Road pavements and PM$_{10}$

Summary of the results of research funded by the Swedish Transport Administration on how the properties of road pavements influence emissions and the properties of wear particles.
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Foreword

In Sweden, as in other countries where studded tires are used in winter, the wear of road surfaces is an important source of ambient air quality through its contribution to particle concentrations in road and street environments. In environments with high traffic and poor ventilation, particles from road wear and resuspension contribute strongly to high levels during dry weather in early spring. Sweden has difficulties in a number of urban areas with EU limit value (implemented as an environmental quality standard in Sweden) for the daily average of inhalable particles (PM10). The national goal for Fresh air is even more difficult than the environmental quality standard to reach in terms of particle concentrations. Several issues have been recognized regarding particle emissions from road surfaces, primarily how the emission of PM10 is affected by various pavement parameters, such as construction, largest stone size and the stone material's resistance to wear. Similarly, alternatives to traditional asphalt pavements have attracted interest as potential elements of the solution to the particle problem. Since the early 2000s, a number of research projects commissioned by the Swedish Road Administration / Transport Administration to clarify these issues. These studies have been carried out by VTI (Swedish National Road and Transport Research Institute) dealing mainly with laboratory studies, while SLB-analys at City of Stockholm Environmental and Health Administration and ITM (Institute of Applied Environmental Research) at the University of Stockholm mainly conducted field studies. This report is a compilation of the most important research results from projects funded by the Swedish Road Administration / Transport Administration on how road pavement characteristics affect emissions and characteristics of PM10.

Uppsala, December 2012

Mats Wendel, Swedish Transport Administration

National Coordinator Road Surface
Summary

Wear particles from road pavements contribute to high particle concentrations in Swedish road and street environments. In order to obtain an idea of how the properties of road pavements can be influenced so as to reduce the emissions, several research projects were performed during the last century, mainly by the Swedish Road and Transport Research Institute (VTI), SLB Analysis at the City of Stockholm Environmental and Health Administration, and the Institution of Applied Environmental Research (ITM), Stockholm University. At VTI, the research was mainly carried out in a laboratory environment using the VTI heavy vehicle simulator. SLB Analysis and ITM mostly worked in the field with air quality measurements and with a survey vehicle called EMMA which measures particle concentrations behind the two front wheels. The studies mainly focused on the wear resistant pavements used on roads and streets carrying high traffic (SMA) since it is normally these roads and streets that cause problems due to high particle concentrations. However, some tests on ABT in the field have also been carried out. The pavement properties studied are those which are shown by experience to have the greatest influence on the overall wear of pavements, i.e. the maximum size of coarse aggregate and the properties of the aggregate in the pavement. Some alternative pavement designs have also been studied. These are porous asphalt, asphalt rubber pavements, and cement concrete pavements.

Overall, the results show that the lower the maximum size of coarse aggregate and the lower the Nordic abrasion value of the aggregate material, the lower the particle formation. Even though experience shows that an AC design wears more rapidly than a similar SMA, no clear differences could be noted between these pavements in the field measurements, probably because the differences are concealed by the dust stirred up which, in field measurements, is difficult to distinguish from direct emission. In the heavy vehicle simulator, rubber asphalt tended in certain designs to produce slightly lower particle emissions, which was not confirmed by the measurements in the field. Porous (quiet) pavement produced lower emissions in the simulator, but since no correct reference pavement was tested, it was considered that the effect was mainly due to the use of a particularly wear resistant aggregate material in the pavement. Measurements in the field were not able to confirm that porous pavements produce lower particle emissions. Cement concrete, on the other hand, was found to cause lower emissions in field measurements, even though there is still some lack of clarity. Particle size distributions in PM10 are similar regardless of which properties of the pavement are changed, and the composition of these particles is fully governed by the mineralogy of the aggregate material.

Several important research questions remain. The significance of the direct emissions in relation to suspended dust and the influence of various factors (texture, meteorology, different sources, drainage etc) on the road dust depot processes is important knowledge for better understanding and modelling of the emissions from roads. More knowledge is also needed on how particle emissions are influenced by different standard designs, alternative designs and materials, as well as by the influence of the age and wear of the pavement. The relative contributions which the different aggregate materials in the pavement make to the emissions are also of interest, since the aggregate is often of high quality, while the local stone which is used as the fill is of considerably lower quality.

Finally, it may be stated that particle emissions are one of several important properties of road pavements. In choosing a pavement, other aspects must also be considered, such as noise properties, other environmental effects (inclusive of LCA), the effect on fuel consumption and tyre wear.
1 Background

In Sweden, as in other countries where studded tyres are used, the abrasion of road pavements is an important source of particulate pollution of the ambient air in road and street environments. This problem is the most serious during dry periods in the winter and spring when the accumulated abrasion dust is suspended by the traffic, and at the same time, studded tyres generate new dust which is directly emitted to the air. In many road and street environments, with a lot of traffic in combination with poor ventilation, the concentrations of inhalable particles (PM10) exceed the diurnal mean value that has been defined as the threshold limit value in the EU, and which in Sweden has been implemented as an environmental quality standard.

Measures on several levels are needed to deal with this problem. Since 2009, local authorities have been empowered to prohibit traffic with studded tyres in certain streets/areas, and both local authorities and the Transport Administration have run information campaigns on the health effects of particulates and on the harmful effects of studded tyres. The other side of the problem is presented by road pavements which are the actual source of particulates. In Sweden, road pavements have been adapted to withstand studded tyres, which means that at present aggregate-rich and coarse pavements with abrasion resistant aggregate are used on most of the heavily trafficked roads and streets. Nonetheless, more than 100,000 tons of road pavement material is abraded from the roads every year. Most of this is not PM10, but much coarser material that ends up in the soil and in the water in the road environment. But a certain proportion (estimated at a few per cent) is PM10 and is the reason that Sweden does not comply with the environmental quality standard and has difficulty in reaching the national environmental quality standards for fresh air.

Several questions have arisen about particulate emissions from road pavements. These have mostly concerned the way the emission of PM10 is affected by various pavement parameters that govern the total abrasion of an asphalt pavement, such as design, largest aggregate size and the abrasion resistance of the aggregate material. In the same way, alternatives to the standard asphalt pavements attracted interest as possible elements of the solution to the problem of particulates. Since the beginning of this century a number of research projects have been carried out on behalf of the former Swedish Road Administration, now Swedish Transport Administration to elucidate these questions. These studies have been mostly performed by VTI (Swedish Road and Transport Research Institute) mainly as studies in the laboratory, while SLB-analys at the City of Stockholm Environmental and Health Administration and ITM (Institute of Applied Environmental Research), Stockholm University, have been mainly engaged in field studies. This report is a summary of the most important results and conclusions from these projects.
2 Method

2.1 Laboratory (road simulator PVM)

A large number of studies have been performed in the VTI road simulator (PVM), an equipment which can be used to generate and study abrasion particles that are formed through the interaction between the tyre and pavement.

The VTI road simulator (Fig. 1) consists of a circular 0.5 m wide track of 16 m diameter that can be surfaced with any pavement. The machine rotates about a central vertical axis on which six wheel axles are mounted. On these, different types of tyre can be mounted. Four of the axles are used and driven by electric motors. During a test, the wheels are lowered down to the track at the desired axle weight, and the wheels cause the machine to rotate. Speed can be varied steplessly up to 70 km/h. At speeds in excess of 50 km/h, an excenter can be engaged, which causes the wheels to run over almost the whole width of the track instead of moving along the same rut.

Fig. 1. Road simulator (PVM). Cooling fans at right.

The room in which the machine is installed can be cooled down to below 0°C (depending on the time of year) and the humidity can be controlled.

Before the actual tests, the pavement to be tested is run in. Running in of the pavement implies that the top bitumen layer is removed by studded tyres while the track is subjected to water spray in accordance with a standard procedure. This is done to free the aggregate from bitumen so that the surface of the pavement is more similar to a normal worn surface. Standard running in comprises about 20,000 – 30,000 revolutions at 70 km/h.
2.1.1 Test design

The VTI road simulator (PVM) is installed in an enclosed room with controlled ventilation. When it is in operation, the pavement, type of tyre and the initial temperature of the room and the pavement can be selected. The standard tyres used for studies of pavements have been studded tyres Nokian Hakkapeliitta 4. All the tests were carried out according to the same schedule (Table 1). During the final hour, the test is often run with a large fan fitted with a filter which acts as a sink for particles, i.e. it purifies the air from particulates.

Table 1. Operating schedule for PVM. "Sink" refers to a fan fitted with a filter which is used to lower the concentration of particles in the room.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1 hour 30 min</td>
</tr>
<tr>
<td>50</td>
<td>1 hour 30 min</td>
</tr>
<tr>
<td>70</td>
<td>2 hours</td>
</tr>
<tr>
<td>70</td>
<td>1 hour with sink</td>
</tr>
</tbody>
</table>

2.1.2 Measurement parameters

The types of instrument that make up the basic equipment for measuring the occurrence of inhalable particles are

- Tapered Element Oscillating Microbalance (TEOM) – The instrument is based on gravimetry and provides a reading every five minutes for the mass concentration of PM10 (mass concentration of particles smaller than 10 \( \mu m \)).

- DustTrak (DT) – Two of these optical instruments were used in the investigations: one for PM2.5 (mass concentration of particles smaller than 2.5 mm) and one for PM10. The temporal resolution for both was three seconds. The method has a higher temporal resolution than TEOM, but is not approved for air quality monitoring

- Scanning Mobility Particle Sizer (SMPS) and Aerodynamic Particle Sizer (APS). – These instruments measure particles in the size interval 7.64 – 300 nm (SMPS) and 0.523 – 17.14 \( \mu m \) (APS). Data in the lower size interval are presented as particle number distribution and those in the larger interval as mass distribution. The reason for this is that nanoparticles have a very low mass, but conversely there are very many of them, while the larger particles have a high mass but they are only a few in number. During the APS measurements a PM10 inlet was used that removes particles larger than 10 \( \mu m \).

Particles for analysis can be collected with a low or high volume sampler. Samples are in most cases also collected with a cascade impactor in order that the elemental composition in the different size fractions may be studied. It is also possible to collect nanoparticles with a nanometer aerosol sampler (NAS).

In addition to particles, measurements are also made of air, tyre and pavement temperatures and relative humidity. The temperature in the room is normally kept below zero degree for tests on winter tyres on different pavements, and at 15° C when combinations with summer tyres are used.

Apart from ambient factors, measurements are also normally made between the tests of pavement wear and stud projection (if studded tyres are used).
2.2 Field tests

In the field tests, both stationary and mobile measurements were made in order to evaluate the significance of different pavements for PM10 concentrations and emissions.

2.2.1 Stationary measurements of concentrations close to the road

Stationary measurements were used to study the effect of a porous pavement on the E4/E20 at Hallunda, Stockholm. Two measuring stations were used. One station registered the concentrations of PM10 and NOx next to the test section, while the other registered the concentrations near an untouched reference section. The same types of instrument were used at both measurement sites, and the instruments also made measurements together at the same site to check that they were comparable. The NOx concentrations were used as an indicator of exhaust emissions and in order to normalise the dilution of emissions with reference to differences in meteorology and topography. Measurements were also made of wind speed, wind direction, vertical and horizontal turbulence, temperature and relative humidity. The difference in PM10 concentration in relation to NOx (indicator for particles from vehicle exhausts) with reference to meteorology is a measure of the difference in particle generation by the pavements.

2.2.2 Mobile measurements of potential emission

Mobile measurements have been used in several measurement campaigns on different types of pavement. A van (VW LT 35 TDI) called EMMA, has been fitted with instruments for the measurement of particle concentrations and with batteries and other equipment, so that the instruments can make measurements for ca eight hours without recharging (Figs. 2 and 3). (Hussein et al, 2007). Different types of instrument have been used for the determination of emissions from roads, consisting of:

- Three (or in some cases, four) instruments for the measurement of total particle concentrations (mass concentrations) behind both front wheels, in front of the van and behind one of the rear wheels, as well as below the van between the rear wheels.
- Two instruments for the measurement of particle size distribution behind the front wheels.

Fig. 2. Measurement system EMMA: Van (VW LT 35 TDI) with instruments
The difference between the particle concentrations behind the wheels and in front of the van is assumed to be proportional to the emission of particles from the carriageway. By simultaneously measuring the emissions with different tyres on the front wheels, the relationship between emissions for different types of tyres is obtained. All measurements relate to dry carriageways. This measuring method is based on a system that was originally developed in the US (Kuhns et al, 2001) and is described in detail in Hussein et al (2007).

In May 2007, comparative measurements of PM10 emissions were also made with the mobile measuring method (ITM method called EMMA) and a Finnish mobile measuring method SNIFTER that has slightly different instruments and measures in a way different from EMMA (Pirjola et al, 2010). The conclusion of the study was that the two systems provide similar results and can be used for the study of relative variations in emissions of PM10 from carriageways. For the quantification of the absolute emissions, (e.g. as grams of PM10 per vehicle kilometre), some form of calibration is needed. Both systems have been used during dry road conditions, which is most important for the highest concentrations along the roads. Emissions from wet roads are considerably lower and are therefore less important to study. It is not clear whether the size of the vehicle is significant for the total emissions from the carriageway. The vehicles used in the EMMA and SNIFTER systems are of the same make (VW LT 35) and are classed as light lorries (3.2 tonnes). Measurements behind the tyres and below the vehicles show that the suspension/emission mostly occurs due to the contact between the tyres and the carriageway, not because of the turbulence generated by the vehicle body. This should mean that the measurements are representative of the variations in the total particle emissions from the vehicles, but further studies should be made of the significance of vehicle-generated turbulence. It seems unlikely that the results from the measurements on different pavements which are presented in this study would have such systematic errors that they cause the differences (or the absence of differences) not to be real or representative of the actual conditions.
3 Results

3.1 Asphalt pavements tested in the laboratory

3.1.1 Relations between pavement properties and PM10 in the laboratory

The focus in the studies on the VTI road simulator has been the most abrasion resistant and usual pavement designs on heavily trafficked Swedish roads, namely SMASMA (stone mastic asphalt), even though a number of other designs have also been tested. The dominant largest aggregate size in the tests has been 11 mm. On Swedish roads, however, 16 mm is dominant. Data relating to aggregate materials and their properties are also given in Table 2.

The most important data for the aggregate material are the Nordic abrasion test which is a ball mill value and the Los Angeles value. The Nordic abrasion value is a measure of the resistance to studded tyre wear, while the fragmentation capacity of the material is determined in the Los Angeles test. Both these tests comprise tumbling certain fractions of the material in drums together with steel balls. The mass percentage of the fraction below a certain size after tumbling, in relation to the mass of the total sample, gives the value of the Nordic abrasion and Los Angeles values. A high value thus indicates less resistant materials.

The variations that have been made are coupled to studies in which both the design and the properties of the aggregate material were investigated. The influence of both the aggregate size and the aggregate material in one and the same design (SMA) has been studied, and various silent and asphalt rubber pavements have also been tested, the latter together with reference pavements. Two pavements, from the Czech Republic and Slovenia, with designs and rock species which generally had properties regarding abrasion inferior to the Swedish and Norwegian pavements, are somewhat different in this context. The variation in the PM10 contents that occurs in tests in the PVM is shown in Fig. 4 which clearly shows the large difference between Nordic pavements designed for studded tyre abrasion and the Mid-European pavements. There is also a relatively large variation within the Nordic pavements.

In order that the influence of the design itself on particle generation may be commented upon, the same aggregate material must be used in different types of design. This has not been the aim in any project so far, and no safe conclusions can therefore be drawn.

Fig. 4 sets out the concentrations of PM10 measured by TEOM in the PVM hall for most of the asphalt pavements tested. The curves reflect the rise in speed during the standard cycle in the PVM (see Table 1). No excenter is used at 30 km/h, and the first peak therefore slowly decreases as the studs make ruts in the pavement, while at 50 km/h the excenter is switched on and a strong and even emission results in a concentration level that reflects a balance between the generation and deposition of particles in the room. At 70 km/h there is usually a resuspension peak when the PM10 that had been caught up in the machine and its close environment is stirred up owing to the rise in speed, and then regains a balance between generation and deposition at a slightly higher level than at 50 km/h.
Table 2. Asphalt pavements used for analyses of the influence of the pavement properties on particle formation.

<table>
<thead>
<tr>
<th>Type</th>
<th>In Fig. 4</th>
<th>Aggregate size</th>
<th>Rock</th>
<th>Origin</th>
<th>Aggregate properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Largest aggregate size</td>
<td>Aggregate material size &gt; 8 mm</td>
<td>Abrasion resistance Ball mill value</td>
<td>Fragmentation Los Angeles</td>
</tr>
<tr>
<td>SMA (ABS)</td>
<td>D</td>
<td>8</td>
<td>Mylonite</td>
<td>Durasplitt</td>
<td>6.1</td>
</tr>
<tr>
<td>SMA</td>
<td>B</td>
<td>8</td>
<td>Porphyry</td>
<td>Gustafs</td>
<td>5</td>
</tr>
<tr>
<td>SMA</td>
<td>E</td>
<td>8</td>
<td>Quartzite</td>
<td>Dalbo</td>
<td>5.7</td>
</tr>
<tr>
<td>PA (ABD)</td>
<td>A</td>
<td>11</td>
<td>Porphyry</td>
<td>Gustafs</td>
<td>5</td>
</tr>
<tr>
<td>SMA</td>
<td>D</td>
<td>11</td>
<td>Quartzite</td>
<td>Kärr</td>
<td>6.1</td>
</tr>
<tr>
<td>SMA</td>
<td>B</td>
<td>11</td>
<td>Porphyry</td>
<td>Gustafs</td>
<td>5</td>
</tr>
<tr>
<td>SMA</td>
<td>E</td>
<td>11</td>
<td>Quartzite</td>
<td>Dalbo</td>
<td>5.7</td>
</tr>
<tr>
<td>SMA rubber</td>
<td>F</td>
<td>11</td>
<td>Quartzitic sandstone</td>
<td>Hardeberga</td>
<td>8.7</td>
</tr>
<tr>
<td>SMA</td>
<td>F</td>
<td>11</td>
<td>Quartzitic sandstone</td>
<td>Hardeberga</td>
<td>8.7</td>
</tr>
<tr>
<td>SMA</td>
<td>C</td>
<td>11</td>
<td>Ryolite</td>
<td>Tösse</td>
<td>4.9</td>
</tr>
<tr>
<td>AR-GAP (GAP)</td>
<td>C</td>
<td>11</td>
<td>Ryolite</td>
<td>Tösse</td>
<td>4.9</td>
</tr>
<tr>
<td>AR-OGFC (GAÖ)</td>
<td>C</td>
<td>11</td>
<td>Ryolite</td>
<td>Tösse</td>
<td>4.9</td>
</tr>
<tr>
<td>ACO (ABS)</td>
<td>G</td>
<td>11</td>
<td>Diorite/Gneiss</td>
<td>Czech Rep.</td>
<td>-</td>
</tr>
<tr>
<td>AC (ABS)</td>
<td>G</td>
<td>11</td>
<td>Limestone</td>
<td>Slovenia</td>
<td>-</td>
</tr>
<tr>
<td>AC</td>
<td></td>
<td>16</td>
<td>Granite</td>
<td>Skärland</td>
<td>7.1</td>
</tr>
<tr>
<td>SMA</td>
<td></td>
<td>16</td>
<td>Quartzite</td>
<td>Dalbo</td>
<td>5.7</td>
</tr>
<tr>
<td>SMA</td>
<td>B</td>
<td>16</td>
<td>Porphyry</td>
<td>Gustafs</td>
<td>5</td>
</tr>
</tbody>
</table>
Fig. 4. PM10 concentrations for 16 different asphalt pavements with different rocks and of different designs, measured by TEOM during typical PVM tests at three speeds (30, 50 and 70 km/h). More information on the pavements is given in Table 2.

Aggregate size
It is well known from previous studies that the largest aggregate size in the pavements (see Fig. 5) influences the total wear inasmuch as coarser material makes for lower wear. This also holds for the PM10 studies made in the PVM (Fig. 6.). As shown in Fig. 7, the total mean wear is also related to the PM10 concentrations in the tests.
Fig. 5. Three SMA pavements with largest aggregate sizes of 8, 11 and 16 mm.

Fig. 6. The relation between largest aggregate size ($D_{\text{max}}$) and mean wear

$$y = -0.176x + 3.4471$$
$$R^2 = 0.877$$

$$y = -0.1349x + 2.8043$$
$$R^2 = 0.8542$$

Fig. 7. PM10 at 50km/h as a function of mean wear in the pavements in the PVM. The linear regression line is based on the porphyry pavements data.

$$y = 1.8969x + 4.8069$$
$$R^2 = 0.9382$$
The properties of the aggregate material

Fig. 8 shows the Nordic abrasion values and Los Angeles values for all the SMA 11 pavements tested in the PVM. It is seen that both the Nordic abrasion and Los Angeles values correlate with PM10 measured in the PVM. The Nordic abrasion value has a slightly higher correlation, but the analysis is weakened slightly by the fact that many of the aggregate materials in the tested pavements have similar Nordic abrasion values.

It has not been considered self-evident that a material of high abrasion resistance also generates little PM10. PM10 makes up only a few per cent of the total wear. One hypothesis is that an aggregate material of high abrasion resistance and thus low total wear may emit more PM10 than an aggregate material of lower abrasion resistance, high total wear but a small proportion of PM10. However, in the tests made in the PVM it is found that total wear and PM10 emission are related to one another in the materials that have been tested. These materials are of generally good quality, and therefore the relation can at least be said to hold for materials with Nordic abrasion values within the range tested. The results do not however exclude the possibility that materials of higher Nordic abrasion values may emit a smaller relative proportion of PM10 than material of higher quality. Tests at the Swedish Cement and Concrete Research Institute (CBI) show, however, that the higher the Nordic abrasion value an aggregate material has, the higher is the proportion of PM10 per kg of material (Döse and Åkesson, 2011).

![Fig. 8. Relations between Nordic abrasion value (left) and Los Angeles value and PM10 at 50 km/h, measured with TEOM for all SMA11.](image)

3.1.2 Properties of PM10 from pavement wear

Hypothetically, it is reasonable to assume that the size distribution within PM10 from road wear varies depending on the mineralogical properties of the aggregate material. In different laboratory tests it has been found, however, that the variation in particle size distribution within PM10 between different pavements is fairly small. The maximum mass concentration is normally at ca 5-8 µm, and the particle mass below 1 µm is small (Fig. 9). These results indicate that the formation process is more important than the material for the way the size distribution of wear particles from studded tyre wear develops.
Fig. 9. Particle size distributions for the particle mass in PM10 formed during wear in a number of different pavements tested in the PVM.

The elemental composition of PM10, in the coarser fractions, is completely dominated by elements associated with the minerals, the distribution of which depends on what aggregate material(s) there are in the pavement (Figs. 10 and 11). In the studies made in the PVM, it is mostly silicon (Si), calcium (Ca), potassium (K) and iron (Fe) which occur. Below ca 1 µm, the relative contribution from a source of sulphur (S) and at times chlorine (Cl) is strong. This source is considered to be tyre rubber or bitumen. Tungsten is an element which can be related to the wear of the studs themselves, the tips of which are made of tungsten carbide. Zinc is usually associated with tyre wear, and is found sporadically in quite small quantities in varying fractions.
Fig. 10. Relative elemental composition in different particle sizes for PM10 from Dalbo quartzite (top), Gustafs porphyry (middle) and Mylonite (bottom).
Fig. 11. Relative elemental composition, without silicon, in different particle sizes for PM10 from Dalbo quartzite (top), Gustafs porphyry (middle) and Mylonite (bottom).
3.2 Asphalt pavements, field tests

*Dense asphalt concrete compared with stone mastic asphalt dense textured asphalt concrete compared with aggregate-rich, different maximum aggregate sizes*

Table 3 shows mobile measurements of emissions for three pavements with AC 11 compared with corresponding reference pavements (TSK, SMA 16 and SMA 11) (Johansson, 2011). The results indicate that the emissions are higher for pavements with smaller maximum aggregate sizes, i.e. AC 11 (Roads 859 and 260) compared with TSK 16 and SMA 16. However, on Road 260 there are sections with both SMA 16 and SMA 11, which means that the comparison refers not only to aggregate size but may also reflect differences between a dense textured and an aggregate-rich pavement. But since there does not appear to be any difference between the close textured AC 11 (30.7±2.3) and the aggregate-rich SMA 11 (33.5±6.3), i.e. two with the same maximum aggregate size, along Road 268, it may be that aggregate size is a more important parameter than whether the pavement is dense textured or aggregate-rich. But this should be verified by further measurements. However, another difference between the pavements is age; the dense textured one with small aggregate size is younger than corresponding reference pavements (the measurements were made in 2010 when the dense textured ones were 1-2 years old). It is not clear what this may mean for the results.

For the summer tyre, the emissions were highest from the dense textured pavements with small aggregate size, which indicates that the suspension of accumulated material is higher from these pavements, probably because wear is higher.

Similar mobile measurements have been made along different roads in Finland (Tervahattu et al, 2008). Measurements were made on 135 occasions over two years. Pavements with smaller aggregate sizes (5, 8, 11 mm) exhibited significantly lower average emissions than reference pavements (11 - 16 mm). However, the differences were very small. In the same way, particle generation was lower from an 11 mm pavement at Espoo than from one with 16 mm, based on 24 measurements in April 2007. However, the difference was not significant (p=0.337) between a "quiet" pavement with a smaller aggregate size and one with larger aggregate size (reference pavement) at Helsinki the same day. For these pavements, the Nordic abrasion values were <7.
Table 3. Particle measurements behind the studded tyre on pavements with different aggregate sizes. The values relate to concentrations behind each tyre (µg/m³) and the ratios between the studded and summer tyre.

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Traffic flow (veh/day)</th>
<th>Nordic abrasion value</th>
<th>Studded tyre</th>
<th>Summer tyre</th>
<th>Ratio studded/summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road 859 Quiet: AC11, paved 2009</td>
<td>4600</td>
<td>&lt;7</td>
<td>43.5 ± 2.6</td>
<td>10.7 ± 4.0</td>
<td>20</td>
</tr>
<tr>
<td>Ref: TSK 16 paved 1997</td>
<td></td>
<td></td>
<td>29.0 ± 4.2</td>
<td>6.9 ± 1.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Road 268 Quiet: AC11 paved 2008/2009</td>
<td>12800</td>
<td>&lt;7</td>
<td>30.7 ± 2.3</td>
<td>19.8 ± 7.7</td>
<td>14</td>
</tr>
<tr>
<td>Ref: SMA 11, paved 2004</td>
<td></td>
<td></td>
<td>33.5 ± 6.3</td>
<td>2.9 ± 2.1</td>
<td>24</td>
</tr>
<tr>
<td>Road 260 Quiet: AC11 paved 2008</td>
<td>10200</td>
<td>&lt;7</td>
<td>32.4 ± 2.4</td>
<td>7.6 ± 1.9</td>
<td>9.7</td>
</tr>
<tr>
<td>Ref: SMA16 paved 2006 &amp; SMA11 paved 2010</td>
<td></td>
<td></td>
<td>22.2 ± 5.8</td>
<td>3.2 ± 4.2</td>
<td>17</td>
</tr>
</tbody>
</table>
3.3 Alternative pavements

3.3.1 Quiet asphalt

Laboratory

Only one pavement with quiet asphalt (also called porous asphalt) has been tested in the VTI road simulator. The pavement tested was of the porous type, which means that water can drain through the top layer through pores in this. Owing to the draining function, noise from the tyres on the carriageway is also absorbed, and the pavement is therefore quieter than an “ordinary” pavement.

![Porous pavement with reddish porphyry in the top layer (1) and greyer quartzite in the bottom layer (2).](image)

The test showed that the PM10 emission was low compared to SMA pavements, but it could not be concluded that this was an effect of the porous construction since the rock material also was of a very wear resistant type with low Nordic abrasion value (porphyry).

Field tests

Both stationary and mobile measurements were used to study the difference in particle generation between a porous pavement at Hallunda along E4/E20 (Norberg et al, 2007). The pavement was a porous pavement consisting of two layers, with the top layer (30 mm thick) more fine grained (8-11 mm aggregate size) and thus intended to act as a filter to prevent clogging of a porous bottom layer (16-22 mm aggregate size) (Fig. 12).

The conclusion, on the basis of the stationary and mobile measurements, was that the emissions from the pavement (when studded tyres were used) are of the same order as emissions from other pavements (Johansson, 2006; Johansson et al, 2007). The difference in PM10 emissions between the pavements (porous and reference) was less than ca 15 per cent.
3.3.2 Cement concrete

Laboratory
At the time of writing, studies in the PVM have been made on two concrete pavements which were identical but for the fact that one contained titanium dioxide in the cement mix (TiOmix). The aggregate material was the same, a local granite, as that in the field tests outside Uppsala which are described in the following sections. A reference pavement of asphalt with the same aggregate material will be tested in 2012 so that the influence of the actual concrete pavement may be directly compared. The concrete tested was found to emit PM10 at the same level as the tested Nordic asphalt pavements which emitted the most PM10 in previous tests. However, this may be due to the properties of either the aggregate material or those of the design, and further conclusions regarding these tests must therefore remain in abeyance until the reference pavement has been tested.

Field tests
Generation of PM10 owing to abrasion and the resuspension of particles on a motorway with concrete and asphalt have been compared outside Uppsala (Johansson et al, 2009). The mobile measurements were made during October on dry carriageways. The measurements showed that the formation of PM10 was approximately 30 per cent lower from the concrete pavement than from the asphalt pavement when studded tyres were used. This applied at all the measured speeds, 70, 90 and 110 km/h. The particle size distribution exhibited a maximum at ca 4 μm on both the concrete and asphalt pavement. The pavements had the same maximum aggregate size, but aggregate material of different abrasion resistance. The Nordic abrasion value of the aggregate in the concrete pavement was 8.2 compared with 5.8 for the asphalt pavement, i.e. the aggregate in the asphalt pavement was more abrasion resistant. In addition, the proportion of fine aggregate material was higher in the concrete pavement. In view of both these factors it was expected that the asphalt pavement would generate a smaller quantity of PM10 than the concrete pavement, but this did not happen. Why the concrete pavement produced lower emissions than the asphalt pavement has not been elucidated.

One partial explanation may be that, because of the finer texture, there is less accumulated material on the concrete pavement.

An estimate showed that the percentage reduction in PM10 generation, if a concrete pavement is used instead of an asphalt pavement with a stud proportion of 70 per cent, may be 28 per cent, 19 per cent and 22 per cent at 70, 90 and 110 km/h respectively. Even at a stud proportion of only 30 per cent, the concrete pavement generates a smaller quantity of PM10 than the asphalt pavement, but the difference is not so large; 18, 4 and 2 per cent at 70, 90 and 110 km/h respectively.

All the above measurements relate to the right-hand lane on the motorway. On some occasions PM10 generation was also measured in the left lane, but only at 110 km/h. PM10 generation then was ca 30 per cent higher on the concrete pavement than on the asphalt pavement. This applies to both the studded and unstudded winter tyre. This may be due to several factors:

- Larger contribution from accumulated material in the left lane. Generally, traffic flow in the left lane is smaller than in the right lane. A lower traffic flow may mean that there is more accumulated material (inclusive of particles <10 μm) lying on the road surface, to be resuspended.
- The left lane may have been less worn than the right lane, which may mean that PM10 generation is higher.

If PM10 generation from the studded and unstudded tyre is weighted together, it is assumed that stud percentage is 70 per cent and it is also assumed that 20 per cent of vehicles travel in the left lane, the concrete pavement produces 6 per cent lower emissions than the asphalt pavement. This was the first study of particle emissions from concrete pavements, and more studies are needed to confirm the results. The significance of the aggregate material and the proportion of fine material in the pavements, as well as the quantity of accumulated material, needs to be further investigated.
3.3.3 Asphalt Rubber pavements

Laboratory

Two projects have been performed in the road simulator in order to find whether admixture of crumb rubber granules in the bitumen phase causes a reduction in particle emissions. In the first case, an asphalt rubber pavement and a reference pavement of the SMA 11 type were tested. The aggregate material was quartzite from Hardeberga in Skåne. In the second case, two asphalt rubber pavements were tested – GAÖ 11 (open-textured asphalt rubber) and GAP 11 (asphalt rubber with gap grading) – and a reference pavement SMA 11 where the aggregate material was Ryolite from Tösse.

The concentrations of PM10 for these tests can be seen in Fig. 4 C and F. According to the results, a reduction in particle emission by 20-25 per cent can be associated with the GAP 11 pavement.

As regards the influence of crumb rubber-admixed asphalt on particle properties, the size distribution of PM10 is not changed appreciably other than with regard to concentration. As previously mentioned, many distributions are bimodal, i.e. they are made up of two fractions (modes) with maxima at different particle sizes. In Fig. 13 it can be seen that GAP 11 appears to reduce both these modes, while GAÖ 11 mostly reduces the coarser mode.

![Graph showing particle mass distributions for PM10](image)

**Fig. 13.** The upper curves show particle mass distributions for PM10 for the pavements. The lower curves show the difference between the mass distributions for the asphalt rubber pavements and the reference pavement.

In the project with quartzite from Hardeberga, a study was also made on whether the composition of PM10 is affected by the presence of rubber in the pavement mix. Studies in SEM/EDX (scanning electron microscope with emission dispersive x-ray diffraction analysis) (Fig. 14) show that the elemental composition is not affected in a way that can be linked to the crumb rubber admixture. However, no special studies of organic compounds have been made.
Fig. 14. Analysed spectra from Dalby with crumb rubber (red) and Dalby without rubber (blue).

Field tests
Mobile measurements of particle generation from asphalt rubber pavements have been made along two roads in the Stockholm region; Roads 262 and E18 (Table 4) (Johansson, 2011). For Road 262 the maximum aggregate size is 11 mm (GAP 11 and SMA 11) and, for E18, 16 mm (GAP 16 and SMA 16). As regards the variations, the results indicate that particle generation is approximately the same from asphalt rubber pavements and the reference pavements. The asphalt rubber pavements are two years younger than the references (the measurements were made in 2010 when the asphalt rubber pavements were two years old).

We have not found any other field study of particle generation from asphalt rubber pavements. An American study shows that the wear of studs is less with a asphalt rubber pavement than with a standard pavement (in their case Portland Cement Concrete) (Allen et al, 2006).
Table 4. Summary of results of particle measurements behind the studded tyre on different asphalt rubber pavements. The values show concentrations behind each stud (µg/m³) and the studded/summer tyre ratios.

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Traffic flow (AADT)</th>
<th>Nordic abrasion value</th>
<th>Studded tyre</th>
<th>Summer tyre</th>
<th>Ratio studded/summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road 262, Quiet: Rubber asphalt GAP11 paved 2008</td>
<td>13000</td>
<td>&lt;6</td>
<td>17.0 ± 0.7</td>
<td>4.5 ± 0.6</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19.3 ± 3.9</td>
<td>14.9 ± 4.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Ref: SMA 11 paved 2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road E18, Quiet: Rubber asphalt GAP16 paved 2008</td>
<td>25000</td>
<td>&lt;6</td>
<td>17.9 ± 1.5</td>
<td>6.2 ± 3.2</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15.8 ± 2.7</td>
<td>5.4 ± 1.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Ref: SMA 16 paved 2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. The significance of the results for the Swedish Transport Administration model

In order to study to what extent the parameters used in the STA (Swedish Transport Administration) model for the calculation of emission factors for PM10 result in emission factors comparable with those obtained in the laboratory, a simple comparative calculation has been made for the tested SMA 11 pavements at 50 km/h. SMA 11 has been chosen because it is the type of pavement which has been tested most in the road simulator (there are only three values for SMA 8 and two for SMA 16 at present, see Table 2). Because emission factors have not been calculated for all tests in the PVM at present, a simplified calculation has been used which means that the concentrations of PM10 in mg/m³ have been multiplied by 50, which has been found to be an approximate factor for the conversion of concentrations into emission factors in the calculations made. The emission factor was then divided by two, since the total wear in the PVM is ca twice as large as in reality, and this is also assumed to apply for the PM10 emission.

In order to calculate the conversion factor (relative abrasion) for the Nordic abrasion values which the pavements in the PVM had, the relationship between Nordic abrasion value and conversion factor for SMA 11 has been calculated in accordance with Table 4 in the Swedish Transport Administration (2009). Emission factors were then calculated from the STA formula for the emission factor for PM10 ($E_{PM10}$):

$$E_{PM10} = \frac{DD}{100} \times 3.4 \times 1000 \times \frac{PPM10}{100} \times RS,$$

where

- $DD$ = studded tyre frequency in %, calculated for the whole year
- $3.4$ = abrasion (g/vehicle km with studded tyres) of the reference pavement (SMA 16)
- $PPM10$ = percentage proportion of PM10 in the abraded quantity
- $RS$ = relative abrasion

In the model, $PPM10$ has been put at 5 per cent in accordance with previous estimates from VTI. For the sake of comparison, DD is put at 100 per cent since this is what is used in the PVM.

With the assumptions and estimates made for this limited material, the agreement is comparatively good (Fig. 15). However, compared with the model, the emissions appear to rise more quickly with increasing Nordic abrasion value in the PVM. The model is sensitive to the proportion of PM10 (doubled proportion results in a doubled emission factor), and the percentage proportion is therefore important for reasonable calculations. To judge from this calculation, 5 per cent is a reasonable assumption, but more accurate calculations and comparisons for different materials, designs and especially estimates from studies in the field are essential to corroborate this assessment.

At present (2012), work is in progress within the Nordic project NORTREP in which various ways of calculating the emission factor for PM10 due to pavement wear are investigated in order to form part of the emission model which is being developed in the project. The above proposition if one of several being tested.
Fig. 15. Emission factors for PM10 calculated with the STA model, compared with emission factors for SMA 11 pavements at 50 km/h, calculated from PVM tests. Changes in the proportion of PM10 in the total abrasion give rise to large changes in the emission factors.
5 Discussion and conclusions

To sum up, the studies both in the laboratory and in the field show that the properties of the pavement influence the particle emissions. For ordinary asphalt pavements, the largest aggregate size and the abrasion resistance of the aggregate material (measured as the Nordic abrasion value) appear to be important. The best results are available for SMA, while only a few isolated measurements have been made for AC. These indicate, that the design – aggregate-rich or dens textured, is not as important for particle formation as the largest aggregate size and the abrasion resistance of the aggregate material.

Of the alternative pavements which have been tested, asphalt rubber and cement concrete are tentatively judged to have positive effects on the emissions, even though the material is relatively small. For cement concrete pavements, further data will be provided by tests in the PVM in 2012. Porous pavements have not been found to produce lower emissions in the tests on which this report is based. According to reports from the Netherlands and Germany, however, this type of pavement can make for lower particle concentrations, the explanation being that road dust is drained off or down into the pavement more easily, and in this way it is made unavailable for resuspension (e.g. Ropertz et al, 2010).

Table 5. Summary of results from tests on PM10 emissions from pavements referred to in this report. "+" signifies LOWER emissions, "=" signifies equivalent.

<table>
<thead>
<tr>
<th>Laboratory (PVM)</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asphalt</strong></td>
<td></td>
</tr>
<tr>
<td>Coarser max. aggregate size</td>
<td>+</td>
</tr>
<tr>
<td>Lower Nordic abrasion value</td>
<td>+</td>
</tr>
<tr>
<td>AC (dens textured instead of aggregate-rich)</td>
<td>?¹</td>
</tr>
<tr>
<td><strong>Asphalt Rubber pavements</strong></td>
<td>=</td>
</tr>
<tr>
<td><strong>Porous pavement</strong></td>
<td>=</td>
</tr>
<tr>
<td><strong>Cement Concrete</strong></td>
<td>?²</td>
</tr>
</tbody>
</table>

¹Only one AC has been tested, without suitable reference.
²Reference pavement for the tested cement concrete pavements, tested in 2011/2012.

Measurements in the PVM reflect the direct PM10 emissions from the abrasion of pavements, when the rapid action of four tyres minimises the accumulation of dust on the carriageway surface itself. In studies in the field, measurements are made of both the direct emissions but also the resuspension of the accumulated material that is already present on the carriageway surface. This component may be extensive and, especially in the early spring when a lot of material has been accumulated in the road environment, it may mask any differences in the direct contribution. In turn, the resuspended material may come from earlier direct abrasion of the pavement, but also other sources, such as sand or material emanating from the road environments.

The mobile measurements also indicate that the variability in particle generation in a real traffic environment is greater because of factors other than pavement properties. This has also been shown by several earlier studies in Sweden (Hussein et al, 2008; Johansson et al, 2009; Pirjola et al, 2010) and in Finland (Kupiainen et al, 2006). The amount of accumulated material may vary because of:

- The abrasion of the carriageway, which is in turn affected by the traffic flows, the proportion of studded tyres, traffic speed and pavement properties (mainly aggregate size and aggregate quality).
- The retention of, and accessibility to, particles on the carriageway, which depends, inter alia, on the texture of the carriageway surface and on meteorological factors (primarily moisture).
• The quantity of imported material (spread of sand and salt, spill, inward transport via vehicle tyres, etc).
• Meteorological factors (duration of wet carriageway, precipitation, etc).

It is interesting to note that the Finnish mobile studies in the field by Tervahattu et al (2008) with the vehicle Sniffer provided the result that pavements with a smaller aggregate size generally produced lower emissions. There may be several reasons for this, but one guess is that the relative contribution by direct wear is masked by resuspension. If the pavements with smaller aggregate size also have a finer texture than those with the coarser largest aggregate size, this may result in less accumulation of road dust on the carriageway surface and thus less resuspension. Initial tests in the laboratory have shown that when the same quantity of dust on the carriageway surface is subjected to an identical resuspension force, less dust is stirred up from a pavement of high texture (Blomqvist et al, 2011). However, these results must be verified.

It is also a reasonable assumption that the road dust that is stirred up by the traffic on a particular pavement need not come only from that pavement. Traffic can probably bring with it dust from adjacent sectors and connecting roads with a different pavement. In such a case, the traffic equalises the differences through the abrasion material and any other material (such as sand and salt) that it brings with it.

A change of pavement is a good measure to reduce abrasion and the PM10 contribution, provided that the existing pavement has been judged deficient from this aspect. In order to lower the PM10 concentrations on a particular street or at a special site (e.g. a school), it is however probable that the measures should cover a reasonably large section of the street, since traffic is likely to even out the resuspendable material along the street or road, and the effect on the local concentrations will probably be very small.

As regards the STA model, it may be said that the assumption that PM10 makes up 5 per cent of total abrasion is an estimate that produces emission factors of the same kind as those calculated from the PVM measurements. Döse and Åkesson (2011) have however shown that the quantity of PM10 per kg material after a Nordic abrasion test had a linear relationship with the Nordic abrasion value, and varied between ca 2 per cent for a Nordic abrasion value of 4 and ca 5 per cent for a value of 10, which also suggests that the proportion of PM10 should vary according to the abrasion resistance of the material used.

This synoptic study focuses on particle generation from the wear of pavements. This is one of important environmental aspects in choosing a pavement. Attention must also be paid to

• Noise
• Other environmental impacts in use (contamination of water and soil)
• Environmental impacts in production and transport
• Consumption of natural resources
• Fuel consumption and exhaust emissions (both particulate, semi-volatile and gaseous)
• Effect on tyre wear
• Impact on thermal balance in towns.

It is also important that the road should be in good condition. A well maintained road provides environmental advantages compared with one that is inadequately maintained, in as much as an even and undamaged surface reduces both rolling resistance, fuel consumption and noise, and also accumulates less dust.

The properties of an adjusted pavement may thus vary depending on the kind of consideration that need be made. On roads and streets where no population is exposed to emission of particles and noise, the other environmental aspects must be considered in relation to safety and accessibility aspects and the costs of construction, operation and maintenance. Where the aspects relating to exposure are prioritised, these and the above aspects must be weighed against one another. Along a motorway with high speeds and buildings near the road, noise may be assumed to be a greater
problem than particle concentrations because of good ventilation. In such a traffic environment, a pavement of sufficiently good abrasion resistance for the high speed, but with a smaller maximum aggregate size to reduce road noise, may be preferable. In an urban environment with low speeds but poor ventilation, the problem relating to road noise may be small, while the particle concentrations are high. In such a case both a coarse textured and abrasion resistant pavement may be an advantage.

6 The need for further studies

For a better understanding of the contribution of road wear to PM10 and the way this varies during the year, studies of the quantity, properties and sources of the road dust reservoir should be made. Apart from the influence of the direct emissions, it is of key importance to understand how accumulated abrasion dust (also of coarser fractions than PM10) contributes to the emissions compared with imported material such as sand and salt. One of the pavement properties which can have an effect on the dynamics of the road dust reservoir, apart from those which have an impact on direct wear, is the texture of the surface which, as far as the authors are aware, has not been studied in conjunction with PM10 emissions. Some aggregate materials are prone to polishing during the time of the year when studded tyres are not used.

Abrasion and particles are only one of the many aspects which need be considered in selecting a pavement. As regards health and environmental effects, it is of continuing interest to study problems relating to aggregate size, texture, abrasion, retention of resuspendable dust and noise, so that the properties may be optimised.

VTI, together with Linköping University and the firm HTC, has discussed the possible environmental advantages of grinding the pavement so that its surface is smooth but the texture is retained (a “negative” texture). Such a texture has a number of potential advantages. According to HTC, smooth surfaces are abraded much less than coarse ones, which could reduce the generation of particles, while at the same time reducing maintenance and extending the life of the road. Noise between the tyre and carriageway is also slightly reduced, as found in a small pilot test on the E4 at Jönköping.

Several aspects also remain regarding the properties of the pavement. Apart from the need for further tests on variable aggregate materials (Nordic abrasion value of greater variation, materials of special properties) in order to corroborate and understand the variation in the results so far obtained, the significance of the relationship between the main material of a pavement (e.g. quartzite or porphyry) and the finer material, which in most cases consists of local aggregate, is also of interest. Local aggregate in most cases has properties inferior to those of the principal material, and may be assumed to contribute a greater proportion to PM10 emissions, at least in the beginning of the life cycle of a pavement. As the pavement is abraded, there should be a balance in the contribution by the different materials. What these contributions are like and how they develop over time is not known. Age and the degree of wear should also affect particle formation, but how this occurs is not studied at present.

Further interesting questions remain as regards alternative types of pavement. Slag is suitable as a pavement material, and this should provide a suitable market for a byproduct from steelmaking. Good results have been obtained in tests, with regard to both durability, friction and abrasion resistance (Jacobson, 2008), but no tests have been made regarding particle formation and the properties of particles from this type of pavement.

As regards the STA model, the proportion of PM10 in total wear should be related to Nordic abrasion value, rather than being a constant. The relation provided by Döse and Åkesson (2011) may perhaps be used. More exact measurements and calculations of this proportion could be made, for instance through collection of material deposited during abrasion tests in the PVM, followed by further size analyses.
Bibliography

7.1 Studies as the basis for this report

Ordinary asphalt pavements


“Quiet” pavements (porous, Asphalt Rubber or of small aggregate size)


Johansson, C., 2011. PM10 emission from quiet pavements in the Stockholm Region. [link to document]

Cement Concrete pavement

7.2 Other work referred to
Blomqvist, G., Gustafsson, M., Bennet, C., Halldin, T.: Emission potential of PM10 suspension from road surfaces is depending on the road surface macro texture, EAC 2011, Manchester, 2011.


8 Glossary
Quick reference table in order to understand different road pavements used in the report.

<table>
<thead>
<tr>
<th>English</th>
<th>Swedish</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA</td>
<td>ABS</td>
<td>Stone Mastic Asphalt</td>
</tr>
<tr>
<td>PA</td>
<td>ABD</td>
<td>Porous Asphalt, also referred as OGFC (Open Graded Friction Course)</td>
</tr>
<tr>
<td>AR-GAP</td>
<td>GAP</td>
<td>Asphalt Rubber, Gap Graded (similar to SMA)</td>
</tr>
<tr>
<td>AR-OGFC</td>
<td>GAO</td>
<td>Asphalt Rubber, Open Graded Friction Course (similar to PA)</td>
</tr>
<tr>
<td>TSK</td>
<td>TSK</td>
<td>Thin Asphalt Layer, combined (produced with a thick tack coat and applied with a spray paver)</td>
</tr>
<tr>
<td>AC</td>
<td>ABT</td>
<td>Asphalt Concrete, dense gradation</td>
</tr>
<tr>
<td>ACO</td>
<td>ABT</td>
<td>Asphalt Concrete, dense gradation</td>
</tr>
</tbody>
</table>