Causes of premature ravelling with single-layer Porous Asphalt

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ABSTRACT: In the Netherlands the average service life of single-layer Porous Asphalt (PA) 0/16 with standard 70/100 pen grade bitumen is 11 years for the slow lane and 16 years for the fast lane. The end of the service life is mainly caused by the loss of coarse material from the surface (ravelling). However, sometimes the service life is much shorter. This paper discusses an investigation into the causes of premature ravelling problems of a PA road section, which occurred within three years after laying.
To find the causes of the premature failing of this road section the mix design, the quality control of the contractor, the end control and the quality of the applied materials were investigated. As a special action the quality of the stone fraction was determined with a petrographic and mineralogical study.
The degree of ravelling on the PA road section was measured under traffic with a laser. Based on the laser measurements the remaining service life was predicted.
From the research results it can be concluded that the premature ravelling is caused by a complex of factors of which the poor quality of the coarse material plays a crucial role. Recommendations are given to prevent premature ravelling problems in the future.

Keywords: Porous Asphalt, ravelling, coarse material, hydrated lime, laser measurements

1. Introduction

In the Netherlands the average service life of single layer Porous Asphalt (PA) with standard 70/100 pen grade bitumen is respectively 11,8 and 16 years for the slow and fast lane [1]. However, sometimes the service life is much shorter or ravelling starts even just after laying. The end of the service life is determined by ravelling, the loss of stones from the surface.
On road section A76 in Limburg in the south of the Netherlands premature damage occurred. Beginning of ravelling and potholes on this road section were determined one year after laying and after two years the contractor had to repair potholes for safety reasons. In this road section two different standard PA mixes were applied. Both PA mixes had the same coarse material, crusher sand, and bitumen, only the type of filler and the percentage of bitumen were different (see table 1). Rijkswaterstaat (RWS) carried out an extensive investigation to find the cause of this phenomenon.
Laser measurements were done to determine the degree of ravelling and to determine if the ravelling increased in time. With input data from the laser measurements the remaining service life could be calculated. In this paper the research into the cause of premature ravelling is reported.

2. History

In 2003/2004 both the slow and fast lanes including the emergency lane in two directions of a part of the motorway A76 had to be covered with a new layer of PA 0/16.
The project was awarded to the contractor offering the lowest price.
The contractor proposed a mix design according to the Dutch National specifications [17] to the road agency. After approval the contractor started paving. During construction (halfway) the contractor proposed for unknown reason a new mix design and after positive reaction the contractor used the new mix for the rest of the project.
Already after 1 year service life the first damage was observed. Damage showed up in small potholes and initial ravelling randomly over the width of the road surface. This is very unusual, because experience has learned that the first ravelling starts to show up in the slow lane after 5 and 8 years of service.
The premature damage has been documented in a report with a photo reportage [2]. In December 2004 Automatic Road Analyser (ARAN) laser measurements were used to assess the severity of ravelling of the whole project and also to determine the other damage types (potholes) with video.
The road agency has confronted the contractor with the premature damage and claimed that it developed before the standard guarantee period of 3 years has passed. Together with the contractor the locations with damage were determined based on the video tapes from the ARAN. The damaged locations were repaired before the winter of 2004 for safety reasons. The contractor repaired all the damaged locations at his own cost. Cost included traffic measures, cleaning and drying of the holes, filling of the holes with special mortar and adhesive and placing fine split on the PMB (polymer modified binder of the mortar) to satisfy skid resistance requirements. Figure 1 shows an example of a location with holes and figure 2 gives an impression of the cleaning and drying of the holes. The surface surrounding the repaired holes was treated with a special developed emulsion to prevent accelerated stone loss. The contractor could not explain the premature damage of the PA. The road agency decided in good consultation with the contractor to try and find the cause of the premature damage. A research plan was made to try and find the cause.
During 2005 again laser measurements were carried out on the total road section to determine if the ravelling was stabilised or increased.

Figure 1: Example of potholes in A76

Figure 2: Cleaning and drying of potholes in A76

3. Approach to find the cause of premature ravelling

Normally the mix design data are compared with the data of the product acceptance from field cores. In the Netherlands product acceptance includes control of five parameters: grading, bitumen content, in place air-voids, degree of compaction and layer thickness.
In this case extra research was necessary to find the reason behind the premature ravelling. The extra research is explained below.

In consultation with the contractor it was decided to drill extra cores at “sound” and “bad looking” spots.
These extra cores were basically used to investigate the cause of premature failure of the PA. The PA cores were horizontally cut in two parts to investigate if segregation could be the cause. The grading, bitumen content and air-voids were determined for the upper and lower parts. Ravelling takes place at the surface, so it is very important that the bitumen is homogeneously divided.
As mentioned above during standard product acceptance the quality of the materials is not investigated. In this case it was decided to determine:

- the penetration of the recovered bitumen,
- the Rigden voids and the percentage $Ca(OH)_2$ of the fraction < 63 μm (filler),
- the quality of the stone fraction by measuring the resistance to crushing, petrografic and mineralogical composition . The material used for this investigation was not recovered from the PA cores, because they could have been influenced by the recovery process, Extra samples were taken at the asphalt plant after the production process.

The extra tests on bitumen, filler and stone fraction were done to find out if to the quality of the basic components could be the reason for premature ravelling.
From some PA cores thin sections were prepared for image analysis to have an impression at micro-level.
Also the process control from the contractor was checked on abnormalities.

In figure 3 an overview is given of the total research carried out.

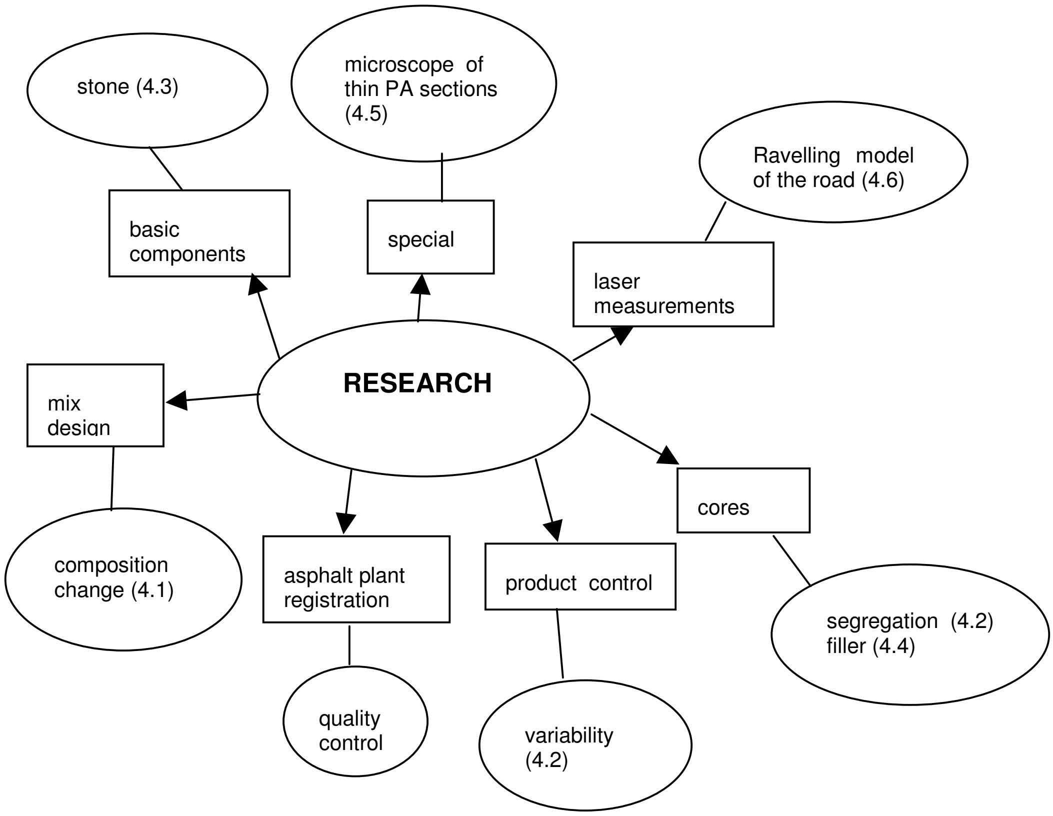


Figure 3: Overview of the total research.

4. Results of the investigations and findings

4.1 Mix design

In table 1 the reference compositions are given for the two PA mixes. The stone fraction consists of Andesit. In the Netherlands no experience was available with this quarry material. The sand fraction consists of crusher sand. For the first and second mix design respectively Rhecom 60 and Rhecal 60 (both middle sort fillers with hydrated lime) were used.
In both mix designs the same pen grade 70/100 was used. The bitumen percentage in table 1 is expressed as the percentage on 100% mineral aggregate.

Table 1: PA mix design

	1st mix design 29 August 2002	2nd mix design 5 June 2003	Requirements RAW 2000 [17]		
On sieve			Min.	target	Max.
C16	2.0	2.0	0.0		7.0
C11.2	22.1	21.8	15.0		65.0
C 8	56.3	56.4	50.0		65.0
C5.6	75.6	74.9	70.0		85.0
2 mm	84.4	84.5		85.0	
63 µm	95.5	95.3		95.5	
Bitumen “on”	4.3	4.5		4.5	

The first mix design shows that the mix just satisfies the requirements for PA. Actually when using a fly ash containing filler like Rhecom 60, it is recommanded to add 0.2% extra bitumen because this filler type absorbs bitumen [3]. Halfway the job the contractor proposed to change the mix. In stead of Rhecom 60 the lime stone containing filler Rhecal 60 was applied and the bitumen content was increased with 0.2%. This is quite remarkeble. Possibly the contractor wanted to correct the bad acting PA mixture in this way. In [4] the grading, the bitumen content and air-voids of the product acceptance were analysed. The product acceptance was done by a certified laboratory [5,6].

4.2 Results of research on the extra cores

In [7] the results of the research on the extra cores are reported. In table 2 the locations of the cores and the condition of the PA wearing course are given. From table 2 it becomes also clear that both mixes gave problems. All cores were drilled on the motorway direction Heerlen. Unfortunally no registrations of the batch mix plant of the productions for these locations were available.

Table 2: Location of cores for extra research (JAN AANPASSEN).

km	Condition	Mix design	Construction
HHR km 12.756	Unsound	29 August 2002	9/10 October 2002
HHR km 12.96150	Sound	29 August 2002	9/10 October 2002
HHR km 12.14125	Sound	5 June 2003	19 October 2003
HHR km 12.189.50	Unsound	5 June 2003	19 October 2003

The PA layer of the 22 cores from the 4 locations were cut horizontally in two equal parts and investigated, so in total 44 half cores (parts) were investigated. From each part the air-voids, the bitumen percentage and the percentage material < 63 µm was determined. The grading was not determined, because drilling and sawing to divide the cores could have influenced the grading.
In figure 4 an overview is given of the investigation on the cores.

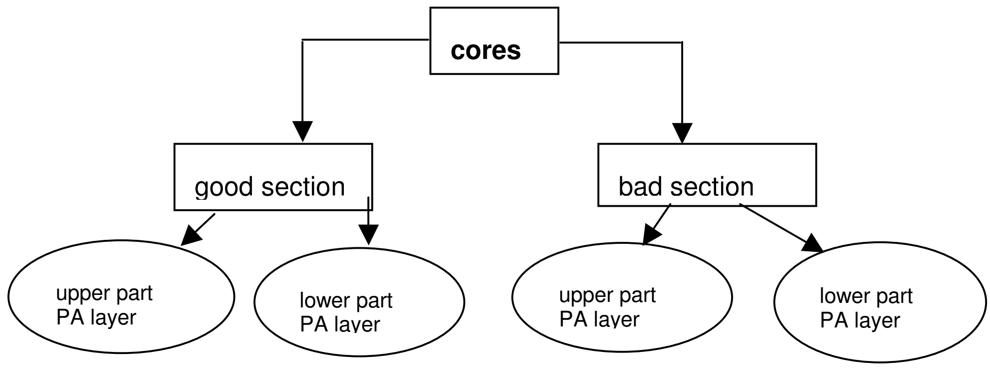


Figure 4: Overview of research on the cores

In figures 5 and 6 examples are given of the bitumen content and the percentage filler < 63 µm in upper and lower part of the PA layer. More detailed information is given in [7].
From a study carried out at Delft University of Technology [8], it can be concluded that PA mixes with a bitumen percentage of < 4 % "on" and air-voids content > 27 % will probably suffer premature ravelling. The results reported in [7] show that 4 of the investigated 44 parts have an air-voids content above 27%. 2 of these 4 parts have an air-voids content above 30 %. 16 of the 44 investigated parts have a bitumen content below 4 %. 13 of them are top parts. 9 of these 13 parts were drilled at locations HHR km 12.18950 and HHR km 12.756 which were in unsound condition [2].

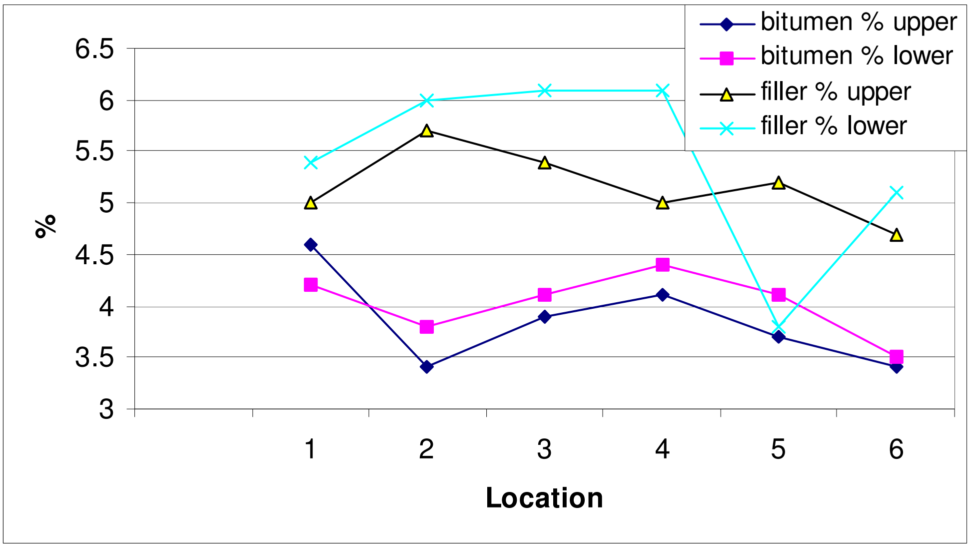


Figure 5: Example of variation in bitumen content and filler smaller than 63 µm over the lane width (location cores) at km 12.18950 for the top parts of the cores.

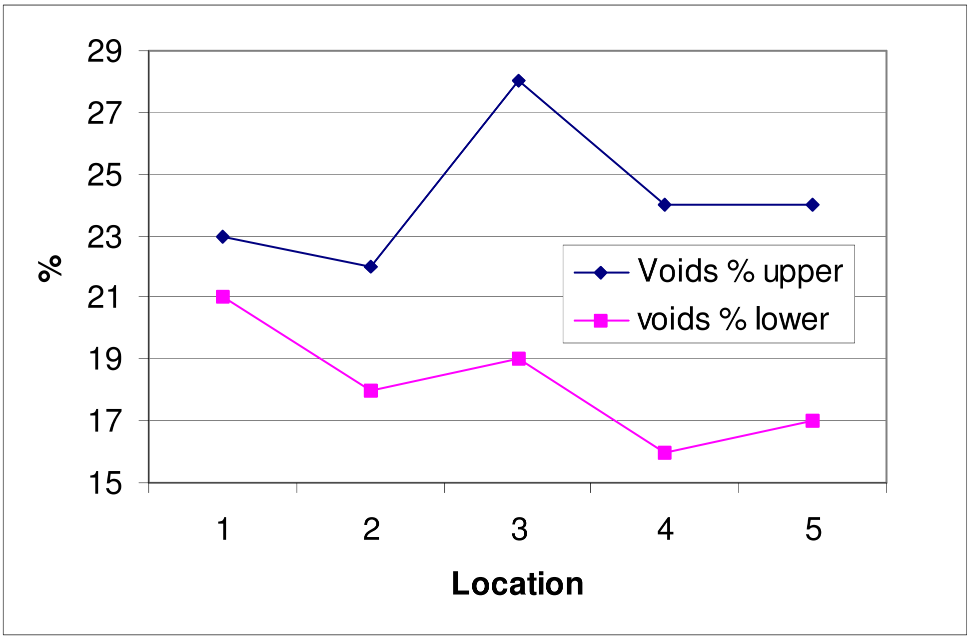


Figure 6: Example of variation in air-voids content of top and bottom parts over the lane width (location cores) at km 12.14125

Because the parts with very high air-voids are not linked to a very low bitumen content, it can be concluded that the degree of the composition of 20 of the 44 was in such a way that only a low service life can be expected.
The results also showed that from 22 parts of location HHR 12.756 and HHR 12961.50 (mix design 29 August 2002) 19 parts had a lower bitumen content than the 4.3 % of the reference mix. 21 of the 22 parts had a filler content(< 63 µm) above 4.5 % as was used for the reference mix.
19 of the 22 investigated parts of locations HHR 12.14125 and HHR 12.18950 (mix design 5 June 2003) had a bitumen content below the target 4.5 % and 21 parts had a filler < 63 µm content above 4.7 % (= target).

Though the maximum deviations of a mix normally are determined of a whole core in comparison with the target mix, in this case also the maximum allowable deviations are applied on the the top and bottom parts.
In that case the deviation of the average bitumen content in comparison with the target composition may be +0.25 % and -0.35 % (n = 11). The deviation of the average content of filler may be 0.9 %.
The mix design of 29 August 2002 allows for an average minimum bitumen content of 3.95 %. The average bitumen content of the top parts is 3.86%, so this is too low. The average bitumen content of the the bottom parts is 4.14%, which is low but within the tolerances.
For the mix design of 5 June 2003 an average minimum bitumen contant of 4.15 % is allowable. The average bitumen content of the top parts is only 3.86 %, which is very low. The average bitumen content of the bottom parts is only 4.18 %, which is also very low but just within the tolerances.
Likewise the filler content of the mix design of 29 August 2002 must be lower than 5.4 %. The filler content of the top parts is however 5.47 %, so the deviation is too much. The average content of filler of the bottom parts is 5.21 %, which is within the tolerances.

For the mix design of 5 June 2003 the maximum filler content is 5.6 %. The average filler content of the top parts is 5.15 %, which is acceptable, while the average fine content of the bottom parts is 5.64 %, which is outside the tolerances.
It can be concluded that the lower bitumen content in combination with the higher filler content will result in a dry mortar, which will have a negative effect on the resistance to ravelling.

4.3 Results of research on the stone fraction
The quality of the stone fraction Andesit was determined at Delft University of Technology. In [9] the results are reported. On the stone fraction the methylene blue test, the Los Angelos test, the flakiness index and minerarological composition were done.
The methylene blue tests were also done on material > 2mm recovered from the cores. In table 3 the most important results are summarised.

Table 3: Summary of the tests on the Andesit stone fraction according to EN 13043

	Stone fraction asphalt plant			Recovered stone fraction	
Fraction	4/8	8/11	11/16	Cores 1 and 4	Cores 2 and 3
Los Angelos (%)	12,3	10.2	10,1		
Methyleen blue g/kg)	8,7	7,6	9,1	9,5	9,5
Flakiness index	20,4	12,2	6,8		
PSV		57		56	

The most important facts and observations from [9] are:

- The resistance to crushing meets the requirments for coarse materal for PA as described in the national Standard RAW 2000 [17];
- Even after repeated washing with tap water the stone fraction colours red brown, while the colour of the fresh not weathered Andesit is beige to dark grey;
- The red colour is a consequence of the many iron oxides, which were created during conversion processes (weathering);
- During the conversion processes also clay material was created, causing high methylene blue values;
- From [10] these high methylene blue values can be judged from “marginal” to “unsound” material;
- Röntgen diffraction (XRD) analysis show that the investigated coarse material consists of quarts, anorthite (Ca-rich plagioklaas), augit (a pyroxene), smectit (a swellable clay!) and hectit;

- The precense of (fine graded) hematite and smectite shows that the investigated sample is weathered;
- The presence of conversion products have as aspected a negative influence on the bonding between bitumen and the coarse material;
- Especially when the material is exposed to moisture (easily in PA), moisture absorption by clay materials wil cause further weakening;
- In combination with segregation of the bitumen early bonding problems can cause damage like ravelling.
- From microscopic description in combination with XRD analysis it appears that the tested stone fraction is not Andesit, but probably Tefrit.

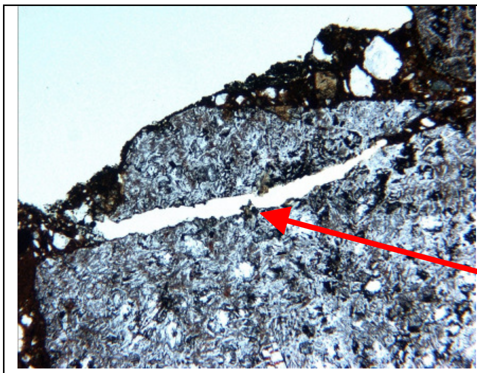
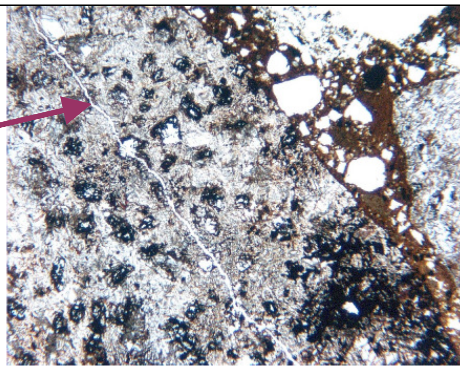
In summary it can be concluded that the quality of this Andesit quarry material seems to be dubious with regards the bonding between bitumen and aggregate and this can be the cause premature ravelling problems. The presence of swelling clay as well as the fact that the material is weathered can be the cause of the very short service life of the PA.

4.4 Results of the filler research

To improve the bitumen properties, the bonding between bitumen and the coarse material and to decrease segregation of bitumen PA has to contain a so-called middle sort filler (high Rigden voids) with hydrated lime (minimum of 25%). In [11] it was determined that the amount of hydrated lime of recovered material < 63 µm from 4 specimens was respectively 4, 3, 4 en 4 %; these percentages are too low compared to the normally accepted amount of at least 14 %. With these small percentages of hydrated lime the possiblility of segregation and debonding will increase.
This low amount of hydrated lime can be caused by a too low percentage of hydrated lime in the factory filler or adding too low amount of factory filler together with a higher amount of baghouse dust. It is also possible that part of the hydrated lime has reacted with the stone in a different way.The first possibility can be excluded, because factory filler is a certified product in the Netherlands. The second possibility is plausible and it is not expected that so much lime can react with the relative low surface of the stone fraction.

4.5 Results on thin section

In [12] results of a limited research on thin sections carried out by Danish Road Institute (DRI) were reported. The thin sections were prepared of two cores taken from the A76. From figure 7 and 8 it can be seen that the cracks that are present in the aggregate probably developed after mixing because they are not filled wth bitumen.

	Crack in aggregate Crack without bitumen	
Figure 7: Aggregate crushed after mixing		**Figure 8:** Crack in aggregate

The cracks probably developed during the compaction process or due to traffic loading. These cracks are remarkable because the resistance to crushing determined with the Los

Angelos test [9] was good. The resistance to crushing was not determined on material recovered from cores but material delivered by the contractor (asphalt plant samples). It is also possible that the material only contains some weak parts. The information from the thin sections is not enough to draw general conclusions. Damage due to high temperatures before mixing could only be a possibility in case the crack did not break the stone during mixing.

4.6 Results of laser measurements

Laser measurements with the ARAN were carried out to determine the size and the severity of the amount of ravelling on the A76 road section. To compare these results with good acting PA (the same mix) also measurements were carried out on road sections of the same age on the A50. Both road sections were 2 to 2½ years old. The results of the A50 hardly show ravelling. The results of the A76 show the beginning of ravelling, which normally starts 6 to 8 years after laying.
The light, moderate en serious degree of ravelling observed is translated in one number to get a total view of the degree of ravelling. This number, the equivalent amount of moderate damage (Meq) is calcultated according the CROW method described in [13]:

$Meq = 0.25 * L + M + 5 * E$ In which: L = the amount of light damage,
M = the amount of moderate damage,
E = the amount of serious damage.

In figure 9 an example is given of the results of laser measurements carried out before and after the winter 2004/2005. It is clear that the Meq after one winter did not increase dramaticly. At some spots the Meq even decreased, but that is probably related to the local reparations by the contractor.

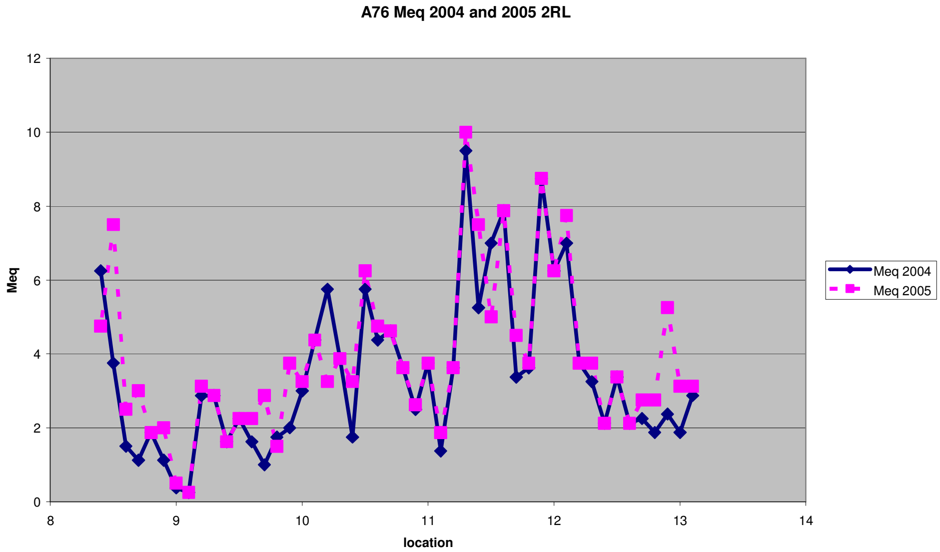


Figure 9: Equivalent moderate ravellig (Meq) measured before and after the winter 2004/2005 on lane 2RL of the A76.

Based on the Meq and the age of the PA it is possible to calculate the remaining service life, using the information given in [1]. The remaining service life matrix plays an important role in those calculations.
The use of table 4 must be explained for clearity. Although this table is valid for dense asphalt mixes with voids contents from 3 to 6%, it can not be applied for PA with void contents around 20%, because of that higher amount of void content PA is more sensitive for ravelling than dense asphalt mixes. On the other hand one can argue that the underlaying model

describes a physical degradation process, by which it is not so relevant what type of asphalt it concerns

Table 4: Remaining service life matrix for ravelling according to [14].

Meq	≤ 3 years	4 – 6 years	7 – 9 years
Meq ≤ 1.25	> 5	> 5	> 5
1.25 < Meq ≤ 2.5	3 - 6	> 5	> 5
2.5 < Meq ≤ 5	2 - 4	3 – 6	4 – 9
5 < Meq ≤ 12.5	0 - 3	2 – 5	3 – 7
Meq > 12.5	0 - 2	1 – 3	2 – 5

Despite the remarks made above the matrix was used to calculate the remaining service life. Starting point was the Meq as calculated based on the laser measurements of 2005. Also an age ≤ 5 years was assumed. If the Meq is greater than 12.5, the remaing service life is set to 0 year. If the Meq is ≤ 1.25 the remaining service life is set to 10 year. This number is based on information given in [15]. In [15] it is reported that the average service life of carriageway wide laid PA in Limburg is 10.7 year for the slow lane (right lane) with a standard deviation of 1.6 year.
In [4] the average service life of the investigated road section of the A76 is calculated in this way. An example of the calculated remaining service lifes is given in figure 10.

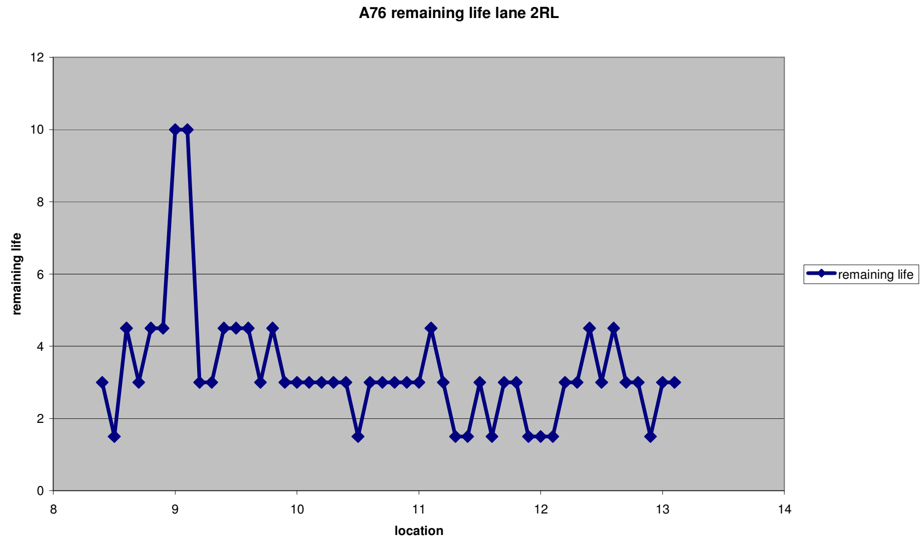


Figure 10: Example of remaining service life of lane 2RL of the A76

With the assumption that the service life as observed in Limburg [1] is according a normal distribution, this means that there is a chance of 14 % that the service life is less than 10.7 – 3 * 1.7 = 5.6 year. With the age of the PA on the A76 in mind and the found service lifes it can be concluded that the PA on the A76 will not achieve a service life of 5.6 year and will perform very poor.

4.7 Mix plant registrations

The available mix plant registrations can be partly connected to the observed damage as reported in [2]. In relation to the mix plant registration the following remarks can be made:

- The amount of added filler and baghouse dust agrees with the targets of the reference mix;
- It is remarkable that in the mix design baghouse dust is used and from the mix plant registration can be noticed that hardly baghouse dust is dosed.

5. Conclusions

The observed damage was much more extensive than expected for a normal PA.
The cause of the early damage must be attributed to a combination of the following facts:
- The quality of the used coarse material is unsuffiecient.
- The contractor has consequently dosed to little bitumen
- The bitumen is segregated. As a consequence of this the top part of the PA has too little bitumen, which is alarming low.
- The amount of filler is in comparison with the bitumen content, by which the too dry mortar becomes brittle and will have bad bonding properties.
- Indications are found that the hydrated lime content in the filler is too low, which can lead to segregation and bonding problems.

Laser measurements are very suitable to measure the degree of ravelling under traffic and to follow the degree of ravelling in time.

6. Recommendations

- It is not sufficient to judge the quality of the coarse material during the usual quality control (density, grading).
- As the quality of PA is strongly influenced by the coarse material quality, one may expect from an expert contractor to determine the quality in more detail, especially for a new type of stone. Important are the investigations into weathering, swelling clay, crushing, weak parts and extensive dust production. It is recommended to check the quality of the coarse material during the production process more frequently.
- Extensive segregation of bitumen (draining) in PA is disastrous for durability, so it is important to keep sufficient bitumen at the top of the PA to achieve a good resistance to ravelling. It is proven in [16] that PA mixes with 1% more bitumen (so-called PA plus) wil have a 2 to 3 year longer service life in case draining can be prevented. It is proposed to focus in the mix design on enough bitumen in the top part of the PA layer.
- It is recommended to keep the amount of baghouse dust as low as possible in PA. As a consequence of to high content of baghouse dust, too little factory filler is dosed indicating too low hydrated lime content in the mix. This will result in a shorter service life, because baghouse dust act as a weak filler (low Rigden voids) causing segregation.

Remark.
The results are not mentioned in this paper, but almost 3 years after opening the road for traffic the investigated road section did not meet the requirements for skid resistance any more. Due to that the contractor had to mill the PA and lay back new PA.
Because skid resistance problems with PA with quarry material with a polishing stone (PSV) value of 57 after such a short time after laying is very unusual, this indicates that the stone quality plays a dominant role in the bad performance of this PA.

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