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NEGATIVE TEXTURE, POSITIVE FOR THE ENVIRONMENT: RESULTS OF HORIZONTAL GRINDING OF ASPHALT PAVEMENTS

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ABSTRACT

A pavement surface having its texture deflections mostly directed downwards is said to have a “negative texture” and is expected to result in positive tire/road noise and rolling resistance properties. Negative textures are typical of porous asphalt pavements, but another way to achieve this is to grind-off the top of the asperities of a rough-textured surface. This paper explores the application of grinding pavement texture by tools operating in the horizontal plane (not to be confused with common “diamond grinding” which is made by tools operating in the vertical plane) on a number of asphalt pavements in Sweden, including porous asphalt and stone matrix asphalt. Noise measurements with the Close Proximity method were carried out to evaluate the different acoustical performance of the ground and the original surfaces. In most cases, also tire/road rolling resistance was measured. Texture and wet friction measurements were carried out to characterize how the grinding operation changed the surface texture. It was demonstrated that the grinding treatment led to a more negatively skewed surface texture, resulting in an A-weighted noise reduction up to 3 dB, while rolling resistance coefficients were reduced by up to 15 %. It is concluded that horizontal grinding indeed creates more “negative textures”, which results in improved noise and rolling resistance properties without sacrificing friction, though with limited longevity.

Keywords: pavement, texture, grinding, noise, rolling resistance
INTRODUCTION: TIRE/ROAD NOISE-REDUCING OPTIONS

To reduce tire/road noise, three possible approaches are feasible (1): (i) optimize the pavement surface texture, (ii) provide high porosity in the top layer(s) of the pavement, and (iii) have a top layer with low stiffness. The first approach aims at reducing tire deflections, thereby reducing tire vibrations emitting noise, and providing improved air drainage in the surface; which reduces the “air pumping” noise mechanism (1). In the second approach, increased porosity in the top layer(s) will partly absorb the sound waves, while simultaneously improving air drainage. Finally, the usage of a low stiffness modulus in the top layer is an approach that leads to reduced tire deflection in the contact patch and thus reduced vibration.

To select which approach is best fitted to a given road section, the trade-offs implied by each alternative should be considered. For instance, a pavement texture optimization should not compromise safety aspects, which means that friction levels should also be observed.

In this paper, the first approach is explored by means of texture optimization by horizontal grinding of the pavement surface; a technique that may also be viewed as “shaving off” the peaks in the texture. Unless otherwise stated, the work presented here was carried out by Swedish National Road and Transport Research Institute (VTI) in a national Swedish project designated ViaFutura. Additionally, this paper briefly mentions a few grinding experiments that had already been performed.

PURPOSE OF THIS PAPER

The objective of this paper is to describe the potential of the horizontal grinding technique applied to pavement surfaces, focusing on the environmental effects, expected from this way of optimizing texture. This was tested and demonstrated with field experiments reported here. Also, potential problems and sacrifices are discussed.

POSITIVE AND NEGATIVE TEXTURES

A pavement surface having its texture deflections mostly directed downwards is considered to have a “negative texture”, generally represented by its two-dimensional profile curve which then also is called a “negative profile”. Such a surface will predominantly have valleys projecting downwards from the centerline. The opposite is a texture having its deflections mostly directed upwards, which is considered to be a “positive texture”, resulting in a “positive profile”. In this case, the surface asperities predominantly are projecting upwards from the profile center line, which generates a predominance of peaks in the contact area. As discussed later, a negative texture results in positive tire/road noise and rolling resistance properties, since the local pressure distribution in the contact patch is more evenly distributed than with neutral or “positive textures”; the latter resulting in higher local pressure near the peaks. These features influence the vibration patterns in the tire and thus noise emission and rolling resistance and perhaps also frictional properties.

This asymmetry in the profile can be quantified by various measures. One of them is “skewness”, where a positive texture gives a positive skew (>0) and a negative texture gives a negative skew (< 0). Skewness ($r_{sk}$) of a profile is defined in ISO 13473-2 (2). Equation [1] indicates how the skewness parameter is calculated, where $RMS$ is the root mean squared deviation, $L$ is the profile length and $Z$ is the profile deviation from the centerline of the profile at the position $x$:

$$r_{sk} = \frac{1}{RMS^3} \left[ \frac{1}{L} \int_{0}^{L} Z^3(x) dx \right]$$

[1]
To illustrate this concept, two artificial surface profiles were generated, one with positive skewness and the other with negative skewness. All other parameters, such as the RMS value, were kept constant. The two surface profiles are presented in FIGURE 1.

![Figure 1: Artificially generated textures with positive skew (a) and with negative skew (b) and their corresponding enveloped surface profiles. The skew of the upper profile is 1.28 and that of the lower profile is -0.82.](image)

When rolling on a rough surface, the tire tread rubber will not deform itself to perfectly envelope the surface. Most importantly, the rubber will not be able to establish contact with narrow valleys in the pavement texture, or to follow steep gradients in the profile, due to the limited resilience of the rubber and the belt it is attached to. This has a direct implication for the noise generation mechanisms, as a different contact pattern will change the tire’s vibration excitation. One possibility to account for this effect is by using enveloping algorithms. Such algorithms estimate how the tire tread surface deflects when contacting the pavement surface.

In FIGURE 1, the pavement profile curve is supplemented with such a curve, called “enveloped surface”. Different algorithms can be found in the literature, as previously reported in the European project ROSANNE (3) and further discussed in (4). The enveloped curve in Figure 1 was generated by the authors using the procedure described in (3), which in turn used the algorithm by von Meier (3).

**GRINDING TECHNOLOGY AND EQUIPMENT**

The grinding machines used in the Swedish experiments were produced by HTC Sweden AB, but of different sizes in each trial. Two such machines are shown in Figure 2(ABC).

Essentially, the machines have one, two or three grinding heads (circular rotating plates, 650-950 mm diameter) on which there are 3-4 grinding discs of 170-270 mm diameter. See Figure 2(AD). Each grinding disc has 3-6 diamond tools mounted in the periphery. The latter grind the surface while the discs rotate, simultaneously as the head rotates with its discs. The diamond tools are available with different coarseness, resulting in various levels of microtexture. The entire machine moves forward at a speed determined by the operator. The lower the speed, the more solid
matter is ground away. For example, in the experiment in 2017, using the small machine in Figure 2, 100 m was ground approximately 1 m/minute; in 2011 it was 2 m/minute. These machines are mainly used for grinding and polishing of industrial concrete floors.

This way of grinding is referred to as horizontal grinding as the grinding tools rotate in the horizontal plane. This shall not be confused with the much more common grinding technique, most often referred to as “diamond grinding” (5), in which parallel “saw blades” work in the vertical plane. While both machine types use diamond tools, the horizontal type was used in this application to reduce macrotexture by “shaving off” the top of the texture, while the diamond grinding machines aim at reducing unevenness while simultaneously creating a longitudinal texture of narrow grooves. The latter is used on cement concrete pavements, while our horizontal grinding has been used only on asphalt pavements (but can equally well be used on concrete).
Each grinding operation was followed by careful vacuuming of the surface, followed by manual sweeping. Traffic blew away any remaining dust.

**FIRST TRIALS**

The method of creating a more negatively skewed surface by grinding off the top aggregates had been explored previously. An early pilot trial to create a "negative texture" for noise reduction was made in 2006 by Sandberg and Ejsmont (6) in cooperation with the company manufacturing the grinding machines, by grinding off the top 1 mm of a dense asphalt concrete pavement with max. 11 mm aggregate (DAC11) on a 40 m long strip in an industry yard.

The effect on tire/road noise at 50 km/h was a reduction of 1 dB (A-weighted overall level) when using the SRTT reference tire but 0 dB for a tire used as a proxy for truck tires. This was discouraging, but the pavement was not suitable for this experiment since it was already very smooth-textured.

To apply the technique to a more suitable pavement, in 2011, Sandberg and Mioduszewski used horizontal grinding on a double layer porous asphalt concrete with max. 11 mm aggregate (DPAC11), hoping to achieve a substantial noise reduction (7). This experiment was conducted before the ViaFutura project was started, but as the methodology and results are consistent with those in this project, this experiment is treated below together with the ViaFutura experiments.

**INTERNATIONAL EXPERIENCE**

Near Melbourne, Australia, in 2013 a project started in which several types of pavements are tested for noise-influencing properties. A few of them were “standard OGA” (Open-Graded Asphalt), having 10 mm maximum aggregate size and being 30 mm thick with a void content of 15%. One of these sections (#2) was treated by “shaving” the slow lane of the section; i.e. grinding off 1-2 mm of the top surface of the asphalt, using a 600 mm rotary diamond cutter (8) normally applied for removing line markings. This pavement and grinding configuration was inspired and selected based on results from Sandberg and Mioduszewski (7).

Tests were conducted during the first year following the installation of the surfaces, and were part of a program intended to take place over a total of five years. CPX tests (9-8) have so far been conducted on eight occasions; between March 2013 and March 2017.

The results have been very positive, with the ground single-layer OGA being the quietest of the five tested pavements (including two non-treated double OGA’s with 10 mm max. aggregate size). Noise reduction versus the non-treated OGA has been 2-3 dB(A) with no deterioration over the four years and the ground OGA is even better than the double-layer OGA’s with no treatment (9).

Additionally, resistance measurements were carried out, using the VicRoads SCRIM device. These were performed three months after laying. The Sideways Force Coefficient was then found to be 0.85 for the untreated OGA and 0.95 for the treated (ground) OGA. The double-layer OGA’s had an SFC of 0.80 (10). In other words, the grinding was favorable for skid resistance.

The authors are not aware of any other published study concerning horizontal grinding of road pavements.

**TEST METHODS**

**Pavement Geometrical Properties**

To analyze how the texture and unevenness were affected by the grinding process, all the tested sections and their reference pavements (generally the same pavement without grinding) were
measured by VTI using a laser RST vehicle (11). However, the measurements in 2017 were carried out by Ramboll Sverige AB, using the same type of measuring vehicle as (11). Texture was collected in accordance with ISO 13473-1 and megatexture in accordance with ISO 13473-5, while unevenness and rut depth were collected in accordance with CEN standards (12, 13).

**Tire/Road Noise**

The Close Proximity (CPX) method was employed in these experiments to analyze the noise resulting from the tire/road interaction. The tests were carried out in accordance with ISO 11819-2 (2) using the Tiresonic Mk4 test trailer. This trailer was designed and operated by the Gdańsk University of Technology (TUG) and is presented in FIGURE 3A. Two test speeds were used, namely 50 and 80 km/h, in accordance with ISO 11819-2. As reference tires, both tire P1, which acoustically represents light vehicles, and tire H1, which represents heavy vehicle tires, were used in accordance with ISO/TS 11819-3 (2).

![FIGURE 3](image_url) The measurement equipment used. A: CPX measuring trailer by TUG. B: reference tire P1. C: reference tire H1 (P1 and H1 used both in the noise and rolling resistance measurements). D: rolling resistance trailer by TUG. E: additional tire used in rolling resistance measurements only (Michelin Primacy).
To allow for temperature normalization, both air and road temperatures were measured simultaneously with the noise measurement. The normalization procedure for temperature followed the procedure required in ISO 13471-1 (2) with a reference temperature of 20 °C. The CPX values were also normalized for tire hardness and velocity variations according to ISO 11819-2 and ISO/TS 11819-3 (2).

Rolling Resistance
Measurements of the rolling resistance coefficient were made by a special trailer and crew from TUG: the so-called "R2 trailer" (see Figure 3D). The method is described in (14). As reference tires, the P1 and H1 tires defined in ISO 11819-3 were used, plus a Michelin Primacy HP tire (225/60R16) used as a second car tire.

Skid Resistance
Skid resistance has been measured by two methods and equipment:
- Saab Friction Tester: This is a test of longitudinal friction at optimum slip on a wetted surface by a car equipped with a small test tire, at 50 and 80 km/h; see (15). It is one of the world’s most commonly used friction testers on airfields, also used on roads.
- Portable Friction Tester: This is a test of wet longitudinal friction, by a special VTI device equipped with a special rubber wheel pushed by an operator over the surface at slow walking speed; see (16).

TESTED PAVEMENTS
This paper reports trials made at four places, with the most essential descriptions summarized in Table 1, where only the ground sections are shown. The type of pavement that was ground and its age are indicated, together with a rough estimation of how much of the peak texture was ground-off. Note that 2011-GR1 was tested also in 2015 and 2013-GR1 and 2013-GR2 were tested also in 2014.

<table>
<thead>
<tr>
<th>Trial designation &amp; year</th>
<th>Road No., lane &amp; location</th>
<th>Pavement &amp; age in years</th>
<th>AADT</th>
<th>Length [m]</th>
<th>Width [m]</th>
<th>Ground-off [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-GR1</td>
<td>E4, L1, Huskvarna</td>
<td>DPAC11 (1)</td>
<td>12000</td>
<td>65</td>
<td>0.95</td>
<td>1-2</td>
</tr>
<tr>
<td>2013-GR1</td>
<td>636, L0, Vikingstad</td>
<td>SMA16 (1)</td>
<td>5600</td>
<td>100</td>
<td>3</td>
<td>0.5-1</td>
</tr>
<tr>
<td>2013-GR2</td>
<td>636, L0, Vikingstad</td>
<td>SMA16 (1)</td>
<td>5600</td>
<td>100</td>
<td>3</td>
<td>1-2</td>
</tr>
<tr>
<td>2014-GR1</td>
<td>636, L0, Vikingstad</td>
<td>SMA16 (2)</td>
<td>5600</td>
<td>100</td>
<td>3</td>
<td>0.5-1</td>
</tr>
<tr>
<td>2014-GR2</td>
<td>636, L0, Vikingstad</td>
<td>SMA16 (2)</td>
<td>5600</td>
<td>100</td>
<td>3</td>
<td>1-2</td>
</tr>
<tr>
<td>2013-GR3</td>
<td>Malmslattsvagen, L1, Linkoping ≈SMA11 (0)</td>
<td>TBD</td>
<td>120</td>
<td>3</td>
<td>0.5-1</td>
<td></td>
</tr>
<tr>
<td>2015-GR1</td>
<td>E4, L1, Huskvarna</td>
<td>DPAC11 (5)</td>
<td>12000</td>
<td>120</td>
<td>0.95</td>
<td>1-2</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>E6, L2, Vellinge</td>
<td>PAC11 (6)</td>
<td>8000</td>
<td>100</td>
<td>0.95</td>
<td>3</td>
</tr>
</tbody>
</table>

Legend: GR = ground pavement, SMA = Stone Matrix Asphalt, PAC = Porous asphalt concrete (single layer) 
DPAC = Double-layer porous asphalt concrete, 11 and 16 = Max. aggregate size in mm 
L0 = one lane in each direction, L1 = slow lane (of two lanes/direction), L2 = fast lane (of two lanes/direction)
Each ground section was also associated with a reference section consisting of the same pavement which was not ground. These were located immediately before and after the ground section, and a minimum of 100 m of each part was measured, i.e. at least 200 m in total. An exception was 2013-GR3 which had a 100 m reference section in L1 in the opposite direction.

One illustration of a trial section is shown in Figure 4. An illustration of a ground surface beside a non-ground surface is shown in Figure 5.

Trial section 2017-GR1 is unique as it has two references. The reason is that when making the measurements on this site, it appeared that the reference section after the ground section (REF2) was quite different from the reference before the section (REF1) in terms of porosity. While REF1 had been totally clogged over its 6-year life, REF2 had some porosity left, which affected noise and permeability. Permeability measurements made with EN12697-40 method gave an average outflow times 272 s on REF1, but only 99 s on REF2 (the ground surface gave 552 s). It means that some pores were still somewhat open on REF2, making it quieter.

RESULTS: TEXTURE CHANGES

As an illustration of the effect of grinding, for 2017-GR1 the grinding process removed 3 kg/m² of material from the road surface. This corresponded to an average of 3 mm removal of the top asperities. Typical profiles are shown in Figure 6, where one profile was extracted from the 2017-REF1 section and the other from the ground section (2017-GR1). The grinding operation resulted in a more negative surface profile with flatter asperity peaks. The profile skewness on REF1 was -0.74 (typically negative as it is a porous surface) and on the ground surface it increased to -1.45. The grinding operation was also reflected by a decrease in the MPD from 1.61 to 0.70 mm.
FIGURE 5  Example of a test section (2017-GR1) not ground (left) and ground (right). The contrast is somewhat enhanced to highlight the differences.

FIGURE 6  Examples of pavement profiles in the REF1 section (a) and in the ground (GR1) section (b); blue for the original profiles; gray for the enveloped versions (see Figure 1 for explanations).

The texture results, MPD and megatexture (rms), expressed in mm, are shown in Table 2 for all the trial sections and their references. Additionally, skew values of a few sections are shown.
TABLE 2  Macrotexture and megatexture values in mm, as well as skewness.

<table>
<thead>
<tr>
<th>Trial ground section</th>
<th>Pavement (reference)</th>
<th>MPD of reference (not ground)</th>
<th>MPD of ground section</th>
<th>Megatexture of reference</th>
<th>Megatexture of ground section</th>
<th>Skewness of reference (not ground)</th>
<th>Skew of ground section</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-GR1</td>
<td>DPAC11</td>
<td>1.69</td>
<td>1.46</td>
<td>0.66</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013-GR1</td>
<td>SMA16</td>
<td>1.44</td>
<td>1.01</td>
<td>0.67</td>
<td>0.55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013-GR2</td>
<td>SMA16</td>
<td>1.44</td>
<td>N.A.</td>
<td>0.67</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013-GR3</td>
<td>SMA11</td>
<td>1.05</td>
<td>0.86</td>
<td>0.46</td>
<td>0.41</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2014-GR1</td>
<td>SMA16</td>
<td>1.23</td>
<td>0.97</td>
<td>0.59</td>
<td>0.55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2014-GR2</td>
<td>SMA16</td>
<td>1.23</td>
<td>1.09</td>
<td>0.59</td>
<td>0.55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2015-GR1</td>
<td>DPAC11</td>
<td>1.39</td>
<td>1.27</td>
<td>0.59</td>
<td>0.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(cl)</td>
<td>1.61</td>
<td>0.70</td>
<td>0.71</td>
<td>0.39</td>
<td>-0.74</td>
<td>-1.45</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(po)</td>
<td>1.66</td>
<td>0.70</td>
<td>0.71</td>
<td>0.39</td>
<td>-0.72</td>
<td>-1.45</td>
</tr>
</tbody>
</table>

Notes: 2013-GR2: MPD value not available due to corrupt data. 2017-GR1: this one has two ref sections; first fully clogged (cl), 2nd with some porosity (po). Skew calculated only for 2017-GR1 so far, working on the rest.

It appears that macrotexture changed substantially after grinding; especially in 2017-GR1 which was deliberately ground more than the other sites. Megatexture changes were small, while skew doubled in the example for 2017-GR1. However, note that despite the grinding, MPD values were still in the range of 0.7 – 1.1 mm, which should not create any wet skid resistance hazards (17).

RESULTS – NOISE

Results for the measurements with the CPX method are presented in TABLE 3 for each tire, pavement and speed. The levels are normalized for air temperature (20 °C), the nominal test speed (50 or 80 km/h) and tire rubber hardness (66 Shore A) (2). Noise reductions rather than the “absolute levels” are shown, as they are more accurate due to paired measurements made during the same runs. For a summary of the results; refer to the Discussion.

TABLE 3  Results of CPX measurements of noise properties; reductions of CPX levels in A-weighted dB (original minus ground surfaces).

<table>
<thead>
<tr>
<th>Trial ground section</th>
<th>Pavement (reference)</th>
<th>Low speed (50 km/h)</th>
<th>High speed (80 km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Noise reduction Tire P1</td>
<td>Noise reduction Tire H1</td>
</tr>
<tr>
<td>2011-GR1</td>
<td>DPAC11</td>
<td>2.7</td>
<td>0.3</td>
</tr>
<tr>
<td>2013-GR1</td>
<td>SMA16</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2013-GR2</td>
<td>SMA16</td>
<td>2.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2013-GR3</td>
<td>SMA11</td>
<td>0.3</td>
<td>-0.4</td>
</tr>
<tr>
<td>2014-GR1</td>
<td>SMA16</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2014-GR2</td>
<td>SMA16</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2015-GR1</td>
<td>DPAC11</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(cl)</td>
<td>3.3</td>
<td>2.1</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(po)</td>
<td>1.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Notes: 2017-GR1: this one has two ref sections; first fully clogged (cl), 2nd with some porosity (po). 2013-GR3 only tested at 50 km/h due to speed limit.
The results are also presented as frequency spectra; see Figure 7 (tire P1) and Figure 8 (tire H1), giving much more detailed information.

FIGURE 7 Third-octave-band frequency spectra for all ground and reference surfaces (not ground). For tire P1, at 50 km/h (above) and 80 km/h (below).
FIGURE 8  Third-octave-band frequency spectra for all ground and reference surfaces (not
ground). For tire H1, at 50 km/h (above) and 80 km/h (below).

RESULTS – ROLLING RESISTANCE
Results for the measurements of rolling resistance are presented in TABLE 4 for each tire and
pavement. Values for 50 and 80 km/h were averaged as they are highly correlated and speed is not
a major factor in rolling resistance. Reductions, rather than the absolute values, are shown, as they
are more accurate due to paired measurements made during the same runs. In this way, any potential drift with time or tire temperature are eliminated, which otherwise may corrupt results. For a summary of the results; refer to the Discussion.

### TABLE 4 Results of measurements of the rolling resistance (RR) coefficient; presented as reductions in % from the original reference (not ground) to the ground surfaces.

<table>
<thead>
<tr>
<th>Trial section</th>
<th>Pavement (reference)</th>
<th>RR reduction Tire P1</th>
<th>RR reduction Tire M1</th>
<th>RR reduction Tire H1</th>
<th>RR reduction Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-GR1</td>
<td>DPAC11</td>
<td>13</td>
<td>9</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>2013-GR1</td>
<td>SMA16</td>
<td>10</td>
<td>9</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>2013-GR2</td>
<td>SMA16</td>
<td>15</td>
<td>13</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>2013-GR3</td>
<td>SMA11</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2014-GR1</td>
<td>SMA16</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2014-GR2</td>
<td>SMA16</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>2015-GR1</td>
<td>DPAC11</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(cl)</td>
<td>13</td>
<td>12</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(po)</td>
<td>12</td>
<td>10</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

Notes: 2013-GR3 and 2015-GR1: not tested for rolling resistance. 2017-GR1: this one has two ref sections; 1st fully clogged (cl), 2nd with some porosity (po).

### RESULTS – SKID RESISTANCE

Results for the measurements of skid resistance are presented in TABLE 5 for each speed, pavement and method, the latter shown as the friction coefficient (FC) using the Portable Friction Tester (PFT) and longitudinal wet skid resistance (SR) using the Saab Friction Tester (SFT). As this parameter was only of secondary interest, not all trial sections were tested.

### TABLE 5 Results of measurements of skid resistance coefficients.

<table>
<thead>
<tr>
<th>Testing speed</th>
<th>Walking speed</th>
<th>50 km/h</th>
<th>80 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial section</td>
<td>Pavement (reference)</td>
<td>FC of ref. (not ground)</td>
<td>FC of ground section</td>
</tr>
<tr>
<td>2011-GR1</td>
<td>DPAC11</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2013-GR1</td>
<td>SMA16</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2013-GR2</td>
<td>SMA16</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2013-GR3</td>
<td>SMA11</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2014-GR1</td>
<td>SMA16</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2014-GR2</td>
<td>SMA16</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>2015-GR1</td>
<td>DPAC11</td>
<td>0.74</td>
<td>0.90</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(cl)</td>
<td>0.93</td>
<td>0.86</td>
</tr>
<tr>
<td>2017-GR1</td>
<td>PAC11(po)</td>
<td>0.90</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Notes: 2017-GR1: this one has two ref sections; 1st fully clogged (cl), 2nd with some porosity (po). 2015-GR1: Measurements only at 70 km/h. Cells indicated as N.A. (not available) mean that no such measurements were made.
DISCUSSION
The basic intention of the horizontal grinding is to create an “extra” negative profile. With the changes in texture values, and studying close-up photos of the surface [only one example shown here, another one in (7)], it appears that this was achieved.

The resulting influences on noise levels varied with the tire and the pavement type. Generally, the highest effects were achieved on the pavements with the highest macrotexture, such as the porous asphalt pavements and the SMA16. On SMA11, the texture was already low and noise reduction was negligible. In the 2017 test, it appeared that the two reference sections were different, as one of them had some remaining porosity, which reduced its noise level in the original state, and thus reduced the “noise reduction” for the ground section. It was more efficient to grind the clogged pavement.

The frequency spectra revealed that the noise reduction occurred at frequencies up to and including 1000 Hz; i.e. the ones assumed to be caused by the impact of texture on the tire tread (1). For the highly porous pavement tested 2011, it appeared that GR1 had increased noise at the higher frequencies, which suggests that the dust from the grinding contributed to clogging.

It appears that noise reductions were consistently smaller when using the H1 tire (which acts as a “proxy” for heavy truck tires). This is logical, as it is known that texture has a relatively small effect on truck tire noise (1). Nevertheless, when achieving 2-3 dB noise reduction for light vehicles, the authors consider this worthwhile, especially when it occurs “on top of” the already substantial noise reduction of porous asphalt (7).

The influence of the grinding on rolling resistance appeared to be more significant than that on noise (17), since reductions around or above 10 % will have significant effects (1-2 %) on fuel or energy consumption of vehicles and consequently on CO2 emissions. As illustrated by the results of the 2015 test, too little grinding may give negligible effects. The two car tires P1 and M1 give higher reductions than the truck tire H1 as truck tires are known to be less sensitive to macrotexture (as for noise).

Many would expect that reducing macrotexture will reduce skid resistance. Our results do not indicate this. On the contrary, small increases in skid resistance were recorded. The reason is that the grinding tools leave a very rough microtexture which balances out the lower drainage of ground surfaces. It was obvious that the microtexture became higher after grinding when touching the surface with fingers, as the surfaces felt harsh and potentially abrasive. The measurements in 2017 with the PFT device were made immediately after grinding and vacuuming, but it was obvious when touching the surface with fingers that considerable dust remained on the surface, which is probably the reason for somewhat lower friction values for the 2017-GR1 data. Nevertheless, one must make sure that the resulting macrotexture after the grinding is sufficient to provide acceptable wet skid resistance (18). On high-speed roads, this limits the pavements suitable for horizontal grinding to those which are either porous or have an MPD value well above 1.0 mm.

One minor disadvantage that has been noticed is that the ground surfaces tend to look a little glossy when vied against the sunlight, since their flatness enhances specular reflection.

A crucial question is how durable are the grinding effects? The 2011 tests were repeated in 2012 (noise only, not included in the tables) and showed that the noise reduction effect was gone. Measurements in 2013-2014 also showed that the noise reducing effect was gone after one year. The rolling resistance reduction, however, was still there, albeit at a lower level. The reason for the loss of the noise reduction is thought to be that edges of the flat upper faces of the asperities are gradually rounded, thus increasing the enveloped profile amplitude, while simultaneously reducing the available drainage volume in the valleys of the profile.
However, in Sweden, studded tires are used during the cold season and they are known to wear out pavement surfaces much more than in countries where such tires are prohibited. Therefore, in countries where studded tires are not used, the authors are confident that the durability of the effects of grinding would be much longer. This is suggested, if not confirmed, by the very positive long-term results reported from Australia (9). It should be noted that the grinding procedure may not be very expensive if applied in a large scale; providing a reasonable cost-benefit ratio when including monetary evaluation for society of the internal costs of the noise and rolling resistance effects (evaluations ongoing).

Finally, it shall be reminded that this type of grinding should not be mistaken for the pavement treatment widely known as diamond grinding. The latter also creates a highly negative texture, but often with side-effects, such as “fins” on the ridges of the grooves, that may more or less balance out the effect of the grooves. However, if the horizontal grinding is used as a post-treatment on a diamond ground pavement (grinding away “fins”), the authors think that very good effects are achievable with such a combined approach.

The authors intend to continue the work by analyzing more profiles for skewness and adding results of rolling resistance measurements on 2017-GR1 in the first week of August.

CONCLUSION

The grinding operation created a more negative texture profile. This appeared to be acoustically favorable (up to 3 dB) but even more important, it reduced rolling resistance (up to 15 %). This was achieved without sacrificing skid resistance. Unfortunately, in the Swedish tests, highly affected by the road wear of studded tires in the cold season, the durability of the noise effect is very low, and also the longevity of the rolling resistance reduction was poor. This was because asperities in the flat pavement surface created by the grinding were worn to the more common rounded shape.

However, experience in Australia, where studded tires do not wear down pavements, suggests that longevity of the noise reduction effect is good. Therefore, the authors believe that under normal pavement wear conditions, the horizontal grinding technology is feasible. Especially, it may be used for porous asphalt surfaces that have lost much of their initial noise reduction, where the grinding may restore noise reduction to a more favorable level. Furthermore, rough-textured pavements such as SMA16 may after grinding be given similar, more favorable effects as the smoother SMA11 pavements.

It is recommended for efficiency and safety reasons that horizontal grinding not be carried out on pavement surfaces having an MPD value below about 1.2 mm, and grinding should not result in an MPD below 0.6 mm.

ACKNOWLEDGMENTS

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