The effect of mineralogy, texture and mechanical properties of anti-skid and asphalt aggregates on urban dust

M. Räisänen · K. Kupiainen · H. Tervahattu

Abstract In northern latitudes mineral dust is formed when cars use studded tyres and roads are sanded to obtain more traction on the icy surfaces. Anti-skid and asphalt aggregates with different textural, mineralogical and mechanical properties were tested with an indoor road simulator fitted with studded and friction tyres. The particle size distribution and proportions of dust from pavement and anti-skid aggregate were analyzed using SEM-EDX. The wear on the road pavement depends on the properties of the anti-skid and asphalt aggregate (particle size distribution, mechanical/physical and textural properties). Anti-skid aggregates, which contain mainly hard minerals (e.g. feldspars and quartz) and which have a low resistance to fragmentation, should be used with caution as they may break more easily into smaller particles and are likely to wear the pavement. By using high-quality anti-skid aggregates it is possible to reduce the amount of urban dust.

Résumé Aux hautes latitudes, la poussière minérale se forme lorsque les voitures utilisent des pneus cloutés et que les routes sont sablées afin d'obtenir une meilleure adhérence sur des surfaces verglacées. Des granulats asphaltés anti-dérapage de diverses propriétés minéralogiques, texturales et mécaniques ont été testés avec un simulateur de laboratoire équipé de pneus cloutés. La granularité des poussières ainsi produites à partir de matériaux de revêtement de chaussée et des granulats asphaltés anti-dérapage a été analysée à l'aide d'un sédimentomètre SEM-EDX. L'usure des matériaux de revêtement de chaussée dépend des propriétés des granulats asphaltés anti-dérapage (granularité, propriétés physiques et mécaniques). Les granulats anti-dérapage qui contiennent principalement des minéraux durs (e.g. feldspath et quartz) et ont une faible résistance à la fragmentation doivent être utilisés avec prudence du fait qu'ils se brisent plus aisément en petites particules et peuvent ainsi contribuer à l'usure du revêtement de chaussée. En utilisant des granulats anti-dérapage de haute qualité il est possible de réduire la production de poussières en ville.

Keywords SEM-EDX · Asphalt aggregate · Anti-skid aggregate · Studded tyre test · Los Angeles test · Petrography · PM_{10}

Mots clés Sédimentomètre · Granulat asphalté · Granulat anti-dérapage · Test au pneu clouté · Test Los Angeles · Pétrographie

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Introduction

The behaviour of asphalt and anti-skid aggregates is affected by their geological, mechanical and physical properties. In northern latitudes, salt is used during wintertime to depress the freezing point of the pavement and anti-skid aggregates are spread on icy road surfaces to increase traction. However, mineral dust originating mainly from the wear of asphalt and anti-skid aggregates is deposited on the ground and during late winter, especially when the surfaces of roads dry out, this dust rises into the air (re-suspension). Urban dust can be hazardous to health and lowers the quality of everyday life in cities. Kukkonen et al. (1999) have suggested that the amount of total suspended particles can be higher in Finnish cities than in central, southern or eastern European cities.

In order to protect people from the effects of airborne particles, new European limiting values for PM_{10} (thoracic

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particles <10 μm) concentrations in the air have been determined (European Council Directive 1999/30/EC). During springtime dust episodes, the actual PM_{10} concentrations in Finnish cities can be higher than the new limiting values. The European Union member states are allowed to exceed the prevailing limiting values in specified areas, if it can be shown that this is caused by the winter maintenance of roads.

Laden et al. (2000) have argued that the most severe health problems are caused by aerosol particles <2.5 μm in size (fine particles). The most important source of these aerosols is considered to be combustion processes. Effects on health are exacerbated in the case of sick or vulnerable people. According to epidemiologists, such as Pope and Dockery (1992) and Dockery et al. (1993), a correlation can be found between fine particles and mortality and cardiovascular diseases. The PM_{10} mineral dusts are generally composed of coarse particles (2.5–10 μm) with some <2.5 μm. Holopainen et al. (1990) and Klockars et al. (1990) have shown how different mineral dusts (e.g. quartz, asbestos and mica minerals) cause negative reactions in clinical cell tests. This is explained by the highly reactive nature of undercoordinated surface atoms of crushed fresh silicates (Klockars et al. 2000). Undercoordinated atoms contain broken bonds between atoms; for example, in quartz a silicon atom can contain only three oxygen atoms instead of four. However, Laden et al. (2000), based on epidemiological examinations, imply that mortality is not associated with the mineral fraction of the urban aerosol.

It has generally been accepted in the Nordic countries, Japan and North America that studded tyres and anti-skid aggregate are a major source of inorganic urban dust, as studded tyres wear the asphalt pavement and anti-skid aggregate is worn by all types of tyres (e.g. Fukuzaki et al. 1985; Alppivuori et al. 1995; Jacobson 1995; Kantamaneni et al. 1996; Lindgren 1998; Pakkanen et al. 2001). Kanzaki and Fukuda (1993) and Lindgren (1998) point out that the worn particles of the pavement can act as a grinding material and thus exacerbate the wearing process. In their road dust study, Kupiainen et al. (2003) found that anti-skid aggregate both wears itself and causes significant wear of asphalt pavements. They called this phenomenon the "sandpaper effect".

Studies on the cause of urban dust are usually focused on either anti-skid aggregate or studded tyres. However, the present study has included investigation of the effect of the particle size distribution, flakiness index, mechanical/physical properties and petrography of both bedrock and blast furnace slag (BFS) aggregates on urban dust with a distinctive mineralogical composition. It is an extension of a study by Kupiainen et al. (2003) on the determination of the origin of urban dust (anti-skid vs. asphalt aggregate) and is based mainly on their dust analyses. The main aim of the present study was to find which properties of the aggregates affect the formation and concentration of PM_{10} mineral dust in urban areas and to answer the question: "Can the composition and amount of urban dust be controlled by the right selection of aggregates?" It is in the public interest to minimize the amount of mineral dust in the air.

Materials and methods

The test procedure

The test was performed indoors with a road simulator (Fig. 1) to minimize external variables that can have an impact on the test results and in order to be able to accelerate the wearing process of the aggregates. In the road simulator, two wheels are attached to the ends of an axle, which is coupled to an eccentric device in order to produce movement affecting a wider area of the pavement. The weight at each wheel was 300 kg. The tests were run with studded and friction winter tyres. Asphalt concrete with a particle size from 0 to 11 mm was used as the pavement material. The tests were run in constant humidity at 4 °C. Samples were collected from a height of 2.5 m with a high-volume particle sampler (PM_{10}-gravimetric Wedding and Associates Sampler). The height of the particle sampler is 2.5 m. The pre-separator filter removed >10 μm particles from the test sample. Samples collected from each filter using double-faced tape were analysed by a scanning electron microscope (SEM) coupled to an energy dispersive X-ray microanalyzer (EDX). The element composition of 100–150 randomly selected dust particles was analyzed with the SEM/EDX. This method has been used more or less similarly in several airborne particle studies previously (e.g. Ganor et al. 1998; Kasparian et al. 1998; Paoletti et al. 1999; Piña et al. 2000; Xu et al. 2001; Breed et al. 2002). However, in this study the focus was on mineral particles, which were grouped using the elemental composition of the individual particles and information on the mineralogy of the aggregates. Hornblende was used as an asphalt vs. anti-skid aggregate indicator. Kupiainen et al. (2003) defined the standard

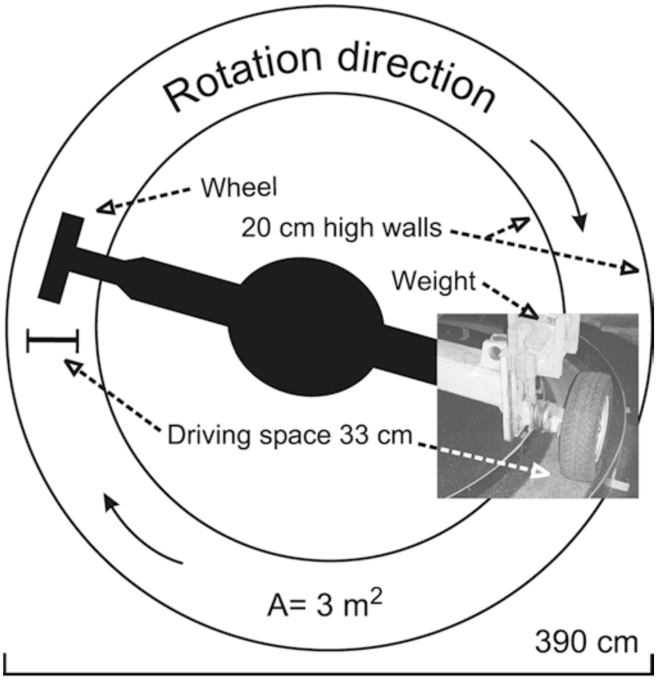


Fig. 1
Road simulator

deviation for hornblende (4.6%) by analyzing five sub-samples from one filter. Each sub-sample contained 100 particles.

Experimental conditions

In real life, the asphalt and anti-skid aggregates may have a similar mineralogy, which makes it difficult to distinguish the origin of dust particles. Additionally, there are other sources of dust particles which complicate the classification further. The major differences between real life conditions and those of the present study are: dry conditions, a circular road simulator ring and 15 km/h driving speed (one comparison was run with a speed of 25 km/h) and asphalt concrete (rocksize < 11 mm) instead of SMA (stone mastic asphalt) pavement. In order to collect the dust, the tests had to be run in dry conditions. Wet conditions are caused by the variation in temperature and the use of salt as a freezing point depressant to melt ice on pavements. A wet surface increases the wear of the asphalt pavement by a factor of at least 2 (e.g. Folkeson 1992; Kanzaki and Fukuda 1993). Water with mineral particles acts as an abrasive material and increases the wear of anti-skid aggregates.

The low speed on the circular test ring produces conditions where intense abrasive wear dominates over fragmentation. City speed limits are between 30 and 50 km/h in densely populated areas where urban dust creates a problem. Jacobson (1995) tested 250 slabs made with different types of aggregates and asphalt in a road simulator (speed 85 km/h, four wheels and wet conditions) and 130 slabs in the real life situation on Swedish roads. The correlation of wear was 0.96 during the test period of 2–3 years. He argues that an SMA pavement with a high percentage of coarse aggregates tolerates 15–40% more wear compared with asphalt concrete with the same maximum particle size.

Selection of aggregates

The major pre-condition for the selection of the test materials was their distinctive mineralogical composition and adequate homogeneity of aggregate source areas. The asphalt pavement and anti-skid aggregates had to have such a mineralogical composition that the origin of dust particles could be specified. The tested aggregates are also used in roads. The asphalt pavement aggregates must have good resistance to the scratches caused by studded tyres in the heavily trafficked roads in the Nordic countries; this was tested with the studded tyre test (European Committee for Standardisation 1998b, EN 1097-9). All the tested aggregates had different mechanical properties, i.e. resistance to fragmentation and abrasive wear.

The mechanical/physical properties of tested aggregates

Standardised EN tests should be performed using the correct particle size. However, there are no EN standards for testing the strength of anti-skid aggregates with a particle size of 2–6 mm. The Los Angeles (LA) test method (European Committee for Standardisation 1998a, EN 1097-2 annex A) suggests options for testing other sizes, e.g. a particle size distribution of 4–8 mm. Matti Mertamo (personal communication) has used the studded tyre test (STT) on some 30 samples with particle sizes from 8–11.2 mm (granitoids, mafic and intermediate volcanic rocks) and found the results were 10–40% lower compared with the standard 11.2- to 16-mm test size (European Committee for Standardisation 1998b, EN 1097-9). The correlation between mechanical properties and particle size of test material is not linear.

The mechanical properties vary a great deal related to the texture and mineralogy of the aggregate. Heikkilä (1991) states that the strength of aggregates depends partly on the number of crushing stages and the setting of the crusher. The rock recovers its strength when the blast induced structural damage, i.e. microcracks and poor shapes (flat and elongated particles) are reduced and the rock breaks along planes of weakness in the successive crushing process. The final crushing produces a better quality aggregate compared with previous crushings. Because anti-skid aggregates are generally produced from the 0 to 6 mm fraction discarded at all crushing stages and from the muckpile, they contain aggregate of varying quality. If high-quality anti-skid aggregates are required, the muckpile fractions should be excluded from the final product. This is especially important with aggregates that tend to contain microcracks. This increases the need for developing new standardized testing methods.

Particle size distribution (European Committee for Standardisation 1997, EN 933-1) and flakiness index (European Committee for Standardisation 1977, EN 933-3)

All the bedrock aggregates used in the present study were crushed in a normal process flow at the quarries. The anti-skid aggregates were wet sieved with a 2 mm sieve before testing. The Ämmässuo granite (GRfi) represents the anti-skid aggregate product used for Helsinki City winter maintenance in previous years. The granite (GR) sample was poorly wet sieved so that the effect of the particle size distribution on the concentration of PM_{10} in the air could be compared.

The particle size distribution (sieving method) was determined with sieves from 0.063–8 mm. The flakiness index (Table 1) defines the amount of flat-shaped particles in weight percent (particle size >4 mm). Fractions were sieved with normal sieves and corresponding bar sieves.

Figure 2 shows that Eurajoki diabase (DB) and Koverhar blast furnace slag (BFS) do not contain many particles below 2 mm and that GR and GRfi samples contain 20 and 43%, respectively. Furthermore, 20% of particles from GRfi are <1 mm.

One sample with a high flakiness index value (29) was prepared. First, the flaky and non-flaky particles were separated with bar sieves. The particles were then mixed in suitable proportions to produce a sample with a flakiness index value of 29.

The studded tyre test (European Committee for Standardisation 1998b, EN 1097-9)

The STT measures the ability of an aggregate to tolerate the abrasive wear of studded tyres. The mass of the test

Table 1
Mechanical and physical properties of aggregates and amount of anti-skid aggregate dispersed on the road simulator ring. *DB* Diabase; *DBfl* diabase with a high flakiness index; *GR* granite; *GRfi* granite with higher percentage of fine fraction; *BFS* blast furnace slag; *MV* mafic volcanic rock; *STT* studded tyre test value; *LA 10–14/4–5.6* Los Angeles test value for fractions 10-14/4–5.6 mm; *FI* flakiness index value

Sample	STT	LA 10–14/4–5.6	FI	Density (kg/m^3)	Mass/area: 2–4 dm^3 (g/m^2)
DB/DBfl	11.6	16/23	11/29	3,010	1,056–2,112
GR/GRfi	20.7	42/43	18/16	2,650	926–1,853
BFS	26.3	28/25	2	2,330	828–1,656
MV	6.2	11/-	-	2,910	-

portion is $(1{,}000\times\rho_s)/2.66$ g±5 g, where ρ_s is particle density. The test material (65% 11.2 to 14 mm and 35% 14 to 16 mm fractions) is placed in a steel drum with 2 l of water and 7,000±10 g of 15 mm steel balls; the mill rotates 5,400 revolutions (90±3 rpm). The result of the STT is an average of two runs and is calculated from the equation:

$$A_N = 100(m_i - m_2)/m_i \quad (1)$$

where m_i is the original mass of test portion and m_2 is the mass after the test (>2-mm fraction).

The Los Angeles test (European Committee for Standardisation 1998a, EN 1097-2)

The Los Angeles (LA) test determines the resistance of an aggregate to fragmentation. The 5,000± 5-g sample (10 to 14 mm fraction) is placed in a steel drum with eleven 45 to 49 mm steel balls (total weight 400–445 g). The drum rotates 500 revolutions (31–33 rpm). According to EN 1097-2 annex A, the test can be performed with fewer balls as an informative test for smaller size fractions. In this study the 4 to 5.6 mm particle size anti-skid aggregate was tested with eight balls. According to the American Society for Testing Materials (1989), the LA test can be carried out with six balls for fractions 2.36–4.75 mm. The LA value is calculated from the equation.

$$LA = 5000 - m/50 \quad (2)$$

where m is the >1.6-mm fraction after the test.

The mechanical properties of the aggregates are given in Table 1. Mafic volcanic rock (MV) is a high-quality aggregate with excellent resistance to both abrasive wear and fragmentation. According to PANK (2000), it can be used in the most demanding road construction applications. Granite (GR) has very poor mechanical properties and it can be used only in the applications demanding minimum quality. Diabase (DB) has good resistance to fragmentation, but quite poor resistance to abrasive wear. The LA test values for the 10 to 14 mm and 4 to 5.6 mm fractions do not behave linearly.

Geological and petrographical properties of aggregates

The wearing of asphalt pavements has diminished a great deal during the past 15 years. Two major reasons for this are the new lightweight studs and the better SMA asphalt pavements used on heavily trafficked roads. The most important factor influencing pavement wear is the quality of aggregates (e.g. Saarela 1992; PANK 1993; Jacobson and Hornwall 1999). In the present study, some aggregates lacked certain minerals found in others (e.g. hornblende in the asphalt aggregate), hence the proportions of asphalt and anti-skid aggregate material in the dust could be analyzed. Modal compositions and the grain sizes of aggregates are given in Table 2.

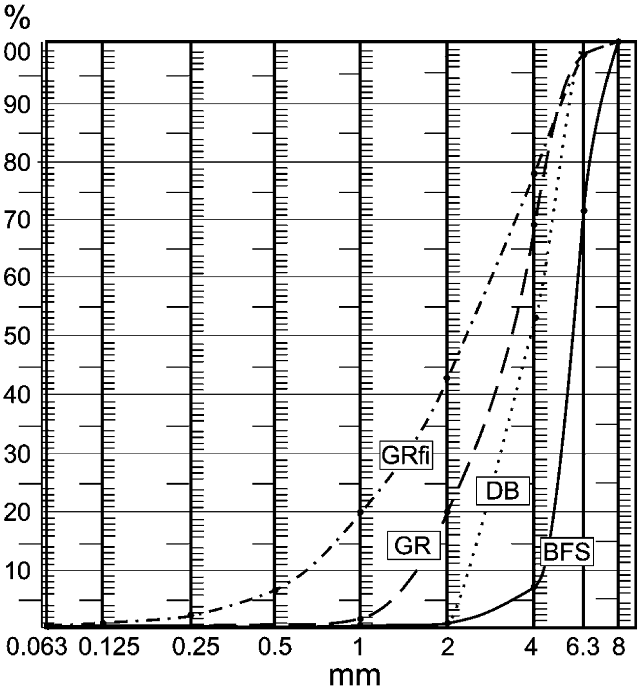


Fig. 2
Particle size distribution curves of anti-skid aggregates. *GR* Granite; *GRfi* granite with higher percentage of fine fraction; *DB* diabase; *BFS* blast furnace slag

The present study is based on the quantity of particles and does not take into account their size or density. This complicates the quality assessment of materials. Nevertheless, the size and surface properties of dust particles are the most important factors with respect to human health. In real life the quality control of urban air is based on the weight of particles in the atmosphere. Kupiainen et al. (2003) report that the correlation between the amount of anti-skid aggregate spread on the test ring and the amount of PM_{10} was 0.79. However, this result is based on the total amount of PM_{10} and does not take into account the proportions of asphalt and anti-skid aggregates or differences in the wearing processes of different rock types (Fig. 3).

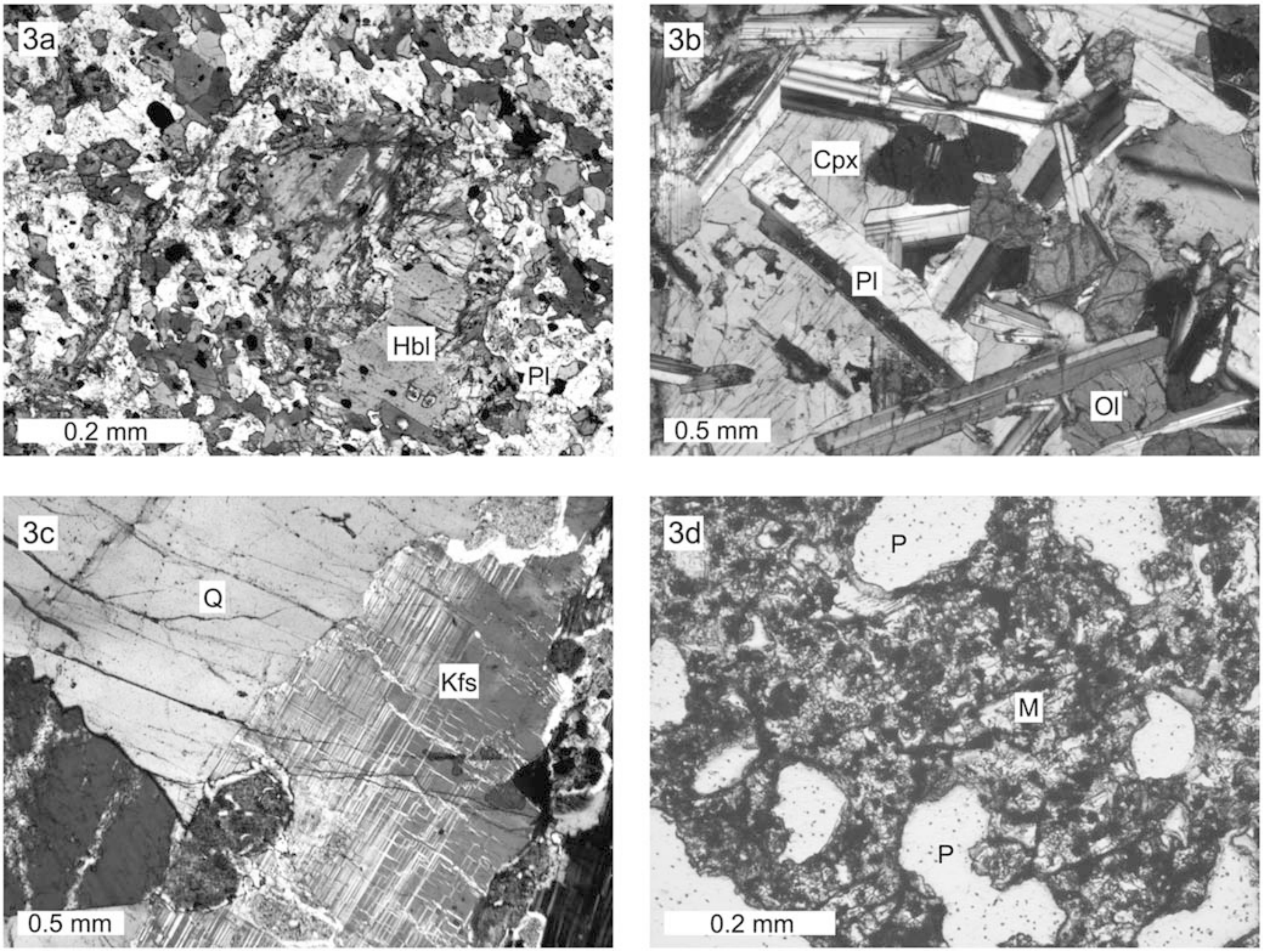
Table 2
Modal composition of natural aggregates. The composition is based on point counting analysis with a polarizing microscope (1,000 equally distributed points/polished thin section)

Mineral	GR	Grain size (mm)	DB	Grain size (mm)	MV	Grain size (mm)
Quartz	30.4	1–6				
K-feldspar	29.6	1–10				
Plagioclase	32.4	1–5	57.4	0.2–2	29.4	0.1–1
Biotite	5.9	0.1–2	3.8	0.1–0.5		
Hornblende					53	0.01–0.5
Clinopyroxene			17.3	1–5		
Olivine			17.5	0.1–1		
Opaque	0.5	<1	4	0.1–2	3.2	0.1
Cummingtonite-grunerite					12.8	0.1–1
Chlorite					1.4	<0.2
Carbonate					0.2	<0.2
Epidote	0.2	<0.2				
Muscovite	0.6	<0.5				

The Patavuori mafic volcanic rock

The Patavuori quarry in southern Finland is located in the Svecofennian (ca. 1,900 Ma) Häme schist belt (e.g. Lahtinen 1996). The main rock type is a massive uralite-plagioclase porphyritic lava, which contains minor mafic pyroclastic interlayers (tuffs and agglomerates). The rock has been metamorphosed at amphibolite facies. There are some variations in the modal composition of the outcrops, but the main mineralogy is the same throughout the quarry. Rocks in the quarry generally lack preferred orientation (excluding the pyroclastic rocks). The

Fig. 3
Petrographical properties of aggregates: **a** Patavuori mafic volcanic rock; **b** Eurajoki diabase; **c** Åmmässuo granite; **d** Koverhar blast furnace slag. *Hbl* Hornblende; *Pl* plagioclase; *Cpx* clinopyroxene; *Q* quartz; *Kfs* alkali feldspar; *Ol* olivine; *M* melilite; *P* pore



fine-grained mafic volcanic rock (lava) has some poikilitic uralite and plagioclase phenocrysts (1–5 mm). Variously shaped, anhedral minerals in the groundmass have irregular, curved and straight grain boundaries (Fig. 3a). Minerals often display intergrowth texture, which, together with the fine grain size, strengthens the rock. The rock contains minor, healed multi-grain cracks.

The Eurajoki olivine diabase

The age of the post-Jotnian olivine diabase in Eurajoki, southwestern Finland, is 1,258±13 Ma (Suominen 1991). It belongs to the Central Scandinavian Dolerite (diabase) group. The diabase is sub-ophitic, medium-grained and composed of anhedral clinopyroxene and Fe-Ti oxides between euhedral and sub-hedral plagioclase and olivine crystals (Fig. 3b). The rock has no preferred orientation. Grain boundaries are straight or curved. There are only few, mainly intragranular microcracks.

The Ämmässuo granite

The Ämmässuo granite belongs to the S-type late-kinematic microcline granites of southern Finland (e.g. Nurmi and Haapala,1986) and is about 1,830 Ma (e.g. Suominen 1991; Vaasjoki 1996). The garnet-bearing granite displays a layered structure in situ. The granite is medium- to coarse-grained, has a hypidiomorfic texture and contains sparsely distributed phenocrysts of k-feldspar (0.5–3 cm). Grain boundaries vary from straight to curved and the rock contains a large amount of microcracks—mainly intragranular, although intergranular and multi-grain cracks are also common (Fig. 3c). Overall, the rock is quite brittle.

The Koverhar blast furnace slag

Molten slag is cooled and solidified rapidly, which results in fine-grained blast furnace slag (BFS) that has a vesicular (porous) texture. The average size of pores is 0.1–1 mm and they are mainly unconnected (Fig. 3d). The surface texture of BFS particles is rough and therefore the total surface area is greater than with the natural aggregates. Due to these properties, the density is lower than in the other materials included in the present study. The composition of BFS is clearly different from the natural aggregates. The main synthetic minerals of BFS are the melilite group minerals. Due to the rapid crystallization and insufficient time for homogenization, the same synthetic rock sample contains mineral compositions of both end members of the melilite group, gehlenite and åkermanite, and compositions between the end members are also common. The texture of BFS particles varies depending on the crystallization location. The more fine-grained gehlenite, with a swallow’s tail form, represents the rapidly crystallized parts of the synthetic magma. The average grain size varies from <0.05–0.2 mm. The grain boundaries are mainly irregular and the mineral grains have no preferred orientation. The texture of BFS is solid, excluding the voids.

Results

The present study is based on three different anti-skid aggregates and one asphalt aggregate. They have different particle size distributions, as well as mechanical and textural properties. Kupiainen et al. (2003) found that many PM_{10} particles originated from asphalt aggregate, although tests were run with friction tyres. The conclusion was that the anti-skid aggregate wears the asphalt pavement and the authors named the phenomenon the “sandpaper effect”. The sandpaper effect increased when the amount of anti-skid aggregate was increased from 2–4 l. The effect of driving speed was tested by increasing the speed from 15–25 km/h (using granite as the anti-skid aggregate). The PM_{10} content was higher, but if the longer distance driven during the same test period (1 h) is taken into account, the emission factor per kilometre is nearly the same. The additional PM_{10} originated from the pavement aggregate. According to Jacobson and Hornwall (1999), the impact of speed on pavement wear is emphasized with higher speeds. The increase of speed from 70 to 90 km/h had little effect on the wear of the pavement, but when the speed was 110 km/h the wear was remarkably higher. Ihs and Gustafson (1996) state that the effect of speed on the wear of a pavement can be described with a parabolic function—a low amount of wear with medium speed (50 km/h) and high amount of wear with low and high speeds.

Different materials act differently such that even though the total amount of dust is the same (Fig. 4) the composition of the dust may be different. Studded tyres wear the asphalt, but they wear the anti-skid aggregate as well (Fig. 4). There was less dust when friction tyres were used, but the most dust still originated from the asphalt aggregates.

Particle size distribution and flakiness index

The particle size distribution of anti-skid aggregate may have an impact on the amount of urban dust. The successive breakage of particles into smaller particles with more wearing surfaces generates more small-size particles, dust and potential pavement grinding material. GRfi produces about three times more PM_{10} dust than when the same aggregate contains fewer 0 to 2 mm particles (GR2) (see Fig. 4). Furthermore, the dust proportion from the asphalt increases by a factor of 3. The result is that small-size particles wear the pavement whilst simultaneously being worn themselves.

The flakiness index did not have a major impact on the PM_{10} concentration produced by the DB samples. However, the sample with a flakiness index of 29 generated less dust from the asphalt aggregate, probably due to the particle form. Flaky particles break more easily compared with cuboid particles. It can also be assumed that flaky particles do not increase the friction as much as cuboid particles.

Mechanical/physical properties and petrography

The classification of dust according to origin (asphalt vs. anti-skid aggregate) (Fig. 4) is based on the amount of

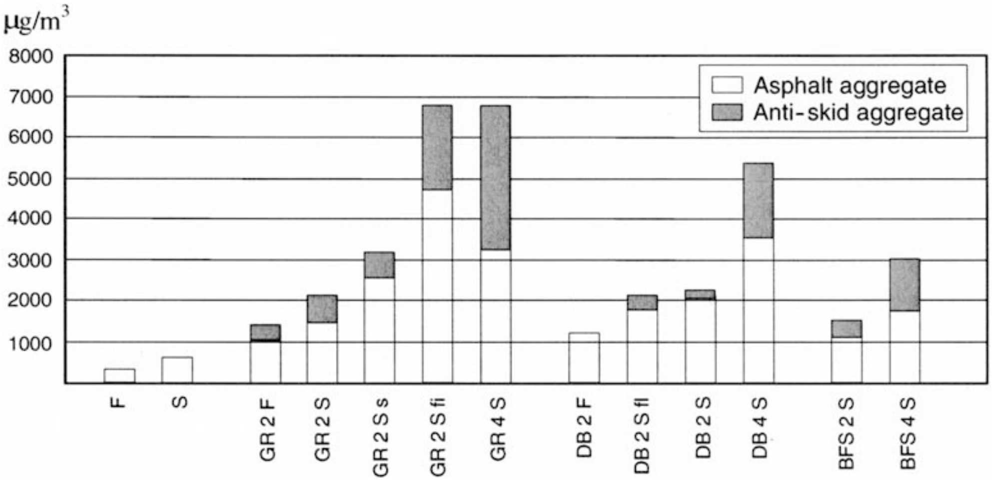


Fig. 4
Proportions of asphalt and anti-skid aggregates in the PM_{10} mineral dust produced with the road simulator. *F* Friction tyres; *S* studded tyres; *2* or *4* 2 or 4 l of anti-skid aggregate; *GR* granite; *DB* diabase; *BFS* blast furnace slag; *fl* flakiness index 29; *s* speed 25 km/h; *fi* anti-skid aggregate with higher percentage of fine fraction. [Modified after Kupiainen et al. (2003)]

hornblende. Hornblende is softer (5–6 on the Mohs scale) than the other main mineral in asphalt (plagioclase is 6 on the Mohs scale); hence it is more susceptible to wearing by studs (8–8.5 on the Mohs scale) and/or anti-skid aggregate. The questions are: how do different minerals wear and is there a correlation between dust particle size and mineralogy? These questions can be answered partly when the mineralogy of all the particle sizes, not only PM_{10}, is determined. For example, are the hornblende particles smaller than feldspar particles? If the size of dust particles correlates with mineralogy, the results are not representative. The main mineral constituents of granite are generally less dense than the main constituents of mafic materials. If the dust is made up of mafic particles, the same volume of PM_{10} particles has 10–15% more weight than if the dust is made up of granitic particles.

The STT value depends on the mineralogy and texture of aggregates (Table 1). Aggregates with a low STT value have good resistance to abrasive wear, but, nevertheless, this type of anti-skid aggregate can wear the pavement, as can aggregates consisting of hard minerals and a high STT value.

Aggregates with a low LA value have good resistance to fragmentation. The results of LA tests with two fractions (10–14 and 4–5.6 mm) did not correlate (Table 1). Diabase and the blast furnace slag anti-skid aggregates (4–5.6) had the best LA values and these anti-skid aggregates also generated the lowest proportions of dust.

Aggregates

PM_{10} emissions from the granite anti-skid aggregate (GR) are high compared with the other materials tested. This is emphasized by the results from the 4-l samples. The reason for this is the brittleness of the granite and its poor resistance to fragmentation. Both granite and diabase wear the pavement, mainly because they have higher average hardness than the asphalt aggregate.

Diabase (DB) has a good resistance to fragmentation (LA test) due to its sub-ophitic texture (interlocking minerals) and lack of microcracks. The STT values are only average because of the medium grain size and lack of quartz. DB anti-skid aggregate can wear the pavement aggregate, because its minerals are harder than the amphiboles in the asphalt aggregate. As a consequence, the DB particles do not break easily into smaller particles and the PM_{10} dust originates almost completely from the asphalt aggregate. DB aggregate consists mainly of 2 to 4 mm and 4 to 6.3 mm fractions, which also reduces its potential as a dust contributor.

The porous texture of BFS lowers its density. BFS is composed mainly of gehlenite, the density of which is about 3. The proportion of pores is ca. 23% [the density difference between gehlenite (3) and the BFS (2.33)]. The 14% difference in density between granite and BFS further lowers the amount of BFS particles in the dust. Due to this and its good resistance to fragmentation (4 to 5.6 mm fraction) BFS generates the least PM_{10} dust.

The LA value of BFS did not increase even when the tests were performed with the 4 to 5.6 mm fraction. This can be explained by the breakage of coarser, weaker particles through the pores (zone of weakness). The rough surface texture increases the proportion of dust from BFS anti-skid aggregate, but the coarser particle size distribution reduces. BFS consists mainly of a 4 to 6.3 mm fraction.

Particle sizes were measured from the display terminal with the scale bar. The accuracy of measurement is about 1 µm (Fig. 5). No correlation between the mineralogy and dust particle size for PM_{10} particles was found. The average PM_{10} particle size was 3.8 µm. The correlation between

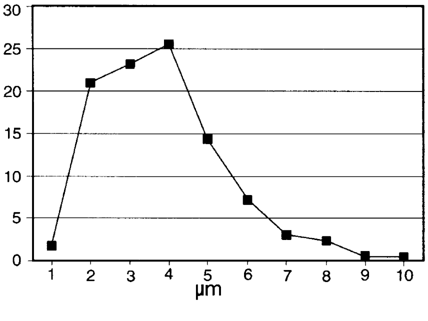


Fig. 5
Particle size of analyzed PM_{10} particles

the mineralogy of asphalt and anti-skid aggregates and the mineralogy of dust requires further study. For example, has the asphalt aggregate the same modal composition as the dust originating from it? In real life, dust concentration is based on the mass of dust and if these results are converted into mass units instead of number of particles, the mass of coarser particles would be emphasized.

Discussion and conclusions

In the crushing process of bedrock aggregates, the excess formation of fine aggregate (0–4 mm) is a drawback. Production of anti-skid aggregates is one way to utilize a part of the fine aggregate. However, the potential for greater dust content increases when the amount of finer material in the anti-skid aggregate increases. Mustonen and Valtonen (2000) state that the amount of dust in the air can be reduced by 15–25%, depending on the properties of aggregates tested, if the 0 to 1 mm fraction is wet screened away. Their study was performed with the same road simulator as used in the research reported here. Mustonen (1998) has tested the suitability of the road simulator for testing anti-skid aggregates. He compared the amount of dust in the air at different levels with the road simulator indoors and the amount of dust in an actual road tunnel. He found that the amount of dust at different levels varied considerably more in the tunnel than in the road simulator room.

In their road dust study Kupiainen et al. (2003) found that the anti-skid aggregate wears the asphalt pavement (the sandpaper effect) more than expected and, as a result, a large proportion of the mineral dust originates from the asphalt aggregate. Therefore, the particle size distribution of anti-skid aggregates should be studied further. The present authors consider that instead of the 0 to 1 mm fraction, the 0 to 2 mm fraction should be wet screened from anti-skid aggregates to be used in densely populated areas; 2 to 6 mm anti-skid aggregate is more expensive to produce, but the results from this study imply that this may improve the quality of air.

According to a literature review by Gustafsson (2001), quartz concentrations, originating from anti-skid or asphalt aggregates, sufficient to cause pneumosilicosis have not been found in the ambient air. However, it is not known if respiratory problems are caused by the composition or concentration of particles. Until the main reasons for particle toxicity or epidemiological influences are clear, further research is needed. Quartz is also recognized as a carcinogenic mineral (e.g. Koskela et al. 1994). Junttila et al. (1994) state that in bedrock quarries the amount of fine-grained quartz (<5 μm) in the air can exceed 0.2 mg/m^3 if the rock contains over 4% quartz and that the proportion of dust from bedrock aggregates at road construction sites or maintenance of roads should be studied further.

To prevent the negative effects of harmful minerals on human health, the mineralogy and texture of anti-skid and asphalt aggregates should be studied in detail. The use of quartz-rich rocks as anti-skid aggregate should be carefully considered. These rocks have a high potential for wearing the pavement due to their hard mineral composition. When quartz-rich rocks are used as anti-skid aggregates, the texture of such material should be solid (good resistance to fragmentation). However, the wearing potential of anti-skid aggregate is also related to the properties of asphalt pavement. With proper aggregate selection, the amount of potentially harmful minerals in urban dust can be minimized.

In the present study the dust ratio asphalt/anti-skid aggregate may be emphasized due to the circular test ring and intense abrasive wear. In real life, the proportion of anti-skid aggregate can be higher than in the present study. Therefore, it is especially important to pay attention to the properties of anti-skid aggregates. The most important factors in the formation of urban dust (the wearing of pavement and anti-skid aggregates) are the particle size distribution and the mechanical and mineralogical properties of the anti-skid and asphalt aggregates. The breakage of particles into successively smaller pieces with more wearing surfaces can be minimized by using anti-skid aggregates with good resistance to fragmentation. These low LA value anti-skid aggregates should be used in densely populated areas. The present study also claims that anti-skid aggregates should be classified according to the location of use and their quality, based on the properties mentioned above. Additionally, in order to be able to test the product (the anti-skid aggregate), new EN standard testing methods for mechanical properties need to be developed for finer particle size aggregates, because the correlation between mechanical tests and test fractions with a different particle size distribution is not linear.

The present study will be followed up with a more extensive study on dust particle size distribution. A comparison between PM_{10} and TSP (total suspended particulate matter) amounts will also be undertaken. The size of particles originating from anti-skid and asphalt aggregates has been studied, for example, in Japan and the Nordic countries (Amemiya et al. 1984; Fukuzaki et al. 1985; Larssen and Hagen 1997; Pekkanen et al. 1997). However, these studies have not investigated the variations in size of different minerals or the origin of dust from asphalt or anti-skid aggregate. Further studies are also required on different anti-skid and asphalt aggregate combinations with varying mechanical and petrographical properties, in order to be able to draw more extensive conclusions on the wearing processes of aggregates. For example, granites with different textures and mechanical properties (asphalt and anti-skid aggregates) will be tested in the next stage of the study, the results of which are expected to be available during 2003–2004.

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