Life-prolonging preventive maintenance techniques for porous asphalt

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ABSTRACT

The Dutch national roads agency Rijkswaterstaat (RWS) is constantly looking for faster maintenance techniques and more cost effective maintenance measures, to extend the service life of Porous Asphalt (PA) with minimal traffic hindrance. End of service life of PA is determined by excessive loss of stones from the surface, called raveling. Raveling is caused by a complex of factors like possible drainage of the mortar (transport, construction, early life), direct loading via the stones, water pressure under the tire, accelerated ageing from the surface, clogging, etcetera.

In the field raveling mainly occurs after the bitumen in the top of the PA layer is strongly aged. Due to the ageing of the bitumen, the mortar bonding bridges between the coarse aggregate become more brittle, which makes them more sensitive for (micro) cracks and/or adhesion loss between stone and the mortar, which probably will lead to raveling. The service life of existing PA could be extended by adding bitumen from the surface, which could fill and heal micro-cracks, rejuvenate the aged bitumen in the mortar and add bitumen to the mortar bonding bridges.

RWS has challenged the Dutch market to develop life-prolonging preventive maintenance techniques for PA. Three potential rejuvenating products, that could fulfill the requirements of RWS, were offered:

- *Pentack® of producer ESHA (emulsion system), applied by ESHA*
- *Modiseal® ZX of producer Latexfalt (hot polymer modified bitumen), applied by contactor BAM*
- *Modimuls® ZV of producer Latexfalt (emulsion system), applied by contractor Heijmans.*

Whether these products actually contribute to the life extension of PA is investigated by InfraQuest (a partnership between RWS, Delft University of Technology and TNO). The three products were applied on existing PA road sections, which were not raveled, and extensive research was conducted on specimens obtained from these test sections for validation. Also a Life Cycle Analysis and Cost Benefit Analysis were performed to investigate whether the examined life extension maintenance measures were cost effective and satisfied the environmental requirements of RWS. In this paper an overview will be given of the approach to the validation studies and the conclusions that could be drawn from the results.

Keywords: Ageing, Maintenance, Porous asphalt, Ravelling, Rejuvenators

1. INTRODUCTION

The Dutch national roads agency Rijkswaterstaat (RWS) is constantly looking for faster sustainable maintenance techniques and more cost-effective maintenance measures, to extend the service life of Porous Asphalt (PA) with minimal traffic hindrance. End of service life of PA is determined by excessive loss of stones from the surface, called raveling. Raveling is caused by a complex of factors like possible drainage of the mortar (transport, construction, early life), direct loading via the stones, water pressure under the tire, accelerated ageing of the bitumen from the surface, clogging, etcetera. In the field raveling mainly occurs after the bitumen in the top of the PA layer is strongly aged. Due to the ageing of the bitumen, the mortar bonding bridges between the stones become more brittle, which makes them more sensitive for (micro) cracks, erosion, adhesion loss between stone and the mortar, which probably will lead to raveling. At the moment the standard maintenance strategy for PA is as follows. All the lanes (emergency, slow, fast lanes) are paved hot to hot together in one run with echelon pavers. Due to the heavy loading of the slow lane, this lane has to be replaced on average after 11 years. The fast lane(s), however have an average service life of 17 years. So the PA layer of the slow lanes is milled of and a new PA inlay is placed. After 17 years carriageway wide PA is replaced with new PA.
This is not a satisfying maintenance strategy, as the new PA inlay of the slow lane has to be replaced far too early. Several life extension measures like Viaral [1] are in use to correct light to medium raveled PA to increase the service life of the slow lane without milling of the PA. With these maintenance technique it is possible to increase the service life with 2 to 4 years, but of course the air voids content is reduced after application with these products. So the raveling is reduced and the noise reduction is improved, but the water drainability is decreased (increasing also splash and spray during rainfall).
The service life of existing PA in the slow lane can also be extended with a preventive maintenance measure by adding bitumen from the surface, which could fill and heal micro-cracks, rejuvenate the aged bitumen in the mortar and add bitumen to the mortar bonding bridges. In case of a balanced approach the functional properties will stay intact, because the air voids content will hardly change.
RWS has challenged the Dutch market to develop life-prolonging preventive maintenance techniques for PA based on rejuvenators. Whether these products actually contribute to the life extension of PA was investigated by InfraQuest (a cooperation between RWS, Delft University of Technology and TNO). Three products were applied on 5 years old PA test sections on motorways, which were not raveled. Possible changes in functional properties were measured and extensive research was conducted on cores obtained from these test sections for validation. Also a Life Cycle Analysis and Cost Benefit Analysis were performed to investigate whether the examined life extension maintenance measures were cost- effective and satisfied the environmental requirements of RWS. In this paper an overview will be given of the approach to the validation studies and the conclusions that could be drawn from the results.

2. PRODUCTS AND APPLICATION

Three potential rejuvenating products, that could fulfill the requirements of RWS, were offered:
- Pentack® of producer ESHA (bitumen emulsion system), applied by ESHA (E product)
- Modiseal® ZX of producer Latexfalt (hot polymer modified bitumen), applied by contactor BAM (B product)
- Modimuls® ZV of producer Latexfalt (bitumen emulsion system), applied by contractor Heijmans (H product).

In this paper the term LVO products is used, which means in Dutch “Levensduur Verlengend Onderhoud”. This means in this case “life extending preventive maintenance with rejuvenators”.
The surface treatment products were applied on test sections and later on pilots, both on motorways by using different application technologies as mentioned below.
Pentack ® (code E). The use of Pentack is mainly based on the improvement (rejuvenating) of the rheological properties of the bitumen in PA. Pentack will also improve the cohesion and the adhesion of bitumen with the stones and the mortar in the mixture by filling up the micro-cracks in the upper part of the PA and correction of the composition of the aged bitumen in PA. Each application is claimed to give a life extension of the PA of 2 to 4 years. No change in functional properties like water drainability, water storage, noise reduction and skid resistance will take place.
Pentack is a bitumen emulsion and contains bio components which increase the penetration value of the aged bitumen in the PA. The dosage of the Pentack depends on the needs of the PA and is computer controlled in such a way that the bitumen emulsion is penetrating in the top 2-4 cm of the PA, exactly where the ageing of the bitumen is the highest. Due to the special flow properties, Pentack infiltrates into the PA after being sprayed on the surface. Dependent on the type of PA and its quality at the moment of application it can be necessary to change the composition of Pentack a bit. The most important components stay the same.
Pentack is applied with a spray-truck (the speed of spray truck is 15 km/h, but the netto speed with sanding, etcetera is 5 km/h). If necessary extra material can be applied locally by hand. To bring the initial skid resistance and brake deceleration at an acceptable level, after a few hours light sanding with crusher sand is applied.
Pentack is considered to be a preventive maintenance action, which can be repeated several times on the same PA. To obtain the best results it is necessary to apply the product before raveling develops, because this cannot be repaired with this action.

Modiseal® ZX (code B). Raveling is the dominant damage in PA. Raveling develops when the mortar bridges, who connect the stones at the surface with surrounding and lower material, fail. This damage develops mostly when the PA is aged. The ageing shows up via a strongly reduced relaxation capacity of the mortar and a strongly reduced bitumen percentage due to mortar erosion. Modiseal ZX is applied to repair both damages. The eroded mortar is strengthened by adding new bitumen to the PA. The applied bitumen contains a rejuvenating component, which improves the relaxation capacity of the aged bitumen in the still available mortar. One treatment with Modiseal ZX will increase the expected service life with 4-6 years. This means that with one treatment in general it is possible to increase the service life of the PA in the slow lane so much, that it is enough for a carriage way wide replacement of PA.
For optimal use of Modiseal ZX the viscosity of the product is tailored in such a way that it penetrates approximately 15 to 20 mm in the PA layer. This is done, because in the upper part the ageing is most severe. Due to ageing in the upper part the relaxation capacity of the mortar is strongly decreased and the erosion of the mortar is strongest in the top. Besides ageing, the mortar bridges in the top of the PA layer are the most heavily loaded, so at this place strengthening is needed most to prevent raveling. For this reason Modiseal ZX is applied at the place where the consequences of ageing, erosion and loading of the material are maximal. Modiseal ZX does not reach the deeper part of the PA with the following advantages:

a. the water draining properties (permeability) of an open layer like PA will stay intact,
b. Modiseal ZX will not reach the lower levels of the PA and will not increase clogging by binding it and will not influence the water draining part of the PA.

Modiseal ZX can be used as a preventive (for example as part of a maintenance planning) and curative (for example when winter damage is expected) maintenance action. Modiseal ZX is applied with a special spray-truck, after which pneumatic tyre rolling and sanding will take place. A lane length of 4-5 km can be prepared in one hour.

Modimuls® ZV (code H): maintenance of PA with Airjet sealen.
An airjet or surfacejet (http://www.libertygasturbine.com/pagina.34.name.surfacejet-liberty.htm) is a truck with an airplane turbine motor able to blow very hot air (up to 550°C) in the PA. The purpose of the Airjet seal method is to increase the service life of PA by blowing sprayed bitumen emulsion deeper in the PA layer. With this technique the bitumen emulsion is brought to the bridges connecting stones over the whole height of the PA. For this reason the bitumen emulsion is blown with an Airjet in the structure, after it is sprayed on the surface with a spray-truck. The bitumen emulsion will in this case also reach specifically the underside of the stones at the surface. The effect of the bitumen emulsion is twofold. First of all a rejuvenating component will revitalise the aged bitumen in the mortar bonding bridges and makes it flexible again. Secondly, a special component is added to repair and strengthen the weakened mortar (by erosion).
The treatment can be applied more than once. A standard maintenance scheme can be: first application before the raveling starts, for example 6 years after construction. A second application can take place 5 years later, when the PA is11 years old. This will increase the service life at least from 11 to 17 years. When the method is applied only once a minimum increase in service life of 4 to 6 years is claimed.

Table 1: Summary information of the three products (information from producers) [2]

Product	**Pentack®**	**Modiseal® ZX**	**Modimuls® ZV**
Code product	**(E)**	**(B)**	**(H)**
Producer	**ESHA**	**Latexfalt**	**Latexfalt**
Construction	ESHA	BAM/Latexfalt	Heijmans/Latexfalt
Binder	Bitumen emulsie	Bitumen (PMB)	Bitumen emulsie
Application PA 16 (+)	0.6 kg/m2	0.4 kg/m2	0.8 kg/m2
Application TL PA 4/8	0.4 kg/m2	0.3 kg/m2	0.8 kg/m2
Application	Spraying, sanding	Spraying, tire roller, sanding	Spraying, blowing, sanding
Rejuvenating mortar	Yes	Yes	Yes
Repair mortar bridge	Yes	Yes	Yes
New binder added	Yes	Yes	Yes
Penetration depth	Viscosity dependent (till 40 mm)	In PA top 15-20 mm	Whole PA depth
Service life increase	2-4 years	4-6 years	4-6 years
Number of applications	At least 2 times	In principle 1 time	Several possible
Speed (lane ready)	4 to 5 km/h	4 to 5 km/h	4 to 5 km/h

The information of the products is summarized in Table 1. All three products are claimed to improve the quality of the mortar bridges between the stones by filling of (micro)-cracks and the addition of new bitumen. All three products also claim that they rejuvenate the aged bitumen, especially the two products based on bitumen emulsion. Product B is predominantly targeting the top 15 to 20 mm and is applied in principle only once during the service life of the PA. The other two products claim a considerable penetration capability in depth form 40 to 50 mm where needed. They can also be applied more than once on the PA. For product H a special treatment after spraying is used with the airjet by blowing hot air into the surface, see figure 1. This will result in penetration of the emulsion even at the underside of the mortar bridges and also forces bitumen emulsion settlement deep in the PA. The airjet was also used to dry the surface before application of the product.

Figure 1: Special equipment used for Modimuls ZV : the air-jet turbine motor [2]

3. RESEARCH PROGRAM

The purpose of the research program was primarily to investigate the possibility of application of the products as a preventive maintenance measure to optimize the maintenance strategy as discussed in the introduction. Figure 2 gives an indication what could be expected from adding the products once or several times. LVO0 means that the LVO product is applied for the first time, LVO0+LVO3 means that after three years for a second time the product has been applied. Another important aspect was to investigate the possibility to prevent winter damage of old (> 8 years) PA that is planned to be replaced after the winter. Soft winters are no problem for these PA layers, but the experience of the last ten years is that severe winters will heavily damage these old PA [2], which makes maintenance in winter under bad weather conditions necessary. To prevent this winter maintenance it is investigated if applying these rejuvenating products before the winter, can help the old PA through the winter.

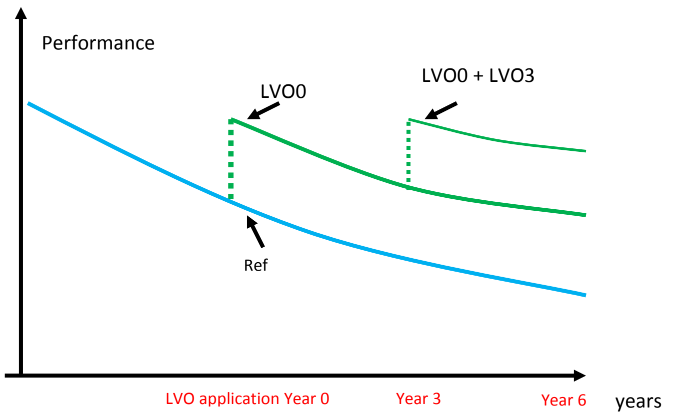

Figure 2: Schematic representation of performance of LVO application over time [3]

In general the following aspects were investigated [3]:

- Application aspects: is it possible to produce a constant application rate on the PA test sections, how can the initial skid resistance be controlled, how fast can the application take place, after how much time can the treated layer be opened for traffic and is it possible to upgrade the process for large length applications (for example 20 km in length during one night)?
- Functional aspects: what is the impact of a preventive maintenance action with these products on important functional properties like skid resistance (safety), splash and spray (visibility, safety) or water drainage capacity, noise reduction (does the product not block the pore structure too much)?
- Material aspects: what happens in the material by adding the product. How deep does it penetrate, is there a rejuvenating action, does the added binder fill micro-cracks and add to the mortar as a whole?
- Environmental aspects: what is the impact of adding these products to the sustainability of the PA layer?
- Implementation protocols for new products: development for a testing protocol for new products in the market?

Application aspects were developed by the companies themselves. As already mentioned in chapter 2, the three products were sprayed initially with a spray-truck, but further actions were different for the three products.
Functional aspects were investigated on the test sections. Skid resistance, brake deceleration, noise levels, surface texture and water drainage were measured. At the same time visual inspections were carried out as well as regular yearly measurements on all the test sections. For material related aspects extensive research work has been conducted for the test sections. Figure 3 gives an overview of the research plan.

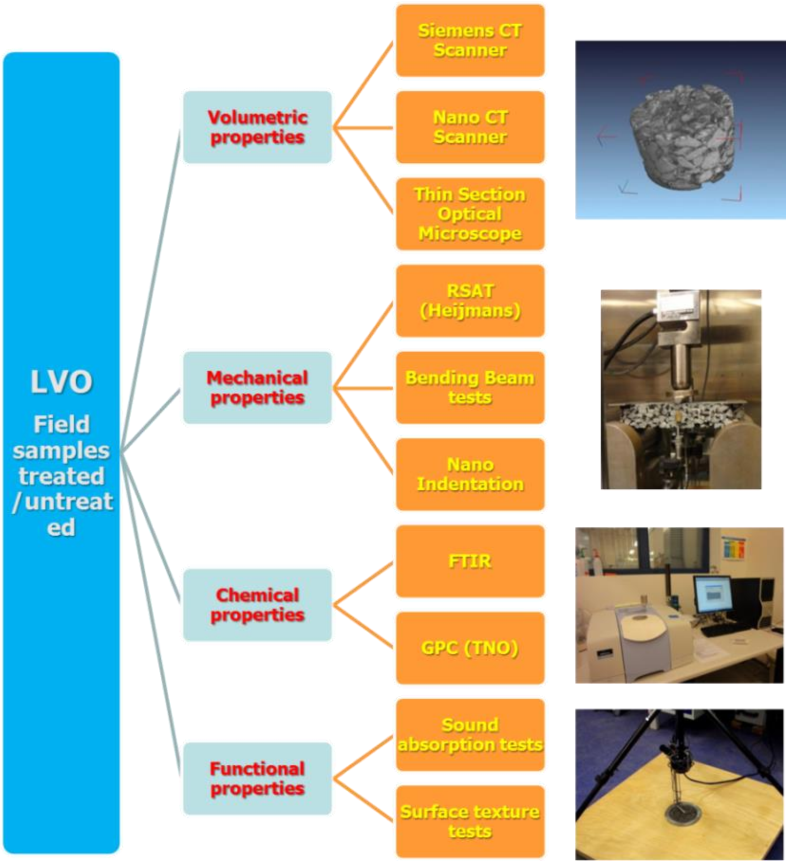

Figure 3: Overview of research plan for a project with the products [3]

As can be seen from figure 3 the focus of the material research was on the volumetric properties (where is the product, what happens with the air voids structure?), the mechanical properties (including bending stiffness and strength, raveling) and the chemical properties including Fourier Transfer InfraRed (FTIR) and Gel Permeation Chromatography (GPC) to check on chemical changes. All the material testing in the laboratory was done on cores taken from the test sections and the pilots. Cores with a diameter of 150 mm were taken from the field for all material investigations.
Figure 2 illustrates the expected performance model after the treatment with the three rejuvenator products in time. In order to determine the real life performance over time, an inspection scheme was developed for test sections on motorways A50 and A73. This scheme includes field inspection and field testing after 1, 3 and 6 years together with material testing. This makes it possible to follow the behaviour of these test sections in time and compare the inspections with the extensive test results of the several sections, including the addition of a second treatment of the rejuvenator products on other sections.
Since 2010, a number of field test trials and pilots with large lengths were organized to investigate the possible extension of the service life of PA by adding the three products to the surface of a PA layer. An overview of these projects (finished/ongoing) is given in Table 2. These field applications included different types of PA mixtures, such as standard PA (with 70/100 pen grade bitumen), PA+ (standard PA with 1% extra bitumen) and two-layer PA (TLPA) with different service lives and conditions. The top layer of TLPA is a PMB. The main types of treatment included regular treatment for preventive purposes (Motorways A6, A50 and A73) and corrective treatment to survive winter damage of certain test sections (motorways A1 and A30). Based on the promising results from these projects, it was decided to further extend this project by means of pilots in the form of up-scaling applications with approximately 5 km long field sections on a number of Dutch motorways (pilots A30, A73HRR, A73HRL, A6, A67 and A15).
The primary aim of these projects was to inform RWS if these products can be used successfully in a preventive maintenance scheme, with as secondary aim if they could be used in a survival scheme before a severe winter. The final target of the research is to develop a procedure to test products in the laboratory before field application.

Table 2: Overview of finished/ongoing projects anno January 2015 [3]

	Highway	PA type (year of construction)	Year of treatment	Length [km]	Maintenance type
Test	A6	PA (2005)	2010	2	Preventive
Test	A50	PA+ (2005)	2010	2	Preventive
Test	A73	TL-PA (2005)	2011	1.5	Preventive
Test	A30	Old PA with ravelling (2003)	Winter 2011	2.4	Winter damage (corrective)
Test	A1	Old PA with ravelling (2001)	Winter 2011	1.1	Winter damage (corrective)
Pilot	A30	PA (2003)	April 2013	4.9	Preventive
Pilot	A73HRR	TL-PA (2007)	June 2013	6.0	Preventive
Pilot	A73HRL	TL-PA (2007)	June 2013	6.0	Preventive
Pilot	A6	PA (2007)	July 2013	4.3	Preventive
Pilot	A67	PA (2005)	September 2013	4.0	Preventive
Pilot	A15	PA (2006)	September 2013	3.8	Preventive

Table 3: TLPA test sections A73: overview of the test sections [4, 5, 6, 7, 8]

Product	**ESHA (Pentack) Code E**			**BAM (Modiseal® ZX) Code B**		**Heijmans (Modimuls® ZV) Code H**			
Section	1b	2	3	5	6	8	9	11+12	13+14
Length [m]	100	200	200	200	200	50	50	200	200
Name	REF	LVO(E)	LVO(E)	REF	LVO(B)	REF	REF	LVO(H)	LVO(H)
Year 0	X	X	X	X	X	X	X	X	X
Year 1		X	X		X			X	
Year 3	X	X		X	X	X		X	
Year 3 second application			X						

REF = Reference section (no treatment) LVO (E) = Section with product E and so on.

As an example of the approach the layout of a test section to investigate the possibility to extend the service life of a TLPA top-layer on the A73 motorway treated in June 2011 with life extension products to the surface of the thin (25 mm) TLPA top layer is shown in table 3. Extensive research was carried out in 2011 to evaluate the treatment on the A73 motor after application [4,5,6,7,8]. A small investigation was conducted in 2012 to evaluate the rejuvenator products one year after the application. Also extensive tests were done 3 years after the treatment with rejuvenator products [3].

4. RESULTS

4.1 Application aspects

Before any treatment in all cases the PA layer was cleaned with a PA cleaner using a high pressure water and vacuum cleaning system to remove as much clogging as possible. The application process of the rejuvenator products is similar to the spreading of bitumen for surface treatments. Producers like Latexfalt and ESHA are very experienced in applying bitumen emulsion or hot bitumen on dense surfaces as part of a surface treatment with a seal. However, PA as used in the Netherlands, has a very open surface texture (air voids content of 20%), indicating that especially the viscous properties of the product are tailor made for this application. Both the bitumen emulsion and the hot bitumen have to show thixotropic behaviour (low viscosity at higher shear stresses and enough high viscosity when the shear stress is low), in order to prevent the bitumen draining immediately to the bottom of the PA layer. Especially for the bitumen emulsion this is an essential property, because it is applied only marginally above ambient temperature. For the hot applied PMB the fast cooling will normally result in immediate strong increase of the viscosity. These properties are developed by the producers and can be shown with rheological tests.

Very interesting is the use of the Airjet seal system with the surface jet in combination with product H. The applied rejuvenator product is forced in the surface layer with help of the hot air at ca. 550°C blown into the surface with the surface jet. Also during moisture circumstances a first run with the surface jet before application of the products can preheat the PA surface to make sure the application of the emulsion is possible. For the H product a second heat treatment with the turbine is essential to penetrate the rejuvenator product over the total height of the PA. With Nano CT scans and microscopic analyses of cores taken after the treatment it was shown that the bitumen emulsion can penetrate deep into the PA [4,5].

The producers and contractors conducted many experiments to solve the possible problems with the initial skid resistance in the first week after application. From the experiments a method applicable for all products was developed to ensure that the skid resistance is at the level before treatment within a few days. After many experiments a broken glass grit 1/3 mm was chosen for the sanding operations after product application.

Extra efforts were necessary for B product to ensure that this product penetrates the air voids optimally and does not stay at the surface of the stones. All treatments had to be done at night, mostly in autumn at low temperature and often strong wind, resulting in very fast cooling. It was necessary to develop a special extra activity after spraying of product B, due to the immediate high viscosity. After spraying of the hot binder, a pneumatic tired roller was used to press most of the bitumen in the available air voids at the PA surface.

4.2 Functional aspects

Noise, skid resistance and brake deceleration measurements were carried out on all the test sections and pilots [3]. Especially the skid resistance tests were important and the results had to satisfy the requirements of the Code of Practice. An example of the typical development of the skid resistance is given in figure as taken from the pilot A15 [3].

From figure 4 it becomes clear that the skid resistance on the treated sections is temporary decreasing, but that within a period of one week the skid resistance increases to the level before treatment. In principle this tendency was found for all other sections.

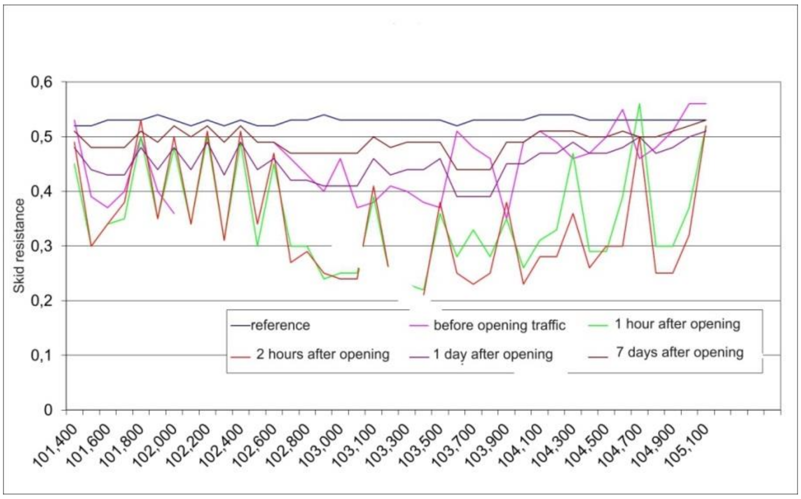

Figure 4: Results of skid resistance measurements during 7 days after the treatment for A15 [3]

The results of the brake deceleration tests on the pilot sections are given in table 4. All the reference sections (R) did meet the requirement of 5.2 m/s2. On treated sections the minimal measured values did not satisfy the requirement the first days after treatment. In case of product B (hot PMB) some problems were observed directly after application. These lower values could be explained in most cases and the problems were solved.

From the results of the noise reduction it can be concluded that for most of the pilots no influence on the noise reduction could be observed [3]. In all cases the effects of the treatments with rejuvenator was marginal. In some cases there was a temporary effect due to the sanding actions after application of the product for skid resistance purposes (probably too high glass grit content), but in general the possible negative effect of the lower air voids content and decreased porosity for the noise absorption was more than compensated by the smoother texture measured after the treatment. In figure 5 the model that summarizes the observed trend by noise experts M+P after many measurements (also in time) shows that after the treatment the slope of the increase in noise in time, is considerably lower for the treated section than for the reference sections who are not treated.

Table 4: Minimum values for the brake deceleration (m/s²) of the pilots the first days after application[3]

	Motorway					
Section	A6	A15	A30	A67	A73 HRL	A73 HRR
REF	> 5.3	> 5.2	> 6.0	> 6.5		> 6.5
E	> 4.5	> 5.4	> 4.8	> 6.0	> 5.0	> 4.8
B	> 4.3	> 3.7	> 5.5	> 4.3	> 4.2	
H	> 5.2	> 5.0	> 6.0	> 5.6	> 5.0	> 4.7

REF = Reference section (no treatment)

Based on the measured noise levels directly after application and in time so far, it is expected that because of the reduction in raveling after the treatment compared to the reference sections, during a number of years after application the noise levels of the treated sections will increase considerably slower that the noise levels from the reference sections. [3,11].

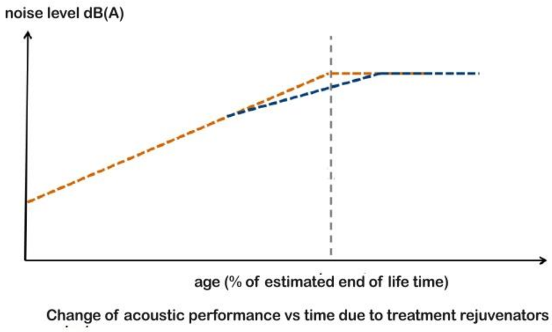

Figure 5: Model developed for the change in acoustic properties in time after application of the products (the blue line) [11]

4.3 Splash and spray.

In order to get an indication on the visibility when driving on the PA during rainy weather, water drainability tests (Becker) were done in the field. Because the results of the Becker test varied enormously already for the reference sections, it was decided to check the air voids contents of the cores and use these values as indication for the possible increase of splash and spray. As said before the air voids content was hardly influenced by the application of the products, so the assumption is that the splash and spray does not increase after one treatment. However, more research need to be done based on the CT scans, especially for the B product, which stays in total in the top 15 to 20 mm. The porosity in the upper 20 mm is an important parameter that can help to explain possible changes in reduction of splash and spray during rainfall.

4.3 Material aspects

The material behaviour was researched as shown in figure 3, with the focus on volumetric properties (change in the porosity, air voids content, etcetera caused by the treatment), mechanical properties (change in mechanical properties related to the treatment) with special focus on the Rotating Surface Abrasion Test (RSAT) testing, chemical properties (softening of the aged binder caused by the rejuvenator?) and functional related material properties (influence of treatment on absorption, texture, drainage, splash and spray). It is not possible to describe the test results extensively in this paper, but the results can be found in [3,4,5,6,7,8,9,15]. Based on the extensive test results on cores from the test sections from motorways A50 and A73 the following general conclusions were drawn for the effect of the treatment on the 5 year old (preventive maintenance) PA layers:

- Siemens CT scans [4] show in general that the air voids content of the treated sections is a little bit lower than for the reference sections in year 0. The Nano CT scans [4] show that the products B and H can be detected at least partly as a separate bitumen addition. This bitumen addition cannot be observed for product E. A second treatment will reduce the voids content further, because binder is added and erosion of mortar will be stopped.

- The nano indentation tests on the mortar bonding bridges [6] clearly show that the mortar bridges from the treated sections have a lower stiffness compared to the mortar from the reference sections. This could be an indication that all three products are capable to rejuvenate the aged bitumen in the mortar bonding bridges.
- The bending tests at a temperature of 5°C [6] show hardly any difference in the stiffness of the beams from the cores from the reference and the treated sections. However, a clear difference in stiffness is observed for the PA 16+ and the top-layer TLPA 8 from the A73. The strength and energy of treated and untreated sections are similar. The bending strength at 5°C is similar for the reference- and treated sections. This means that the investigated sections were still in good condition at the moment of application of the products..
- The microscopic observations [5,9] clearly show that products B and H are visible as bitumen addition at the mortar bonding bridges. No separate bitumen could be observed from samples from the product E sections. With tyhe used analysis techniques it can be seen that products B and H clearly add bitumen to the mortar bonding bridges between the stones (the mortar bonding bridges are surrounded with new bitumen) and they also fill micro-cracks. With other techniques (see figure 6) used by ESHA (http://www.eshainfrasolutions.nl/) it can be shown that product E also adds bitumen to the mortar of Porous Asphalt.

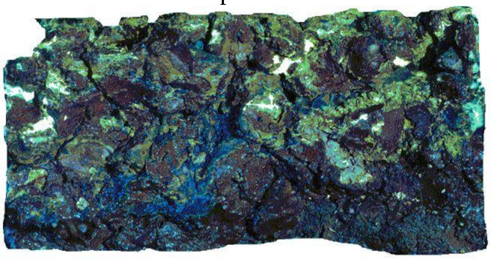

Figure 6. UV picture of Porous Asphalt treated with product E

- FTIR results [3,6,9] show that in general the PA layer from the reference (untreated) sections are aged significantly stronger in the upper part of the layer than in the lower part (based on the so-called Ico values for the increase in ketones C=O). Sometimes it was possible to detect a product with FTIR, in most cases only product B.
- In addition to the FTIR tests it was shown on samples from the motorway A73 that with GPC all three products could be detected through quantification of the influence of these bitumens on the molecular mass distribution of the aged binder in the PA. By using horizontal slices over the height it was even possible to check the distribution over the height [15]. This method is essential to proof that the products are applied and how deep they are entered into the PA layer.
- From statistical analyses on the air voids contents from motorway A50 [16] it is clear that the air voids content varies considerably over the length of the PA layer, even for one section. This makes it very difficult to present firm conclusions due to the variability over the length.

A special test in the program was the RSAT to investigate the resistance to raveling of PA [14]. Normally the RSAT is carried out on slabs, but is this case it was more practical to compose a specimen from three cores with a diameter of 150 mm. A loaded steel wheel with a solid rubber tire drives back- and forward on the composite PA specimen, which is mounted on an axle which only can rotate in one direction. The test temperature normally is 20°C, but in this case a test temperature of 5°C was chosen because a lower temperature is more discriminative for research into raveling of PA. To simulate the shear loading of traffic, the direction of the axle varies a little from the direction of movement. To achieve this, the wheel was fixed in an angle of 33.7° spread the abrasion force over a certain area the specimen rotates slowly, driven by the abrasion forces themselves. In the forward movement of the wheel the specimen is rotating with it and in the backward movement of the wheel the rotation of the specimen is blocked. In this stage the forces are at maximum. The resistance to raveling is expressed as the total amount of loose stones after 24 hours of testing.

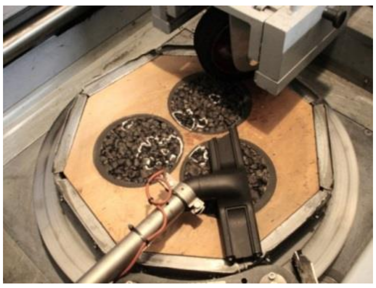

Figure 7: RSAT on 3 cores taken from the test sections [14]

In Table 5 the results are given for test section on motorway A73. From the results of the RSAT [3] it is clear that the treated cores give lower stone loss than the reference cores. This advantage of the treatment in this test is confirmed in all cases (also after 1, 3 years) . For all test sections the RSAT gave this tendency.

Table 5: RSAT (5° C, 24 uur) results after 0, 1 and 3 years after application for A73 [3]

	Cumulative stone losss year 0		Cumulative stone loss year 1		Cumulative stone loss year 3	
	Section code	Stone losss [g]	Section code	Stone loss [g]	Section code	Stone loss [g]
Reference sections	7E1 7B5 7H8 7H9	57.1 (5 h) 64.5 (5 h) 22.8 28.5			7E1D 7B5D 7H8D	34.8 16.2 10.5
E section	7E2 7E3	12.3 41.5 (17 h)	7E2E	6.92	7E2D 7E3DX	6.2 7.6
B section	7B6	34.63	7B6E	0.5	7B6D	0.2
H section	7H11+7H12 7H13	6.93 29.47	7H11E	4.3	7H13D	1.1

5 h respectively 7 h means that RSAT had to be finished due to severe raveling after 5 or 17 hours.

The outcome of the research on the test sections of A50 and A73 is summarized in table 6 for all the tests and shows what they can detect. The conclusions from these tests will be used in further research on the pilots and for acceptance testing of new products on the market.

Table 6: Overview of the effect of the different tests based on the results [2]

subject	Test	Product		
		E	B	H
Detection of product (new bitumen)	Siemens CT	-	-	-
	Nano CT	-	yes	yes
	Microscopy	-	yes	yes
	GPC	yes	yes	yes
Recovery bridges	Nano indentation	yes	yes	yes
	Microscopy	yes	yes	yes
Depth detection	Nanotom CT	-	yes	yes
	microscoop	-	yes	yes
	GPC	yes	yes	yes
Improvement in resistance to raveling	RSAT	yes	yes	yes
	Bending test	-	-	-

Comparison of the results of the material testing as given in in Table 5 with the effects claimed by the producers as summarized in table 1 in chapter 2 shows that:

- All 3 products demonstrate a rejuvenating effect on the aged mortar (based on nano-indentation results) as claimed by the producers.

- For 2 products (B en H) it is proved that also new bitumen is added in addition to strengthening of the mortar bonding bridges (nano CT and microscopy), as claimed.
- All 3 products fill cracks (microscopy) as claimed.
- The depth penetration is as predicted by the producers: product B stays in the upper 20 mm. Product H is penetrating over the whole height of the PA layer and product E can also be detected over the height (GPC, FTIR, nano CT).
- Product H is detected everywhere in the PA, also at the underside of mortar bonding bridges and at all places. This means that they reach with the surfacejet the distribution they claim (nano CT, microscopy)

In summary: the products satisfy all the claims stated by the producers.

4.4 Environmental aspects

The economic consequences of the preventive maintenance method were investigated with the results of an environmental lifecycle impact analysis (LCI), combined with a cost analysis [13]. The reference unit for the calculations was:

- Construction and maintenance of 1 km PA 16+ with a thickness of 50 mm, over the whole width (including emergency lane) for a motorway with traffic class 4 (heavy traffic) during a full maintenance cycle of 34 years.

The quantities per treatment with the products were E = 0.5 kg/m^2, B = 0.4 kg/m^2 H = 0.8 kg/m^2. The producers provided all information necessary for the LCI and LCA, including the exact composition of their products with additives for their LCI profile.

The economic analysis was only done for the construction- and demolition phase. An example is given in Figure 7.

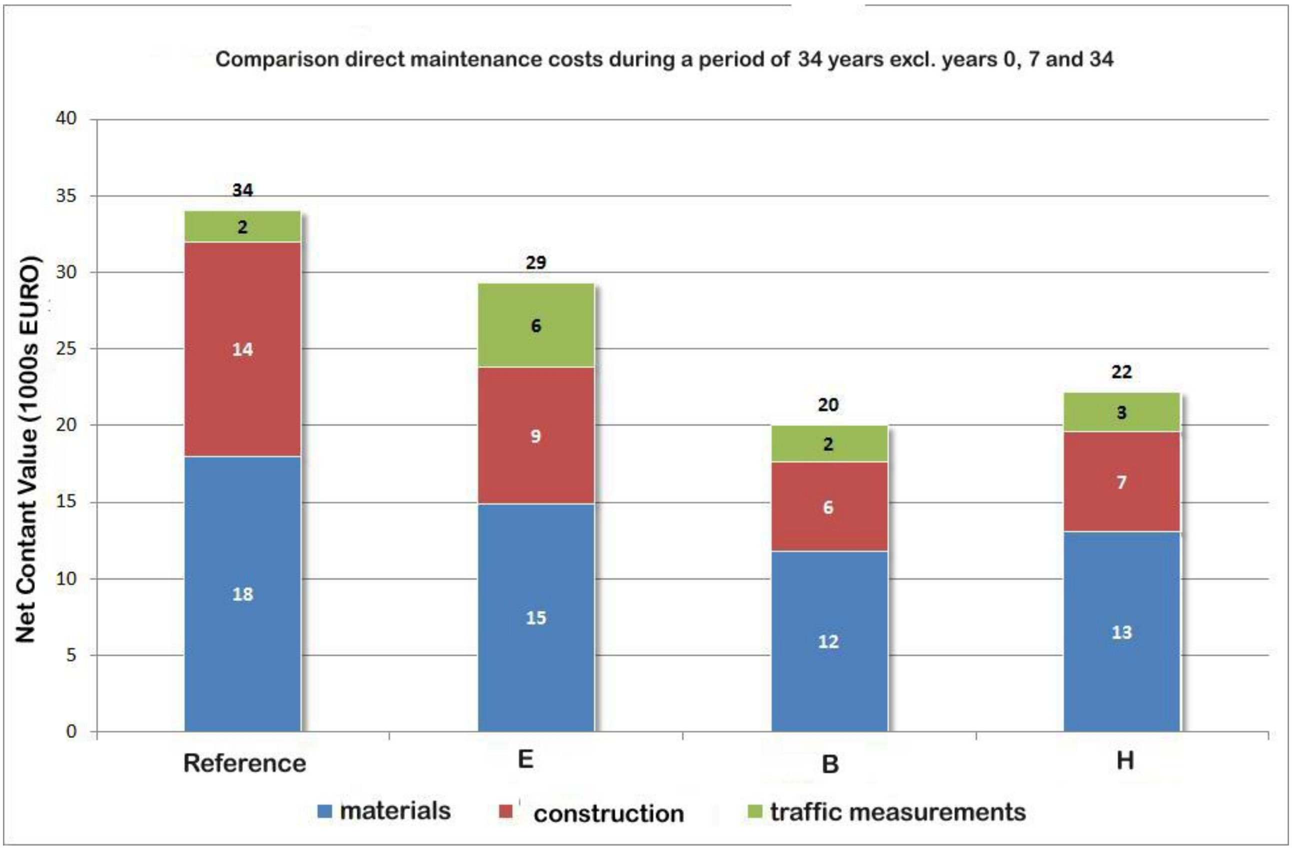

Figure 8 Economic costs [13]

In general the maintenance system with the treatments performed better than the conventional maintenance system [13].

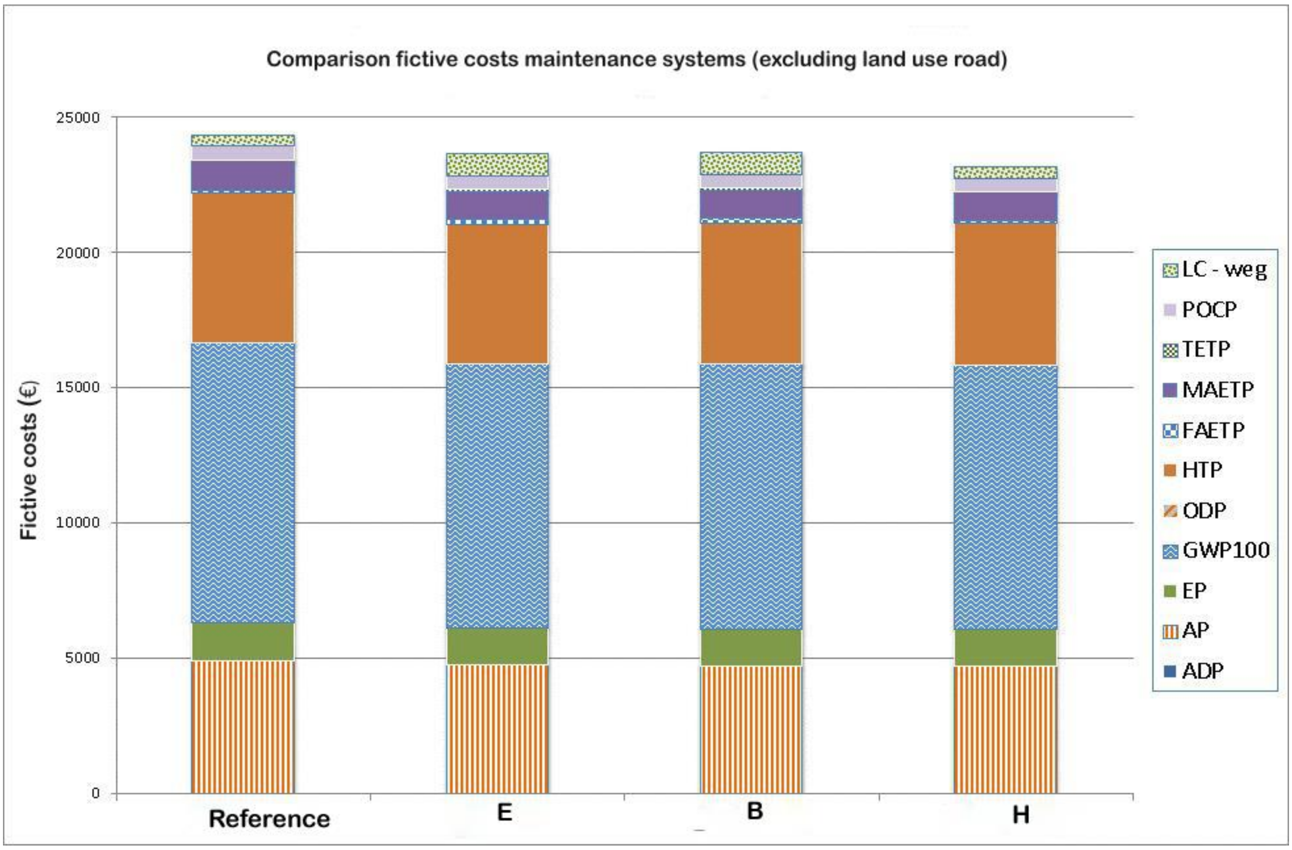

Figure 9: Environmental impact [13]

Without the effect category Land use (raw materials) the environmental impact of the products is even half the value of the impact of the conventional maintenance techniques. Of course there is uncertainty because of the many assumptions that had to be made, but with help of future results of the pilots (long stretches with commercial speeds) this can be improved strongly.

4.5 General.

Visual inspections after 3 and 4 years [3] reported that the treated sections showed practically no raveling, while the reference sections showed considerable ravelling.
Treatment of the winter damage sections was very successful [3]. The winter damage sections could easily get through a severe winter without increase of raveling, making it possible to plan the maintenance in spring or summer after the winter. In all cases the winter damage sections were behaving so good that it was no problem to leave them in place for more than 2 years after treatment.
One problem with the use of the treatments is to predict the right time for the treatment. This should ideally be the moment just before raveling starts [3,9,12,16]. At the moment yearly visual inspections are the basis for estimating the moment raveling is starting, but we need a more reliable method to know the actual state of the PA. A first step is at the moment to use yearly Laser Crack Measurement System (LCMS) as a scientific inspection method to determine the degree of raveling in time [16]. A trigger is needed to determine the right moment for the treatment [3,9,12,16].

5 CONCLUSIONS

Material research

- Several techniques are necessary to get insight into the working of the rejuvenating products. The combination of RSAT (raveling test) + material testing shows that the PA treated with the 3 products strongly improve the raveling resistance compared to the PA reference (untreated) sections.
- The material research has delivered enough technical information for an admission protocol for other products.
- Research is needed to develop a trigger for the right moment of treatment with the products.

Functional aspects

- Skid resistance: the experience is that short after application the skid resistance is critical, but sanding is an adequate measure to keep it at acceptable level before full recovery after at maximum one week.
- The noise reduction in time after treatment (via CPX measurements) will be better than for the reference. The noise level after application is similar to the reference, but the decline in time is slower.

- Water drainability should be related to the variation in the air voids content in PA for each section. This is necessary, because even in one section the air voids content in PA varies considerably.

General:

- The untreated reference PA sections are still in place. The last winters of 2013/2014 and 2014/2015 were soft, but the winters inform 2008 to 2013 were severe winters, especial in 2012 strong frost periods and considerable frost-thaw cycle were reported.
- Based on the research (including inspections, etcetera) a minimum service life extension of 3 years is used for these treatments in maintenance schemes.
- With regards to a second treatment, it is unsure yet if clogging will play a future role after a second application, especially when the air voids content in the bottom part of PA is low after a treatment (10%).
- Application protocol: a schematic model with a decision tree and ratings is developed for the application protocol of the products. A distinction between the three tested product can also be made in the model.
- Specification protocol: a general protocol for this type of product has been developed to allow new products to enter the market (validation protocol).
- With conservative assumptions an LCA and economic analysis have shown that the sustainability profile of this preventive maintenance action compares positive to the standard maintenance strategy.

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