Laboratory measurements on poroelastic test slabs from full scale test sections

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Summary

The EU financed PERSUADE project aims at developing poroelastic road surfacing (PERS) with high noise reducing properties. In the summer/autumn 2014 six full scale test sections were constructed, with different material composition or construction technique. The different versions of the PERS are either made as factory produced slabs or as on site constructed road pavements. Test slabs have been produced in moulds at the test sites during construction. The test slabs are produced in order to compare material and construction depending parameters, other than the noise levels from the different surfaces. The laboratory tests performed at the test slabs are: acoustical absorption measured in an impedance tube to describe the acoustic performance of the materials; permeability by Beckers tube method and built in air void by thin-and-plane section analysis, to describe the open structure of the surfaces; mechanical impedance is measured to describe the dynamic stiffness of the elastic material; surface texture is measured to describe the surface which is met by car tyres. On the background of all these measurements the test surfaces are compared, in order to give an evaluation of the noise reducing potential of the tested test slabs. The noise reducing potentials from the tests slabs are compared to CPX measurements at the full scale test sections, whereby the most dominating noise reducing properties of the surfaces are identified.

PACS no. 43.50.Lj

1. Introduction

The EU financed PERSUADE project aims at developing poroelastic road surface (PERS) with high noise reducing properties. The PERS surface is constructed from stone aggregates and rubber granulates from scrapped tyres, and bound together with polyurethane. Prior before making full scale test sections of the PERS material, are laboratory tests and small scale test sections tested. These tests are the background for six full scale sections produced in summer/autumn 2014. Together with production of the full scale sections are test slabs for laboratory testing produced - either made as factory produced slabs or as test-slabs produced in moulds at site during construction of full scale test sections. Several measurements have been performed at the slabs to compare material and construction depending parameters, other than the noise levels from the different surfaces.

The parameters measured in relation to the air pumping noise reducing mechanisms are the *air void*, the *permeability* and the *acoustical absorption*. The parameters measured in relation to the tyre vibration noise reducing mechanisms are the *texture* and the *mechanical impedance*. The most dominating noise reducing properties of the surfaces are identified by comparing the laboratory measurements with noise measurements at the full scale sections.

2. Test surfaces

The test slabs have been produced from recipes deviating a bit from each other and under different conditions for construction. The main difference between the surfaces is whether the surface is produced at the road construction site or as prefabricated plates at a factory.

Table I. Basic informations about the seven test slabs.

Location and name	*Herzele*	*Kalvehave II*	*Nova Gorica II*	*Sjögestad - HET*	*Sjögestad – In-situ*	*Krakow - Road*	*Krakow - Slab*
Thickness	42 mm	35 mm	30 mm	30 mm	33 mm	24 mm	21 mm
Maximum aggregate size	5 mm	5 mm	3 mm	3 mm	5 mm	5 mm	5 mm
Place of construction	Outdoor at test site	Outdoor at test site	At factory	At factory	At factory	Outdoor at road	Outdoor at test site

The other main differences are the maximum aggregate size and the thickness of the surface. An overview of the seven pavements is illustrated in Table I. The *Krakow* surfaces are respectively cut outs from the road lane and a slab from a mould at site during construction.

3. Air void

A method to investigate the air void in the surfaces is to perform plane section analysis. The plane sections are prepared from a slice of material cut from a test slab. These slices are impregnated with epoxy resin containing fluorescent dye, which fills out the air voids. The sizes of the plane sections correspond to the width and height of the samples and the thickness is approximately 10 mm. When the plane sections are exposed by UV-light, does the air voids light up in a green colour. The measured air voids by image analysis is illustrated in Table II.

Another way to describe the air voids in the surface is to perform permeability measurements by letting water flow through the surface. The method used is called *Becker's tube,* which is a permeability measurement method used by the Danish Road Directorate. The method is basically the same as used in EN 12697-40 [1], but with differences in tube diameters and amount of water flowing through. The outflow time through the surface must be less than 30 seconds to be in good condition and if the outflow time is longer than 75 seconds is the surface considered clogged [2]. The outflow times for the surfaces are illustrated in Table II. Permeability is not measured at *Nova Gorica II*, as the test slabs is smaller than the diameter of the tube. The table illustrates that a high percentage of air voids does not necessarily result in a low outflow time in permeability measurements. The immediate impression of the three surfaces with an outflow times less than 0.5 seconds is that they're very porous, and the results are therefore not surprising. The unexpected correlation between percentages of air voids and outflow time for *Sjögestad – HET*, might be due to air voids not connecting to each other, and the flow resistance inside the air void channels. Both *Herzele* and *Kalvehave II*, which both have 5 mm maximum stone aggregates, seem to have a lower flow resistivity than *Sjögestad - HET*.

Table II: Measured air voids in percent from image analysis, and outflow time in seconds from the permeability measurements from the different surfaces.

Surface	*Measured air void [%]*	*Permeability, outflow time [s]*
Herzele	23	6.2
Kalvehave II	28	8.5
Nova Gorica	30	-
Sjögestad - HET	36	20.5
Sjögestad - In-situ	35	< 0.5
Krakow - Road	34	< 0.5
Krakow - Slab	35	< 0.5

4. Acoustical absorption

The absorption is measured at drill cores in an impedance tube, according to ISO 10534-2 [3], using the transfer function method. The assumption in the method is that the material is homogeneous, which the PERS material deviates from by mainly consisting of air, rubber and stone aggregates. The important parameters for porous road surfaces are the porosity of the pavement, the thickness of the pavement, the air flow resistance and the aggregate sizes [4]. The average absorption spectra of PERS are illustrated in 1/3 octave bands, at Figure 1.

The figure illustrates how the *Nova Gorica II* and *Sjögestad – HET* have similar spectra with the lowest peak frequency. They both have the same maximum aggregate size, thickness and is produced at the same factory. The *Herzele* and *Kalvehave II* have spectra which are alike with an absorption peak at the frequencies where the noise

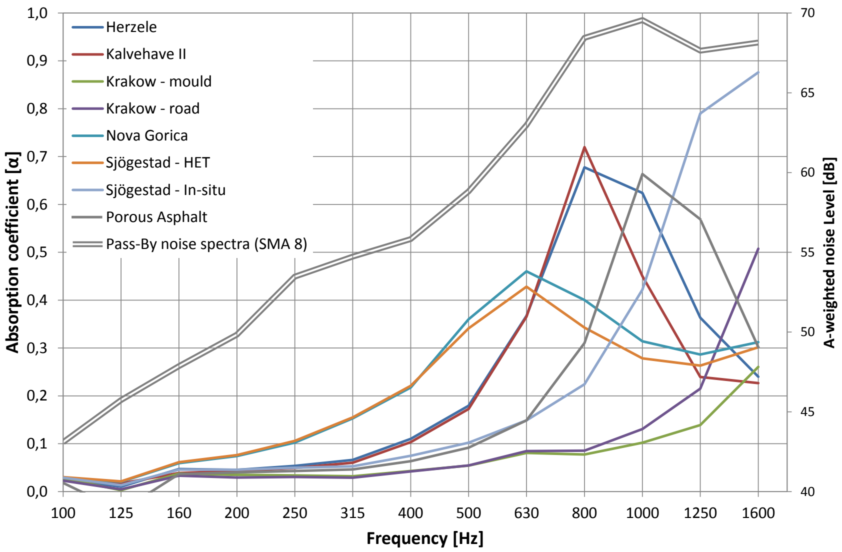

Figure 1: Primary axis: Average absorption coefficient in one-third octave bands. A new Porous Asphalt is included as a reference surface.
Secondary axis: Pass-By noise spectra from a new SMA 8 pavement is included as reference.

spectra is highest, but *Herzele* has a broader peak, which will result in more absorption from the surface. The *Sjögestad - In-situ* has a relatively low absorption at the lower frequencies, but a high absorption in 1250-1600 Hz, where the noise spectra is still at a high level. Both of the *Krakow* surfaces have a very limited absorption in the frequency range illustrated in the figure. A spectrum of a new porous asphalt is included in the figure as a reference. The design goal is to obtain the maximum absorption in the 1000 Hz band [5], as the emission from vehicles is highest in that octave band, which is illustrated in the figure.

Table III: Peak frequency in 1/3 octave bands and maximum absorption coefficient of the different surfaces. The intervals represent measurements at different drilling cores.

Surface	*Peak frequency [Hz]*	*Absorption coefficient [α]*
Herzele	800-1000	0.75-0.92
Kalvehave II	800	0.64-0.78
Nova Gorica	630	0.40-0.53
Sjögestad - HET	630	0.31-0.56
Sjögestad – In-situ	1250-1600	0.86-0.97
Krakow – Road	1600	0.42-0.57
Krakow – Slab	1600	0.23-0.30

From the spectra in Figure 2 and the listing in Table III, it is clear that the *Herzele, Kalvehave II* and *Sjögestad - In-situ* are the most absorbent surfaces. The two surfaces with 3 mm maximum aggregate size have a noticeable absorption, but the maxima of the absorption are not in the area where the road noise has its maximum.

5. Texture

The texture of the surfaces was measured with a static laser of 1.5 m, measuring parallel lines separated with 1 cm. The resolution of the instrument is 0.1 mm in the length direction (x) and 9 µm in the height direction (z). The laser has a sampling frequency of 16 kHz and a spot size of 0.1 mm. The measurements are made with a sample distance of 0.18 mm.

The Mean Profile Depth (MPD) of the surfaces is illustrated in Table IV together with the three reference surfaces. The table illustrates that the two factory produced surfaces *Nova Gorica II* and *Sjögestad – HET* have the lowest MPD values and are the smoothest surfaces, with an MPD value similar to the *SMA 6+8*. The rest of the surfaces have a MPD which is similar to the *Porous Asphalt* and the old AC11d From the profile recordings are texture spectra calculated according to ISO/DTS 13473-4 [6]. The texture spectra of the different surfaces are illustrated in Figure 2 together with the spectra from the three reference pavements. The figure illustrates that *Nova Gorica II* is the only PERS surface which deviates from the others, by having lower levels from 31.5-2 mm. *Sjögestad – HET* has a spectrum similar to

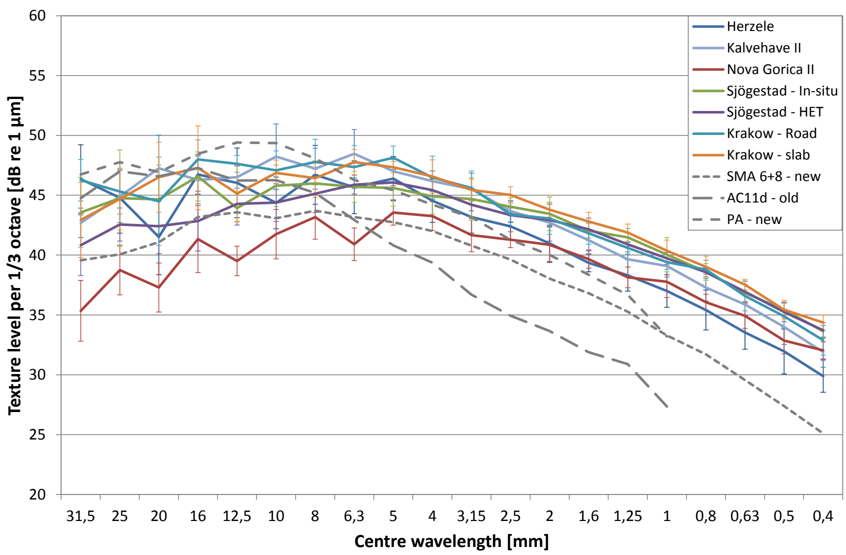

Figure 2: Average texture levels of the different surfaces in third octave bands, illustrated with standard deviations. Stone Mastic Asphalt (SMA6+8-new), Asphalt Concrete (AC11d-old) and Porous Asphalt (PA-new) are included for comparison.

Nova Gorica II, but with a higher magnitude. The other surfaces have spectra's similar to *SMA 6+8*, with different magnitude shifts.

Table IV: Average MPD and standard deviation of the PERS surfaces and three reference road surfaces.

Surface	*Average MPD [mm]*
PERS Herzele	1.0 ±0.3
PERS Kalvehave II	1.2 ±0.2
PERS Nova Gorica	0.4 ±0.1
PERS Sjögestad - HET	0.5 ±0.1
PERS Sjögestad – In-situ	0.9 ±0.1
PERS Krakow - Road	1.0 ±0.3
PERS Krakow - Slab	1.0 ±0.2
PA, new	0.9
AC11d, old	1.0
SMA 6+8, new	0.4

The aim for the texture levels regarding noise is to have a high texture level at the short wavelengths (0.5-10 mm) and a low texture level at longer wavelengths (10-500 mm) [5]. From these considerations are *Nova Gorica II* and *Sjögestad - HET* surfaces assumed to least noisy surfaces, as the ratio between the texture levels at low and high wavelengths are biggest. These to surfaces have the smallest maximum aggregate size, which is the reason for the relation between the long and short wavelengths

The general assumption about the relation between texture and tyre/road noise is that the texture at short wavelengths is considered to be related to air displacement mechanisms and the long wavelengths are considered to be related to mechanical vibration generating mechanisms [5]. It is important to notice that the *Nova Gorica II* and *Sjögestad - HET* surfaces might not be the most efficient concerning reduction of airflow related mechanisms, but still have the possibility to be the quietest surface from not generating as powerful mechanical vibrations.

6. Mechanical impedance

The experimental setup of the mechanical impedance measurements is composed of a hammer delivering an impact force $f(t)$, an impedance head measuring the direct force $f_d(t)$ and the direct acceleration $a_d(t)$ at the impact location and an accelerometer measuring the transfer acceleration $a_t(t)$ at a certain distance from the impact point. The actual measurement equipment, setup and calculation steps are illustrated in [7]. The test slabs were glued on a concrete base during the test. The direct mechanical impedance is calculated from a Fourier transform, and the results are illustrated in Figure 3. Each curve represents the result of a test obtained from a series of six impacts. The curves at the different test sites have quite similar shapes. At low frequency, there is a linear decrease of the mechanical impedance which is typical of an ideal spring. At high frequencies, there is a linear increase of the mechanical impedance which is

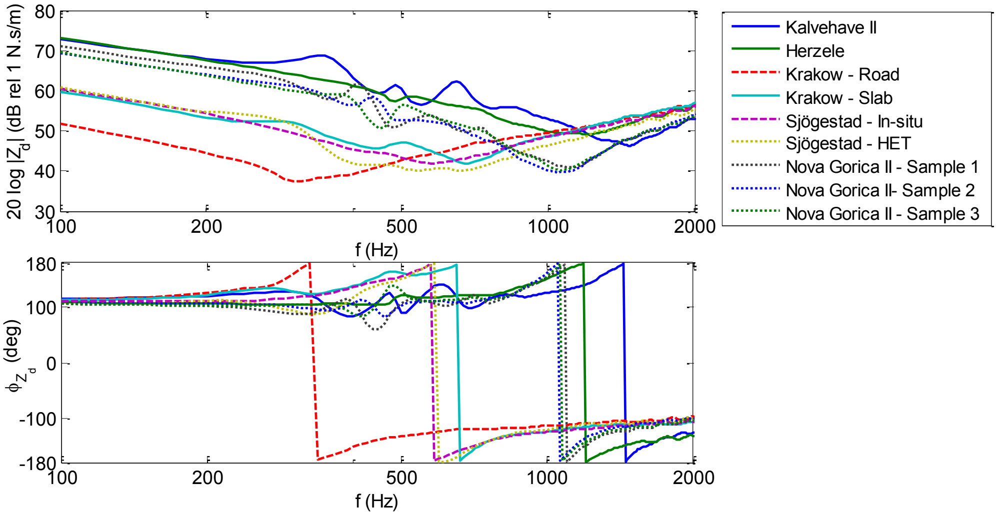

Figure 3: Direct mechanical impedance of the different PERS samples tested in laboratory

typical of an ideal mass. At medium frequencies, there is a minimum value at a frequency corresponding to the resonance of the mass spring system. The minimum value corresponds to the damping of the system. At the resonance frequency a typical phase shift is also observed.

The magnitude differences observed in Figure 3 can be qualitatively assessed from a simple Single Degree Of Freedom (SDOF) system consisting in a mass m over a parallel spring/dashpot combination. The stiffness of the spring is denoted k while the damping constant of the dashpot is denoted c. The natural frequency of such a system is $f_0 = \sqrt{k/m}$.

The SDOF parameters can be assessed manually from the experimental data. First the natural frequency f_0 is determined from the phase shift in Figure 3, then the damping constant c is estimated from the magnitude value of the mechanical impedance in Figure 3 at the resonance frequency, which is close to the minimum value. The stiffness k is estimated from the value of the dynamic stiffness D_d at low frequency, i.e. between 100 Hz and 200 Hz.

The dynamic Young's modulus E of the PERS can be estimated from the dynamic stiffness k, using equation 1.

$$E = \frac{kh}{\pi r^2} \qquad (1)$$

where h is the thickness of the PERS assumed to be homogenous and r = 0.01 m is the radius of the circular steel plates glued on the PERS. The PERS thickness for each test site is given in Table I. The average dynamic Young's modulus of the surfaces is illustrated in Table V, together with usual data for a dense asphalt concrete and a car tyre.

Table V: Average dynamic Young's modulus of the seven PERS samples, a dense asphalt concrete and a car tyre.

Surface	*Average dynamic Young modulus [MPa]*
Herzele	371
Kalvehave II	214
Nova Gorica	190 ±21
Sjögestad -HET	64
Sjögestad – In-situ	63
Krakow - Road	21
Krakow – Slab	39
Dense asphalt concrete	≈17000
Car tyre	20-100

From the table is it clear that the order of magnitudes is the same for the car tyre and the *Sjögestad* and *Krakow* surfaces. The three other surface has a Young's modulus value 2-4 times as high as the car tyre, but as the Young's modulus value of the dense asphalt concrete is more than 200 times as high as the tyre value, are the surfaces still considered much better impedance matched. The excitations from the PERS surfaces will therefore be less strong than the excitations from an ordinary road surface, leading to potential reduction of tyre vibrations.

7. Noise reduction

In order to identify the most dominating properties of the noise reducing elements in the surfaces, are the noise reduction from the different surfaces considered. The different locations of the full scale sections cause the noise measurements to be made under different speeds, therefore noise reduction is considered. The noise reductions from the different surfaces are illustrated in Table VI. The reduction is reduction in CPX levels from an 8.5 year old AC11d reference surface from [8], which has a CPX reference level at 100.5 dB at 80 km/h. The *Nova Gorica II* is measured as SPB, and afterwards converted to CPX level with a relation described in [8]. The reductions from all the surfaces are considerable in relation to the new SMA 8 surface. Especially the two *Sjögestad* and *Krakow* surfaces have a remarkable reduction.

Table VI: CPX noise reduction of the new PERS, in relation to a an 8 year old AC11 reference in [8]. A new SMA 8 is included for comparison.

Surface	*Noise reduction [dB]*
PERS Herzele	8.7
PERS Kalvehave II	8.6
PERS Nova Gorica	7.0
PERS Sjögestad - HET	12.1
PERS Sjögestad – In-situ	10.5
PERS Krakow	12.1
SMA 8 new	3.0

8. Conclusions

The aim of the laboratory measurements was to identify the most dominating noise reducing properties. The properties are either related to the tyre vibration generating mechanisms or the air-pumping, so the individual result is only describing the performance for that particular measurement. As the two *Sjögestad* and the *Krakow* surfaces have the highest reduction are these the most interesting.

Sjögestad - HET has a poor permeability despite the high air void percentage. The surface has neither a high absorption, which complies with the permeability. This indicates that the reduction of the air-pumping is not the most important effect of this surface. Regarding the tyre vibration mechanisms is the surface a smooth surface – expressed by the MPD value. The texture spectra illustrates too some noise reducing properties, by having high texture levels at the short wavelengths and lower levels at the long wavelengths. The dynamic stiffness of the surface is of the same magnitude as a car tyre as intended. The comparison of the laboratory results and noise measurements indicates therefore that the reduction of tyre vibration generating mechanisms is the most dominating for that surface.

Krakow has similar noise reduction to *Sjögestad – HET*. The surface has a high air void and a good permeability and will therefore reduce the air-pumping mechanisms. The absorption from the surface is low within the measured frequency range. The surface is rougher than *Sjögestad - HET*, and does not stand out regarding the texture spectra. The surface is by far the softest surface. This indicates that the benefits of this surface are the very low dynamic stiffness and reduction of air pumping due to the high air void content.

Sjögestad – In-situ has the second best noise reduction. The surface has similar high air void and a good permeability as *Krakow* and will therefore reduce the air-pumping mechanisms. The absorption from the surface is high at the high frequencies. The texture of the surface is similar to *Krakow*. The mechanical impedance of the surface is similar to *Sjögestad – HET*. This indicates that the benefits of this surface are a low dynamic stiffness and a high acoustical absorption.

Acknowledgement

The measurement programme has been performed by the staff at DRD and Ifsttar in the EU project PERSUADE, led by Dr. Luc Goubert from the Belgian Road Research Centre (BRRC). The work is financed by the European Commission through the 7th Framework Programme and by the Danish and French partners.

References

[1] EN 12697-40:2012 - Bituminous mixtures – Test methods for hot mix asphalt – Part 40: In situ drainability.

[2] M. Haider, H. Bendtsen, M. Berengier, R. Nilsson, R. Nilsson: SILENCE project, deliverable F.D10: Guidelines for low-noise road surface maintenance and rejuvenation. http://www.silence-ip.org, 2008.

[3] ISO 10534-2 - Acoustics -- Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer-function method.

[4] M. J. Crocker, D. Hanson, Z. Li, R. Karjatkar, K. S. Vissamraju: Measurement of the Acoustical and Mechanical Properties of Porous Road Surfaces and Tire/Road Noise. Journal of the Transportation Research Board, Volume 1891, 2004.

[5] U. Sandberg; J. A. Ejsmont: Tyre/road noise reference book. INFORMEX, Sweden 2002.

[6] ISO/DTS 13473-4: Characterization of pavement texture by use of surface profiles - Part 4: Spectral analysis of surface profiles.

[7] H. Bendtsen, R. S. H. Skov, B. Andersen, E. Olesen, A. Neidel, J. Raaberg, J. Cesbron: PERSUADE project: Performance of PERS at the Kalvehave test site. http://persuadeproject.eu, 2014.

[8] National Danish Road Guideline; 2.G System for documentation af støjreducerende slidlag "SRS". http://vejregler.lovportaler.dk/