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Experimental studies about the impact of traction sand on urban road dust composition

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Abstract

Traffic causes enhanced PM_{10} resuspension especially during spring in the US, Japan, Norway, Sweden and Finland, among other countries. The springtime PM_{10} consists primarily of mineral matter from tyre-induced paved road surface wear and traction sand. In some countries, the majority of vehicles are equipped with studded tyres to enhance traction, which additionally increases road surface wear. Because the traction sand and the mineral matter from the pavement aggregate can have a similar mineralogical composition, it has been difficult to determine the source of the mineral fraction in the PM_{10}. In this study, homogenous traction sand and pavement aggregate with different mineralogical compositions were chosen to determine the sources of PM_{10} particles by single particle analysis (SEM/EDX). This study was conducted in a test facility, which made it possible to rule out dust contributions from other sources. The ambient PM_{10} concentrations were higher when traction sand was used, regardless of whether the tyres were studded or not. Surprisingly, the use of traction sand greatly increased the number of the particles originating from the pavement. It was concluded that sand must contribute to pavement wear. This phenomenon is called the sandpaper effect. An understanding of this is important to reduce harmful effects of springtime road dust in practical winter maintenance of urban roads

Keywords: PM_{10}; SEM/EDX; Mineral dust; Sanding; Paved roads; Fugitive dust; Studded tyres; Aggregate

1. Introduction

In Northern latitudes with constant snow coverage during winter months (December–March), high particle concentrations have been observed. High concentrations occur especially during the spring in urban areas with high traffic volume (Amemiya et al., 1984; Fukuzaki et al., 1986; Noguchi et al., 1995; Kantamaneni et al., 1996; Kukkonen et al., 1999). The particles are deposited in snow, and when snow melts, road surfaces dry out, and a proportion of the dust is resuspended by traffic. Springtime suspended particles form one of the most serious problems regarding air pollution in Finland. This is particularly true when measured levels are compared with the national

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guidelines (Kukkonen et al., 1999; Tiittanen et al., 1999). During these spring conditions, road dust consisting primarily of mineral matter dominates the particulate mass (Pakkanen et al., 2001a,b). A similar phenomenon has been observed in other countries as well, (e.g. Amemiya et al., 1984; Fukuzaki et al., 1986; Noguchi et al., 1995; Kantamaneni et al., 1996). Apart from the discomfort caused by the dust, respirable mineral particles, e.g. aluminosilicates and crystalline quartz have been implicated in human disease with lung cancer as most severe (Puledda et al., 1999; Powell 2002; NIOSH, 2002). Whether these effects are significant in urban conditions is still unknown. Studies of exposure to mineral and resuspension particles have shown evidence of toxicity and a possibility of adverse health effects (Tiittanen et al., 1999; Klockars, 2000; Salonen et al., 2000). However, an epidemiological study by Laden et al. (2000) found no association between increased mortality and fine mineral particle concentrations.

The mineral dust in the particulate mass mainly results from the use of anti-skid methods to enhance traction on snowy or icy road surfaces. Such methods include spreading of traction sand on the road surfaces and equipping tyres with metal studs or a special rubber design, and salting the road to prevent sliding. The traction sand is crushed into smaller particles under the tyres and the pavement aggregate is worn by interaction with the tyres. In Finland, approximately 90% of the cars have studded tyres, but especially in the urban areas traction sand is widely used in addition. The Finnish National Road Administration has studied pavement wear by studded tyres and evaluated the possible dust problems arising from it, (e.g. Alppivuori et al., 1995). The main hypothesis has been that traction sand is the most important source of the springtime road dust.

The dust problem induced by the use of anti-skid methods has been acknowledged also in Japan, Sweden and in the US. In Japan, studies have shown that the use of studded tyres is responsible for elevated particle concentrations during winter and spring (Amemiya et al., 1984; Fukuzaki et al., 1986; Noguchi et al., 1995). Bringfelt et al. (1997) have developed a local PM_{10} dispersion model for Swedish cities that takes into account an increase in road dust emissions due to the use of anti-skid aggregate and studded tyres. Elevated levels of particulate emissions caused by road sanding have been observed in a study made in the US (Kantamaneni et al., 1996). However, the presence of vehicles with studded tyres was not reported in that study. The US Environmental Protection Agency's AP-42 model gives an approximate guideline to apply a factor of 4 for emissions on roads where sand has been used (Kantamaneni et al., 1996).

The particulate mass problem caused by different anti-skid methods has not been well studied and for only one method at a time. However, these methods are often used in combination. This study seeks to determine the source contributions and relative PM_{10} concentrations in situations where traction sanding and studded tyres are used together or individually. As the mineralogy of the sanding and pavement aggregates can be very similar, it is very difficult to identify the source of dust. In urban conditions other sources can complicate the situation. This study was conducted in a test facility where spring time temperature conditions could be simulated and other sources of particles besides traction sand and surface wear could be ruled out. The rock materials for the pavement aggregate and traction sand were chosen because it was possible to identify the particles originating from these two sources based on individual particle analysis with SEM/EDX.

2. Materials and methods

2.1. The test conditions

The test facility (an approx. 180-m^3 volume room) was originally designed for testing the bearing capacity of different types of pavement structures. It has also been used in studies of the dust exposure of road maintenance staff (Mustonen and Valtonen, 2000). For this study, the test room was cooled to a temperature of 4 °C to represent the typical temperature in spring conditions. Two wheels were attached to an electrically powered rotating axle (Fig. 1), with adjustable rotating speed. It was adjusted to move sideways so that the driving space of the tyres was 33 cm. The

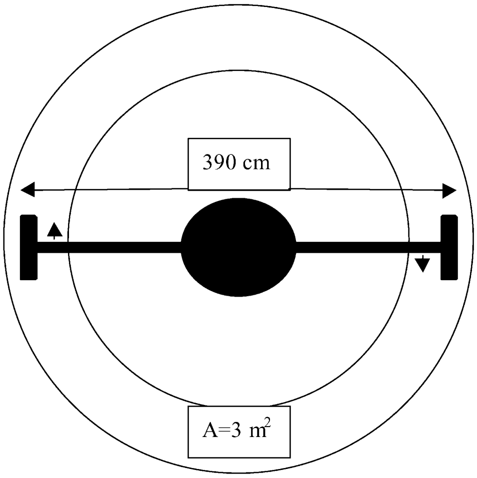

Fig. 1. Schematic picture of the axle system with direction of rotation and the distance between the tyres. The area of the driving space is also shown.

diameter of the test ring was 390 cm. The tests were performed with either studded tyres (Nokian Hakkapeliitta 1, 175/70R13) or with winter tyres lacking studs (Nokian Hakkapeliitta Q, 175/70R13). The tyre pressure was 2.0 bar and the weight for each tyre was 300 kg. The driving ring was surrounded with low walls to prevent the traction sand from flying off.

The road surface of the test facility was asphalt concrete 11 (maximum rock size 11 mm) with an approximate composition of: 90% crushed bedrock; 5% mineral filler (carbonate rock); and 5% bitumen. This research was based on using anti-skid aggregates with a different mineral composition than the pavement aggregate. The most important difference was the content of hornblende (53% in the asphalt stone and 0% in the traction sands; Table 1) which was used as a tracer of mineral matter originating from the pavement. Three different rock types, which are also quarried and used in various applications in road building and maintenance, were selected. Granite and diabase were used as anti-skid aggregates and mafic volcanic rock was used as the crushed bedrock aggregate in the asphalt. The detailed mineralogy of the aggregates (Table 1) was analysed with the point-counting method, in which the modal composition (in vol.%) is determined with a polarising microscope from 1000 equally distributed mineral identifications from a polished thin section of the rock. In addition, blast furnace slag was used in two tests. All of the sands were sieved with a 2-

Table 1
Modal compositions of the aggregates used, based on point-counting analyses of polished thin sections (1000 points/one rock type)[a]

Mineral type	Mafic volcanic rock (asphalt)	Granite (traction sand 1)	Diabase (traction sand 2)	Chemical formula
Quartz	0	30.4	0	SiO_2
K-feldspar	0	29.6	0	$KalSi_3O_8$
Plagioclase	29.4	32.4	57.4	$(Na,Ca)Al(Si,Al)Si_2O_8$
Hornblende	53	0	0	$Ca_2(Mg,Fe)_4Al(Si_7Al)O_{22}(OH,F)_2$
Biotite	0	5.9	3.8	$K(Mg,Fe)_3(Al,Fe)Si_3O_{10}(OH,F)_2$
Muscovite	0	0.6	0	$KAl_2(AlSi_3O_{10})(OH,F)_2$
Olivine	0	0	17.5	$(Mg,Fe)_2SiO_4$
Clinopyroxene	0	0	17.3	$(Ca,Mg,Fe)_2Si_2O_6$ (Augite)
Chlorite (group)	1.4	0.3	0	$(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$
Epidote	0	0.2	0	$Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$
Kummingtonite-grunerite	12.8	0	0	$(Mg,Fe)_7Si_8O_{22}(OH)_2$
Oxides	3.2	0.5	4	Fe_3O_4 (Magnetite) $FeTiO_3$ (Ilmenite)
Carbonate	0.2	0	0	(CO_3)-group

[a] All figures are given as percentages.

Table 2
The test descriptions[a]

Test	Tyre	Sand type	Amount of sand (dm^3)	Other
No. 1	Studded S01	–	0	Day 1
No. 2	Studded GS2	Granite	2	Day 2
No. 3	No studs GN2	Granite	2	Day 2
No. 4	Studded CS2	Blast furnace slag	2	Day 3
No. 5	Studded CS4	Blast furnace slag	4	Day 3
No. 6	Studded GS2*s*	Granite	2	Day 4 (speed 25 km/h)
No. 7	Studded DS2	Diabase	2	Day 5
No. 8	Studded DS4	Diabase	4	Day 5
No. 9	Studded GS2*x*	Granite	2	Day 6 (traction sand: <2-mm fraction 43%)
No. 10	Studded GS4	Granite	4	Day 6
No. 11	Studded DS2	Diabase	2	Day 7
No. 12	No studs DN2	Diabase	2	Day 7
No. 13	No studs N0	–	0	Day 8
No. 14	Studded S02	–	0	Day 8

[a] Driving speed was 15 km/h, unless mentioned otherwise.

mm sieve. The <2-mm fraction for granite was 20.3%, for diabase 0.3% and for the clinker 0.4%. One sample (GS2*x*) was not sieved for these tests and its <2-mm fraction was 43%.

The tests were conducted during a period of 7 days, one test in the morning and one in the afternoon. The tests are shown in Table 2 and the amount of sand dispersed in Table 3. The short distance between the wheels and the rotating motion result in a grinding effect that is rarely found in normal street conditions. Therefore, we used relatively low speeds (15–25 km h^{-1}) in the tests. After each test, the dust was allowed to settle for 30–45 min and, after that, the room was vacuumed and ventilated. The background concentration of particles was measured each morning before the tests and once between tests. All background concentrations were 75–90% lower than the test concentrations.

2.2. The sampling and analysis

Ambient particles were collected on polycarbonate filters with a high-volume particle sampler (PM_{10}-gravimetric Wedding & Associates Sampler). The inlet was at a height of approximately 2.5 m. Each test took 1 h, which was also the length of the sampling time.

The elemental composition of individual particles was studied with a scanning electron microscope (SEM-ZEISS DSM 962) coupled with an energy dispersive X-ray microanalyzer (EDX-LINK ISIS with ZAF-4 measurement program). This instrumentation has been used in individual particle studies, (e.g. Mamane et al., 1980; Kasparian et al., 1998; Ganor et al., 1998; Paoletti et al., 1999; Breed et al., 2002). The SEM/EDX samples were prepared by pressing a tape (Scotch Ruban Adhesive) attached to an aluminum plate onto the filter surface covered with particles. A minimum of two samples from each filter was made. The samples were sputtered with carbon (Agar SEM Carbon Coater) to make the sample surface conductive. The accelerating voltage was 20 kV. The total X-ray count rate was calibrated

Table 3
The amount of dispersed traction sand

Sand	Volume (dm^3)	Mass (g)	Mass/area (g/m^2)
Granite	2	2798	926
	4	5596	1853
Diabase	2	3190	1056
	4	6379	2112
Blast furnace	2	2501	828
slag	4	5002	1656

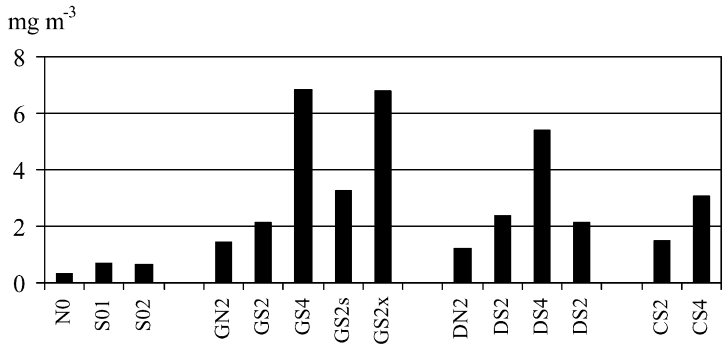

Fig. 2. Ambient mass concentrations (mg m^{-3}) in individual tests. For abbreviations see Table 2, tyre.

to 1500 counts s^{-1} with cobalt. From each particle an X-ray spectrum was collected with a preset time of 15 s.

The elemental composition of 100–150 randomly selected particles were analysed and recorded with ZAF-4 from each filter. Particles were classified according to the chemical composition. The accuracy of the classification was studied by analysing 500 particles from one sample (GS2) and dividing it into 100 subsamples, which were then compared with each other. The S.D. of the individual classes varied between 0.5 and 4.9. The shape and size of the particles were recorded and the EDX spectrum was measured and saved with ZAF-4. The elemental weight percentages of Al, Ca, Cl, Fe, K, Mg, Na, O, S, Si and Ti for each particle were calculated. If other elements were clearly observed, their presence was also recorded. The ZAF correction method assumes flat samples. This is rarely the case with complex sized and shaped particles and the atomic concentration may, therefore, be biased (Paoletti et al., 1999). As in the case of Paoletti et al. (1999), the particle types were determined by distinguishing the presence and proportional concentrations of the typical elements, (e.g. for mineral types, see Table 1). This classification could be made with good confidence.

Particles with a geometric diameter below 1 μm were ignored from the analysis. This was thought to be the lowest limit to obtain reliable results from individual particles with this technique (Jambers et al., 1995). Thus, a limit did not cause problems for the study because the main focus was on mineral particles that are rarely below 1 μm in diameter.

3. Results

3.1. The particulate mass concentrations

The PM_{10} mass concentrations are shown in Fig. 2 and the abbreviations are explained in Table 2. Without traction sand (S01, S02 N0) the PM_{10} concentrations were much lower than with traction sand. Approximately twice as much PM_{10} dust was formed with the studded tyres than with the non-studded tyres. This did not seem to depend on traction sand (S0/N0 = 2.0, GS2/GN2 = 1.5, DS2/DN2 = 2.0). The use of traction sand raised concentrations in every case. The amount of sand dispersed correlated with the PM_{10} concentrations (Fig. 3). The deviation is suspected to have been caused in part by difference in the properties of the rocks. The test with the 43% <2-mm fraction raised the PM_{10} concentration over 10-fold compared to the test without sand (GS2*x*/S0 = 10.7) and three-fold compared to the test with the 20.3% <2-mm fraction (GS2*x*/GS2 = 3.2). The particle concentration at a higher speed (25 km h^{-1}) was 1.5 times higher than the concentration at 15 km h^{-1} (GS2*s*/GS2 = 1.5).

Emission factors for PM_{10} particles were estimated by assuming that the PM concentration is distributed equally in the room. In the tests without traction sand, the emission factor was 0.01 for non-studded and 0.02 g km^{-1} for studded tyres.

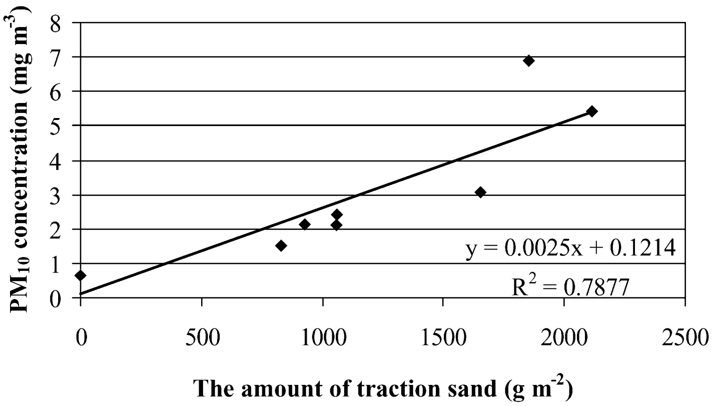

Fig. 3. The correlation between ambient PM_{10} concentrations and the amount of traction sand used for the studded tyres.

The use of traction sanding increased the emission factors. The emission factors with 900-g m^{-2} sand were 0.03–0.05 g km^{-1}. The same amount of aggregate with <2-mm sand grains increased the emission factor to 0.16 g km^{-1}. The higher speed (25 km h^{-1}) did not significantly affect the emission factor. The emissions with studded tyres were somewhat higher than with non-studded also in the sanded tests. The emission factor with 1800-g m^{-2} sand and studded tyres were 0.07–0.16 g km^{-1}.

The results from this study are at the lower end of the large range of emission factor estimates found in previous studies for paved road dust (see Table 4) (Claiborn et al., 1995; Kantamaneni et al., 1996; Bringfelt et al., 1997; Venkatram et al., 1999). It is possible that the PM did not disperse equally to the test room as assumed which might lead to an underestimation of the emission factor. It is also obvious that street side conditions cannot be totally simulated in laboratory experiments like these: (1) other sources than road abrasion components were excluded in our tests. They may have a measurable contribution to road dust in

Table 4
A comparison of emission factors (g km^{-1}) for road dust

	PM_{10} emission factor estimate (g km^{-1})	Remarks
This study[a]	0.01–0.02	Without traction sand
	0.03–0.05	With 900 g m^{-2} traction sand
	0.16	With 900 g m^{-2} traction sand (with <2-mm sand grains)
	0.07–0.16	With 1800 g m^{-2} traction sand
Bringfelt et al. (1997)[b]	0.05	0–19 km h^{-1}
	0.28	19–28 km h^{-1}
Claiborn et al. (1995)[c]	0.5–34	Paved road resuspension
Kantamaneni et al. (1996)[d]	0.4–2	Without traction sand
	1–2	With traction sand
Venkatram et al. (1999)[e]	0.1–3	Paved road resuspension

[a] Test conditions to represent road abrasion by a light duty car, speed 15–25 km h^{-1}.
[b] Light duty vehicles.
[c] A field study, roads and streets with varying traffic volume.
[d] A field study, four-lane street, sand (predominant 0.95 cm size distribution) dispersed 12 h prior to sampling.
[e] A freeway and three major streets.

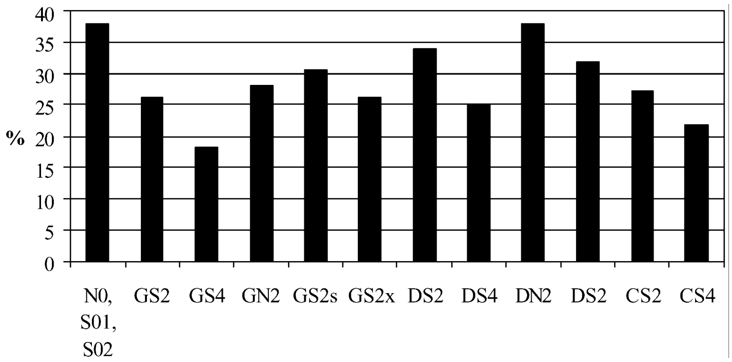

Fig. 4. The abundance (%) of hornblende in the PM_{10} samples. For abbreviations see Table 2, tyre.

field conditions (Rogge et al., 1993). (2) Low speeds (15–25 km h^{-1}) were used during the tests. Higher speeds also increase the road dust emissions (Bringfelt et al., 1997; Kuhns et al., 2001). (3) Emission factors for heavy-duty vehicles were not measured in our study, e.g. Bringfelt et al. (1997) have reported higher emissions for heavy-duty vehicles than for light duty and they may contribute to the emission estimates made in field conditions.

Despite the uncertainties, it is possible to estimate the relative effect of traction sanding on PM_{10} emissions. In the field study by Kantamaneni et al. (1996), road sanding increased the emission factor on average 1.4-fold. In the US Environmental Agency's AP-42 model an approximate guideline for emissions on roads with traction sand has been to apply a factor of 4 (ref. from Kantamaneni et al., 1996). In this study the emissions increased three- to eight-fold as a function of sand dispersed (with 900 g m^{-2} and 1800 g m^{-2} sand, respectively Fig. 3).

It can be concluded that the type of tyre, the amount of sand dispersed and the properties of the sanding material all affected the PM_{10} concentrations. With studded tyres more PM_{10} dust was formed than by winter tyres without studs. For more generalised conclusions about the effect of the tyre, studies with a larger variety of designs are needed. An important factor was the spreading of traction sand, which significantly raised the PM_{10} concentrations. The concentrations correlated with the amount of sand used. The share of small size fractions in the sanding material also raised the PM concentration.

3.2. Composition of the PM_{10} dust

The amount of dust originating from traction sand and from asphalt was studied by counting the fraction of different mineral types in the PM_{10} dust samples and comparing these fractions to the mineralogy of the rocks. The most important difference between aggregates was that the sanding materials did not contain hornblende, which was the most abundant mineral type in the mafic volcanic rock of the asphalt aggregate (Table 1).

Since all the hornblende must originate from the asphalt aggregate, its abundance was used as a basis to study the sources of the particles. The fraction of PM originating from the asphalt was calculated by the difference from the abundances in the tests with and without sanding (Fig. 4). It was observed that the mineralogy of the mafic volcanic rock is not exactly representative of the shares of different minerals in the airborne dust (geological variation at the quarry). Consequently, the tests without the sand (S01, S02 N0) were used as the basis for calculations instead of the mineralogy.

In addition, other particle classes were observed that originated from other sources than aggregates. Class 120 (particles with Na–Mg–Al–Si–S–K–Ca–Fe, often also C) was suspected to be either a bitumen/mineral mixture from asphalt filler or particles from tyres (Rauterberg-Wulff et al., 1995;

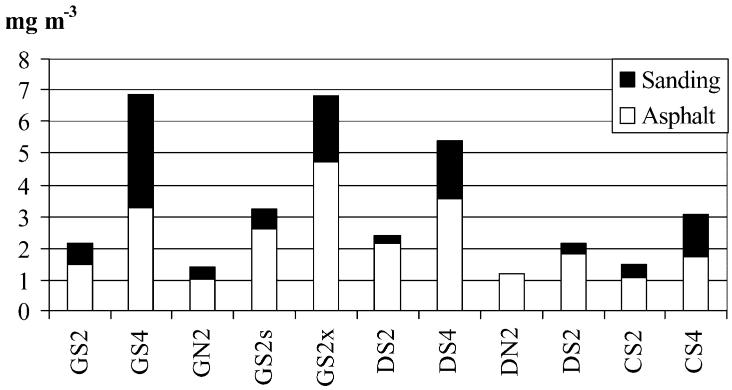

Fig. 5. The average shares of the PM_{10} from the asphalt and the traction sand. For abbreviations see Table 2, tyre.

Camatani et al., 2001). The share ranged from 1% (GS2) to 9% (DS2). The carbonates, ranging from not detected in GN2 to 6% in DN2, probably came from the filler material.

Using only the particle concentration data would lead to the conclusion that the PM_{10} dust originates mainly from traction sanding. A compositional analysis of the dust by SEM/EDX showed that a large percentage of the particles contained hornblende and thus, must originate from the asphalt (Table 1). It was concluded from the analyses of the particle concentrations and the analyses of the particle chemistry, that the traction sand is not only crushed into small PM_{10} particles but also increases the asphalt pavement wear. Road sanding increases the PM_{10} concentrations but the sources of the particles are both the sanding material and the road pavement. This phenomenon was named 'the sandpaper effect'.

The share from the asphalt ranged from 36% (GS4) up to 100% (DS2 and DN2), with the average of all tests being 74%. In Fig. 5, the averages of individual tests were combined with the concentration data (Fig. 2). The more sand was used, the more particles originated from the sanding material (GS4/GS2, DS4/DS2, CS4/CS2). The traction sand with the higher <2-mm fraction (GS2*x*) did not result in a higher share of PM_{10} dust from the sanding material. The increase in speed (GS2*s*) raised the share of dust originating from the asphalt. It is important to note that in the tests using tyres without studs (GN2, DN2) the sandpaper effect was also significant.

The rock properties affect the PM_{10} concentrations. Based on the averages in our tests, the diabase seemed to result in lower PM_{10} concentrations but had a larger sandpaper effect than the granite (Fig. 5). Räisänen et al. (2002) are preparing a more detailed study of the geological and mechanical properties of anti-skid and asphalt aggregates. That study is based mainly on the same materials and data as this one. In order to make general conclusions about the connection between the rock properties and the PM-concentrations, more detailed studies with more rock types included have to be conducted.

4. Discussion and conclusions

The problem of the high springtime particle concentrations caused by snow and ice control methods has been acknowledged in several countries (Amemiya et al., 1984; Fukuzaki et al., 1986; Noguchi et al., 1995; Kantamaneni et al., 1996; Bringfelt et al., 1997; Kukkonen et al., 1999). The mineral dust originating from the asphalt pavement aggregate or the traction sand has been identified to be the main component of the PM (Amemiya et al., 1984; Fukuzaki et al., 1986; Noguchi et al., 1995; Kantamaneni et al., 1996; Kukkonen et al., 1999; Pakkanen et al., 2001a,b). Previous studies have focused only on the effects caused by the use of only one of the anti-skid methods, either the traction sand (Kantamaneni et al., 1996) or studded tyres (Amemiya et al., 1984; Fukuzaki et al., 1986; Noguchi et al., 1995). To the knowledge of the authors, the present study is the first one to take the combined effect of these two methods into account.

The results of the present study are interesting from the point of view of the 1999 European Union's legislation on air quality. In the cities of Northern member states including Finland and Sweden, the springtime road dust can cause the PM_{10} concentrations to exceed the European Union's new air quality limit values for thoracic particles (PM_{10}) given in the European Council Directive, 1999. If the limit values are exceeded, a member state must implement action plans to reach the limit value. However, the member state can designate areas where the limit values are exceeded due to the resuspension of particulates following the winter sanding of roads.

The results of this study show that when both traction sand and studded tyres were used, the use of traction sand increased the concentrations of PM_{10}, which might support the dominant role of sanding material in the dust. However, a study of the particle chemistry showed that a significant part of the particulate matter came from asphalt. This result indicates that the pavement wear is strongly increased by the grinding impact of sand under the tyres, which produces dust also from the asphalt aggregate. This phenomenon was named the sandpaper effect. Its understanding is important to reduce harmful effects of springtime road dust in practical winter maintenance of urban roads. Dust emissions an the sandpaper effect were dependent on several factors, such as the mechanical and mineralogical properties of both the sanding and pavement aggregates, the quantity of traction sand used, the size distribution of the sand grains as well as the type of tyres.

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