Poroelastic Road Surfaces - State of The Art

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ABSTRACT: Poroelastic Road Surfaces (PERS) constitute a specific group of pavements containing a great amount of crumbled rubber. In most cases rubber aggregate constitutes about 20% of the mixture (by weight) and a polyurethane resin is used as a binder. As a result, PERS is characterized by a much higher elasticity than asphalt and a high porosity typical for drainage pavements. Due to this, tire/road noise is greatly reduced and on top of this, rubber aggregate that is obtained from scrapped car tires is utilized with advantage for the environment. The paper presents a historical outline of attempts of creating poroelastic surfaces, discusses problems that have already been solved and remaining problems. The results of the PERSUADE project funded within 7th EU Framework Programme have also been discussed, where 6 small scale and 8 full scale test sections have been created, some of which were quickly destroyed while others are still existing.

The basic problem with PERS is the relatively low durability of this pavement. This problem manifests itself both by debonding PERS surface from its base layer and by degrading of the PERS material by loosening of the aggregate (raveling). In the opinion of the authors of this paper, to improve the durability of PERS, some changes in the method of joining this pavement to the under-layers should be developed. Improvement may be achieved by introducing an additional fiber-reinforced interface layer optimized on one side to bind to the asphalt pavement and on the opposite side to be joined to PERS. It is also important to test the possibility of using a binder different than polyurethane that will join the mineral aggregate with the rubber aggregate in a better way and improve surface treatment of aggregate and rubber particles.

So far the tested PERS pavements have shown unrivaled performance in terms of noise reduction for car tyres. Compared to reference surfaces, noise reduction is up to 12 dB, making PERS surfaces the quietest pavement that exists. The rolling resistance of passenger car tyres on PERS surfaces is similar to the existing asphalt and concrete pavements but unfortunately, on high side of it. Regrettably, the rolling resistance of the truck tires is significantly higher on PERS surfaces than on classic surfaces. An additional valuable feature of PERS pavements is its positive impact on safety in the event of a vehicle fire associated with spillage of fuel. A PERS surface prevents the spread of fire and reduces its intensity (size of the flames). This feature promotes the use of these surfaces in tunnels, and petrol stations. The results obtained in Sweden indicate that PERS also has favorable traction properties in winter, limiting the danger of black ice.

KEYWORDS: Poroelastic Road Surface, Tyre/Road Noise, Rolling Resistance, Fire Risk

1. What is a poroelastic road surface and why to use it

According to [1] a poroelastic road surface (PERS) *is a wearing course for roads with a very high content of interconnecting voids so as to facilitate the passage of air and water through it, while at the same time the surface is elastic due to the use of rubber (or other elastic products) as a main aggregate. The design air void content is at least 20 % by volume and the design rubber content is at least 20 % by weight.*

Generally, there are two different variants of PERS. The first one contains only rubber aggregate (in form of granules or fibers) and elastic binder (bitumen or polyurethane type). The second variant that seems to be more promising due to higher skid resistance contains also mineral aggregate. In both cases the most important attributes of the final PERS material is its high elasticity and open voids making the surface porous. All other materials used for making wearing courses of roads (see Fig. 1) lack at least one of those features.

Road pavement that is elastic and porous has some important advantages over other types of road surfaces. The most important one is its ability to reduce tire/road noise more than any other known road surface (including drainage asphalt). The second advantage over dense pavements is its vast spray/splash reduction in wet conditions. Recently it was also established that PERS has very favorable properties in case of fuel spill fire by damping the flames and preventing fire spread. Nevertheless, effectiveness of traffic road noise reduction seems to be the most important factor stimulating further research and development of PERS. As the rubber granulate used in PERS may be manufactured from scrap tires the surface may also be considered as important link in the recycling process of tires.

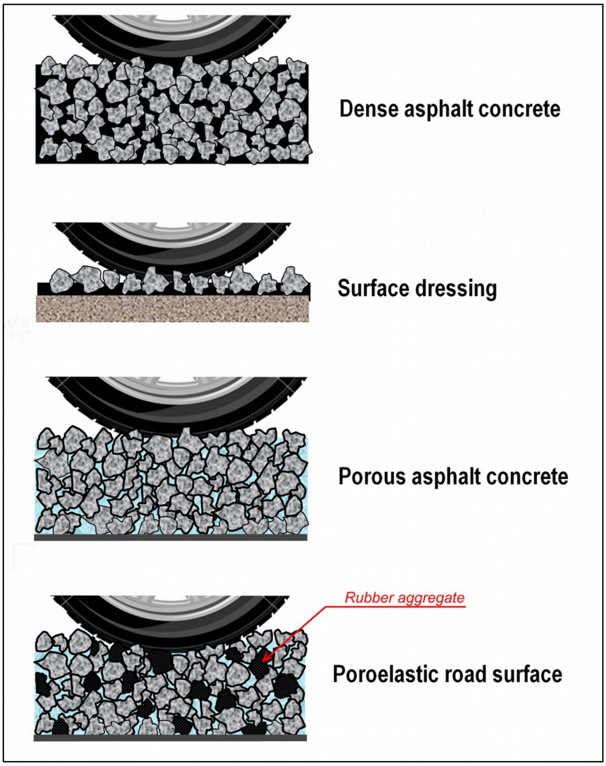

Figure 1: Different types of wearing courses

There are two major groups of mechanisms responsible for generation of tire/road noise. The first group is related to impacts between tread elements and the pavement. This group consists of radial vibrations of tread elements at the leading and trailing edge of the tire/pavement foot-print, tangential vibrations of tread elements, adhesion "stick-snap", sidewall vibrations, tire belt/carcass vibrations and stick-slip. Considerable elasticity of PERS reduces and dumps impact excitations. As the pavement is porous, it is not necessary to use big size aggregate (that creates impacts) to provide good skid resistance in wet conditions as the drainage properties of PERS help to remove water from the tire/pavement interface.

The second group of noise mechanisms are mechanisms that are related to airflow. When tire rolls on pavement the air is "pumped out" at the leading edge and "sucked in" at the trailing edge, air resonates in tread grooves forming channels in the foot-print and at the trailing region of tire Helmholtz resonance is present. All those mechanisms are reduced due to "ventilation" and sound absorption provided by porous structure of the PERS.

2. Brief history of PERS development

The poroelastic road surface was invented and patented at the end of the 1970s by Mr Nils-Åke Nilsson, at that time at the acoustic consultant company IFM Akustikbyrån AB in Stockholm. A first and very brief presentation of the surface was made in 1979 [2].

At first only small scale laboratory experiments had been made, indicating that poroelastic road surface may be at about 5 dB(A) less noisy than typical dense asphalt concrete. Soon after positive laboratory tests the experimental test section was laid on closed-down Torslanda airport in Sweden. Tests performed by the inventor using Pass-By method indicated noise reduction of 8 dB(A) in relation to the dense asphalt concrete. Around 1985 the surface was for the first time tested by the Technical University of Gdańsk (TUG) using the Close-Proximity method - see Fig. 2. After intensive development in late 1990s it was possible to optimize structure of PERS and reach 10 dB(A) reduction of noise [3].

Figure 2: CPX measurements of poroelastic road pavement on Torslanda Airport by Tiresonic Mk. 1 trailer

From the very beginning of PERS development, durability of this pavement was the most important issue. The results of tests were ambiguous as in some cases the PERS surface performed fairly well for many months, while in other cases the failures were almost instantaneous. Nevertheless in all cases noise reduction was spectacular. As the first test sections were laid in Scandinavian countries where winters used to be rather severe it appeared that snow ploughs may rip of the surface if they are not properly adjusted (see Fig. 3).

Figure 3: Damages to PERS by snow plough ending experiment in Oslo [4]

The first PERS mixes contained only rubber aggregate of various shape and polyurethane or bituminous binders. The experiments indicated that skid resistance of such pavements was rather low so Mr. Nilsson decided to add sand and stone aggregate to the mixtures. Unfortunately, details of those compositions were not disclosed.

In 1994 development of PERS started in Japan at the Public Works Research Institute (PWRI). The first important conclusion of the early research campaign was finding that dense asphalt concrete is not acceptable as a basecourse for PERS. If PERS is laid on such a surface the separation of PERS from the basecourse starts very soon after the pavement is trafficked. Instead of dense asphalt concrete a so called "semi-flexible surface" was proposed. This surface was manufactured on the base of porous asphalt which was filled with cement mix.

The second finding was that PERS material composed only with rubber granulate and binder has very low skid resistance in wet conditions thus can't be used on public roads. To fix this problem it is necessary to add small stone aggregate and/or sand to the mix.

Some of the PERS materials used during Japanese experiments (plates glued by epoxy resin to the semi-flexible basecourse) survived as long as 9 years on PWRI test track but one must consider that traffic on those pavements was occasional and never very dense. During the last period of the experiment the PERS plates were still intact but they separated from the basecourse, mostly around their corners. Interesting finding of the tests was that poroelastic road surfaces are very resistant to wear by studded tires. In comparison to dense asphalt concrete the wear of PERS was 5-10 times smaller.

After the initial stage of PERS testing few full-scale experimental test sections were built on major highways. Unfortunately, in each case the sections had to be rebuilt after few months due to routing, separation or too low skid resistance. After those failures more tests on PWRI test track were performed including bonding the PERS material to the basecourse with double-sided adhesive tape that proved to be rather durable.

In 2006 a new campaign of experiments was started by Yokohama Rubber Co. using mix with rubber and mineral aggregate. Rolling resistance measured by Yokohama (using a very simple and uncertain method) showed that PERS performs better in this respect than dense asphalt concrete. Noise measurements have also shown a very good performance of PERS in comparison to DAC 0/11 with noise reduction in range of 10-12 dB(A).

In Europe most of the PERS development was carried out in Sweden. VTI developed a mix that was intended to on-site laying and tested several prefabricated PERS panels manufactured by Tokai, Rosehill and Bilgutex. Laboratory tests confirmed that PERS material has considerably better wear resistance when studded tires are in use than dense asphalt concrete. Tests of rolling resistance performed at the TUG for passenger car tires have shown that rolling resistance on PERS is very similar or even lower than on dense asphalt concrete. Laboratory tests (see Fig. 4) indicated that rolling resistance of passenger tires for Rosehill PERS is only marginally higher than on very smooth (sandpaper like) surface Safety Walk and considerably lower than on very rough (surface dressing like) replica APS-4 (see Fig. 5)

Figure 4: Testing of rolling resistance of passenger car tire on Rosehill PERS at TUG

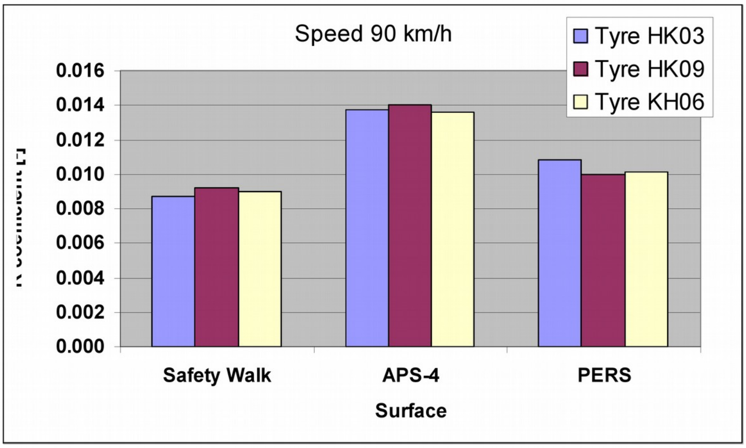

Figure 5: Comparison of rolling resistance coefficients for different pavements

A full scale experiment was performed by VTI in 2004 on one of the two-lane streets in a residential area in Stockholm (see Fig. 6). The results of CPX measurements performed with TUG's trailer Tiresonic Mk.3 indicated that all tested PERS materials provided considerable tire/road noise reduction in relation to dense asphalt concrete (see Fig. 7).

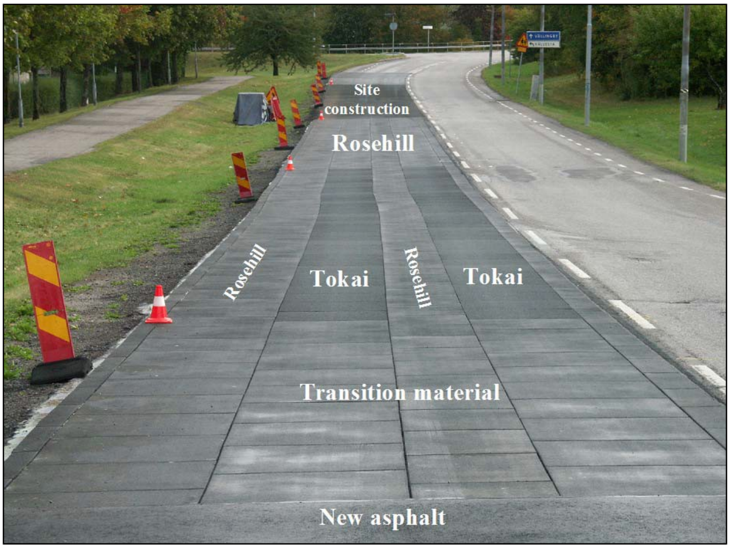

Figure 6: Test site in Stockholm with layout of different PERS types [4]

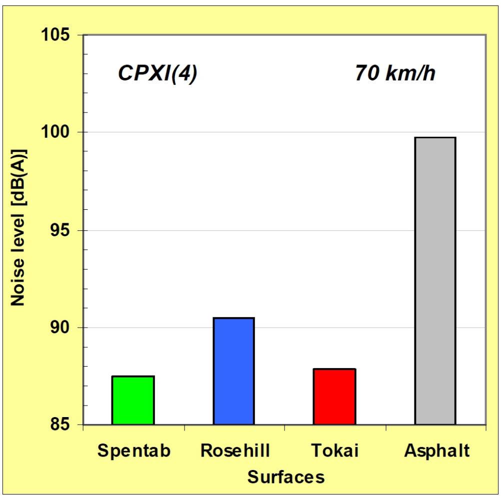

Figure 7: Results of CPX noise measurements averaged for four reference tires

A very important and interesting observation made during Stockholm experiment was that black ice occurred more frequently on PERS surfaces but "normal ice" and packed snow disappeared quicker than on dense pavements.

Unfortunately, after a few months PERS section was removed due to insufficient strength and durability of the asphalt layers beneath the PERS. Probably the most important conclusion drown from the Stockholm tests was that it is absolutely essential to have a very strong asphalt base course, without any weak adhesion between asphalt layers (even with 30-50 mm thick asphalt).

During the period 2002-2008 many tests of PERS and very dense elastic surface Regupol were performed also in the Netherlands on a non-trafficked road in Kloosterzande. Tire/road noise as well as rolling resistance were measured but results of noise reduction were rather disappointing. Rolling resistance on PERSE was also rather high but in this respect Regupol performed very well.

3. The PERSUADE project

By 2008 some European road research institutes took the initiative to draft a proposal for an FP7 call of the EC. A consortium of twelve partners from eight countries was formed, comprising six road research institutes, two contractors, two universities and two specialist partners with some special know-how. The proposal was approved and in September 2009 the six year project PERSUADE [5] started. PERSUADE is an acronym for PoroElastic Road Surface for Avoiding Damage to the Environment. The aim of the PERSUADE project was to develop PERS from a yet experimental concept to a usable noise abatement measure.

The problems to be solved and questions to be answered about PERS at the beginning of the project were numerous: how to produce a mix which would yield a durable, highly noise reducing pavement with a sufficient skid resistance? How to avoid the PERS to ravel or to loosen from the sub layer? What in the case of a fuel spill? Or in the case of an accidental vehicle fire on a PERS section? How to build PERS without increasing rolling resistance? Which precautions should be taken to protect road workers and people living around from hazardous fumes? What to do with PERS at the end of its lifetime? What about economic aspects?

In order to find an answer to all relevant questions a comprehensive research program was drafted, consisting of the following work packages (WP):

- WP1: Project management
- WP2: Mix design
- WP3: Structural design
- WP4: Test tracks
- WP5: Monitoring of the test tracks
- WP6: Environmental issues
- WP7: Cost-Benefit Assessment
- WP8: Dissemination

3.1. PERSUADE full scale test tracks

After the testing of different mixtures and different laying techniques in the laboratory and the practicing with small scale pilot test tracks, the consortium felt confident enough to proceed with the construction of full scale test tracks on trafficked roads. The first full scale test tracks were built in the summer of 2013 in Kalvehave, Denmark and in autumn/winter 2013-2014 in Linköping, Sweden. The Danish test track was replaced in the summer of 2014 by the second Danish test track. In the autumn and winter of 2014 test tracks were subsequently built in Herzele (Belgium), Sjögestad (Sweden), Krakow (Poland) and Nova Gorica (Slovenia).

A summary of the full scale test tracks built on trafficked roads in the frame of the PERSUADE project is given in Table 1.

The construction of the full scale test tracks is comprehensively described in [6]. Below are pictures from the Danish test tracks (Fig. 8, 9 and 10), the Belgian test track (Fig. 11), the Swedish test tracks (Fig. 12 and 13), the Polish test track (Fig. 14) and the Slovenian test track (Fig. 15).

Table 1: *Summary of the full scale test tracks built in the frame of PERSUADE*

Full scale test track	Country	Date of constr.	Dimensions (L × W × H) [m]	Type of construction	Mix	Remarks
Kalvehave I	DK	8/2013	86 × 3,5 × 0,03	In situ	Arnakke[1]	Removed in June 2014 after heavy ravelling occurred
Kalvehave I	DK	6/2014	86 × 3,5 × 0,03	In situ	Arnakke[2]	Test track removed in July 2015 after ravelling + loosening of patches
Herzele	B	9/2014	50 × 3,2 × 0,045	In situ	Arnakke[2]	Test track removed in May 2015 after loosening from sub layer. But no ravelling had occurred at all.
Linköping	S	7/2013	25 × 1 × 0,03	Prefabricated panels	HET mix[3]	Constructed under poor conditions. Removed after loosening after about 6 months.
Sjögestad I	S	9/2014	(2 ×) 24 × 1 × 0,03	In situ	variation of HET mix[4]	Manual application. Removed and replaced after some time with HET prefab plates.

[1] 20 % of rubber
[2] with anti-dripping agent
[3] 38 % of rubber
[4] 34 % of rubber

Sjögestad II	S	8/2014	(2 ×) 30 × 1 × 0,03	Prefabricated slabs	HET mix[3]	Glued with epoxy. Best performing test track of project; removed after 2,5 years.
Krakow	PL	9/2014	65 × 3 × 0,03	In situ	Arnakke[1]	Loosening from sublayer already after one week, probably due to mistake with tack layer. Also unwanted early opening for traffic. Removed after one week.
Nova Gorica	SI	11/2014	20 × 3 × 0,03	Prefabricated slabs glued on cement concrete blocks in lab	HET mix[3]	A small part (2 m long) the slabs were glued directly on a concrete sublayer, which was not a success (quick debonding).

Figure 8: Construction of the first Danish full scale test track in Kalvehave (Kalvehave I): the fresh PERS mix in front of the gussasphalt paver was first spread manually (left hand side) and then compacted (right hand side)

Figure 9: The Kalvehave I full scale test track (August 2013)

Figure 10: The Kalvehave II full scale test track (June 2014) (Pictures: H. Bendtsen)

Figure 11: The Belgian full scale test track in Herzele, just after completion

Figure 12: Swedish full scale test track constructed with PERS prefabricated slabs in Linköping in February 2014 (PERS slabs only applied in the right hand wheel track)

Figure 13: Swedish full scale test tracks in Sjögestad in February 2016, i.e. 1,5 years and two winters after construction. The Sjögestad II surface with the PERS prefab panels (applied only in both wheel tracks) can be seen on the foreground. Note some scars by the snowplough and some raveling. The slightly lighter coloured PERS surface in the background the original in situ constructed PERS test track (Sjögestad I)

Figure 14: The Polish full scale test track near Krakow, just after completion (Picture: K. Mirski)

Figure 15: Just finished Slovenian full scale test track in Nova Gorica (Picture: D. Kokot)

3.2. Monitoring of the test tracks

The monitoring time was unfortunately much shorter than originally assumed (less than 1,5 year instead of planned four years). This was due to delays in the construction of the test sections, mainly since the team had to work longer with developing durable mixes. Nevertheless, a lot of information regarding important road surface parameters was extracted from the test sections [7]:

3.2.1. Friction

The friction on the full-scale test sections, measured with high-speed devices, was no problem, provided necessary pre-conditioning of the material was done in some cases.

3.2.2. Noise reduction

The noise reduction was impressive. Compared to SMA 0/16 which is very common e.g. in Sweden, a noise reduction for cars between 8 and 12 dB(A) was obtained and compared to SMA 0/11, which is a more common reference in Europe, the noise reduction was found to be between 6 and 10 dB(A). The range indicates the differences between the various test sections and PERS material used there. The PERS mix with the higher rubber (a.o. the PERS mix of the prefab slabs used for the Sjögestad II test track) content yielded the highest noise reduction. Sound absorption was quite good, but varied significantly from test section to test section.

3.2.3. Rolling resistance

The rolling resistance for car tyres on PERS was found to be of the same order as for SMA 0/16, hence 10 – 20 % higher than the best performing conventional pavements, but for truck tires it was about 50 % higher. However, as PERS is only intended for application on a very limited fraction of the network (on hotspots), this will not influence the fuel consumption and CO_2 emission significantly.

3.2.4. Winter behavior

An important issue that has been studied is the winter behavior and it turned out that PERS behaves differently under winter conditions: the surface temperature drops on average 30 minutes earlier below zero and remains on average 40 minutes longer below zero than the reference pavement. However, one shall note that the surface is so soft that tyres rolling on it will break any ice or packed snow that may form on the surface so, in fact, in black ice conditions, the PERS seems to be much less slippery than conventional dense asphalt. The winter behavior is different from that of conventional impervious pavements but not very different from that of porous asphalt, and can be handled with an adapted winter maintenance strategy, as described in the project deliverables.

3.2.5. Durability

Generally, the durability of the full-scale test tracks was and is still an issue. In spite of the laboratory results, some (and sometimes a lot) ravelling appeared on the test tracks, except on the Belgian test track, which performed excellent for this criterion. It is not clear yet why the Belgian test section showed a good ravelling resistance while the Danish test section did not do so, as the mixes used were almost the same. It might have been due to quite different traffic volumes and conditions. Also the type of finisher and thereby compaction was somewhat different.

Delamination from the sub-layer was another issue: on all test tracks where the PERS layer was glued on a bituminous sub-layer, the PERS layer delaminated 9 to 14 months after construction. The Polish test track disintegrated already after a week, but this was probably due to a construction error related to the timing of applying the tack layer. It is likely that the action of heavy vehicles, and the existence of standing water, play important roles in the delamination of PERS glued on asphalt. PERS on an asphalt sub-layer on a road without heavy vehicles could probably survive much longer. PERS on a semi-flexible sub-layer (as on the Swedish test tracks in Sjögestad), and glued with epoxy, performs better in this respect. The final tests in the laboratory on the large wheel tracking device, simulating the action of heavy vehicle tyres combined with other influences such as thaw-frost cycles, brine and UV, confirmed the findings on the full-scale test tracks: the binding with epoxy on a semi-flexible or concrete test track is more durable.

3.3. Laboratory tests of noise and rolling resistance

Full scale road tests described above were supplemented with numerous laboratory tests. Parameters typical for road pavement assessment like rutting, durability, porosity and sound absorption were tested for numerous mixes. Also many tire/road noise and rolling resistance measurements were carried out. TUG's roadwheel facility used for those tests is presented in Fig. 16. Unfortunately, outer drum roadway facilities impose severe requirements related to the pavement mechanical strengths, as the pavement is subjected to considerable centrifugal force and to laying technology so in situ constructed PERS materials could not be used. Only PERS-HET material prefabricated as 30 mm thick slabs was suitable for drum tests.

Figure 16: Truck tire/road noise testing on roadwheel facility at TUG

Tire/road noise laboratory tests have shown great noise reduction on PERS in comparison to other surfaces both for passenger car tires (Fig. 17 and 18) and truck tires (Fig. 19). Difference between overall sound level measured on PERS-HET and DAC16 at 80 km/h was 10.3 dB for tire P1 and 10.9 dB for tire H1. Slightly smaller reduction of tire/road noise (in range of 7-10 dB) was measured also for truck tires.

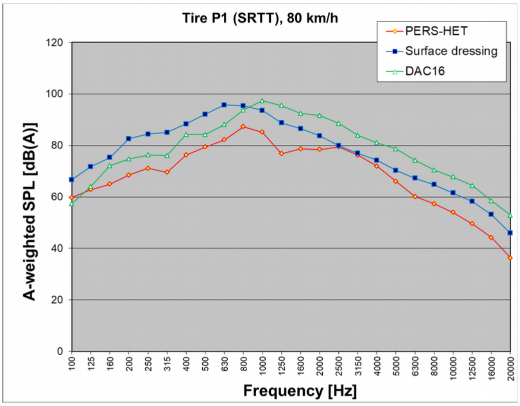

Figure 17: Tire/road noise spectra (tire P1 according to ISO/TS 11819-3:2017) tested on PERS-HET and replicas of Surface Dressing (12mm) and DAC 16

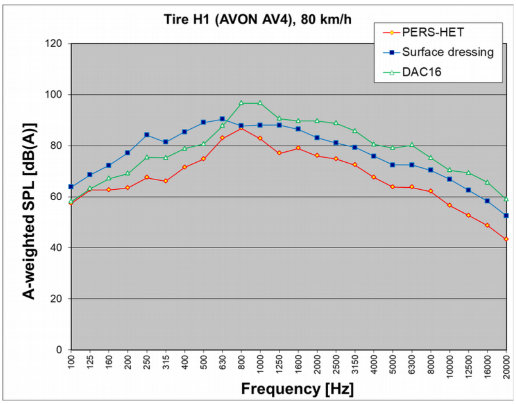

Figure 18: Tire/road noise spectra (tire H1 according to ISO/TS 11819-3:2017) tested on PERS-HET and replicas of Surface Dressing (12mm) and DAC 16

Tests of rolling resistance performed for passenger car tires at 80% of their maximal load and capped inflation pressure of 210 kPa indicated that rolling resistance on PERS-HET is much lower than on Surface Dressing 12 mm but slightly higher than on DAC 16 - See Fig. 19. However, very unfortunately, rolling resistance for truck tires measured on PERS-HET was nearly 50% higher than on

DAC 16 - see Fig. 20. It was observed that for loads imposed on PERS-HET by truck tires the pavement deflected considerably thus hysteresis of rubber aggregate in this pavement lead to substantial energy losses in the pavement and increase of its temperature clearly recorded as thermal images.

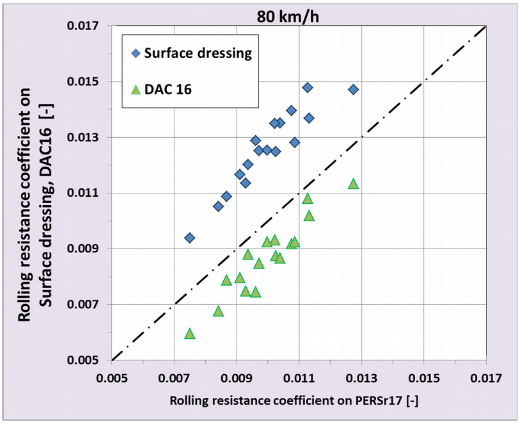

Figure 19: Comparison of Rolling Resistance Coefficients obtained for different passenger car tires on PERS-HET, DAC16 and Surface Dressing 12; speed 80 km/h

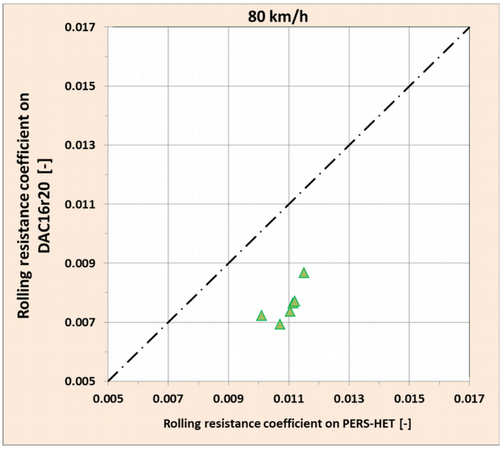

Figure 20: Comparison of Rolling Resistance Coefficients obtained for different truck car tires on PERS-HET and DAC16; speed 80 km/h

3.4. Conclusions from the PERSUADE project

The project was a partial success. The positive aspects are: the demonstration that PERS can be quite ravelling resistant (comparable to thin asphalt layers), that it is not toxic and that there is no fire risk! On the contrary, PERS can be used for better fire protection in, for example, tunnels [8, 9]. Obtaining a good friction is not a major problem and its noise reduction is comparable to a 4 m high noise screen on both sides of the road. Application techniques have been developed, tested and well documented. PERS can dramatically reduce the production of fine dust from studded tires. Winter behaviour is an issue but, as for porous asphalt, this can be overcome with an adapted winter strategy. In some cases the product can be beneficial from an economic point of view. And when the noise reduction is taken into account it is a sustainable solution.

The project team was not completely successful in demonstrating the long term durability: the monitoring time of the full scale test sections became shorter than planned due to some delays with finding and testing durable mixes, but also the construction was delayed, and most test sections failed prematurely. The team learned that PERS on an asphalt sublayer combined with a significant volume of trucks is not a good combination as it leads to delamination within about one year. If water is not properly evacuated from the PERS after rainfall, this might speed-up the delamination. However, on a road without trucks, or a low proportion of trucks, this type of PERS application may work. On the other hand, based on the observations on the Swedish and Slovenian test sections and the test in the wheel tracking device, it was found that a PERS glued on a semi-flexible sub-layer appears to work, even under the action of truck tyres. Most convincing evidence comes from the PERSUADE test track in Sjögestad, Sweden. The prefab slabs glued on the semi-flexible resisted well the action of a significant volume of heavy trucks as well as the demanding conditions of a harsh climate. The test track was removed after 2,5 years by the road administration. Nevertheless, the PERSUADE project team believes it could have survived longer and even much longer under less harsh conditions.

4. Acknowledgement

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