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Noise-reducing double-layer porous pavement with steel slag aggregate in the top layer

Ulf Sandberg[1]
Swedish National Road and Transport Research Institute (VTI)
581 95 Linköping
Sweden

ABSTRACT

This paper presents results of a trial replacing the natural aggregate in the top layer of a double-layer porous asphalt pavement with steel slag. An almost 200 m long motorway section was paved with this material, on the same road and lane as a comparable conventional pavement. Performance in terms of macrotexture and noise properties are monitored for an entire life-cycle of 7 years.

The results in terms of noise reduction compared to the common Swedish reference pavement (SMA 16) indicated an initial noise reduction of about 7 dB; similar to the same pavement with natural aggregate. After 5-7 years of service its noise reduction is similar to or marginally better than the conventional double-layer asphalt pavement. This is surprising since the steel slag pavement appears to clog a little faster than the conventional. Probably, there are (unknown) properties in the slag material which balances out the clogging effect.

At present this pavement has reached an age of 7 years with still satisfactory overall performance, which is comparable to conventional double-layer porous pavements serving the same road. Consequently, recycling steel slag in such paving applications is a win-win situation.

1. INTRODUCTION

In Sweden, due to wear of studded tyres, only hard aggregates with low abrasion can be used in the surface course of road pavements. An alternative to stones or crushed rock with high abrasion resistance which has the potential to be durable enough is steel slag. Field tests with steel slag aggregates in dense asphalt pavements have been made in some Swedish locations and showed results enough promising to justify more studies. When the E4 motorway through Jönköping-Huskvarna needed repaving in 2017 with a new generation of double-layer porous asphalt, an opportunity to make a trial by replacing the natural aggregate in the top layer with steel slag appeared. How this pavement has performed compared to more common pavements over its lifetime is presented in this paper.

2. OBJECTIVES OF THIS PAPER

This paper reports the performance of a double-layer porous pavement in which the top asphalt layer has steel slag aggregate instead of natural stones. The performance is reported essentially in terms of

[1] ulf.sandberg@vti.se

noise emission compared to reference pavements produced as standard SMA 16, as well as a regular double-layer porous pavement of same age and same location.

3. TEST OBJECT AND ITS REFERENCES

3.1. Location and test object data

The test objects are located on motorway E4 through the city of Huskvarna (just north of Jönköping), with lake Vättern on the western side and a popular residential area on the eastern side, built on a slope with most of the private houses having a beautiful lake view. The motorway has two lanes per direction, where the right lane is designated K1, and the left lane designated K2. The considered motorway section, approx. 3 km long, is paved with noise-reducing double-layer porous pavements. Some general facts of the test section are listed below:

- Motorway, two lanes per direction. Posted speed limit: 90 km/h
- AADT: 26000 vehicles (17 % heavy vehicles). Distribution between lanes: 70 % in K1 and 30 % in K2, the main part of the heavy traffic in K1. It follows that in the lane considered here (K1), the AADT was 18000 with 25 % heavies
- Layer thickness, nominal: top layer 30 mm, bottom layer 50 mm
- Aggregates in the upper layer: in K1, porfyr (kkv < 5), max. size 11 mm. The kkv value indicates that the aggregate is among the best one can find in Europe
- Aggregates in the bottom layer: diabase in all lanes (also in DPAstsl), max. size 16 mm
- The air voids content was initially targeted at 25 % which compared well with samples drilled from the road. However, the pavement samples containing steel slag had just above 20 % voids
- Binder in the conventional DPA: highly modified polymer bitumen Endura D1 from Nynäs, 6.0 % (by weight) in the DPA and 4.5 % (by weight) in the DPAstsl
- Steel slag product: EAF slag named "Smedjebacken" obtained from NCC (used only in the fraction of 4-11 mm), Nordic Ball value kkv < 7. This is a very good value, accepted by the Transport Administration for use on highways
- Two adhesives were used in the mix, cement and amine (Wetfix)
- The cross fall of all test sections was increased to 3 %, so that water would easier drain out sideways from the pavement. Normally it is 2.5 %
- The two layers are not laid hot-on-hot but are laid on two consecutive days.
- Except the steel slag variant, the pavements are laid in both directions, with two lanes in each.
- The contractor for this test road is Svevia AB.

In this study, three pavements are compared:

- DPA: The regular double-layer asphalt pavement on E4 in Huskvarna, which was paved (in both layers) in 2017. It is laid in both directions and, in both lanes, K1 and K2. Length approx. 600 m.
- DPAstsl: This is the same as the DPA, except that the top layer uses steel slag aggregate instead of stones and modified mix proportions due to this in the top layer. It is laid only in lane K1 in the northern direction, at the same time as the DPA. This section runs between appr. 41660 and 41840 m in the road distance system; i.e. 180 m in length.
- SMA 16 ref: This is the average of a mix of several SMA 16 pavements measured in several years and conditions and is used as a Swedish national reference for noise measurements. They

typically differ by less than ±1 dB from the average. This average seems to have been more or similar stable in time than the reference tyres.

Also, a fourth double-layer porous variant is used on this motorway section, namely a variant where the bottom layer is re-used from the previous generation (in service 2010-2017) and the top layer is new (laid in 2017). In 2017, the old top layer was milled off while the bottom layer was kept and constituted the bottom layer for a second generation (2017-2024). But this variant is less relevant to compare with the steel slag variant. It means that if nothing else is stated only lane K1 is considered, since steel slag is not in K2, and the K1 and K2 lanes carry different traffic.

3.2. Steel slag

Figure 1 shows a part of the steel slag pavement on motorway E4, while Figure 2 shows a close-up picture of the surface of the steel slag compared to the conventional aggregate. Both pictures were shot at in inspection made in 2021, at an age of 4 years.

The performance of the steel slag pavement DPAstsl is compared primarily with the variant named DPA above, since both have the same new bottom layer with natural stone aggregate and differ only in the top layers' aggregate. Comparison is also made with dense reference pavements SMA16.

Figure 1: The conventional pavement (in lane K2 - left) and the steel slag pavement (in lane K1 - right). Photo shot after four years of traffic exposure. Note the dark colour of the steel slag. Dark traces are shadows from the streetlights.

3.3. Reference pavements

In this project, the reference noise level has been an average of noise levels measured on four to six different SMA 16 surfaces of an age between 2 and 8 years. The number varies year-to-year depending on how many SMA 16 that are tested by us the particular year. In this way, some of the natural variation within this pavement type and condition is averaged out. It was originally considered by the authors that using this "average SMA 16" as a reference, rather than a selected noise level measured by the CPX method, is more stable, but recent development in ISO have changed this assumption. The variation between reference tyres and their stability following wear and ageing have been significant sources of uncertainty; something which is now changing as a result of development in

ISO. Nevertheless, in this paper, the “average SMA 16” as the annual reference is used. An example of how the surface of an SMA 16 surface appears is shown in Figure 3.

If one wants to translate the noise reductions to a reference surface corresponding to SMA 11 and dense asphalt concrete DAC 11 (which is the virtual reference surface in recent European prediction models) one should reduce the noise reductions reported here by approx. 1.3 dB.

Figure 2: 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.

Figure 3: Typical appearance at one year of age of the surface of (both) porous pavements subject of this study (on the left) and a reference pavement (on the right). The coin’s diameter is 25 mm.

3.4. Project duration

Both DPA pavements were paved in the summer of 2017 (August). The expected lifetime was originally 7 years. However, the DPA in lane K1 was repaved already in May 2023 (after 6 years), despite this author thought that its condition and the required noise reduction would have justified one more year. The steel slag pavement is in service still in the summer of 2024 (after 7 years). As the Transport Administration has no plans to repave it in 2024 it will probably live for at least 8 years.

The repaving of the DPA in May 2023, which happened before VTI had a chance to make noise measurements, means that it is difficult to make fair comparisons between the two DPA pavements longer than for 5 years. More about this later.

4. MEASUREMENT METHOD

All acoustic measurements have been made with the CPX method ISO 11819-2 [1], supported by the reference tyres specified in ISO/TS 11819-3 [2] and with temperature corrections to noise levels as specified in ISO/TS 13471-1 [3]. A CPX trailer and crew from the Gdansk University of Technology (GUT) have been used; see Figure 4.

Measurement results presented here have been processed at the reference speed of 80 km/h. Measurements reported here are only for the tyres running in the right wheel tracks.

Measurements have been made also in other lanes and wheel tracks and also at 50 km/h but are not reported in this paper. Most actual traffic runs at speeds 80-90 km/h.

Apart from acoustic measurements, geometrical measurements have been made by the VTI Laser RST vehicle, yielding results in terms of macrotexture (MPD according to ISO 13473-1), mega-texture, unevenness and ravelling. Also, wet friction and rolling resistance have been measured at some occasions and, at the age of four years, permeability tests with the water outflow method were made; see later in this paper. Only the most relevant measurement results are reported in this paper.

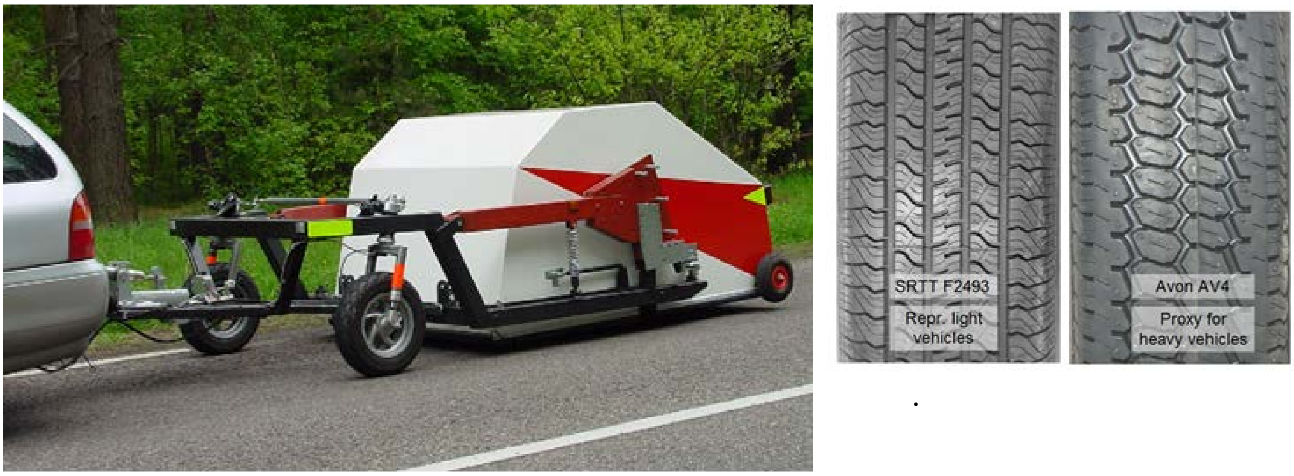

Figure 4: The CPX trailer from GUT. A reference tyre, with its two microphones, is mounted in the middle of the enclosure. The tread pattern of two reference tyres (P1 and H1 according to ISO/TS 11819-3) that were used are shown at the right.

5. RESULTS OF NOISE MEASUREMENTS

In principle, the steel slag pavement (DPAstsl) and the conventional pavement DPA are the same except for the aggregate in the top layer of the double-layer pavement and the changes in binder needed because of the aggregates. They were laid the same day (or maybe one or two days apart) and are exposed to approx. the same traffic with approx. the same speeds. Comparisons should display only the effect of the top layers of the two pavements.

Results of the measurements of noise emission in years 2017-2023 are presented in Figure 5 as noise reduction in A-weighted CPX levels in dB. The data is for the speed of 80 km/h, and is averaged for the two reference tyres P1 and H1, since the two tyres generally show the same trends on porous pavements. The black curve is for the steel slag (DPAstsl) and the red curves are for the DPA with conventional aggregate. The solid red curve is based on all available data in lane K1 (average of the southern and northern directions) while the broken red curve (– — —) is based only on the DPA in the southern direction (K1 lane). Originally, the plan was to use all data available for the reference in the K1 lane, but at the end of the time period it appeared that the two directions differed more and more in noise reduction, so this is why the broken red line is introduced, which is for the only direction in which the steel slag was laid.

The Transport Administration very surprisingly repaved lane K1 in early 2023, but saved the steel slag, which means that the main reference curves finish in year 2022. Instead, the author decided to add another reference pavement, namely the DPA in lane K2 in southern direction, which is the fast lane beside the slow lane where the steel slag is laid. This is shown in the figure as the broken red curve (- - -), continuing past 2022.

A plausible reason for the remarkable difference in the red curves may be transportation by dominating westerly winds of dirt from the west to the east, and/or by southerly winds from the adjacent dense pavements, in both cases potentially causing extra clogging. The steel slag was laid only in the southern direction and would not suffer from dirt transported by westerly winds but may suffer from dirt transported by southwesterly winds. Another possibility could be that the paving was performed slightly different in the two directions for an unknown and unintentional reason, but since the noise reduction in the first two years was the same in both directions, this seems less likely.

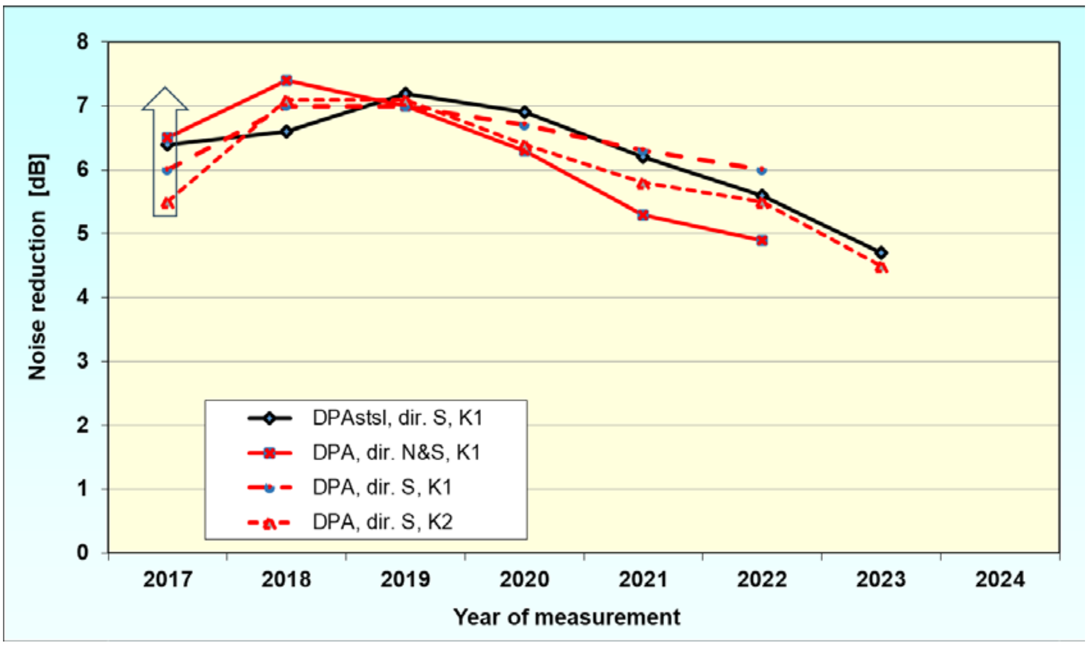

Figure 5: Measured noise reduction over time, starting with paving (in 2017) and continuing until 2023 (to be supplemented in 2024). For the red solid curve, all available data are used; i.e., both directions for the conventional DPA. The broken red curves use data for the southern direction only. Regarding values measured in 2017, see the text above.

The data show that the steel slag DPA in the last years perform better than the conventional DPA, when using all available data for the conventional DPA as the reference, but the two DPA versions perform essentially equally well when only the southern direction data are used. It is interesting to note that the DPAstsl in the slow lane performs equally well as the DPA in the fast lane, despite the traffic volume is much higher in the slow lane.

The results for the first year (2017) shall be used with caution, as it appears that the values measured in 2017 were influenced by some rainwater remaining in the bottom layer. It is estimated that this decreased the noise reduction in 2017 by 0.5 – 1.5 dB but it is not known to what extent this excess noise is different for the three pavements. This is indicated in the diagram as a block arrow pointing upwards for the 2017 data.

In Figs. 6 and 7, frequency spectra are shown for some of the cases in Fig. 5, but only for years 2018 (at an age of one year) and 2022 (at an age of five years). The spectra for the reference SMA pavements show the typical "peaky" shape with the peak at 800 Hz, which is common for pavements with 16 mm max aggregate size. The porous pavements all show the commonly observed levelling of the mid-frequencies; especially the 630 and 800 Hz bands where the sound absorption has maximum effect. At the higher frequencies, the effect of porosity is to eliminate the air pumping generation mechanism and the horn amplification effect.

At the age of five years, the air voids are partly clogged and sound absorption not so important any longer, which appears as the spectra become "peaky", almost like the dense SMA pavements. But there is still enough air ventilation in the texture and pores which still have access to the surface, to reduce air pumping and the horn effect; albeit not as well as at the age of one year.

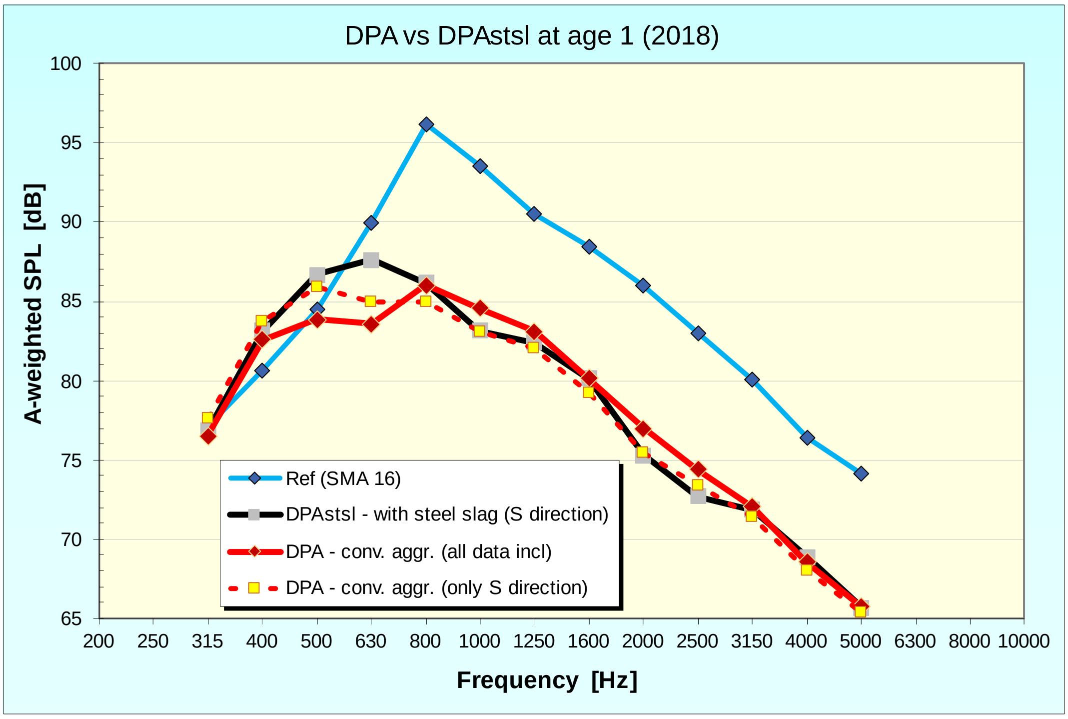

Figure 6: Third-octave frequency spectra for the steel slag pavement compared to the reference pavement (SMA 16) and DPA with conventional aggregate (with both directions or with only south direction included). Measurements in 2018 at an age of one year, at 80 km/h and average for the P1 and H1 reference tyres.

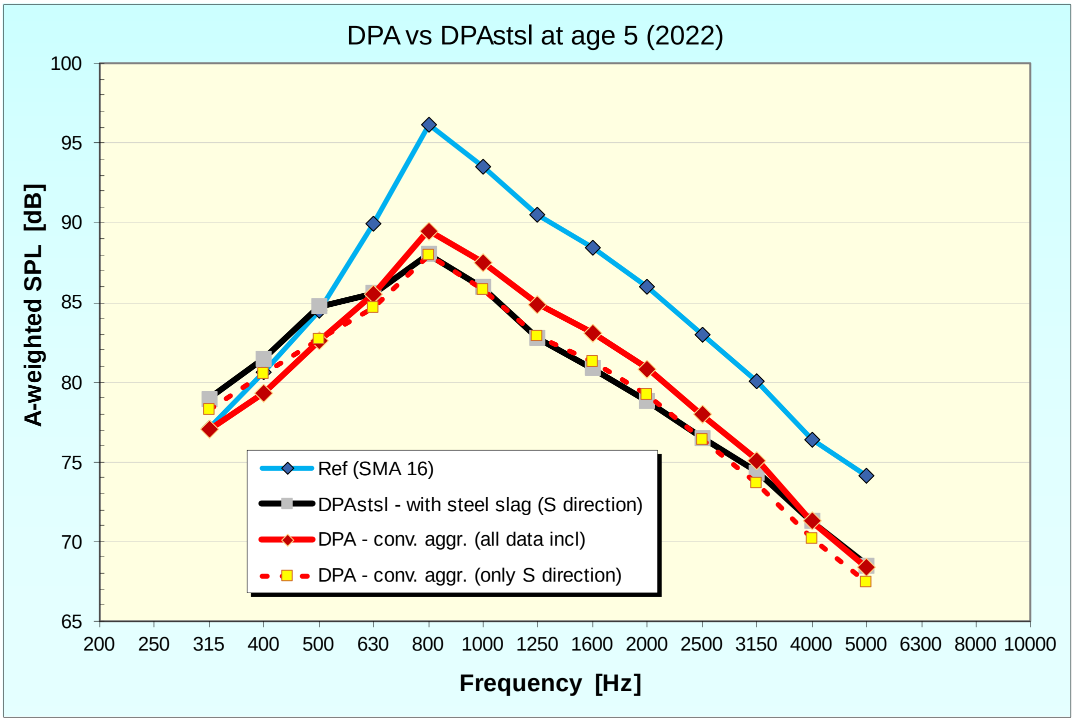

Figure 7: As the previous figure, but for measurements in 2022 at an age of five years.

6. RESULTS OF OTHER MEASUREMENTS

6.1. Rolling resistance

Measurements of rolling resistance were made only in 2018 as part of another project by a special trailer from GUT [5]. The test was made at a speed of 80 km/h. Temperature (here measured as ambient air temperature) has a great influence on rolling resistance, but as the two pavements were measured simultaneously, and measured temperatures are almost the same, the comparison between them is not affected by the temperature. Although the rolling resistance coefficients showed an advantage for the steel slag of around 2 %, this difference was not statistically significant.

6.2. Permeability

Permeability is a property describing how well (fast) water may pass through the porous layer(s). Porous pavements (in Sweden) generally lose permeability already during the first few years, due to clogging and (to a less extent) compaction. In this study, there was no opportunity to measure permeability until there was a general inspection one day in 2021 when traffic was blocked from one lane at a time, allowing work to be done with staff on the pavement.

The measurements of permeability showed that the steel slag surface is substantially less permeable than the conventional pavement, after four years of traffic exposure (86 seconds of outflow time for DPAstsl vs 47 for DPA, in southern direction in both cases) [5]. This is mostly due to clogging as also the visual appearance suggest. In Figure 2, which is from the same occasion, it appears that the potential pores open to the surface, as indicated by black spots, are fewer in the steel slag surface. The question is why there has been more clogging or “densification” on DPAstsl than on DPA and also why it does not show up significantly in the frequency spectra one year later (Fig. 7). At least partly, a reason may be that the initial air voids was less than 25 % for the steel slag.

6.3. Geometrical parameters (rut depth, texture and roughness)

Measurements of the geometrical parameters, rut depth, texture and roughness, were done annually, usually by the RST system of VTI. However, the measurements in 2017 were done before the new pavements were paved, so no data are available when the pavements were brand new (late August-September 2017). Also, the MPD values for 2022 are taken from PMSV4 database, since the RST calculations of MPD changed slightly between 2021 and 2022 [5]. Results are presented in Table 9-4.

Table 1: Rut depth, texture (MPD) and roughness (IRI), for the DPA versus the DPAstsl pavements, as measured in lane K1 in the southern direction.

Parameter	Pavement	2018	2019	2020	2021	2022	2023
Rut depth, in mm	DPA	2.1	4.9	5.0	5.8	7.83	N.A.
Rut depth, in mm	DPAstsl	2.7	6.5	6.2	7.6	10.8	12.2
MPD in the wheel tracks, in mm	DPA	1.69	1.63	1.61	1.63	1.80	N.A.
MPD in the wheel tracks, in mm	DPAstsl	1.52	1.27	1.18	1.16	1.42	1.77
MPD between the wheel tracks, in mm	DPA	1.70	1.86	1.77	1.68	1.95	N.A.
MPD between the wheel tracks, in mm	DPAstsl	1.94	1.86	1.71	1.69	1.76	1,70
IRI (international roughness index)	DPA	0.99	0.85	0.91	0.95	1.16	N.A.
IRI (international roughness index)	DPAstsl	0.73	0.75	0.83	0.83	0.94	1.0

It is clear that the steel slag section has changed its geometrical properties more than the DPA with conventional aggregate. The change is most remarkable for the MPD (Mean Profile Depth). If we assume that the MPD in the wheel tracks when the pavements were new in the early autumn of 2017 was 1.70 mm for the DPA and 1.94 mm for the DPAstsl (= MPD in 2018 between the wheel tracks), the MPD has been increased by 6 % for the DPA and reduced by 27 % for the DPAstsl in 2022. Simultaneously, the rut depth has increased from 0 mm in new condition in 2017 (if the screeds worked fine) to 7.8 mm for the DPA and 10,8 mm for the DPAstsl in 2022.

6.4. Wet friction and standing water

Wet friction was measured in two ways:

– Using the Saab Friction Tester (SFT), driving at 70 km/h and measuring with the test tyre with water ejected in front of the tyre; see [5]. This was made only in November of 2018. Measurements were made only in the right wheel track.
– Using the VTI Portable Friction Tester (PFT), operated at walking speed and measuring with a test tyre and water sprayed manually in front of the device [5]. This was made only in May 2021.

In both cases, the measurements are mainly characterizing the microtexture influence on the friction. Values equal to or above 0.50, respectively 50, are considered as acceptable by the Transport Administration for newly laid asphalt pavements.

Results showed similar performance by the DPA and the DPAstsl, with a friction coefficient of 0.60 to 0.64. The measured values are acceptable, but not excellent. However, the measurements show only the microtexture influence on wet friction. The drainage of water is most important at high speeds, and since the pavements are of the drainage type, which avoid water standing on the pavement, the wet friction at high speeds (80-90 km/h on this road) should be excellent.

The author drove over the test sections one day in May 2021 when there was heavy rain which had been pouring down for a considerable time on that day. One could then fear that the clogging of the four-year-old pavements, especially the steel slag, would prevent an effective vertical drainage through the top layers, resulting in water standing in the wheel tracks. This did not happen as can be seen in Figures in [5]. It appeared that both porous pavements were essentially dry, while the adjacent dense pavement was flooded by water.

Later observations have not been made in heavy rain, but in “moderate” rain both porous pavements were still free of standing water in 2023. It suggests that even though the pavements seem to be almost totally clogged, rain can penetrate down into the pavements to some extent.

7. OTHER OBSERVATIONS

In Sweden, due to wear of studded tyres in wintertime, pavement surfaces have a dark “black” colour only before the first winter. In the winter, most bitumen responsible for the blackish colour will be worn away and after that the pavement surfaces with natural aggregates will essentially have the colour of the aggregate; i.e. not very dark.

For steel slag it is different: the slag will keep its dark grey (blackish) colour over its lifetime, and thus look like a rather new asphalt pavement. This is good for traffic safety as the glare in dark is not so bad and the contrast between road markings and pavement surface is much better.

The project started with several laboratory tests, which are not reported here but in another document [5]. It showed that dimensioning a slag mix is different from dimensioning a conventional mix, mainly due to the great different in mass density. This made it difficult to obtain the same high void content as with natural aggregates (20 vs 25 %).

8. DISCUSSION

8.1. Why use steel slag in road pavements?

Steel slag is a waste material but can also be considered a green resource because it has a great potential to substitute natural aggregates in pavements and reduce the environmental impact of virgin resources from quarries. Some countries have huge stockpiles and landfills of steel slag which are leaching heavy metals. When the slag is included in asphalt, leaching becomes negligible. In some countries, it is pointed out that natural aggregates of good quality will soon become rare and steel slag will be a good and much needed replacement.

Using steel slag in pavements therefore has environmental advantages. Nevertheless, there is also at least one disadvantage, namely the higher weight will mean higher transportation costs of the raw slag to the asphalt plant and further out on the construction site.

In this project, the author wanted to study whether the use of steel slag could give better durability and better acoustic longevity. It was thought that the binder would stick better to the steel slag than to the natural aggregates and thus give better durability. If so, such better durability may be traded for higher voids content and thus higher noise reduction. In reality, we were unable to get the desired air voids content of the mix, and the lower initial air voids probably resulted in earlier clogging.

Looking closely to slag particles, they often seem to contain some micro-porosity. Can such micro-porosity contribute to noise reduction by reducing the local air pressure gradients that cause the generation of noise called air pumping? If so, it may perhaps balance the effect of lower air voids in a conventional DPA.

8.2. Why is noise reduction in the conventional DPA so different in the two directions?

A crucial issue in evaluating the noise reduction of the steel slag pavement DPAstsl versus the conventional DPA is the variation we fund in the noise reduction in the two directions. The DPAstsl was only laid in the southern direction. The original idea was to use for comparison the total length of the DPA; i.e. both directions. However, although the two directions gave approx. the same noise reduction in both north and south directions the first years, with increasing time, there appeared to be more and more differences between the directions. The northern direction in 2023 gave 3.8 dB vs 6.0 dB of noise reduction in the north versus the south direction.

We cannot find a robust explanation for this. It has not happened, at least not to that extent, in the earlier generation of DPA pavements on this motorway, so it is a new phenomenon. Among the potential causes, these are worth mentioning:

- The paving in the two directions, although it should be identical, in practice became somewhat different, maybe with higher air voids content in the southern direction
- The motorway runs essentially north-south but dominating winds are westerly. It could mean that particles are blown by wind from west to east, i.e. dirt from the western lanes (running south) blows onto the eastern lanes (running north) and may increase clogging there
- Particles may also blow from adjacent dense pavements to the DPA and the DPAstsl. If so, this would be worst in the northern direction of the DPA which follows immediately after a single-layer PA south of the DPA. The PA is becoming clogged already after 2-3 years and then may act as a “semi-dense” pavement from which dirt may be transported onto the DPA in the wakes after the vehicles. The DPAstsl, on the other hand, is joined by a dense SMA at its southwestern end. Dirt from the SMA may be blown onto the DPAstsl when there are southwesterly winds, which happen quite frequently. But the DPA for the southern direction has no potential external source of dirt, other than rare cases when easterly winds are strong.

The issue is planned to be further studied in later analyses of the conditions at the site and more detailed analyses of the noise measurements. At least it is safe to say that porous pavements may differ a lot in noise reduction over time even if they are paved in identical ways and with identical mixes.

Another noteworthy observation is that water might remain in double-layer PA much longer than expected so far. In the CPX standard, it is indicated that one shall avoid CPX measurements before 24 h have passed since a rain event. This time is not enough under certain conditions. In this case, the problem occurred when measurements were made in the autumn 2017, in cloudy weather with very little wind and when daylight only lasted for 8 hours. It had rained 24-30 hours before the measurements, yet it seemed that the deeper parts of the pavement were not dry. This is an unfortunate combination of conditions that may be rare, but the problem shall be observed.

8.3. Using the DPA in the lane adjacent to the DPAstsl for comparison

Very disappointingly, the Transport Administration repaved the main DPA reference pavement already in early 2023, before we had an opportunity to make measurements on it a last time, which meant that our long-term comparison of DPA with DPAstsl was destroyed after only 5 years of pavement service of the DPA. However, they saved the steel slag from repaving, probably since it looked to be in better condition. This means that as of today (May 2024) the steel slag is still there and will be measured in just a few days after this is written. It will then be 7 years old which was the expected lifetime. According to the Transport Administration, no re-paving will be made on this motorway section in 2024, which means that in 2025 we might get measurements results after 8 years of service, which will be more than ever before in Sweden.

For this occasion, we compare the DPAstsl with another DPA reference, namely the DPA in southern direction which is running beside the DPAstsl in lane K2. This carries much less traffic than the DPAstsl in lane K1, which makes the comparison a bit conservative for the steel slag. It appears that the DPAstsl has performed equally well in terms of noise reduction as the DPA in the K2 lane so far (Figure 5) and this is despite the traffic has been much higher on the steel slag pavement than on the conventional pavement.

9. CONCLUSIONS

Based on the above results and discussion, the following conclusions are drawn:

Overall, the performance of the steel slag pavement has been at least as good as the conventional DPA in all studied aspects, except that the rutting is marginally greater than for the DPA, albeit still acceptable. Noise reduction is similar to that of the best DPA section, but better than the average DPA sections, and equally good as the DPA in the fast lane despite the latter carries much less traffic.

Given that the asphalt mix with steel slag probably can be better optimized in both material selection and proportioning, the use of steel slag in trials like this 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. This suggests that further development and trials are important for the environment.

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