Asphalt mixture performance and testing

Longer lifespan of Porous Asphalt due to the addition of homopolymer HT polyacrylonitrile fibres

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Abstract

The Dutch national roads agency Rijkswaterstaat (RWS) is constantly looking for more durable and more cost- effective noise reducing wearing courses for motorways. When more noise reduction is required than single layer Porous Asphalt 16 (PA 16) more and more two-layer Porous Asphalt (TLPA) is applied. Standard TLPA consist of a 25 mm thick PA 8 and a 45 mm PA 16. In order to extend the lifetime of the standard top-layer PA 8, which contains polymer modified bitumen (PmB), test sites were constructed with PA 8 with pen grade 70/100 bitumen and homopolymer high tenacity polyacrylonitrile fibres. From yearly monitoring it appeared that PA 8 with pen grade 70/100 bitumen performed much better than the standard PA 8 with PmB. The expected lifetime is 4 years longer. To find out why the field performance of this alternative PA 8 mixture is much better, lab test were carried out on lab prepared samples and on 6 year old material from core out of the test sites. This research consisted of microscopic investigation on thin slices, DSR (master curves and fatigue resistance) measurements on mortars and numerical calculations. In this paper the results of the lab test are discussed and the results of the monitoring of the investigated test sites are given.

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1. INTRODUCTION

After successful experiments with test sites since 1972 the policy in the Netherlands is to apply only noise reducing surface courses on motorways since 1990. Mostly Porous Asphalt 16 (PA 16) is applied, but also two-layer PA and thin noise reducing mixtures are used. More than 90% of the total motorways have now PA as surface course. Besides the very good noise reduction, PA has also other advantages such as:

- good water storage and drainage capacity. This reduces splash and spray water during precipitation. As a consequence of that road markings are better visible and no aquaplaning can happen
- a very good resistance to permanent deformation due to the stone-to-stone contact of stone skeleton of PA
- a good quality of the run-off water. The traffic causes a self-cleaning effect during precipitation in the traffic lanes, but the clogging of traffic and environment is stored in the air voids of the PA emergency lanes. Because the emergency lanes are cleaned twice a year, the quality of run-off water of PA is much better in comparison with dense surface courses.

From the first start the binder used in PA 16 was a paving grade (pen grade) 80/100 bitumen, later on pen grade 70/100 bitumen was used, and the bitumen content was 4.2% in the total mixture. To extend the service life of PA 16, 26 PA test sections were constructed from 1988 to 1993 on ringway A10 Amsterdam [1]. One of the ideas was that PmBs could help to extend the lifespan, so SBS-, EVA- and rubber modified bitumens were applied in PA 16 test sections with bitumen percentages of 4.2 and 5.2%. In the PA 16 mixtures with 4.2% pen grade 80/100 bitumen no drainage inhibitors were necessary, but in the case of PA 16 mixtures with 5.2% pen grade 80/100 bitumen organic and inorganic drainage inhibitors were added to limit bitumen drainage. In the PA 16 mixtures with polymer modified bitumens (PMBs) no drainage inhibitors were necessary, because of the higher viscosity of those binders. Those PA test sections were monitored by yearly visual inspections to follow the degree of ravelling until end of lifespan. The conclusion of this research was that the PA 16 mixtures with 5.2% bitumen had a 2 to 3 years longer lifespan than the PA 16 mixtures with 4.2% bitumen and it did not matter whether the bitumen was modified or not. Based on this research Rijkswaterstaat (RWS), the Dutch national roads agency, decided to apply PA 16 with 5.2% pen grade 70/100 bitumen as the standard surface course for Dutch motorways for new constructions and carriageway wide maintenance. This standard mix is called PA 16+ (in Dutch DZOAB 16) and as a drainage inhibitor mostly cellulose fibres are used. So, the Netherlands is the only country in the world where pen grade bitumen is used in PA, in all other countries PmBs or high modified PmBs are used as a binder in PA.

Since 1989 also experiments were carried out with two-layer PA test sections consisting of a 25 mm thick top-layer PA 8 with 25% air void content and a 45 mm thick PA 16 bottom-layer with 25% air void content. From the very first application always PmBs have been applied in PA 8 mixtures, despite the gained knowledge in [1]. It was generally assumed that PmBs would make a positive contribution to the lifespan of PA 8. Only in 2005 arose an opportunity to construct a first test site on motorway A15 nearby Leerdam with the top-layer PA 8 of two-layer PA with pen grade 70/100 bitumen as a binder instead of a PmB. To ensure that this mixture would not fail prematurely, Rotating Surface Abrasion Test (RSAT) [2] tests were carried out on lab produced slabs. To take care for a good homogeneous distribution of the pen grade 70/100 bitumen mostly cellulose fibres are added. Because in PA 16 test sections [3] good experience had already been gained with homopolymer high tenacity polyacrylonitrile fibres (called “special fibres” in the rest of the paper), not to be confounded with acrylic fibres, the same type of fibres were used in the PA 8 mixtures with pen grade 70/100 bitumen and PmB. It was expected that these special fibres, due to the high specific surface, would work as a good drainage inhibitor as well as a reinforcement of the mortar bridges of the PA 8. The special fibres could be delivered in a length of 3.2 and 6.4 mm. In table 1 the results are given of carried out RSAT tests. All 4 investigated PA 8 mixtures contained the same constituent materials, except the binder and fibres, and the same binder content (5.75%).

Table 1: RSAT results

Investigated mixture	Binder type	Homopolymer high tenacity polyacrylonitrile fibre length (mm)	Loss of stones after 24 h (g)	Average loss of stones after 24 h (g)
Standard PA 8	PmB (Cariphalte XS)	-	9 and 6	7.5
Modified PA 8	PmB (Cariphalte XS)	6.4	5.4 and 4	4.7
Modified PA 8	Pen grade 70/100 bitumen	6.4	45 and 47	46
Modified PA 8	Pen grade 70/100 bitumen	3.2	22 and 14	18

In figure 1 the average RSAT results (x), average results plus two times the standard deviation (X+2 st. d) and average results minus two times the standard deviation (X-2 st. d) are given. It can be seen that addition of 6.4 mm long fibres to the standard PA 8 mixture with PmB did not improve the ravelling resistance.

Because RSAT with PA 8 with pen grade 70/100 bitumen with 3.2 mm long special fibres acted much better in the RSAT than the PA 8 with pen grade 70/100 bitumen with 6.4 mm long special fibres, the mixture with the 3.2 mm long special fibres was chosen for the test site although the results were a bit less than the standard PA 8 with PmB. Apparently the fibre length must be adjusted to the maximum grain size of used PA. Because only 6.4 mm long fibres were available for a second test section with fibres, it was also decided to construct a test site with PA 8 with PmB with 6.4 mm long fibres, although better results were expected of 3.2 mm long fibres. Also 4 other PA 8 mixtures with PmB not containing fibres, but modification in the grading, were constructed, see table 3.

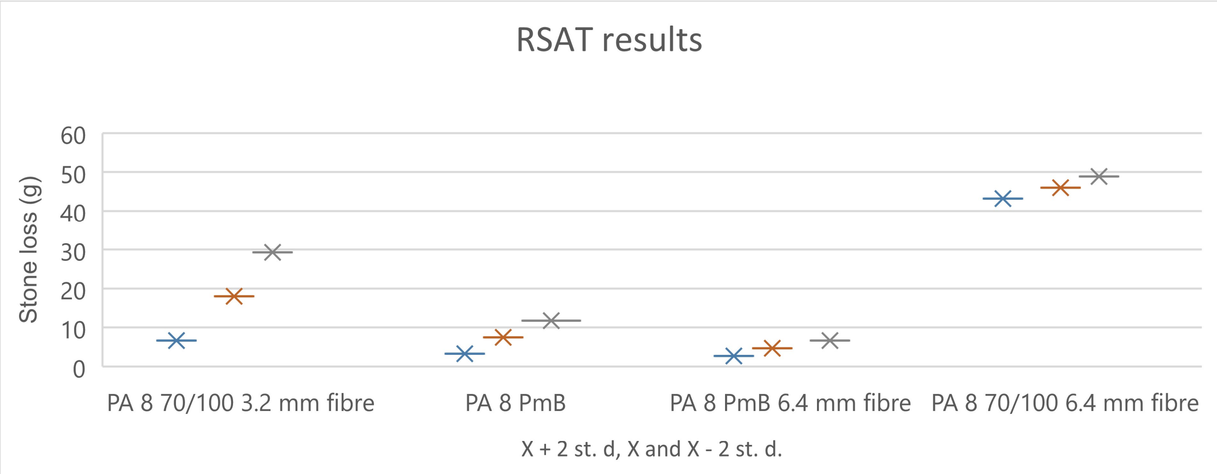

Figure 1: 95% confidence interval of RSAT results

Those six PA 8 test sections were followed yearly by visual inspections focused on monitoring the degree of ravelling over time until end of lifespan. After 6 years the two PA 8 test sections with the special fibres were still in very good condition. PA 8 with code DV had to be replaced already after 4 years. After 6 years PA 8 mixtures with codes BAM, H1 and H2 showed after 6 years' service life medium to severe ravelling. When it was known that PA 8 with pen grade 70/100 and the special fibres performed so well compared to the standard PA 8 with PmB [5], other contractors have started experimenting with application of these special fibres in PA test sites.
In this paper the results of lab tests carried out with mortars containing special fibres will be shown as well as experiences with PA 8 test sites containing special fibres.

2. GOAL OF THE STUDY

The goal of the present study is to determine independently whether addition of special fibres leads to a longer lifespan of PA 8 mixtures and if so, try to find out which mechanisms take care for this longer lifespan.
All the studied PA 8 test sections, except one, have not yet achieved end of lifespan. Therefore, based on the year of construction and remaining lifespan determined in 2019, the expected lifespan has been calculated.
To determine the possible lifespan extension of PA 8 with pen grade 70/100 bitumen and special fibres, the estimated lifespan of all test sections with these mixtures are compared with the average lifespan of standard PA 8 with PmB.

3. CHARACTERISTICS OF THE USED ACRYLIC FIBRE

To improve the properties of PA mixtures, various types of modifications have already been investigated in the past. It was already reported in [1] that use of 1% more bitumen in PA 16 leads to a lifespan extension of 2 to 3 years. Adding polymers to bitumen per se has not led to a better ravelling resistance, but adding more bitumen has. This higher bitumen content must be homogeneously distributed in the PA layer, because if too much bitumen has drained, this will negatively influence the ravelling resistance.

Based on the research results of [1] RWS has decided in 2007 to use PA 16+ (PA mix with 1% extra pen grade 70/100 bitumen) as a standard surface course for new constructions and carriageway wide maintenance projects. From 2015 PA+ has been included in the national standard [4]. In [4] article 81.26.04 paragraph 06 it is stated: "In PA 16+ measures against binder drainage must be applied to ensure that the difference between the bitumen content at the top and bottom part of the layer does not exceed 0.7%". In the PA 16+ mixtures from [1] organic and inorganic fibres were already used as a drainage inhibitor. In the current PA 16+ mixtures only cellulose fibres are used, whether or not in pellets. The fibres are sufficient as a drainage inhibitor.

However the PA 8 test sections A15 Leerdam, which were constructed in 2005, have shown that fibres with special properties, besides acting as a good drainage inhibitor can also have a contribution to lifespan extension of PA 8 mixtures. It is obvious that such good results cannot be achieved with any type of fibre. Therefor the characteristics of the used special fibre are given in table 2.

Table 2: Properties of homopolymer high tenacity polyacrylonitrile fibre.

Density (g/m^3)	1.18
Humidity (%)	< 2 or 18%
Chemical composition (% ACN)>	> 99% MW polymer [D] ≈200.000
MW polymer (D)	≈ 200.000
Cut length	0.2 mm; 1.5 mm; 3.2 mm, 4.0 mm; 6.4 mm; 8.0 mm; 12 mm; 16.0 mm and 20 mm
N° single fibres per g of acrylic fibre (6.4 mm length)	1,365,000
Nominal diameter (micron)	7.1-12.7
Tenacity (N / mm^2); (MPa);	> 721; > 708
E-modulus (N/mm^2); (GPa;	> 16774; > 16.5
Tg [° C] in air	110
Tm [° C] in air	330
Cas N °	25014-41-9
Customs code	5503/3000
Chemical resistance	Soluble in DMAC; DMSO; DMF; $ZnCl_2$; NaSCN; HNO_3
Total resistance	UV, biological and weathering

4. THEORY AND LAB RESEARCH

Before zooming in on the field behaviour, the possible effect of acrylic fibres for the purpose of extending the lifespan of PA will be discussed. Initially there was widespread surprise about the good field behaviour of PA 8 with pen grade 70/100 bitumen and special fibres, but when this was a fact, they also wanted to understand the mechanism behind it. In 4.1 the theoretical considerations will be discussed and in 4.2 the studies conducted on PA 8 with special fibres will be summarized briefly.

4.1 Theory

It was already concluded in [1] that the ravelling resistance can be improved by increasing the bitumen content. This only works if the higher bitumen content is distributed as homogeneously as possible in the PA layer, especially in the upper part because of the ravelling resistance. In the Netherlands normally cellulose fibres are used as drainage inhibitor for PA 16+, where pen grade 70/100 bitumen is used as a binder. With PA 8 drainage inhibitors are not necessary, due to the use of PmB with higher viscosity the binder drainage is limited.

Using polymers as a drainage inhibitor is expensive and may possibly lead to problems with reuse in the future [6]. In [6] also a plea is made for limiting the use of PmBs in the Netherlands, because the use of PmBs is seen by those authors as an obstacle to the circular economy. In their opinion it is stated that a circular economy means that today's products are the constituent materials for tomorrow and that when making the right choices with regard to constituent materials, a good distinction must be made between recyclability and circular reuse. In a replacement market in the Netherlands, where road construction is currently located, the intention is to reuse as much asphalt in new asphalt mixtures as becomes available when removing old asphalt (Reclaimed Asphalt (RA)). For asphalt with pen grade bitumen this is already common practise in the Netherlands for more than 3 decades, but if RA with different types of PmB have to be reused, this probably can lead to problems. A possible problem with reusing PmBs may be that not every type of PmB is compatible with other PmBs or with pen grade bitumen. A disadvantage of the use of PmBs for energy consumption is the higher needed production temperature and certainly when reusing reclaimed polymer modified asphalt (PMA). In addition to a higher energy consumption, this will lead to higher emissions at the asphalt mixing plant. In the pursuit of ever higher recycling rates in the content of the circular economy, these possibly disadvantages should be avoided as much as possible.

A solution for the above mentioned problems is the use of only pen grade 70/100 bitumen in PA mixtures in combination with special fibres in the top-layer PA 8 for two-layer PA, which also improves the mortar properties, so that at least an equivalent or longer lifespan is obtained compared with the standard PA 8 top-layer with PmB.

Homopolymer high tenacity polyacrylonitrile fibres are imbedded in the mortar and stay in the mortar during service life, because the mortar does not erode due to the strengthening effect of the fibres. Also the fibres themselves cannot split or fragment, so there is no danger that parts of the fibres will be lost and find their way into water sources.

Various theories have been developed about how the improved mortar properties can lead to a possible improved field behaviour of PA. One of the most plausible theories is the following. In the Innovation Noise Project [7], the German Rheinisch Westfälische Technische Hochschule (RWTH) and Danish Road Institute (DRI) independently from each other have concluded on bases of microscope studies of thin slices of about 8 year old PA, that erosion (micro damage) occurs in the mortar bonding bridges of PA, see figures 2 (mortar with pen grade 70/100 bitumen and special fibres) and 3 (standard mortar with PmB and no fibres). In figure 2 the mortar bonding bridges have a smooth surface and no micro damage can be seen. In figure 3 poor mortar bonding bridges can be seen. Due to erosion, the bitumen content is decreased and the aging can penetrate further in the direction of the stones. Both is negative for the resistance to ravelling.

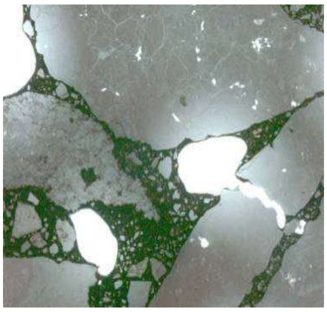
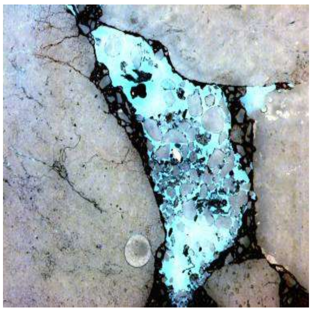

Figure 2: Healthy mortar **Figure 3: Eroded mortar**

By using special fibres, the mortar bonding bridges are reinforced, so that the outer shell remains intact over time and does not erode. As a consequence of this shield, the bitumen content does not decrease and the mortar bridges will not erode, giving the PA containing special fibres a longer lifespan.

4.2 Lab research

In 2005 six modified PA 8 test sections (top-layer of two-layer PA) were constructed on motorway A15 nearby Leerdam with the goal to improve the early skid resistance. The results of the early skid resistance measurements are reported in [8]. No measuring vehicle was available for mixtures R1 and R2, so the early skid resistance results are unfortunately unknown. For more detailed mixture information see table 1. For information: the early skid resistance problems with PA are solved by gritting a small amount broken fine material before the first roller passage, see [8].

Table 3: PA 8 test sites on motorway A15 nearby Leerdam

Code	Test site mixture	Location [km-km]	Lane
DV	PA 8 with PmB and addition of fine broken glass slag	105.340 - 105.010	fast
BAM	PA 8 with PmB and fine mineral components	105.340 - 105.010	slow
H1	PA 8 with PmB and fine sand	105.010 - 104.680	fast
H2	PA 8 with PmB and a combination of fraction 2/6 with 4/8	105.010 - 104.680	slow
R1	H2 with PmB and 6.4 long special fibres	104.680 - 104.340	slow
R2	H2 with pen grade 70/100 bitumen and 3.2 long special fibres	104.680 - 104.340	fast

All six PA 8 test sites were monitored yearly by visual inspections to follow the degree of ravelling until end of service life. After 6 years monitoring it became apparent that, mixture R1 and especially mixture R2 with pen grade 70/100 bitumen performed very well. To investigate why these mixtures performed so well, investigations were carried out on new lab-prepared material and 6-year-old material.

In [9] the results of laboratory and numerical studies are presented to find an explanation for the good field behaviour of PA 8 with pen grade 70/100 bitumen and 3.2 mm long special fibres. Based on polarization and fluorescence microscopic examination of thin slices of samples, which were made out of cores from actual road surfaces, from new laid test sites (A2) in 2010 (just after laying) and field aged test sites (A15) laid in 2005 with and without special fibres, it was determined that the special fibres are well distributed in the mortar and acted very well as a drainage inhibitor, see figure 4. Also the surfaces of the mortar bonding bridges looked smooth, while the mortar bonding bridges of the other mixtures with PmBs showed already some erosion.

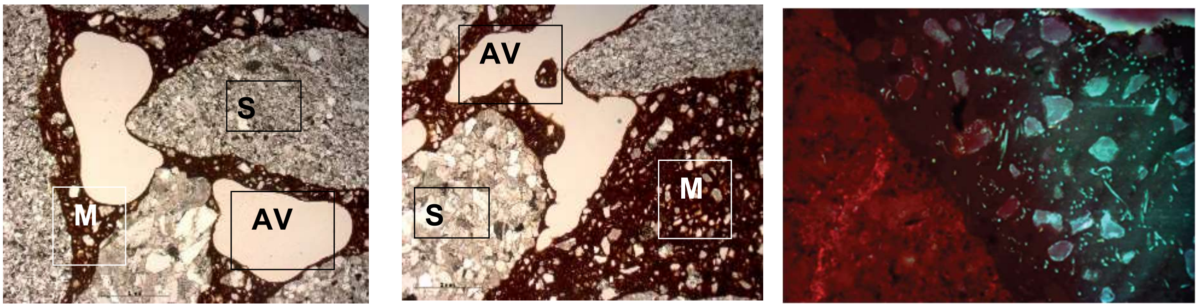

Figure 4: Left and middle: Air voids (A) shape, mortar (M) surface and stone (S) in young asphalt with 0.1 % and 0.3% acrylic fibres respectively. Right: distribution of fibre

In [9] Dynamic Shear Rheometer (DSR) measurements were performed on recovered mortar from 6-year-old PA 8 mixtures R2 and H1 to determine master curves, see figure 5.

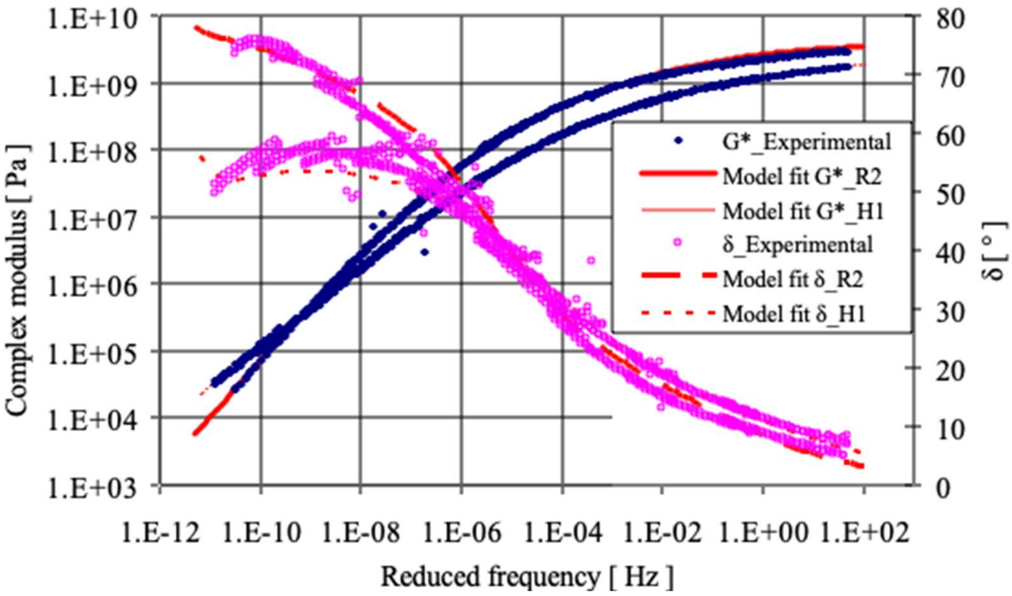

Figure 5: Master curve comparisons of R2 and H1 mortars, T_{ref} = -10°C

Figure 5 shows that the mortar with pen grade 70/100 bitumen and special fibres (R2) is relatively stiffer in a wide range of temperatures than the mortar with PmB (H1). R2 has a higher G* value. Only at very high temperatures mortar R2 shows a somewhat softer behaviour.

In [9] for the DSR fatigue study, 2 mortar mixtures with pen grade 70/100 bitumen (mix composition based on PA 16) were manufactured in the lab; mortar R is without and mortar P is with special fibres. Before producing the test samples (column diameter 6 mm, length 20 mm, see figure 6) for DSR testing, the bitumen is aged with Rolling Thin Film Oven (short term aging). The test conditions are: sinusoidal torsional mode at -10 and +10°C at 10 rad/s. The applied strain level varied between 0.4 and 1.5%. For a criterium to end the test is chosen for 50% of the initial stiffness. Figure 7 shows the test results of the tests performed at 10°C.

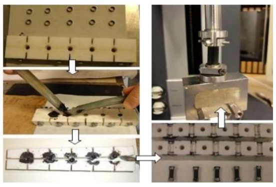

Figure 6: DSR sample preparation and test setup

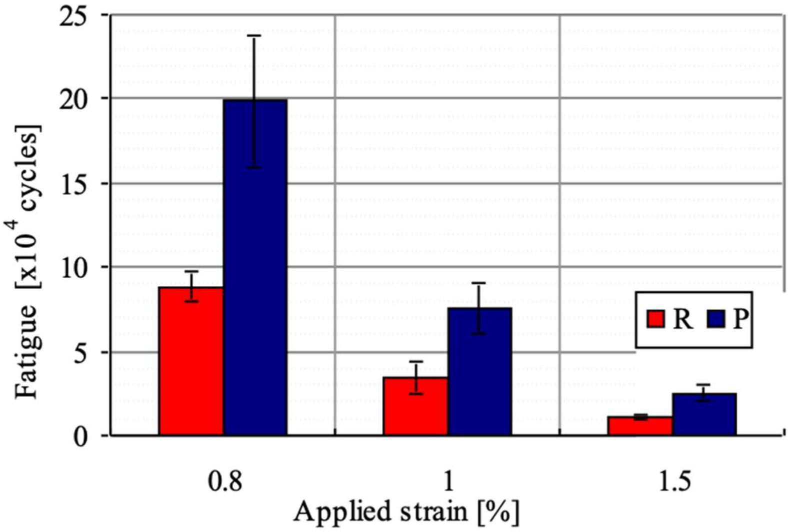

Figure 7: Results of DSR fatigue tests for investigated mortars at 10°C and a frequency of 10 rad/s, R is mortar without fibres and P is with special fibres.

From the results shown in figure 7 can be concluded that mortars with special fibres have a better resistance to fatigue than mortars without fibres.

Based on numerical Life Optimization Tool (LOT) calculations [9] in relation to the frost problems with PA in the winter 2008/2009, research was carried out on recovered mortars from good and poor acting PA mixtures. To this end, relatively young PA road sections were selected where frost damage was observed and relatively old PA road sections that showed no frost damage. The relative damage was calculated on the research results per 24 hours. It appeared that frost-sensitive PA mixtures had a stiffer mortar than the PA mixtures without frost damage and that the mortar stiffness was not depended on the age of PA. In figure 8, an arbitrary limit value has been chosen for good (0) and poor (1 & 2) acting PA mixtures. In [9] the recovered mortars of the 6-year-old PA 8 mixtures R2 and H1 were investigated. The results of this are plotted together with the results of [10] in figure 8.

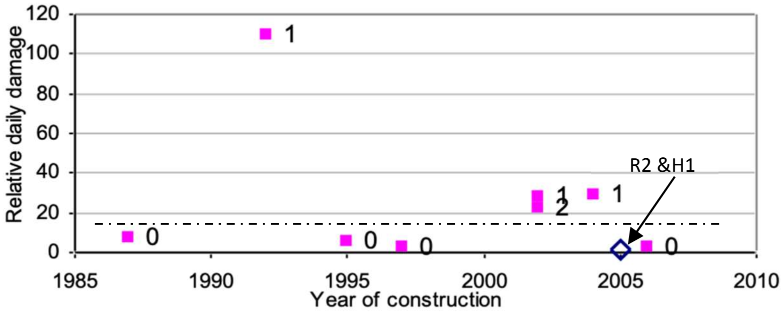

Figure 8: H1 and R2 mix performance comparisons with available PA performance data from [9]; ΔT = 3°C

Figure 8 shows that both the PA 8 mixtures H1 and R2 are in the range of well-functioning PA mixtures. Based on this result, it can be concluded that PA 8 mixtures with pen grade 70/100 bitumen and special fibres act equal in terms of frost resistance. So, durable PA 8 mixtures can be designed without the use of PmBs.

On basis of the results of [9] it can be concluded that the better acting of PA 8 with pen grade 70/100 bitumen and 3.2 mm long special fibres is the result of a combination of the following four mechanisms:

- the special fibres work as an excellent drainage inhibitor, in particular the short special fibres are distributed well homogeneously in the mortar and the drainage inhibiting effect remains guaranteed during the lifespan
- the mortar bonding bridges are reinforced with special fibres, as a result of which no or virtually no micro-damage (erosion) occurs over time. As a result, no bitumen loss occurs and aging penetrates less deeply into the mortar bonding bridge towards the coarse aggregate
- application of special fibres in mortar improves the resistance to fatigue
- application of special fibres improves the stiffness at high speeds and/or lower temperatures.

It is remarkable that a longer lifespan can be achieved with PA 8 with pen grade 70/100 bitumen and short special fibres in comparison with PA 8 containing PmB and no fibres. It had already been concluded in [1] that PA 16+ mixtures with pen grade 70/100 bitumen act well if organic or inorganic fibres are added as a drainage inhibitor and the use of PmBs does not in itself have a direct positive lifespan-extending effect. This is the case if PmBs are also applied in a higher content. The present study shows that the use of short special fibres and pen grade 70/100 bitumen in PA 8 mixtures leads to a longer lifespan than using only PmBs.

5. FIELD PERFRORMANCE OF PA 8.

This chapter is about the field performance of test sites on motorways with PA 8, as a top-layer of two-layer PA, containing pen grade 70/100 bitumen with special fibres and PA 8 containing PmB. Especially attention is paid in how many years longer lifespan of those mixtures can be expected in comparison with the reference: PA 8 with PmB. In 5.1 first the maintenance strategy of two-layer PA will be discussed and the average lifespan of PA 8 and PA 16 of the two-layer PA will be given per slow and fast lane.

5.1 RWS Maintenance strategy of two-layer PA

Starting point is a motorway with two carriageways and one carriageway consists of an emergency lane, a slow lane and a fast lane. For new construction, the PA 8 top-layer and PA 16 bottom-layer are constructed carriageway wide, mostly with pavers in echelon to avoid hot-to-cold longitudinal joints. The average lifespan of the PA 8 top-layer is on the slow and fast lane respectively 9 and 12 years. These average lifespans will be used as a reference to calculate how much longer the lifespans are of the PA 8 test sites with special fibres. The shorter lifespan of the slow lane is caused by the higher traffic loading. At the end of service life, the PA 8 on the slow lane is milled and new PA 8 is constructed. If the PA 8 of the fast lane has achieved end of service life, both the top and bottom-layers are replaced by new top- and bottom-layers. On basis of calculations of materials costs, traffic nuisance and so on is has shown that this is the most cost-effective maintenance strategy for two-layer PA structures.

5.2 PA 8 test sites

Because all the examined PA 8 test sites, with the exception of one, have not yet achieved end of service life, use was made of planning data of RWS. RWS measures yearly the condition of the whole motorway network to plan when maintenance has to be carried out. Besides the degree of ravelling, which in almost all cases determines the end of service life of PA, also measurements are carried out to determine the skid resistance, rut depths and so on. The RWS maintenance report of 2019 showed when maintenance was planned per 100 m segment length of the test sections examined. In all cases ravelling is the normative damage for maintenance. If the year of construction of the PA 8 test section is known and the year when maintenance is planned, the expected lifespan can be calculated of the PA 8 test sections. The older the test sections are and the shorter the remaining lifespan is, the more reliable the expected lifespan is.

No distinction was made in terms of traffic loading in the PA 8 test sections. It is known that the traffic loading influences the lifespan of PA 8; the difference in lifespan of the fast and slow lane is a proof of it. The locations of the PA 8 test sections considered are generally situated in motorways with an average or more than average traffic volume, so that the results may be considered representative.

Also, when examining the PA 8 test sections, it was not investigated whether the weather conditions during construction had an impact on the quality of PA 8. Because they are test sections, it can be assumed that the weather conditions (temperature and wind) met the requirements applicable during construction.

Table 3 gives an overview of PA 8 test sections with special fibres, which were constructed since 2005. For more background information see [11]. Contractor Heijmans constructed test sections R1 and R2 on behalf of RWS with the aim of improving the initial skid resistance and braking deceleration. The coarse and fine aggregates and grading of both mixtures was the same, only the binder and used fibre length was different. In mixture R2 pen grade 70/100 bitumen was used in combination with 3.2 mm long special fibres and in mixture R1 PmB was used in combination with 6.4 mm long special fibres. Contractor KWS has constructed the PA 8 test sections 10049 to

10052 with different percentages of pen grade 70/100 bitumen and different percentages 3.2 mm long special fibres:
10049 – 5.2% pen grade 70/100 bitumen and 0.1% special fibres
10050 – 5.6% pen grade 70/100 bitumen and 0.1% special fibres
10051 – 5.6% pen grade 70/100 bitumen and 0.2% special fibres
10052 – 5.8% pen grade 70/100 bitumen and 0.3% special fibres.
Because with standard PA 8 on Velperbroekplein (a roundabout with an arc beam of 330 m and traffic lights) due to shear loading and accelerating and braking traffic nearby traffic lights only lifespans were achieved ranging from 1 to a maximum of 6 years, RWS commissioned contractor De Jong to construct PA 8 with Cariphalte XS as a PmB in combination with 3.2 long special fibres with the idea to extend the lifespan. In table 3 the data are given of all known PA 8 test sites with special fibres. The year that maintenance is planned was received from RWS. Based on yearly measured data of the degree of ravelling RWS is able to estimate when replacement of the PA 8 is necessary. The criterium for end of lifespan of PA 8 is if severe ravelling (25% of the stones in the upper stone layer in the wheel path has disappeared) occurs in 25% of the PA 8 surface.

Table 3: Data PA 8 test sites with special fibres

CodePA 8 test sites	Binder type	Fibre length	Location	Year of construction	End of lifespan	Maintenance planned in	Estimated lifespan
R2	Pen grade 70/100	3.2 mm	Leerdam A15 Fast lane	2005	-	2022	17 years
R1	Cariphalte XS	6.4 mm	Leerdam A15 Slow lane	2005	2014	-	9 years
10049	Pen grade 70/100	3.2 mm	Maarsen A2 Slow lane	2011	-	2024	13 years
10050	Pen grade 70/100	3.2 mm	Maarsen A2 Slow lane	2011	-	2024	13 years
10051	Pen grade 70/100	3.2 mm	Maarsen A2 Slow lane	2011	-	2024	13 years
10052	Pen grade 70/100	3.2 mm	Maarsen A2 Slow lane	2011	-	2024	13 years
11011	Cariphalte XS	3.2 mm	Roundabout Velperbroekplein	2014	-	2012/2022	7 to 8 years

6. INTERPRETATION OF PA 8 TEST SITE DATA

Based on the PA 8 test sections 10049 to 10052, it can be concluded that the expected average lifespan of PA 8 with pen grade 70/100 bitumen with 3.2 mm long special fibres is 13 years. This is an improvement of 4 years compared to the average lifespan of the standard top-layer PA 8 of two-layer PA containing PmB and no fibres. It is strange that there is no difference in lifespan expectancy between the different test sections 10049 to 10052, while the bitumen and fibre contents vary between respectively 5.5 and 5.8% and between 0.1 and 0.3%. A possible reason could be that due to the low percentage stone loss in 2019, the possible minimum differences between the PA 8 test sections are not yet clearly visible and therefore not sufficiently distinctive. A difference in ravelling behaviour could be observed within a few years, partly because the stone loss develops progressively over time.

The expected lifespan in the fast lane of the oldest PA 8 test section with pen grade 70/100 bitumen and special fibres is 17 years, which also means a even 5-years-longer expected lifespan compared to standard PA 8 with PmB and no fibres. This confirms the experiences with the slow lane.

Besides the longer lifespan the application of pen grade 70/100 bitumen and acrylic fibres in PA 8 instead of PmB has the following advantages:
- in terms of material costs, it is cheaper
- the production costs are lower, because of a lower production temperature
- due to the lower production temperature it causes less emissions
- it will cause no problems with reuse in the future.

The standard PA 8 with PmB, to which 6.4 mm long special fibres have been added, has reached the end of lifespan after 9 years, which corresponds with the average lifespan of standard PA 8 with PmB. Apparently the longer special fibres do not help to have a longer lifespan of standard PA 8. In [9] it was already established by means of microscopic examination of thin slices from the 6 year old PA 8 test sections, that the mortar bonding bridges of PA 8 with 6.4 mm long special fibres showed more micro damage (erosion) and it was noticed that these fibres were not as homogeneous divided as the 3.2 mm long special fibres. In [1] it had already been concluded that with both binders, pen grade 70/100 bitumen and PmB, equal lifespans can be achieved. Only with higher binder contents both binders can lead to longer lifespans in PA.
At the roundabout Velperbroekplein the applied PA 8 with PmB and 3.2 mm long special fibres is expected to have a lifespan of 7 to 8 years, which is considerably longer than the up to 6 years achieved so far, especially in view of the increase in traffic volume over the years. Apparently the special fibres contribute to the lifespan extension of PA 8 in arc beams of a roundabout, where mortar bonding bridges are more heavily loaded by shear loading in combination with accelerating and braking traffic at traffic lights than in straight motorways.

From field observations it is clear that PA 8 with pen grade 70/100 bitumen has a better resistance to ravelling and as a consequence a longer lifespan in comparison with standard PA 8 with PmB without fibres. With the current lab tests the predictability for the field ravelling behaviour is poor, especially to substantiate the mentioned theory in the last paragraph of chapter 4.1. To proof this theory new tests or a test set should be developed. Maybe a combination of tests results in a better predictably for field ravelling of PA mixtures? One could think about a combination of first artificial aging followed by loading with moister with the Moisture Induced Sensitivity Test (MIST) [12] and finally testing Indirect Tensile Strength Ratio (ITSR). One should consider such combinations to mimic the field loading for PA mixtures in a better way.

7. CONCLUSIONS

The following conclusions can be drawn on basis of data concerning construction year and RWS maintenance planning of PA 8 mixtures with pen grade 70/100 bitumen and homopolymer high tenacity polyacrylonitrile (special) fibres :

1. Application of pen grade 70/100 bitumen and 3.2 mm long special fibres in PA 8 leads to a 4 year longer lifespan in comparison with standard PA 8 with PmB without fibres. This applies for both, the fast and slow lane in straight motorways
2. Application of pen grade 70/100 bitumen with special fibres instead of PmB in PA 8 has the following advantages:
   - the material costs are lower
   - due to the lower production temperature the emissions at the asphalt mixing plant are lower
   - as a consequence of the lower production temperatures the energy costs are lower
3. Application of 6.4 mm long special fibres to standard PA 8 with PmB does not extend the lifespan
4. On roundabouts with an arc beam up to 330 m, a lifespan of 7 to 8 years can be expected with PA 8 with PmB and 3.2 mm long special fibres, which at least 1 to 2 years longer than in the past with standard PA 8 with PmB.

8. RECOMMENDATIONS

To carry out less maintenance, which is less harmful to the environment and causes less traffic hindrance, the following cost-effective maintenance scenario is recommended for PA 8.
Start with carriageway wide construction of two-layer PA, consisting of a top-layer PA 8 with pen grade 70/100 bitumen and 3.2 mm long special fibres and a bottom-layer PA 16 with only pen grade 70/100 bitumen. If the ravelling process starts after approximately 6 years on the slow lane, carry out on this lane preventive maintenance with rejuvenators, see [13]. By monitoring the with rejuvenators treated and untreated (reference) PA test sections, it is concluded in 2019 that with preventive maintenance the lifespan of PA mixtures can be extended with at least

3 years [14]. So, if this goes also for PA 8, the lifespan of both the fast lane and the slow lane treated with rejuvenators have the same lifespan of 17 years. If the PA 8 of both lanes have achieved the end of service life, only the PA 8 top-layer have to be milled carriageway wide and a new PA 8 with pen grade 70/100 bitumen and 3.2 mm long special fibres can be laid back. Repeat the same preventive maintenance for the PA 8 on the slow lane. After again 17 years the end of service life of both lanes is achieved. Then the whole two-layer PA (top- and bottom-layer) must be removed and the process can start all over again.
In addition, this maintenance scenario, if PA 8 is constructed with in echelon pavers, prevents longitudinal joints from forming between the lanes, which always leads to weaker place.
This appears to be the most cost-effective maintenance strategy for two-layer PA, which has the least impact for the environment and produces least traffic hinderance.

From field observation it is obvious that PA 8 with pen grade 70/100 bitumen and special fibres has a better resistance to ravelling and as a consequence a longer lifespan than the standard PA 8 with PmB. In this case the predictability for field ravelling behaviour of the current lab tests is poor, especially to proof the theory mentioned in the last paragraph of 4.1. So, the recommendation is to find new test methods or a combination of test methods, which mimic the field behaviour of PA 8 mixtures in a better way than only one of the current tests.

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Annex

1. EXTENSION OF PAPER "Longer lifespan of Porous Asphalt due to addition of homopolymer HT polyacrylonitrile fibres"

Following the paper written in 2020, there are the three adjustments:
1. correct an error concerning the year of construction of the PA 8 test sites on the A2 Maarssen
2. update since 2020 of the average lifespan of standard PA 8 used by Rijkswaterstaat (RWS)
3. research into the environmental impact of PA 8 with bitumen 70/100 and special fibres.

1.1. Correction error

Table 3 of the 2020 paper shows an incorrect year of construction for the PA 8 test sites on motorway A2 nearby Maarssen with code 10049 to 10052. This should be 2010 instead of 2011. Also must be mentioned that in 2019 all PA 8 test sites were replaced by PA 5. The reason was not end of lifespan, but the test sites were replaced because of higher requirements for noise reduction.

1.2. Update new insight of Rijkswaterstaat

Based on monitoring lifespans of PA 8, RWS has adjusted the average lifespan of PA 8 on the fast lane. Since 2020, an average lifespan of 12 years has been used for this instead of the 13 years used in the 2020 paper.

Based on the changes in 1.1 and 1.3 table 3 of the 2020 paper is adapted as follows, see table 4.

Table 4: Data PA 8 test sites with homopolymer HT polyacrylonitrile fibres

Code PA 8 test sites	Binder type	Fibre length and % in mix	Location	Year of construction	Replaced in year	Maintenance planned in 2019	(Estimated) lifespan	Expected lifetime extension
R2	Pen grade 70/100	3.2 mm 0.15%	A15 Leerdam Fast lane	2005	-	2022	17 years	5 years
R1	Cariphalte XS	6.4 mm 0.15%	A15 Leerdam Slow lane	2005	2014#	-	9 years	0 year
10049	Pen grade 70/100	3.2 mm 0.1%	A2 Maarssen Slow lane	2010	2019*	2024	14 years	5 years
10050	Pen grade 70/100	3.2 mm 0.1%	A2 Maarssen Slow lane	2010	2019*	2024	14 years	5 years
10051	Pen grade 70/100	3.2 mm 0.2%	A2 Maarssen Slow lane	2010	2019*	2024	14 years	5 years
10052	Pen grade 70/100	3.2 mm 0.3%	A2 Maarssen Slow lane	2010	2019*	2024	14 years	5 years
11011	Cariphalte XS	3.2 mm 0.15%	Roundabout A12: Velper-broekplein	2014	-	2021/2022	7 to 8 years	2 to 3 years

Due to end of service life
* Replacement was not due to end of service life, but for noise reducing reasons PA 8 was replaced by PA 5.

As a result of changes 1.1 and 1.2 all test sections with PA 8 with pen grade bitumen 70/100 and special fibres on both, the slow and fast lane, have an expected life span of 5 years longer than the standard PA 8 with PmB.

Because these lifespans have not yet been realized, it is justified to claim that the lifespan of PA 8 with pen grade bitumen 70/100 and special fibres has a lifespan of at least 4 years longer than PA 8 with PmB.

1.3 LCA – PA 8 with pen grade bitumen and special fibres

When the Dutch Government lists a call for a tender on the maintenance or construction of a new motorway, contractors have to add the environmental impact of the offered asphalt mixture to the documentation for the benefit of circularity. Not only the environmental impact of production and transport of the constituent materials and the production of the asphalt is important for the LCA calculations, but also the lifespan of the offered asphalt mixtures. The 4 year longer lifespan of PA 8 with pen grade bitumen 70/100 and special fibres in comparison with PA 8 with PmB is an advantage for LCA results. For sake of independence this environmental impact must be based on the National Environmental Database and reviewed by an independent company and certified by a reviewer. Therefore an LCA analysis is needed, which is in line with the Dutch requirements. The results are expressed in a "MKI" (MilieuKosten Indicator, in English: Environmental Costs Indicator). The MKI is a weighted environmental footprint expressed in Euro's. The higher the indicator, the bigger the environmental impact. These LCA calculations are carried out in conformity with the ISO 14040, ISO 140442 and NEN-EN 15804. The environmental impact is calculated for the following phases: **A1** all used materials, **A2** - transport of materials, **A3** - Production processes, **A4** - Transport to the job site, **A5** - Construction phase, **B** - Use phase – leaching, **C1-C4** - Demolition and waste treatment phase and **D** - Reuse and recycling.

If the lifespans of PA 8 with pen grade bitumen 70/100 and special fibres are kept the same (10 years), only phase A1 is different, the MKI of is PA 8 with pen grade bitumen 70/100 and special fibres is a little bit better. However, if the 4 year longer lifespan of PA 8 with pen grade bitumen 70/100 with special fibres is taken into account, the environmental impact for the slow lane is reduced to 0.037 MKI/m^2/year for 13 years lifespan and for the fast lane with 0.030 MKI/m^2/year for 16 years lifespan, see figure 1. If a lifespan of 17 years is used for PA 8 with pen grade bitumen 70/100 and special fibres, the MKI is even more favourable. See for more detailed information about the calculated MKI [1].

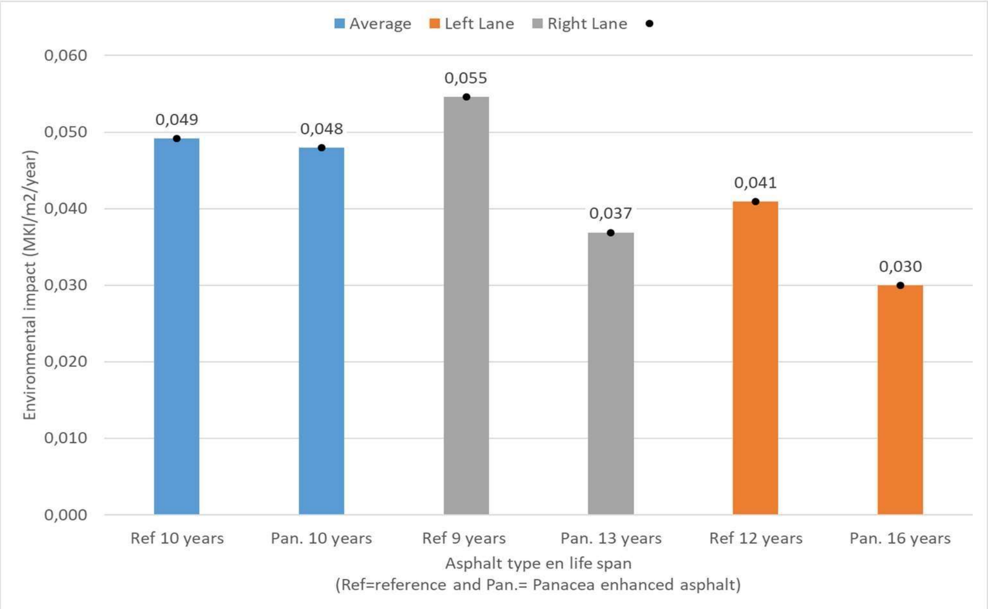

Figure 1. Sensitivity analysis on lifespan of the PA 8 mixtures with pen grade bitumen 70/100 and special fibres (Pan) and PA 8 with PmB (Ref) expressed in MKI/m^2/year.

2. CONCLUSION

It can be concluded that the environmental impact of PA 8 with pen grade bitumen 70/100 and special fibres is 30% less than the reference PA 8 mixture with PmB.

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