

Double-layer porous asphalt – Performance of innovative noise-reducing variants

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ABSTRACT

Since 2010 double-layer porous asphalt (DPA) pavements have been used on motorway E4 through the Swedish city Huskvarna. The pavement has been a great success despite the challenge to use porous pavements in a country where studded tyres are used in wintertime, resulting in excessive surface wear and subsequent clogging of pores. In this paper, seven interesting trials on this road related to the noise reduction of the pavement are reported:

1. Paving DPA hot-on-hot: Commonly, when paving DPA, it is considered necessary to do this “hot-on-hot” which means that the top layer must be applied while the bottom layer is still hot. This project has shown that it works fine to pave the two layers in two different days.
2. Rejuvenating the surface may almost totally clog the pores in the top layer. In an attempt to extend the technical lifetime, the slow lane was rejuvenated by application of a Fog Seal. This filled the remaining porosity which resulted in a great loss of noise reduction.
3. The effect of the bottom layer is analysed in relation to the top layer. One part of the section had a single-layer PA, the performance of which could be compared to another section where the same PA layer had been laid on a bottom layer, thus creating a DPA. It appeared that 2/3 of the noise reduction is due to the bottom layer of the DPA.
4. Reusing the bottom layer: On one part of the new pavement laid in 2017, only the top layer of the old DPA section was milled-off and then repaved with a new top layer, while the bottom layer was reused. The noise reduction which is lost by reusing the old bottom layer is only around 1 dB (of the initial 7-8 dB), or 0.5 dB as an average.
5. Steel slag has been used instead of stone aggregate in the top layer in one trial. The performance of this trial is analysed in comparison to the conventional aggregate.
6. Grinding off the peaks in the surface has a favourable effect on both noise reduction and rolling resistance. This is a way to produce an “extra negative texture”.
7. End-of-life noise reduction: After a few years, the top layer is clogged; yet, the pavement provides a considerable noise reduction. Surprisingly, 1-3 dB of noise reduction remains even when there is full clogging. Reasons for this are discussed.

1. BACKGROUND

Since 2010 double-layer porous asphalt (DPA) pavements have been used on motorway E4 through the Swedish city Huskvarna. This followed a Swedish court decision that the noise emission on this section of the motorway must be lowered by actions including the use of a noise-reducing pavement. The Transport Administration then set up a target of 5 dB noise reduction by the pavement.

Since then (2010), the pavement has been a great success despite the challenge to use porous pavements in a country where studded tyres are used in wintertime, resulting in excessive surface wear and subsequent clogging of pores. A number of earlier applications of similar pavements had been disappointments. The main part of the noise-reducing section is 2.7 km long and has two lanes in each direction, while there is on the southern side also a single-layer porous pavement a few hundred metres long. The posted speed limit is 90 km/h and AADT is about 26 000, with a heavy vehicle proportion of 15 %. However, the heavy vehicles are dominated by 25 m long articulated trucks with a GVW of 35-60 tons. A picture of the main section is shown in Figure 1. The motorway runs between lake Vattern and an area with a school, a museum and plenty of homes on the land side, where the homeowners did not want noise barriers to ruin the lake view.



Figure 1: Overview of motorway E4 through Huskvarna (just north of Jönköping).

The first generation of DPA was in service between 2010 and 2017 and the second generation has been in service since 2017. The reason for repaving in 2017 was not that the pavement was in poor technical condition; it was based on noise measurements showing that the noise reduction had reduced below an acceptable target. This paper reports experiences from both pavement generations.

Fortunately, road contractor Svevia AB, made some actions and modifications in the DPA in both generations, such as rejuvenation, cleaning, different binder proportion, and different aggregates. They also allowed the Swedish National Road and Transport Research Institute (VTI) to make tests by grinding the texture horizontally. VTI has been contracted to make measurements on these various sections; for noise annually and for other parameters less frequently. Due to this, there is a wealth of information and experience which is worth sharing. In this paper, seven interesting trials on this road related to the noise reduction of the pavement are reported, but in some cases also other parameters such as rolling resistance, skid resistance and geometrical features are reported.

2. MEASUREMENT METHODS

Noise measurements have been performed annually, and sometimes more than one time per year, by using the “Close Proximity (CPX) method”, as standardised in ISO 11819-2 (Figure 2). The measured values have been processed and presented as the difference between DPA and a reference pavement, the latter corresponding to a "middle-aged" SMA 16. In reality, the reference values are averages from measurements performed annually on 3-6 different SMA 16 pavements of age varying between 1 and 9 years.

CPX (noise) levels are shown in this paper with the unit “dB”, and all overall levels and frequency spectra are A-weighted to represent human perception of sound. Often, other authors are expressing this in a unit “dB(A)” which, however, is in violation to ISO standards.

The measurements use two “reference tyres”; one that is considered representative of passenger car tyres (designated P1) and one representative of heavy truck tyres (designated H1), according to ISO/TS 11819-3 (Figure 3). Measurements were carried out at 70 and 90 km/h, but since no significant effects of speed on the noise differences and changes have been detected, only the average noise levels are presented in this paper. From 2017, the speeds 70 and 90 were changed to 50 and 80 km/h. In this paper, only noise averaged for 70 and 90, or for 80 km/h are used. Since it appeared that noise reductions are rather similar for tyres P1 and H1 for the DPA pavements (which is not the case for some other pavement types), in this paper, the noise levels for the two tyres have been averaged too. In addition, ISO/TS 13471-1 was used to normalize noise measurements to 20 °C.



Figure 2: CPX noise measurements with the TUG Tiresonic Mk4 trailer on the DPA pavement on E4, Huskvarna. The test tyre is mounted in the middle of the trailer hood.



Figure 3: Tread patterns of the two reference tyres used during the CPX noise tests. From left to right: SRTT (P1) and Avon AV4 (H1).

To characterize geometrical road surface properties, measurements with laser-based profilometer systems (VTI RST) have been performed annually for all relevant parameters, such as IRI, rut depth, macrotexture, megatexture, etc. Some measurements have also been made of rolling resistance and skid resistance. For those, refer to the references given.

3. PAVING DPA HOT-ON-HOT OR NOT?

Commonly, when paving DPA, it is considered necessary to do this “hot-on-hot” which means that the top layer must be applied in the same operation while the bottom layer is still

hot. First, the bottom layer is laid by a high compaction screed directly behind the paver. Immediately following, the wearing course (top layer) is laid by the second screed; both should be in a single process or at least with a minimum of time delay between the two layers are laid. The “hot on hot” paving technique is assumed by most in the business to be necessary later to avoid separation of the two layers. Therefore, usually, a dual-layer paving machine is used to make sure that the bottom layer has not cooled-off until the top layer is laid. A less expensive way is to use two single-pavers operating as close as possible to each other. The dual single-layer paving technique, in which there is some minor cooling of the bottom layer before the top layer is applied, has been used 14-20 years ago in Sweden (before the project described here) with varying results, mostly negative.

However, in this project, in the paving operations both 2010 and 2017, the two layers were



laid on two consecutive days, lane by lane. No special means were taken to enable this, other than not allowing traffic on the newly laid layer. Ambient air temperatures were 10-15 °C.

During the first lifecycle (2010-2017) and in the present lifecycle (2017---present) no significant delaminations or separations between the layers, have been noticed. Consequently, the project has shown that it works well to pave the two layers in two different days. See Figure 4.

Figure 4: Applying the top layer on the second day of paving (August 2017). Photo: T. Vieira.

4. THE EFFECT OF REJUVENATION WITH A SPRAYED ASPHALT EMULSION

In the first lifecycle, in an attempt to extend the technical lifetime, the slow lane was rejuvenated (in both directions) by application of a Fog Seal, which is a specially formulated asphalt emulsion (a thin liquid oil). This happened in the late summer of 2013; i.e., when the pavement was three years old. A similar treatment was applied already when the pavement was 3 months old but only on a 100 m long section of the slow lane in southern direction. The idea behind this was to see if the rejuvenation would prolong the lifetime of the pavement by reducing ravelling and whether it would influence noise reduction.

At an age of one year, the effect of the Fog Seal applied on the new DPA was a noise increase of 0.4 dB. This minor difference diminished in later years. When checking the visual appearance of the surfaces with and without Fog Seal when they were new, it was difficult to see any difference; both had plenty of open pores in the surface. The amount of sprayed emulsion was too thin to clog the pores visually in the surface at that time, but probably

some of it poured down into the pores and reduced the sound absorption of them. This effect appeared as a difference in frequency spectra with and without Fog Seal, as there are 0.4-1.2 dB higher levels at the typical peak of the sound absorption in the 500-1000 Hz spectral bands, as well as for frequency bands above 4000 Hz (these spectra not shown here).



Figure 5: Applying Fog Seal on the slow lane, after three years of service. Photo: N G Göransson.

The effect appeared to be much more serious when the Fog Seal was applied when the pavement was three years old, since then the pores had been partly clogged so a small amount of emulsion spray was enough to clog most of the remaining porosity. Unfortunately, the road contractor did not leave any comparable part of the DPA unsealed, so direct comparison to see the effect is not possible. However, Figure 3 shows the noise reduction by time (year) for the slow lane (sprayed with Fog Seal) and the fast lane (not treated). Between years 3 and 4, there is an abrupt loss of noise reduction. That it is due to the loss of sound absorption (as caused by clogging) appears when one compares frequency spectra (not included here for space reasons) since the typical effect of lower spectral levels due to sound absorption at 500-1000 Hz is gone for the slow (sprayed) lane.

Figure 6 shows the difference between the two lanes, where the lane sprayed with Fog Seal showed a dramatic loss in noise reduction compared to the not sprayed lane when the next measurement was made. Note that irrespective of the spraying, the slow lane should have a little less noise reduction, due to the higher traffic volume and heavier load in that lane. Normally, the drop between 2013 and 2014 should not have been more than 1 dB; thus, the rejuvenation had a dramatic effect on noise; estimated by the author to be ca. 2 dB extra loss of noise reduction. Again, in later years, the effect diminishes, which may be caused by some of the pores clogged by the spray may have become opened-up by the wear of studded tyres and/or by the air and water pressure in the heavy truck tyre/road interface.

There were no signs of less ravelling or damages in the sprayed lane than in the untreated lane, so it seems that the rejuvenation was unnecessary also from the point of durability. Therefore, in the new pavement cycle starting in 2017, so far (2022) no rejuvenation has been made, and yet the technical surface condition is about the same as in the first lifecycle.

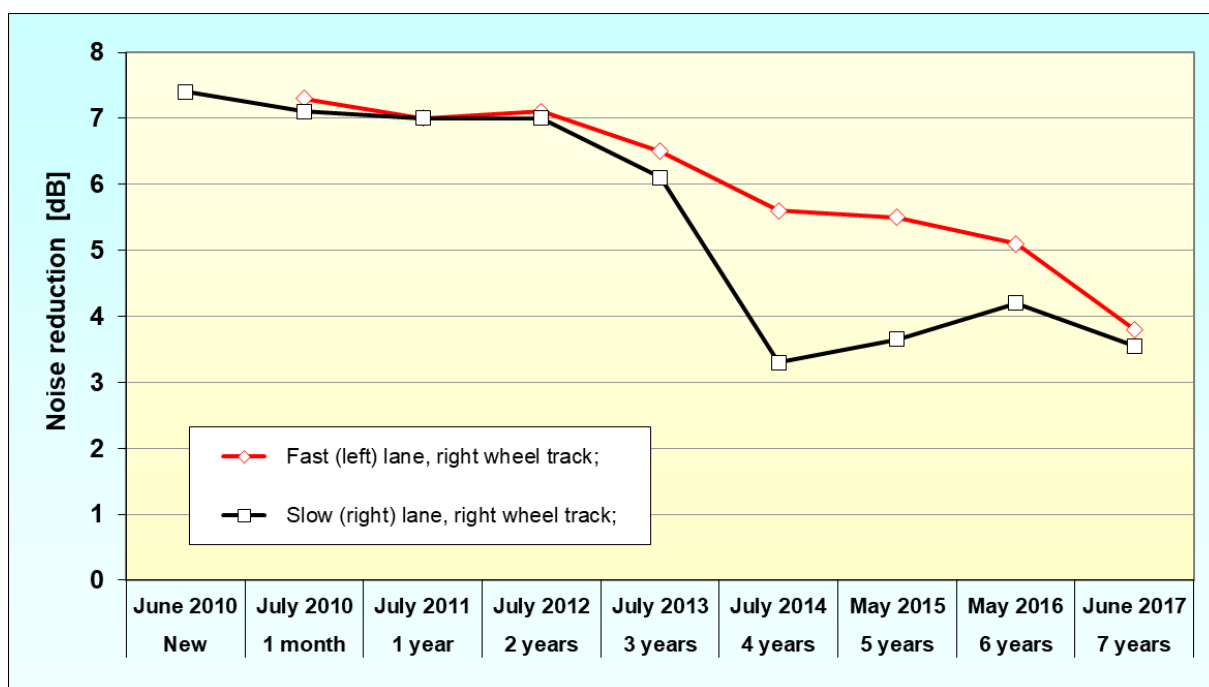


Figure 6: Difference in noise reduction between the two lanes, where the slow lane was sprayed with Fog Seal in the autumn of 2013 while the fast lane was not sprayed. Averages of the two tyres and two directions.

5. THE EFFECT OF THE BOTTOM LAYER

One part of the studied motorway had a single-layer porous asphalt (PA), the performance of which could be compared to the adjacent section in the same lanes where the same PA top layer had been laid on a porous bottom layer, thus creating a DPA. Both the slow and fast lanes in the northern direction were paved in this way. Comparable measurements were made at three occasions: July 2010 (age one month), June 2011 (age 12 months) and July 2011 (age 13 months). The difference between the last two measurements was that a trial to clean the surfaces were made between them, which turned out to be inefficient. Here are some data about the two pavements:

- DPA 11/16 with max aggregate size 11 mm in the top layer, and max 16 mm aggregate in the bottom layer; top layer 30 mm thick, bottom layer 50 mm thick.
- PA 11 which is exactly the same composition as the top layer in the double-layer pavement, except that it is approximately 35 mm thick. All layers had 25 % air voids target.

The measured noise levels showed noise reductions compared to the reference pavement (SMA 16) as presented in Table 1. Figure 7 shows the frequency spectra measured on the single-layer and double-layer at an age of one month compared to the ref. SMA 16 pavements which were 1-5 years old.

Table 1: Results of tyre/road noise measurements with the CPX method at 90 km/h, for tyres P1 and H1, expressed as noise reductions in A-weighted dB, at three occasions.

Type of pavement	Thickness [mm]	July 2010		June 2011		July 2011	
		P1	H1	P1	H1	P1	H1
PA single-layer	35	2.3	1.1	2.8	2.2	2.5	2.3
DPA double-layer	30+50 = 80	7.6	7.3	7.8	7.5	7.8	7.6
DPA - PA	45	5.3	6.2	5.0	5.3	5.3	5.3

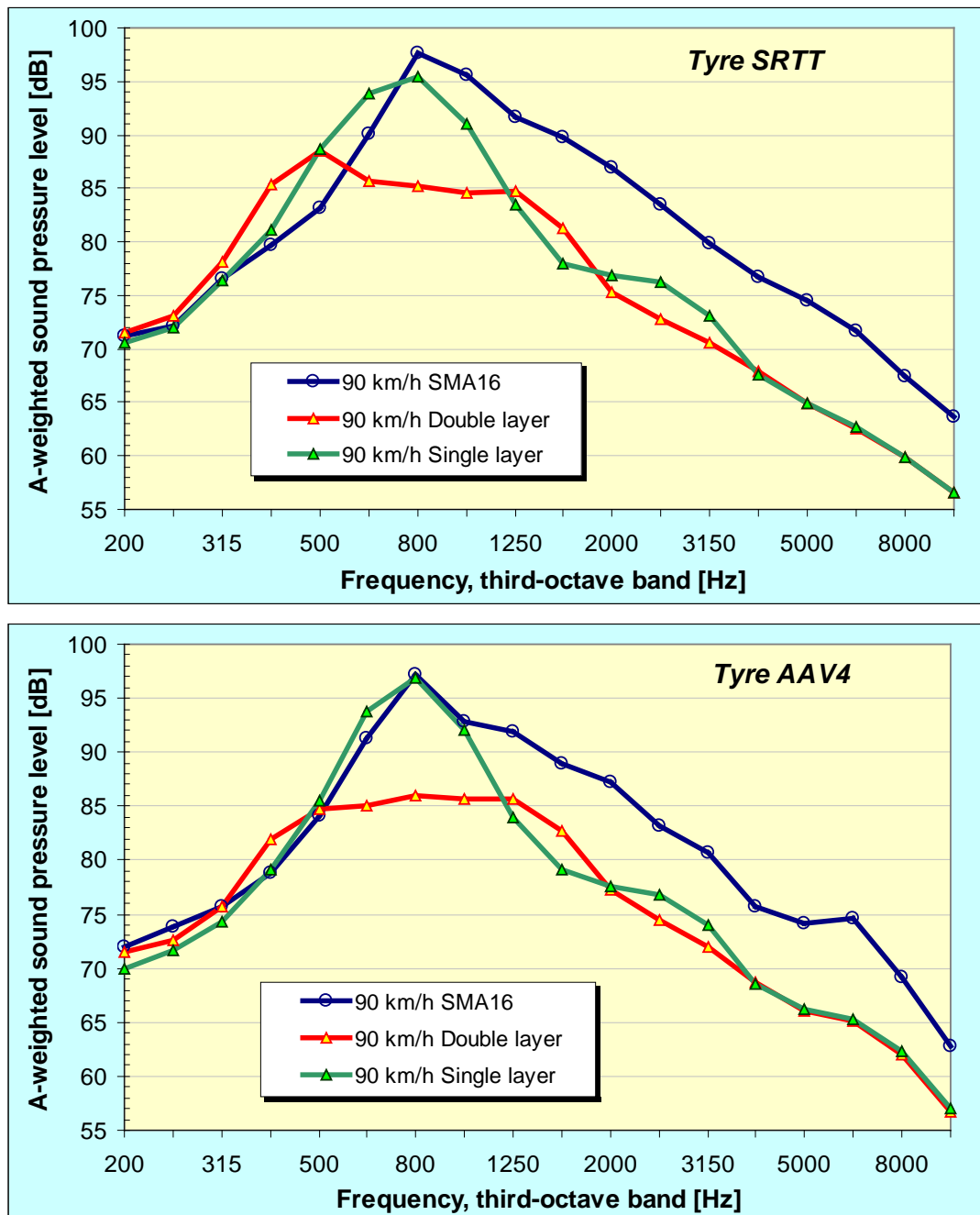


Figure 7: Third-octave band frequency spectra for tyres P1 (SRTT) above and H1 (AAV4) below, measured at 90 km/h. Averages for the slow and fast lanes.

It appears that the single layer pavement has its major noise reduction at 1250-1600 Hz while the double-layer has its major effect at 630-1000 Hz. Measurement speed was 90 km/h. Measurements were made also at 70 km/h and a few tests also at 50 km/h, but as the results correlate very closely with those at 90 km/h they are not reported here. Measurements were not made in following years as the PA pavement changed its condition after 2011 more than the DPA which made comparisons irrelevant.

The only physical difference between the single- and double-layer porous pavements would be that in the double-layer pavement there is an extra bottom layer. The top 30 mm in the double-layer is designed and composed "exactly" like the 35 mm thick single-layer pavement. Texture measurements confirmed that there is no texture difference between the single- and double-layer porous asphalt pavements. Air voids measurements on bore cores indicated that air voids was 25 % in both pavements according to the paving contractor.

The frequency spectra results suggest that the main reason for the noise reduction in both cases is sound absorption. For the single-layer (approx. 35 mm thick) the most effectively reduced frequency bands are 1250-1600 Hz, which are twice as high as that of the 80 mm thick double-layer (630-800 Hz); i.e., the sound absorbing frequency peak is approximately proportional to total layer thickness. This has been observed before; see e.g. [1]. Unfortunately, it was not possible to make sound absorption measurements, as it would require a complete closing of the road, alternatively using bore cores suitable for sound absorption measurements by the tube method, which were not available to the author.

It is rather amazing that it appeared that 2/3 of the noise reduction is due to the bottom layer of the DPA, which happens 30 mm or more below the surface. However, it is because the single-layer is so thin that its main sound absorption range is above the frequency range where most of the (A-weighted) energy of the tyre/road noise is located for a non-absorbing pavement, such as the SMA 16 in Figure 7, whereas the double-layer sound absorption range fits the range of maximum noise energy almost perfectly. For more information about this chapter, refer to another paper which is focused on the effect of the bottom layer [2].

When the top layers will get clogged and sound absorption is diminishing, the remarkable effect of the bottom layer will gradually decrease. However, before the top layer is clogged, the voids in the bottom layer will act as an extra volume where dirt can accumulate instead of sticking in the top layer. Thus, the bottom layer will delay the dirt accumulation in the top layer and in this way retain noise reduction considerably longer. Note that with 25 % air voids, the DPA contains about 2.3 times as much voids volume than the PA.

6. REUSING THE BOTTOM LAYER

There is one more interesting issue related to the bottom layer of the DPA. The DPA's bottom layer contains approx. 63 % of the material. If it can be reused in a second lifecycle, it would mean substantial savings in money and in aggregate and bitumen consumption. But the requirement is that it can have much or most of its accessible porosity remaining after milling off the top layer. It is also necessary that the top layer can stick on the bottom layer without using so much adhesive that it clogs the pores, or that binder from the top layer flows down into the pores. In the paving project in 2017, it was decided to try using the bottom layer on most of the low-noise section, hoping that noise reduction would not be too compromised. Fortunately, the contractor left a part of the section, on which both the bottom and top layers were renewed, to make it possible to study the difference. This was a very risky part of the project, never (?) before tried on a DPA.

Consequently, on the main part of the new pavement laid in 2017, only the top layer of the old DPA section was milled-off and then repaved with a new top layer, while the bottom layer from 2010 was reused. On another (shorter) part, the entire DPA was repaved. This was made in both directions and on both lanes.

The question is how effective this pavement will be when the bottom layer already is partly clogged in its first 7 years of service. A question is also whether the adhesion between the old and new layer could be durable enough without creating a partly dense joint between the new top and the old bottom.

When this is written, the new pavement has been in service more than two thirds of its expected lifetime, namely 5 out of the 6-7 years, as assumed from the first lifecycle. Consequently, it is possible to preliminary evaluate how well the new paving principle has worked out. The following summarizes the results.

The results in terms of overall A-weighted (CPX) noise levels are shown in Figure 8 as noise reduction compared to the reference SMA 16 pavement type (which is at 0 dB). The results shown are averages at 80 km/h for both tyres as well as for both the southern and northern direction of lanes and for both the slow and fast lanes.

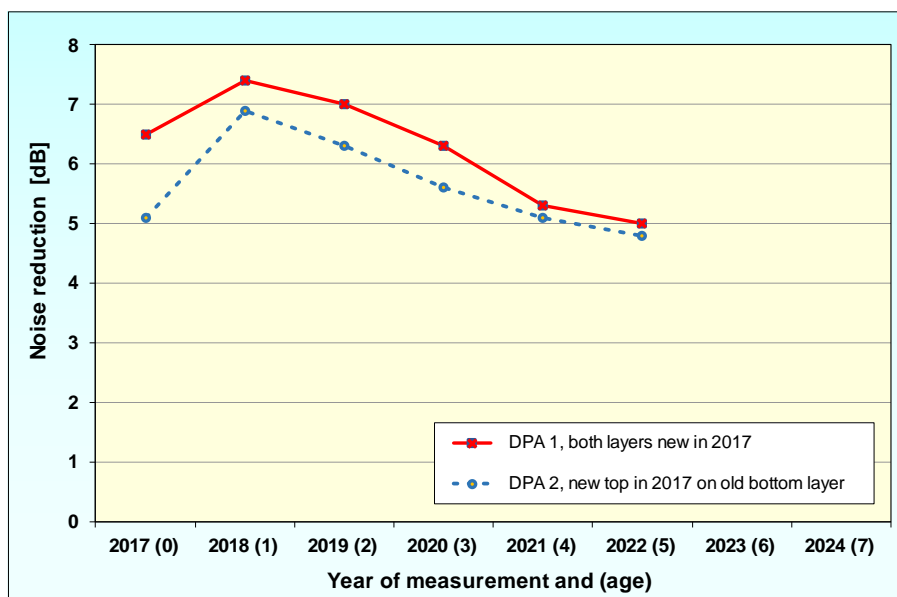


Figure 8: Noise reduction at 80 km/h versus measurement year and age, compared to similar measurements on a mix of Swedish SMA 16 pavements. See further the footnote below*.

In 2022, the results indicated that the noise reduction which is lost by reusing the old bottom layer is only around 0.2 dB (of the current 5 dB). Figures 9 and 10 show the frequency spectra of the two pavements, where DPA 1 is the fully repaved one and DPA 2 is the one where the bottom layer from 2010 was reused. Figure 9 shows the situation in 2018 when the pavements were one year old. Then, frequency bands 630-1000 are very much reduced, which indicate that sound absorption is effective, and this is the case for both DPA 1 and DPA 2, but marginally more for DPA 1. It means that the bottom layer from 2010 is still reasonably open. Figure 10 shows the situation in 2022 when the pavements were 5 years old. Then most of the difference to Figure 9 is at frequencies 630-1000 Hz, which suggests that the sound absorption has been reduced by pores having become clogged. Both in 2018 and 2022, frequencies 1250-1600 Hz for DPA 2 have somewhat lower levels than DPA 1 which suggest that DPA 2 has sound absorption more resembling that of a single-layer.

The author offers the following conclusions: (1) Reusing the bottom layer in a second lifecycle worked well; only about ½ dB of lifecycle noise reduction is lost, (2) The reused bottom layer saves a lot of paving money and resources, at the cost of only a minor loss of noise reduction.

Much more information is found in a special paper about this effect, although including data until only 2021 [3].

* The measurements in 2017 have been found to be influenced by water remaining under the surface, probably in the bottom layer, from rain 24+ hours earlier. The CPX standard allows measurements 24+ hours after rain but in this case the weather, although not rainy, was rather chilly, cloudy, and windless. Under such unfortunate conditions, 24 hours is not enough to dry up a thick pavement like this 80 mm thick DPA. It is estimated that both noise reductions in 2017 (at 0 age) are 1.0 – 1.5 dB too low due to this.

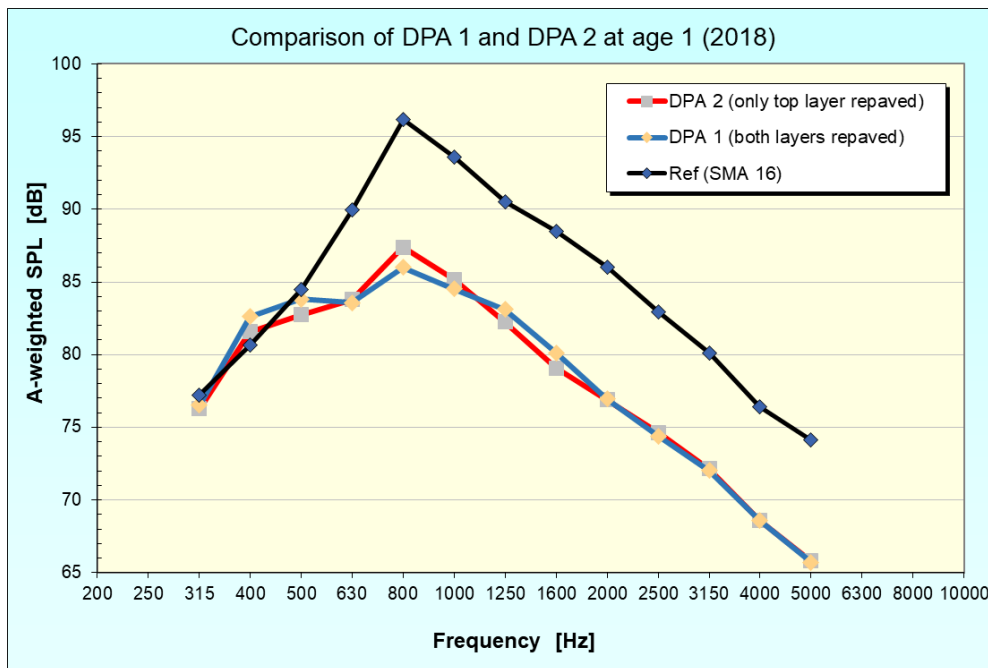


Figure 9: Frequency spectra measured on DPA 1 and DPA 2 at an age of one year, with the mix of SMA 16 pavements as reference. Average for the two tyres, the two lanes and the two directions.

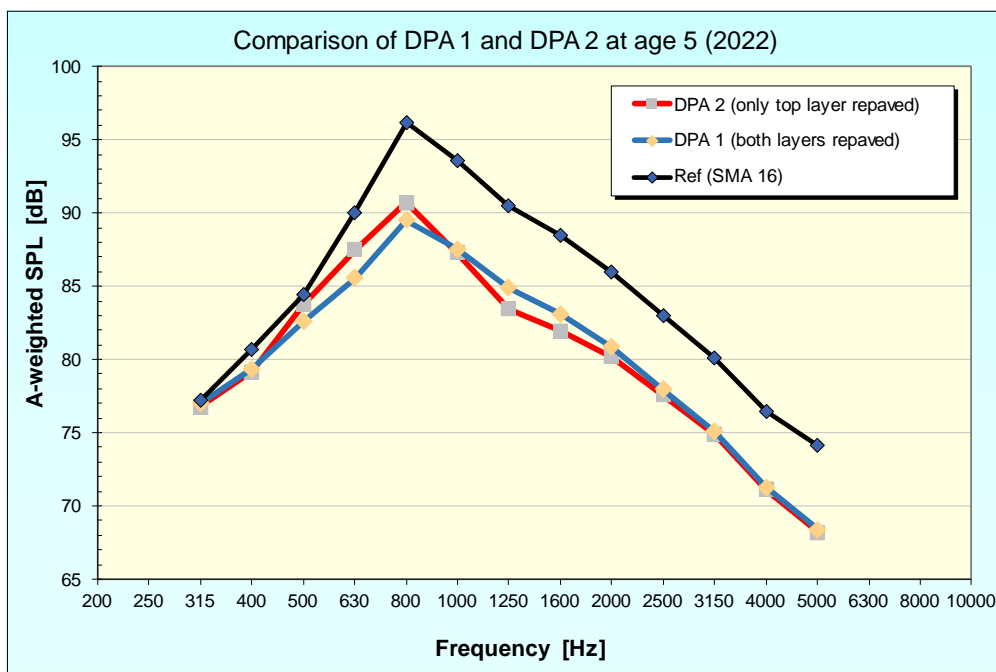


Figure 10: Frequency spectra measured on DPA 1 and DPA 2 at an age of five years, with the mix of SMA 16 pavements as reference. Average for the two tyres, the two lanes and the two directions.

7. STEEL SLAG USED INSTEAD OF STONE AGGREGATE

When the low-noise pavement section through the city of Huskvarna was repaved in 2017, an opportunity appeared to make a trial suggested by the author by replacing the natural aggregate in the top layer with steel slag. Consequently, a little less than 200 m of the southern end of the low-noise section, in the slow lane only, was built with a new conventional bottom layer and a new top layer where all aggregate above 4 mm was EAF

(Electric Arc Furnace) steel slag. To compare with, the part of the DPA which was completely repaved at the same time (called DPA 1 in the previous chapter), was used. The two pavements are identical except for the steel slag and modified mix proportions due to this in the top layer. Figure 11 shows a comparison of the two surfaces after 4 years of service.



Figure 11: Surface of the double-layer asphalt pavement with conventional stone aggregate (top half), and steel slag (bottom half), at an age of four years. The coin's diameter is 24 mm.

The results after five years of service are shown in Figure 12, as noise reduction in A-weighted CPX levels in dB. Noise reduction is calculated as the difference to the average level of a number of SMA 16 pavements.

There are two reference curves (in red). The solid unbroken curve is for measurements of the conventional DPA in both directions, while the broken curve is when only the data for the southern direction is used; the direction where the steel slag is laid. Normally, one would use as much data as is available; however, in this case it may be that the northern direction is more exposed to dirt

blowing from the southern lanes due to prevailing winds and therefore is getting clogged a bit earlier than the southern lanes.

Also other measurements are available on these two pavements, namely rolling resistance, skid resistance, permeability and geometrical characteristics such as macrotexture (MPD), unevenness (IRI), rut depth and estimations of ravelling. These results as well as a lot more information (also of other trials with steel slag) are available in a full report of this project [4]. Among the results it can be mentioned that macrotexture is reduced with time, much faster and much more on the steel slag surface than on the conventional DPA. This does not cause a significant change in the noise reduction, but it is very positive to rolling resistance, and thus for energy consumption of traffic and its CO₂ emissions. Until 2021 (last measurement), ravelling was not worse on the steel slag than on the conventional DPA, but rutting occurs at a rate of 2 mm/year for the slag surface compared to 1.6 mm/year for the DPA. However, these rates are normal for Swedish highways using SMA pavements and considering the traffic by very heavy trucks and studded tyres on cars in wintertime.

Overall, the performance of the steel slag aggregate is very promising with at least as good performance in noise reduction as the conventional DPA, and with better performance in terms of rolling resistance. At the moment, durability also seems to be comparable. Given that the steel slag and the mix using it probably can be better optimized, the use of steel slag in trials like this one is recommended at a larger scale.

Steel slag is a waste material too little utilized, causing huge stockpiles with risks of leaching harmful substances in countries with substantial steel production. Furthermore, in some

countries high quality natural aggregates will soon become rare and may require transportation from quarries far away. Steel slag is heavier to transport but the undesired effects of this may soon be balanced out by traffic on slag pavements needing less driving energy [4].

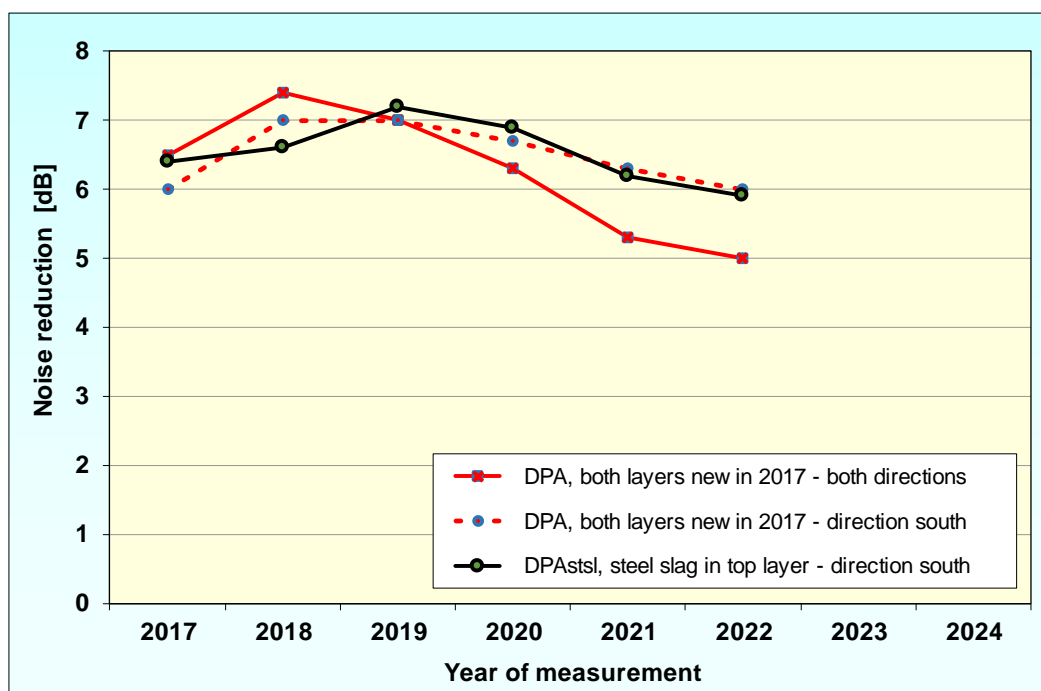


Figure 12: Measured noise reduction over time, starting with paving (in 2017) and ending with the situation the previous autumn (2022). For the red unbroken curve, all available data are used; i.e., both directions for the conventional DPA. The broken red curve uses data for the southern direction only. Regarding values measured in 2017, see footnote in Chapter 6.

8. GRINDING THE SURFACE TO PRODUCE AN “EXTRA NEGATIVE TEXTURE”

Grinding of cement concrete pavements to reduce unevenness and noise is common since a long time, in particular in the USA. Grinding is then made with wheels equipped with diamond blades rotating in the vertical plane. This creates narrow vertical/longitudinal grooves in the pavement and is favourable to both noise reduction and skid resistance. It is not applied to asphalt pavements.

In this chapter an alternative type of grinding is studied. In this case plates with diamond heads rotate in the same plane as the pavement, thus shaving off peaks in the pavement texture. The result is a pavement with a "negative texture". This type of (horizontal) grinding has been applied in Sweden in various ways to stone mastic asphalt pavements as well as to porous asphalt pavements. The first major experiment was made in 2011 on a small part of the low-noise DPA pavement [5], later supplemented with grinding of SMA pavements [6]. The experiment in 2011 was allowed by the road contractor to cover only a 65 m long and 0.9 m wide strip in the right wheel track of the slow lane on the DPA pavement; see Figure 13. This was ground by a grinding machine shown in Figure 14. In later years, full-scale experiments were made on several roads with the same technology but bigger machines, able to grind almost a full lane simultaneously. Most of these later experiments were conducted on SMA 16 pavements. See a full report in [6].

In Figure 15 there is a comparison of how the surface texture looks from a low angle, before and after the grinding.



Figure 13: Ground strip of approximately 65 m x 0.9 m (bright part of the lane) as it appeared before it was vacuum cleaned.



Figure 14: Grinding machine from HTC Sweden AB used in the 2011 experiment. The large disc as well as the four smaller discs rotate during the grinding. Behind the lifted part is a bag where most of the ground-off material is collected (not visible in this picture).

same runs on the ground strip as well as a stretch of the conventional non-ground DPA immediately following the ground strip.

The change in frequency spectra shown in Figure 16 is summarized as overall difference in A-weighted CPX levels in Table 2, where also the results of difference in rolling resistance (RR) are included. For the RR measurement method and further information, please refer to [5,6]. Finally, it shall be mentioned that also skid resistance is improved by the grinding, since the grinding discs have rough surfaces which creates microtexture on the aggregates which is rougher than the original non-ground microtexture [6].

It must be admitted that the positive effects diminish rather quickly. Measurements in later years suggested that the advantages are approximately halved each year. This is because the edges of the flattened surfaces are worn down by the studded tyres.



Figure 15: Non-ground surface (left picture) and ground surface (right picture). The coin has a diameter of 25 mm. The photos are shot at similar but not exactly identical locations.

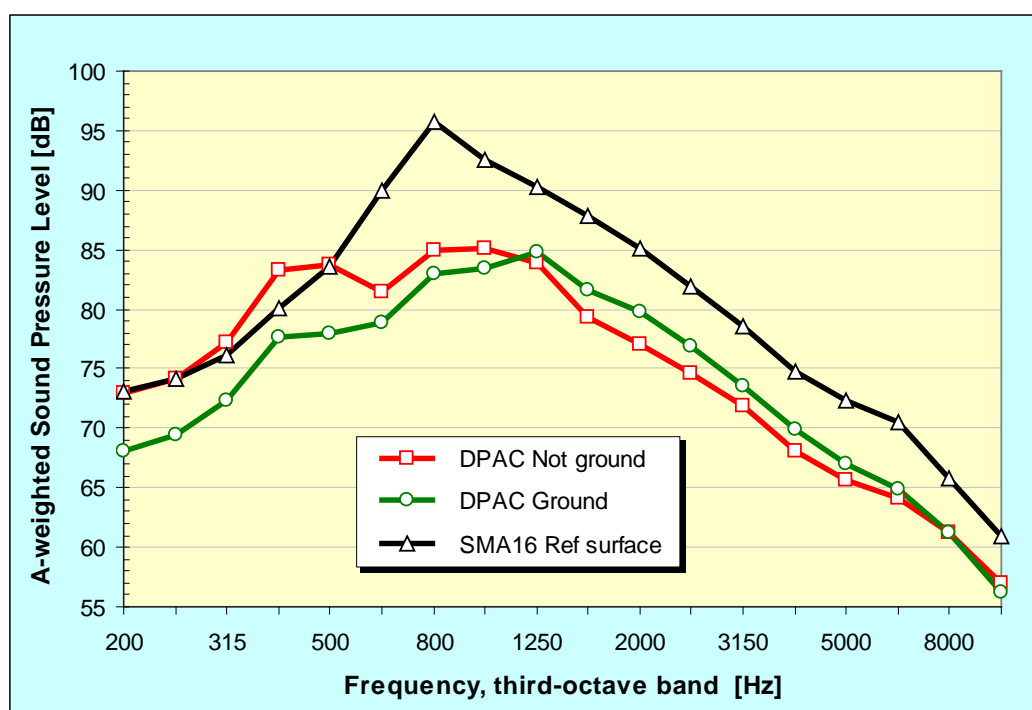


Figure 16: Comparison of A-weighted third-octave band frequency spectra for the ground and non-ground surfaces (DPA), also compared to the reference SMA 16 pavements. Average for the two tyres and for 70 and 90 km/h speeds.

Table 2: Summary of the performance of the grinding on noise reduction and rolling resistance coefficient. Values processed/summarized from [5,6].

Pavement/surface	A-weighted CPX noise level [dB]		Rolling resistance coeff. [%]	
	Tyre P1	Tyre H1	Tyre P1	Tyre H1
Ref. surface (SMA 16)	98.2	97.0	N/A	N/A
Non-ground DPA	91.6	90.2	1.03	1.57
Ground DPA	89.2	89.7	0.90	1.47
Red. vs non-ground	2.4 dB	0.5 dB	13 %	7 %
Reduction vs SMA 16	9.0	7.3	N/A	N/A

To have a durable effect, grinding about each second year would be needed for Swedish conditions. In countries which do not allow studded tyres, the grinding would be much more durable. This was proved in an Australian experiment [7], which implemented our idea based on ref. [5]. The horizontal grinding technique can be a tool to extend the acoustic lifetime by one or more years, which has significant economic values, given how expensive DPA pavements are and it also saves natural resources by extending the lifecycle. When the project was started in 2011 the grinding company HTC was very positive to the idea, but with a new owner later it was decided to discontinue with this application of their machines.

9. END-OF-LIFE NOISE REDUCTION

One would expect that when the pores in an PA or DPA have become clogged, while travelling is not yet substantial, the noise property of the pavement would approach that of an SMA with similar max. aggregate size. But experimental studies suggest that even when PA:s are effectively clogged, they retain a certain noise reduction compared to SMA:s.

Based on Table 1, which compares DPA #1 with an SMA with similar max. aggregate size (11 mm), it is concluded that the DPA #1 reaches an end reduction of around 3.5 dB for the untreated lane and 2.5 dB for the lane treated with a sealing. The former would not be fully clogged but the latter would be mostly clogged. The last row in the table represents the very first part of the section, which has additional and full clogging, as it is adjacent to a dense pavement from which extra dirt is pulled in. This part seems to have a remaining noise reduction of 2 dB (values rounded to half decibels). The subject is presented in detail in [8]. The main reason for this is that in a PA, the larger stones are closer together than in an SMA with more continuous grading. A tyre tread rolling on these larger stones will not penetrate so deep into space between the stones. Then, tyre tread will be less deformed by the texture.

Table 3: Noise reduction in A-weighted dB by year of DPA #1 compared to a reference of SMA 11 (average of several Swedish SMA 11 of various age). Average for tyres P1 and H1, at 80 km/h, in the right wheel track of the slow lane.

Pavement, lane, and eventual treatment	2010	2013	2014	2016	2017
SMA 11 Ref pavement (Swedish average)	Ref	Ref	Ref	Ref	Ref
Untreated area (fast lane) of DPA	7,1	5,4	5,1	4,3	3,5
Treated area (slow lane), sealed from 2014	6,7	5,0	2,5	3,3	2,6
Most clogged area (adjacent to dense asphalt)	(6,7)	(4,8)	(2,0)	1,8	1,9

10. SOME EXPLANATORY NOTES

In this paper, the Swedish pavement SMA 16 has been used as a reference for noise reduction calculations. When measuring CPX levels of 4-9 such pavements annually and averaging the results, a stable reference is obtained. However, in other European countries, SMA 11 pavements are much more common, and in east Asia SMA 13 is more common. When comparing noise reductions in this paper with measurement results obtained with SMA 13 as a reference, noise reductions reported here would be about 0.8 dB lower, and if SMA 11 would be the reference, noise reductions would be about 1.3 dB lower [9].

In the studied road section, also a test of the effect of increasing binder content by 0.5 %, and attempts of cleaning the porosity have been made, but space is insufficient for reporting these results in this paper.

11. CONCLUSIONS

The low-noise section of the E4 motorway through the city of Huskvarna has so far, over a time period of 12 years, provided an interesting scientific “playground” where the performance of several technologies have been possible to explore. This paper has collected and updated the results of the various studies conducted by VTI. The conclusions are:

- It is not necessary to lay DPA pavements with pavers laying two layers simultaneously.
- Rejuvenating (seal) a PA when it already is partly clogged will ruin its noise reduction.
- Approx. 2/3 of the noise reduction of the DPA in new condition is due to the bottom layer.
- By reusing the old bottom layer of a DPA one time, the noise reduction loss is only around 1 dB (of the initial 7-8 dB), or 0.5 dB as an average over the lifecycle.
- Using steel slag as the aggregate in the top layer may improve, or at least not compromise noise reduction, and may reduce rolling resistance due to lower macrotexture.
- Grinding of the peaks of the top layer texture will reduce both noise and rolling resistance.
- A fully clogged DPA will still provide some noise reduction vs SMA, if ravelling is low.

It is hoped that this will provide inspiration for implementing the results on road pavements in a wider sense but also for continuing research on optimizing low-noise porous asphalt pavements further.

12. ACKNOWLEDGEMENTS

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