What you measure is what you get? – a novel approach for specifying and controlling acoustic quality of road surfaces

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Summary

The acoustic quality of porous road surfaces can be optimized by defining an optimal texture and sound absorption for a given traffic mix. This is normally done in the design phase of a project. But how to ensure that the acoustic quality that is achieved production phase is similar to the designed quality? This can be checked with SPB or CPX measurements, but these might not be the most suitable conformity of production testing in all cases. The alternative is to specify acoustic quality by specifying civil engineering properties such as stone grading, layer thickness and porosity. We found that this might lead to wrong conclusions: surfaces within the civil engineering specs might underperform acoustically and surfaces outside the specs might be rejected while their acoustic quality is fine.

We investigated an alternative approach where we specified the acoustic quality based on layer thickness and degree of compaction. With these parameters, the acoustic performance of a single road surface mixture design can be accurately predicted and controlled. This method is now used for the first time in the Netherlands.

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1. Introduction

Low-noise road surfaces are very effective noise reduction measures for traffic noise. These roads are designed such that road texture and acoustic absorption are optimal for a certain traffic mix. But they should also comply with (civil engineering) boundary conditions such as durability, friction and rolling resistance.

The specification of the optimal design for a certain road is often expressed in civil engineering terms like stone mixture, grading curve, layer thickness, and porosity. But knowing the optimal parameters is only half of the story: How to treat deviations from the optimal recipe? Can less porosity be compensated for by a thicker layer? What if we change the granulate supplier? Does the road surface still perform within the limits that are set by the client or the environment?

For the reconstruction of the main highway in the Rotterdam harbor area, we were faced with these questions. The road surface for this road was optimized for maximum noise reduction and durability, knowing that the number of heavy vehicles is much larger on this road than on any other road in the Netherlands.

In the production practice, you seldom or never get the optimum road. Good quality means that the deviation from the optimum is as small as possible. But what deviations are allowed? In a joint effort, the constructor, acoustic consultant and infrastructure manager decided on a new approach to specify and evaluate the acoustic quality.

2. COP testing alternatives

The goal of the new approach was ensure that the acoustic quality of the actually constructed road was in conformance with the design optimum, allowing for a small deviation of the optimum sound reduction. To know the deviation, the quality of the constructed road surface needs to be evaluated just after production.

The so-called conformity of production testing can be done on the basis of acoustic measurements, by directly measuring the sound reduction with the SPB and/or CPX method. The advantage of this method is that you are exactly measuring what you want to know. But there are several practical drawbacks: for SPB, the road needs to be under traffic (so you cannot measure directly after production) you need a good measurement position (which is difficult on multilane highways with noise barriers, viaducts etc.). CPX is a good alternative but requires suitable weather conditions, a lot of extra measurement effort (especially on multilane roads) so careful planning and hence a lot of extra costs.

To overcome these drawbacks, we investigated a different approach. Our idea was to use the drill core samples that are already taken from the road for the conventional civil engineering COP testing and use them for acoustic COP testing. If this would turn out to be possible, then little to no extra measurement effort would be required and the acoustic quality would still be ensured.

3. Sensitivity of the acoustic quality to road property variations

In short, the acoustic quality of a road surface depends on the texture and sound absorption (for non-elastic surfaces). The newly designed surface of the Rotterdam harbor highway is a single layer porous asphalt mixture with a maximum 8mm stone grading and optimized for noise reduction and durability. This pavement type is normally referred to as OPA8. In the design phase (to find the optimum design) it already became clear that the tuning the sound absorption was key to optimize the sound reduction for the specific passenger car/truck traffic mixture; the texture had only a small influence.

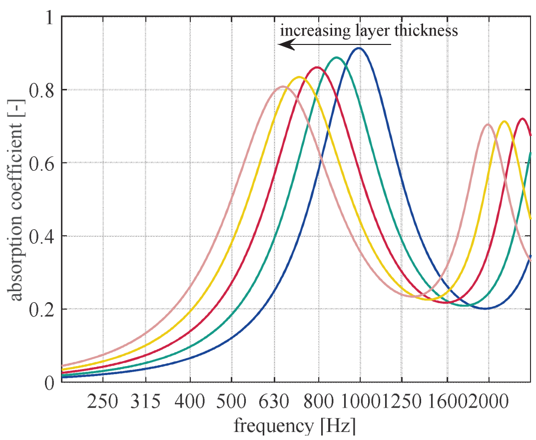
The texture depends on stone grading [2], stone shape and paving process. By controlling the grading and paving process, the texture quality could already be guaranteed so no extra COP testing was required.

The absorption depends on (the acoustic parameters) porosity, flow resistance, tortuosity and layer thickness [3]. These parameters influence the shape of the absorption spectrum and therefore the resulting noise reduction of the pavement. This is explained next.

The optimum road surface design was found to have an absorption spectrum with a distinct maximum at about 800 Hz. The frequency of the maximum is dependent on layer thickness and tortuosity. The shape of the maximum (which should be as high and wide as possible) depends on porosity and flow resistance.

The porosity should be as high as possible to have the absorption maximum as wide as possible. To ensure the dissipation of acoustic energy, the flow resistance should be high enough, but not too high, because then the surface will become acoustically reflective.

The dependence of the absorption on layer thickness and porosity is illustrated in Figure 1. Here we see that, in theory, we can control the frequency of the maximum absorption with the layer thickness and the width of the maximum with the porosity.



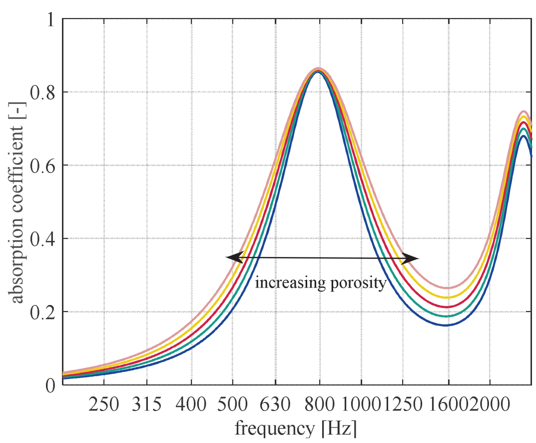


Figure 1. Theoretical influence of layer thickness and porosity on the absorption spectrum of the OPA8 road surface, while keeping the other parameters constant.

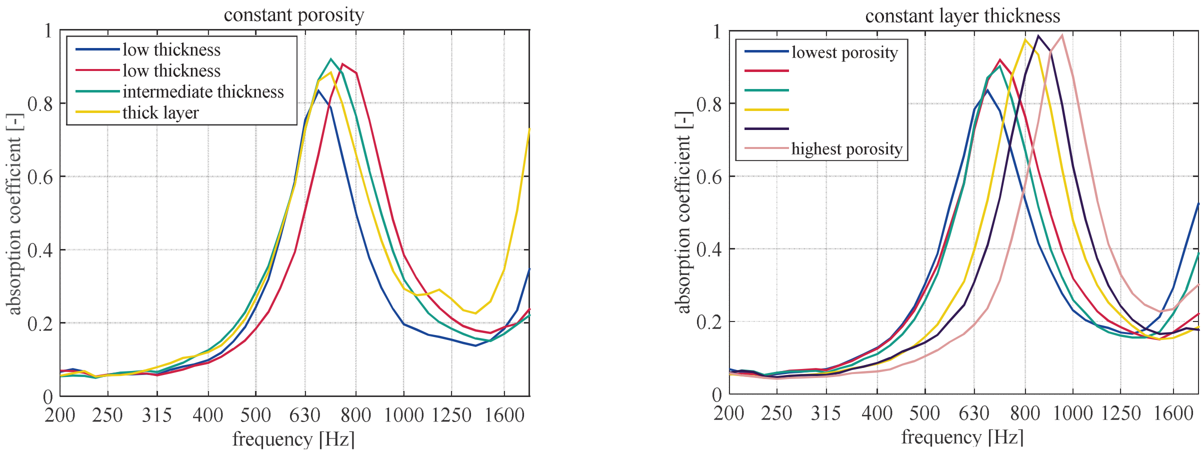


Figure 2. Influence in practice on the measured sound absorption of OPA8 drill cores by changing layer thickness with constant porosity (left) and by varying porosity and constant layer thickness (right).

It is common practice (at least in the Netherlands) to specify acoustic quality with the parameters porosity and layer thickness. We found that this does not guarantee that a certain acoustic quality is achieved. This is illustrated in the measured absorption spectra from several drill cores in Figure 2. We experienced for instance that the layer thickness is controllable in the production process, but in practice, the absorption maximum is not the same for layers with the same layer thickness. This is because a certain layer thickness can be achieved by varying the compaction and hence the porosity, flow resistance and tortuosity.
The same holds for porosity. We compared the absorption of cores with the same porosity but different layer thicknesses, the theoretical behavior was not observed. Instead, the absorption of the surfaces with the thinnest layers had the maximum at the lowest and highest frequency and other (thicker) layers have a maximum in between. Again the cause for this is that flow resistivity and tortuosity are left out of the equation/evaluation. We concluded that porosity and layer thickness alone are not sufficient to guarantee acoustic quality in COP testing.

4. Sound absorption and the degree of compaction

Including flow resistance and tortuosity in the COP testing is not straightforward because these parameters are not part of the standard testing standards for civil engineering and in the case of tortuosity no standardized practical measurement method exists.
We used a different approach. We investigated the relation between the civil engineering parameters: percentage accessible air cavities, degree of compaction, layer thickness, and the acoustic parameters: flow resistance, porosity, tortuosity and layer thickness and their relation to the absorption spectrum. If we are able to predict the change in absorption spectrum, we can also predict the change in sound reduction. This can be done with the porous surface module of the SPERoN/AOT model [4].
From investigations in the design phase, we already knew that degree of compaction is an important civil engineering parameter. It influences the porosity, flow resistance, and tortuosity in a linear manner (see Figure 3). So we

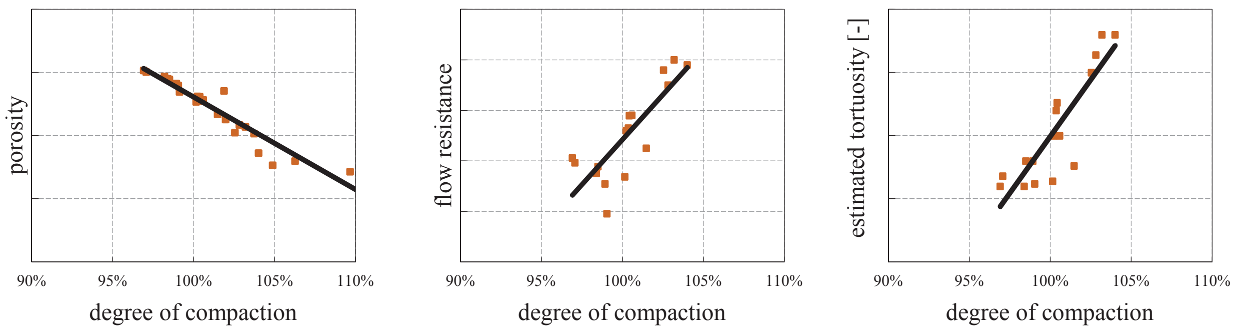


Figure 3. Influence of the degree of compaction on porosity (left), flow resistance (middle) and estimated tortuosity (right) for OPA8 road surface mixture

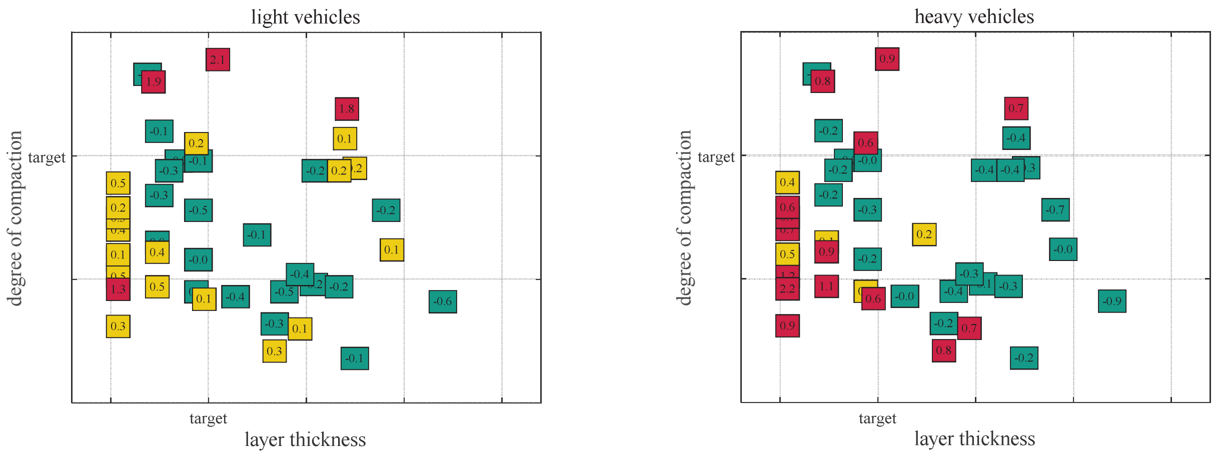


Figure 4. Change in noise reduction for varying layer thickness and degree of compaction for light vehicles (left) and heavy vehicles (right). The colors indicate the change in noise reduction with respect to the reference design (i.e. *target* layer thickness and *target* degree of compaction). Green indicates more noise reduction than the reference, yellow indicates up to 0.5 dB less noise reduction and red means over 0.5 dB less noise reduction. (the indicated thicknesses refer to acoustic layer thickness, unless indicated otherwise, see section 5.1).

have chosen the degree of compaction as a suitable candidate parameter for COP testing of the OPA8 mixture.

To investigate the relation between civil engineering parameters and noise reduction, we measured the absorption spectrum from over 40 drill cores for OPA8. Then we used the SPERoN/AOT to calculate the change in noise reduction compared to the optimum design. In this way, we could relate layer thickness and degree of compaction to expected noise reduction, or in COP terms: deviation from the noise reduction from the reference design. This change is different for heavy and light vehicles because their emission spectrum is different (see Figure 4).

The results show that there is a clear region in the graph where the road surface performs similar to the reference design. This allows for a margin in both layer thickness and degree of compaction during the production. When we go outside this region, the sound reduction is less than desired.

The influence of layer thickness can be understood by looking at the pass-by spectra for the reference design of OPA8 in Figure 5 and understanding how a change in absorption spectrum influences the pass-by spectra. We have added the spectrum of two-layer porous asphalt with a larger total layer thickness to illustrate the effect of changing the layer thickness.

When the layer thickness is decreased (at a certain degree of compaction), then the frequency of the absorption maximum shifts to higher frequencies (see Figure 1, left). This increases the noise reduction at these higher frequencies but reduces the noise reduction at the lower frequencies. For light vehicles, this will decrease the peak in the pass-by spectrum at 1250 Hz but will increase the peak at 630 Hz. In terms of the overall level, these

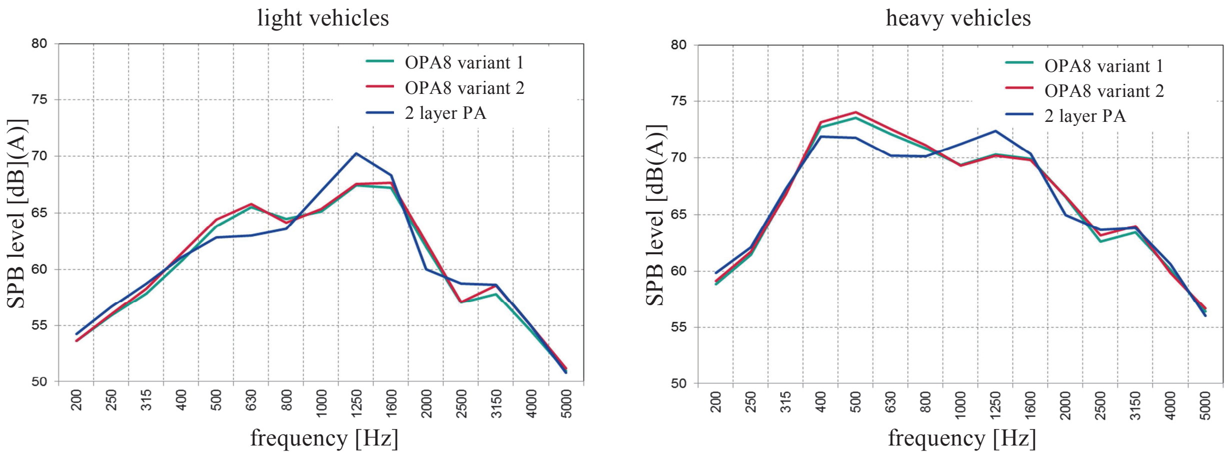


Figure 5. Measured pass-by sound spectra for light vehicles (left) and heavy vehicles (right) on two variants of OPA8 and a two-layer porous asphalt surface.

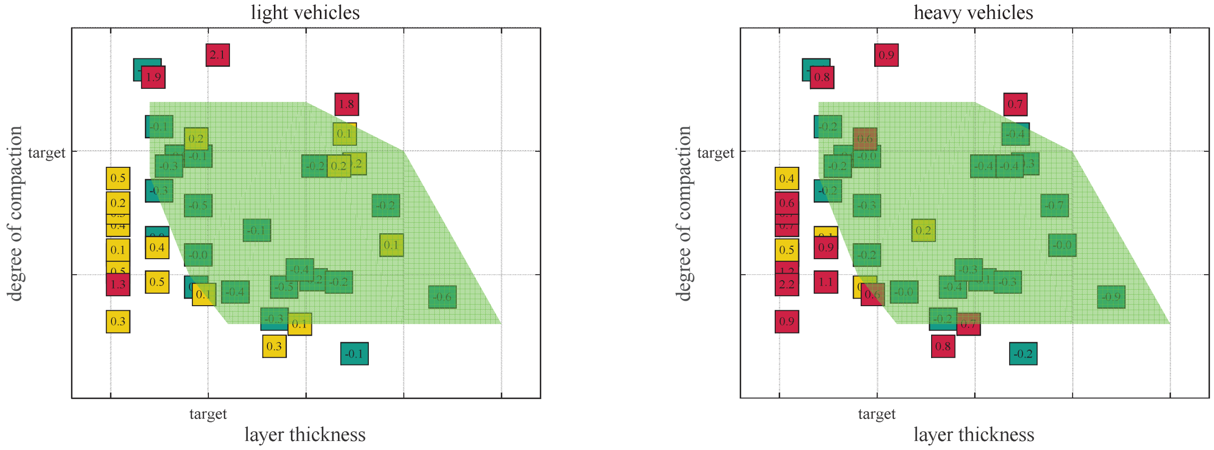


Figure 6. Acoustic COP green area for OPA8 in relation to the change in sound reduction for light vehicles (left) and heavy vehicles (right).

changes compensate one another. For heavy vehicles, there is only a distinct peak at 500 Hz, so an increased frequency of maximum absorption will increase the noise level at 500 Hz, but this is not compensated for by a decrease of the noise level at 1250 Hz, resulting in a higher overall level. So for this pavement design, the effect of a lower layer thickness is much more prominent for heavy vehicles than for light vehicles.

The influence of the degree of compaction is little more complex. Increasing the degree of compaction (with the same layer thickness) will decrease the porosity but at the same time increase the flow resistivity and tortuosity. At first, this will keep the effective layer thickness the same and the loss of porosity is compensated for by the increase in flow resistance. However, when we go too far from the target degree of compaction, the porosity will become too low and the flow resistance will become too high so the shape of the absorption maximum will change: it will become lower and less wide. This means that the effective absorption effect becomes smaller and hence the noise reduction will decrease.

When the degree of compaction is lowered, the porosity will become higher at the cost of a lower flow resistance. These effects counteract each other until the layer's flow resistance gets too low and the absorption maximum will get too low to provide sufficient noise reduction. Also a porosity that is too high is also unwanted from a civil engineering perspective as it decreases the durability of the road surface.

5. The COP green zone

5.1. definition

From the investigation, we know how layer thickness and degree of compaction influence the sound reduction. From this knowledge we can derive the limits for acoustic COP testing. We defined the so-called green area. We defined the green area such that only a deviation up to 0.2 dB from the reference was acceptable. This gives the result shown in Figure 6.

A thing to consider is the definition of layer thickness. Civil engineers measure the layer thickness by visually observing the change in material between the top layer to the base layer. From an acoustic point of view, the layer thickness is the thickness of the layer with accessible air cavities. In practice there is always a thin interface of about 2-3 mm between base and top layer where the pores are filled with bitumen and hence are not accessible. Therefore, one has to consider that the acoustic layer thickness is always 2-3 mm smaller than the layer thickness that the civil engineers report. It is easy to compensate for this observation by shifting the green curve on the horizontal axis and explicitly stating either 'acoustic' layer thickness or 'civil engineering' layer thickness.

The green areas in Figure 6 delimit the *acoustic* COP, not the *civil engineering* COP. If we also incorporate the durability requirement, then we have to increase the lower limit for degree of compaction. The upper limit was the same from an acoustic and civil engineering point of view. At a low degree of compaction, the bonding is not sufficient and a high degree of compaction there is a risk of stone crushing. Both phenomena deteriorate the lifetime expectancy of the

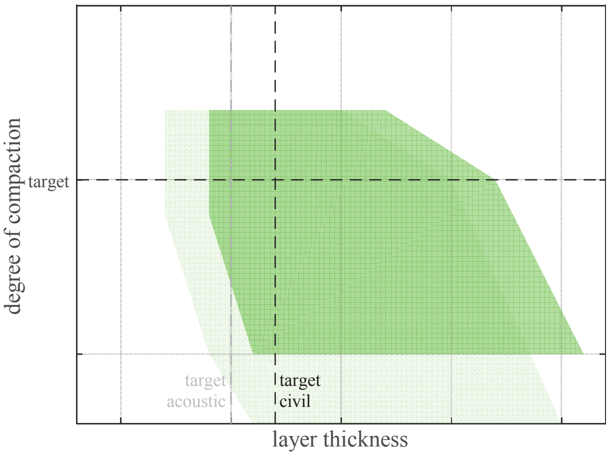


Figure 7. Proposed approval area for combined acoustic and civil engineering COP testing. The light green area is the acoustic COP area from Figure 6.

pavement. If we take these civil engineering limits into account in addition to the acoustic limits, and shift the area to compensate for the way civil engineers measure layer thickness, then we get the COP green area displayed in Figure 7.

5.2. Usage in practice

Using the green zone fits perfectly into the civil engineering COP processes. The degree of compaction and layer thicknesses are determined as part of the standard procedures. If the properties of a drill core that is taken during production fall inside the green zone, then we can expect that the noise reduction is similar to the sound reduction of the reference design.

What happens if a drill core falls just outside the green area depends on the contract between road constructor and infrastructure manager. Some options are:

- additional CPX or SPB measurements to check the predicted noise reduction;
- giving a discount to the client;
- taking the lower initial noise reduction into account when calculating the life-time average noise reduction and possibly scheduling earlier replacement when the end of the acoustic lifetime is reached;
- directly replacing the surface with a surface that falls within the green area specification.

We think that a combination of the first and third option is the most realistic and best fits to the interest of both the road constructor and infrastructure manager.

5.3. Application notes

What is new about this green area is that it also defines an upper limit for layer thickness. The fact that a too thick layer is negative for the sound reduction of the pavement for light vehicles is often overlooked.

When using the green area for a certain asphalt mixture design, one has to take into account that the shape of the green area depends on:

- the traffic mixture on the road;
- the deviation of the sound reduction that the infrastructure manager is willing to accept.

If any of these factors change, then the green area has to be replaced. Fortunately, this does not require new measurements but only using the prediction model again to incorporate the changed requirements regarding traffic mixture and allowed deviation.

If the design of the asphalt mixture changes significantly, then the procedure to obtain the green area has to be repeated, but this would also be necessary if the COP limits were defined in terms of layer thickness and porosity.

6. Conclusions

We proposed an acoustic COP method that uses parameters that are obtained during the normal civil engineering COP testing. We took drill core samples from the road and used absorption measurements and the SPERoN/AOT tyre/road noise model to devise a two parameter characterization (layer thickness and degree of compaction) of the road surface.

By using degree of compaction and layer thickness, we can predict the change in noise reduction with respect to the noise reduction of a reference mixture design. With this knowledge, we can define the COP limits from an acoustic point of view: the so called green area.

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