with reduced speed on main roads in Oslo, Norway, has shown that reduction in driving speed gives significant reduction in PM10 level (Hagen et al., 2005). Heavy vehicles cause more turbulence compared to passenger cars because of the size and design of the vehicle and tires (Johansson et al., 2004).

2. Materials and methods

The PTM, Tröger, Prall, asphalt materials, car tires, particle sampling and measuring apparatus used are described in the next sections.

2.1. Pavement testing machine (PTM)

The PTM at VTI was used to simulate the pavement wear. The machine has an electrically powered rotating axle with four wheels and adjustable rotating speed (Figure 3). The axel system is tuned to move sideways. The diameter of the test ring is ca. 6 m, and the machine is located in a closed room with controlled ventilation. In this machine wear particles from pavement and tires can be studied separately, without interference of particles from exhaust and other sources (Gustafsson et al., 2005). The machine also accelerates the study, and pavement types, car tires, friction materials, driving speeds and temperatures can be varied. Asphalt plate samples are made in the laboratory under controlled conditions, and these plates are glued to the circular track, run over by four wheels. Earlier studies at VTI have shown very good correlation between the studded tire wear on the road and in the machine (Wågberg et al., 2003). Jacobson (1995) reports a correlation factor of R^2=0.96-0.98. The method is described by EN 13863-4:2004 (CEN, 2004 B).

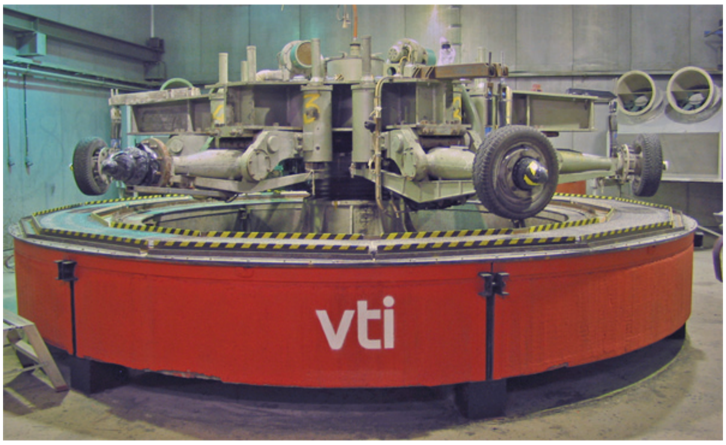

Figure 3. Pavement testing machine (Gustafsson et al., 2007)

2.2. Tröger equipment

The Tröger equipment has been used for testing asphalt samples from AC and SMA with different D_{max}. Tröger is described by EN 1871:2000 Annex K (CEN, 2000) and Statens vegvesen (2005 A). This method was originally designed for testing abrasion of road marking materials, but has also been used to determine the studded tire wear resistance for asphalt pavements (Hveding et al., 1986, Skoglund and Uthus, 1994, Horvli, 2004). The apparatus is shown in Figure 4. The dry pavement sample (height 30 mm and diameter 100 mm) is mounted on an eccentric swiveling rotating table (30 rotations per minute). Steel needles (52 needles, each 2 mm in diameter) are hammered on the sample by a compressed air gun (5 bar), simulating the beat and scratching influence from the tire studs (Lerfald, 2007). Particles torn loose from the core have been sampled by a modified wet vacuum cleaner (with deionized and distilled water) and dried. The wear (W) is expressed as:

$$W = (Mi-Ms)/\rho \qquad [4]$$

where Mi = mass of original test specimen (g)

Ms = mass of test specimen after testing (g)

ρ = density of tested material (g/cm^3)

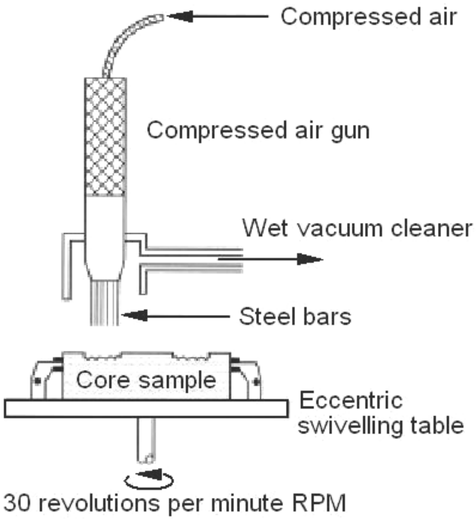

Figure 4. Tröger apparatus (adopted from Statens vegvesen, 2005 A)

Studies at VTI have shown a correlation between the studded tire wear on the road and Tröger test of R^2=0.68-0.99 (Jacobson, 1995). A disadvantage with the method is poor reproducibility (Skoglund and Uthus, 1994).

2.3. Prall equipment

The Prall equipment has been used for testing asphalt samples from the PTM. The Prall method is described by EN 12697-16:2004 (CEN, 2004 A). It was developed to determine wear resistance of asphalt concrete, but has also been used for other asphalt mixtures. The apparatus is shown in Figure 5. The pavement sample (height 30 mm and diameter 100 mm, conditioned in water at 4-5ºC) is put in a test chamber with 40 steel balls (12 mm in diameter). The steel balls hammer the sample driven by a stay rod which rotates with 950 rotations per minute, and cooling water is flushed through the chamber (2 liter/minute). Particles torn loose from the sample are washed out by the cooling water into a collector. The Prall produced dust can then be dried and characterized. Studies at VTI have shown a correlation between the studded tire wear on the road and Prall test of R^2=0.89-0.96 (Jacobson, 1995, Raitanen, 2005).

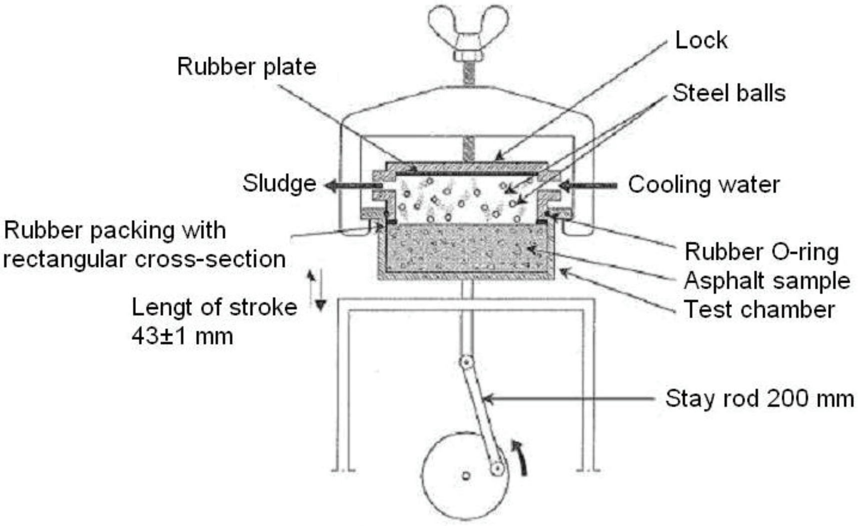

Figure 5. Prall apparatus (adopted from EN 12697-16:2004)

2.4. Asphalt materials

The material tested in the PTM was SMA with D_{max} of 11 mm (SMA 11). The use of SMA compared to AC has reduced the pavement wear up to 20 % in some parts of Norway (Bakløkk, 1997), and given about 40 % longer service life (Skoglund and Uthus, 1994). The SMA aggregate composition was Durasplitt (mylonite), Lyngås gravel (glacifluvial deposit), and Breivik filler with bitumen 70/100 and fiber. The binder content was 6 %. The grading of SMA 11 is shown in Table 1. Durasplitt is a wear resistant rock material frequently used in Norway on pavements with high traffic volumes. The rock has fine/moderate mineral texture, abrasion value of 0.38, Sa-value of 1.66 and mill value of 6.1 (Myran and Horvli, 1998).

Table 1. Aggregate grading (%), PTM

Aggregate Size (mm)	Durasplitt 8-11	2-4	0-2	Gravel 0-9	Filler
SMA 11	52	20	16	5	7

The materials tested with Tröger were asphalt core samples taken from six different test sections in the Trondheim area (Rv 715 Trolla) with AC and SMA both with D_{max} of 6, 8 and 11 mm. The pavements were laid in 2005, and the core samples taken in 2006. The traffic amount at Trolla is 2600 vehicles per day with a speed limit of 70 km/h. The aggregate composition was Vassfjell (gabbro and greenstone), Heggberget gravel (river gravel), and Hylla filler with bitumen 70/100 and amin (0.3-0.5 %). The binder content was 6.1, 5.9 and 5.6 for AC 6, AC 8 and AC 11 respectively, and 6.6, 6.4 and 5.8 for SMA 6, SMA 8 and SMA 11 respectively. The aggregate grading is shown in Table 2. Vassfjell is a wear resistant rock material much used in the Trondheim area. The rock has medium/coarse mineral texture, abrasion value of 0.49, Sa-value of 2.08, mill value of 10.7, Los Angeles coefficient of 13.5, and polished stone value of 53 (Myran and Horvli, 1998). For each test section three asphalt cores were tested in the Tröger apparatus.

Table 2. Aggregate grading (%), Tröger

Aggregate	Vassfjell				Gravel			Filler
Size (mm)	8-11	4-8	3-6	0-4	0-6	0-8	0-11	0-0.5
AC 6			25	33	37			5
AC 8		25		33		37		5
AC 11	25	10		15			45	5
SMA 6			50	20	22			8
SMA 8		50		20		22		8
SMA 11	45	15		15			18	7

2.5. PTM tires

The tires used in the PTM study were both studded tires (Nokian Hakkapellitta 4) and non-studded winter tires (Nokian Hakkapellitta RSi). Four tires were installed at the PTM. Different shares of studded tires were used in the study with SMA 11, with five combinations: 100 % studded tires, 75 % studded tires/25 % non-studded winter tires, 50 % studded tires/50 % non-studded winter tires, 25 % studded tires/75 % non-studded winter tires, and 100 % non-studded winter tires. All tests were performed with speed 30-70 km/h and temperature -6 to 6ºC (Gustafsson et al., 2007). Rubber samples from the tires were gathered to compare the dust composition to the tires.

2.6. Sampling of dust

Samples of dust produced with the PTM were collected during driving using a wet vacuum cleaner (with deionized and distilled water) mounted with the inlet behind one of the tires. The produced dust was then dried and characterized. Sampling of dust produced from the SMA 11 was performed behind a studded tire and a non-studded winter tire while the machine was running at 60 km/h. The sampling time was 30 minutes. The sampling from a studded tire was performed while the PTM was equipped with 3 studded tires and 1 non-studded winter tire, while sampling from a non-studded tire was performed while the PTM was equipped with 2 studded tires and 2 non-studded winter tires.

Samples of the dust produced with Tröger were also collected using a wet vacuum cleaner (se Figure 4) with distilled and deionized water. The sampling time was 20 minutes. The investigation included three parallel core samples for each of the pavement types.

2.7. Particle measuring apparatus

Four different measuring apparatus were used to monitor particles while running the PTM; Tapered Element Oscillating Microbalance (TEOM), 2 DustTraks (DT), Aerodynamic Particle Sizer (APS) and Scanning Mobility Particle Sizer (SMPS). The TEOM is a gravimetric measurement of PM10, the DT measures particles optical for PM10 or PM2.5, while APS and SMPS measures number of particles in different sizes for nanoparticles (0.016-0.75 μm) and mass concentration for coarser particles (0.75-18 μm) (Gustafsson et al., 2007).

In addition to particles, the air temperature, the humidity and the pavement and tire temperatures were monitored during testing.

3. Results and discussions

Results from the project are described in the next sections. The effect of D_{max}, type of tires and speed on pavement wear and road dust generation are discussed.

3.1. Aggregate maximum size

In Figure 6 the amounts of fine material sampled with Tröger is shown. The material is divided into fraction < 10 μm (1 μm = 0.001 mm) and > 10 μm since regulations regarding particulate matter and air quality (European Council Directive 1999/30/EC) are specified for particles below 10 μm (PM10). According to Figure 6 AC 6 gives lowest amount of fine material, followed by SMA 6, SMA 8 and SMA 11. AC 8 and AC 11 gave highest amount of fines. The PM10 fraction was in average 54 % for SMA and 60 % for AC. The standard deviation was ranging from 0.3-5.4.

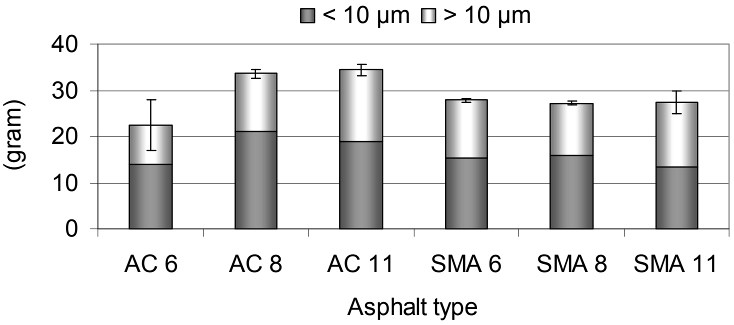

Figure 6. Amount (gram) and particle size of fine material sampled from the asphalt cores during Tröger wear

The amount of coarse aggregate in asphalt pavements is important for the wear resistance as discussed in section *1.1 Aggregate size and mechanical strength*. Amounts of rock material > 2 mm and 4 mm in the asphalt samples tested are shown in Table 3. This may explain some of the differences in the total rutting between SMA and AC measured in the field. However, all test sections had a pavement thickness of 2.5 cm. This thickness is too thin especially for SMA 11 and AC 11, and deformation properties of the layers beneath the top layer will influence the measured values.

Table 3. Amount of rock material > 2 mm and 4 mm (%) in the asphalt samples

Pavement type	AC 6	AC 8	AC 11	SMA 6	SMA 8	SMA 11
Amount > 4 mm (%)	13.7	30.4	45.9	12.7	47.6	57.5
Amount > 2 mm (%)	36.1	47.7	63.7	59.6	63.7	65.9

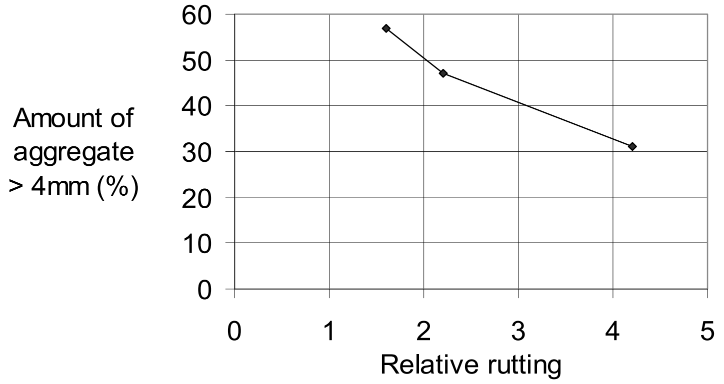

Figure 7. Correlation between aggregate > 4 mm (%) and the relative PTM rutting (Horvli and Værnes, 2006)

Figure 7 describes how the relative rutting of the pavement changes as a function of aggregate > 4 mm. The data is based on tests in the PTM on SMA 11, AC 11 and AC 8 with the same aggregate type. The figure shows that the relative rutting is doubled when the amount of aggregate > 4 mm is reduced from 50 % to 30 %.

The rutting (transversal evenness) on the test sections at Rv 715 Trolla has been measured each year, and the rutting area is displayed in Figure 8. The rutting area (cm^2) is defined as the area of the transversal section through the wheel paths. The values for 2005 represent the initial rutting, while that for 2006 and 2007 represent rutting caused by wear and deformation. Therefore the ranking provided by the Tröger testing does not fully agree with the ranking shown by the observed values. Figure 8 indicate SMA 6 as the pavement type with lowest rutting, AC 8 and 11 have slightly higher rutting, followed by SMA 8 and 11. AC 6 has the highest measured rutting.

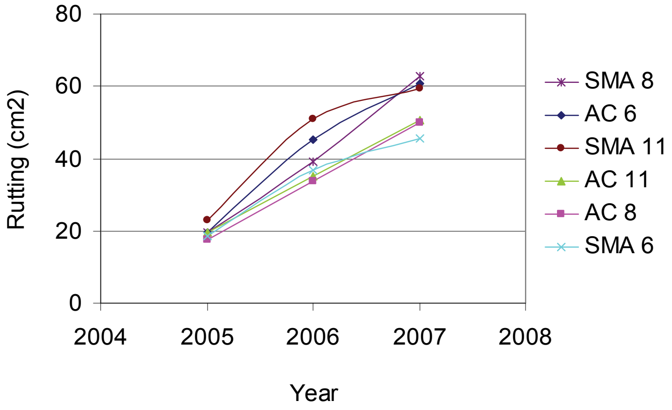

Figure 8. Rutting at Rv 715 (cm^2) for the pavement types investigated

Tröger appears to distinguish poorly between the different pavement types. Tröger test measures only wear, field measured rutting includes both wear and deformation. In addition overheating during laboratory testing of the asphalt cores may have changed the properties of the mortar (especially for AC 6 and SMA 6) giving other conditions not comparable to actual conditions in field during winter time. The number of samples tested for each asphalt type is probably too low in order to have a good statistical analysis. However, according to the standard EN 1871:2000 Annex K (CEN, 2000) the Tröger test is carried out on only three specimens unless the deviation between individual values and mean does not exceed 10 %. The Tröger values for the materials were calculated to 9.6, 13.5 and 13.8 for AC 6, AC 8 and AC 11 respectively, and 11.2, 11.1 and 14.3 for SMA 6, SMA 8 and SMA 11 respectively. AC 6 gave a deviation between individual values and mean > 10 % and two more samples were tested, but these gave no better result.

It was difficult to control the temperature during the Tröger testing. The temperature increased in the asphalt samples. This may have influenced on the results. Former studies in Finland has shown correlation between wear (SPS) and temperature (Skoglund and Uthus, 1994); the wear was lowest at 0°C to -5°C, and increased by 50 % for a temperature change to -10°C or +5°C. The increased temperature during Tröger testing probably makes the binder more flexible, causing the asphalt samples to deform more easily, especially for the lower D_{max}. The effect of this might be a reduction in the measured wear and dust generation in the Tröger test.

The particle size distribution of Tröger produced dust measured with Coulter LS 230 (laser diffraction, 0.04-2000 µm) is shown in Figure 9. AC pavements cause dust with slightly finer particle size compared to SMA pavements. There is a trend indicating that lower D_{max} gives a slightly finer particle size distribution compared to larger D_{max}, but for SMA 8 the dust shows finer particle size distribution compared to SMA 6.

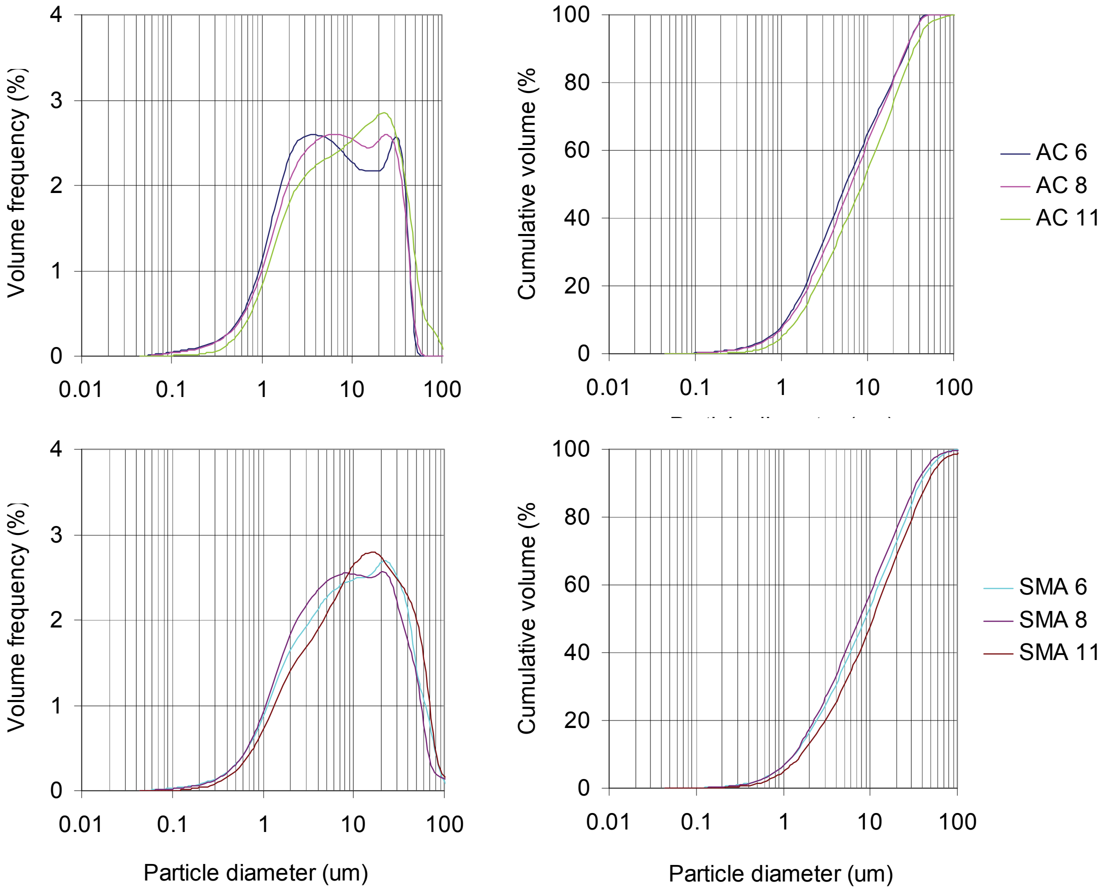

Figure 9. Size distributions as volume frequencies (%) and cumulative volumes (%)

3.2. Types of tires and speeds

Results from the PTM regarding type of tire used and driving speed are described in the next sections. Amounts, particle size, shape and composition have been determined. All these factors are important in evaluation of health risk associated with exposure to road dust.

3.2.1. Amount of dust

Figure 10 shows how driving speed and percentage of studded tires affects the PM10 concentration for SMA 11 measured with DustTrak. Road dust generation increase with both speed and amount of studded tires. The data are based on the median value of PM10 measured with DustTrack for 20 minutes towards the end of each period with each speed (30, 50 and 70 km/h) and tire configuration.

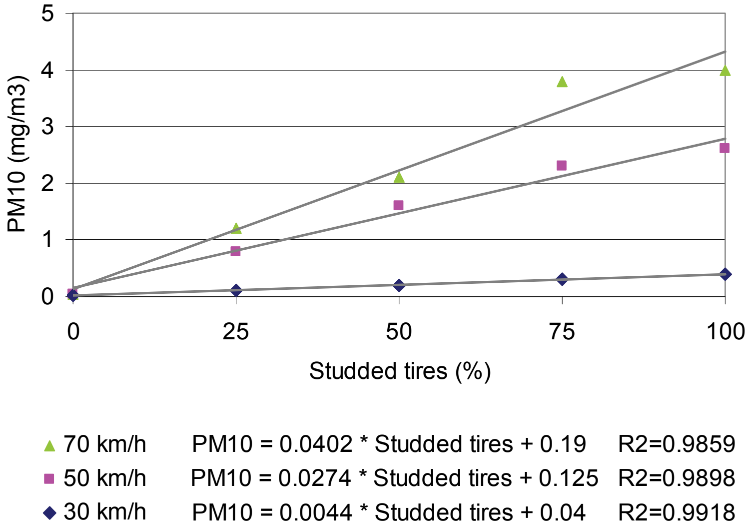

Figure 10. PM10 as a function of studded tires with different driving speeds for SMA 11

The soft material in the non-studded winter tires may cause higher release of the produced road dust and higher concentrations of PM10 in the air because of the "suction pad effect" (personal communication, Tervahattu, 2006). The anti-slippery impact of non-studded winter tires (friction tires) is caused by the high amount of lamellas and softer rubber material. When lamellas touch the road surface, air between the lamellas is pressed out. When lamellas get unfastened, air is "sucked" in again between the lamellas. Loose particulate matter is consequently lifted from the road surface and suspended in the ambient air. This phenomenon was named the "suction pad effect". This may have caused high concentrations of PM10 measured in the air at tire configurations with non-studded winter tires even though the production of road dust is low.

3.2.2. Particle size and shape

Particle size distribution of dust samples from SMA 11 at 60 km/h determined by Coulter LS 230 is shown in Figure 11. The dust samples from studded and non-studded winter tires are almost identical regarding size distributions, with those from non-studded tires having just a bit finer grading.

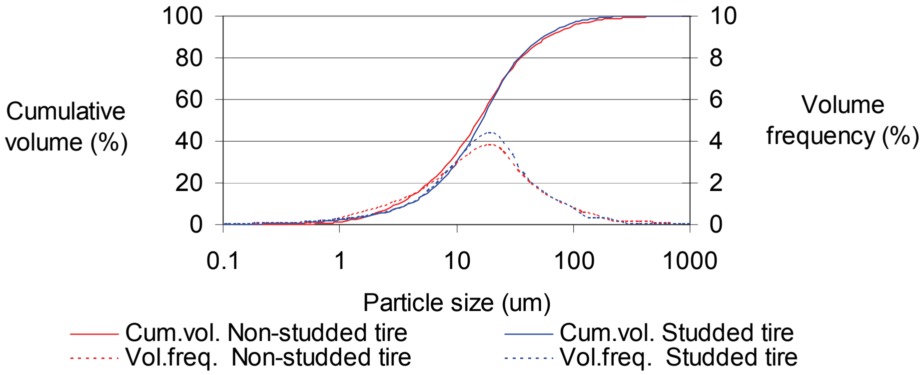

Figure 11. Size distribution as volume frequency (%) and cumulative volume (%) for SMA 11, 60 km/h

The particle shape (roundness) was obtained by image analysis by Pharma Vision 830 (5-2000 μm). The roundness distribution of dust samples from SMA 11 at 60 km/h is shown in Figure 12. Roundness is a measure of the length/width relationship, with values between 0-1. A perfect circle has roundness 1.0, while a needle shaped object has roundness close to 0. For both samples 10 000 particles were characterized. The dust samples from studded and non-studded winter tires are almost identical regarding shape.

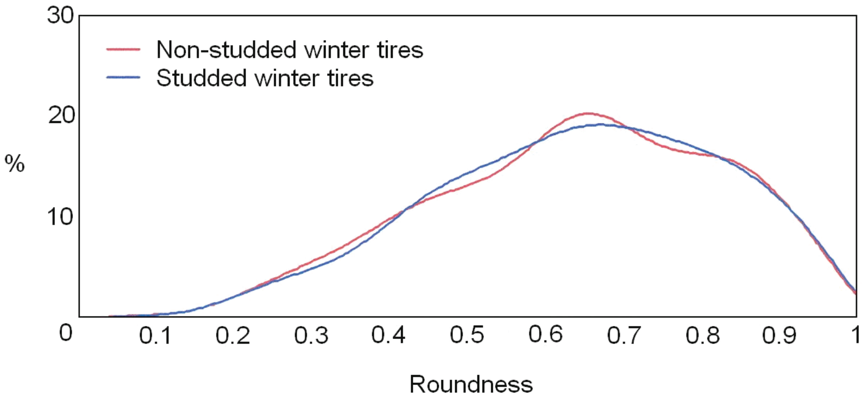

Figure 12. Roundness distribution by number (%) for SMA 11, 60 km/h

The mass size distributions measured by APS are shown in Figure 13. According to the figure 100 % studded tires give finer particles compared to lower amounts of studded tires.

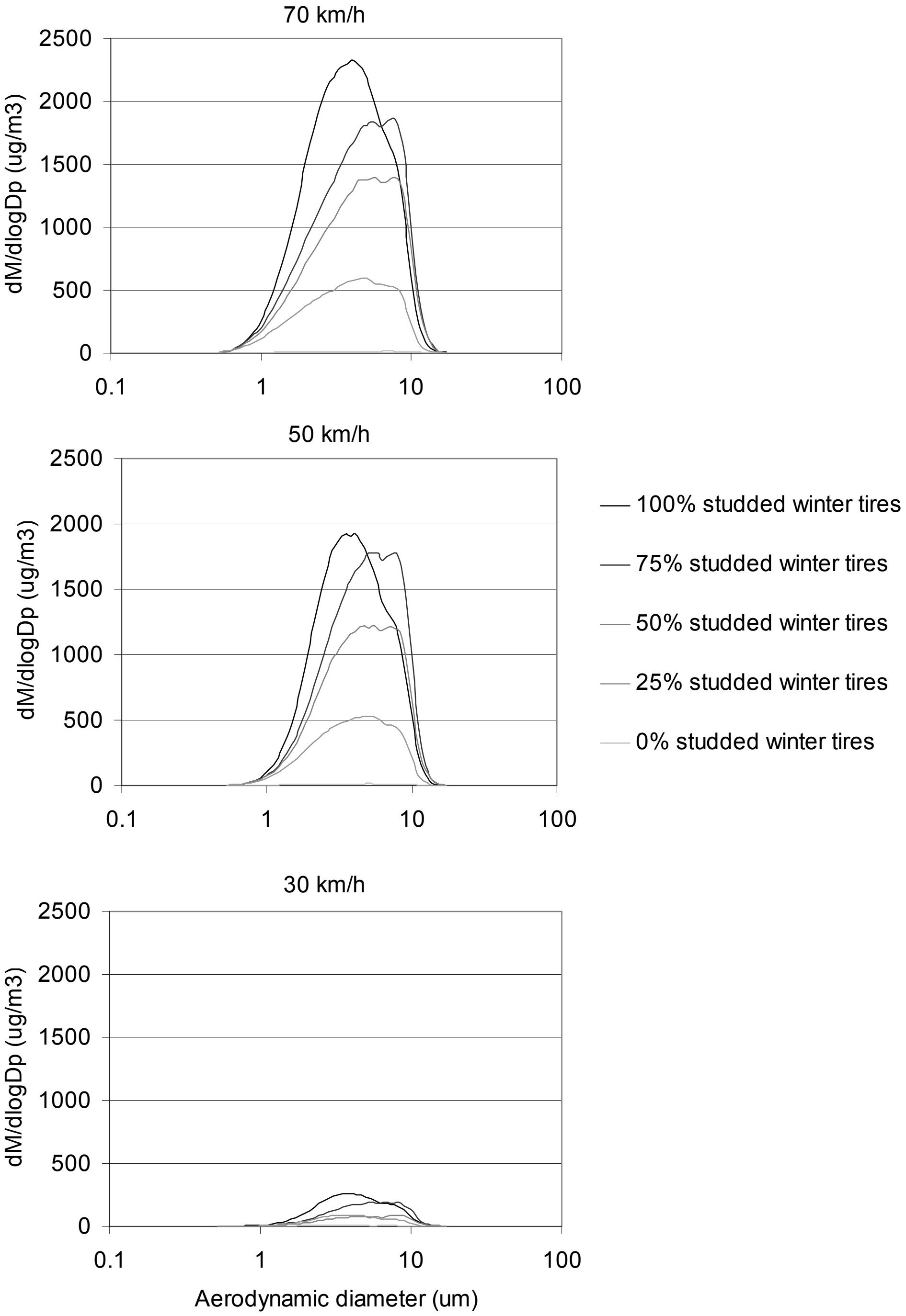

Figure 13. Mass size distribution (µg/m^3) with different driving speeds (km/h) and shares of studded tires (%)

3.2.3. Amount and composition of dust

Studded tires and non-studded winter tires affect the wear of pavements and road dust production differently. The studs clearly increase the pavement wear and the PM10 concentration in the air (see Figure 10 and 13). The amount of road dust produced behind one tire in the PTM was 10.0 g and 4.5 g for studded and non-studded winter tires, respectively (SMA 11, 60 km/h, 30 minutes). Thus, studded tires produced 122 % more road dust than non-studded winter tires at 60 km/h for the actual pavement type. However, the amount of dust collected behind one tire can be affected by the other tires and the "suction pad effect" making it difficult to determine the amount of dust generated by a single tire.

The amount of organic and mineral matter from SMA 11 sampled behind one tire at the PTM at 60 km/h for 30 minutes is shown in Figure 14.

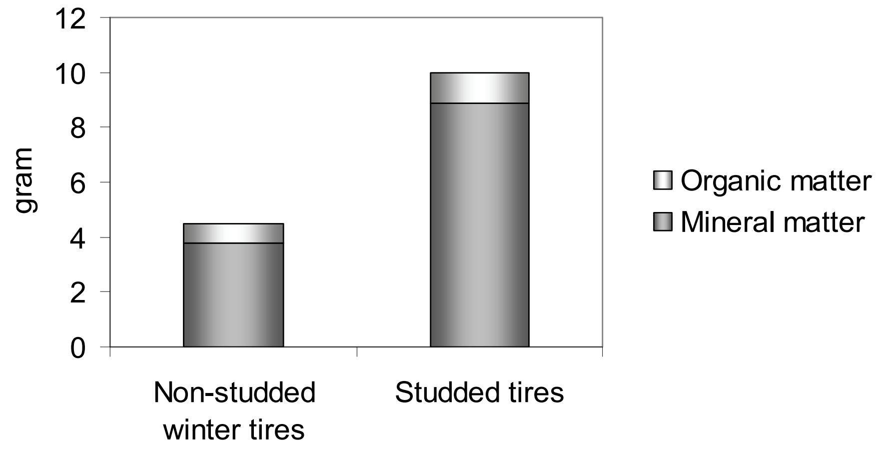

Figure 14. Amount (gram) and composition of road dust from SMA 11 sampled at 60 km/h for 30 minutes behind one tire in the PTM

The content of rubber from tire wear in proportion to binder, evaporation of crystal water in some minerals and gasification of calcareous minerals (such as the filler) in the asphalt was determined by annealing at 850°C for 4 hours. A weight loss of 11.3 % and 15.5 % was detected for the samples collected behind a studded and non-studded winter tire, respectively.

Tröger and Prall are simple asphalt laboratory tests simulating pavement wear from studded tires on asphalt cores by use of steel needles and balls, respectively, and are not influenced by rubber from tires. Dust samples produced in Tröger and Prall were also annealed and gave about the same values on ignition loss as the studded tire sample in the PTM. The loss on ignition (%) of dust samples from PTM (both non-studded and studded winter tires), Prall and Tröger is displayed in Figure 15. This point out that non-studded winter tires are softer and are more worn compared to studded tires.

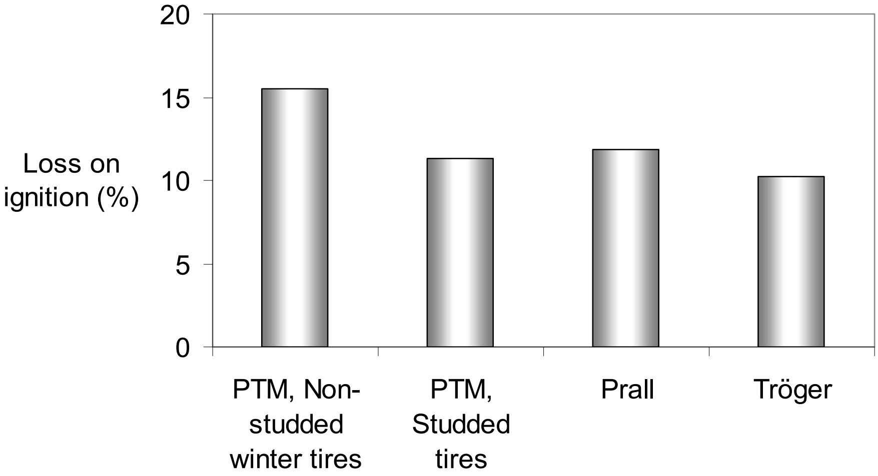

Figure 15. Loss on ignition (%) of dust samples produced with different wear equipment

The mineralogical composition was found by x-ray diffraction (XRD) which is a qualitative and semi-quantitative method. The method is based on dissimilar diffraction of the x-ray beam because of different lattice spacing for different minerals. The mineralogical composition is given in Figure 16. Before XRD analysis, the samples were sieved at 10 μm to see if there were differences in composition between the fractions > 10 μm and < 10 μm. This was done because regulations regarding particulate matter and ambient air quality (European Council Directive 1999/30/EC) are set for the fraction below 10 μm, since this is the inhalable fraction for humans.

Minerals found in the samples were quartz, plagioclase, mica, chlorite, calcite and epidote. Non-studded tires seem to generate more quartz and less plagioclase compared to studded tires for the SMA 11 pavement. This is in contrast to what was expected; studded tires are assumed to generate more dust from hard minerals like quartz compared to non-studded tires. However, XRD is a semi-quantitative method and the concentration estimate may be in error by a factor of two or more (Skoog et al, 1998).

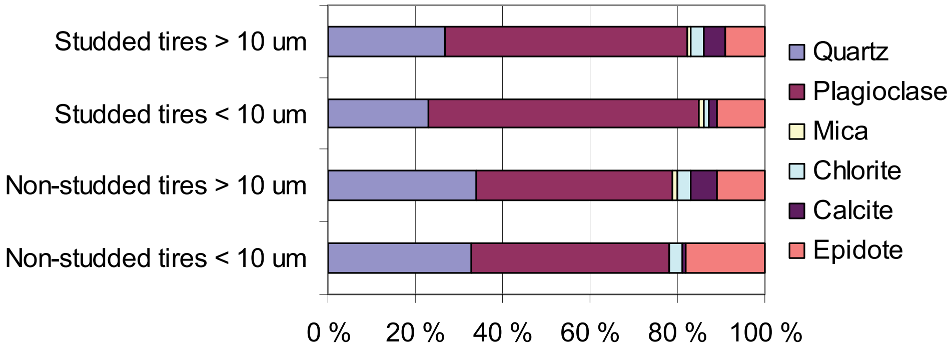

Figure 16. Mineralogical compositions (%) with different tires, SMA 11 (PTM)

4. Conclusion

Results from the study on aggregate size:

- The study has shown that the D_{max} has little or no effect on dust generation.
- AC pavements produce more dust than SMA pavements.
- Tröger seem to correlate poorly with rutting measurements in field in regard to amount of dust generated since the rutting is caused both by deformations and pavement wear.
- The amount of coarse aggregate (> 2 mm) is important for asphalt pavement wear.
- SMA pavements generate dust with slightly coarser particle size distribution compared to AC pavements.
- Low D_{max} seems to give dust with slightly finer particle size distributions compared to pavements with coarser D_{max}.

Results from the study on driving speed and tire types:

- The study has clearly shown that the amount of studded tires and driving speed are important factors for pavement wear and road dust generation.
- There is a significant increase in pavement wear when the driving speed is increased. The effect of speed is not as evident for change from 50 to 70 km/h as for change from 30 to 50 km/h.
- Studded tires produce 122 % more road dust than non-studded winter tires at 60 km/h in the PTM machine with SMA 11.
- Dust samples produced by asphalt testing laboratory equipment (Tröger and Prall) gave no significant differences in ignition loss compared to the PTM with studded tires. This indicates that the difference in loss on ignition between the PTM samples (generated with studded and non-studded tires), which was 4 %, is related to wear of the rubber in non-studded winter tires.

Recommendations for further research:

- Further research is needed to study the deformation properties of the pavements investigated to quantify the deformation and wearing part of the rutting. The rutting was measured in field, further laboratory investigations would give more information about relative deformation and wearing properties between the different pavement types tested. The rutting at the test sections in Trolla (Rv 715) should be followed up closely for several years in the future.
- Additional testing in the PTM of a pavement with D_{max} lower than 11 mm and same aggregate composition as was used in this study would give valuable information about the effect of lower D_{max} on asphalt wear and road dust generation.
- The Tröger testing should be continued with more samples, since three parallels are too few. The problem with overheating of samples with low D_{max} could be improved with use of Prall.

5. Acknowledgement

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PAPER V

The influence of driving speeds and tires on road dust properties

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Abstract

Road dust is an important contributor to ambient particulate matter (PM). Driving speeds and type of tire influence on the amount of dust generated and resuspended. These factors are also believed to affect the particle properties. In this study the amounts of dust generated with different driving speeds and tire types have been investigated. In addition, particle size, particle shape and particle composition are described. The dust material investigated was produced in an indoor pavement testing machine at the Swedish National Road and Transport Research Institute. The specimens were made from a stone mastic asphalt with aggregate size of 8 mm (SMA 8). The testing was performed at different driving speeds; 20-70 km/h, and with three types of tires; studded tires, non-studded winter tires and summer tires. Results from the study show that studded tires generate large amounts of dust compared to non-studded winter tires and summer tires. The driving speed affects both amount of dust generated, size and shape of the particles.

Keywords: Driving speed, pavement wear, studded winter tires, non-studded winter tires, summer tires, road dust characterization, pavement testing machine

1. Introduction

Measurements of PM10 levels in Trondheim city have shown high levels of airborne particulate matter along busy urban roads during winter and spring time conditions. PM10 is the mass of particles with a diameter below 10 µm (Skaug, 2001). Traffic is the most important source of PM10, and the use of studded tires contributes largely to the amount of particles generated from pavement wear. In the period 2003-2007 the daily average PM10 concentration above 50 $\mu g/m^3$ was observed about 250 times, i.e. about 50 times each year. This is above the European Union ambient air quality standard. According to the European Union directive the daily averages of PM10 should not exceed 50 $\mu g/m^3$ for more than 35 days during each year (European Council Directive 1999/30/EC). The most efficient measure to reduce generation of road dust from pavement wear is to reduce the use of studded tires. However, the driving speed may also contribute to reduced pavement wear and resuspension of dust particles.

The driving speed is an important factor for wear of asphalt pavements. The driving speed affects the impaction energy from the studded winter tires. Higher driving speed increase the wear (Johansson et al., 2004), the wear is 20 % higher for 90 km/h compared to 75 km/h, and 20 % higher for 75 km/h compared to 50 km/h (Bakløkk et al., 1997, Bakløkk, 1997). Swedish tests have shown 44 % higher wear for 85 km/h compared to 60 km/h for light weight studs (Haakenaasen, 1995). Swedish tests in the pavement testing machine (PTM) have indicated a factor of 2.5 when the speed increases from 30 to 50 km/h, and a factor of 4 from 30 to 70 km/h, for the emission of PM10 (particles < 10 µm in size).

The effect of studded tires can be divided into wear because of abrasion and fragmentation as shown in Figure 1. At low driving speed the abrasion effect dominates, while fragmentation forces increases at higher driving speeds (Skoglund and Uthus, 1994).

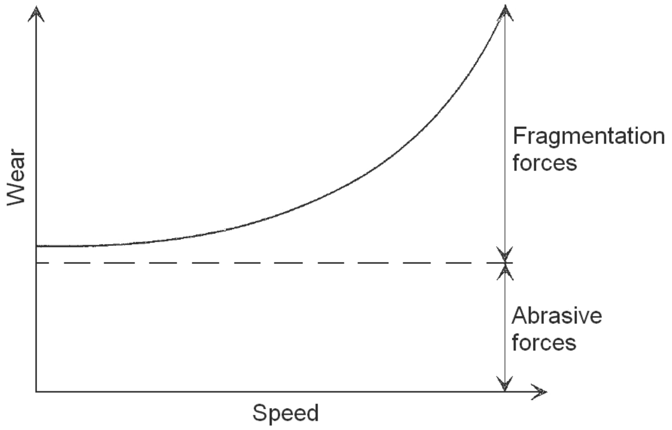

Figure 1. Pavement wear as a function of speed (Skoglund and Uthus, 1994)

The driving speed also has large influence on the turbulence from the vehicles, and this is important for the resuspension of particles. Higher driving speed gives higher turbulence. Experiments with reduced speed on main roads in Oslo, Norway, have shown significant reductions in PM10 level (Hagen et al., 2005). The size and design of the vehicle and tires are important for turbulence (Johansson et al., 2004).

Type of tires is another important factor affecting the amount of generated and resuspended dust from pavement wear. According to Norman and Johansson (2006) a 10 % decrease in vehicles using studded tires can reduce the weekly average PM10 levels by about 10 $\mu g/m^3$, and the annual PM10 value can be reduced by 1 $\mu g/m^3$ (Bartonova et al., 2002). Laboratory measurements from Sweden and Finland show that studded tires give respectively 50-100 and 2-9 times higher PM10 values compared to non-studded winter tires (Johansson, 2007). The total emissions of ambient PM from pavements include both accumulated material on the road (resuspension) and generation of new particles because of pavement wear from tires. For studded tires the resuspension has been measured to 16-43 % of the total emission, while for non-studded tires the resuspension was > 87 % (Johansson, 2007).

However, the emissions of PM10 are under discussion. Field studies in Sweden have found 2-6.4 times higher emission of PM10 from studded tires compared to non-studded tires (Hussein et al., 2007), while Finnish field studies suggest higher emissions from non-studded tires because of the suction pad effect caused by the lamellas (Johansson, 2007).

This paper is divided into two parts. In part one the effects of reducing driving speed of passenger cars is discussed; both the amount of dust in the air and the particle properties. In part two the results from an investigation on three different tire types are presented, also with regard to amount of dust generated and particle properties.

2. Materials and methods

The road dust material used in this study is particles produced and collected in an indoor pavement testing machine (see Figure 2) at the Swedish National Road and Transport Research Institute (VTI). The machine has an electrically powered rotating axle with four wheels and adjustable rotating speed. The axle system is tuned to move sideways. The diameter of the test ring is ca. 6 m, and the machine is located in a closed room with controlled ventilation. In this machine wear particles from pavement and tires can be studied separately, without interference of particles from exhaust and other sources (Gustafsson et al., 2008). The machine also accelerates the study, and pavement types, car tires, friction materials, driving speeds and temperatures can be varied. Studies at VTI have shown very good correlation between the studded tire wear on the road and in the machine (Wågberg et al., 2003). Jacobson (1995) reported a correlation factor of R^2=0.96-0.98.

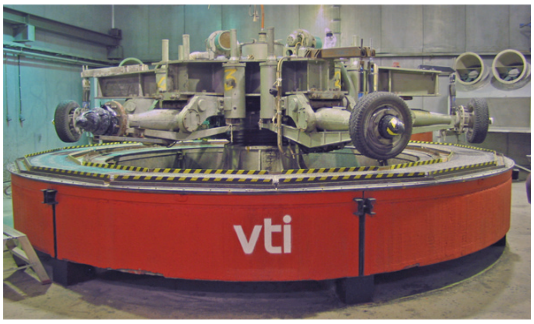

Figure 2. Pavement testing machine (Photo VTI)

The asphalt pavement material tested was stone mastic asphalt with maximum aggregate size 8 mm (SMA 8). The SMA 8 composition was Durasplitt/mylonite (55 % 4-8 mm, 18 % 2-4 mm, 17 % 0-2 mm), Lyngås gravel (5 % 0-8 mm) and Breivik/lime filler (5 %) with bitumen 70/100 and fiber.

The sampling was performed with different driving speeds and tires, relative humidity 74.6-81.0 % and temperatures between -1 and 6.3 ºC, representing normal winter conditions (Gustafsson et al., 2007). Samples of dust were collected during driving using a dry cyclone (Michelin Dyson DC 19) with the inlet mounted behind one of the tires, as shown in Figure 3. Two DustTraks were used for monitoring the PM10 and PM2.5 level in the air during testing.

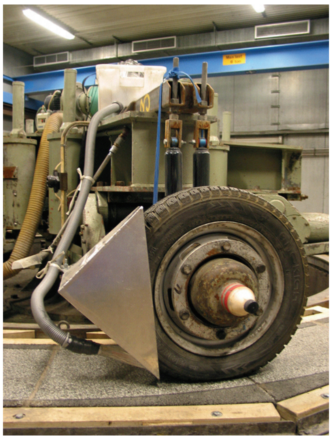

Figure 3. Sampling setup (Photo VTI)

The study was divided in two parts. Part one includes investigation of particle properties related to different driving speeds (20-70 km/h) with studded tires. Part two describes differences in particle properties generated with three types of tires; studded tires (Nokian Hakkapeliitta 4), non-studded winter tires (Nokian Hakkapeliitta RSi) and summer tires (Nokian NRHi Ecosport).

Methods used for particle characterization were gravimetric analysis, laser diffraction for particle size measurements in the range 0.04-2000 µm (Coulter LS230), image analysis for particle shape/roundness determination in the size range 5-2000 µm (Pharma Vision 830), annealing furnace to find the ignition loss at 710 °C (inorganic and organic content) and x-ray diffraction (XRD) to find the mineralogical composition (Philips PW 1830). Field emission scanning electron microscopy (FE-SEM) was used for high resolution imaging of sampled material. (Zeiss Ultra 55 Limited Edition).

3. Results and discussions

3.1. Effect of driving speed

Total amount of dust generated at different driving speeds is difficult to determine. However, mass concentration of PM10 may give an indication of the amount. During testing, PM10 was measured in the laboratory with a DustTrak, and average PM10 level was estimated after the concentration was stabilized in the room. The PM10 concentration seems to be linearly dependent on driving speed, as shown in Figure 4.

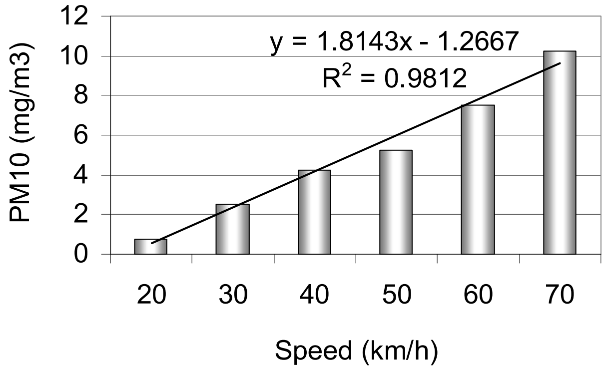

Figure 4. Concentration of PM10 (mg/m^3) as a function of driving speed (km/h)

Dust samples were collected in the PTM during different driving speeds with studded tires. Particle size distribution as a function of speed is displayed in Figure 5. The figure shows that for all speeds the curves have maximum value corresponding to a size of about 20 µm, indicating that a relatively large amount of the dust has size of around 20 µm. The lower the speed, the higher the relative amount of dust particles with size of about 20 µm will be. The higher the speed, the higher is the relative proportion of finer dust particles.

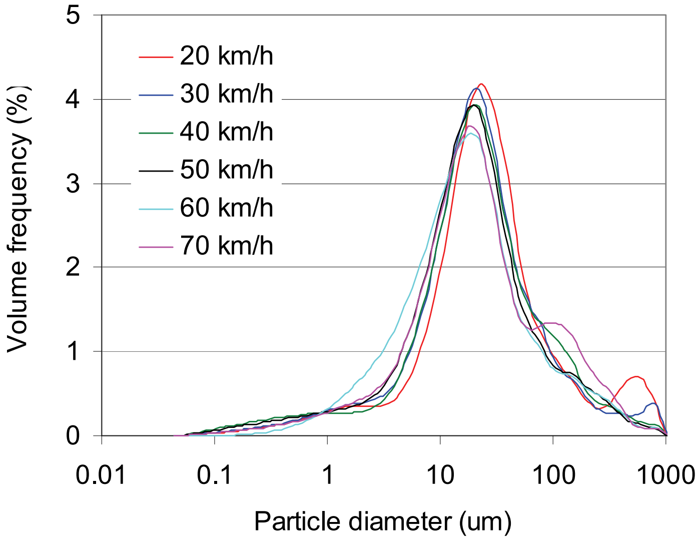

Figure 5. Size distributions (volume frequencies) as a function of driving speed

In Table 1 the cumulative portion of PM20, PM10 and PM2.5 is displayed as a function of speed is displayed. There is a trend showing that increasing speed gives increasing amount of PM20, PM10 and PM2.5. However, at 70 km/h the amount seems to drop a little.

Table 1. Cumulative volume (%) of PM20, PM10 and PM2.5 as a function of driving speed

Speed (km/h)	20	30	40	50	60	70
PM20 (%)	37	44	44	48	53	47
PM10 (%)	20	26	26	30	35	29
PM2.5 (%)	7.0	7.6	8.1	8.5	8.6	7.6

Minerals found in dust samples generated from studded tires are plagioclase, quartz, epidote, calcite, chlorite, alkali feldspar and mica. Plagioclase, quartz and epidote constitute about 90 % of the mineral content in the dust samples.

Table 2. Mineralogical composition (%) of dust generated by studded tires

Plagioclase	Quartz	Epidote	Calcite	Chlorite	Alkali felspar	Mica	SUM
52	27	10	6	2	2	1	100

Figure 6 show the roundness distribution for dust samples as a function of driving speed. Roundness is a measure of the length/width relationship, with values between 0-1. A perfect circle has roundness 1, while a needle shaped object has roundness close to 0. For all samples 10 000 particles were characterized.

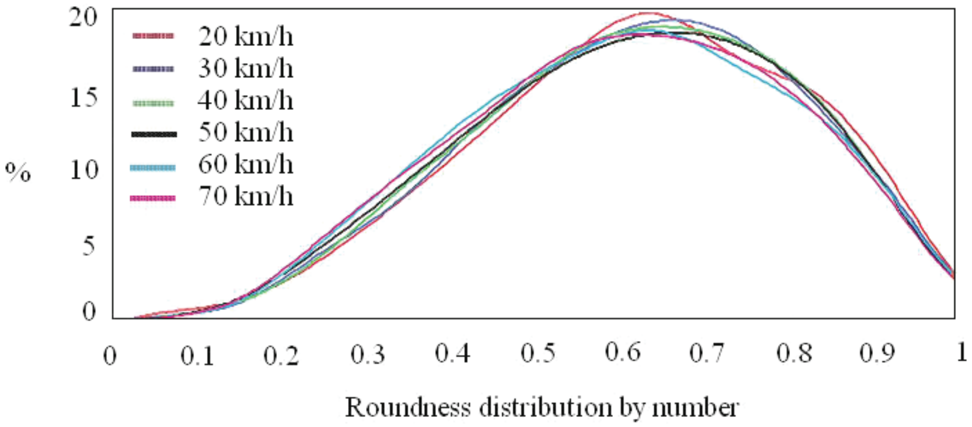

Figure 6. Dust roundness distribution by number (%) for different driving speeds (studded tires)

In Table 3 mean values for roundness are given. The values indicate that increasing speed generate more irregular particles. This is in accordance with the theory that fragmentation forces increase with increasing speed. Small particles after crushing are more elongate, complex and angular compared to larger particles, and the increasing complexity of particle shape is expected to continue down to 1 µm (Durney and Meloy, 1986). In addition Fuerstenau et al. (1990) found that the reduction ratio of particles increases linearly with energy input. That implies that the increment in surface area is proportional to energy input, which in this study is due to driving speed.

Table 3. Mean roundness values of dust generated by studded tires for different driving speeds (km/h)

Speed (km/h)	20	30	40	50	60	70
Roundness (mean)	0.623	0.619	0.618	0.613	0.606	0.604

3.2. Effect of tire type

The effect of tire type was investigated with studded tires, non-studded winter tires and summer tires in the PTM at 70 km/h. Dust samples generated from the three tire types were analyzed. Amounts of total suspended particles (TSP), PM10, PM2.5, PM0.1 and inorganic matter is displayed in Table 4. At 70 km/h studded tires generate 40 and 30 times more TSP compared to non-studded winter tires and summer tires, respectively. These values are in accordance with studies done by Gustafsson et al. (2008). In addition, the amount of PM10 is much higher for road dust generated from studded tires compared to non-studded winter tires and summer tires. However, the PM2.5 fraction is large both for studded and summer tires. Summer tires generate low amount of coarse particles (PM2.5-10), but high amount of fine particles (PM2.5). The difference in inorganic content is small (4 %) between studded and non-studded winter tires, but large between studded tires and summer tires (16 %). This difference is probably caused by the wear of rubber from the tires. The loss on ignition (organic fraction) in the dust samples come from wear of rubber from tire and bitumen in the asphalt, evaporation of crystal water in some minerals and gasification of calcareous minerals. Visual inspection of the dust samples showed increasing black color from studded tires to non-studded winter tires to summer tires. This may be explained by the organic content (rubber).

Table 4. Amount of dust as a function of tire type

Tire type	TSP (gram/h)	PM10 (%)	PM2.5 (%)	PM0.1 (%)	Inorganic content (%)
Studded tires	92.7	29	7.6	0.14	89.5
Non-studded winter tires	2.3	13	3.5	0	85.5
Summer tires	3.0	10	7.8	0.11	73.4

The particle size distribution for the three different tire types investigated is shown in Figure 7. The figure shows that for dust generated by studded tires the curve has a maximum value corresponding to a size of about 20 μm, which indicates that a relatively large amount of the dust has size of around 20 μm. Maximum value for dust generated by non-studded and summer tires corresponds to a size of 30 μm, i.e. studded tires generate finer particles compared to non-studded winter tires and summer tires. The non-studded and summer tires generate dust with similar size distribution.

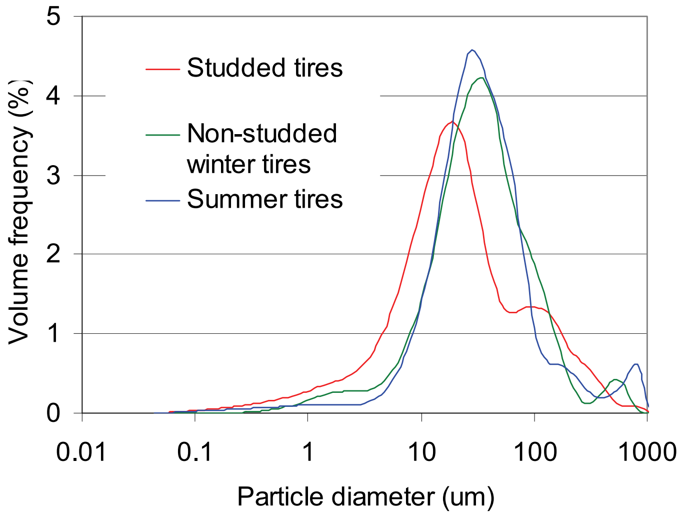

Figure 7. Size distributions (volume frequencies) as a function of tire type

The particle shape analysis of dust samples generated by different tire types show that non-studded winter tires give particles with highest roundness, followed by studded tires and summer tires. Results from the particle shape analysis are shown in Figure 8 and Table 5.

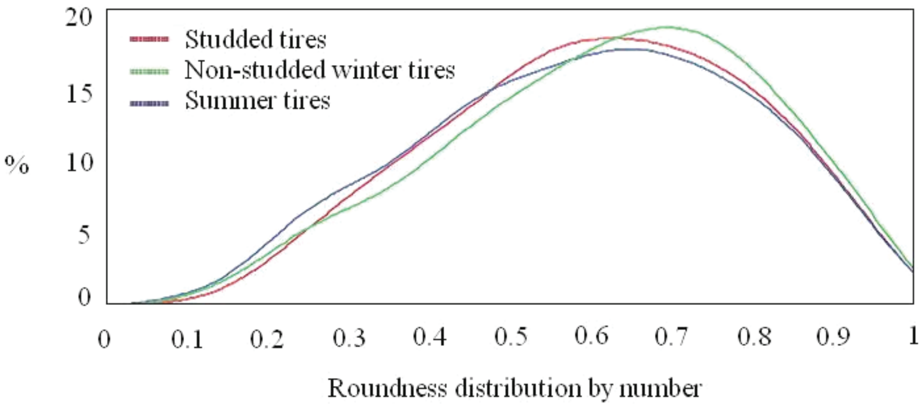

Figure 8. Roundness distribution by number (%)

Table 5. Mean roundness values of dust generated by different tires at 70 km/h

Tire type	Studded tires	Non-studded winter tires	Summer tires
Roundness (mean)	0.604	0.615	0.592

In Figure 9, 10 and 11 SEM images of dust generated by studded and summer tires are shown. The symbol "O" means the major component is organic material, and the symbol "I" means this is inorganic material. These images illustrate that dust generated by summer tires has particles with larger size and contains relatively larger proportion of organic material compared to the dust generated by studded tires. However, several of the particles are conglomerated, often with organic material binding the particles together. Sometimes mineral particles cover the organic material, other times the mineral particles are kneaded into the organic material. The sizes of the mineral particles generated by pavement wear are in reality much smaller than the agglomerate shown on the images and measured by laser diffraction (Figure 7). The mineral particles may become detached from the agglomerates as they enter the human respiratory system, and may become potentially more harmful.

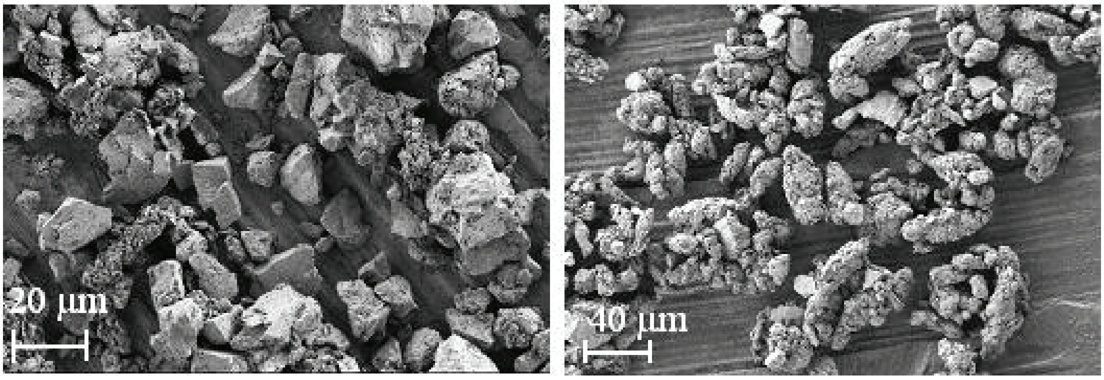

Figure 9. SEM pictures of dust particles generated by studded tires (left) and summer tires (right). Secondary electron detector, accelerating voltage 1 kV, working distance 4 mm. Photos: Brynhild Snilsberg

Figure 10. SEM pictures of dust from studded tires. Secondary electron detector, accelerating voltage 1 kV, working distance 5 mm. Photos: Brynhild Snilsberg

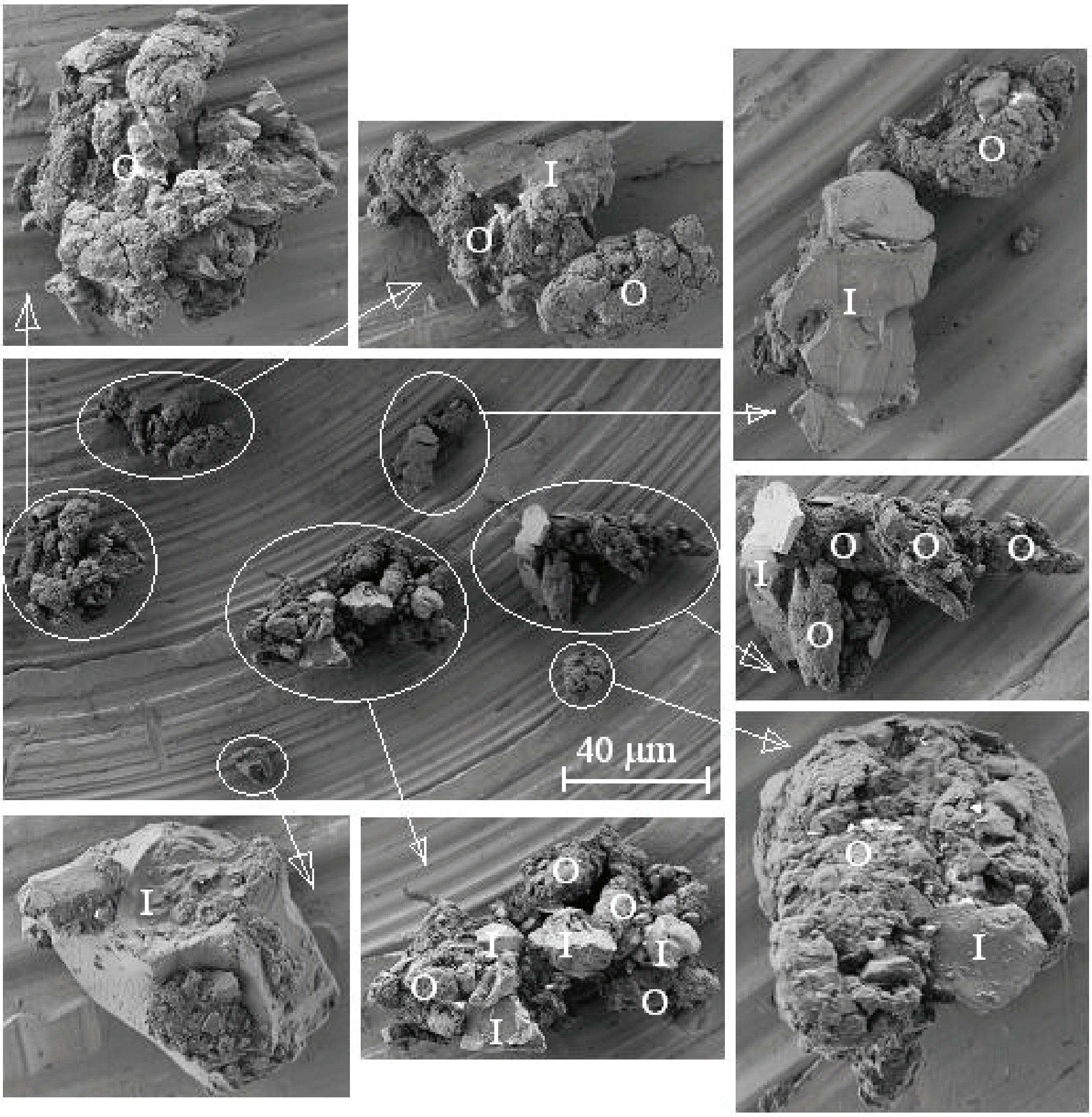

Figure 11. SEM pictures of dust from summer tires. Secondary electron detector, accelerating voltage 1 kV, working distance 5 mm. Photos: Brynhild Snilsberg

4. Conclusion

The main findings from this study can be summarized as follows.

Results from the study on driving speed using studded tires:

- The PM10 concentration increases linearly with increasing driving speed when using studded tires.
- The main part of the dust is around 20 µm. However, at increasing driving speed, the higher is the relative proportion of finer dust particles.
- Increasing driving speed generate more irregular particles.

Results from the study on different tire types:

- Studded tires generate about 30-40 times more dust compared to non-studded winter tires and summer tires.
- Studded tires generate dust with finer particle size distribution compared to non-studded winter tires and summer tires. The PM10 proportion generated from studded tires is about three times more compared to non-studded winter tires and summer tires. The main part of dust from studded tires is around 20 µm, while dust from non-studded winter tires and summer tires is around 30 µm.
- The rubber in the summer tires are more worn compared to studded and non-studded winter tires.
- Summer tires generate the most irregular particles, followed by studded tires and non-studded winter tires.

5. Acknowledgements

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Appendix

A Density of road dust

Density measurements of dust downfall samples from 2005 were measured with Accupyc 1330.

$\rho_{particle}$ = 2.12 g/cm^3 for dust downfall in March-April 2005

$\rho_{particle}$ = 1.71 g/cm^3 for dust downfall in April-May 2005

The density is higher for the period March-April compared to April-May. This is probably caused by larger content of organic material towards the summer. Organic material has lower density compared to mineral particles which result in lower density measured for the whole sample.

B Supplement to Paper IV

Wheel track testing of asphalt types used in Trolla

Wheel track testing of asphalt types used in Trolla was performed to find the relative deformation values. Rutting measured in field includes both deformation and wear.

In Table B-1 presents results from the Wheel track (permanent deformations) testing of the pavements from Rv 715 Trolla investigated in Paper IV. The asphalt samples for Wheel track were made in laboratory.

Table B-1. Final rutting depth (mm)

Wheeltrack	Sample 1	Sample 2	Average
AC 6	1.97	2.07	2.02
AC 8	3.5	3.53	3.52
AC 11	3.06	3.39	3.23
SMA 6	2.19	2.32	2.26
SMA 8	2.61	2.61	2.61
SMA 11	3.49	3.09	3.29

Based on results from field measurements of rutting (Paper IV) and laboratory testing of permanent deformation with Wheel track, no connection between maximum aggregate size and deformation properties of the asphalt is found.

Prall testing

The result from the Prall testing is shown in Figure B-1. The columns are average values from four samples of each asphalt mixture, and the standard deviation is displayed.

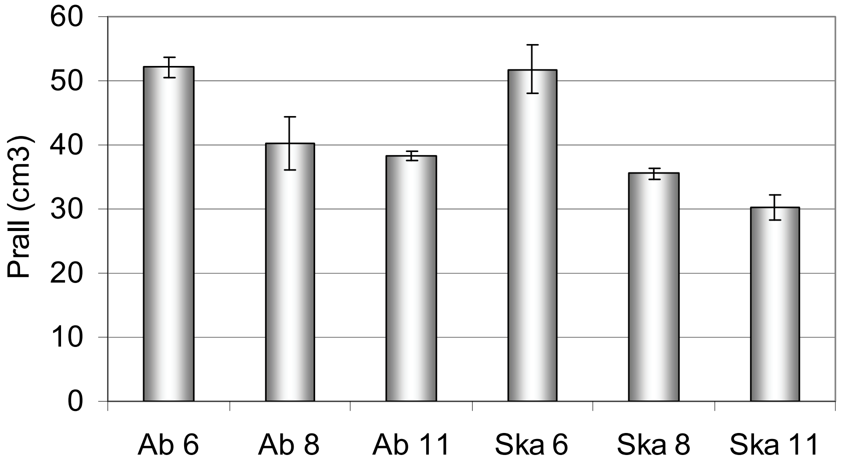

Figure B-1. Average Prall values (cm^3)

The results point out that asphalt mixtures with 6 mm maximum aggregate size are less resistant against wear by studded tires compared to asphalt mixtures with 8 mm and 11 mm maximum aggregate size (D_{max}).

C Significance of aggregate type on production of fines

Objective

The objective of the study was to investigate amount and properties of fines (< 0.063 mm) generated from different rock types using the Nordic ball mill.

Materials and methods

Aggregate quality is reported to be more important for asphalt pavement wear resistance than the maximum aggregate size, D_{max}. In this study six different aggregate types were tested in the Nordic ball mill for particle generation. The selected rock types often are used as aggregate in high volume roads in Norway.

The aggregate testing was performed by Kahn (2007). Each material was run in the Nordic ball mill according to EN 1097-9:1998 (CEN, 1998) with water and steel balls for one hour. The weight loss (material < 0.063 mm) after testing in the Nordic ball mill gives indication of the aggregate material resistance against studded tires.

Material less than 0.063 mm was separated after testing with wet sieving, and the material was dried. Afterwards, gravimetric measurement, particle size distribution, specific surface area and particle shape distribution of the fine fraction was determined. Methods used for particle characterization were laser diffraction to get particle size distributions by Coulter LS 230 (0.04-2000 µm), BET to find the specific surface area of material < 0.063 mm using FlowSorb II, and image analysis to get the particle shape (roundness) by Pharma Vision 830 (5-2000 µm).

The aggregate grading tested was according to the grading of stone mastic asphalt (SMA) with maximum aggregate size, D_{max}, of 11 mm. This gives an aggregate grading of 69 % 4-11 mm and 31 % 0.063-4 mm. Aggregate materials tested are shown in Table C-1.

Table C-1. Aggregate materials tested

Name	Type	Density	KM	LA	PSV
A	Greenstone	3.056	9.6	16.9	49
B	Mylonite	2.765	5.2	10.3	50
C	Hornfels	2.849	3.8	9.3	48
D	Mylonite	2.789	6.1	10.7	56
E	Quartzite	2.645	5.3	19.1	
F	Quartzite	2.635			

Results

In Figure C-1 the amount of fines produced from the different aggregate types are presented (adopted from Khan, 2007). The particle size distribution is shown in Figure C-2, specific surface area in Figure C-3 and particle shape distribution in Figure C-4.

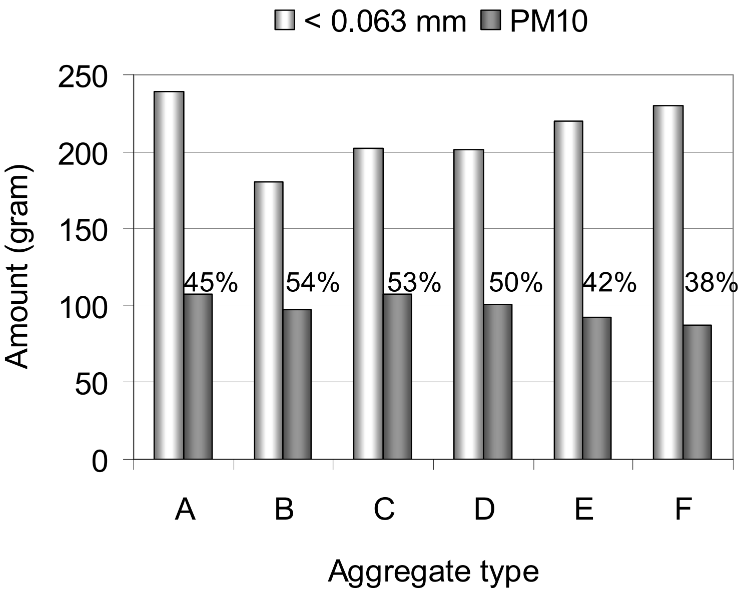

Figure C-1. Amount of fines < 0.063 mm produced (gram)

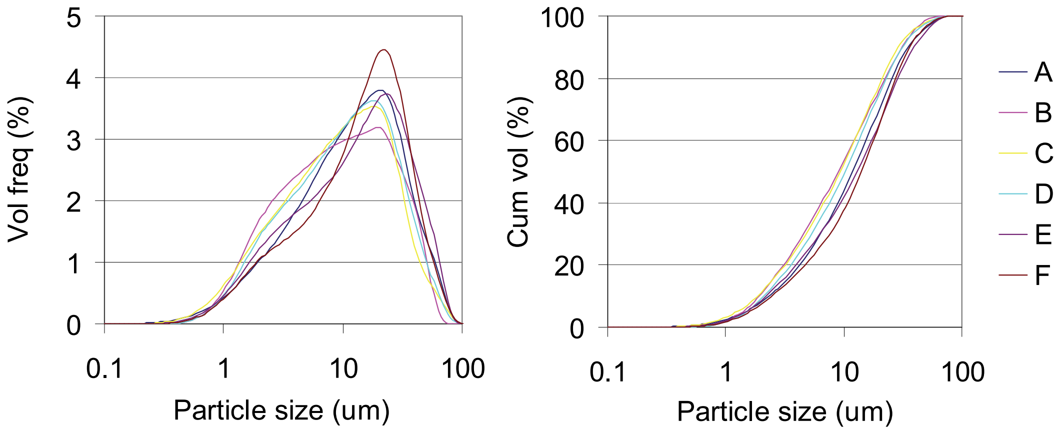

Figure C-2. Particle size distribution (μm)

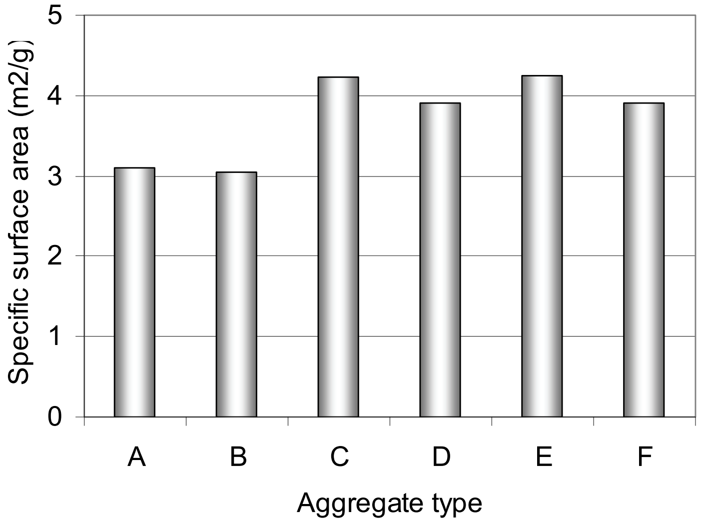

Figure C-3. Specific surface area (m^2/g)

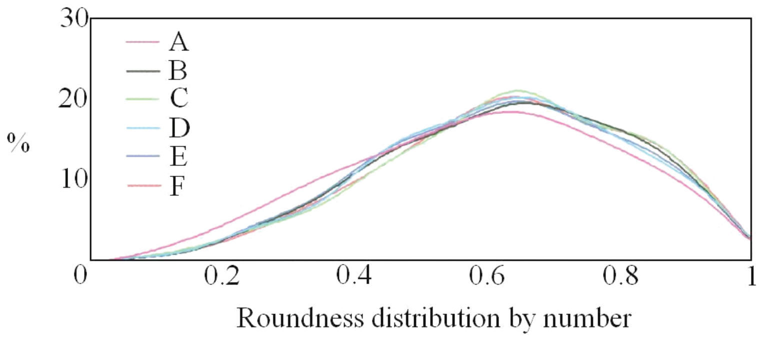

Figure C-4. Particle shape

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