Samenvatting
Omdat de levensduur van PAC nogal variabel is en om de onderhoudskosten binnen de perken te houden wordt allerwegen gezocht naar methoden om de gemiddelde levensduur te verlengen en de variatie daarin te beperken. Duidelijk is dat de kwaliteit van het gelegde mengsel en de spreiding daarin een belangrijke rol speelt. Omdat er relatief weinig bekend is over in welke mate de aanvangskwaliteit van enkellaags PAC beïnvloed wordt door de aanleg condities is de uitvoering van een bepaald project uitvoerig gemonitord. Daaruit bleek dat de samenstelling van het gelegde PAC nogal varieerde, meer dan aanvankelijk was gedacht. Niettemin kon een vergelijking worden opgesteld waarmee het holle ruimtepercentage, de sleutelgrootheid bij PAC, kan worden voorspeld uit de mengselsamenstelling, de mengtemperatuur en verdichtingsenergie. Naast deze bevindingen worden de resultaten gerapporteerd van een onderzoek naar tweelaags PAC. Tweelaags PAC mag dan betere geluidsreducererende eigenschappen hebben maar er kunnen doorlatendheidsproblemen ontstaan door het relatief lage holle ruimtepercentage in het grensvlak tussen boven- en onderlaag. Aangetoond is dat de graderingen van boven- en onderlaag goed op elkaar moeten worden afgestemd om een voldoend hoge doorlatendheid te kunnen waarborgen. Verder wordt aangetoond dat de gradering cq de textuur van de bovenlaag van grote invloed is op de geluidsproductie.

Trefwoorden
PAC, rafeling, verdichting, geluidsreductie, doorlatendheid
1. **Introduction**

Porous asphalt concrete is extensively used in the Netherlands on the main highway system. The reasons for this are the noise reduction capabilities of this particular type of wearing course. Single layer PAC with a thickness of 50 mm and a 0/16 mm gradation is the most widely used type of PAC. Table 1 gives an overview of the lifetimes of PAC as observed in the Netherlands and reported in (1).

**Table 1: Application of PAC in the Netherlands**

<table>
<thead>
<tr>
<th></th>
<th>Total length [km]</th>
<th>50%</th>
<th>Mean lifetime</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands</td>
<td>2269</td>
<td>11.6</td>
<td>11.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Limburg</td>
<td>183</td>
<td>10.6</td>
<td>10.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Noord-Brabant</td>
<td>396</td>
<td>11.7</td>
<td>11.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Noord-Holland</td>
<td>199</td>
<td>12.4</td>
<td>12.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Noord-Nederland</td>
<td>397</td>
<td>11.2</td>
<td>11.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Oost-Nederland</td>
<td>538</td>
<td>12.2</td>
<td>12.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Utrecht</td>
<td>172</td>
<td>12.3</td>
<td>12.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Zeeland</td>
<td>68</td>
<td>12.8</td>
<td>13.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Zuid-Holland</td>
<td>266</td>
<td>11.2</td>
<td>11.6</td>
<td>2.3</td>
</tr>
</tbody>
</table>

It is a well known fact that PAC is vulnerable to influences of traffic and climate because of its very open structure; especially ravelling is a problem of main concern. It has been shown (2, 3) that the composition of the mixture controls for approximately 65% the lifetime of PAC wearing courses with other factors like traffic and climate have a relative influence of about 35%. This shows the huge influence of the mixture composition on PAC performance. Little information however is available on which factors influence the mixture composition and what the actual variation in mixture composition actually is. Therefore the construction of a particular project was extensively monitored in order to be able to answer these questions.

2. **Influence of working conditions on the quality of single layer PAC mixtures as laid**

As has been mentioned above, mixture composition has a significant influence on raveling in PAC. This means that it would be extremely helpful if knowledge on how the mixture quality depends on things like construction techniques and working conditions. It is remarkable however to notice that little to no research is done in this field. Of course there is a lot of qualitative information but quantitative data are lacking. The authors considers this as a serious drawback because how can we achieve real benefits from our research work on materials with e.g. enhanced characteristics if we don’t know and if we cannot quantify how working conditions affect the quality of the materials as laid. To say it very boldly “all our fine research leads to
nothing if things are screwed up in the field”. At the end of the day it is the contractor who has full control over the quality of the laid materials.

Of course, the quality of the materials as laid strongly depends on the skills of the contractor. However also contractual issues, union related issues, competition between asphalt and concrete mixtures, weather conditions, working conditions etc have a large influence on the quality produced. One should e.g. not be surprised if the quality of the asphalt mixtures as laid is a bit disappointing if the finisher drives at a too high speed and if the number of rollers is too little to obtain the right degree of compaction. Also one should not be surprised about a disappointing quality if the contractor has to place PAC type mixtures (sensitive for cooling down and segregation) in adverse weather conditions and during the night.

Although authorities and contractors agreed with the principal author that obtaining information and quantifying the factors that control the quality of asphalt mixtures is an important issue, both parties were somewhat reluctant to participate in such a project. The reasons for this attitude were mainly based on things like “the cook doesn’t allow you in the kitchen to see how the food is prepared”, on mistrust from contractor’s side in terms of “what is the client going to do with all the information you are going to collect, will he penalize me afterwards”, with attitudes from the clients side like “if the quality control shows that nothing is wrong, why should I improve my style of supervising and contracting”. All the observations made here are not new, the point however is that we seem to have some problem by saying these things in the open and by taking their consequences.

Given the need to enhance the lifetime of PAC and to reduce the variation in life-time, a contractor could finally be convinced to participate in a study to determine the effect of working conditions on the quality of the product as laid (4). It should be noted that the contractor involved, Mourik Groot-Ammers bv, was extremely helpful in making this project a success.

**Description of the project**

The project that could be monitored in detail was a project on highway A12 leading from the Hague to Utrecht. The project consisted of the widening and partial replacement of the existing lanes using single layer PAC as a wearing course. The total length of the project was 9.1 km, the total amount of PAC involved was around 16700 tons. Because it was a widening project, most of the work could be done during day time. The project was executed between the 8\textsuperscript{th} of October and the 23\textsuperscript{rd} of November 2003. Table 2 gives an overview of the quantities involved at various dates.

From the information given in table 2 it is clear that extensions were used to the finisher in order to be able to lay the required width in one run. Compaction was done by means of one three wheel roller (13 tons) and two tandem rollers, one with a weight of 8 tons, the other with a weight of 10 tons. Most of the time however compaction was achieved with the two tandem rollers and every now and then only one tandem roller was used. It should be noted that no vibration is allowed when compacting PAC; this is to avoid crushing of the aggregates. Figure 1 gives some pictures of the equipment used.

During the project a number of measurements and investigations were made. These comprised amongst others:

1. Continuous registration of the weather conditions.
2. Assessment of the effect of the speed of the finisher on the quality of the material as laid.
3. Detailed evaluation of the placement of a particular batch of the asphalt plant. This involved measurement of mixture characteristics from samples taken from a particular truck load, measurement of the change in temperature during transportation – laying – compaction.

4. Measurement of the degree of compaction in relation to the number of roller passes and temperature by means of a nuclear device.

5. Measurement of the variation in bitumen content and the degree of compaction along the width of the paver and the length of the project.

6. Measurement of the resilient modulus and shear strength of cores taken from the project.

Table 2: Details on the quantities produced at the specific project

<table>
<thead>
<tr>
<th>Section</th>
<th>Date of construction</th>
<th>Section length [m]</th>
<th>Average width [m]</th>
<th>Paved area [m²]</th>
<th>Paving time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8th Oct 2003</td>
<td>2239</td>
<td>6.0</td>
<td>13428</td>
<td>From 7.00 – 16.30</td>
</tr>
<tr>
<td>3</td>
<td>9th Oct 2003</td>
<td>928</td>
<td>6.4</td>
<td>5942</td>
<td>From 7.00 – 13.00</td>
</tr>
<tr>
<td>5</td>
<td>5th Nov 2003</td>
<td>484</td>
<td>6.23</td>
<td>2988</td>
<td>From 8.00 – 12.30</td>
</tr>
<tr>
<td>4</td>
<td>14th Nov 2003</td>
<td>4468</td>
<td>9.93</td>
<td>43109</td>
<td>From the evening till the afternoon of Nov 15</td>
</tr>
<tr>
<td>4</td>
<td>15th Nov 2003</td>
<td>4468</td>
<td>11.02</td>
<td>49160</td>
<td>From the evening till the afternoon of Nov 16</td>
</tr>
<tr>
<td>2</td>
<td>23th Nov 2003</td>
<td>946</td>
<td>20.01</td>
<td>18939</td>
<td>At night</td>
</tr>
</tbody>
</table>

Figure 1: Overview of the equipment used, from left to right: the paver with extensions, the three wheel roller compactor, a tandem roller
Observed variation in mixture composition

Variation in mixture composition can take place because of variations during the production of the asphalt mixture. Furthermore variations might develop during trans-portion and laying because of segregation of the aggregates in the mixture and because of dripping off of the bituminous mortar. It should be noted that PAC is sensitive for both.

Because temperature was considered to be a main parameter controlling the quality of the mixture as laid, the temperature history of 9 truck loads was recorded in detail. Table 3 shows some results. The temperature trajectory was from around 155 °C when leaving the plant to around 60 °C, 30 minutes after start of compaction.

Table 3: Cooling rate at various phases of the construction process

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration [min]</th>
<th>Temp. gradient [°C/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>From plant to arrival at job</td>
<td>42 – 80</td>
<td>-0.06</td>
</tr>
<tr>
<td>From arrival to dumping in hopper</td>
<td>5 – 15</td>
<td>-0.29</td>
</tr>
<tr>
<td>From dumping in hopper to just in front of screed</td>
<td>3 – 5</td>
<td>-5.08</td>
</tr>
<tr>
<td>0 - 10 minutes after start compaction</td>
<td>10</td>
<td>-2.83</td>
</tr>
<tr>
<td>10 – 20 minutes after start compaction</td>
<td>10</td>
<td>-2.52</td>
</tr>
<tr>
<td>20 – 30 minutes after start compaction</td>
<td>10</td>
<td>-1.52</td>
</tr>
</tbody>
</table>

Note: Temperature measurements were done when the trucks left the plant. All trucks were insulated trucks. The sometimes long duration of the trip from the plant to job had to do with delays caused by traffic jams due to the construction job.

In order to investigate the variation in mixture composition 5 cores were taken in the transverse direction along the width of the screed at 9 locations. At 3 of those locations the speed of the paver was 4 m/min, at 3 locations it was 6 m/min, and finally a speed of 8 m/min was used on the last three locations. Figure 2 shows the variation in void content as measured from the cores taken at different positions along the width of the finisher, and at different locations.

Figure 3 shows the bitumen content taken at various locations along the project. At each location the bitumen content was determined on three samples. The first sample was taken from the truck just before the truck left the plant, the second sample was taken from the same truck at arrival at the job, while the last sample was taken from the same batch just in front of the screed. Figure 4 shows the penetration of the bitumen from the same samples as the ones shown in figure 3. One will immediately notice the sudden change in penetration at location 7. Although every possible effort was made to determine the reason for this change, nothing illogical seemed to have occurred.

From the results obtained it is quite clear that a significant amount of variation in the composition of the PAC was observed over the width as well as over the length of the project. It should be noted however that the variations observed were all just within the specification limits.
Figure 2: Variation in void content over the width of the screed as measured on 9 locations as a result of three different speeds of the finisher.

Figure 3: Variation in bitumen content.
Variations in mixture composition observed in other projects

The large amount of variation observed was in line with observations made in a study performed by CROW (5). In that study cores were taken over the width of the screed on 5 different projects and the following observations were made.

1. In the horizontal direction along the width of the screed with extensions, the following was observed. In both outer sections, the extensions of the screed, the bitumen content is on the average 0.4 % (m/m) lower than in the centre part. In the outer sections there is also 3 % (m/m) more aggregate with a diameter larger than 11.2 mm and the void content is 2 % higher.

2. In the vertical direction the following differences were observed.
   a. On the average the bitumen content in the lower part of the PAC layer is 0.7 % higher than in the upper part. The lower part also contains 1 % more sand and 2 % more mastic (mixture of bitumen, filler and fine part of the sand).
   b. The lower part of the PAC at the extensions contains on the average 2.6 % more aggregate on sieve 8 mm while this number is 3.8 % for the upper part.

The study concluded that the variations in the horizontal direction are a result of segregation while the differences in the vertical direction are caused by dripping off of mastic. Potential improvements to the mixture to avoid segregation and dripping off were moving from a 0/16 gradation to a 0/11 gradation and the use of polymer modified binders.

Unfortunately the number cores available in this project was too limited to investigate the differences in composition between the top and bottom part of the PAC cores.

Figure 4: Variation in the penetration and T\&b of the recovered bitumen
Mechanical characteristics

As mentioned before, mechanical tests are not a part of the mixture design and quality control process. This is because it was believed that a test like the Marshall test will not give useful information. Although this statement is correct it might result in situations where the mixture is acceptable from an environmental (noise) point of view but lacks mechanical durability. This means that there is a need for a mechanical test that gives meaningful results.

Furthermore, the worst thing that can happen to a project is that the mixture as laid has been taken out because it doesn’t pass the requirements. Removal and replacement of the PAC wearing courses cost not only a lot of money and time but it also means a significant amount of unnecessary hinder to traffic. This means that there is a need for procedures that allow poor quality mixtures to be recognized during paving allowing removal and replacement during the course of the project. Commonly used mixture composition tests simply take too much time and are therefore not fit for this purpose. A fast, non destructive test to determine the mechanical characteristics that can be performed on site is very interesting provided it is capable of giving relevant information.

Resilient modulus assessments on site using Spectral Analysis of Surface Waves (SASW) techniques were believed to be a very attractive type of test. The test is non destructive, fast and the equipment can be moved around very easily.

A pre-investigation has therefore been performed to determine the influence of the void content on the resilient modulus of PAC mixtures. More specifically, the influence was determined of the compaction temperature (compaction was done at T = 100, 120, 140 and 160 °C, stone content was 85%) as well as the influence of the amount of aggregates larger than 2mm (stone contents 82.5, 85, 87.5 and 90%, compaction temperature was between 140 and 145 °C) on the void content and density as well as on the resilient modulus. In all cases the bitumen content was kept the same. Compaction was done by means of the standard Marshall procedure (2 x 50 blows). The resilient modulus tests were performed at 20 °C and 8 Hz.

The relationships as determined between temperature during compaction and the density or void content are shown here-after:

\[
\begin{align*}
D &= 2.04 T + 1756.5 \\
VC &= 30.68 - 0.081 T
\end{align*}
\]

Where:  
- \(D\) = density \([\text{kg/m}^3]\),
- \(T\) = temperature at compaction \([\circ \text{C}]\),
- \(VC\) = void content [%].

The relationships between the stone content and density or void content appeared to be:

\[
\begin{align*}
D &= -1782 \ln (SC) + 9969 \\
VC &= -291 \ln (SC) + 70
\end{align*}
\]

Where:  
- \(SC\) = stone content (percentage of the aggregate on the 2 mm sieve)

From these results it is clear that both stone content and temperature during compaction influence the density and void content. The void content of course also influences the resilient modulus but no unique relationship between void content and modulus could be found. For
specimens where the void content was varied by varying the stone content, the relation between void content and resilient modulus appeared to be:

\[ \log S_{\text{mix}} = -0.022 \text{VC} + 4.087 \quad r^2 = 0.96 \]

In case the void content was varied by varying the compaction temperature, the relation between void content and modulus was:

\[ \log S_{\text{mix}} = -0.055 \text{VC} + 4.670 \quad r^2 = 0.96 \]

Where: \( S_{\text{mix}} \) = resilient modulus at 20\(^{\circ}\)C and 8Hz loading frequency [MPa].

All this implies that the resilient modulus seems not to be a very good parameter to assess the quality of the PAC. This finding was further confirmed by resilient modulus tests performed on samples taken from the road during the project. The results of these tests are shown in figure 5. Although a clear trend is visible, the relationship shows too much scatter to be used for practical purposes. The relationship between void content and resilient modulus that was obtained from these tests is given below.

\[ \log S_{\text{mix}} = -0.03 \text{VC} + 3.97 \quad r^2 = 0.25 \]

Where: \( S_{\text{mix}} \) = resilient modulus at 20\(^{\circ}\)C and 8 Hz loading frequency [MPa], \( \text{VC} \) = void content [%].

![Figure 5: Relationship between the resilient modulus and the void content as determined from samples taken from the road](image-url)
The low value for $r^2$ indicates that the relationship is disappointingly weak, and also a large amount of scatter around the trend line was observed. Clearly the void content is not the only parameter that influences the resilient modulus. This could somewhat be expected from the results of the pre-investigation mentioned above, from the fact that the bitumen content showed a high variation and from the fact that at locations 7 – 9 a softer bitumen was used (see also figure 4). It should be noted that the resilient modulus from samples taken from the center part of the screed or taken close to the joint, showed the largest deviation from the trend line.

Probably other techniques like radar, infrared etc have to be applied to allow the quality of PAC mixtures to be measured in a non destructive way and at a reasonable speed.

3. **Modeling the influence factors**

One of the most important parameters of single layer PAC is the void content. The void content should be high enough to provide the required noise reduction. The effect of the void content of PAC mixtures on the noise reduction (assuming the texture stays the same) can roughly be calculated using:

$$DL = 0.4 \ VC - 4.2$$

Where:  
**DL** = reduction in noise level [dB(A)],  
**VC** = void content [%].

On the other hand, the void content should not be too high to avoid durability problems. It would therefore be very useful if one is able to predict the void content from the conditions prevailing during construction (temperature, compaction etc.) and an attempt was therefore made to develop such a relationship. In the first phase of the analysis linear regression techniques were applied. Using the available information, the following generalized equation was developed to predict the void content.

$$Y = 39.51 - 0.09 \ X_1 - 0.81 \ X_2 + 0.05 \ X_3 -0.23 \ X_4 - 0.01 \ X_5$$

$r^2 = 0.70$

Where:  
**Y** = void content [%],  
$X_1$ = temperature of asphalt when truck leaves the plant [°C],  
$X_2$ = mass percentage bitumen [% m/m],  
$X_3$ = percentage aggregate on sieve C8 [% m/m],  
$X_4$ = mass percentage filler [% m/m],  
$X_5$ = compaction characteristic [kN/m$^3$].

The equation was capable to predict the void content within ±2% (45 data points). For 35 of the 45 data points the predicted void content was ±1 % of the observed value. The compaction characteristic is defined as:

$$X_5 = \frac{n \ P}{L \ D^2}$$
Where: 
\[ P = \text{load on the roller drum [kN]}, \]
\[ L = \text{length of the drum [m]}, \]
\[ D = \text{diameter of the drum [m]}, \]
\[ n = \text{number of roller drum passes}. \]

Table 4 shows the contribution of the different parameters to the predicted void content. The influence on the void content is calculated as the difference in void content using the maximum and minimum value of the input parameter considered.

The table clearly shows that in spite of the fact that all kind of factors have an influence on the void content of PAC mixtures, proper compaction seems to be the most essential one. It seems therefore appropriate to equip rollers with devices that measure automatically the density of the mixture to ensure that an as homogeneous as possible density and void content are obtained.

**Table 4: Influence of the individual parameters on the void content**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min. value</th>
<th>Max. value</th>
<th>Influence on void content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_1 ): Temperature of mix at plant</td>
<td>(^{[\circ C]})</td>
<td>148</td>
<td>165</td>
<td>1.58</td>
</tr>
<tr>
<td>( X_2 ): % Bitumen</td>
<td>[% m/m]</td>
<td>3.8</td>
<td>4.4</td>
<td>0.49</td>
</tr>
<tr>
<td>( X_3 ): % Aggregate on sieve C8</td>
<td>[% m/m]</td>
<td>59</td>
<td>68</td>
<td>0.45</td>
</tr>
<tr>
<td>( X_4 ): % Filler</td>
<td>[% m/m]</td>
<td>3.8</td>
<td>6.6</td>
<td>0.64</td>
</tr>
<tr>
<td>( X_5 ): Roller characteristic</td>
<td>[kN/m(^3)]</td>
<td>97</td>
<td>700</td>
<td>5.91</td>
</tr>
</tbody>
</table>

Note: the temperature at the plant was taken as explaining variable and not the temperature in the hopper or the pavement surface during compaction because it was much easier to take temperature measurements at the plant than on site; furthermore table 11 shows that, because insulated trucks were used, only a small temperature drop occurred during transportation.

4. **Aspects related to double layer porous asphalt mixtures**

It is a well known fact that double layer PAC provides an even higher noise reduction than the traditional single layer PAC. The question however is what the best gradation for top and bottom layer is to obtain the best result in terms of noise reduction, permeability and skid resistance. In this research (6), which was done in close cooperation with Koninklijke Wegenbouw Stevin contractors, only attention was paid to noise reduction and permeability.

Until now 4/8 mm sized aggregate is used in the top layer and 11/16 mm in the bottom layer. The problem however is that in the interface between top and bottom layer the finer particles of the top layer fill the pores at the top of the bottom layer resulting in a lower void content and as a result in a lower absorption coefficient and lower permeability. A lower permeability will make the PAC layer more prone to clogging and also problems with water drainage during wet weather might occur.
As a first step in the analysis, double layer PAC samples were made with various gradations for the top and bottom layer. These samples were prepared using gyratory equipment. Further differentiation was made in “hot on hot” and “hot on cold” specimens. This was done in order to investigate the effect of using a so called “double layer” paver which allows paving of two layers on top of each other at the same time. The void content over the height of the sample was then determined by means of CT scanning. Figure 6 and 7 as well as table 5 show some results.

Table 5 and figure 7 clearly show that the reduction of the void content in the interface between the top and bottom layer of a double layer PAC can be quite significant.

Noise reduction depends on the amount of noise that is produced and the amount of noise that is absorbed. The noise production depends amongst other things mainly on the texture of the pavement surface; a rougher surface will produce more noise. The noise absorption depends amongst other things on the void content of the wearing course. For a given thickness and gradation, the absorption will increase with increasing void content. These observations clearly show that the capabilities of a road surface to reduce noise should always be rated in terms of production AND absorption. Noise absorption measurements clearly showed that the void content in the interlayer between the top and bottom layer of double layer PAC strongly influenced the noise absorption. This is shown in figure 8 where the absorption characteristics are given of the double layer PAC mixtures shown in figure 7.

Figure 6: CT scan pictures of a double layer PAC; in the N(orth)W(est) corner the complete sample is shown, the NE corner shows a slice through the top layer, the SE corner shows a slice through the bottom layer, the SW corner shows a slice through the interface between top and bottom layer.
Mean void content 2/6 11/16 hot on hot
Mean void content 2/6 11/16 hot on cold
Height [mm]
Void content [%]

Figure 7a: Void distribution over the height of a 2/6 mm top layer (from 0 – 30 mm) on a 11/16 mm bottom layer

Mean void content 4/8 8/11 hot on hot
Mean void content 4/8 8/11 hot on cold
Height [mm]
Void content [%]

Figure 7b: Void content over the height of a 4/8 mm top layer on top of a 8/11 mm bottom layer
Table 5: Minimum void content in interlayer between top and bottom layer of double layer PAC made with different gradations

<table>
<thead>
<tr>
<th></th>
<th>2/6 mm top layer</th>
<th>2/6 mm top layer</th>
<th>4/8 mm top layer</th>
<th>4/8 mm top layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hot on hot</td>
<td>Hot on cold</td>
<td>Hot on hot</td>
<td>Hot on cold</td>
</tr>
<tr>
<td>8/11 mm bottom</td>
<td>14.3 %</td>
<td>17.5 %</td>
<td>18.8 %</td>
<td>20.0 %</td>
</tr>
<tr>
<td>11/16 mm bottom</td>
<td>11.2 %</td>
<td>12.8 %</td>
<td>16.8 %</td>
<td>18.3 %</td>
</tr>
<tr>
<td>16/22 mm bottom</td>
<td>11.6 %</td>
<td>11.2 %</td>
<td>14.2 %</td>
<td>16.4%</td>
</tr>
</tbody>
</table>

Figure 8a: Noise absorption characteristics of a 2/6 mm PAC on top of a 11/16 mm PAC bottom layer
The results shown in figure 8 tend to indicate that the gradation of the top PAC layer should be carefully designed with respect to the gradation of the bottom PAC layer. However, also the noise production part must be considered. In order to determine the effect of a finer texture relative to a higher absorption, use was made of results of a research project of the Road and Hydraulics Engineering Division of the Dutch Ministry of Transport. On a particular project, double layer PAC test sections were laid, most of them having a 4/8 mm top layer while a few had a 2/6 mm top layer. In all cases the bottom layer was an 11/16 mm bottom layer. Results of noise measurements showed that the finer graded surfaces produced on average 1.5 dB(A) less noise when traveled by person cars driving at a speed of 120 km/h. Furthermore the absorption coefficient showed to have only a limited influence on the noise level as measured. Figure 9 shows some results.

From this figure it can be concluded that the negative effect on noise reduction of a lower void content in the interface between top and bottom layer in case of a 2/6 mm PAC layer on top of a 11/16 mm PAC bottom layer is only marginal when the noise production as measured is considered. This implies that reduction of the noise production by means of a finer texture is more important than a higher absorption of noise.
Noise level [dB(A)] in relation to texture and absorption coefficient

![Graph showing noise level in dB(A) vs. absorption coefficient (%)](chart)

**Figure 9: Noise level produced by person cars when driving at a speed of 120 km/h in relation to the gradation of the top layer and the absorption coefficient**

The question still remains whether or not a lower void content at the interface between top and bottom layer has a negative influence on the permeability of the double layer PAC. In order to investigate this, the vertical permeability of various double PAC mixtures was measured as well as the influence of “hot on hot” and “hot on cold”. Figure 16 shows some results.

Figure 10 shows that finer graded 2/6 mm top layers resulted in a lower permeability. Furthermore it appears that for the samples with a 2/6 mm top layer, the permeability tends to increase with increasing void content of the interface. For the samples with a 4/8 mm top layer this is less obvious. These conclusions are of course not surprising. The fine graded 2/6 mm top layer will have a high porosity but the pores are smaller than in case of a 4/8 mm top layer resulting in a lower permeability.

In order to be able to compare these results with the permeability for single layer PAC, these measurements were also performed on two cores of single layer PAC taken from the road. These cores had a void content of around 20 % and the permeability showed to be around $4.2 \times 10^{-3}$ m/s, slightly higher than the permeability determined in this research for samples with a 2/6 mm top layer.

From these results it was concluded that the permeability could be an issue when such fine graded wearing courses are selected for noise reducing purposes. However, more research on this aspect is certainly needed to arrive to definite conclusions.
Figure 10: Effect of the void content in the interface, and the gradation of the top and bottom layer on the permeability

5. Conclusions

The following conclusions have been drawn:

1. The variability in void content, bitumen content and characteristics of the recovered bitumen as observed on a particular project was high. It is believed that this has partly to do with the sensitivity of PAC mixtures for segregation and dripping off (drainage) of the bituminous mortar from the stone skeleton.

2. The resilient modulus of PAC samples prepared in the lab was dependent on the void content in the mixture but it made a difference whether the variation in void content was obtained by varying the compaction temperature or by varying the stone content.

3. There was a clear relation between the void content of samples taken from the road and the resilient modulus. Nevertheless the relation was too weak and it showed too much scatter to be used for quality control purposes.

4. The void content of PAC mixtures as laid depends mainly on the compaction effort, temperature is of secondary importance.

5. The void content in the interface between the top and bottom layer of double layer PAC depends on the differences in gradation between top and bottom layer.

6. The void content in the interface between top and bottom layer of double layer PAC influences the vertical permeability and the noise absorption characteristics.

7. Noise production can be significantly reduced by selecting a fine textured top layer for double layer PAC.
8. When selecting a PAC mixture for noise reducing purposes, both the noise production and absorption have to be taken into account.

6. References