A PARADOXICAL DESIGN OF A LOW-NOISE PAVEMENT

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In the city of Rotterdam, a new low-noise pavement has been designed. An important aspect besides noise reduction was an optimal resistance against high mechanical stresses caused by cornering trucks. Durability tests and an Acoustic Optimization Tool were applied simultaneously to optimise the mix. After 6 years of successful monitoring the mix was adapted to comply with ISO 10844 for test tracks. The single sided requested tolerances were significantly smaller than the normal variations in mix design and road construction. Various measurements showed that the realised surface satisfied the ISO standard within a very tight margin band. This paper describes the mix design, monitoring results, mix optimisation, civil engineering aspects, and measurements for the conformity of production.

Keywords: Test track, ISO 10844, measurements, design, trucks

1. Introduction

Traffic noise is considered to be a severe threat for public health [1]. In various policies it is stated that the noise levels in cities have to be diminished. In order to lower the noise levels of traffic significantly, a number of acoustic measures are available. These measures can be ordered in three categories concerning the path of sound: the source, the transmission, and the receiver. The source of traffic noise are the respective vehicles on a trafficked road. The vehicle related emission can be roughly divided into propelling (or engine) noise and tyre-road (or rolling) noise [2].

In industrialised cities like Rotterdam, with one of the largest harbours in the world, noise from trucks is dominant in the overall noise emission from traffic. However, there are many situations that do not allow the application of low-noise pavements because of their low mechanical resistance against wringing heavy traffic. Therefore, a stable and durable low-noise pavement for trucks had to be developed and tested [3].

According to the standard ISO 10844 [4], to develop and test (silent) vehicles and tyres a standardised test area with a normalised surface has to be used. The somewhat odd question was whether the newly developed low-noise pavement in Rotterdam was suitable for acting as an non low-noise ISO 10844 surface. The Standard incorporates a number of restrictions to the applied asphalt mix of the surface in order to limit its noise reduction.

The paradox is to design a mix which is suitable as a low-noise pavement according the strict Dutch Noise Scheme and, as a “not low noise” testing surface according the strict ISO Standard as well.
2. NOISE OF TRUCKS

In order to design a new mix that meets the required properties for trucks, one must look into the different noise emission of these trucks. In fig. 1 an example of the respective noise emissions of tyres and engines of a passing truck at 50 mph is shown [5].

The noise emission of the various truck tyres that are in use differ significantly [6]. However, the various emissions are increasing monotonously with increasing speed and, also, the respective emissions are highly correlated. This means that it is possible to design a mix that is almost equally effective for all present truck tyres.

It is known that the application of a low-noise pavement can be effective in reducing the noise form trucks [7]. The reduction of rolling noise, however, is limited to about 3 dB(A) at 50 km/h. From internal research it has been shown that the so-called Thin Layers affect engine noise as well. So, an idling truck on a Thin Layer will show a small noise reduction. Therefore, combining these two effects, the expected noise reduction is about 4 dB(A) at 50 km/h. From practice, it is known that these road types are not durable in case of heavy wringing traffic. Therefore, a low-noise pavement had to be designed which has less noise reduction but, simultaneously, is significantly more stable then present products.

3. Pavement for heavy vehicles in Rotterdam

In the Netherlands, it is common practice not to apply low-noise pavements on crossings or narrow curved roads. In these cases the influence of the acoustical behaviour of the surface is significantly less than in cases with free flowing traffic due to lower speeds and accelerating vehicles [8]. However, policy in the city of Rotterdam demanded that low-noise pavements should be applied also on crossings. Therefore, DCMR, the Environmental Protection Agency, in cooperation with the city of Rotterdam has initiated a project for the development of a low-noise pavement for heavy traffic. The goal of this project was a noise reduction of about 2 dB(A).

3.1 Design

3.1.1 Some definitions

Mix: a composite material of aggregate (stones), binder (bitumen), and additional materials.
Test slab: a mix applied in a small matrix under laboratory conditions.
Pavement: the actual mix applied on a road with standard spreaders and compactors.
Surface: the actual mix applied on a road with standard spreaders and compactors in the driving lane (i.e. pavement) and also at the propagation zone of the test area.
**Porosity**: open air voids that are accessible. This definition differs from the widely applied one in road construction.

### 3.1.2 Theory

Starting point of the design was a standard Thin Layer. The Acoustic Optimisation Tool (AOT) SIROTOL [9] has been applied to perform the various optimisations. SIROTOL is developed to calculate the acoustical effects of small changes in mixes with an accuracy of about 0.1 dB(A). As mentioned earlier, the new pavement had to have an initial noise reduction of 2 dB(A) for heavy vehicles relative to the Dutch reference pavement of dense asphaltic concrete (AC 16 Surf). The minimal functional lifetime with respect to noise reduction had to be 7.5 years.

A low-noise pavement needs a minimum amount of porosity (open air voids). Porosity influences positively the suppression of aerodynamic mechanisms and the horn effect [10]. However, porosity also influences the durability of a road surface negatively. In order to be able to reduce the porosity and maintain the required noise reduction, a relative fine mix is needed. The loss of aerodynamic noise reduction is then compensated by extra mechanical noise reduction due to a smoother texture. The interchanging of these effects is quite complicated and the optimal balance depends heavily on speed of traffic and type of vehicles.

### 3.1.3 Laboratory research

First, in laboratory, absorption and texture measurements on samples have been performed. The measurement results have been analysed by SIROTOL to verify the noise reduction.

Four test samples (dimensions 30 cm x 50 cm) have been constructed with the new mix. The absorption was measured by a MicroFlown device [11] in a matrix of 3 by 3 points in the centre of the test sample in order to minimise the influence of parasitic absorption near the edges of the samples. The texture was measured in 5 parallel lines of 30 cm with a laser profilometer [12].

The absorption and texture results have been analysed in SIROTOL and it showed that the noise reduction was within 1 dB(A) from the theoretical prediction. The quality of the test samples was, therefore, very good which was surely not always the case in comparable studies.

Also, the contractor performed durability tests on these samples to determine the mechanical resistance against ravelling and rutting. The description of these tests and the interpretation of the results are outside the scope of this paper. To summarise these results: it was shown that the requested life time of more than 7 years could be achieved.

### 3.2 Tracks and measurements

In the city of Rotterdam, the new surface has been constructed on four tracks with a high intensity of heavy traffic. The official opening, with vast interest from politics and press, was on 28 September 2011. For test purposes, 2 types of the mix were chosen: one with an open-air void of about 9% and the second with about 12%. The tracks have been tested by performing noise measurements (according the SPB [13] and the CPX [14] method) and skidding resistance measurements during 7 years. The absorption and texture have also been measured in situ and bore cores have been taken to perform civil engineering tests and to test of the conformity of production.

#### 3.2.1 Noise measurements

On two of the test tracks SPB measurements have been performed. These were used as calibration of the CPX measurements on all test tracks. This means that a limited number of SPB measurements can be used for a larger number of tracks. This conformity of production procedure is standard in the Netherlands. The results of the noise measurements for heavy and light vehicles can be seen in table 1.
Table 1: Test tracks and their respective initial noise reductions for heavy and light vehicles at 50 km/h.

<table>
<thead>
<tr>
<th>mix (air voids)</th>
<th>noise reduction [dB(A)]</th>
<th>measured</th>
<th>predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>light</td>
<td>heavy</td>
</tr>
<tr>
<td>I (9%)</td>
<td>2.1</td>
<td>2.3</td>
<td>2</td>
</tr>
<tr>
<td>II (12%)</td>
<td>3.8</td>
<td>4.0</td>
<td>4</td>
</tr>
<tr>
<td>III (9%)</td>
<td>3.0</td>
<td>3.2</td>
<td>2</td>
</tr>
</tbody>
</table>

From table 1 it can be seen that there is some variety in measurement results but that the measured noise reductions correlate well with the predicted values. The significantly higher noise reduction of mix III relative to mix I is caused by a higher porosity which was measured from bore cores.

Furthermore, the test tracks have been monitored for 7 years. In table 2 the respective measured noise reductions for heavy vehicles have been presented.

Table 2: Mix types and measured noise reductions for heavy vehicles at 50 km/h.

<table>
<thead>
<tr>
<th>mix (air voids)</th>
<th>noise reduction [dB(A)]</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (9%)</td>
<td></td>
<td>2.1</td>
<td>2.8</td>
<td>2.4</td>
<td>1.9</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>II (12%)</td>
<td></td>
<td>3.8</td>
<td>3.2</td>
<td>2.3</td>
<td>2.1</td>
<td>1.9</td>
<td>1.4</td>
</tr>
<tr>
<td>III (9%)</td>
<td></td>
<td>3.0</td>
<td>2.5</td>
<td>2.4</td>
<td>2.0</td>
<td>1.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

From table 2 it can be seen that the annual degradation of the noise reduction for the 9% and 12% variant is about 0.2 dB and 0.4 dB, respectively. This is significantly better than the nominal value for Thin Layers of 0.5 dB. Based on these monitoring results, mix I with 9% open air voids has been chosen for further development in the second part of the research. It is now known under its commercial name Redufalt 2G and has an official noise label according to the Dutch Noise Scheme.

4. Surface for test areas according ISO 10844

4.1 Test areas

A Dutch truck manufacturer owns two noise testing areas according ISO 10844 to perform type testing of their vehicles (see fig. 2).

Figure 2: Bird’s eye view of the round and square noise testing area.
The first (round) and second (square) area were compliant with ISO 10844, version 1994, and ISO 10844, version 2011, respectively. In 2015, both areas were at the end of their lifetimes. The new test areas were to meet again the respective versions of the Standard. ISO 10844 (especially the 2011 version) is very strict in limiting certain civil engineering parameters of the mix to be applied in order to limit its noise reduction.

The objectives of the second project were twofold: 1. to tweak the new mix to the strict civil engineering limits, 2. to apply a mix that is compliant to both versions of the Standard, simultaneously. Additionally, the manufacturer required significant smaller tolerances because they were to be considered single sided.

4.2 Choice of mix

The Standard, version 1994, allows an average porosity of 8% with no individual value higher than 10%. The MPD cannot be lower than 0.4 mm and the maximum stone size should be around 8 mm. The total thickness of the top layer is minimal 30 mm. The bitumen is not to be modified.

The Standard, version 2011, allows an average porosity of 8% for frequencies between 315 and 1,600 Hz. This equals an absorption of 0.08 per octave band. The MPD is to be 0.5±0,2 mm and the maximum stone size should be around 8 mm. The total thickness of the top layer is minimal 30 mm.

Additionally, the manufacturer requested stricter single sided boundaries. Since measurements do not know single sides accuracies they had to be transformed into symmetrical tolerances. This implied that the requested tolerances were about half of those requested in the Standard. Then the problem arose that these tolerances became smaller than those found in normal civil-engineering practice.

Now, no model calculations were necessary since they are not normative in the Standard. The porosity and texture of the tracks with mix type I in Rotterdam met the respective demands. This implies that the new mix could be compliant with the Standard, version 1994 as well as with version 2011.

4.3 Laboratory test slabs

First, laboratory test slabs of the new mix and a well-known reference SMA 8 were made. On these slabs texture and absorption measurements were performed with identical equipment as in the case of Rotterdam. The results were then analysed with SIROTOL and calibrated with the noise measurements from Rotterdam to improve accuracy. The percentage open air voids or porosity was measured from bore cores taken from the slabs.

From these measurements it was concluded that:

1. The estimated texture depth (ETD) met the Standard, version 1994
2. The mean profile depth (MPD) did not meet the Standard, version 2011
3. The average porosity met the Standard

It is known form various other tests that the texture of a test slab often is “rouglier” than from a real track with an identical mix. In laboratory, it is very complicated to mimic the actual in situ compaction. This implied that the MPD of the test area most likely would meet the Standard. It is possible to adapt the texture by applying a special surface dressing so that the MPD in practice will meet the Standard, 2011 version. The advantage is that the same mix could be applied on both test areas. This means that the homogeneity would be higher since the asphalt spreaders could run in a continuous operational mode and under identical weather conditions.

From these results and those from the tracks in Rotterdam it was decided to put Redufalt 2G on both test areas.
4.4 Measurements

4.4.1 CPX measurements

Since the test areas are used to measure the emission of vehicles it is very important to know precisely the acoustic behaviour of the new top layer relative to the old top layers. For this purpose, multiple CPX measurements have been performed on both test areas before and after reconstruction. In table 3 the average results have been presented.

Table 3: Averages and standard deviations of the measured CPX levels at 50 km/h before and after reconstruction.

<table>
<thead>
<tr>
<th>area</th>
<th>round</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>north</td>
<td>south</td>
<td>north</td>
<td>south</td>
<td>north</td>
<td>south</td>
</tr>
<tr>
<td>before</td>
<td>average</td>
<td>90.4</td>
<td>90.8</td>
<td>91.5</td>
<td>91.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>st.dev.</td>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>after</td>
<td>average</td>
<td>90.5</td>
<td>90.6</td>
<td>90.2</td>
<td>90.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>st.dev.</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

From table 3 it can be seen that only the results of the square area have improved significantly. It is important to realize that CPX results are based on tyres for passenger cars rather than on truck tyres. However, from the measurements in Rotterdam a high correlation (> 0.9) has been found between the results for these two types of tyres. The results from the test areas, therefore, can be used to predict accurately the performance of the top layers in case of truck tyres. In table 4 the results have been compared to those of Rotterdam. One can see what the effect has been of tweaking the Rotterdam mix to the Standard.

Table 4: Measured average noise reductions for heavy vehicles at 50 km/h.

<table>
<thead>
<tr>
<th>noise reduction [dB(A)]</th>
<th>Rotterdam</th>
<th>truck test area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

4.4.2 Texture measurements

Only the Standard, version 2011, demands texture measurements with a laser profilometer [12]. The pattern of measurement points can be seen in fig. 3.

Figure 3: Overview of the pattern for texture measurements according ISO 10844, version 2011.

The results of the measured texture (MPD) can be seen in table 5.
Table 5: Averages and standard deviations of the Mean Profile Depth (MPD) before and after reconstruction.

<table>
<thead>
<tr>
<th>area</th>
<th>round</th>
<th>square</th>
<th>left</th>
<th>right</th>
<th>left</th>
<th>right</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>average</td>
<td>1.8</td>
<td>1.7</td>
<td>0.8</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>st.dev.</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>after</td>
<td>average</td>
<td>0.7</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>st.dev.</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

The high MPD form the round square before reconstruction was caused by its rough texture that is characteristic of Porous Asphalt 16 that was applied there. Now, both areas satisfy the demands of the Standard concerning texture.

4.4.3 Absorption measurements

On the exact same locations at which the texture measurements have been performed (see fig. 3) absorption measurements have been performed. The absorption has been measured by means of an impedance tube [15]. Additionally, the absorption was measured at some points in the propagation zone between driving lane and microphone positions.

The results of the maximum absorption can be seen in Table 6.

<table>
<thead>
<tr>
<th>area</th>
<th>round</th>
<th>square</th>
</tr>
</thead>
<tbody>
<tr>
<td>driving lane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average left</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>average right</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>st.dev. left</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>st.dev. right</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>propagation area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average left</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>average right</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Both areas satisfy the demands of the Standard concerning absorption with the smallest of tolerance.

4.5 Monitoring

According the Standard, texture and absorption measurements have to be repeated regularly. In 2017 the texture as well as the CPX measurements have been repeated.

<table>
<thead>
<tr>
<th>area</th>
<th>2015</th>
<th>2017</th>
<th>2015</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPX</td>
<td>90.6</td>
<td>90.0</td>
<td>90.3</td>
<td>90.9</td>
</tr>
<tr>
<td>texture</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

As can be seen the measured values did a little during the first year of use.
5. Conclusions

With the right tools it is possible to design a low-noise pavement that is durable. Application of this pavement is no longer restricted to straight road sections.

Noise monitoring in Rotterdam showed an annual decay of noise reduction of 0.3 dB(A) which is significantly less than found for other road types.

The civil engineering properties of the new mix meet the demands in ISO 10844, both versions 1994 and 2011.

From these two projects the following paradoxical conclusions can be made simultaneously:
1. Redufalt 2G has a high enough noise reduction in order to be labelled as low-noise pavement according the strict Dutch Noise Scheme.
2. Redufalt 2G has a low enough noise reduction in order to meet the strict ISO 10844.

REFERENCES