Noise-reducing properties of pavements using steel slag as aggregate in asphalt mixes

Double-layer porous asphalt on E4 in Huskvarna, with steel slag aggregate in the right lane.

Final 2023-03-16

By Ulf Sandberg

Swedish National Road and Transport Research Institute (VTI)

BVFF/Trafikverket project 2015-021

"Lågbullerbeläggning med stålslagg på E4 i Huskvarna"

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PREFACE

This project intends to study the possibility to use steel slag aggregate in a low noise porous asphalt pavement and the acoustic performance of such a pavement.

It has been part of the Swedish BVFF research programme, where BVFF stands for “Bana väg för framtiden” which translates to “Make a way for the future”. This particular BVFF project, No. 2015-021, has been sponsored by The Swedish Transport Administration (Trafikverket) through contract No. TRV 2015/56557.

From 1 January 2023, BVFF is replaced by an organization named “Centre of Competence in road engineering”.

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ABSTRACT

Noise-reducing properties of pavements using steel slag as aggregate in asphalt mixes

By Ulf Sandberg, Swedish National Road and Transport Research Institute (VTI)

BVFF/Trafikverket project 2015-021 “Lågbullerbeläggning med stålslagg på E4 i Huskvarna”

The original purpose of this project was to construct a test section of a double-layer porous asphalt pavement where steel slag was used as the aggregate in the wearing course. The contents of the project also included a summary of the performance of earlier tests with steel slag as the aggregate in dense pavements in Sweden. It was also found that including an international literature review would be very useful. The literature review was not comprehensive but included the latest and most relevant findings.

Among many advantages for steel slag over natural aggregates, the literature mentions durability, less rutting and dark colour. Also polished stone values and abrasion resistance are generally high. The main disadvantage is the higher mass which makes transportation from steel works to paving sites more expensive.

Some of the dense Swedish steel slag pavements presented in this report have served well for long times, under moderate or high traffic volumes. The overall assessment comes out quite positive. Only one of the Swedish trials have been a disappointment.

The main subject in this report, is a test of steel slag aggregate in the top layer of a double-layer porous asphalt pavement paved in 2017 on motorway E4 in Huskvarna, in this report followed until 2023. This project started, as planned, in 2016 with laboratory studies aiming at gaining experience of designing steel slag pavements with high air voids content for durable performance, especially with traffic noise reduction in focus.

This trial section was paved simultaneously when the double-layer pavement through Huskvarna had to be repaved where then the main section could serve as a control or reference section. Both the test and the control sections had an identical bottom layer while the top layer of the test section had the stone aggregate replaced by steel slag. In this way it has been possible to compare the performance of the steel slag section with a longer section of double-layer porous asphalt which is using only natural coarse aggregates.

The study in Huskvarna has been truly holistic since many functional properties have been studied. Noise was the initial main issue in the project, but also rolling resistance, many geometrical properties related to wear, permeability and friction have been monitored or checked at certain occasions. Noise has been monitored each year by means of the CPX method.

The noise reduction so far (after the fifth year) has been equally good or better for the slag section than the natural aggregate section and has changed with time less than the conventional pavement. A major advantage of the slag section in Huskvarna is the reduced macrotexture which implies that rolling resistance on the slag section is lower by up to 6 %, which reduces energy consumption of the traffic, while simultaneously reducing CO_2 emissions.

Based on the results of this experimental study and review of other experience, several recommendations are presented.

Keywords: Pavement, steel slag, noise reduction, rolling resistance, porous asphalt, waste material, aggregates.

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SUMMARY

Noise-reducing properties of pavements using steel slag as aggregate in asphalt mixes

By Ulf Sandberg, Swedish National Road and Transport Research Institute (VTI)

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In Sweden, due to wear of studded tyres, only hard aggregates with low abrasion can be used in the surface course of road pavements. Therefore, the only alternative to stones or crushed rock 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 Huskvarna needed repaving in 2017 with a new double-layer porous asphalt, an opportunity to make a trial with replacing the natural aggregate in the top layer with steel slag appeared, which triggered this project.

Therefore, the original purpose of this project was to construct a test section of a porous asphalt pavement where steel slag was used as the aggregate in the wearing course. The test section should be sufficiently long to allow appropriate tests of noise reduction and be suitably located. The acoustic and technical performance should be studied over a few years in comparison to a control pavement of the same kind but having conventional and natural stone aggregate.

During the time of the project, it was decided also to summarize the performance of earlier tests with steel slag as the aggregate in dense and porous pavements. As these trials were not funded for systematic studies, the data from these projects are limited, but nevertheless of interest. It was also found that including an international literature review would be very useful.

Originally, the project was set-up for a time period of three years (2016-2018). With laboratory testing of material to start with, it meant that in the best case the performance of a field test could be followed in only two years, which is far too short to determine the durability of the test pavement. Due to intentional delays in the project, when this report is written, the test section has reached the age of five and a half years, which allows at least preliminary evaluation of its long-term performance since it is expected that the acoustical lifetime of a conventional porous pavement of this type is approximately seven years in the current Swedish conditions.

The literature review showed that international experience of steel slag in pavements has been consistently positive. Steel slag can be considered a green resource because it has a great potential to substitute natural aggregates 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.

Reports of field experiments are not as frequent as reports about laboratory studies, and only a few ones report long-term performance. Only in Singapore and a minor study in Spain, steel slag has been used in porous asphalt, and none has used it in double-layer asphalt such as the test in this report.

Among many advantages for steel slag over natural aggregates, the literature mentions durability, less rutting and dark colour. Also polished stone values and abrasion resistance are generally high. The main disadvantage is the higher mass which makes transportation from steel works to paving sites more expensive. However, with high-quality natural aggregates being more and more depleted, even natural aggregates may cause long and expensive transportation. Furthermore, while the natural aggregates are not for free, the slag is a waste material, so the economic comparison may come out any way.

Despite all positive assessments in the international literature, one must remember that for Swedish conditions, slag performance is more complicated, due to our relatively good resources of high-quality aggregates and use of steel studs in winter tyres; the latter is what requires such high-quality aggregates. Furthermore, a larger proportion of our steel slag is already recycled, compared to most other countries.

Some of the Swedish steel slag pavements presented in this report have served well for long times, under moderate or high traffic volumes. The overall assessment in Chapter 10 comes out quite positive. Only one of the Swedish trials have been a disappointment. On the other hand, there is neither one that can be considered as a really great success.

As mentioned, the main subject of this project, and of this report, is a test of steel slag aggregate in the top layer of a double-layer porous asphalt pavement laid in 2017 on motorway E4 in Huskvarna. This project started, as planned, in 2016 with laboratory studies aiming at gaining experience of design of steel slag pavements with high air voids content for durable performance, especially with traffic noise reduction in focus. These studies provided a basis for the experimental field test starting in 2017. However, the final mix was prepared, and the paving was made by Swedish road contractor Svevia, as the field trial was part of Svevia's contract with the Swedish Transport Administration (Trafikverket) for this part of motorway E4.

As planned, it was possible to get a study object on E4 in Huskvarna, for a limited distance (a little less than 200 m in the slow lane, designated lane K1 in Sweden). This was paved simultaneously when the double-layer pavement through Huskvarna had to be repaved. This object had a bottom layer identical to the rest of the fully renewed section through Huskvarna, while the top layer had the stone aggregate replaced by steel slag (for the grading 4-11 mm). In this way, it has been possible to compare the performance of the steel slag section with a longer control section of double-layer porous asphalt which is using only natural coarse aggregates. Thanks to the time extension of the project from the original three years (2016-2018), it has been possible to study the performance of this slag pavement compared to a similar top layer with conventional stone aggregate over a five-year period. Since the pavement is expected to have an acoustical lifetime of seven years, this gives a good picture of the long-term properties of such a steel slag pavement.

The study in Huskvarna has been truly holistic since many functional properties have been studied. Noise was the initial main issue in the project, but also rolling resistance and many geometrical properties related to wear, permeability and friction have been monitored or checked at certain occasions. Noise has been monitored each year by means of the CPX method of measuring noise properties of road pavements, according to international standards (ISO 11819-2, ISO/TS 11819-3 and ISO/TS 13471-1); all of them developed for such purposes.

The steel slag pavement on E4 in Huskvarna has served well so far, despite it was laid in the slow lane (K1) where there is exceptionally high traffic by articulated trucks, since E4 is the main transportation corridor between southern Sweden and the Stockholm area, and further north along the coast. For example, much of the cargo traffic between Finland/Estonia/Latvia and western Europe goes this way.

The noise reduction so far has been equally good or better for the slag section than the natural aggregate section and has changed with time less than the conventional pavement. The first year it was about 7 dB and presently, after five years, it is still as high as 6 dB. If this trend continues, the slag appears to have an acoustical advantage over the stone aggregate. When the slag pavement is new and has significant permeability and sound absorption, noise is reduced mainly by the sound absorption combined with lower air pumping due to air drainage in the tyre/road interface. By time, these noise-reducing mechanisms are exchanged with and balanced out by the lower vibration excitation to the tyre by the lower texture.

A major advantage of the slag section in Huskvarna is the reduced macrotexture, which has not led to a loss of noise reduction; rather the opposite. Similar effects have been noticed on other steel slag test trials. The reduced macrotexture means that rolling resistance on the slag section is lower by up to 6 %, which reduces energy consumption of the traffic, while simultaneously reducing CO_2 emissions.

The use of steel slag in pavements has another positive effect on the CO_2 balance: through the carbon dioxide emissions from steel and slag production being allocated to the steel production, the use of slag contributes to reduced carbon dioxide emissions compared with the extraction of crushed rock.

Based on the results of this experimental study and review of other experience, the following are some of the presented recommendations:

The successful steel slag section in central Linköping indicates that a dense slag pavement with maximum aggregate size of 11 mm performs better than SMA 11 and potentially equally well as one would expect with an SMA 16. With such a replacement for SMA 16 one would win significantly lower rolling resistance, which reduces CO_2 and noise emissions proportionally in an urban or suburban situation and yet have the same lifetime. It would also save the consumption of natural aggregates. Therefore, this pavement option should be considered more frequently.

The overall results suggest that the use of steel slag as aggregate in road pavements have advantages which justify increased research and development of this waste product. Steel slag is not a uniform product, and it should be possible to find the best type for use in Swedish pavements, which requires the highest possible abrasion resistance due to wear of studded tyres. It is probable that there may also be ways to improve it. One must be aware that different steel slag products have different wear resistance, which may vary substantially, as mentioned in the report. The dimensioning of the asphalt mix and tailoring the best possible binder for this material, is a challenge which needs to be studied, since the trial in this project is unlikely to use the optimum design.

The achieve a voids content in porous pavements using steel slag as the aggregate, which is equally high as when using stone aggregate is difficult, most probably due to a lack of experience in dimensioning asphalt mixes with the much heavier steel slag. It is recommended to make further attempts to design a mix with steel slag reaching voids contents of at least 25 %. With such a mix, and a slag variant which has high wear resistance, there is a potential for better noise reduction over the lifecycle than for the presently successful double-layer porous asphalt in Huskvarna; especially allowing a longer lifetime until the threshold of minimum noise reduction is reached.

More recommendations are presented in Chapter 12.

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SAMMANFATTNING

Bullerreducerande egenskaper hos asfaltbeläggningar med stålslagg som ballast

Av Ulf Sandberg, Statens väg- och transportforskningsinstitut (VTI)

BVFF/Trafikverket projekt 2015-021 “Lågbullerbeläggning med stålslagg på E4 i Huskvarna”

Vägbeläggningar i Sverige kan, på grund av dubbdäcksslitage, endast använda hårda och nötningsbeständiga material som ballast i slitlager. Därför är stålslagg det enda alternativet till sten eller krossat berg som har potential att vara tillräckligt hållbart. Laboratorieförsök med stålslaggspartiklar har gjorts av VTI för ett tiotal år sedan med delvis goda resultat och fältförsök med stålslagg i täta asfaltbeläggningar har gjorts på några svenska platser de senaste två decennierna som visat tillräckligt lovande resultat för att motivera fler studier.

När E4:an genom Huskvarna behövde asfaltera om 2017 med ny dränasfalt med dubbla lager uppstod en möjlighet att göra ett försök med att ersätta det naturliga stenmaterialet i toppskiktet med stålslagg, vilket kom att bli upphov till detta forskningsprojekt.

Det ursprungliga huvudsyftet med detta projekt var att konstruera en testsektion av en porös asfaltbeläggning, s k dränasfalt, där stålslagg användes som ballast i slitlagret. Testsektionen skulle vara tillräckligt lång för att möjliggöra lämpliga tester av bullerreduktion och vara lämpligt placerad. Den akustiska och tekniska prestandan skulle studeras under några år i jämförelse med en beläggning av samma slag men med konventionellt stenmaterial.

Under projektets gång beslöts att även inkludera en sammanfattning av resultaten från tidigare tester i Sverige med stålslagg som ballast i täta beläggningar. Då det under projektets gång blev uppenbart att användning av stålslagg som vägmaterial var ett ännu viktigare forskningsområde utomlands beslutade författaren att inkludera även en genomgång av den senaste internationella litteraturen.

Ursprungligen var projektet planerat att utföras under en tidsperiod på tre år (2016-2018). Med laboratorieprovning av material under första året, innebar det att man i bästa fall kunde följa utförandet av det planerade fältprovet under endast två år, vilket är alldeles för kort för att bestämma provbeläggningens beständighet. På grund av avsiktliga förseningar i projektet, när denna rapport skrivs, har provbeläggningen uppnått en ålder av fem år, vilket möjliggör åtminstone en preliminär utvärdering av dess långsiktiga prestanda eftersom det förväntas att den akustiska livslängden för en konventionell porös beläggning av denna typ är cirka sju år under nuvarande förhållanden på den aktuella vägen.

De internationella erfarenheterna av stålslagg i vägarnas slitlager har genomgående varit positiva. Stålslagg kan betraktas som en grön men ganska outnyttjad resurs eftersom den har stor potential att ersätta naturliga stenmaterial och minska miljöpåverkan från krossning av bergmaterial. Vissa länder har enorma lager och deponier av stålslagg från vilka det läcker ut bl a tungmetaller till mark och vattendrag. När däremot slaggen ingår i asfalt blir urlakningen försumbar. I vissa länder påpekas att de naturliga stenmaterialen av god kvalitet som duger för användning i vägars slitlager håller på att ta slut och att stålslagg kan bli en bra och välbehövlig ersättning.

I den internationella litteraturen, som tycks domineras av länder i östra Asien och Australien, är rapporter om fältexperiment inte lika frekventa som rapporter om laboratoriestudier, och mycket få rapporterar handlar om stålslaggsbeläggningars beständighet. Endast i Singapore och en mindre studie i Spanien har stålslagg använts i porös dränasfalt, och ingen har använt det i dubbellagers dränasfalt av liknande slag som fältförsöket i denna rapport.

Bland många fördelar för stålslagg framför naturliga stenmaterial, nämns hållbarhet, mindre spårbildning och mörk färg. Även beständighet mot polering och nötning av bildäck framhålls som viktiga fördelar. Den största nackdelen är den högre massan som gör transporter från stålverk till beläggningsplatser dyrare. Men eftersom stenmaterial av hög kvalitet blir mer och mer en bristvara, kan även dessa behöva hämtas från avlägsna platser och orsaka långa och dyra transporter. Trots alla positiva omdömen i den internationella litteraturen måste man komma ihåg att för svenska förhållanden är slaggens prestanda gentemot naturliga material mer komplicerad, på grund av våra relativt goda resurser av högkvalitativa stenmaterial och användning av dubbar i vinterdäck; då de senare ju är precis vad som kräver sådana högkvalitativa stenmaterial i Sverige.

Vissa av de svenska stålslaggsbeläggningarna som presenteras i denna rapport har fungerat bra under ganska lång tid under måttliga eller höga trafikvolymer. Den samlade bedömningen av dessa försök (kapitel 10) är ganska positiv. Endast ett av de svenska försöksobjekten har varit en besvikelse. Å andra sidan finns det heller inget som kan betraktas som en stor succé.

Huvudämnet för detta projekt och denna rapport är som nämnts ett test av stålslagg som ballast i det översta lagret av en dubbel dränasfaltsbeläggning lagd sommaren 2017 på E4 genom Huskvarna. Här bör nämnas att det är endast de grövre kornen (över 4 mm) som utgörs av stålslagg. Detta projekt startade 2016, som planerat, med laboratoriestudier som syftar till att skaffa erfarenhet av att designa stålslaggsbeläggningar med högt hålrum för en bra beständighet, särskilt med reduktion av trafikbuller i fokus. Dessa studier utgjorde en bas för det experimentella fältförsöket med start 2017. Den slutliga mixen portionerades och förbereddes dock, och beläggningen utfördes, av vägentreprenören Svevia, eftersom fältförsöket var en del av Svevias kontrakt med Trafikverket för denna del av motorväg E4.

Studieobjektet på E4 i Huskvarna kom att utgöra en begränsad sträcka, lite kortare än 200 m i det långsamgående körfältet (betecknat K1) i södra riktningen. Denna asfalterades samtidigt med dubbeldränbeläggningen i övrigt genom Huskvarna, vilket är en ca 3 km lång vägsträcka mellan Vättern och ett bostadsområde i Huskvarna. Man hittar lätt beläggningen genom dess mycket mörkare yta längs med avfart nr 100 ”Huskvarna Södra”.

Projektets studieobjekt har ett bottenlager som är identiskt med resten av den bullerreducerande sektionen genom Huskvarna, medan det översta lagret fick det grövre stenmaterialet ersatt med stålslagg (av kornstorlekarna 4-11 mm). Bindemedlet är detsamma, dock i en annan proportion och med reservation för att Svevia kan ha adderat något förstärkande material (exakt recept är en företagshemlighet). Stålslaggen är av s k EAF-typ som kommer från Smedjebacken. På detta sätt har det varit möjligt att jämföra stålslaggsektionens prestanda med en längre sektion av dubbel dränasfalt som endast använder stenmaterial i topplagret. Tack vare tidsförlängningen av projektet från de ursprungliga tre åren (2016-2018) har det varit möjligt att studera prestandan hos denna slaggbeläggning jämfört med ett liknande toppskikt med konventionell stenmassa under en femårsperiod, i nuläget. Eftersom beläggningen förväntas ha en akustisk livslängd på sex eller sju år ger detta en bra bild av de långsiktiga egenskaperna hos en sådan stålslaggsbeläggning.

Studien i Huskvarna har verkligen varit holistisk eftersom många funktionella egenskaper har studerats. Bullerreduktionen jämfört med den konventionella dränasfalten var den initiala huvudfrågan i projektet, men även rullmotstånd, många geometriska egenskaper relaterade till slitage, permeabilitet och friktion har studerats eller kontrollerats vid vissa tillfällen.

Bullerreduktionen har uppmätts varje år med hjälp av den s k CPX-metoden, som är utformad för att mäta just bulleregenskaper hos vägbeläggningar på ett reproducerbart sätt, enligt internationella standarder (ISO 11819-2, ISO/TS 11819-3 och ISO/TS 13471-1); alla utvecklade för sådana ändamål. Mätningen görs med en särskild mätvagn som bogseras efter en personbil och där ett provdäck i mätvagnens mitt har två mikrofoner monterade 20-25 cm från däckets kontaktyta mot vägen. Dessa skyddas av en huv som skärmar av icke önskvärda oljud utifrån så att mikrofonerna mäter endast ljudet från däck/vägkontakten. Två sådana standardiserade provdäck används: ett som representerar personbilars känslighet för vägytans inverkan på bullret, och ett annat som representerar motsvarande för lastbilsdäck. För just denna typ av beläggning ger dessa provdäck ungefär samma buller, så slutresultatet utgörs av ett medelvärde av dessa. Mätningar har skett vid 50 och 80 km/h men där den senare är den mest relevanta och som ligger närmast trafikens verkliga hastighet.

Stålslaggbeläggningen på E4 i Huskvarna har fungerat bra hittills, trots att den lagts i det långsamma körfältet (K1) där det är exceptionellt hög trafik med långa lastbilskombinationer, eftersom E4 är den huvudsakliga transportkorridoren mellan södra Sverige och Stockholmsområdet, och vidare norrut längs kusten. Till exempel går mycket av godstrafiken mellan Finland/Estland och Västeuropa denna väg.

Bullerreduktionen hittills har varit lika bra eller bättre för slaggdelen som för den konventionella dränasfaltbeläggningen och har förändrats med tiden mindre än den konventionella beläggningen. Strax efter anläggningen var bullerreduktionen ungefär 7 dB, vilket sedan långsamt har sjunkit till nuvarande ungefär 6 dB (hösten 2022). Om denna trend fortsätter verkar slaggen ha en akustisk fördel gentemot den ordinarie dränasfaltsbeläggningen. När slaggbeläggningen är ny och har betydande permeabilitet och ljudabsorption, reduceras bullret främst av ljudabsorptionen i porerna i kombination med lägre s k luftpumpning i däck/vägkontakten på grund av luftdränering i gränssnittet däck/väg. Med tiden byts dessa bullerreducerande mekanismer ut med, och balanseras, av den lägre vibrationsexciteringen till däcket genom den mindre grova texturen i vägytan.

En stor fördel med stålslaggssträckan i Huskvarna är den minskade makrotexturen som har uppmätts årligen. Liknande effekter har märkts i andra stålslaggsförsök. Den minskade makrotexturen från anläggningsåret gör att rullmotståndet på stålslaggssträckan år 2022 är lägre än på den ordinarie sträckan med upp till 6 %, vilket minskar trafikens energiförbrukning och samtidigt minskar CO_2-utsläppen. Den senare förbättringen är en viktig faktor i den totala utvärderingen av försöket, varvid kan nämnas även att vägens jämnhet är bättre med stålslagg än med konventionellt stenmaterial, vilket innebär bättre komfort för trafikanterna samt mindre risk för att markvibrationer från den tunga trafiken ska skapa några problem.

Dock har spårdjupet på stålslaggsträckan ökat med ungefär 2 mm per år, vilket kan jämföras med den ordinarie sträckan som har en spårdjupsökning med ca 1,6 mm per år. Det är ingen stor skillnad och inte heller någon alarmerande hög förslitning utan ganska liknande vanliga beläggningar av typ ABS 16 som exponeras för samma trafik. Det är oklart vad som orsakar förslitningen; normalt beror spårdjupet på spår av den tunga trafiken i kombination med dubbdäcksslitage, men i detta fall kan även någon annan mekanism vara inblandad.

Användningen av stålslagg i beläggningar har ytterligare en positiv effekt på CO_2-balansen: genom att koldioxidutsläppen från stål och slaggproduktion redan har belastat stålproduktionen. Därmed bidrar användningen av slagg som ersättning för stenballast till minskade koldioxidutsläpp genom att den ersätter krossning och utvinning av sten.

Baserat på resultaten från denna experimentella studie och genomgång av andra erfarenheter presenteras följande rekommendationer:

Författaren upptäckte en sträcka med stålslagg (liknande en beläggning av typ ABS 11) som finns vid Resecentrum i centrala Linköping och gjorde vissa mätningar på denna i projektet. Resultatet indikerar att denna täta slaggbeläggning med max ballaststorlek på 11 mm presterar bättre än beläggningar av typ SMA 11 med vanligt stenmaterial, genom att spårdjupsökning per år är betydligt mindre. Den presterar potentiellt lika bra som man kan förvänta sig av en SMA 16. Med en sådan ersättning för SMA 16 skulle man vinna betydligt lägre rullmotstånd genom lägre makrotextur, vilket minskar koldioxid- och bullerutsläpp proportionellt i en stads- eller förortssituation. Det skulle också spara konsumtionen av naturliga stenmaterial. Därför bör detta beläggningsalternativ övervägas oftare.

De övergripande resultaten tyder på att användningen av stålslagg som ballast i vägbeläggningar har fördelar som motiverar ökad forskning och utveckling av denna restprodukt. Stålslagg är inte en enhetlig produkt och det borde vara möjligt att hitta den bästa typen för användning i svenska beläggningar som kräver högsta möjliga nötningsmotstånd på grund av slitage på dubbdäck. Det är troligt att det också kan finnas sätt att förbättra denna typ av vägbeläggning. Dimensioneringen av asfaltblandningen och att skräddarsy bästa möjliga bindemedel för detta material är en utmaning som behöver studeras, eftersom försöket i detta projekt sannolikt inte kom att använda den optimala designen.

Att uppnå ett hålrumsinnehåll i porösa beläggningar med stålslagg som ballast som är lika högt som vid användning av stenmaterial är svårt, bl a på grund av för bristande erfarenhet av dimensionering av asfaltblandningar med den mycket tyngre stålslaggen. Det rekommenderas att göra ytterligare försök att utforma en blandning med stålslagg som når hålrumshalter på minst 25 %. Med en sådan blandning finns det en potential för betydligt bättre ljudreducering över livscykeln än för den nu framgångsrika dubbla dränasfalten i Huskvarna; särskilt att tillåta en längre livslängd tills tröskeln för minsta ljudreducering nås.

Författaren predikterar att stålslaggsbeläggningen på provsträckan i Huskvarna kommer att ge ca 5 dB i bullerreduktion fram till åldern 7 år, dvs år 2024. Den kanske inte behöver läggas om ens efter denna tid. Men mycket beror på om stensläppen kommer att öka de närmaste åren. I vart fall bör beläggningens funktion följas upp noga så länge den finns kvar. Den har hittills ökat våra kunskaper avsevärt om hur användbar återvinningen av detta material är i vägbeläggningar, bl a för att åstadkomma bullerreduktion och reduktion av rullmotstånd, dvs trafikens energiförbrukning och koldioxidutsläpp.

Litteraturöversikten lyckades inte finna någon europeisk standard eller ISO-standard som handlar om stålslagg som ballast i vägbeläggningar. Däremot finns det ett par ASTM-standarder som utkommit nyligen som tillsammans med riktlinjer från vissa nationella dokument som redovisas kan utgöra en bas för ett nytt europeiskt eller internationellt arbete för standardisering inom detta specialområde, vilket rekommenderas här.

Författaren rekommenderar att det just startade försöket i Danmark med att använda partiklar av krossat glas som ballast i slitlager, att helt eller delvis ersätta stenmaterial, följs upp för att kontrollera om detta avfallsmaterial kommer att visa sig vara lika användbart som stålslagg i vägbeläggningar. Man kan ha funderingar på om glaset kan poleras för lätt eller att det krossas av svenska dubbdäck, men det är värt att se hur den danska beläggningen presterar de närmaste 10 åren.

Det föreslås att Trafikverket och stålindustrin samarbetar för att få fram en optimal slaggprodukt för vägbeläggningsändamål och studera om den kanske kan förbättras ytterligare genom urval, förbearbetning eller annan förädling.

Slutligen föreslår författaren att stålslagg används i mycket större utsträckning än idag i vägars slitlager, helst med samtidig FoU inom området som stöd. När man bedömer den eventuellt extra kostnaden för transporter av den tyngre stålslaggsballasten bör man dels överväga hur den ställer sig till transportkostnaderna för lika nötningsbeständigt stenmaterial (som också kan behöva transporteras lång väg) tillsammans med den miljöfördel som man får av mindre rullmotstånd för trafiken och eventuell bullerreduktion.

1 Introduction

The conventional aggregate in road pavements is stones or crushed rock of various kinds, from relatively soft limestone to really hard diabase or quartzite. In parts of the world where studded tyres are not used, softer “artificial” materials such as expanded clay (or “Leca”) have been used and fly ash is used as a mineral filler. But in Sweden, due to wear of studded tyres, only hard aggregates with low abrasion can be used. Therefore, the only alternative to stones or crushed rock which has the potential to be durable enough is steel slag. Field tests with steel slag aggregates have been made in some Swedish locations and showed results enough promising to justify more studies.

Steel slag is a by-product from the production of steel when hot metal is converted to crude steel. Metallurgical slags currently include the iron-making slag of a Blast Furnace (BF), steel slag divided into Basic Oxygen Furnace (BOF) slag, the Electric Arc Furnace (EAF) slag, and secondary refining slag that are the Ladle Furnace (LD) and the stainless steel slag [Loureiro et al, 2022]. Contrary to its name, it should not contain steel; instead, it is a mix of CaO, SiO2, Al2O3, MgO, and iron oxides. The compositions depend on the actual steelmaking process.

Studies carried out by the European Commission in 2009 showed that the percentage of slag per ton of steel produced in the EU is in the range of 12-15 % [Bosurgi et al, 2022]. It is thus clear that this is either a waste material or a potential resource of high importance to both economy and environment. China heavily dominates the world production, followed by India, Japan, USA, Russia and South Korea. In Europe, most steel slag is produced in Germany and Turkey. When it comes to steel production per capita, China is about twice as large as Sweden, also Russia and South Korea are larger, but in comparison to Germany and Turkey, Sweden is about the same. Just over 80 % of the slag produced in Sweden today is used in different applications, both internally within the steel plants and externally [Jernkontoret, 2022]. This leaves about 20 %, or around 300 000 tons of steel slag which is not used. This is the type described as high alloy electric arc furnace slag [Jernkontoret, 2022].

To be competitive to conventional aggregates, the slag must show some advantages that can balance out the disadvantages, such as the increased cost of transportation as the slag is much heavier than stones and is available only in connection to steel industries. Such advantages could be better adhesion to binders, and possibly less wear by the tyres. In this project, there was hope that the better adhesion between binder and slag could allow higher air voids or less ravelling, both of which might be used for increasing the acoustical lifetime of a porous asphalt pavement.

So far, Swedish projects with porous asphalt have been unsuccessful in those respect, with the very prominent exception of motorway E4 through Huskvarna in Jönköping. In this location a 2.7 km long double-layer porous asphalt with 11 mm max aggregate had been laid in 2010 by the company Svevia AB, which had to be repaved only in 2017. This means that the porous asphalt showed almost as long durability as a regular SMA 16 pavement, and definitely no worse than an SMA 11 would have been, bearing in mind that in wintertime, the majority of cars would run on studded winter tyres and that the heavy vehicle proportion is high.

With the hope that a well-designed asphalt pavement using steel slag would increase the acoustical durability somewhat, it was decided to add a test section with steel slag aggregate on a part of this low noise section of E4 through Huskvarna in conjunction with the repaving of the entire low noise section in 2017. This was realized as a 100+ m long section in one of the southern-going lanes, in just the top layer of the double-layer pavement, the performance of which is the main focus in this report.

2 Purpose and limitations of this project

The original purpose of this project was to construct a test section of a porous asphalt pavement where steel slag was used as the aggregate. The test section should be sufficiently long to allow appropriate tests of noise reduction and be suitably located. The acoustic and technical performance should be studied over a few years in comparison to a pavement of the same kind but having conventional stone aggregate.

During the time of the project, it was decided also to summarize the performance of earlier tests with steel slag as the aggregate in dense and porous pavements. As these trials were not funded for systematic studies, the data from these projects are limited, but nevertheless of interest.

Originally, the project was set-up for a time period of three years. With laboratory testing of material to start with, it meant that in the best case the performance of a field test could be followed in only two years, which is far too short to determine the durability of the test pavement. However, due to delays in the project, when this report is written, the test section approaches the age of five years, which allows at least preliminary evaluation of its long-term performance since it is expected that the acoustical lifetime of a conventional pavement of this type is approx. seven years.

Another limitation is that there are many types of steel slag and only one could be tested here. The same applies to the mix (gradation, binder type and binder content) which may not have been the optimal choice in this project.

3 Why could steel slag aggregate improve a pavement?

In comparison to crushed rock or stone aggregate, steel slag particles are generally more irregular, with few flat surfaces. The surfaces may also be somewhat porous. These are good properties for achieving excellent adhesion between aggregate and asphalt binder. It may also potentially provide for better porosity in the mix. In case the slag has higher resistance to studded tyre wear, there may also be less emission of particles in the air and particles that my fill the pores.

Among potential disadvantages, the density is a significant disadvantage as it may have up to double the density of crushed stone. This will give significantly higher transportation costs between the source and the road construction site. The much higher density may also give problems in determining the proportion of binder since one cannot use the experience from work with conventional stone aggregates. Another potential problem to observe is during the paving: as for conventional aggregates, the mix must have an appropriate temperature and it must then be observed that the much higher density of the steel slag aggregate will require longer heating time in order to reach the same and stable temperature as conventional aggregate.

Even though the surface of the slag particles may be somewhat porous they generally lack the micro-texture of the best stone materials, which may have an effect on wet tyre/road friction.

If a well-proportioned mix of aggregate, filler and binder can be achieved, potentially due to the better binder-aggregate adhesion, the mix may be designed with a higher air voids volume for the same structural strength as when using conventional aggregate. Alternatively, for the same air voids volume, the mix may be less prone to ravelling and thus provide longer life. Another alternative may be that without sacrificing durability, one may utilize the advantages of the slag aggregate to use a smaller maximum aggregate size. In either case this would be very favourable to low-noise porous asphalt pavements. Also, SMA pavements may potentially be designed with smaller aggregates (say 8 instead of 11 mm) without losing lifetime.

Now, the above are hopeful speculations, albeit based on logical reasoning, but it must be proved in field tests. This is what this project attempts to do.

4 Steel slag material as pavement aggregate

4.1 General

Steel slag is a by-product from the production of steel when hot metal is converted to crude steel in an oxygen furnace, or during melting of scrap in an electric arc furnace (EAF). Contrary to its name, it should not contain steel; instead, it is a mix of CaO, SiO2, Al2O3, MgO, and iron oxides. The compositions depend on the actual steelmaking process [ScienceDirect, 2022].

In general, steels slag is not corrosive and will not rust. However, it was noted in South Korea about 20 years ago that there had been some rust on the slag after rainy weather caused corrosion [Kim, 2022]. The colour of the slag is generally dark grey. Contrary to asphalt pavements with conventional aggregates, which appear black as long as the bitumen is not worn off the aggregate by tyres, steel slag surfaces remain dark grey through their lifetime. Consequently, such pavements may look “fresh” to the public even when they are old.

A picture of a typical slag is shown in Figure 4-1. Note the irregular shape of the particles.

Figure 4-1: Steel slag from Smedjebacken in Sweden, fraction 8/11 mm. The coin’s diameter is 24 mm.

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4.2 Materials available in Sweden

In Sweden, electric arc furnace slag remains an insufficiently utilised resource for asphalt production, despite the many good properties it possesses. The market is growing at present, however [Jernkontoret, 2022].

In an earlier study at VTI the available slags were tested in various ways, of which some data are presented in Table 4-1 [Wiman, 2015]. Water absorption is a measure proportional to the porosity of the slag particles. This is important for determining the amount of binder and potentially may have a minor influence on noise. The density is also a parameter which must be considered for determination of binder amount. Note the large difference in density between the slags, which is an effect of the mix of substances.

Table 4-1: Slags tested by VTI earlier, with data collected from [Wiman, 2015].

Source of slag	Water absorption [%]	Density [Mg/m^3]
Skärlunda	1.1	2.64
Ovako Hofors	1.5	3.57
Vargön	1.7	3.22
Merox, LD	2.2	3.51
Ovako, Bar	2.3	3.67
Uddeholm	3.0	3.58
Merox, Hyttsten	3.1	2.67
Outokumpu	3.7	2.83
Sandvik	4.2	2.54
Befesa	4.3	2.67
Höganäs	4.4	3.43

In addition to the slags in the table, VTI has used slag from Smedjebacken more recently, see further Chapter 6.

5 Observations in the literature

5.1 Earlier studies by VTI

VTI has studied properties of steel slag aggregates and pavements earlier. These are presented in the following reports and one presentation:

- Stålslagg i asfaltbeläggning: en kunskapsöversikt samt fältförsök i Dalarna. By Torbjörn Jacobson, VTI. VTI notat 5-2008.
- Stålslagg i asfaltbeläggning: fältförsök 2005-2012. By Nils-Gunnar Göransson and Torbjörn Jacobson, VTI and Trafikverket. VTI notat 19-2013.
- Slaggasfalt, delrapport A, Ballastegenskaper och slitageegenskaper enligt Prall. By Leif Viman, VTI. VTI notat 10-2015.
- Slaggasfalt, delrapport B, Stabilitet och skjuvegenskaper hos slaggasfalt. By Leif Viman and Safwat Said, VTI. VTI notat 19-2015.
- Slaggasfalt, delrapport C, Slitage och bildning av inandningsbara partiklar (PM_{10}). By Leif Viman and Mats Gustafsson, VTI. VTI notat 24-2015.
- Slaggasfalt - provningar på VTI. By Leif Viman, VTI, and Anders Gudmarsson, Peab. VTI PowerPoint presentation, undated but probably from 2015.
- How do we improve the durability of porous asphalt? By Torbjoern Jacobson (Trafikverket), Ulf Sandberg (VTI), and Leif Viman (VTI). Conference paper at Eurobitume 2016, Prague, Czech Republic.
- Viman et al (2016): “Evaluation of Slag as aggregates in Asphalt Mixtures”. Proc. of Eurobitume 2016, Prague, Czech Republic.

Except for the last two, they are written in Swedish, but with an English summary. Most of these are listed in the References of this report. The most interesting observations and measured data are presented in Chapter 8 as they are also indirect study objects in this project. A kind of summary report for the documents 2013-2015 above is also available as [Lind, 2015].

5.2 Comprehensive review published in 2022 by Portuguese authors

A very comprehensive and useful article was published by Portuguese authors in 2022 [Loureiro et al, 2022]. Their article reviews and discusses the characteristics and performance of steel slag aggregate (SSA) and recycled concrete aggregate (RCA) when used as aggregates in asphalt mixtures. The article includes an impressive list of 180 references.

Based on the various studies analyzed, they concluded that incorporating SSA or RCA in asphalt mixtures for road pavements has functional, mechanical, and environmental advantages. However, it is essential to consider some possible drawbacks of these aggregates. These advantages and drawbacks are listed in a table which is copied below (Table 5-1). The table was cropped to include only steel slag by this author, since it is the subject of this report.

Among the advantages, this author would emphasize three of them in this report, namely (1) the excellent wearing and polishing resistances, (2) increases in the mechanical performance of asphalt mixtures regarding water sensitivity and rutting resistance and (3) that it may be used as a self-healing promoter. The two first would be important advantages in porous asphalt pavements. The third is because steel slag allows the use of heating by way of microwave radiation to heal cracks in the pavement. It is also mentioned that the porous surface of slag particles permits a distinct interaction with the bitumen and crumb rubber compared to natural aggregates. These factors should mean improved performance of the asphalt mixtures with steel slag when modified with crumb rubber.

Among the disadvantages, this author would emphasize four of them in this report, namely (1) untreated slag may leach heavy metals, increase pH values, and present long-term expansion problems, (2) higher variability depending on steel slag origin and treatment, and (3) demands new specifications.

Table 5-1: Advantages and drawbacks of steel slag in asphalt mixtures. From [Loureiro et al, 2022].

Advantages	Drawbacks
• Minimizes depletion of natural resources • Reduces consumption of natural aggregates • May reduce the production costs • Reduces waste landfill • Presents excellent wearing and polishing resistances • Can replace high amounts of NA • Increases the mechanical performance of asphalt mixtures regarding water sensitivity and rutting resistance • May be used as a self-healing promoter	• Increases the transportation costs due to its higher density • Reduces the mixture workability and increases air void and binder contents due to its rough and porous surface • Untreated SSA may leach heavy metals, increase the eluates' pH values, and present long-term expansion problems • Shows higher variability depending on steel slag origin and treatment • Demands new specifications • Increases equipment wearing and production complexity

5.3 Swiss project with steel slag (EOS)

In Switzerland, in 2004, several test sections was paved with dense-graded Elektroofenschlacke (EOS), i.e. Electric (Arc) Furnace Slag which is essentially similar to our EAF. They used aggregates with either 4 or 8 mm maximum size and a polymer modified binder. Two of the test sections also had rubber granules added. One of the aims was to obtain more durable noise reduction. Initially, these EOS pavements gave 4-5 dB quieter noise levels than the Swiss reference (a noise level used in their traffic noise prediction STL 86+). After 6 years of quite high traffic volumes (> 10 million passes) the noise reduction was down at 0 - 0.5 dB for the two EOS with rubber granules, and 1 dB for the two EOS without rubber. This author thinks that the noise reductions reported are expected for any asphalt concrete (AC) with such small aggregates, which is supported also by the Swiss data for regular AC. It was concluded after 6 years that EOS pavements showed similar influence of age on the performance compared to the regular pavements [ASTRA-BAFU, 2011].

Thus, these EOS pavements did not seem to offer clear advantages.

There is a new Swiss project, "Urban Mining" conducted at EMPA (https://www.empa.ch/web/s308/urban-mining), which includes some work on steel slag. Regarding the urban mining project and use of slag they have only laboratory results including surface texture so far. A report will be published later in 2022 [Poulikakos, 2022].

5.4 Application of steel slag in asphalt pavements in Italy

In an Italian study [Bosurgi et al, 2022], an experimental laboratory analysis was carried out to evaluate the possibility of using steel slag aggregates in innovative surface asphalt mixtures. The experimental phases relied on the comparison of the performance offered by an innovative mixture with steel slags, with those offered by a traditional mixture using natural limestone and basaltic aggregates.

For both mixtures, which were dense, a polymeric compound was used together with an adhesion activator for balancing effects of the high percentages of silica that hinder satisfactory adhesion between binder and aggregates.

The experimental results indicated an overall equivalence between the two mixtures in terms of mechanical performance, with clear environmental benefits for the mixture including steel slags, due to the reduction of virgin materials and bitumen percentages. Further, the experiments showed higher crushing resistance of steel slags compared to the limestone and basaltic aggregates.

With the aim to define innovative solutions for asphalt pavement to be used along the highway network, the research center of Fiano Romano (RM) investigated the friction properties of asphalt mixtures made with the addition of steel slag. The project approach aimed at the development of a sustainable engineering where the supply of natural sources is limited, and the use of recycled materials is encouraged.

A further laboratory study [Nodari, Crispino & Toraldo, 2020] focused on the evaluation of the effects of both high amounts of reclaimed asphalt (RA -- from 15 up to 60% by weight) and RA plus steel slag aggregates (from 55 up to 71% by weight). The investigated mixtures were found to be promising for future development of bituminous mixtures with high environmental compatibility.

In a field experiment, the authors experimented with an asphalt surface treatment where the aggregate component was essentially made of steel slag [Tozzo et al, 2022]. As a guide for the design of a proper mix for a layer thickness of 25-30 mm, a discontinuous grain size typical of stone mastic asphalt (SMA) was used. The new mix was named Grip Mastic Asphalt (GMA) and was laid in a curve on the Italian A1 motorway. It was compared to a “traditional wearing course” nearby, as well as a “micro-surfacing” called Griproad. The following results were achieved (somewhat edited by this author):

- GMA costs are equivalent to an open graded wearing course of the same thickness
- Field measurements confirm that the performance of GMA in terms of adherence are higher than a traditional wearing course
- The performance of GMA in terms of adherence are comparable to that offered by GRIPROAD, since the lower microtexture is partly compensated by an excellent macrotexture (important in wet pavement conditions) obtained from the particular particle size of the GMA mixture
- The GMA is compatible with the underlying layers of traditional bituminous asphalt pavement, differently to GRIPROAD where the resin-induced cracking lead the deterioration of the support
- The GMA could be easily integrated in the production of a traditional asphalt plant commonly used in the maintenance works.

5.5 Application of steel slag in asphalt pavements in South Korea

The following is the result of a presentation made by Dr Kyungwon Park at Pavetec Korea at the international conference ICRE 2022-10-05 [Park, Lee and Jang, 2022] and a follow-up meeting 2022-10-16 between Dr Park and this author [Park, 2022].

In South Korea, it is predicted that natural aggregate resources will be exhausted within 20 years. Under these circumstances, 7.2 million tons of steel slag produced annually and currently being mostly deposited, has become interesting as an important resource that can replace natural aggregates. However, it is just recently when this opportunity has been subject to trials.

So far two trials have started and are ongoing, being reported in a presentation in October 2022 [Park, Lee and Jang, 2022]. The first attempt used steel slag in an asphalt mix on the “Hyun Dai Steel Access Road” in Incheon, which now had been monitored for 63 months. Experience and test results of this field experiment were presented, but also a lot of laboratory tests were reported.

Hyun Dai means the same as Hyundai. Hyundai Steel Co., Ltd, is a steel producing company which is a member of the Hyundai Motor Group. Therefore, the tested road is an access road to the steel company. This road carries 99 % of heavy trucks, at a low speed (20 km/h).

It should be noted that in South Korea the dominating road pavements are SMA13 and AC13 (the latter referred to as “HMA” for Hot Mix Asphalt). They are, by regulation, paved with a thickness of up to 50 mm (minimum 2.5 times the max aggregate size). In the presented comparisons, the AC13 (“HMA”) is the reference unless otherwise is mentioned. When steel slag is used it is replacing the stone aggregate in the HMA for the gradings of 5 mm and above. The author thinks that it is a pity that the comparison was not made with SMA13 which would have made it easier to compare with Swedish conditions.

Two of the three Korean authors have a connection to the steel making company, but Dr Park has an own independent consulting company (www.paveteckorea.com). It is possible that the study has been sponsored by Hyundai, which means that it cannot be excluded that some statements or predictions are coloured by this.

First, Figure 5-1 shows properties of the slag aggregate according to the study. Then, Table 5-2 shows results of laboratory tests of the mix used in the field experiment.

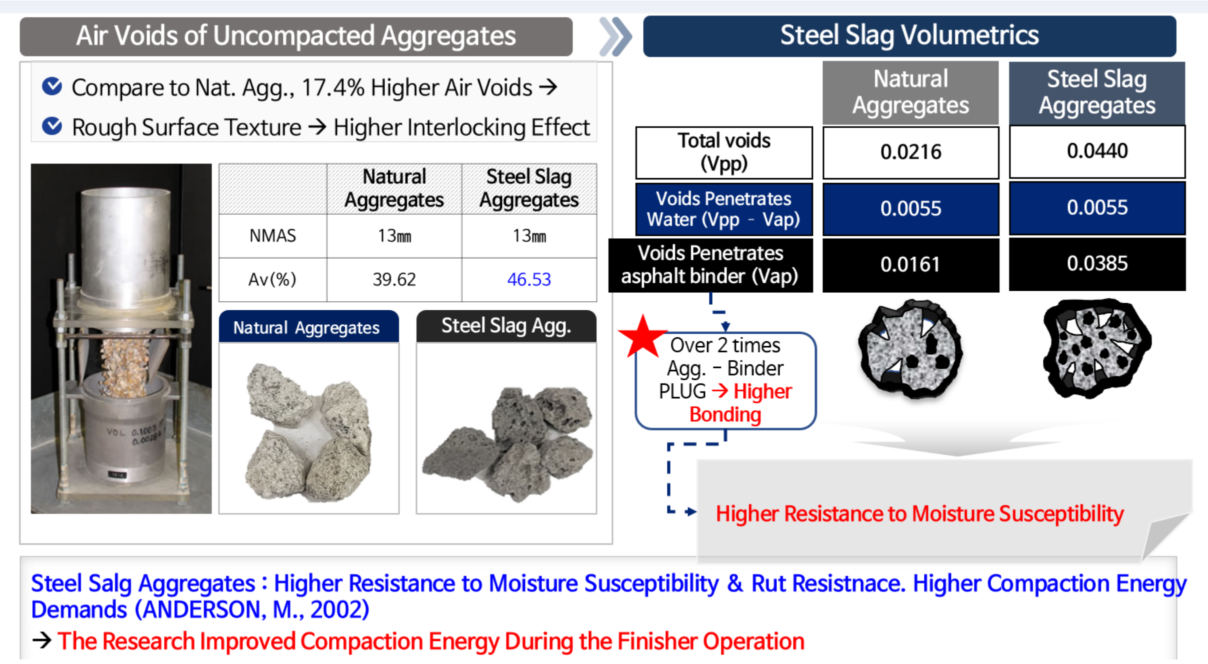


Figure 5-1: Page from [Park, Lee and Jang, 2022] showing properties of steel slag vs typical natural aggregate. NMAS is Nominal Max Aggregate Size, Av% is air voids in a mix of unbound aggregate.

Table 5-2: Test results of HMA with steel slag vs typical natural aggregate; from [Park, Lee and Jang, 2022]

No.	Test Types	Test Results			Remarks
		Test Condition	HMA	Steel Slag	
1	Dynamic Modulus Test	54℃, 10Hz	864MPa	1,302 MPa	Rut Resistance 1.5 Times Increase
		20℃, 10Hz	9,412 MPa	8,493 MPa	Crack Resistance 1.1 Times Increase
2	Accelerated Pavement Test	Rut Depth @ 563,200 (ESALs)	16.1㎜	8.5㎜	Rut Resistance 2.0 Times Increase
3	Pavement Condition Survey	Performance Life @ NHCPI = 4.0	App. 30Months	App. 64Months	Performance life 2.0 Times Increase
4	FWD Test	Elastic Modulus	Avg. 390	Avg. 552	1.4 Times higher Elastic Modulus
5	Acoustic Absorptivity Test	Variable Hz Acoustic Absorptivity Coeefficient	Avg. 0.30	Avg. 0.34	Acoustic Absorptivity 2~9% Increase
6	Road Noise Test	CPB	Avg. 82.4dB	Avg. 75.6	Road Noise 5~9dB Decrease

Comments to Figure 5-1:

- Compared to conventional aggregate, in an unbound and uncompacted mix, slag has 17 % higher air voids
- The rougher surface texture of the aggregate of the slag gives a higher interlocking effect (this author's comment is that this must depend on which aggregates one compares)
- Steel slag aggregate (the individual particles) has a more porous structure than natural aggregate (4.4 % compared to 2.2 %) which means that asphalt binders can penetrate substantially better into the aggregate surface of steel than stone aggregate (Vap 3.8 versus 1.6 %) and thus provide better bonding. This author's comment is that also this must depend on what kind of aggregates are used; however, this property is well recognized in the literature.
- It follows that steel slag also gives higher resistance to breakup due to moisture.

Comments to Table 5-2:

- It is remarkable that the accelerated pavement test (a rig with heavily loaded tyre rolling straight forward and backward) showed two times better rutting resistance
- That "road noise" was reduced by 5-9 dB is based on a very questionable CPB measurement with one car and should not be considered as trustworthy according to this author.
- The measurement of sound absorption was made by another company, using the narrow tube, which is not the best one to use here, and the results of an absorption coefficient of 30-34 % are far from realistic.

The following observations are noteworthy regarding the field test on Hyun Dai Steel Access Road:

- Under the conditions mentioned, at a service time of currently 63 months, crack resistance had improved by a factor near 10, which is inconsistent with the laboratory test which showed just 10 % improvement
- Under the same conditions, rut resistance was 30 % better, IRI was 20 % lower and (predicted) lifetime was 2.2 times longer.
- The mentioned results were measured by a Korean "Pavement Condition Survey Vehicle KRISS".

It should also be mentioned that the Korean authors have found that applying an additional vibration compaction force behind the finisher (but integrated with it) will save the number of compactions by a roller from 3 to 2, which saves production time; see Figure 5-2.

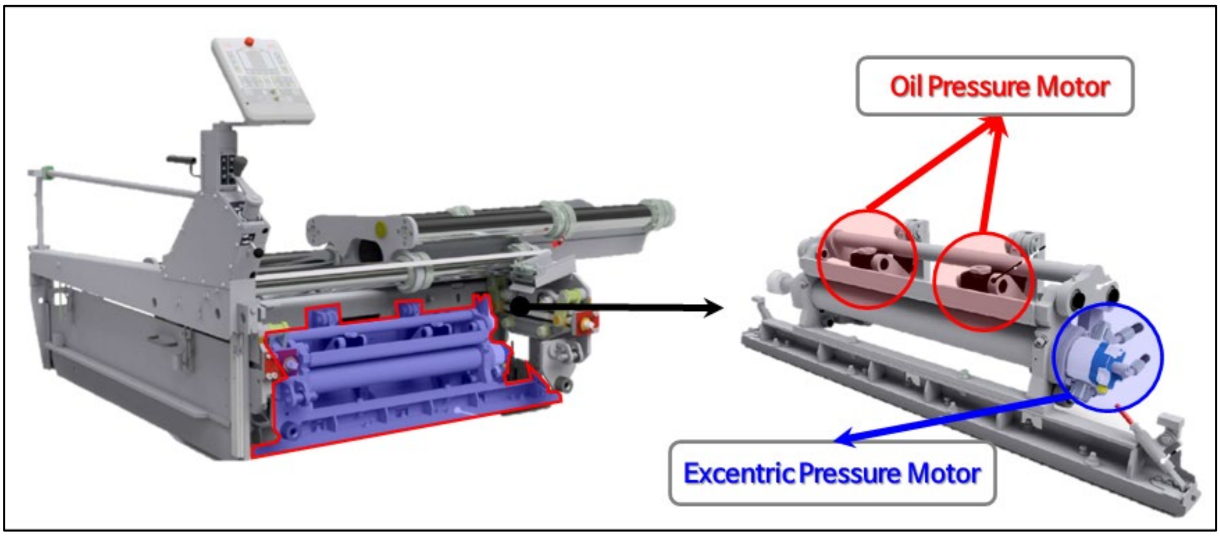


Figure 5-2: The extra vibrator applied on the finisher (see text).

In the other field study, Dr Park has paved steel slag mixed as an SMA on the Seoul-Incheon Highway Underpass (a tunnel in Incheon City Michuhol-Gu). As in all cases so far, the steel slag aggregate is only used for the gradings above 5 mm; the smaller aggregate and filler are normal.

There is then a bottom layer of SMA13 and a top layer of SMA10, it is unclear why this is so. Due to temporary flooding in the tunnel, following a sea level increase, the regular pavement there (an SMA 13) has had to be repaved each year (!). However, the new pavement with steel slag has not yet had to be repaved, due to its better resistance to moisture. In one of the tunnel directions, the first slag pavement was constructed in Nov. 2019 as a trial. Since the road authority was very satisfied with the trial the other direction (two lanes) was paved in June 2020. It is a little unclear whether the slag explains all the improvement, but it looks good. See Figure 5-3.

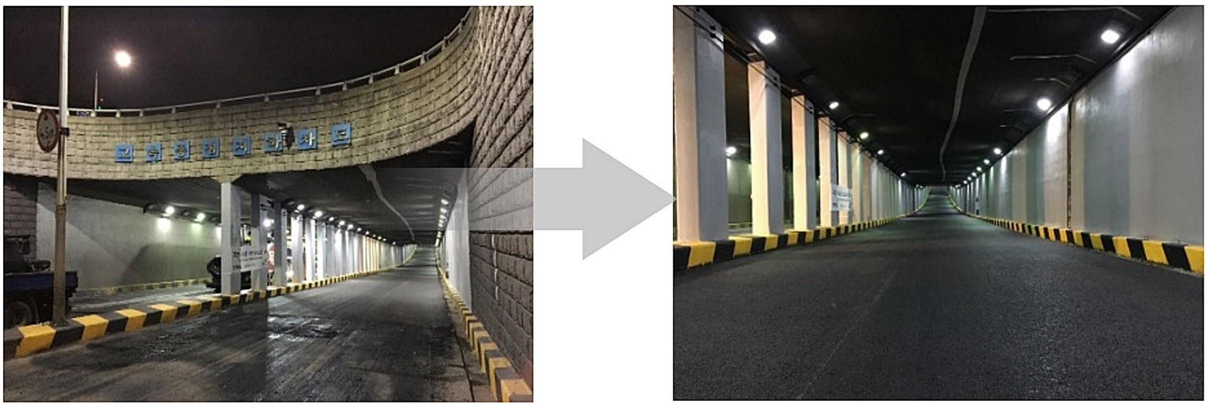


Figure 5-3: The tunnel in Incheon City which was repaved with a steel slag pavement, before and after the June 2020 construction.

In addition to the above study, the same author is currently starting research on using steel slag also in a porous asphalt pavement. However, no publications are yet available.

As for the availability of steel slag for road pavement use, it was claimed that a great part of the South Korean highway network could potentially be paved with steel slag and be a solution to the projected depletion of natural aggregate sources. The material would not be expensive as it is a by-product, but it was admitted that transportation from the three steel mills in South Korea to the road locations would be a challenge. However, with exception of one province, most of South Korea could be reached with sea, river and road transportation of the heavy material.

It is claimed that the increased transportation costs would be more than balanced out by the longer lifetime of steel slag pavements compared to regular HMA. However, the road authority has not yet accepted that economic expectation. Nevertheless, the pavement has recently got a certificate to be used on highways. Dr Park expects to pave about 30 000 tonnes of slag pavement next year.

5.6 Application of steel slag in asphalt pavements in Singapore

Steel slag has been used as an aggregate in road pavements in Singapore since the 1990’s. In an experimental study, data obtained from network-level condition surveys using Sideway-Force Coefficient Routine Investigation Machine (SCRIM), Laser Crack Measurement System (LCMS), and Falling Weight Deflectometer (FWD) were analyzed, using different analytics tools to assist with maintenance decision making [Nyunt et al, 2022]. As a part of this study, a pavement with steel slag was included.

Three different asphalt mixes were evaluated: (i) gap-graded asphalt mix with 50 % calcine bauxite aggregates, denoted as M1, (ii) open-graded asphalt mix with 100 % steel slag aggregates, denoted as M2 and (iii) gap-graded asphalt mix having the same gradation as M1 but with 100 % granite aggregates, denoted as M3. Each of them was evaluated on three different locations which had pavements of different ages (1-119 months).

In summary, from the safety condition assessment, it was observed that the asphalt mix with calcine bauxite aggregates (M1) provides a good and sustained skid resistance over the longer lifespan, compared with the other types of asphalt mixes with steel slag (M2) and granite aggregates (M3), which had similar skid resistance performance. The calcine bauxite asphalt mix has shown to be one of the effective measures in reducing self-skidding incidents.

In a follow-up to the SURF 2022 paper, this author has communicated with the main author [Nyunt, 2022] since the porous asphalt with steel slag used in the study (pavement type M2) is highly relevant for this report. This has resulted in the following information from two earlier papers.

In an earlier study, steel slag aggregates of the EAF type were used to replace granite aggregates (for the entire grading) in the construction of a porous asphalt (PA) pavement [Fwa et al, 2013]. Two new asphalt mix types using steel slag aggregate of different gradations (i.e., maximum aggregate size of 13 mm and 16 mm) were tested in the laboratory and then their performance was monitored on a road. These were only single-layer PA:s with designed air voids content of approximately 15 % (*note that in Sweden, we do not consider such pavements as effective for noise reduction*). The reference (conventional) mixes were a traditional dense-graded mix W3B used in Singapore (only used in the laboratory tests), as well as two mixes used in Singapore which are named Drainage mix (20-25 % voids) and a wearing course designated OGW (voids 7-9 %). They had maximum aggregates of 16 mm and 13 mm, respectively, and used polymer modified binder.

From the results obtained in the field tests, covering a 4-months monitoring period, it was observed that the new asphalt mixes with steel slag provided sufficient drainage of water, displayed comparable wet-pavement skid resistance (measured by SCRIM) and better reduction in tyre/road noise as compared with conventional types of asphalt mix used in Singapore back then. The authors noted that macrotexture of the steel slag mixes visually was lower than that of the conventional mixes and assumed that this was the reason for the results. This observation was also reported in the subsequent study in [Yoong et al, 2019].

In a later paper [Yoong et al, 2019], steel slag was used as the aggregate in a single-layer porous asphalt mix (max. aggr. 13 mm, voids 14 %) and compared with a gap-graded mix (max. aggr. 19 mm, voids 8 %) and a dense mix (max. aggr. 19 mm, voids 5 %). The two latter mixes had conventional granite aggregate. This design does not make it possible to draw conclusions about the performance of the steel slag. However, the purpose of that study was to investigate the effect of adding crumb rubber or natural rubber latex to each of the above mixes.

Among the results relevant to the present report, it appeared that noise levels (measured with the OBSI method) were consistently 1-2 dB lower for the latex modified binder (7.5 % of the binder weight) than for the PMB binder of the steel slag mixes. The effect of the crumb rubber was inconsistent and insignificant. Both the latex and crumb rubber additions (for steel slag mixes with similar design voids content) reduced the permeability of the mixes substantially in the lab. In this study, the mix with the highest voids gave a substantially lower noise emission, namely approx. 5 dB (also aided by the lower aggregate size).

A few additional observations by [Nyunt, 2022] are worth mentioning here:

- Vehicle drivers appreciate the improved contrast between road markings and pavement of the relatively dark steel slag as the pavement looks new all the time.
- For minor repairs, usually conventional asphalt is used, which will leave distinct patches in the surface, visually emphasizing that there are repairs.
- Asphalt mixes with steel slag aggregates are susceptible to workmanship, resulting in excessive/premature loss of aggregates at some of the project sites.

5.7 Application of steel slag in asphalt pavements in Malaysia

A study in Malaysia was conducted to investigate the use of steel slag as a conventional aggregate replacement in porous asphalt mixtures [Hainin et al, 2014]. Two porous asphalt gradations, designated as Grade A and Grade B, were used in a laboratory study in accordance with the new Malaysian specification for porous asphalt. Air voids and max aggregate sizes were not specified in the paper.

The samples of steel slag aggregate mixtures produced were tested for resilient modulus, rutting and permeability, which were later compared with conventional aggregate mixtures. The conventional aggregate was obtained from "Malaysian Rock Product (MRP)" quarry. The results show that there is a significant difference in terms of resilient modulus between the steel slag aggregate-based mixture and the conventional aggregate-based mixture. The same scenario was observed in the rutting test, where the steel slag aggregate mixture possesses a higher rut resistance. However, the mixtures made from conventional aggregate had higher permeability values compared to the steel slag mixtures. It was concluded that the use of steel slag could perform admirably during high traffic loading.

The paper mentions an interesting feature of steel slag, namely that this slag aggregate retains heat considerably longer than natural aggregates (*this is due to the higher mass*). The higher heat retention of steel slag aggregates can be advantageous for asphalt pavement construction, as less energy is used during the paving works.

5.8 Application of steel slag in asphalt pavements in Australia

In the 1990's in Australasia[1] there were significant improvements in road technology, particularly in the area of pavement materials development and road stabilisation. Slag played a significant part in these improvements. Moreover, there is now considerably more data available on the performance of slag-based road materials to the extent that slag materials and blends are now considered to be a premium roadbase material and stabilising binder by many experienced users [ASA, 2002].

To provide support for this development, an organization covering the Australasia region, named Australasian Slag Association Inc. (ASA), has been established. ASA published its first guide for use of slag in roads already in 1993 and has since updated it and published another one [ASA, 2002][ASA 1999]. The latest guide even includes a long list of typical examples of the use of slag on roads in the Australasia region; all of them in Australia. However, from the previous sections, we know that a lot of such pavements already exist also in Malaysia and Singapore. This list includes roads in cities, on highways and expressways.

These ASA guides are, as far as this author is aware, the most comprehensive guides currently existing on this subject. In addition to the guides, the Australian state Victoria, has published a Technical Note on Steel Furnace Slag Aggregate" [Anon., 2011]. This Note lists the following possible applications of steel slag in roadworks:

- Sprayed sealing and asphalt applications
- Skid resistant sealing aggregate
- Base and subbase pavement construction
- Hard stand areas
- Construction fills
- Subsurface drainage filter materials
- Grit blasting.

The features of steel slag aggregates are listed as follows:

[1] Australasia in this case is Australia, New Zealand, Indonesia and other south-east Asian countries.

- Strong and very durable.
- Excellent cubical shape which creates very strong interlocking properties as well as minimizing potential shear failures.
- High resistance to abrasion and impact, which provides increased serviceability advantages
- High skid resistance due to high polished aggregate friction values
- Strong affinity to bituminous binder due to its high alkalinity
- Recovered by-product, reducing mining of virgin aggregate resources
- Typically denser than natural rock aggregate.

As a potential disadvantage the note mentions a certain expansion due to small percentages of unhydrated lime inclusions can remain undissolved in the steel slag. Expansions of 2 – 20 % have been reported. Therefore, aggregates must be allowed to undergo a conditioning (weathering) process to reduce the quantity of free lime to acceptable limits prior to use in road construction. In order to achieve this, steel slag aggregates should be allowed to stand in stockpiles exposed to the weather for a period of one to three months. An acceptable method for conditioning in Australia is to thoroughly water the slag one day per week over a four week period (or longer if appropriate) to create a “dry and wet” cycle [Anon., 2011].

Although the ASA guides do not consider leaching of harmful substances as a problem, the reader may want to check Section 5-9 below.

The ASA Guide of 2002 lists suitable applications of slag in road pavements (Table 5-3). Note that blast furnace slag is not listed as suitable for heavy duty roads and roundabouts and is not used in asphalt wearing courses.

Table 5-3: Suitable applications of steel slag aggregate in road pavements. BOS = basic oxygen steel, EAF = electric arc furnace. From [ASA, 2002].

Application	BOS & EAF Slags	Blast Furnace Slag
Asphalt	All applications including; heavy duty roads and high stress areas like roundabouts	Lightly trafficked roads, intermediate asphalt layers, carparks.
Sprayed sealing	All applications including; heavy duty roads and high stress areas like roundabouts	Lightly trafficked roads, carparks, Strain Alleviating Membrane Interlayers (SAMI) applications.

5.9 Steel slag in China

The annual output of steel slag in China is about 100 million tons (the largest in the world), and the cumulative stockpile stock has exceeded 1 billion tons. However, in China, the utilization rate of steel slag is only 30 %. The continuous increase of steel slag accumulation has become a problem affecting the sustainable development of China’s and even the world’s steel industry [Gan et al, 2022].

Given this huge steel slag resource in China it is no surprise that there are numerous articles or other documents from China dealing with utilization of steel slag in pavements. The following is only a small selection of references.

The feasibility of using steel slag aggregates in SMA mixtures has been studied by [Wu et al, 2007]. Both laboratory and field studies were made. Steel slag was obtained from Wuhan Iron & steel (Group) Corporation by a hot-sprinkling method and used as substitute for basalt. After three years of aging, the f-CaO (free calcium oxide) content of steel slag fell below 6 % which was accepted. The most essential conclusions included:

- All the volume performances of SMA mixture containing steel slag as aggregates can meet the related requirements of specifications, though the substitution of steel slag for basalt increases the optimal bitumen content slightly.
- Expansion rate of SMA mixture with steel slag is below 1 % after seven days, which ensures the stability of steel slag in SMA mixtures.
- Compared with SMA mixture with basalt, the high temperature property of SMA with steel slag is improved, the better physical properties of steel slag enhance the ability of resisting permanent deformation at high temperature.
- The test roads showed excellent performances after two years of service.
- Consequently, steel slag obtained by the hot-sprinkling method, after three years of aging, is a very suitable aggregate with porous structure for preparing SMA mixtures.

The asphalt absorption of steel slag has been studied by [Chen et al, 2013]. These authors consider that “the huge asphalt absorption of slag has been a main obstacle to the utilization of slag”. The results they present suggest that the value of asphalt absorption of steel slag (AAOS, which is the weight of asphalt absorbed by per 100 g steel slag) is much higher than the ones of limestone or basalt.

An interesting application of steel slag in winter climates such as in Sweden, is the possibility of using it for de-icing purposes. Chinese researchers have explored the feasibility of the usage of steel slag as the aggregate of asphalt mixtures for microwave de-icing [Gao et al, 2017]. The idea is that steel slag is much easier to heat with microwaves than conventional aggregates. Objectives included to ascertain the most effective volume and particle sizes for partial replacement of conventional aggregate. The de-icing mechanism of microwave heating pavement seems to be used already in China, as it is claimed in the article that “microwave heating (MH) vehicles in China have been well developed, and their schematic diagram is shown in” Figure 5-4.

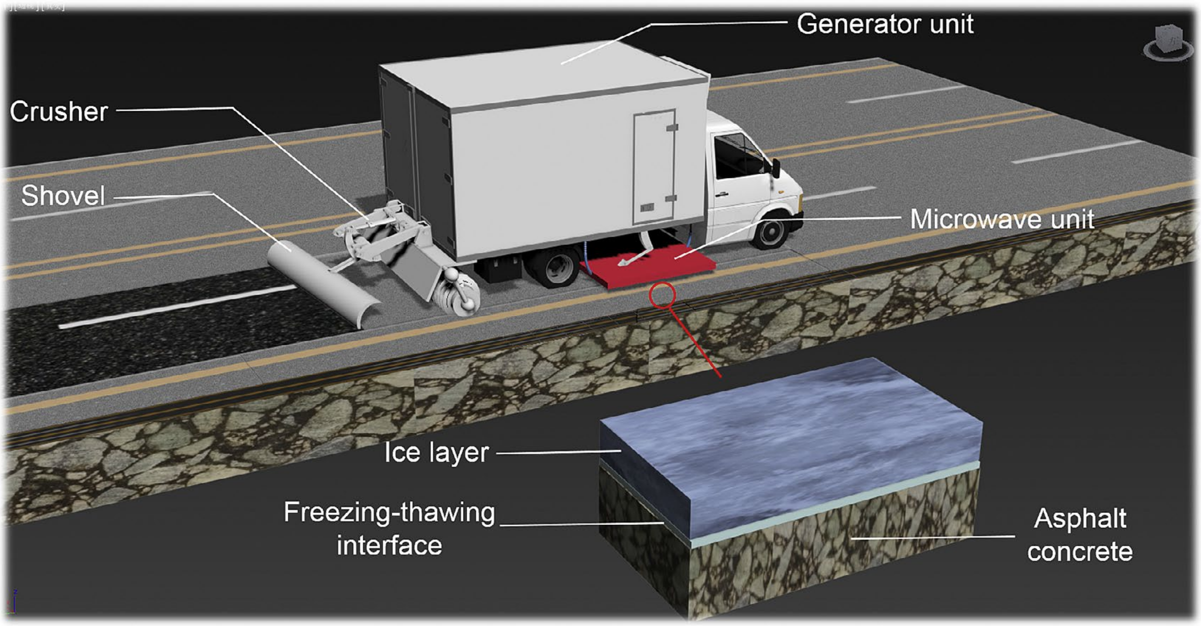


Figure 5-4: The Chinese MH vehicle. From [Gao et al, 2017].

Unfortunately, the article does not present any actual field experiment in which a road has been de-iced. Instead, it includes several laboratory experiments. It has been found that the particle sizes of 9.5 mm, 2.36 mm and 0.6 mm are considered as the most effective sizes. The suggested steel slag volume content is 40 % and 60 %; and the particle sizes of steel slag are selected as mentioned above. One of the potential problems is mentioned as the risk of overheating the pavement. The comprehensive evaluation results on supply sources, environmental hazard and cost vs benefits of steel slag show great feasibility of its utilization in asphalt mixtures for microwave de-icing, which is helpful to alleviate the supply shortage of natural aggregates and improve the safety of road traffic in winter.

The optimum content of steel slag in SMA 13 asphalt mixes was investigated by a group of Chinese researchers [Gao et al, 2021], and the performance of these mixes was evaluated. Five SMA 13 asphalt mixes with varying steel slag content (0 %, 25 %, 50 %, 75 %, and 100 %) were designed and prepared experimentally. The fine aggregate part was limestone with a particle size of 0–3 mm. Several laboratory tests were made. The results showed that compared to normal SMA 13 asphalt mixes, the high-temperature stability, water stability, and shear resistance of the SMA 13 asphalt mixes increased and then decreased as the steel slag content increased. The dynamic modulus of the SMA 13 asphalt mixes increased with increasing steel slag content, but the volume expansion at a 75 % steel slag content was 0.446 % higher than at a 0 % steel slag content. Based on the experimental results, the optimum content of steel slag for SMA 13 asphalt mixes was determined to be 75 %. It should be noted that the conventional aggregate replaced by steel slag was limestone, as this is a common aggregate in China.

Although it is stated in the article that “Road performance verification was performed”, there was actually no on-road experiments reported.

Another laboratory study about the microwave heating revealed that when 50 % of 4.75–9.5 mm aggregates and 50 % of 9.5–13.2 mm aggregates were replaced by steel slag, the microwave heating efficiency was optimal [Chen et al, 2022].

Not many Chinese studies appear to have tested long-term performance of steel slag pavements. An exception is a study by [Li et al, 2022]. To study the performance degradation of asphalt mixtures with various content of steel slag under heavy loading, some large-sized basalt hot mixed asphalt mixtures (BHMA) and steel slag hot mixed asphalt mixtures (SHMA) were prepared in a form of specimens and a heavy loading wheel tracking test was conducted. The maximum aggregate size was 16 mm and the filler material was always basalt. The aggregate characteristics of basalt and steel slag were measured. The deformation and skid resistance of the asphalt mixture with different content of steel slag was tested and analyzed. The test machine was a “Multifunctional pavement material tester” at Wuhan University.

Due to the particle characteristics of steel slag aggregate, it was found that a low content of steel slag can effectively improve the resistance to deformation and skid resistance of the asphalt mixture under heavy loading. The response of SHMA can still meet the pavement technical requirement after long-term heavy loading service. The main change in the mixture under heavy loading is the crushing of the 9.5–16 mm aggregate, and the content of this part also significantly affects the deformation. The deformation/rutting is shown in Figure 5-5. It appears that the lowest rutting is obtained with 25 or 50 % steel slag proportion. This study explains the mechanism of degradation of SHMA under heavy loading: the large aggregate is crushed and forms a new aggregate skeleton structure.

The study also shows that the steel slag aggregate (even when only 25 % is slag) is superior to polishing, as measured with the British Pendulum Tester. Texture depth decreased dramatically already after 10 000 cycles in the loading tester and stabilized between 0.5 and 1.0 mm, where the steel slag had higher texture depth than the basalt.

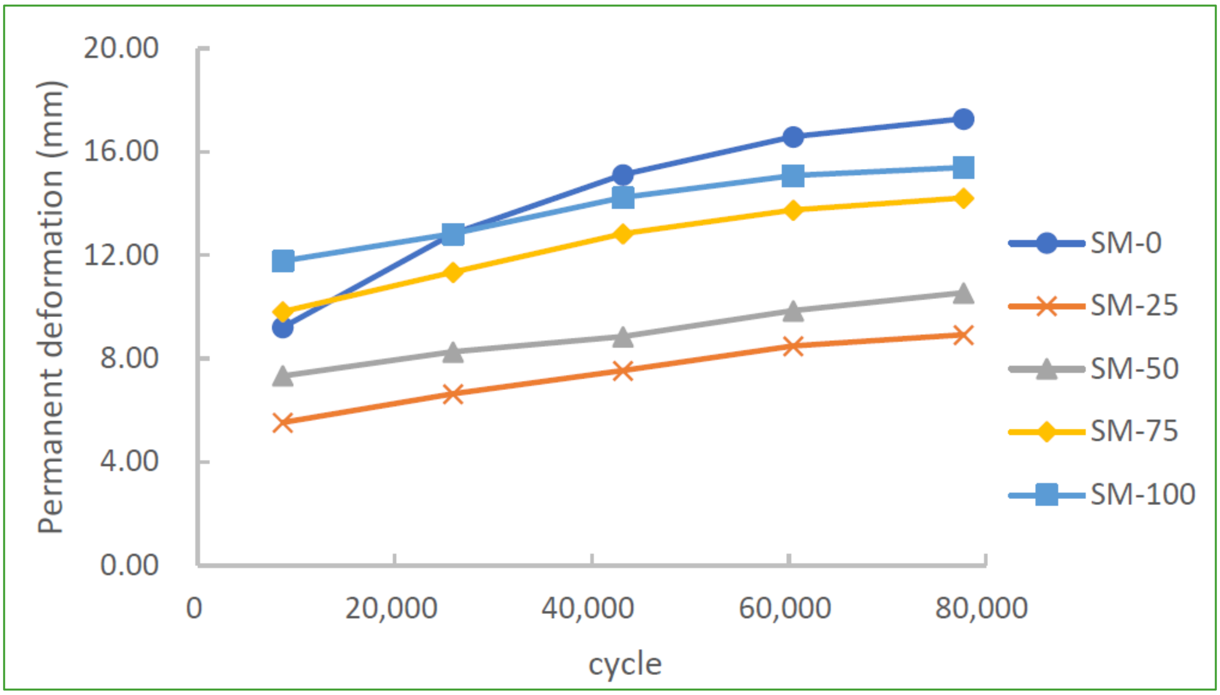


Figure 5-5: Effect of steel slag content on permanent deformation. SM-0 – SM-100 are indications of the proportion of conventional aggregate replaced by steel slag, where 0 is no slag (100 % basalt) and 100 is 100 % slag. From [Li et al, 2022].

The large-scale promotion of steel slag (SS) in pavement construction remains challenging due to the concern of swelling potential, according to [Liu et al, 2023]. That study combined molecular dynamics simulations, surface free energy theory, and X-ray computer tomography to characterize the moisture damage resistance of asphalt mixtures incorporating SS. A case study of the life cycle assessment of SS asphalt pavement under different application strategies (two gradation types and three volume contents) was conducted, including global warming and human-related health impacts. The results indicate the higher polarity and abundant alkaline components of SS contribute to the bonding strength and tend to reduce the moisture susceptibility. The adhesion of steel slag to asphalt is 137.58 %, 120.39 % and 37.06 % higher than that of granite, basalt, and limestone, respectively.

The increased consumption of asphalt and transport mass of SS during mixture production are detrimental to the overall environmental impacts. However, the use of SS avoids the damage of exploitation (*the authors refer to stock-piles of slag*) and eliminates the huge risks of landfill accumulation. These two benefits are enormous and cannot be accurately estimated, according to [Liu et al, 2023].

Another very recent Chinese article has studied how conventional and steel aggregates can be best mixed [Ji et al, 2023]. The authors were concerned that different wear resistance could lead to differential wear among the aggregates. They found that 50 % steel slag maximised the differential wear effect and gave the highest tyre/road friction and the “richest” surface macrotexture. The authors recommended that the steel slag content in the steel-slag-modified SMA should not exceed 50 %. The more mineral composition and higher average hardness of steel slag were the sources of its excellent skid resistance. This author’s comment is that the results will depend on the wear properties of the aggregates selected.

5.10 Application of steel slag in asphalt pavements in Spain

The properties of Electric arc furnace (EAF) slag were studied in a Spanish review article [Skaf et al, 2017]. Its main properties, the problems with its application, and the important features of the mixtures made with this slag were analyzed. It was concluded that the use of EAF slag is mainly recommended in partial replacement of the coarse aggregate, in all types of bituminous mixtures, following appropriate pre-treatment. This use of the EAF slag improves the mechanical performance and durability of the mixes, as well as their long-term sustainability, according to [Skaf et al, 2017]. This review is very well done and is highly recommended for those who need to learn more about this subject.

In a later article, with the same first author, a porous asphalt mixture with Ladle Furnace Slag (LFS) was studied [Skaf et al, 2019]. This paper presented a pilot experience of applying a Porous Asphalt (PA) mixture that incorporated LFS. The overlay of a thin surface layer of this material was applied to an existing (dense) bituminous pavement. The LFS was mixed with coarse and fine siliceous aggregates, while the filler was limestone. Note that the LFS was only of fractions up to 4 mm (with 20 % being filler); i.e., the coarse aggregate was siliceous. The PA mix used max. aggregate size of 11 mm and 20 % of air voids target. Thus, the combination of the components resulted in 81.1 % of coarse siliceous aggregate, 5.6 % fine siliceous aggregate, 10.0 % LFS and 3.3 % of limestone filler (by weight of the total aggregates).

The main investigative results included the validation of the laboratory mix design through large-scale mixing, laying, and compacting, followed by extensive laboratory and finally field tests. The field investigation used a wearing course of about 320 m^2, by applying the PA with a thickness of 4 cm, over a dense bituminous pavement in good condition. The project covered two separate areas: a parking lot of 4.5x30 m^2 and a two-lane 6.0 m wide road of approximately 30 m in length; see Figure 5-6. The location was within the facilities of the University, an access road with mainly local traffic (number of vehicles per day is around 200 light vehicles, with a negligible number of heavy vehicles.

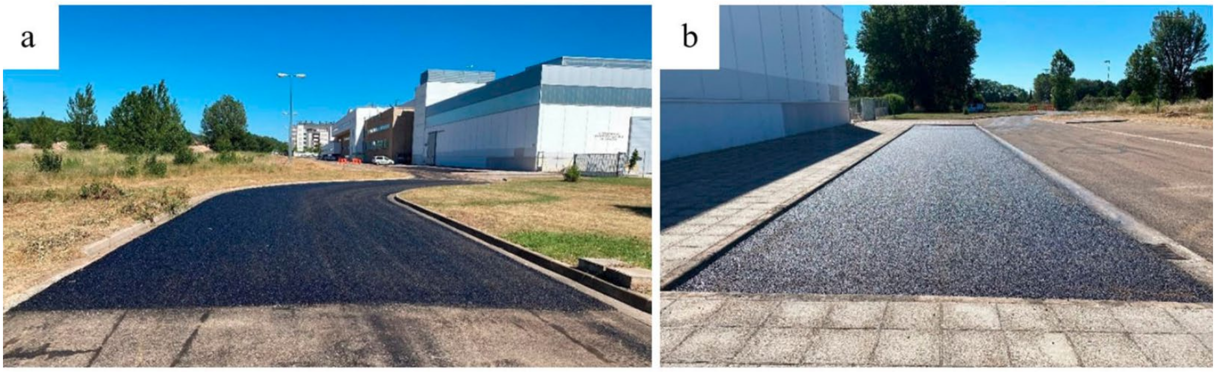


Figure 5-6: Finished pavement of the road section (a) and finished pavement of the parking lot (b). From [Skaf et al, 2019].

Laboratory tests of bore cores indicated a voids content of 21 % and permeability and skid resistance tests showed acceptable results too. Furthermore, the incorporation of up to 10 % LFS in porous asphalt mixtures turned out to be feasible, with no need for preliminary physical or chemical treatments. Neither workability nor compactability issues were observed in the execution of the pavement, and no ridging, rutting, cracking, or stripping were visible on the surface during the first months of use.

The project was later reported also in [Skaf et al, 2022]. However, despite it was published three years after the first one, that article was essentially a copy of the previous one and included no later test results.

5.11 Steel slag in USA

Surprisingly, this author has not seen a lot of literature about steel slag in pavements from USA. Nevertheless, 16 states and the District of Columbia are reported to have used steel slag aggregate (SSA), according to [Anon, 2015], where also a review for each state is listed. The review is summarized as follows: “None of the states allow the use of SSA in cement concrete applications due to the concerns for expansion. Moist curing of the SSA or an expansion test is required when the aggregate is used for non-HMA applications. Some states use uncured SSA in HMA surface course mixes; others only use it in base course mixes. Most states use the SSA as a high friction aggregate in surface courses due to an absence of hard aggregates in particular locations. The cost of SSAs is normally equivalent to the cost of natural aggregates that are imported from long distances."

Furthermore, the report states: "Most of the states that use SSA are located in the steel producing states between Minnesota and Iowa on the west and Pennsylvania, Virginia and West Virginia on the east. The requirements for acceptance of the aggregates varies between the states, with some requiring moist curing or an expansion test and others allowing its use in hot-mix asphalt without curing or expansion testing. Most states use the SSA in the top layer of the pavement to increase the frictional properties of the pavement; however, two states do not allow SSA in the top layer, so use is mixed." [Anon, 2015].

A study of special interest for Nordic winter climate was published in [Wen et al, 2015], dealing with use of steel slag to mitigate the wear of studded tyres. The study is summarized as follows: "This study evaluated the performance of hot-mix asphalt (HMA) that contains steel slag aggregate (SSA) as a surface material to mitigate studded tire wear. The physical properties of the SSA were assessed to determine its suitability in HMA. Four percentages (0, 20, 40, and 60%) of SSA were used in asphalt mixes, and the mix designs for the HMA were conducted in accordance with Superpave mix design. The performance of the mixes was evaluated comprehensively in terms of studded tire wear resistance, thermal cracking resistance, moisture susceptibility, and rutting. The results indicate that the addition of steel slag increased the mixtures' studded tire wear resistance, dynamic modulus values, thermal cracking resistance, and rutting resistance. The inclusion of SSA had no effect on top-down fatigue cracking resistance and moisture susceptibility. Based on these laboratory test results, SSA could be especially beneficial in the northwest region of the United States in surface courses where studded snow tires are used regularly, and could be used to extend the service life of the pavement.".

Indeed, it seems very promising for our project. However, note that a maximum of 60 % of the aggregate was steel slag and the reference natural aggregate was basalt. The latter material can vary a lot in abrasion value (kkv), and therefore it is difficult to evaluate the results in comparison to using rhyolite or diabase, as was used in the E4 Huskvarna pavements in Chapter 9. In the Washington project, the Los Angeles (LA) Abrasion was 18.6 % for the steel slag and 20 % for the basalt aggregate. According to some data this author has found in the literature, LA Abrasion would correspond to around 10 in micro-deval values, which would in turn correspond to a kkv value of around 14 (discussion with Dr B Kalman at VTI); i.e., far worse than the aggregates used on E4 in Huskvarna (see Section 9.2.1). Consequently, the better performance in terms of studded tyre wear of the slag in the Washington study would probably not hold for a Swedish case.

The FHWA has issued User Guidelines related to steel slag and other waste and by-product materials in pavements [FHWA, 2016]. The guidelines include extensive presentation of origin and typical material properties of steel slag and states that "Processed steel slag has favorable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics, and high bearing strength". Among the material properties, the Los Angeles Abrasion value is listed as 20-25 %, which suggests that the slag used in the Washington study mentioned above was an unusually good slag.

5.12 Leaching risk of steel slag

A Chinese study has thoroughly studied the potential for leaching of steel slag [Gan et al, 2022]. The following is a copy of the main part of the abstract, which well summarizes the study:

Steel slag has good mechanical properties, but there is a risk of leaching of heavy metal elements during the steel slag stockpiling process and after paving asphalt pavement. Therefore, this work firstly investigated the effect of different influencing factors on the leaching concentration of heavy metal elements during the steel slag stockpiling process and analysed the leaching mechanism by micro-structure. Then, the gray relational analysis method was adopted to compare the magnitude of the effects of asphalt type, grade type, binder content and temperature on the leaching con- centration of heavy metal elements in steel slag asphalt mixes. The results showed that the leaching concentration of heavy metal elements from steel slag increased rapidly due to the acid rain effect. With the formation of $CaSO_4$ crystals to fill the micro-pores on the steel slag surface, the leaching concentration of heavy metals slowed down. Cu is the element with the largest leaching risk coefficient. The increase of specific surface area and the decrease of pH value will increase the leaching risk of heavy metals in steel slag. The leaching risk of steel slag was significantly reduced after it was prepared into asphalt mixes. The main influencing factor for the leaching risk of heavy metal elements from steel slag asphalt mixes is the type of grading, the secondary factors are temperature and asphalt content. Considering the high temperature environments during use, it is recommended to use dense-graded asphalt mixtures in areas of high temperatures.

Limestone from Jiangxi Province and basic oxygen furnace (BOF) steel slag aged more than two years were used as aggregates in the Chinese study. The aggregate smaller than 4.75 mm was limestone in the prepared asphalt mixes. To illustrate how the study was made, the following Figure 5-7 is included here (is Figure 1 in the original article).

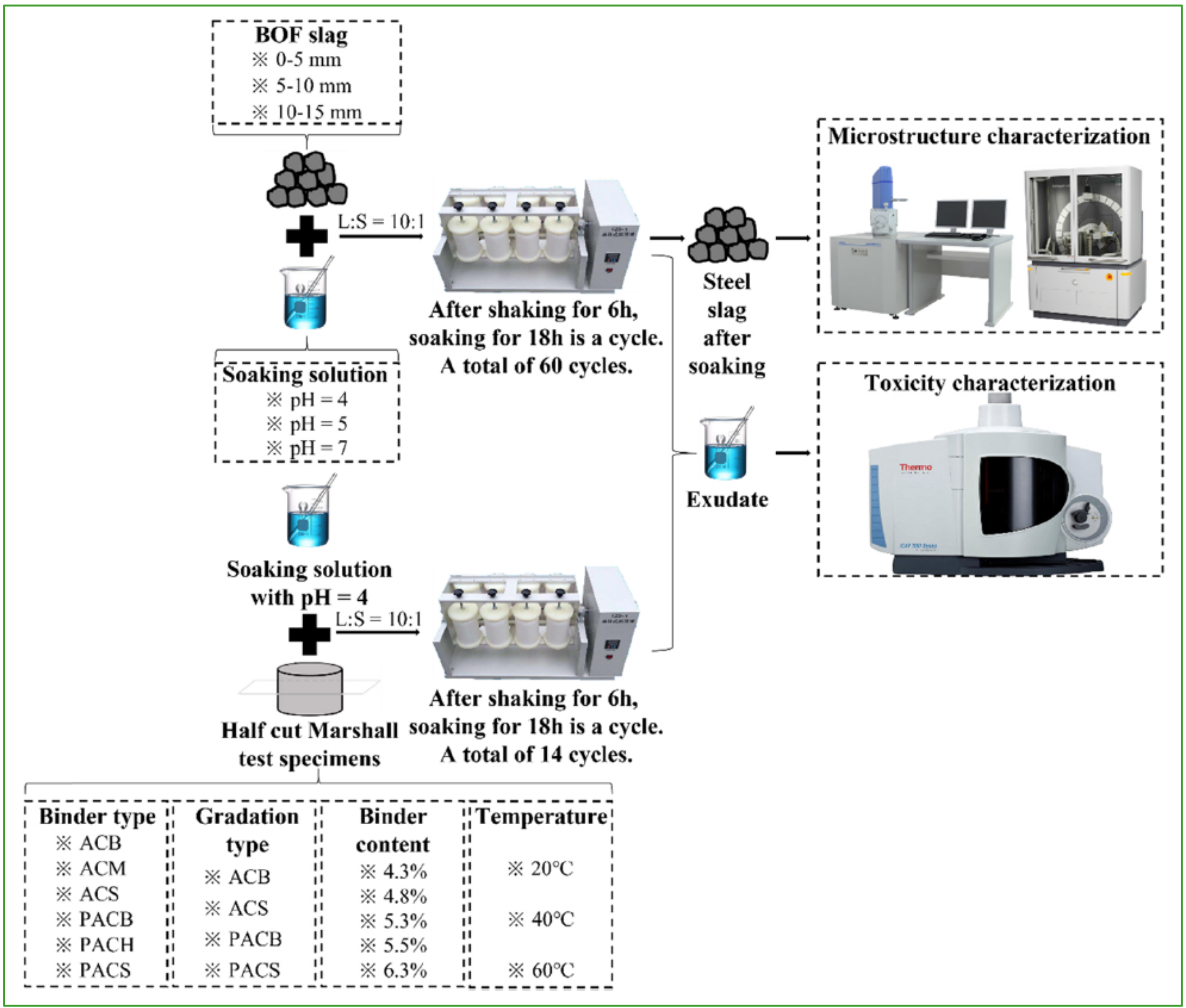


Figure 5-7: Test flow chart. Notes: L:S = Ratio of liquid mass to solid mass; ACB=AC-13 + Binder-free; PACB = PAC-13 + Binder-free. From [Gan et al, 2022].

One important thing mentioned only in the main text, and not in the abstract above, is that the leaching concentration of heavy metal elements from steel slag was significantly reduced after preparation into asphalt mixture, and it was much lower than the limit value.

Some notes by this author about the study's relevance to Swedish conditions:

- The study tested only BOS slag, not EAF or any other type of slag. In Sweden, only EAF slag has been used so far in the experiments reported in later chapters. This author does not know if this is an important issue.
- The pH value of acid rain in Jiangxi Province in China (where the study was made) is between 4 and 5. In Sweden it is somewhat higher (around 5) which may make leaching in Sweden a bit smaller.
- With the increase of temperature, the leaching concentration of heavy metal elements from steel slag asphalt mixtures increases. However, in Sweden, we generally have lower temperatures than in the region of the Chinese study.
- Finally, when the slag is incorporated in the asphalt mix, the risk of leaching is reduced substantially according to the study. This would mean that if slag stockpiles are turned into slag in asphalt pavements, it would be very good for the environment.

5.13 Other international literature

A Turkish article from Bartin University reports an extensive laboratory study of how porous asphalt using EAF steel slag aggregate (potentially) can be optimized by adding fibres of polypropylene, glass or basalt, or by adding crumb rubber for reinforcement [Oral & Cetin, 2022]. Two versions of porous asphalt were used, one with 6.0 % and the other with 6.5 % bitumen, with target air voids without additives of 21-22 %. Slag was used partly as filler and for all gradings of the aggregate, where max. size was 19 mm. See Figure 5-5 for grading curve. All combinations of the four additives, and the two bitumen contents, were subject to tests including void ratio, permeability, cantabro particle loss, indirect tensile strength (ITS) and moisture susceptibility.

A few things which stood out were:

- Polypropylene fibres of 0.4 and 0.6 % increased air voids to around 25 % (which would be very favourable for noise reduction). This can be explained by the polypropylene fibres causing shrinkage in the bitumen matrix. All other combination of fibres and bitumen content reduced the void ratio.
- The increased void ratio did not show up as increased permeability. Permeability was reduced significantly with increased fibre content and especially for the samples containing 6.5 % bitumen.
- Cantabro particle loss, commonly used to characterize ravelling sensitivity, increased substantially with the polypropylene fibres for the 6.0 % bitumen samples. This, of course, makes the gain in air voids useless. Generally, other than in the mentioned case, the Cantabro particle loss varies significantly and inconsistently with fibre content, fibre type and bitumen content.
- ITS, not surprisingly, is improved consistently by the higher bitumen content, especially with fibre contents of 0.2 and 0.4 %.
- The crumb rubber additive did not show any significant improvement.

The study includes a table with various optimum combinations; however, none that really seems generally remarkable. In case a high air voids ratio is required, as for noise reduction while still having reasonable particle losses, there is no clear winner. Figure 5-8 shows the mixture gradation (Type-3) which was selected according to the Turkish Highways Technical Specification (THTS).

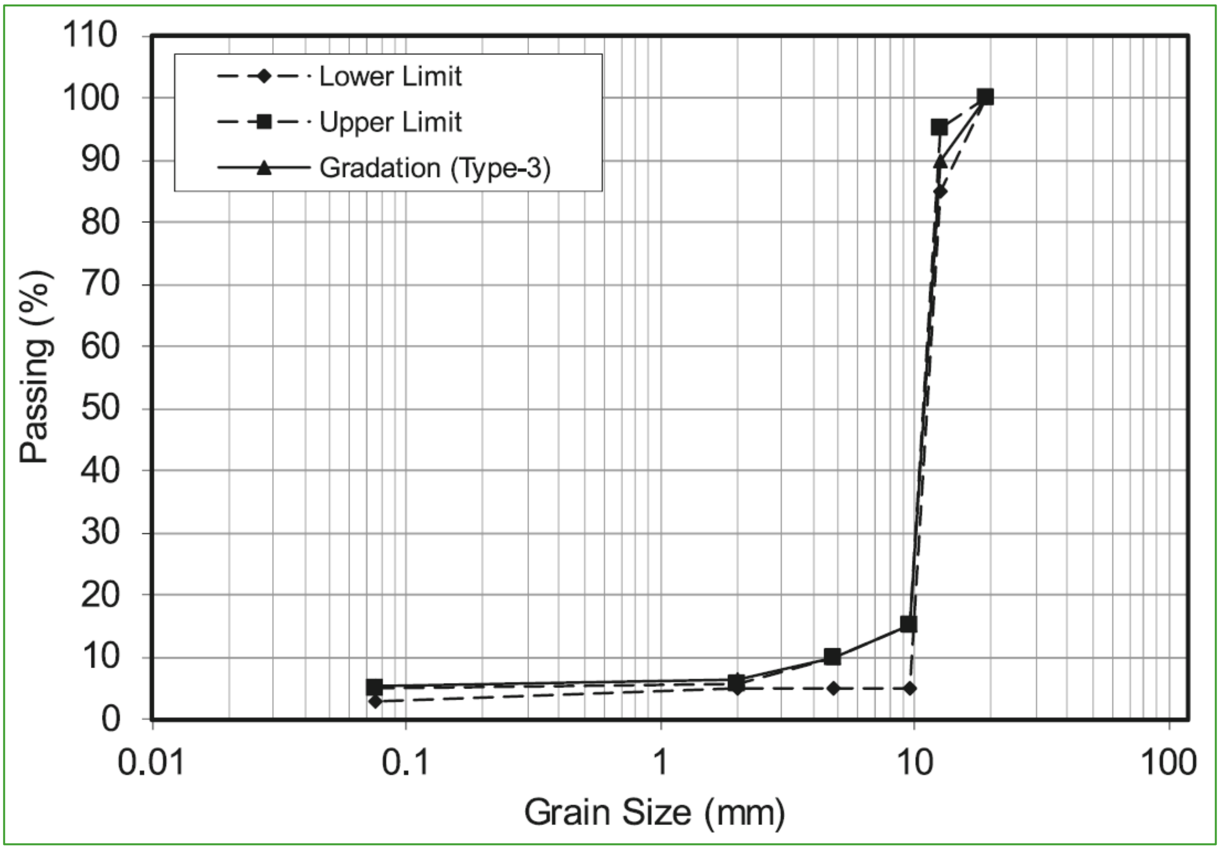


Figure 5-8: The mixture gradation (Type-3), which was selected according to the Turkish Highways Technical Specification. From [Oral & Cetin, 2022].

There is no porous asphalt road pavement in Turkey applying the result of this study; in fact, it is unclear if there is any porous asphalt pavement in Turkey.

This author has the following comments:

If it were not for the poor Cantabro results, the alternative with polypropylene fibres of 0.4 % in 6.0 % bitumen, which increased air voids from 22 to 25 % (which is difficult to achieve with steel slag), would be an attractive candidate for a low noise mix. The reason for the poor Cantabro results is thought by the Turkish authors to be that the hot asphalt binder was incompatible with the fibre due to the low melting point of the fibre. Maybe one can find a fibre which endures the hot mix?

Despite the article does not give a clear answer to which combination that is the best for application on a road where noise reduction is required, the systematic study by the Turkish authors may be a useful guide for how optimum mixes may be obtained in the future with steel slag aggregate. One shall then note that also small particles (below 3-4 mm) were steel slag, which in other literature referenced above is not recommended. Therefore, it would be interesting to repeat the study but with conventional materials below 4 mm particle size. However, the results for the performed test are not expected to be very different in such a case.

This author communicated with the article's co-author, Prof Cetin, to get some supplementary information above. The main author was a master's student.

Finally, a couple of a bit odd studies shall be mentioned, using other waste material than steel slag as aggregates in pavements.

In Denmark, NCC has recently used crushed glass particles from windows as aggregate in a pavement in Aarhus, Denmark [NCC, 2022]. The percentage of glass is 35, while the conventional aggregate is granite. They have a control section with conventional aggregate nearby. It is claimed that the cost per square metre is similar for both pavements, while the use of glass replacing granite is favourable environmentally. Now the performance of the two pavements will be compared the next years.

Crushed grass particles, although from bottles, have also been tried by Pakistani researchers [Hamid et al, 2023], whose study aimed at evaluation of various structural, functional and durability parameters of asphalt containing waste borosilicate glass (BSG). They found that fatigue resistance of asphalt was influenced negatively by the BSG, although this negative effect was insignificant for up to 5 % dosage.

Another trial with alternative aggregate is reported in [Liew et al, 2021]. Seashells were collected from a restaurant in Malaysia and prepared for use as aggregate in a porous asphalt pavement. Laboratory samples containing between 0 and 50 % seashell aggregate, maximum size 14 mm, were prepared and tested with common laboratory equipment. Results were mixed; for example, seashell mixes had lower stability but higher permeability. No field test was mentioned.

Seashells would not be in abundance in Sweden, so this material would hardly be considered useful in Swedish pavements. There would be better use of such waste material.

5.14 International standards

This author has found no European standard for the use of steel slag in pavements, but rather close is a “final draft” document from the European Commission about “Quality Protocol for Steel Slag” [Anon, 2014]. It was developed by the Environment Agency and WRAP (Waste & Resources Action Programme) in consultation with Natural Resources Wales and industry. The Quality Protocol is applicable in England and Wales. It sets out the end of waste criteria for the production and use of steel slag aggregates in construction applications. This author is not aware of any updates or further development of this. In this regard, note also the guidelines reported above, namely [ASA, 2002], [ASA 1999] and [FHWA, 2016].

ASTM International, originally a standards organization for America, but nowadays international, has a Road and Paving Materials Committee D04, which recently produced a standard for Slag Product Classification [ASTM D8021, 2020]. This document provides guidance as to the appropriate/typical mineralogy observed when iron and steel slag is produced during a variety of processes in the manufacture of iron and steel. Even more important, is the ASTM Standard Specification for Steel Slag Aggregates for Asphalt Paving Mixtures [ASTM D5106, 2022].

5.15 Summary of international experience

This literature review is not a full state-of-the-art, since it is impossible to cover all literature on this subject within the budget of this project. Nevertheless, the documents reviewed here have been selected since they are mostly very recent (most of them only one to three years old) and they of course seem to be very interesting or relevant for this project. It has been more interesting to find reports about field testing of steel slag rather than laboratory testing of small samples and if the slag has been utilised in porous asphalt it has been extra interesting.

It is amazing for this author how much literature that seems to have been published the latest years regarding the use of steel slag in road pavements. It appears to be driven by the interest in sustainable solutions of which re-use of raw material is essential. In some countries, it seems to be driven by the risk of natural aggregates becoming more and more difficult to find in needed amounts and qualities.

There seems to be extra high interest in solutions utilizing steel slag in the east Asia – Pacific region (China, Korea, Malaysia, Singapore, and Australia). There seems to be plenty of steel slag that is not yet used in other applications, while in some cases the predicted availability of quality natural aggregates may become desperate, so it will undoubtedly be an important aggregate resource in the future.

Steel slag can be considered a green resource because it has a great potential to substitute natural aggregates and reduce the environmental impact of virgin resources from quarries, as reported by, among others, [Loureiro et al, 2022] and [Park et al, 2022]. Especially, the Chinese researchers have lifted this important aspect since they have huge stockpiles and landfills of steel slag which are leaching heavy metals. Also in South Korea, it is pointed out that the natural aggregates will soon become rare and steel slag will be a good replacement.

Almost all the literature regards the steel slag as a very useful product and negative views or experience are rarely reported. Apart from the environmental advantages of utilizing waste material and saving natural resources, the following advantages and disadvantages are almost consistently reported. First the advantages:

- Mixes in asphalt pavements become strong and very durable
- The slag can be used not only in stone mastic or dense asphaltic concrete but also in surface dressings (aka chip seals)
- High resistance to abrasion and impact (however, see note below about studded tyres)
- High resistance to rutting
- High skid resistance due to generally high polished aggregate friction (PSV) values
- Strong affinity to bituminous binder due to its high alkalinity and micro-porosity
- Moisture susceptibility seems to be lower
- The darker colour gives an impression of being a newly laid asphalt pavement, and gives much better contrast to lane or other white markings on the road surface

The disadvantages or potential problems would include the following:

- There is a potential for swelling which is not always negligible
- The mass is higher for the same pavement area which increases transport cost (although quality natural aggregates sometimes must be transported from distant quarries)
- There is a variability between various slags (of course there is also a big variability between different stone material)
- Requires new specifications due to higher density and absorption of binder
- The darker colour makes it easier to spot repairs in the pavement if those are made with natural aggregates

It should be remembered that the international experience is not entirely applicable to Swedish conditions since we generally have relatively good resources of high quality natural aggregates, while at the same time needing this because of wear of studded tyres.

The literature review has revealed some properties or experience that is worth mentioning but which is not found in many documents:

A Chinese study focused on leaching of harmful substances. This appeared to be a problem in slag stockpiles, but as soon as the slag is incorporated in an asphalt mix, this is considered as negligible.

Replacing all the coarse aggregates seems to be the most common use of steel slag. However, some studies claim or show that it is better to replace the natural aggregate only partially, such as only by 50/50. This is contrary to what has been tried in Sweden.

While some studies have used steel slag for both the fine and coarse aggregates, most studies claim that one should avoid using the slag as the fine aggregate. Slag should not be used as filler.

Binder contents have been around 6 % and PMB has been used frequently. However, using crumb rubber as a binder modifier has been reported as both positive and negative.

Steel slag aggregate retains heat considerably longer than natural aggregates due to the higher mass. The higher heat retention may require less energy during the paving works.

A Chinese study reports that a pavement mix with about 50 % steel slag as coarse aggregate was favourable for de-icing purposes, through heating the road surface by means of microwave radiation from a special truck.

The use of steel slag in porous asphalt has been reported in a few cases, especially in laboratory studies, but application on in-service roads have only been reported in Singapore. No application in double-layer porous asphalt has been found.

Particularly one study exploring how (porous) asphalt mixes with steel slag aggregate can be optimized for a general purpose (which seemed to be as a pavement on parking areas) was interesting, but it failed to find a mix that would be consistently good for low noise purposes [Oral & Cetin, 2022]. Nevertheless, it should be studied in any new project aiming to improve porous asphalt mixes with steel slag aggregate.

Spanish authors reported a study of a porous asphalt mixture with Ladle Furnace Slag (LFS), which is not so common and abundant as EAF slag. They presented a pilot experience of applying a Porous Asphalt (PA) mixture that incorporated LFS, with aggregate sizes below 4 mm. An application on a non-public road with very little traffic was reported as successful.

The use of steel slag in asphalt exposed to studded tyre wear has been reported in only one case found by this author, namely in a laboratory study in the state of Washington, USA. They found that slag would be more resistant to stud wear than natural aggregate, but it appears that the natural aggregate they used was of a quality hardly accepted in Sweden.

This author has found no European standard for the use of steel slag in pavements, but a “final draft” document from the European Commission about “Quality Protocol for Steel Slag” [Anon, 2014] seems to have been an attempt. It sets out the end of waste criteria for the production and use of steel slag aggregates in construction applications. However, the ASTM International, originally based in USA but nowadays international, has very recently published two standards, mentioned earlier in this chapter.

6 Laboratory tests in this project

Soon after the start of the project, laboratory testing was made with the purpose to design a suitable and potentially durable pavement layer using steel slag as aggregate (ballast) in a noise-reducing asphalt pavement intended to be paved later.

The test objects were the following five Marshall specimens (cores with 100 mm diameter), packed manually into a highly porous mix using two different binders:

1. Porous asphalt with max 11 mm aggregate (PA 11), steel slag from Smedjebacken, with Nynäs Endura D1 binder
2. Porous asphalt with max 11 mm aggregate (PA 11), steel slag from Smedjebacken, with unmodified bitumen 70/100
3. Porous asphalt with max 11 mm aggregate (PA 11), ref stones from Skärlunda, with Nynäs Endura D1 binder
4. Porous asphalt with max 11 mm aggregate (PA 11), ref stones from Skärlunda, with unmodified bitumen 70/100
5. Porous asphalt with max 8 mm aggregate (PA 11), steel slag from Smedjebacken, with Nynäs Endura D1 binder

The following activities and standard tests were made:

1. Compaction of Marshall specimens
2. Estimations of the Marshall specimens to obtain grading curve, binder content and air voids
3. Determination of the resistance to wear by abrasion from studded tyres (a special Nordic test giving a result called the Nordic Abrasion Value, in Swedish “kulkvarnsvärde”) [EN 1097-9]
4. Los Angeles abrasion tests (aggregates in a rotating steel drum with impact by steel balls)
5. Sound absorption tests using the Kundt’s tube method

The laboratory tests are presented in Annex A of this report (in Swedish). A summary of findings follows:

1. It was necessary to base the proportioning on aggregate volume instead on mass, as the steel slag is much heavier than stones
2. The PA (porous asphalt) with steel slag and Nynäs Endura D1 binder gave acceptable results in terms of Nordic abrasion value (kulkvarnsvärde)
3. The Los Angeles abrasion tests give poorer values, but this test is much less relevant for steel slag since the heavier particles will be impacted with much higher forces than for the lighter stones
4. Use binder proportion (Endura D1) of 4.9 %
5. Air voids of 24-26 % were obtained for the slag, which gave high values for the sound absorption
6. Modified bitumen (Nynäs Endura D1) vs unmodified (70/100) gave much better results, especially for sound absorption and resistance against wear
7. The results suggest a suitable basis for field testing on motorway E4 in Huskvarna, as a top layer on the double-layer porous asphalt.

7 Measurement methods and equipment

7.1 Noise measurements in this study

All noise measurements made by VTI in this study have been made with the CPX method and using the services and "CPX trailer" of the Gdansk University of Technology (GUT). The measurement method is standardised in ISO 11819-2:2017 and using the reference tyres specified in ISO/TS 11819-3:2017. There are two microphones located beside the tyre sidewall, at a distance of 0.2 m from the sidewall (counted perpendicular to the sidewall). The tyre and the microphones are covered by an enclosure to protect it from external noise sources. Figures 7-1 and 7-2 shows the CPX trailer and Figure 7-3 the tread pattern of two reference tyres.

Figure 7-1: Overview of the measuring "CPX trailer" used in the CPX noise measurements by VTI presented in this study. The trailer belongs to GUT and is operated by its crew during our measurements.

Figure 7-2: The "CPX trailer" with its enclosure pulled up for change of tyre and for calibration of the two microphones at the left of the tyre/road contact patch. Note the sound-absorbing material covering the walls of the enclosure.

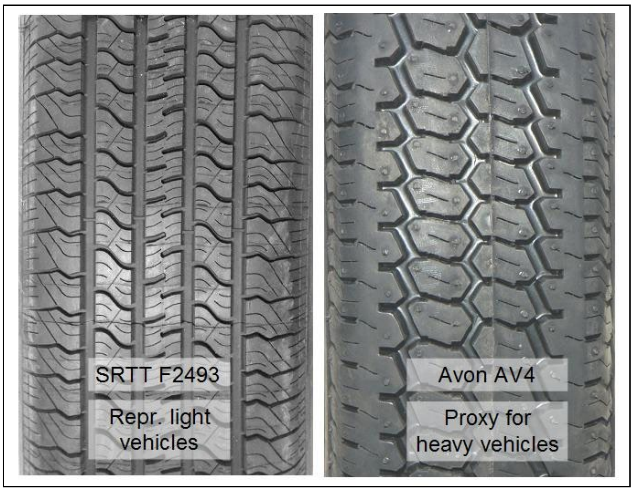


Figure 7-3: The two reference tyres used in all noise measurements (according to ISO/TS 11819-3). Tyre P1 ("SRTT") at the left and tyre H1 ("AAV4") at the right.

The two reference tyres are selected by ISO to represent two types of traffic:

P1: represents traffic by passenger cars. P stands for Passenger cars and 1 for the first generation of this reference tyre.

H1: represents traffic by heavy vehicles. H stands for Heavy vehicles and 1 for the first generation of this reference tyre.

The H1 tyre is a tyre constructed for small “light trucks” in a dimension similar to that of large passenger cars (and to the P1 tyre). This means that it can be used on a light trailer such as the one showed in Figures 7-1 and 7-2 which makes the method practical, and yet it is a useful “proxy” for heavy truck tyres in this application. By “representing” it means that these tyres classify or rank road surface noise properties in the same way as general passenger cars and general heavy vehicles, as determined by experimental studies.

Note that several measurements were made before the CPX method was formally standardised in 2017. However, in all essential functions, the equipment and the application of the method already at the first measurements in 2008 met the standard requirements. Exceptions are for the correction for air temperatures deviating from the reference temperature (20 ^{o}C) which were not applied until abut 2017 and for correction for reference tyre rubbers becoming stiffer by age (also applied from approximately 2017). The temperature correction is specified in ISO/TS 13471-1:2017 and the rubber stiffness is specified in ISO/TS 11819-3:2017. However, normally the measurements are comparisons between steel slag pavements and reference pavements, normally SMA 16 (ABS 16), at times when temperatures and rubber stiffnesses did not differ much. Therefore, the lack of those corrections before 2017 would not influence any “noise reductions” more than half a dB. However, comparisons between years before 2017 could be subject to errors up to 1 dB.

7.2 Tyre/road noise versus traffic noise and acoustic classification of road surfaces

The CPX method measures only the noise from the tyre/road interaction – i.e., tyre/road noise. In real traffic, most vehicles emit also noise from engine, exhaust, transmission, fans, etc, which is often referred to as power unit noise or propulsion noise. For traffic at constant speed, tyre/road noise is considered to generally dominate the total vehicle noise from light vehicles at speeds above 30 km/h. For heavy vehicles at constant speed, the speed over which tyre/road noise dominates is usually considered to be 45-50 km/h. For future traffic conditions, with the rapidly change from ICE-powered vehicles to electric vehicles, tyre/road noise will be the only major noise source, as long as the speeds are not illegally high, when air turbulence noise may become influential.

This means that measurement of only tyre/road noise is considered as enough to classify the acoustic properties of road surfaces, as power unit noise will have only a marginally limiting effect. In the future it can be completely neglected. Therefore, in the ongoing work in the European Standards organization (CEN), the committee and working group CEN/TC 227/WG 5, developing a standard for classifying the acoustic properties of road pavements, is basing its work on the use of the CPX method, and at least its reference tyre P1, possibly also the tyre H1.

Consequently, the use of the CPX method and its measures in this study is fully in-line with present standardization efforts.

7.3 Acoustic measures and measuring conditions

Measuring results are presented as (CPX) noise levels in the unit dB (deciBel). They are always in this report A-weighted, which means that a standardised so-called A filter has been applied to the sound pressure signal from the microphones (or to its digital correspondence in the frequency domain). The A filter is intended to weigh the sound in a similar fashion as the human ear is sensitive to different frequencies at fairly low sound levels. The A-weighting is almost exclusively used in similar noise measurements. Frequently in noise measurement reports worldwide, the use of the frequency weighting A is indicated in the unit as dB(A). However, this is not accepted by ISO which instead specifies that one should write that it is the “A-weighted sound level” expressed in dB.

In this report, the noise levels are always A-weighted, and the unit is mostly expressed as dB. However, in a few cases, the unit may be expressed as dB(A) in order to avoid revising a diagram for deleting the (A).

In some cases, in addition to reporting noise levels in dB, the sound is analysed for its frequency content and presented as frequency spectra in third-octave bands. Also in this case, these spectra have been A-weighted before they are presented. The frequency range is then covering at least 350 to 5000 Hz, which is the range of the highest interest and validity of tyre/road noise. However, often the range 200 to 10000 Hz is covered, although it contains only marginally more data of interest for assessing the acoustic properties of the road surfaces.

CPX noise measurements are usually made as time averages over most of the test section length. If the test section is very long and rather homogeneous, the length may be limited to (say) 400 or 600 m. The speeds are usually 50 and/or 80 km/h, which are the reference speeds nominated in ISO 11819-2, depending on the speed limit on the road. However, in some cases 70 or 90 km/h are used instead of 80 km/h.

Road surfaces must be dry when noise measurements are made. If it is a porous pavement, it is required to wait a minimum of 24 hours after the latest rain until a noise measurement is acceptable, to allow for the entire wearing course to dry up.

7.4 Texture and other geometrical measurements

Texture measurements were made in most years, using the RST vehicle of VTI, see Figure 7-4. This normally include Mean Profile Depth (MPD) and megatexture (amplitude) in the two wheel tracks and between wheel tracks, expressed in mm. Furthermore, it measures rut depth (in mm) and International Roughness Index (IRI). It is also possible to estimate ravelling; albeit it requires substantial labour time.

Alternatively, texture measurement results can be retrieved from the annual road surface testing programme of the Swedish Transport Administration. They are reported in the database PMSV4 [PMSV4, 2023] and, consequently, the author has picked out the texture and rut depth data from that database a few times. The measurements in the PMSV4 database are made with the same quality requirements as the RST vehicle of VTI, and they are calibrated each year against each other, so comparisons are valid.

Figure 7-4: The Road Surface Tester (RST) vehicle of VTI. The box in the front of the vehicle protects a number of laser sensors for triangulation measurements, including three for texture measurements. Picture from VTI-Aktuellt No. 3, 2016.

Ravelling was also measured manually, by photographing defined framed squares of the surface and counting the missing stones within the frame. This was made only in 2021.

7.5 Permeability measurements

At one occasion (2021) when parts of the tested sections were closed for visual inspection in one direction at the time, water permeability (a.k.a. drainability) was tested by means of the outflow method according to CEN standard EN 12697-40. This was made by using equipment for this purpose owned by VTI; see Figure 7-5. Water is let out through a valve in the bottom of the tube and the time for water to reduce its level in the tube by 100 mm is recorded. The result is an outflow time expressed in seconds. The tube is in contact with the road surface via a soft and wide rubber ring, which blocks water from running out horizontally; thus, it is (ideally) only the vertical drainability which is measured.

7.6 Wet friction measurements

Wet friction properties have been measured with VTI's Saab Friction Tester (SFT). SFT is the standard equipment used by Trafikverket (TRV) and Luftfartsverket to measure friction on Swedish roads and airfields. Under the car body (which is a Saab) there is a small wheel with a special tyre that is lowered to the road surface and partially braked during the measurement, while water is ejected in front of the test tyre to create an average of 0.5 mm water depth. In this way, the wet friction is measured during braking, which gives approximately optimal friction of a similar type as ABS on cars. In the measurements on E4 in Huskvarna, the wet friction was measured only in the right wheel track in the slow lane.

TRV applies a limit value for approval of 0.50 for newly constructed road surfaces, measured at 50 km/h. Measurement usually takes place at 50 and 70 km/h, where this is legal. It is known that SFT device is sensitive to the microtexture of the road surface, but less sensitive to the macrotexture. Figure 7-6 shows an SFT during measurement at another location.

Figure 7-5: Measurement of permeability (drainability) by the water outflow method. Two persons stand on the plate to provide the vertical load on the meter (as a load of 100-200 kg is required in EN12697-40 for tightening of the rubber ring on the surface).

Figure 7-6: A Saab Friction Tester (SFT), with its test tyre and the water ejection nozzle visible in the middle under the rear of the car.

For shorter test sections, VTI sometimes also measure wet friction with a slow mobile device (measuring at walking speed) named the VTI Portable Friction Tester (PFT). The PFT was used in 2021 only when there was a partial closure of the road, lane by lane.

This equipment has a small air filled tyre, Trelleborg T991 3,0-4 4PR inflated at 100 kPa, with a 40 mm wide and 5 mm thick rubber ring glued around its circumference. The rubber is a product designated Trelleborg 48-1617 with Shore A of 63. The PFT is pushed over the test surface at slow walking speed, while the wheel is partly braked (not blocked) and the rubber is slipping on the pavement surface. The force to keep the tyre rolling (slipping) is measured and taken as a measure of the friction. During measurement, water is sprayed immediately in front of the PFT if the surface is not already in wet condition. The data resulting from this test are valid for comparing the surfaces at the given conditions only. Figure 7-7 illustrates the measurement on E4 in Huskvarna in 2021.

Figure 7-7: Measurement of wet friction with the PFT device on the main section of E4 in Huskvarna. Note the spraying of water in front of the 3-wheeled PFT.

7.7 Rolling resistance measurements

Measurement of rolling resistance was made on one occasion (2018), using the “R2 trailer” of GUT. The testing of rolling resistance was made by using a non-standardised method named "the trailer method". Presently, there is no standard available for such tests; thus, this method is the result of the collected experience by essentially GUT, but also of other partners such as BRRC and VTI. Attempts to produce a draft for a standard using this method were presented in project ROSANNE (http://rosanne-project.eu/). The measurements utilized the GUT RR2 trailer; see Figure 7-8 where the trailer runs over a test section in another project. The test tyre is protected by an enclosure in order to eliminate the effect of ambient wind and air drag.

As test (reference) tyres, the same tyres as in Figure 7-3 were used. However, also a third tyre was used; i.e. a Goodyear Efficient Grip Performance, dimension 225/60R16, designated GEGP. The reason is that GUT has used this tyre in numerous other rolling resistance measurements as a representative market tyre; thus, it enables comparison to a lot of other measurements.

Also air, road surface and tyre surface temperatures are collected during the measurements. However, as no temperature correction for rolling resistance was available at that time, no such corrections were made here. Anyway, the temperature was similar on both the tested pavements (average 11 ^{o}C), so any temperature correction would give the same comparison results. Tests were made by running the trailer with its single test tyre at constant speed a number of times over the test sections. Test speed was 80 km/h.

Figure 7-8: The rolling resistance trailer by GUT running over a test section in another project.

7.8 Sound absorption measurements

There were no sound absorption measurements made on these test sections, since it would have required closing of the entire road for a significant time, which is unacceptable. It would not be enough to close just one lane, which may have been acceptable for safety reasons, but the noise from passing vehicles in other lanes would have made sound absorption measurements difficult or even practically impossible.

Since no bore cores have been drilled so far, neither have laboratory measurements been possible. Nevertheless, they may be made in a later year.

8 Dense pavements with steel slag aggregate in Sweden – description and measured data

8.1 Early tests reported in VTI reports in 2008-2015

In VTI Notat 5-2008, it was reported that there were positive experiences from Halmstad and Laholm where EAF slag had been used as wearing course on densely trafficked roads and streets since the beginning of the 1990's. And in Denmark, EAF slag from, for instance, steel production in Smedjebacken had frequently been used in roundabouts and on densely trafficked roads and streets [Jacobson, 2008].

Several test sections with steel slag in the wearing course, based on the SMA 11 (ABS11), had been laid in Dalarna in 2005, 2006 and 2007. At Smedjebacken (2005) and Borlänge (2006), the bituminous pavements with slag were laid in roundabouts and on Road 68 (2007) at Horndal (Avesta), a test section of 300 meters was laid; see further Section 7.2 below. These pavements containing slag had been experienced as positive regarding noise emissions, this due to the relatively smooth surface. However, measurements on this had not yet been done when the Notat was written but were conducted later; see Section 7.2.

Finally, it was warned that the composition and properties of steel slag can vary from steel plant to steel plant and even within one and the same process in a steel plant.

In VTI Notat 10-2015, published in 2015, three early field trials were reported:

1. Short section in an industry area in Oxelösund (Merox)
2. Short section in an industry area in Vargön (Vargön Alloys)
3. Roundabout in Smedjebacken (mentioned already in Notat 5-2008)

All of them were close to steel industries. Analyses and tests were made only on bore cores (more than 10 years old at the time) and indicated promising performances. The results are reported in [Wiman, 2015].

The same trial sections were considered in VTI Notat 19-2015, where bore cores were used to analyze the sheer strength and stability of the samples [Viman and Said, 2015]. In addition to these bore cores from roads, a binder course of the type DAC 16 with 70/100 bitumen produced in the laboratory with slag from 10 different steel producers and one reference with conventional aggregate were all analyzed. The results showed that bituminous pavements with slag had worked very well until then (2015). Studies of the bituminous mixes and the bituminous pavements with slag show very good properties of stability, stiffness and durability, properties that make them especially suitable for exposed roads and streets, and as in this case, roundabouts. Even the wearing resistance was found to be acceptable for Swedish conditions, (with studded tyres used in wintertime). No loss of aggregate, cracking or other defects were observed. Also [Viman and Gudmarsson, 2015] present test results from this study.

VTI Notat 24-2015 did not mention new field tests but conducted tests of particle formation and wear characteristics using the Road Simulator (PVM) at VTI [Viman and Gustafson, 2015]]. In this experiment an SMA 8 pavement with slag from Ovako Bar was paved in the PVM and compared to an earlier test in the road simulator on an SMA 11 pavement with the same slag materials. Road wear measurements in the PVM presented an unclear picture, probably because of the slag used contained more steel residues than normal slag, resulting in a very uneven surface with protruding sharp steel pieces after some wear of the surface. Nevertheless, it was concluded that particle formation from SMA 8 slag asphalt, measured as PM_{10}, was at the same level as previously tested SMA 11 with slag and at similar level as most asphalt wearing courses made from natural aggregates.

The main results from the above mentioned documents are available in English in [Viman et al, 2016]. This includes a table showing the results of wear tests by the Prall and the Nordic Ball Mill methods. The latter showed values between 8 and 33 ("kkv") for 19 tested slags, where 3 were below the limit of 10 which the Transport Administration considers as useful for medium- and high-volume highways.

Consequently, these early studies showed a quite consistently positive picture of the use of steel slag aggregate in asphalt pavements.

8.2 Road 68 in Horndal, Avesta

This test section was laid on National Road 68, immediately north of the village Horndal in Avesta county. This road has one lane in each direction and an AADT of 2200 (heavy vehicle proportion 21 %), with a speed limit of 80 km/h on the test section which was 300 m long and laid with steel slag in only one direction while the other one had a similar pavement SMA 11 (ABS 11) with conventional aggregate.

The slag came from Smedjebacken and had been tested in the VTI laboratory to give a Nordic Abrasion Value ("kulkvarnsvärde") of 6.6, which is a good value. The slag included fractions 4/8 and 8/11 mm and constituted 74 % of the weight of the mix (fractions below 4 mm were ordinary stone and sand). Binder proportion was 5.7 %. The binder was bitumen 100/150. More pavement data is presented in [Gunnarsson & Jacobson, 2013].

The pavement was laid in 2007 (in both directions). A visual inspection on-site was made after 6 years. It was noted then that the surface still looked to be in good condition, with some minor inhomogeneities. It was thought that the binder content maybe should have been 0.1 % lower (5.6 %). In May 2022, an inspection in the Transport Administration's PMSV4 road data model suggests that the slag pavement was still there in the summer of 2021 (then almost 14 years old) and looked good based on the surveying vehicle's camera. The surface of the other direction (having conventional aggregate) looked worse.

Some measurements of texture and rut depth are known for this test section and its reference pavement; see Table 8-1. Note that the MPD values for the SMA 11 (ABS 11 conv) in 2012 are substantially higher than what is normal for an SMA 11 (ABS 11). The noise measurements indicated a noise reduction of 1 dB for the reference tyre (P1) representing passenger cars and 0 dB for the reference tyre (H1) representing heavy vehicles. The noise reduction is most probably due to the somewhat lower texture values on the steel slag during its first year. Had (reference) noise measurements been made on the most common pavement, SMA 16 (ABS 16), the noise reduction of the steel slag had been 1 – 2 dB higher, due to the combined effect of the smaller maximum aggregate size and the small reduction due to the slag aggregate instead of stones.

Unfortunately, no more measurements were ordered or made.

Table 8-1: Texture and rut depth measurement results in 2012 and 2021 for the steel slag (ABS 11 slag) and its reference pavement (ABS 11 conv).

Pavement and year	Rut depth	MPD left track	MPD between tracks	MPD right track
ABS 11 slag, 2012	Not known	0,83 mm	0.98 mm	0.73 mm
ABS 11 conv, 2012	Not known	Not known	Not known	Not known
ABS 11 slag, 2021	8 mm	0.6 mm	1.0 mm	0.7 mm
ABS 11 conv, 2021	8 mm	1.2 mm	1.3 mm	1.2 mm

Table 8-2: Noise measurement results in 2008 when the pavements were one year old.

Pavement and year	Tyre P1		Tyre H1	
	50 km/h	80 km/h	50 km/h	80 km/h
ABS 11 slag, 2008	93.2 dB	99.3 dB	91.2	98.4
ABS 11 conv, 2008	94.1 dB	100.3 dB	91.4	98.2
Noise reduction	0.9 dB	1.0 dB	0.2 dB	-0.2 dB

8.3 Järnvägsgatan in Linköping (2014 --)

This pavement was laid in 2014 on Järnvägsgatan in Linköping in two lanes per direction, plus exit lanes (adjacent to the Central station). See Figure 8-1, which was shot during the quietest part of the day.

There are two light-controlled intersections in this section, so there are extra stresses of stop-and go, and turning traffic, of which busses constitute a significant part. Having been subjected to an AADT of 14000 (among the highest in Linköping City), with the majority of vehicles having studded tyres in winter, the pavement is still (in 2022) in remarkably good condition. The length is approx. 450 m which including the exit lanes will be a total of approx. 2.0 km of lane-length. The steel slag (EAF) comes from Smedjebacken and has a maximum aggregate size of 11 mm [Höijer, 2022]. Linköping considers it as having been more durable than conventional SMA which normally would need repaving as early as each 5th year on this street [Höijer, 2022]. Unfortunately, no technical studies were made for this pavement, except a measurement of texture and rut depth by VTI in this project in 2022; see Table 8-3.

Figure 8-1: Steel slag pavement, 8 years old, on Järnvägsgatan in Linköping (central station at the right). Only the northwestern direction is shown here, the southeastern direction has two lanes outside the photo on the left. The joint between the steel slag (darker part) and the conventional SMA pavement (brighter part) is visible near the bottom of the photo. Photo by the author.

It appears that the rut depth of the steel slag is substantially higher than for the conventional pavement; albeit it is not unusually deep considering the age (8 years) and the traffic with studded tyres. The conventional pavement has the advantage of being only two years at one end and four years at the other end. The trend is the same in both lanes K1 and K2, but K1 with the higher traffic load has deeper ruts.

In Table 8-3, in one column, the rut depth values have been normalized to rut depth increase per year to make the comparison of rut depth fair (then the age of the conventional pavements was set at three years, as an average for the pavements at both ends). It appears that the steel slag pavement has had significantly lower rutting per year in both lanes.

Table 8-3: Texture and rut depth measurement results in 2022 for the steel slag (ABS 11 slag) and its surrounding reference pavement (ABS 11 conv.). Average for both directions.

Pavement and age	Rut depth	Rutting per year	MPD left track	MPD between tracks	MPD right track
ABS 11 conv., lane K1, 3 years	6.5 mm	2.2 mm	0.96 mm	1.01 mm	0.98 mm
ABS 11 slag, lane K1, 8 years	14.0 mm	1.8 mm	0.76 mm	1.04 mm	0.76 mm
ABS 11 conv., lane K2, 3 years	5.1 mm	1.7 mm	1.00 mm	1.03 mm	1.01 mm
ABS 11 slag, lane K2, 8 years	9.5 mm	1.2 mm	0.88 mm	1.10 mm	0.96 mm

With regard to the macrotexture, MPD:s are similar for both pavements and both lanes between the wheel tracks but lower in the wheel tracks. As for rut depth, the slag pavement appears to have been worn more (due to being more than double as old) since its MPD is substantially lower than for the conventional pavement, in both wheel tracks. But this is mainly for the slow K1 lane, as in the K2 lane the MPD has not changed so much.

The author thinks that it is interesting to study the colour of the pavement. An asphalt pavement would stay dark between the wheel tracks and become brighter in the wheel tracks as the bitumen is worn off, but this steel slag is opposite. The darker colour in the wheel tracks is unlikely to be caused by bitumen being pressed up, as may happen with asphalt in the summer, since the photo was shot in April when the daytime temperatures vary between 0 and 12 degrees C. Instead, it is the dark aggregate which has become exposed by the studded tyres. The brighter parts between the wheel tracks may be dirt or perhaps some oxidation?

8.4 Skälbyvägen in Järfälla and Malmabergsgatan in Västerås

8.4.1 Description and location

In Järfälla, which is a city just north of Stockholm, there is a road called Skälbyvägen which runs through mostly residential areas through most of the city. Normal speed limit there is 50 km/h and traffic volume was 16000 AADT during the time of the studied pavements. The road contractor in Järfälla, Peab AB, laid a steel slag pavement on part of Skälbyvägen in 2010, joining a similar pavement but having regular stone aggregate. The road has one lane in each direction. This is what the author knows about these pavements which will be compared later:

Swedrain 8: This is a proprietary asphalt pavement constructed by Peab AB with max aggregate size 8 mm. It has an open texture with marginally higher porosity than for an SMA pavement (air voids 6 %). It is similar to an SMA 8, despite its name. The aggregate has a Nordic Ball Abrasion Value (kkv) of 7. This is considered a good value for use in highway pavements. It was laid in 2009 in 25-30 mm thickness over an 800 m distance but was repaved in 2018.

Swedrain 8 with steel slag, here denoted **SwedrainSlag 8**: This is a proprietal asphalt pavement constructed by Peab AB with max aggregate size 8 mm. It is similar to Swedrain 8, but where the fraction 4-8 mm has been exchanged with steel slag from Smedjebacken. It was laid in 2010 but was repaved in 2018. The total distance is about 400 m. See Figures 8-2 and 8-3.

The same pavement as reported above was laid also on Malmabergsgatan in Västerås. This would have been in 2015. Malmabergsgatan is a local street, with speed limit of 50 km/h, running through a residential area. VTI was not commissioned to make any measurements there, but Västerås City had some L_{Aeq} measurements made at a façade of a building nearby, claimed to show a noise reduction of 4-5 dB [Jansson, 2018], although the pavement they compared with is not known. Probably it was an old and worn asphalt pavement.

8.4.2 Noise measurements

VTI was contracted to make noise measurements there (with the CPX method) in 2013 and 2014 but had then already made measurements by own initiative in 2011. Test speed was only 50 km/h in 2013 and 2014 but 40 and 60 km/h in 2011. The 2013 measurements were made in November, in rather chilly weather (9-11 °C). The 2014 measurements were made in August 2014 in (ideal) temperatures of 20-22 °C while measurements in 2011 were made at 24-26 °C. For comparison, also the national average of SMA 16 pavements [Sandberg, 2021] was used as a reference; in addition to the Swedrain 8.

Figure 8-2: Pavement of SMA 8 type but with steel slag as aggregate, on Skälbyvägen in Järfälla (just north of Stockholm). The photo was shot when the pavement was new.

Figure 8-3: Pavement SwedrainSlag 8 with steel slag as main aggregate, laid in 2010 on Skälbyvägen in Järfälla (just north of Stockholm) by Peab Asfalt AB. The coin has a diameter of 21 mm and the photo was shot when the pavement was new.

The results are shown in Table 8-4. Temperature corrections were made according to ISO/TS 13471-1 to a reference air temperature of 20 °C. It appears that the Swedrain 8 surfaces are 2-3 dB(A) quieter than the reference ABS 16. The slag pavement provides 4-5 dB noise reduction in new condition. Probably, the Swedrain pavement would do so too, but we have no measurements when it was new.

The Swedrain with steel slag gives marginally lower noise levels as the comparable Swedrain with stone aggregate on the same road (Skälbyvägen). As an average over the time span measured, it reduces noise levels by 3.5 to 2.5 dB for light, respectively heavy traffic. For both the Swedrain 8 and SwedrainSlag 8 pavements, there is a clear increase in noise by time and age, which is not surprising since the 8 mm aggregate size is subject to heavy wear by studded tyres in wintertime. The main noise reduction is due to the lower max. aggregate size, as earlier studies have suggested that the effect of reducing aggregate size from 16 to 8 mm is about 2 dB when excluding new surfaces [Sandberg, 2006]. 2 dB is exactly what we have in 2014. The steel slag vs stones as material contributes very little extra.

There was a reason for making the measurements in 2011 between the wheel tracks, namely that it was believed that the texture between the wheel tracks would be essentially the same as for the entire surface when it was new, one year earlier. Therefore, in the table, the age is indicated as "0/1" years.

Table 8-4: Measured noise levels averaged for both directions. Note that the 2011 measurements were made at 40 and 60 km/h and the value at 50 km/h has been interpolated. In contrast to 2013 and 2014, made in the right wheel track, the measurements in 2011 were made between the two wheel tracks.

Pavement	Year and (age)	Tyre P1		Tyre H1	
		Speed [km/h]			
		40/60	50	40/60	50
SwedrainSlag 8	2011 (0/1)	85.2/90.6	88.2	86.1/92.1	89.5
Swedrain 8	Not measured 2011				
SMA 16 (national reference)	Average of many		93.5		93.1
SwedrainSlag 8	2013 (3)		90.2		90.5
Swedrain 8	2013 (4)		90.3		90.5
SMA 16 (national reference)	Average of many		93.5		93.1
SwedrainSlag 8	2014 (4)		91.2		91.3
Swedrain 8	2014 (5)		91.3		91.1
SMA 16 (national reference)	Average of many		93.5		93.1
SwedrainSlag 8	Average 2011-2014		89,9		90.4
Swedrain 8	Average 2013-2014		90.8		90.8
SMA 16 (national reference)	Average of many		93.5		93.1

A number of frequency spectra, Figures 8-4 (for Tyre P1) and 8-5 (for Tyre H1), have been added. A reference spectrum is included in each diagram, representing the national reference of an SMA 16 pavement; which is an average of many SMA 16 pavements measured over several years. The spectra of the SwedrainSlag 8 pavement measured in 2011 and 2014, as well as the Swedrain 8 measured in 2014 are included for comparison with the reference pavement. The latter was not measured in 2011 so that comparison is not possible.

The frequency spectra show the advantage of the steel slag pavement when it was in new condition. At the lower and medium frequencies for the P1 tyre it is 7-8 dB while at the higher frequencies it is around 5 dB. For the H1 tyre the advantage is mainly at the medium frequencies. This is logical since the H1 tyre is less sensitive to the lower macrotexture of the slag pavement.

It also appears that in 2014, there are no significant differences between the two Swedrain pavements; implying that whether the aggregate is stone or steel slag does not matter.

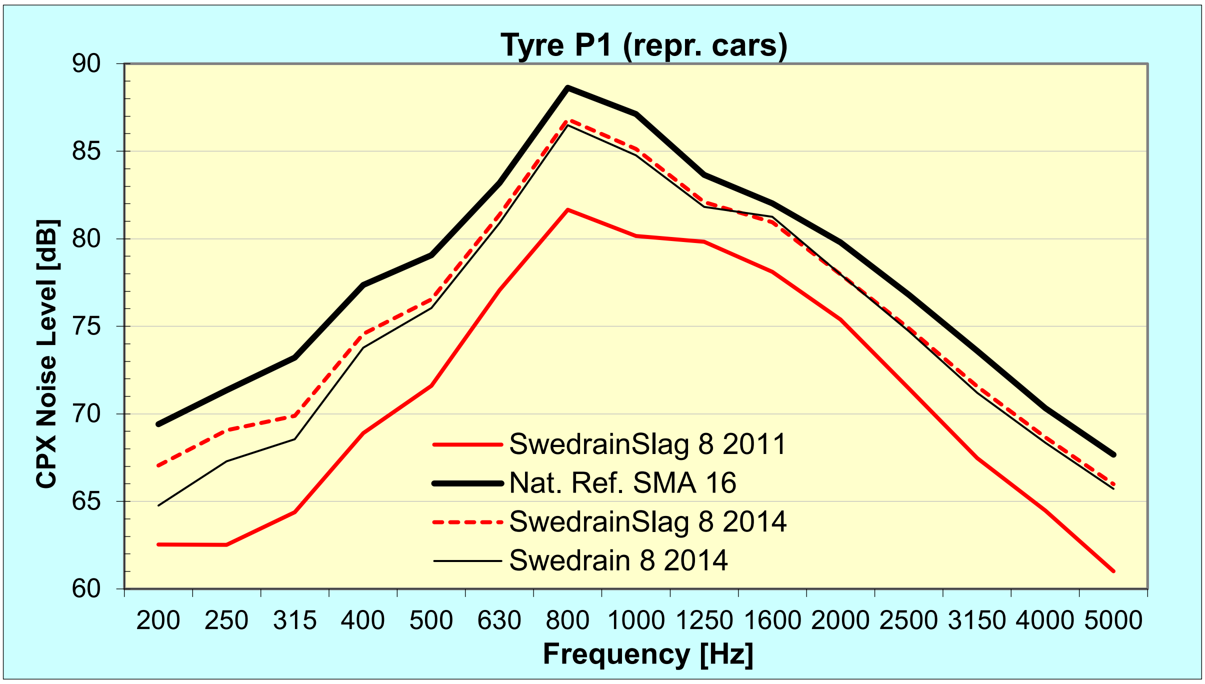


Figure 8-4: A-weighted third-octave-band frequency spectra for the measurements done with the P1 reference tyre. See the text for comments.

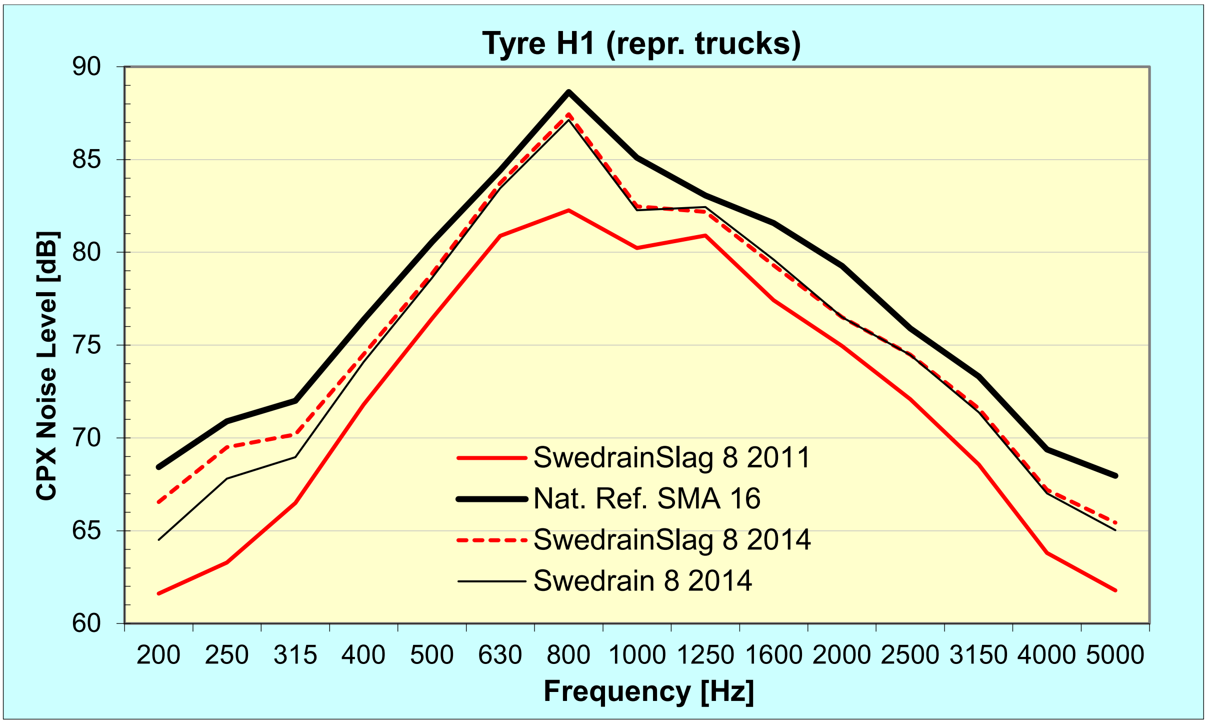


Figure 8-5: A-weighted third-octave-band frequency spectra for the measurements done with the H1 reference tyre. See the text for comments.

When the two Swedrain pavements get older, in the measurements in 2014, they approach the performance of the SMA 16, but yet with a noise reduction of 1-3 dB, which is due to the smaller aggregate (8 vs 16 mm) and the lower texture following from it. However, the relatively open texture (MPD above 0.7 mm as shown in the next section) provides noise reduction by reducing the air pumping generation mechanism also at the high frequencies.

From a detail study of frequency spectra, there is no clear sign of any effect of porosity on noise emission or propagation, since this would have caused a dip at one or two frequency bands in the range 800-1600 Hz (as is shown in Section 8.7); i.e. there is no sign at all of sound absorption. Thus, the somewhat higher than normal air voids content has no acoustic effect. The surfaces perform as regular SMA (ABS) surfaces with 8 mm max. aggregate size.

8.4.3 Texture and rut depth measurements

Measurements were made in September 2014 using the VTI RST vehicle only on surface SwedrainSlag 8 (steel slag). The values below are averages of two runs in both directions.

Results:

IRI, right wheel track	1.2 mm/m
IRI, left wheel track	0.9 mm/m
Megatexture, right wheel track	0.26 mm rms
Megatexture, between wheel tracks	0.31 mm rms
Megatexture, left wheel track	0.26 mm rms
Macrotexture (MPD), right wheel track	0.74 mm
Macrotexture (MPD), between wheel tracks	0.90 mm
Macrotexture (MPD), left wheel track	0.73 mm
Rut depth (based on 2,6 m lane width)	9.7 mm

These are no values which are unexpected after four years of service. In 2011, also texture measurements were made, but only MPD between the wheel tracks. The result was then 0.82 mm; i.e. the MPD has not changed much between the almost new unworn condition and the condition in 2014.

8.4.4 Concluding remark

It shall be noted that the traffic volume on this road is very high, and that the majority are cars. Most of the cars would have used studded winter tyres in the winter season, which has worn the surfaces more rapidly than what is normal. A lifetime of 8-9 years under such circumstances is fairly good and shows that such a pavement can be used for noise reduction even in the Swedish climate with studded tyres and an AADT of 16 000, at least when speeds are around 50 km/h.

8.5 Östra Bangatan in Örebro City (2017 - 2018)

8.5.1 Description and location

In 2017, a steel slag pavement was laid by construction company NCC on Östra Bangatan in Örebro, as ordered by Örebro City; see Figure 8-6. The slag they used is from Smedjebacken; consequently, probably the same as described in Chapter 6. The max aggregate size is 8 mm. The intention was to create an SMA 8 type of pavement, but with steel slag as aggregate. The air voids appeared to be much higher than intended; i.e. around 10 % according to the city. This is too little to be favourable for noise, but too high to give good structural strength. Therefore, the city and the contractor have had a conflict about this section (result unknown), but as of April 2022, the pavement is still there; however, not in good condition, mainly due to ravelling and studded tyre wear in the wheel tracks.

Figure 8-6: Steel slag on Östra Bangatan in Örebro, laid in 2017. The joint with the SMA pavement is shown at the bottom of the photo. This photo shot by the RST crew of VTI in May 2019.

The steel slag section is located in north-eastern Örebro City, in the northern part of Östra Bangatan street, between the intersections with Dalbygatan and the motorway E18; see Figure 8-7. The street has two lanes in each direction and the AADT was 20500 in 2016 with an estimated 5 % heavy vehicle traffic. Posted speed limit was 70 km/h before the pavement was laid but was reduced to 60 km/h after the steel slag pavement had been constructed.

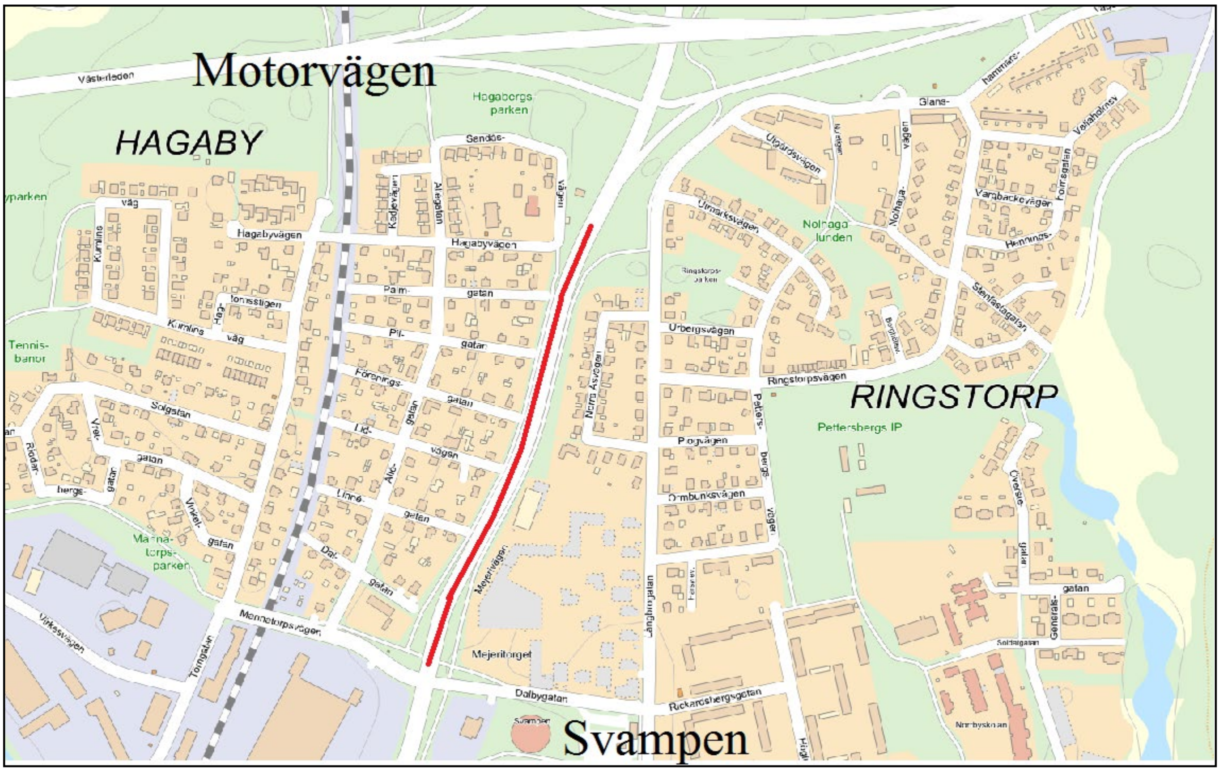


Figure 8-7: The location of the studied Östra Bangatan street section in north-eastern Örebro City. Motorway E18 at the top.

8.5.2 Studied objects (steel slag versus reference SMA)

The following two test objects were studied:

- Steel slag pavement named Viacogrip 8 EAF by its producer NCC (Nordic Construction Company). It is constructed as a variant of SMA 8 (maximum aggregate size 8 mm), but with steel slag as aggregate. Paved in August 2017. Air voids content was intended to be 1.5 to 7 %, but later appeared to be more like 10 %. Nominal thickness 25 mm. Figure 8-8 shows the appearance of the surface in the autumn of 2017 (a few months old). Unfortunately, the Nordic Ball Mill value (kkv) of the slag is not known to this author.
- Pavement SMA 11, laid in 2012 as repaving. It is the old pavement on the street before part of it was repaved with Viacogrip 8 EAF in August 2017. Noise measurement on this pavement was made just before the new pavement replaced it. In 2017 it was rather worn; patches of the layer were even said to be worn away.

These were measured for a length of 400 m in each lane and direction. The total length of the section was around 600 m but parts in the beginning and end were used for acceleration and deceleration of the CPX trailer.

In addition to these pavements, the average value measured in 2017 for a number of SMA 16 laid 3-6 years earlier was used as a reference in 2017. Such a reference pavement is suitable as a national reference because SMA 16 is the most common pavement on our national roads, and which has been shown to give a relatively stable noise level over time in Sweden. In this case, the mean value has been calculated over all five measurements of such pavements made in 2017, at locations near Jönköping, Lund and Stockholm. For the measurements in 2018, a similar reference was used, but then utilizing an average of several SMA 16 pavements measured in that year (2018).

The noise measurements were made in both directions (north and south), in both the slow (K1) and fast (K2) lanes, and in two lateral tracks (right wheel track and between the right and left wheel tracks).

Figure 8-8: View of the surface of Viacogrip 8 EAF at an age of a few months (before first winter). The pen in the picture has a length of around 140 mm. Photo: Jens Gärskog, Örebro City.

8.5.3 Noise measurement results

The results are first presented as noise levels separated by tyres, speed, lane, direction of travel and pavement in Table 8-5. Also (arithmetic) averages have been entered in the table. CPXP and CPXH are A-weighted noise levels in dB, measured with tyre P1 and tyre H1, respectively.

The table also includes reference values for the old SMA 11 repaving that was measured at the "pre-measurements" in 2017; which means that this pavement was in worn condition. In addition, there are reference values for SMA 16 (see above), because they constitute references for noise measurements of this kind that VTI performed in 2018 and because it should be the most stable reference we currently have.

The results in the table show that the old wearing course on Östra Bangatan, which was an SMA 11 type, gives only 0.4 dB lower noise level than the SMA 16 reference in 2018. Normally, the difference between SMA 16 and SMA 11 is about 1.3 dB, but here it is only 0.4 dB. This is probably due to the fact that the old pavement was in poor condition. The results also show that lane K2 (fast lane) has slightly lower noise levels that lane K1 (slow) in 2017 as well as in 2018, which may be due to less traffic in K2.

Table 8-6 shows a summary of the values in Table 8-5, expressed as noise reductions, in A-weighted dB. It can be seen that K2's steel slag pavement in 2018 is still slightly better than K1's; however, not a difference great enough to be heard.

Table 8-5: Noise levels (A-weighted and temperature-corrected) for the two reference tyres at the two driving directions, and in the two lanes. The noise data of the old pavement (SMA 11 repaving) is included, as well as reference values for SMA 16 in 2018. See further the text section.

Pavement type	Driving lane	Speed [km/h]	CPXP (tyre P1)		CPXH (tyre H1)		Notes
			North	South	North	South	
SMA 16 ref 2018	K1	50	93.0		92.7		Average for 50 km/h: 92,9
SMA 16 ref 2018	K1 & K2	70	98.1		97.8		Average for 70 km/h: 98,0
Average	K1 & K2	50 & 70	95.6		95.3		**Average for the tyres: 95,5**
SMA 11 repaving Average 2017	K1 & K2	50 & 70	95.7		95.1		**Average for the tyres: 95,4**
Viacogrip 8 EAF	K1	50	91.6	91.6	91,8	91,4	Average for K1/50: 91,6
Viacogrip 8 EAF	K1	70	96.9	96.7	96,8	97,0	Average for K1/70: 96,9
Viacogrip 8 EAF	K2	50	91.2	91.5	91,2	91,5	Average for K2/50: 91,4
Viacogrip 8 EAF	K2	70	96.3	96.6	96,3	96,3	Average for K2/70: 96,4
Average	K1 & K2	50 & 70	94.0		94.0		**Average for the tyres: 94,0**

Table 8-6: Noise reduction for Viacogrip 8 EAF compared with the older pavement on the street, as well as with the general SMA 16 reference (average of measurements on 5 different SMA 16 in 2018).

Pavement type	Driving lane	Noise reduction compared to the old pavement (SMA 11 repaving)	Noise reduction compared to the reference pavements SMA 16
Viacogrip 8 EAF year 2017	K1	3.1 dB	3.3 dB
Viacogrip 8 EAF year 2017	K2	3.4 dB	3.8 dB
Viacogrip 8 EAF year 2017	Average K1 & K2	3.2 dB	3.5 dB
Viacogrip 8 EAF year 2018	K1	1.2 dB	1.3 dB
Viacogrip 8 EAF year 2018	K2	1.5 dB	1.6 dB
Viacogrip 8 EAF year 2018	Average K1 & K2	1.4 dB	1.5 dB

To be supplemented with measurements in 2019 which were found just recently

Frequency spectra in third-octave bands are shown in Figures 8-9 to 8-10. To reduce the amount of data, each curve is an arithmetic mean of the two speeds of 50 and 70 km/h and the two directions north and south. The four curves in each diagram are shown to illustrate interesting differences.

The differences between the older SMA 11 repaving and the new steel slag Viacogrip 8 EAF (2017) were significant; as a result of smaller aggregate size and thus a smoother surface for the latter, which gives differences up to and including 1000 Hz. The fact that the older pavement was in poor condition also contributed to the difference; especially in the area below 600 Hz, where the megatexture has a great impact. However, the difference between the two lanes K1 and K2 is so small that it can be neglected. It would have been acceptable to also calculate the mean for K1 and K2 instead of reporting the curves separately. It is a little strange that there was a pronounced peak at 1250 Hz for the tyre H1 on the steel slag pavement. This is a rather unusual observation.

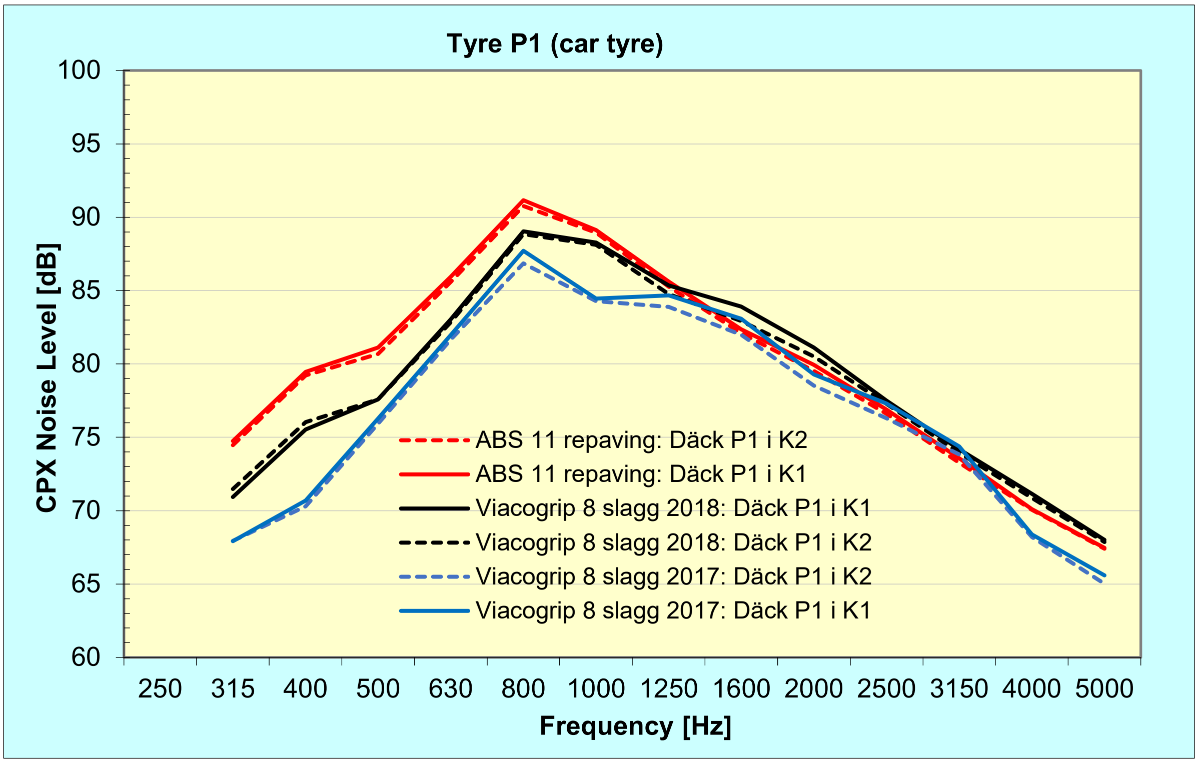


Figure 8-9: A-weighted frequency spectra for the reference tyre P1, averaged for the north and south directions and the speeds 50 and 70 km/h. The curves show the differences between the old and the new pavement in 2017 (SMA 11 vs steel slag), as well as between the two lanes K1 and K2. The spectrum for steel slag in 2018 has also been added.

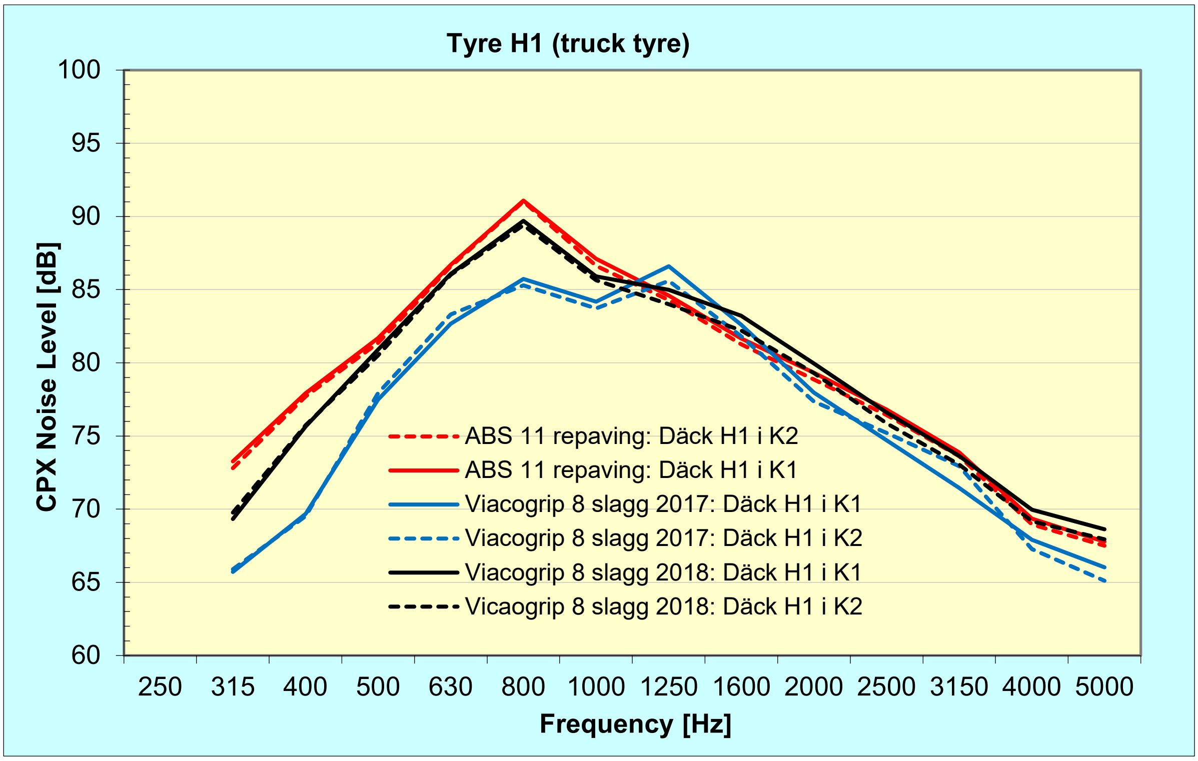


Figure 8-10: As the previous figure, but for reference tyre H1.

However, the slag pavement in 2018 has changed significantly. It has become more similar to the older SMA, and the difference is now small. The 8 mm aggregate size should actually give slightly lower noise than is the case in 2018. Given the lower noise levels at mainly 800 and 1000 Hz (which is typical for drainage pavements) in 2017, it is possible that there was a certain porosity (air voids) which was clogged during the winter.

Of course, monitoring the pavements in a longer time perspective would have been desirable, but the sponsor of the measurements (Örebro City) was not interested in it.

8.5.4 Texture and rut depth measurement results

Unfortunately, no texture and rut depth measurements were made when the steel slag pavement was new (in 2017), as such were not requested by the sponsor. Nevertheless, measurements were made in early May 2018, which then was possible only on the steel slag (Viacogrip 8 EAF). Due to the risk that the pavement could have been changed by the unusually hot summer of 2018, since the slag surface is so dark, a new measurement campaign was made in September 2018. Additionally, another measurement campaign was made in May 2019. Finally, new measurements were made in June 2022.

Rut depth was measured simultaneously with texture. The results for rut depth are shown in Figure 8-11. Contrary to the texture, the rut depth changed only slightly during the summer but had apparently reached about 5 mm during the winter. One year later it had increased by about 2 mm. That is a fairly significant rut depth for a pavement only two years old. At an age of five years, ruts are 10-16 mm.

The results expressed as mean profile depth (MPD according to ISO 13473-1) are shown in Figure 8-12. As can be seen in the figure, the MPD values were quite similar in both the lanes K1 and K2 as well as in the three tracks that were measured (left and right wheel tracks and between the wheel tracks) in May 2018. But during the summer of 2018, major changes took place in the wheel tracks; especially in lane K1. Normally, the changes usually take place during the winter when the studs wear the surface. The large changes should have to do with the hot summer. Texture is further reduced slightly in 2019.

Finally, it should be mentioned that the unevenness expressed as the IRI (International Roughness Index) was also measured. It was about 1.2 mm/m, which is a good value, but in K1 in the northern direction the value was about 1.8, which is not so good for a new road surface.

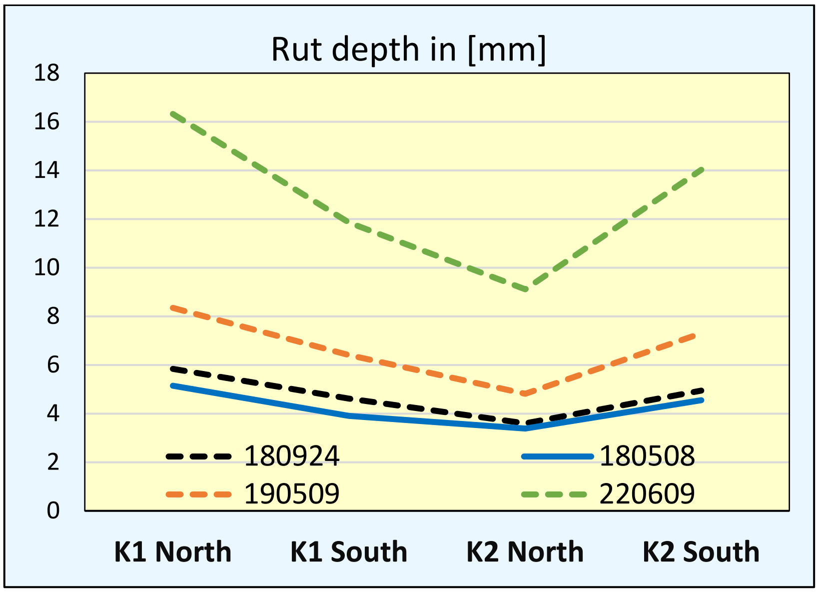
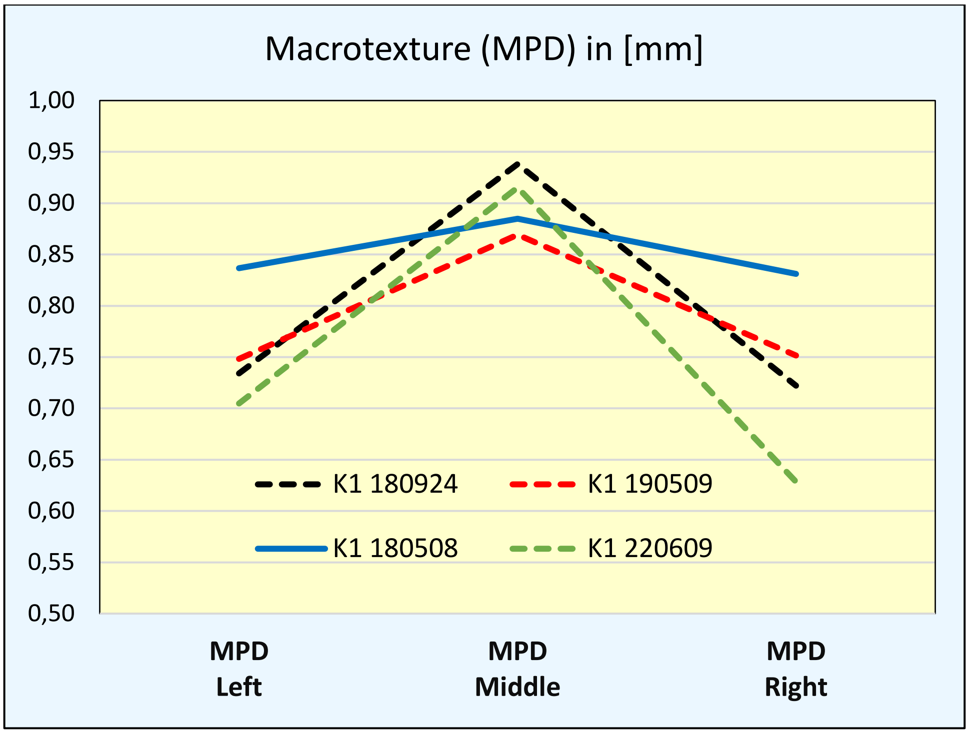


Figure 8-11: Rut depth expressed in mm, at both occasions when measurements were done in 2018; i.e. before and after the hot summer season, and also in 2019 and 2022.



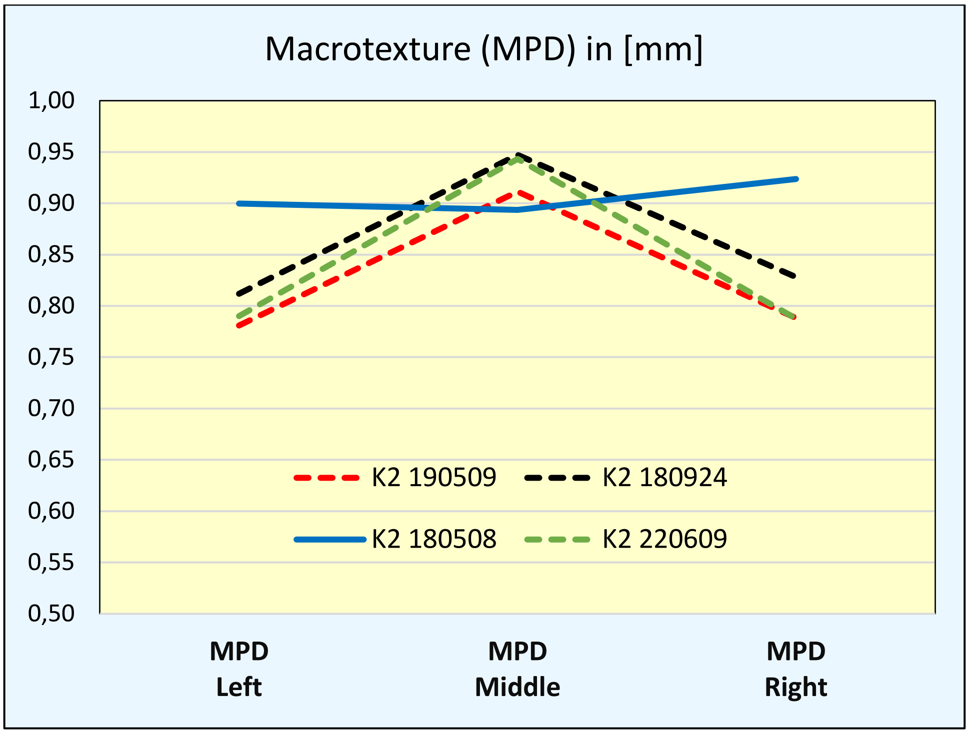


Figure 8-12: Macrotexture expressed as MPD in mm, at both occasions when measurements were done in 2018; i.e. before and after the hot summer season, and also in 2019 and 2022. Data for lane K1 above and for lane K2 below.

8.5.5 Wet friction

Within the framework of a doctoral project, certain friction values were measured in week 43 in 2018. Those that were measured were right wheel tracks in both the northern and southern direction in the K1 lane. Measurements were not made in the K2 Lane. Measurements were performed with VTI's Saab Friction Tester (SFT); see above. The measured values represent approximately the friction you get when braking, when ABS is activated. Figures 8-13 and 8-14 show the results for each direction. The results appear to be normal for asphalt pavements in good condition.

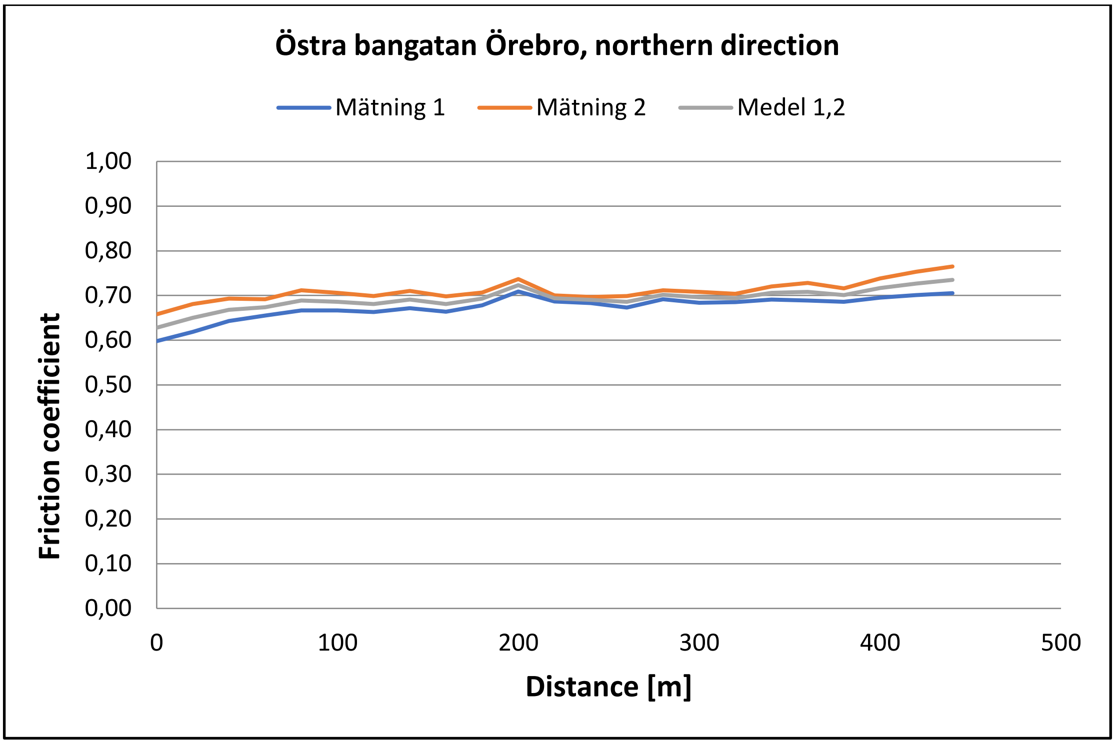


Figure 8-13: Wet friction coefficient over the steel slag section measured in the autumn of 2018, in northern direction in the right wheel track of lane K1. Two measurements and its average (in grey).

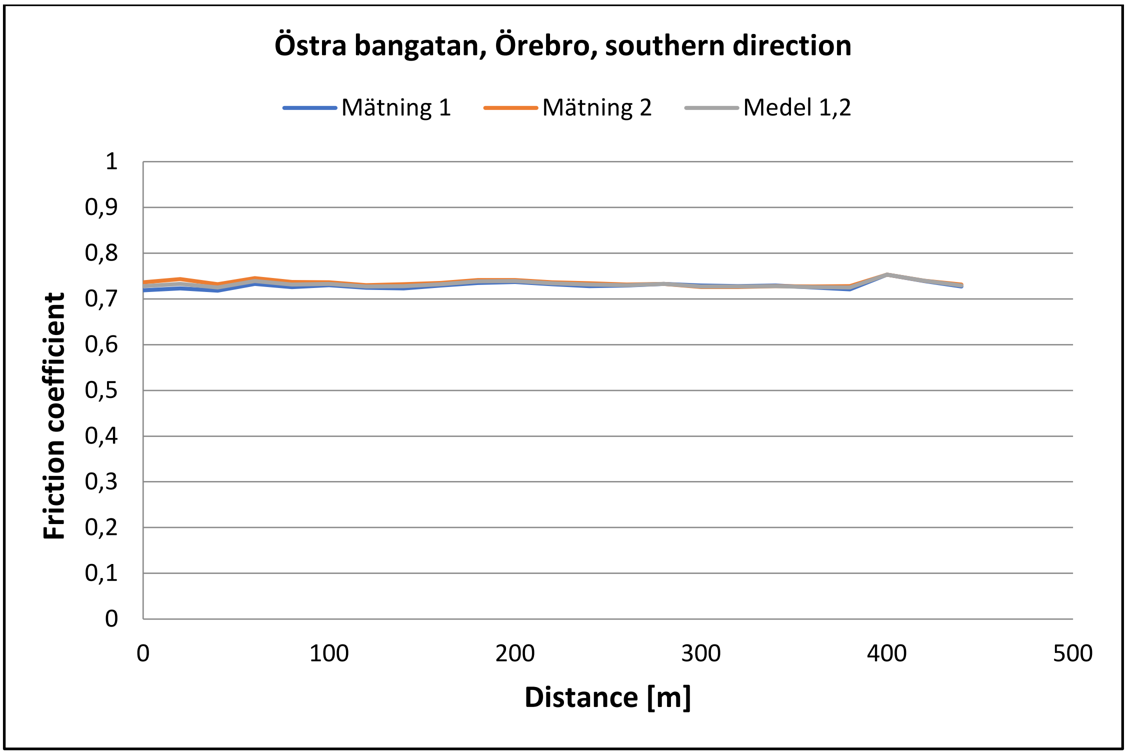


Figure 8-14: Wet friction coefficient over the steel slag section measured in the autumn of 2018, in southern direction in the right wheel track of lane K1. Two measurements and its average (in grey).

8.5.6 Discussion

The summer of 2018 was extremely hot. The measurements therefore took place at about 30 degrees air temperature and the noise values have since been corrected to a reference temperature of 20 °C. However, temperature coefficients for steel slag have never been determined, since this type of pavement is so unusual, so the equivalent value for ordinary SMA has been used. Given that steel slag is darker than common SMA pavements, resulting in more solar energy being absorbed, it is possible that this may have resulted in too high noise levels at the reference temperature of the steel slag. The error can, however, be a maximum of 1.0 dB, but much more likely it is only a few tenths of a dB.

It is remarkable how the rut depth varies between lanes and in directions. There is no consistent variation which may explain these differences as being due to different traffic in the two directions, or in the two lanes. The only speculation that the author can offer is that the construction and paving was different in the different lanes and directions and, in some cases, this has resulted in excess wear. Visual observation in 2022 shows that the ruts are relatively narrow, which is a result of rather narrow lanes, which causes vehicle drivers to drive in the same lateral position. This causes deeper but narrower ruts. There were a few places where the ruts had almost reached down to the underlying pavement.

8.5.7 Concluding remarks

The steel slag pavement reduced the noise level by 3-4 dB in new condition compared to both the old and worn pavement (SMA 11) on the street before it was repaved and compared to the common Swedish reference of SMA 16 pavements. This is common and not more than expected for a new asphalt pavement; especially when the maximum aggregate size is 8 mm. The noise reduction became significantly less in 2018 than it did when it was new, as less than half of the original noise reduction remained. This is a little more noise reduction loss than expected since the aggregate is much smaller (8 mm against 11 and 16 mm, respectively), and approx. what one would expect by an SMA 11 pavement.

Frequency spectra give some indications that a certain porosity may have occurred in the new state in 2017, which may have given some sound absorption, but which was blocked after clogging in the winter of 2017/2018.

Measurements of the texture of the surface show that a major change took place during the hot summer of 2018, but the noise measurements were made at the beginning of the hottest period, so it is not possible to correlate noise changes with the texture changes. It is not possible to state with reasonable certainty any reason why the steel slag pavement deteriorated acoustically so quickly.

Rut depth after one year of service was higher than expected. This may be because of the small max aggregate size (8 mm), which is extra sensitive to studded tyre wear, but another reason may be that the higher voids content than intended in the new pavement may have caused compaction by traffic in the wheel tracks. Between 2018 and 2019 rut depth increased by approx. 2 mm. This is normal-to-good for a pavement with 8 mm aggregate size and the traffic volume on this street. But it is strange that there is such a remarkable difference between the southern and northern directions and that it is not consistent between lanes K1 and K2. No obvious explanation can be offered for this.

The overall conclusion is that the Örebro test section did not appear to be as successful as hoped, given its small aggregate size; nevertheless, its performance is not seriously poor except in two directions and lanes. At the moment (2022), the pavement is five years old and in visually acceptable condition in two lanes and directions, which in the good lanes is not too bad for an 8 mm aggregate size mix exposed to such high traffic volumes. There are some inconclusive suggestions that the different lanes and directions were paved less well to cause the big differences in rut depth.

The slag pavement in Örebro, which should have been similar to the one on Skälbyvägen, did not perform as well as the latter. The traffic per lane is lower but speeds are higher, which makes the comparison irrelevant. A potential reason may have been that the Nordic Ball value was not good enough.

9 Using steel slag in a porous pavement – E4 in Huskvarna

9.1 E4 in Huskvarna (2010 - 2017)

9.1.1 Test sections

Motorway E4 connects southern Sweden with its middle and northern parts. One sensitive part is the motorway passing through Jönköping and Huskvarna cities, especially Huskvarna since along the motorway there is a residential area overlooking Lake Vättern. Therefore, by court decision, Trafikverket had to provide noise reduction on this part.

The goal of the pavement of E4 through Huskvarna was to lower the noise level by at least 5 dB on average for this road section. When noise reduction is below 3 dB the pavement must be renewed. To achieve this, two layers of PA were laid in the summer of 2010 on a more than 3 km long section in both directions. The contractor for this road is Svevia AB.

The main section (2.7 km long) was paved with a double-layer porous asphalt, DPA. In addition, some shorter parts were paved with certain variants of the main pavement. One of them was a part with porous steel slag. This was laid as a single-layer PA using steel slag as the main aggregate, only in the southern direction, in lane K2 (fast lane), with a length of 140 m. In addition, there was a 25 m section which was laid as a top layer with steel slag, laid on the normal lower layer for the DPA. See Figures 9-1 and 9-2.

Figure 9-1: The conventional DPA pavement (in lane K1 - right) and the steel slag pavement (in lane K2 - left). The short distance at the bottom of the photo is the end of the 140 m long single-layer steel slag section, and the rest of the dark surface is the 25 m long section with steel slag on top of a pervious bottom layer. Photo shot after one year of traffic exposure. Note the dark colour of the steel slag.

Figure 9-2: Surface view of the conventional DPA pavement (upper half) and the steel slag pavement (lower half). The photos were shot after one year of traffic exposure.

Facts of the test road on E4 in Huskvarna (2010-2017):

- Motorway, two lanes per direction, right lane designated K1, and left lane designated K2
- Posted speed limit: 90 km/h
- AADT: 12 000 vehicles (20 % heavy vehicles) in both lanes per direction. 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 with steel slag considered here, the K2, the AADT was 3500 with almost 0 % heavies.
- Length of main section of the DPA: 2.7 km
- Length of the section with single-layer PA and steel slag as the aggregate: 140 m
- Length of the section with double-layer PA and steel slag as the aggregate in the top layer: 25 m
- Layer thickness of the PA: upper layer 30 mm, lower layer 50 mm
- Layer thickness of the PA with steel slag: upper layer 30 mm (steel slag), lower layer 50 mm
- Binder: Endura D1 from Nynäs, 6.3 %
- Sections with steel slag, binder: Endura D1 from Nynäs, 5.9 %
- Aggregates in the upper layer: in K1, rhyolite; in K2, diabase (north) and rhyolite (south), max. size 11 mm.
- Aggregates in the bottom layer: diabase in all lanes, max. size 16 mm
- The cross fall was increased to 3 %, so that water would easier drain out sideways from the pavement. Normally it is 2.5 %
- Void content of the PA with conventional aggregate: 25-27 % (in samples from the road)
- Void content in the pavement samples containing steel slag: just above 20 %
- Two adhesives were used, cement and amine (Wetfix).

It must also be mentioned that the steel slag was laid as the start of the PA section for traffic going south. It is well-known that dirt is pulled-in with vehicle air wakes from the dense pavement just ahead of the PA. Therefore, it is expected that dirt will faster than usual clog the section nearest after the dense asphalt pavement.

9.1.2 Noise

The measurements of noise showed the results presented in Table 9-1. The noise measurements were continued until June 2017, but the last three years are not shown in the table as they are not of great interest for this particular study on steel slag pavement due to the lack of noise reduction. Note that uncertainties for the short steel slag surface are higher than normal due to the problems to hit exactly on the right section. However, it appears that from an initial reduction of 1.3 to 2.9 dB it was already 4 years later only approx. 1 dB. The latter is approx. what one can expect from just the difference in max. aggregate size of 11 vs 16 mm and leaves no room for any extra advantage of the material being steel slag. Essentially, the PA with steel slag after two years is just as an SMA 11 with steel slag. If the pavement had not been paved immediately after a dense pavement, the initial noise reduction may, however, have remained at 1-3 dB for a longer time.

The 25 m section with steel slag in the top layer and conventional PA as the bottom layer was too short to give meaningful noise measurements.

The noise measurements intended for the steel slag section in 2013 showed totally unrealistic results (approx. 4 dB noise reduction). Probably, the measurements did not hit the right section.

Table 9-1: A-weighted noise reduction in dB of the main section of the PA pavement at 80 km/h, based on CPX noise measurements for two tyres at six different times. The noise reductions are relative to the annual average of the noise levels of 3-4 SMA 16 pavements.

Pavement	Reference tyre	New June 2010	1 month July 2010	1 year July 2011	2 years July 2012	3 years July 2013	4 years July 2014
PA with steel slag (single layer)	P1		2.9	1.7	0.7	See text	1.3
	H1		1.3	2.2	0.3	See text	0.9
DPA with conven-tional aggregate	P1	8.1	7.2	6.8	6.6	6.0	3.6
	H1	6.7	7.0	7.2	7.4	6.2	3.0
SMA 16 (Swedish reference)	P1	ref	ref	ref	ref	ref	ref
	H1	ref	ref	ref	ref	ref	ref

9.1.3 Texture and rut depth

In 2017, at an age of 7 years, the steel slag on E4 in Huskvarna looked to be in very good condition. Hardly a single stone had come loose according to a visual inspection. Measurements of the rut depth on the steel slag on E4 in Huskvarna 2016 (based on PMSV4 data) constantly indicated a rut depth of 4 mm on the steel slag surface. On the (equally old) DPA with conventional aggregate (rhyolite) that comes immediately after the steel slag in the same lane, the rut depth varies between 4 and 8 mm. It is worth noting that, yet the DPA has a stone material with a ball mill value (kkv = kulkvarnsvärde) of 3, which is among the best available, against the steel slag's value of 7.

Nevertheless, the steel slag PA is still in service when this is written in 2022 at an age of 12 years. According to PMSV4, in 2021 the rut depth was 7-8 mm. It should be noted that it is located only in lane K2 where traffic as estimated to be around AADT 3600 with few heavy vehicles. Visually, in 2022 it looks to be in good condition; see Figure 9-3.

Figure 9-3: The steel slag pavement (the dark surface in lane K2 - left). Photo from PMSV4 in 2021-06-13, after 11 years of traffic exposure [PMSV4, 2021]. Note the dark colour of the steel slag and how homogene it looks to be. Also note the marked difference in colour compared with lane K1 (right) which is paved with SMA 16. At the end of this section, there is the start of the DPA pavements laid in 2017.

9.1.4 Discussion and conclusion

The steel slag experiment on E4 in 2010-2017 was of no practical use, since it was laid immediately after a dense pavement, implying that it was fully clogged only after a couple of years. Also, it was only a thin single layer PA with a moderate voids content, which does not give a noise reduction of practical significance. However, it showed that wear was no worse than for the conventional high-quality aggregate, or even less.

9.2 E4 in Huskvarna (2017 --)

9.2.1 Test sections

In this study, two or sometimes even 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.
- DPAstsl: This is the same as the DPA, except that the top layer uses steel slag aggregate instead of stones. 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.
- 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.

It means that whenever comparisons are made, only lane K1 is considered. Figure 9-4 shows a part of the steel slag pavement on motorway E4, while Figure 9-5 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.

Figure 9-4: 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.

Here are some detailed facts for the tested road sections:

- Motorway, two lanes per direction, right lane designated K1, and left lane designated K2. But the steel slag was used only in the K1 lane.
- Posted speed limit: 90 km/h
- AADT: 12 000 vehicles (20 % heavy vehicles) in both lanes per direction. 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, the K1, the AADT was 8500 with 30 % heavies)
- Length of main section of the DPA: 600 m
- Length of the section with DPA and steel slag as the aggregate in the top layer: 180 m
- Layer thickness of the DPA: upper layer 30 mm, lower layer 50 mm

- Binder in the conventional DPA: Endura D1 from Nynäs, 6.0 % (by weight)
- Layer thickness of the DPA with steel slag: upper layer 30 mm (steel slag), lower layer 50 mm
- Binder for steel slag layer: Endura D1 from Nynäs, 4.5 % (by weight)
- Steel slag product: Smedjebacken via 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
- Aggregates in the upper layer of the DPA in K1: porfyr (kkv < 5), max. size 11 mm. The kkv value indicates that the aggregate is among the best one can find
- Aggregates in the bottom layer: diabase in all lanes, and also for the DPAstsl, max. size 16 mm
- The cross fall was increased to 3 %, so that water would easier drain out sideways from the pavement. Normally it is 2.5 %
- Void content of the DPA with conventional aggregate: approx. 25 % (in samples from the road)
- Void content in the pavement samples containing steel slag: somewhat below 25 %
- Two adhesives were used in the mix, cement and amine (Wetfix).

Figure 9-5: 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.

9.2.2 Noise emission

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. 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.

The measurements of noise emission in years 2017-2022 showed the results presented in Figure 9-6. The data is for the speed of 80 km/h, in lane K1, and is averaged for the two tyres P1 and H1, since the two tyres show the same trends. The black curve is for the steel slag (DPAstsl) and the red curves are for the DPA with conventional aggregate. The unbroken red curve is based on all available data (both the southern and northern directions) while the broken red curve is based only on the DPA in the southern direction.

The reason for the remarkable difference in the red curves is that the conventional DPA performs better in the southern than in the northern direction. One plausible reason may be transportation by westerly winds of dirt from the west to the east, and/or by southerly winds from the adjacent dense pavements, in both cases causing 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 some dirt transported by southerly winds. However, another possibility could be that the paving was performed slightly different in the two directions for an unknown and unintentional reason.

The data show that the steel slag DPA in the last three 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 equally well when only the southern direction data are used.

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.

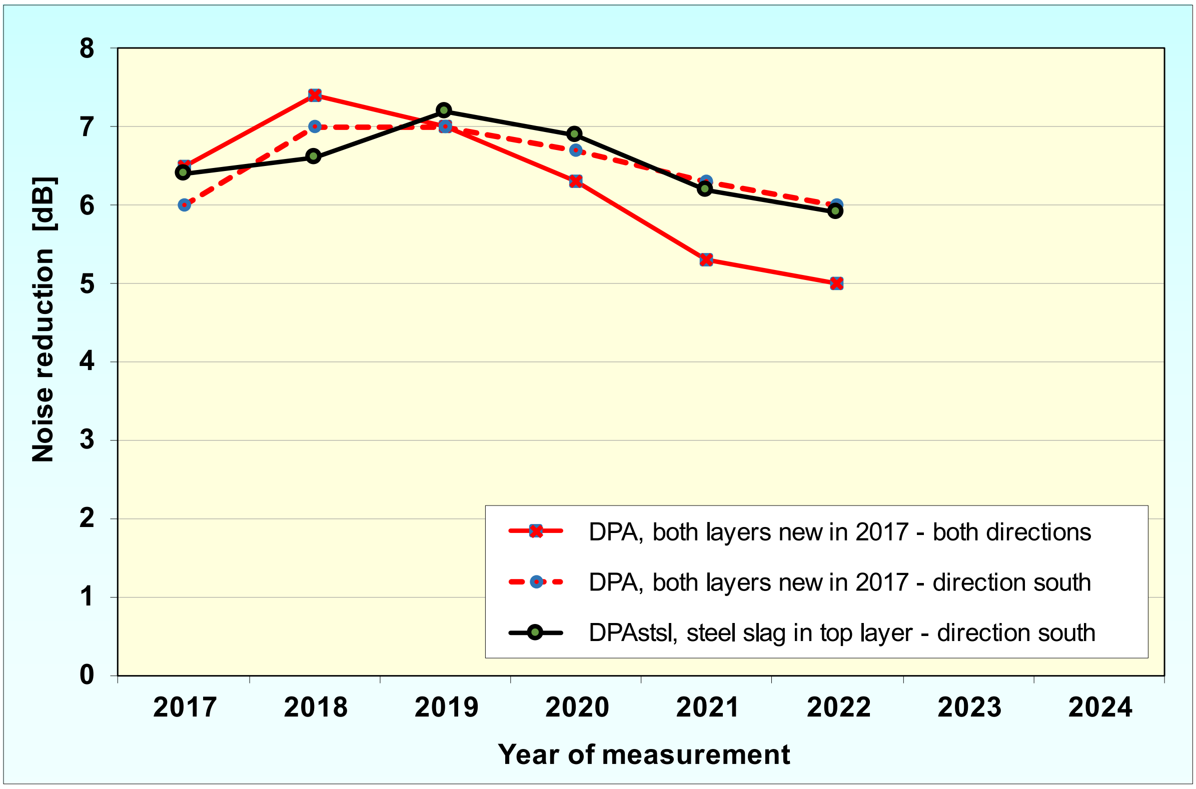


Figure 9-6: Measured noise reduction over the lifetime (so far), starting with paving in 2017. Here, all available data are used; i.e., both directions for the red curve. Note that the values measured in 2017 were influenced by some rainwater remaining in the bottom layer; see the text for more information.

At least, it is conservative to say that the DPA with steel slag performs equally well as the DPA with conventional aggregate. Depending on how one interprets the significance of the difference between the two directions of conventional DPA, an alternative conclusion could be that the steel slag performs better with time than the conventional aggregate.

In Figs. 9-7 and 9-8, frequency spectra are shown for the three cases in Fig 9-6, but only for years 2018 (at an age of one year) and 2022 (at an age of five years).

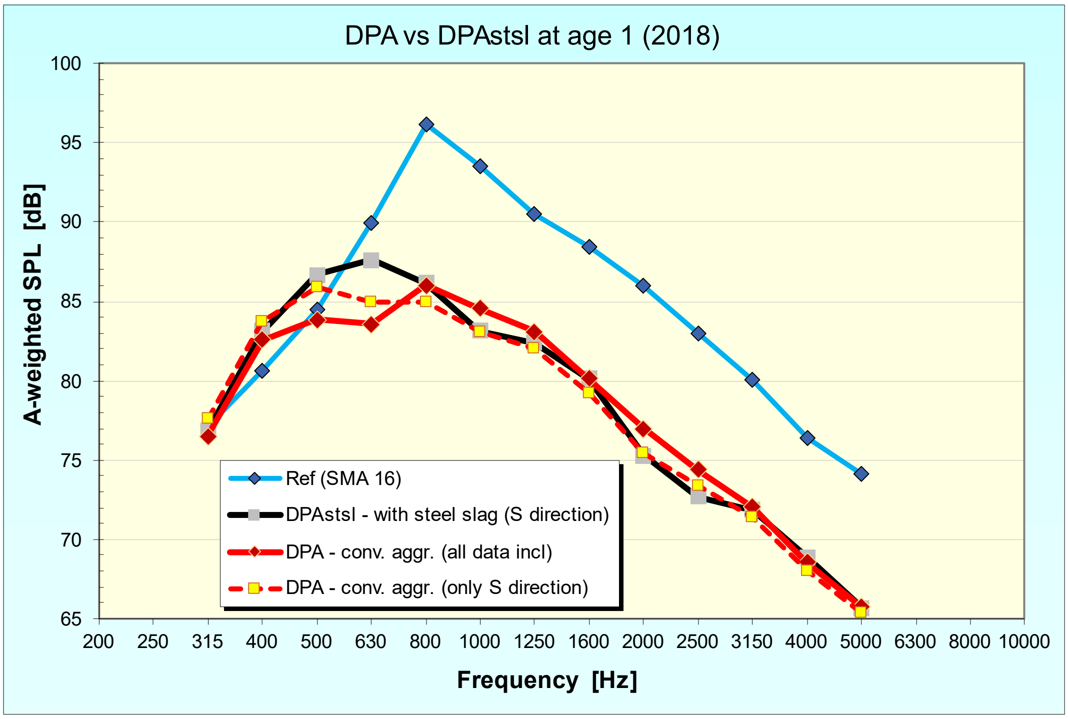


Figure 9-7: Third-octave frequency spectra for the steel slag pavement compared to the reference pavement (SMA16) and DPA with conventional aggregate (with both directions or with only south direction included). Measurements in 2018 at an age of one year, at 80 km/h.

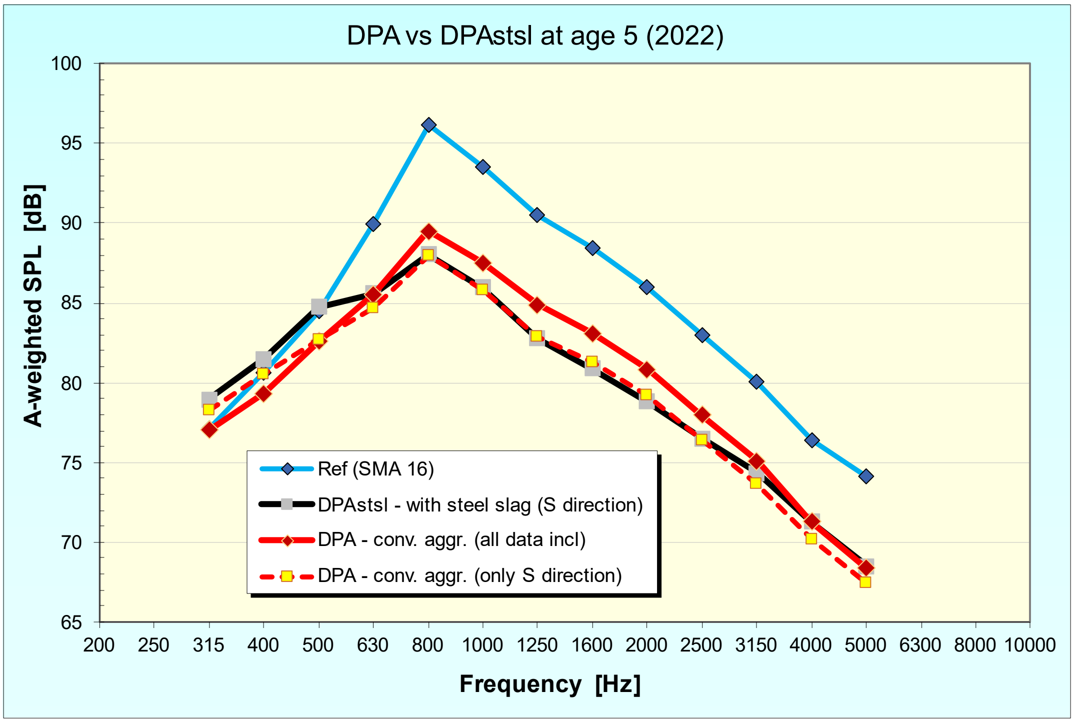


Figure 9-8: As the previous figure, but for measurements in 2022 at an age of five years.

The differences shown in the spectra between pavements, between ages one and five and between the directions (shown only for the conventional DPA as the steel slag was only in the southern direction) are caused by complicated changes or differences in macrotexture depth, sound absorption due to porosity and air drainage due to non-enveloped valleys in the macrotexture. The only consistent feature is the noise reduction of the DPA:s at the medium and high frequencies (7-8 dB at age one and 5-6 dB at age 5), which is due to the reduction of the air pumping noise generation mechanism, combined with sound absorption. The latter is reduced between ages one and five, due to clogging, which is the main cause for the reduced overall noise reduction in 2022 for both DPA:s as shown in Figure 9-6.

9.2.3 Rolling resistance

The measurements of rolling resistance were made only in 2018 as part of another project (PhD education for Mr Tiago Vieira) by the GUT trailer shown in Section 7.7. The results are presented in Table 9-2. They are measured 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.

Table 9-2: Results of the measurements of rolling resistance, using three test tyres (see section 7.7).

Pavement	Tyre	Rolling resistance coefficient (in %)	Air temperature
DPA (conventional aggregate)	P1	1.26	9.3
	H1	1.36	11.7
	GEGP	1.08	11.7
	Average	**1.233**	**10.9**
DPAstsl (steel slag aggregate)	P1	1.27	9.5
	H1	1.33	11.7
	GEGP	1.03	11.7
	Average	**1.210**	**11.0**

Although the rolling resistance coefficients show an advantage for the steel slag of around 2 %, this difference is not statistically significant.

9.2.4 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 the results presented in Table 9-3. The time in seconds is a measure of the permeability, where low values show better permeability and high values show worse permeability. For a newly laid porous asphalt, the values would normally be around or below 10 seconds. For a dense asphalt pavement, the values would be several minutes.

The results show that the steel slag surface is substantially less permeable than the conventional pavement, after four years of traffic exposure. This is mostly due to clogging as also the visual appearance suggest. In Figure 9-5 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. See the discussion below.

Table 9-3: Results of the measurements of permeability, using the water outflow method (see further Section 7.5). The time in seconds is a measure of the permeability, where low values show better permeability and high values show worse permeability. Measurement only in 2021.

Pavement	Lateral position	Outflow time (in seconds)
DPA (conventional aggregate)	In wheel tracks	60
	Between wheel tracks	36
	Average of all measurements	**47**
DPAstsl (steel slag aggregate)	In wheel tracks	107
	Between wheel tracks	43
	Average of all measurements	**86**

9.2.5 Geometrical parameters (rut depth, texture and roughness)

Measurements of the geometrical parameters, rut depth, texture and roughness, were done annually 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. The results are presented in Table 9-4.

Table 9-4: Rut depth, texture (MPD) and roughness (IRI) measured by the VTI RST system, for the DPA versus the DPAstsl pavements, as measured in lane K1 in the southern direction.

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

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 (the 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.

It is interesting that the roughness is consistently a little lower for the steel slag pavement than for the pavement with conventional aggregate. IRI:s in the range of 0.7 to 0.8 is extremely good; especially after more than half of the lifetime of the pavements. The same trend (better evenness for steel slag than for conventional aggregate) has been reported in foreign countries.

See further the discussion in section 9.2.8.

9.2.6 Ravelling

The loss of aggregate particles (stensläpp in Swedish and ravelling in English) has been estimated in two ways, described below:

1. By visual inspection, using the French Window
2. By analysis of digital profile curves of the texture

Visual inspection, using the French Window: Ravelling (particle loss) was estimated only at a physical inspection in 2021, by counting missing particles (size 4-11 mm) within a so-called "French Window". This is a frame put on the pavement within which an area the size of 200 mm by 200 mm is visible. The window is standardized in EN 12272-2. A picture of using this characterization method is illustrated in Figure 9-9. The outcome is the number of lost particles in relation to the total number of particles counted in the frame (in %). To get statistically relevant results, one must repeat the procedure on more locations on each studied object. Unfortunately, too few windows were recorded on each site, but the data is better than nothing.

Figure 9-9: Photographing the French Window with the purpose to count missing particles in this area later. The procedure is repeated in more locations on each test section.

Digital profile analysis of the texture: This is a crude method designed by the RST group at VTI, conducted as follows. From the texture profile curve, a new profile curve (envelope) is created which follows the profile down to 30 % from the top of the profile, at which level the envelope curve is horizontal until it meets the upgoing profile again. Then the difference between the actual profile and the envelope is used to determine occasions when a "hole" in the pavement (i.e., the difference curve) is greater than 21 mm in amplitude (depth) and 21 mm in extension (length). The number of such occasions over a 20 m distance is taken as the particle loss value (ravelling). The procedure is repeated over 20 m segments and the average value over the section length is calculated. This is conducted separately for three lateral positions: in the left wheel track, in the right wheel track and between the wheel tracks. Since the data for the two wheel tracks are similar, in this study the average for the wheel tracks is reported.

The data are presented in Tables 9-5 and 9-6. It appears that there is no big difference between the two pavements, although the particle loss values for the steel slag aggregate are lower than for the conventional aggregate each year.

Table 9-5: Ravelling (particle loss values) determined by the visual inspection method, for the DPA versus the DPAstsl pavements, as measured in lane K1 in the southern direction. The values shown are the percentage of lost particles divided by the total number of particles in each French Window.

Year	Wheel track	DPA (conventional stone aggr.)	DPAstsl (steel slag aggr.)
2021	Left	1.5 and 1,9 %	1.2 %
	Right	1.5 and 1.0 %	0.6 %
	Average value	1.5 %	0.9 %

Table 9-6: Ravelling (particle loss values) determined by the digital profile analysis method, for the DPA versus the DPAstsl pavements, as measured in lane K1 in the southern direction.

Year	DPA		DPAstsl	
	Stone loss value in the wheel tracks	Stone loss value between the wheel tracks	Stone loss value in the wheel tracks	Stone loss value between the wheel tracks
2018	134	102	121	96
2019	143	109	132	101
2020	152	124	149	97
2022	Not analysed	Not analysed	Not analysed	Not analysed

Both ravelling test methods show consistently an advantage for the steel slag over stone aggregate.

9.2.7 Wet friction

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 Section 7.6. 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 the test tyre and water sprayed manually in front of the device; see Section 7.6. This was made only in May of 2021.

In both cases, the measurements are mainly characterizing the microtexture influence on the friction. The results are shown in Table 9.5. Values equal to or above 0.50 or 50 are considered as acceptable by Trafikverket for newly laid asphalt pavements.

Table 9-5: Results of the measurements of wet friction. Results are expressed as the friction coefficient and friction value. The latter becomes similar to the former, by dividing it by 100.

Pavement	Lateral position	Friction coefficient measured by SFT	Friction value measured by PFT
DPA (conventional aggr.)	In wheel tracks	0.64	60
	Between wheel tracks	Not measured	Not measured
	Aver. of all measurements	**0.64**	**60**
DPAstsl (steel slag aggr.)	In wheel tracks	0.63	61
	Between wheel tracks	Not measured	64
	Aver. of all measurements	**0.63**	**63**

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.

9.2.8 Rainy weather

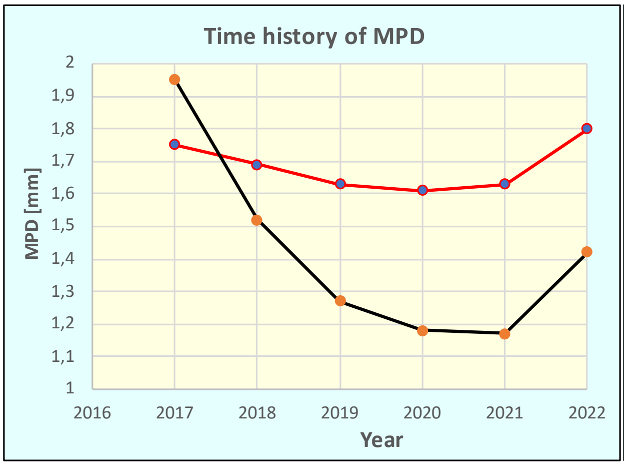
The author drove over the test sections one day in May 2021 when there was heavy rain which had been pouring down for a considerable time on that day. One could then fear that the clogging of the four year old pavements, especially the steel slag, would prevent an effective vertical drainage through the top layers, resulting in water standing in the wheel tracks. This did not happen as can be seen in Figures 9-10 to 9-12. It appears that both porous pavements are essentially dry, while the dense pavement is flooded by water.

9.2.9 Discussion

A problem with understanding why we have got the results reported here is that we have no information from the paving contractor about details in the composition of the mix and its materials. It shall also be stressed that the test section has probably one or two years more until it will be repaved. Better conclusions may be drawn then.

For noise emission properties, the results so far (after 5 years) suggest that the steel slag aggregate either has the advantage over the conventional aggregate of showing a more stable noise reduction over time, as was predicted in the project application, or has similar acoustic performance, depending on whether all data for the DPA pavement are considered or only those in the same direction as the steel slag. And yet, this slag pavement is not optimized like the one with conventional aggregate, since the same initial voids content (and thus sound absorption) was not achieved. In a future follow-up, gaining from the experience in this project, this should be possible.

The geometrical properties (rut depth, texture, roughness) of the two DPA pavements were somewhat different already in the beginning, but those increased by time. See Figure 9-13. Measurements were not made in 2017, but in the figure, it has been assumed that when the pavements were new, they had no ruts (zero rut depth) and the MPD was the same in the wheel tracks as between the wheel tracks; the latter being just marginally higher in 2017 than in 2018. Both pavements got reduced texture but increased rut depth by time; but this trend was more pronounced for the steel slag than for the conventional pavement. Note that the high rut depth values in 2019 might be due to measurement issues.



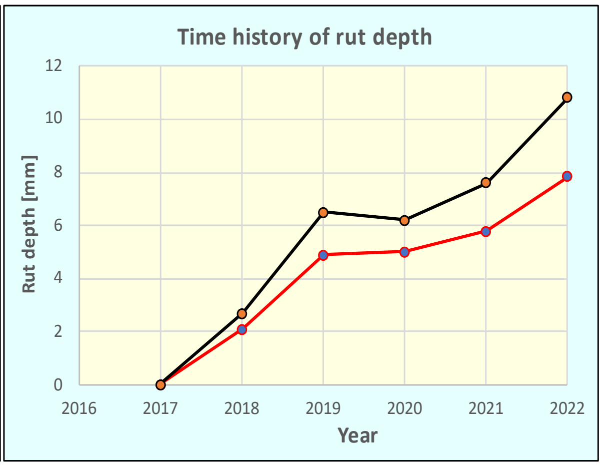


Figure 9-13: The development over time of MPD in the wheel tracks (left part) and rut depth (right part). Data for the DPA are the red curves and data for the DPAstsl are the black curves.

Figure 9-8: DPA pavement during heavy rain.

Figure 9-9: DPAstsl pavement during heavy rain. The dense SMA pavement is visible further away.

Figure 9-12: The dense SMA pavement during heavy rain. Same rain conditions for all three photos.

It would be easy to imagine that the reduction in texture and increase in rut depth of the steel slag layer are due to wear by the (studded) tyres. However, the author thinks that it is more complicated. The rut depth increase is (relatively) a smaller difference between the pavements than the change in MPD. Further, while the change in MPD is very fast, both in 2017-2019 and in 2021-2022, it seems to have no correlation to the rut depth change which is rather stable at 2 mm per year for the DPAstsl and 1.6 mm for the DPA. Neither does ravelling seem to be the cause for the rutting as it should have increased the MPD. This does in fact happen between 2021 and 2022, but not before 2021. If ravelling is the cause of the increase in MPD between 2021 and 2022, then it is about the same on both pavements. It would be important to make a visual inspection of the pavements in 2023 as well as a new measurement of ravelling.

Therefore, the reasons for the change in texture and rut depth on the steel slag is a mystery. Some speculations about the reasons follow.

It is remarkable that almost all large changes occurred during the first two years for both pavements and for both MPD and rut depth. Wear of the surfaces cannot be so much higher in the two first years and then be very low. Therefore, the author believes that the major changes over the two first years are due to compaction and perhaps also orientation of the particles (flattening the surface by the forces of heavy vehicle tyres), caused by the very high volume of heavy goods vehicles, rather than wear by studded tyres. It may be that the coarse aggregate more easily is compacted and simultaneously orientates itself on the steel slag than on the natural material. Both processes will make the pavement denser (in combination with clogging by wear particles) which may explain why the permeability of the steel slag is so much lower. The good thing if this hypothesis is true is that the rutting is not caused mainly by wear but by orientation of the aggregates.

An alternative, or contributing, reason for the higher changes in texture and permeability of the slag pavement could be that perhaps the binder content was somewhat higher than would have been optimal. Since the pavement is always "blackish" it will absorb more solar energy and thus in very hot weather have a higher risk for some bleeding the first two summers. The very high proportion of heavy vehicles in the traffic would amplify such potential trends.

The author has consulted the two foremost experts at VTI (Prof Erlingsson and Dr Kalman) regarding the assumption that the steel slag is more sensitive to compaction by heavy vehicle traffic than stone aggregates, but none of them has any idea of how this can be explained. Other studies (Chapter 5) have consistently concluded that steel slag is less susceptible to compaction by heavy loads; although the tested lane in our case indeed is subject to very high volumes of heavy trucks.

Nevertheless, the rut depth after five years (11 mm) is not alarming; it is only a little greater than what is normal for conventional SMA 16 pavements with similar traffic. For example, in the same lane a bit further south on the road, the ABS 16, had a rut depth of 8.2 mm after 5 years of service (2014-2019) according to PMSV4 [PMSV4, 2023]. One should also note that the aggregate in the reference pavement (the DPA) was exceptionally good, with a Nordic Ball value (kkv) < 5 as compared to < 7 for the slag here. So far, steel slag with better kkv values than the one used in this project is not known, as the best slag [Viman et al, 2016] tested was 8 (see 8.1).

Consequently, it may be that a combination of three effects may be the explanation, as this speculation suggests:

- The first years the texture reduced very fast, but rutting was no worse than over the entire 5 year period. This might be due mostly to an orientation of the aggregate to the high loads of truck tyres, to make the tyre/road forces in the interface as evenly distributed as possible. There might be some compaction as well, Some bleeding could also be a contributing factor as the steel slag is absorbing more radiation due to its dark surface.
- The studded tyres may have crushed the coarse aggregates into smaller ones (as reported in one international reference; see Section 5.9) which may have been the main reason in later years.

- The increased macrotexture between year 4 and 5 is difficult to explain by other things than ravelling. However, even if it is ravelling, this has not caused a remarkably higher noise, which is strange. In 2023 we hope that a new ravelling analysis can be made.

If the author's speculation about the compaction and orientation of particles is correct, it would mean that the steel slag could be more acoustically efficient in the lane(s) where not as many heavy vehicles travel as in this project, where the heavy vehicles constitute about 30 % of the vehicles – a quite exceptional proportion, although not unusual on roads with such intensive goods transportation.

It would be interesting to know why the evenness of the steel slag pavement is better than of the pavement with conventional aggregate. Low unevenness (IRI) is important for the comfort in vehicles running on the road as well as it causes less vibrations in the ground that potentially could be felt in nearby houses. It also has some effect on rolling resistance for heavy vehicles. Improved evenness has been noted in some of the literature referenced in Chapter 5, so it may be a systematic effect, the reason of which is unknown.

The constant "blackish" colour of the steel slag will give the visual impression of a fresh pavement in good condition, in contrast to the conventional aggregate, where all kinds of cracks, damages or wear are easily visible. This is an advantage which shall not be neglected since the idea of low noise pavements is to make people feel better. There is a story this author heard in Denmark where people were dissatisfied with a cement concrete pavement and wanted it replaced with asphalt. The road authority sprayed a thin layer of bitumen (or maybe it was a very thin slurry?) on the surface which made people happy since they thought that now they had got a new black asphalt there.

Despite the above, if surface damages as serious as potholes occur, such should be as visible as possible, and they will be more difficult to spot by drivers on steel slag. But, so far, this author has not seen or heard of a pothole on any of the steel slag pavements.

The darker surface gives better contrast to lane, median or other road markings which is a valuable safety feature throughout the lifecycle. Due to the microporous properties of the slag particles, the surface does not get glossy and retroreflection properties are good while specular reflections from oncoming vehicles or low incident-angle sunshine would be lower than on most regular asphalt. A potential disadvantage would be the absorption of light from streetlights. However, on motorways or roads for only motorized traffic, there should never be any people or animals on the road and in many cases it is almost impossible to enter the road or motorway as a pedestrian or cyclist. Nevertheless, in cases of accidents or loss of vehicle power, there may occasionally be people on the road. In such rare cases, the streetlight on steel slag may be less bright than on worn asphalt and make detection of objects on the road a bit more difficult, although steel slag would be much better than <u>new</u> asphalt in this respect.

The steel slag and conventional aggregate seem to have similar wet friction properties as measured by the devices we use in Sweden. They measure essentially the microtexture effect on the friction. Nevertheless, what is more important is the wet friction at high speeds which is determined also by drainage properties, and as long as the water is not staying in the wheel tracks, the wet friction values will be acceptable. Our observations so far in rainy weather (in 2022) is that no water stays in the wheel tracks in normal rains, despite the surfaces look rather clogged. This is assisted by the higher-than-normal crossfall of 3 % on the E4 section through Huskvarna.

According to Table 9-2 there is a 2 % advantage in rolling resistance for the slag pavement over the conventional one. This was measured in 2018 when the MPD was 1.52 mm for the slag against 1.69 mm for the conventional aggregate in the wheel tracks. This is not far from what the general formula for rolling resistance (RR) and MPD relations predicts, with a coefficient of 0.0017 in the expression

$$\Delta RR = 0.0017 * \Delta MPD$$

which was obtained in the MIRIAM project [Sandberg et al, 2011] and would predict a 3 % advantage. Rolling resistance has not been measured later on these two pavements, but if the same formula is applied to predict the rolling resistance in 2022, based on the MPD:s in Table 9-2, the advantage in rolling resistance would increase to 6.5 %. That would be significant for driving energy savings. In addition, the unevenness difference would be an extra favour; however only for heavy vehicles, and to a lesser extent.

9.2.10 Conclusions for the E4 project

The study of the steel slag aggregate versus conventional aggregate in the top layer of a double-layer porous asphalt in this project, after five years of traffic exposure, has indicated the following:

Noise reduction (compared to a mix of SMA 16 pavements) has been largely similar for the two pavements; except that the steel slag shows a smaller or similar loss of noise reduction over time than the conventional aggregate pavement, depending on whether both road directions are considered or not. If this trend continues over the rest of the acoustical lifetime, the slag pavement could show a more favourable noise reduction over the lifecycle; alternatively, the slag pavement may stay in service for one or two years longer than the conventional aggregate before it has lost 50 % of its initial noise reduction.

The lower texture for the slag pavement, means that it provides lower rolling resistance for vehicle tyres rolling on the pavement, which is a significant advantage in terms of energy consumption. However, the substantial increase in texture depth (MPD) in 2022 (for both pavements) may be a sign of increased ravelling and it will be important to check if it will continue in 2023. The same goes for rut depth. Similar trends, however, seem to occur for the conventional DPA.

The lower permeability of the slag pavement would reduce its acoustical performance, as sound absorption and elimination of what is called “air pumping noise” would suffer; however, the lower texture seems to compensate for this acoustical effect. Simultaneously, the lower permeability would suggest that vertical transport of water away from the surface will suffer, which potentially may create water staying in wheel tracks in rainy weather. So far (the end of 2022), this potential problem has not been observed in (normal) rainy weather. It seems that the much-reduced porosity open to the surface is still enough for transporting water away from the surface, aided by the high pressure by the heavy vehicle tyres. However, this feature should be monitored in the next few years by visual observations in rain.

Nothing has indicated that there is any significant difference in wet friction of the two pavements, despite the difference in texture.

One shall not neglect the advantage of the water storage that exists in the porous asphalt layers, for both types of surface. In this case, the water easily runs to lake Vättern, but in more general locations, such water storage may be very favourable to local rainwater drainage systems.

The constant “blackish” colour of the slag pavement (which is unusual on Swedish asphalt pavements due to the use of studded tyres which already after one winter removes all bitumen on asphalt surfaces) has a psychological advantage since it gives people the (erroneous) impression that it is a new pavement. In contrast to pavements with conventional aggregate, cracks, damages, ravelling and wheel tracks are almost invisible even when they are significant.

Even more important, the contrast between the slag surface and painted road lane markings is better and constant throughout the lifetime than with conventional aggregates. It is absolutely a significant safety feature. In contrast to this, there may be rare occasions when streetlight is more absorbed by steel slag than on worn asphalt and when an unwanted object or pothole on the road may be less detectable.

When it comes to ravelling, the steel slag aggregate shows an advantage over the stone aggregate, but in both cases the particle losses (ravelling) are low, at least up until 2021. However, in 2022 the situation is unclear due to the measured, sudden increase in texture between 2021 and 2022.

Unevenness is still in 2022 very low (IRI below 1.0), which is comfortable for the road users and reduces the risk of vibrations in the ground caused by passage of heavy vehicles.

The only functional feature which is a disadvantage for the slag compared to stone aggregate seems to be higher rutting, although it is not alarming. It seems to have been fairly linear with about 2 mm per year. As mentioned in the discussion, it is a premium type of steel slag used here with kkv < 7, but the stone aggregate in the reference pavement (DPA) had an even better value (< 5) which is exceptional. However, so far (after 5 years of service) this rutting has not indicated that there will be pools of water standing in the wheel tracks, neither that it has had any other effect on the performance of the pavement. Nevertheless, negative effects of the rutting may show up in later years.

It should be noted that the conventional porous asphalt is based on an aggregate which is among the best available and its design and composition is based on significant earlier experience. However, the steel slag aggregate composition is not yet tried out as extensive as the conventional DPA. The grading and binder content are not sufficiently tested to be optimum. This suggests that there is some room for further improvements.

10 Overall evaluation of the Swedish steel slag sections

An attempt to make an overall assessment of the trials in Sweden with steel slag aggregate, as presented in Chapters 8 and 9, is presented in Table 10-1. Note that all test sites have been exposed to traffic by studded tyres in wintertime.

Table 10-1: Overall assessment of the trials in Sweden (as described in Chapters 8 and 9). See the codes beneath the table for explanations. Age in years

Location	Age	Traffic	Noise	Friction	Durability	NMAS	Other
Early tests by VTI	varies	varies	?	N/A	+	varies	
Road 68, Avesta	1-14	L HH	+	N/A	+/-	11	
Järnvägsg., Linköp.	8	LLL H	N/A	N/A	+++	11	
Skälbyväg., Järfälla	0-3(-8)	LLL H	++	N/A	+?	8	
Ö. Bangat., Örebro	0-5	LLL H	+	N/A	-	8	
E4 Huskvarna, K2	0-7(-12)	LLL H	+	N/A	++	11	
E4 Huskvarna, K1	0-5	LLL HHH	+	+	+	11	RR ++

Codes: L = light vehicle traffic, H = heavy vehicle traffic, RR = rolling resistance, K1 = slow lane, K2 = fast lane, NMAS = Nominal maximum aggregate size (in mm). Number of L or H indicate relative volume of traffic. Number of + or – indicate relative advantage of the slag.

In summary, the table appears to give a quite positive picture of the steel slag aggregate. Only one of the trials have been a disappointment. On the other hand, there is neither one that can be considered as a really “great success”.

11 Overall conclusions

This project was originally intended to study only a porous steel slag pavement on E4 in Huskvarna. However, the study came to include also a review of all (to the author) known pavements with steel slag in Sweden in the past 20 years. Even though they have not been systematically monitored, an overview of those gives valuable insight into the performance of such pavements in general. Also, a review of international experience has been included in this report.

The international experience of steel slag in pavements has been consistently positive. Steel slag can be considered a green resource because it has a great potential to substitute natural aggregates and reduce the environmental impact of virgin resources from quarries. Some countries have huge stock-piles 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 the natural aggregates of good quality will soon become rare and steel slag will be a good and much needed replacement.

Reports of field experiments are not as frequent as reports about laboratory studies, and very few ones report long-term performance. Only in Singapore and a minor study in Spain, steel slag has been used in porous asphalt, and none has used it in double-layer asphalt such as the test in this report.

Among many advantages for steel slag over natural aggregates, the literature mentions durability, less rutting and dark colour. Also polished stone values and abrasion resistance are generally high. The main disadvantage is the higher mass which makes transportation from steel works to paving sites more expensive. However, with high quality natural aggregates being more and more depleted, even natural aggregates may cause long and expensive transportation. Despite all positive assessments in the international literature, one must remember that for Swedish conditions, slag performance is more complicated, due to our relatively good resources of high-quality aggregates and use of steel studs in winter tyres; the latter requiring such high-quality aggregates.

Some of the Swedish steel slag pavements presented in this report have served well for very long times, under moderate or high traffic volumes. The overall assessment in Chapter 10 comes out quite positive. Only one of the trials have been a disappointment. On the other hand, there is neither one that can be considered as a really “great success”.

The main subject of this project, and this report, is a test of steel slag aggregate in the top layer of a double-layer porous asphalt pavement paved in 2017 on E4 in Huskvarna. This project started, as planned, in 2016 with laboratory studies aiming at getting experience of designing steel slag pavements with high air voids content for durable performance, especially with traffic noise reduction in focus. These studies provided a base for the experimental field test starting in 2017. However, the final mix was prepared, and the paving was made by Swedish road contractor Svevia, as the field test was part of Svevia’s contract with the Swedish Transport Administration (Trafikverket) for this part of motorway E4.

As planned, it was possible to get a study object on E4 in Huskvarna, for a limited distance (a little less than 200 m in the slow lane, designated lane K1 in Sweden). This was paved simultaneously when the double-layer pavement through Huskvarna had to be repaved in the summer of 2017. This object had a bottom layer identical to the rest of the fully renewed section through Huskvarna, while the top layer had the stone aggregate replaced by steel slag (for the grading 4-11 mm). In this way it has been possible to compare the performance of the steel slag section with a longer section of double-layer porous asphalt which is using only natural coarse aggregates. Thanks to the time extension of the project from the original three years (2016-2018), it has been possible to study the performance of this slag pavement compared to a similar top layer with conventional stone aggregate over a five-year period. Since the pavement is expected to have an acoustical lifetime of six or seven years, this gives a good picture of the long-term properties of such a steel slag pavement.

The study in Huskvarna has been truly holistic since many functional properties have been studied. Noise was the initial main issue in the project, but also rolling resistance, many geometrical properties related to wear, permeability and friction have been monitored or checked at certain occasions. Noise has been monitored each year by means of the CPX method of measuring noise properties of road pavements, according to international standards (ISO 11819-2, ISO/TS 11819-3 and ISO/TS 13471-1); all of them developed for such purposes.

The steel slag pavement on E4 in Huskvarna has served well so far, despite it was laid in the slow lane (K1) where there is exceptionally high traffic by articulated trucks, since E4 is the main transportation corridor between southern Sweden and the Stockholm area, and further north along the coast. For example, much of the cargo traffic between Finland/Estonia and western Europe goes this way.

The noise reduction so far has been equally good or better for the slag section than the natural aggregate section and has changed with time less than the conventional pavement. If this trend continues, the slag appears to have an acoustical advantage over the stone aggregate. When the slag pavement is new and has significant permeability and sound absorption, noise is reduced mainly by the sound absorption combined with lower air pumping due to air drainage in the tyre/road interface. By time, these noise-reducing mechanisms are exchanged with and balanced out by the lower vibration excitation to the tyre by the lower texture.

A major advantage of the slag section in Huskvarna is the reduced macrotexture without loss of noise reduction. Similar effects have been noticed on other steel slag test trials. The reduced macrotexture means that rolling resistance on the slag section is lower by up to 6 %, which reduces energy consumption of the traffic, while simultaneously reducing CO_2 emissions.

The use of steel slag in pavements has another positive effect on the CO_2 balance: through the carbon dioxide emissions from steel and slag production being allocated to the steel, the use of slag contributes to reduced carbon dioxide emissions compared with the extraction of crushed rock [Jernkontoret, 2022].

Finally, it is obvious that the higher mass density of steel slag makes transportation per km from the slag deposition to the road more expensive than for conventional aggregates. However, when using the best available stone aggregate, this may have to be transported an even longer way, so to be fair one will have to consider both transported mass and distance. This will obviously be different from case to case. Maybe most important of all, one should also consider that exceptionally high wear-resistant stone aggregate is a rare and expensive natural resource, while the slag is a waste material.

12 Recommendations

Based on the results of this experimental study, it is recommended that:

The successful steel slag section in central Linköping indicates that a dense slag pavement with maximum aggregate size of 11 mm performs better than SMA 11 and potentially equally well as one would expect with an SMA 16. With such a replacement for SMA 16 one would win significantly lower rolling resistance, which reduces CO_2 and noise emissions proportionally in an urban or suburban situation. It would also save the consumption of natural aggregates. Therefore, this pavement option should be considered more frequently.

The overall results suggest that the use of steel slag as aggregate in road pavements have advantages which justify increased research and development of this waste product. Steel slag is not a uniform product, and it should be possible to find the best type for use in Swedish pavements, which require the highest possible abrasion resistance due to wear of studded tyres. It is probable that there may also be ways to improve it. The dimensioning of the asphalt mix and tailoring the best possible binder for this material, is a challenge which needs to be studied, since the trial in this project is unlikely to use the optimum design.

The achieve a voids content in porous pavements using steel slag as the aggregate which is equally high as when using stone aggregate is difficult, most probably due to too lack of experience in dimensioning asphalt mixes with the much heavier steel slag. It is recommended to make further attempts to design a mix with steel slag reaching voids contents of at least 25 %. With such a mix, there is a potential for significantly better noise reduction over the lifecycle than for the presently successful double-layer porous asphalt in Huskvarna; especially allowing a longer lifetime until the threshold of minimum noise reduction is reached.

The international review suggests that it may be better to mix steel slag with natural aggregate rather than use 100 % steel slag for the coarse material. This should be further explored, but for Swedish circumstances with studded tyre wear, this author is in doubt whether it is a good idea to mix those aggregates. If they have different resistance to studded tyre wear (different kkv values), the weaker material will be worn away before the stronger materials, which will increase the macrotexture and in that way the pavement may lose its main advantage for noise and rolling resistance.

The trial on E4 in Huskvarna should be followed-up through its entire lifetime, and when a new pavement is needed, it is recommended to use steel slag on a new section, in both lanes and both directions. The possibility of improving an asphalt mix with steel slag as coarse aggregate to achieve a longer acoustic lifetime of porous asphalt pavements is still a realistic task which is recommended for further work.

Road contractor Svevia has several bore cores from the pavements on E4 in Huskvarna. It is recommended to make analyses of those, for sound absorption, voids content and computer tomography. There was no room for this in the present project. Furthermore, it will be important to try and figure out what mechanisms are behind the changes in macrotexture and rut depth in the E4 Huskvarna project, as such information may give hints on how to improve the design.

The literature review failed to find any European standards related to the use of steel slag in pavements, and no ISO standards were found. However, a couple of ASTM standards, together with a few national guidelines reviewed here, can be used for further development of such standards in Europe and/or within ISO, which is recommended.

The author recommends that the trial just started in Denmark to use crushed glass particles as an aggregate in wearing courses, partly or fully replacing stone aggregate is followed-up to check if this waste material will show a potential to be as useful as steel slag in road pavements.

It is further recommended that the Swedish Transport Administration cooperates with the steel industry to find the optimal slag product for use in wearing courses of roads, and study whether the product perhaps can be further improved by selection, pre-processing or other refinement.

As shown in in [Viman et al, 2016] the various steel slags vary substantially in wear resistance as measured by the Nordic Ball Mill or the Prall methods. Research should be made to identify the best slags, why they are good, and also if slags which are not so good can be improved in some way.

Finally, the author suggests that steel slag is used to a much greater extent than today in road wearing courses, preferably with simultaneous R&D in the field as support. When assessing the possible extra cost for transport of the heavier steel slag aggregate, one should also consider how it compares to the transport costs of equally abrasion-resistant stone aggregate (which may also need to be transported long distances), together with the environmental benefit of less rolling resistance for traffic and eventual noise reduction.

13 Acknowledgment

Thanks are due most of all to Mr Erik Oscarsson at the Swedish Transport Administration (Trafikverket) for his support as the responsible person for this BVFF project at the sponsoring organization. Also, Mr Johan Falk at Trafikverket's regional office in Jönköping has provided valuable support for this project. He was later succeeded by Ms Sofia Forsberg in the same office.

The following staff has participated in the project, apart from the author (not a comprehensive list):

- Dr Tiago Vieira, previously at VTI, performing the laboratory tests (Annex A)
- Mr Thomas Lundberg, VTI, responsible for all geometrical measurements with the RST vehicle
- Mr Andreas Waldemarsson, VTI, performing the laboratory tests (Annex A) and technical review
- Mr Håkan Wilhelmsson, VTI, performing on-site field testing of friction and water permeability
- Mr Mikael Bladlund, VTI, performing wet friction (SFT) measurements
- Dr Piotr Mioduszewski and Dr Gregorz Ronowski, from the Gdansk University of Technology (GUT), performing the CPX (noise) measurements

Led by Mr Gustav Pettersson, the Swedish road contractor Svevia AB in Jönköping successfully constructed and paved the steel slag pavement and its reference pavements. The author is very grateful for Svevia accepting to lay a steel slag pavement as a test section on motorway E4 in Huskvarna to become the test object in this project. Mr Pettersson has also been open with pavement data, which is much appreciated. Without his very fruitful cooperation, this project could not have been conducted.

Some of the measurements were possible to combine with measurements in 2018 in a doctoral project (for Dr Tiago Vieira) sponsored by Trafikverket and VTI, which is gratefully acknowledged.

Finally, also the sponsors of the measurements on the Örebro section (by Örebro City) and Järfälla section (by Peab AB) shall be gratefully acknowledged. Those measurements, although not allowing systematic, annual monitoring, are important for widening the experience of using steel slag pavements in different compositions and at different locations and on different types of road.

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Annex A: Results of the laboratory tests

The following pages present the methods and results of the laboratory tests made soon after the start of the project. They are copied from a power-point presentation (in Swedish).

Stålslaggsprojektet: Resultat från laboratorieförsök

Av:
Tiago Vieira
Andreas Waldemarson
Ulf Sandberg

Svevia, Jönköping, 3 juli 2017

1

Ballast och bindemedel

Material	Bindemedel
Stålslagg (från Smedjebacken)	70/100 bitumen (referens)
	Nynas Endura D1
Skärlunda (referens - sten)	70/100 bitumen (referens)
	Nynas Endura D1

2

2

Modifierat bindemedel

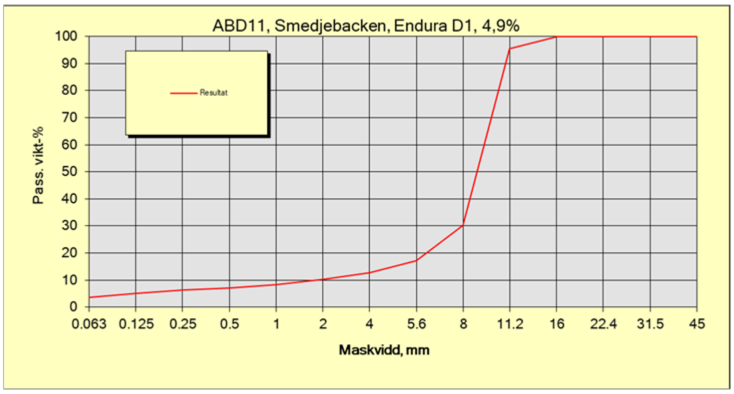
Sverige
ISO 9001:2000

Nynas Endura D1

Nynas Endura D1 är ett högmodifierat bindemedel med mycket god beständighet mot åldring, lämplig att använda till bullerdämpande beläggningar.

ABD 11 - Kornkurva

- ABD 11
- Stålslagg och sten har olika densitet => Volym-proportionering



ABD 11 - Blandning

1. Stampning av Marshall-provkroppar:

   - Med blandare : provkroppar blev inte bra, det fanns nästan ingenting kvar efter en Los Angeles test.

   - Manuell blandning istället

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ABD 11 - Laboratorietester

1. Stampning av Marshall-provkroppar
2. Kulkvarn- och Los Angeles-tester

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ABD 11 - Laboratorietester

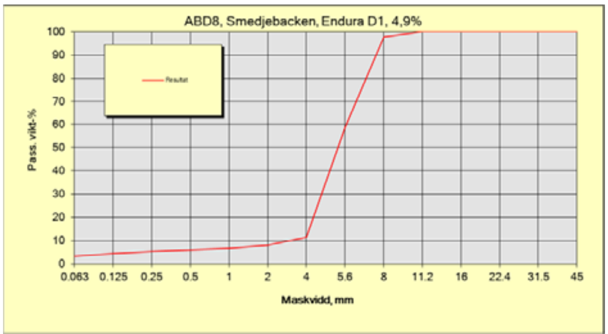
1. Stampa Marshall-provkroppar
2. Kulkvarn- och Los Angeles-tester
3. Ljudabsorptionsmätningar

ABD 8 - Laboratorietester

Stålslagg + Nynas D1

1. Stampa Marshall-provkroppar
2. Kulkvarn- och Los Angeles-tester
3. Ljudabsorptionsmätningar

Bezeichnung	OPA 0/8
Schichtaufbau, Schichtdicke	einlagig, 4cm
Mischgutsorte	0/8
Hohlraumgehalt [Vol.-%][65]	25,3
Bindemittelgehalt [M.-%][65]	6,3
0-0,09 mm	3,7
0,09-0,25 mm	0,3
0,25-0,71 mm	
0,71-2,0 mm	
2,0-5,0 mm	4,5
5,0-8,0 mm	87,3
8,0-11,2 mm	4,2
11,2-16,0mm	
16,0-22,4 mm	

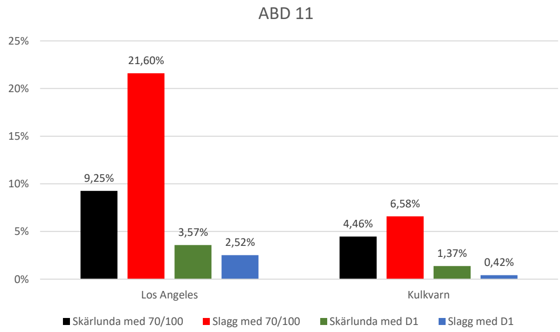


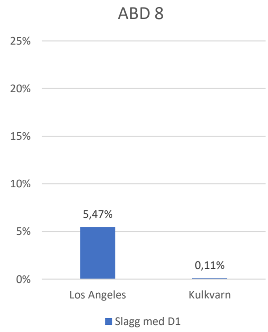
(S. Alber, "Veränderung des Schallabsorptionsverhaltens von offenporigen Asphalten durch Verschmutzung". Universität Stuttgart, 2013)

Resultat

ABD 11			70/100		D1	
	Test		Los Angeles	Kulkvarn	Los Angeles	Kulkvarn
	Skärlunda	Medel	9.25 %	4.46 %	3.57 %	1.37 %
		Standard Av.	1.44 %	0.44 %	0.65%	0.39 %
	Stålslagg	Medel	21.60 %	6.58 %	2.52%	0.42 %
		Standard Av.	4.77 %	3.19 %	0.82 %	0.10 %

ABD 8			D1	
	Test		Los Angeles	Kulkvarn
	Stålslagg	Medel	5.47 %	0.11 %
		Standard Av.	--	0.04 %





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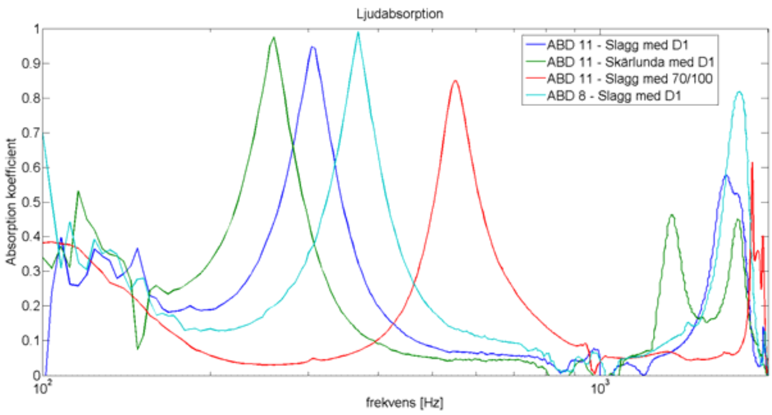
Resultat av ljudabsorptionsmätningar



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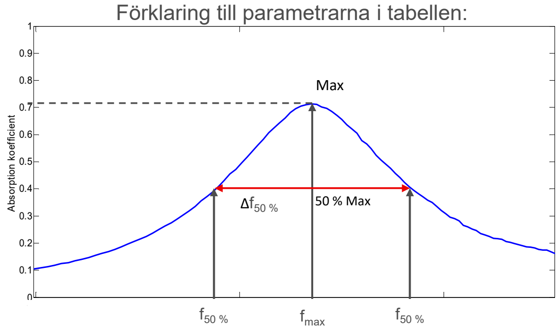
Resultat av hålrums- och ljudabsorptionsmätningar

		ABD 11			ABD 8
		Slagg med 70/100	Slagg med D1	Skärlunda med D1	Slagg med D1
Hålrumsinnehåll		25.3 %	23.7 %	18.1 %	25.7 %
Provkroppens höjd - h [mm]		64.8	63.3	63.8	63.4
Absorptionskoefficient	Max ljudabsorptionskoeff.	0.85	0.95	0.98	0.99
	Frekvens vid max [Hz]	548	304	260	368
	Frekv. vid max/2 "f50 %" [Hz]	628	348	296	415
	Δf50 % [Hz]	160	88	72	94

Förklaring till parametrarna i tabellen:



Resultatsammanfattning

				Stålslagg med 70/100	Stålslagg med D1	Skärlunda med D1	Skärlunda med 70/100
ABD 11	Ljudabsorption	Hålrumsinnehåll		25.30 %	23.66 %	18.12 %	
		h (mm)		64.84	63.32	63.86	
		Absorptions-koefficient	Max	0.849	0.948	0.976	
			f_{max} [Hz]	548	304	260	
			$f_{50\,\%}$ [Hz]	628	348	296	
			$\Delta f_{50\,\%}$ [Hz]	160	88	72	
	L. A. och Kulkvarn	Los Angeles	Medel	21.60 %	2.52 %	3.57 %	9.25 %
			Std. Av.	4.77 %	0.82 %	0.65 %	1.44 %
		Kulkvarn	Medel	6.58 %	0.42 %	1.37 %	4.46 %
			Std. Av.	3.19 %	0.10 %	0.39 %	0.44 %
		Hålrumsinnehåll	Medel	24.67 %	21.76 %	22.77 %	23.28 %
			Std. Av.	1.39 %	0.85 %	0.86 %	0.64 %
		h (mm)	Medel	64.44	63.65	62.93	63.98
			Std. Av.	0.35	0.24	0.24	0.26
ABD 8	Ljudabsorption	Hålrumsinnehåll			25.72 %		
		h (mm)			63.39		
		Absorptions-koefficient	Max		0.991		
			f_{max} [Hz]		368		
			$f_{50\,\%}$ [Hz]		415		
			$\Delta f_{50\,\%}$ [Hz]		94		
	L. A. och Kulkvarn	Los Angeles	Medel		5.47 %		
			Std. Av.		-		
		Kulkvarn	Medel		0.11		
			Std. Av.		0.04 %		
		Hålrumsinnehåll	Medel		25.84 %		
			Std. Av.		0.70 %		
		h (mm)	Medel		62.73 %		
			Std. Av.		4.00 %		

Slutsatser

- ”ABD” 11 – med stålslagg och Nynäs Endura D1 bitumen: gav acceptabla resultat med kulkvarnstester (Los Angeles-testerna är mindre relevanta för stålslagg)
- Använd bindemedelshalt (Endura D1) 4.9 %
- Hålrumshalter på 24-26 % erhållna för slaggen, ger höga värden för ljudabsorptionen
- Modifierat bitumen (Nynäs Endura D1) vs omodifierat (70/100) ger mycket bättre värden, särskilt för ljudabsorptionen och resistensen mot slitage
- Resultaten lämpliga som utgångspunkt för försök på väg (E4 Huskvarna), som toppbeläggning på dubbel dränasfalt

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