Effect of in-situ treatment on porous asphalt durability and ravelling

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ABSTRACT: This study evaluated the durability of in-situ treated porous asphalt pavement surface (ZOAB) layers using surface treatment agents, both with and without rejuvenating effects. Field cores were extracted from four highway sections before and after treatment to analyze their impact on durability and raveling resistance. Fourier Transform Infrared Spectroscopy showed that the application of these agents led to reduction of carbonyls and sulfoxides without the formation of additional chemical functional groups. Further, micro-computed tomography revealed no significant changes in void distribution or material phases. The rotating surface abrasion test demonstrated that treated sections exhibited 67–82% lesser aggregate loss compared to control, attributed to the effects of applied treatment agents. Overall, the study highlighted that in-situ surface treatments, both rejuvenating and non-rejuvenating, are promising approaches for sustainable pavement maintenance.

1 INTRODUCTION

Porous asphalt is an engineered mixture comprising very little to no fine particles such that the minimum design air void content is 20% (CROW, 2000). Due to high porosity, the use of porous asphalt mixtures (also referred to as ZOAB in The Netherlands) in the surface layer helps reduce traffic noise and hydroplaning risk but also makes it susceptible to deterioration. Raveling is a common distresses in ZOAB (Hagos, 2008) as the exposure to oxygen, moisture, ultraviolet radiations, etc., accelerate material ageing, increasing bitumen viscosity and resulting in stiffer mixtures prone to aggregate loss.

Therefore, it is important to restore the properties of aged bitumen and use maintenance measures that can preserve the pavement condition and extend its service life. In-situ rejuvenation has emerged as a promising approach that extends the service life of pavements by restoring the original asphaltene to maltene ratio (Karlsson & Isacsson 2006). It involves spraying a compound over the existing pavement's surface, targeted at immediate diffusion into asphalt concrete to restore the properties of the aged binder. The first investigation in the United States reported that the rejuvenator penetrated to a depth of about 9.5 mm into the dense asphalt surface, and softened the binder as confirmed by penetration and viscosity measurements of extracted bitumen (Brown & John-son 1976). Another study recommended that in-situ rejuvenation must be conducted on pavements having void content higher than 7% to allow the product to penetrate to a depth of 9.5 mm from the surface and rejuvenate the oxidized binder (Estakhri & Agarwal 1991). Computed tomography scans have confirmed rejuvenator presence at depths of 9-20 mm in ZOAB, with porosity remaining above 20% (Zhang et al. 2015).

Some researchers have highlighted that surface treatments, involving the application of a thin layer of asphalt or other materials, can effectively preserve pavement surfaces (Herrington & Alabaster 2007; Qian & Lu 2015). For example, porous epoxy-modified asphalt mixtures demonstrated superior cohesive properties compared to standard open-graded porous mixtures at 10°C (Herrington & Alabaster, 2007). These mixtures also offer excellent resistance to moisture damage, maintain desired permeability, enhance sound absorption, and improve the durability of ZOAB. Additionally, the use of surface treatment agents, both with and with-out rejuvenating effects, can yield significant economic benefits by extending pavement service life (Singh & Varveri, 2024; Zuniga-Garcia et al., 2018).

Based on the literature, it may be stated that although multiple studies have explored the effects of surface treatment on aged bitumen and asphalt mixture properties, limited efforts have been made to investigate the durability of in-situ treated ZOAB. Thus, the objective of this research was to investigate the durability and raveling resistance of ZOAB before and after in-situ treatments, including a rejuvenator and preservative agent. The results of this study are part of an ongoing investigation that is aimed at evaluating the service life extension of ZOAB and test methods to capture the influence of these treatments on Dutch highway network.

2 METHODOLOGY

The pavement sections investigated herein were constructed between 2011 and 2014, and since then they have been continuously exposed to traffic and environment. Section A and C were constructed with dense ZOAB mix, while sections B and D were designed with a two-layered porous asphalt mix. A single treatment has been applied and multiple field cores of 150 mm diameter were drilled from the pavements before (15-30 cores) and about 2-3 months after treatment (12-18 cores). Sections A, B, and D received in-situ treatments with rejuvenation effects (spraying a bitumen-like compound that could fill the micro-cracks and rejuvenate the aged bitumen in the mortar), while section C underwent a non-rejuvenating surface treatment (applying an engineered compound that penetrates through micro-cracks and interconnected pores to seal the surface, keeping water out and slowing the ageing process). This research does not delve into investigating the mechanism of treatment agents but exploring their influence on durability of ZOAB.

2.1 *Chemical analysis*

To identify the development of additional chemical functional groups due to in-situ treatment, Fourier transform infrared spectroscopy (FTIR) was used in attenuated total reflection mode. From the field specimens, the top slice was cut having a thickness varying from 10-15 mm, and the bitumen was extracted in accordance with International standards (EN 12697-3+A1, 2018). The characteristic peaks and FTIR spectral regions such as sulfoxides, carbonyls, and aromatics were used for analysis. FTIR spectra (two independent measurements) were obtained in the mid-infrared range of 4000 to 650 cm^{-1} with 16 scans per specimen and a resolution of 4 cm^{-1} to identify functional groups present in the samples. The carbonyl and sulfoxide indices were expressed as the ratio of area of specific bands of spectrum to the sum of area under aliphatic bands using Equations 1 and 2.

$$Carbonyl\ index = \frac{A_{1700}}{A_{1460}+A_{1376}} \quad (1)$$

$$Sulfoxide\ index = \frac{A_{1030}}{A_{1460}+A_{1376}} \quad (2)$$

where, A_{1700} = tangential peak area under the curve and above the tangential line between wavenumbers 1750 and 1610 cm^{-1}; A_{1030} = tangential peak area under the curve and above the tangential line between wavenumbers 1030 and 924 cm^{-1}; A_{1460} = tangential peak area under the curve and above the tangential line between wavenumbers 1525 and 1395 cm^{-1}; and A_{1376} = tangential peak area under the curve and above the tangential line between wavenumbers 1390 and 1350 cm^{-1}.

2.2 *Micro-computed tomography*

The internal microstructure of the ZOAB field cores and the presence of different material phase (due to in-situ treatment) were investigated using micro-computed tomography (micro-CT). The imaging was performed on 45 mm diameter cylinders before and after treatment. All the micro-CT scans were performed under identical spatial resolution (voxel size of 90 μm). The projection images were post-processed using a non-commercial software and the images were segmented into different phases based on thresholds of greyscale pixel intensity.

2.3 *Rotating surface abrasion test*

The ravelling resistance of the control, i.e. untreated, and treated sections was evaluated using rotating surface abrasion test (RSAT). Though RSAT measurements are typically performed at 20°C, past Dutch experience has shown that raveling becomes more severe at low temperatures (CEN/TS 12697-50, 2018; Houben & Van De Ven 2014). Hence, the test temperature of 5°C was used. Three drill cores of 150 mm diameter were used to create an RSAT plate (see Fig. 1) and the specimens were subjected to 86,600 wheel passes. A minimum of three replicates were tested for each section, with an exception of one test section, for which only two replicates were tested for the treated mixtures, due to the absence of suitable drill-cores to produce a third test plate. The weight of aggregates larger than 2 mm lost during the test was recorded at various time intervals (1, 4, 8, 12, 16 and 20 h) as well as after the completion of the test (24 h).

Figure 1. Arrangement of RSAT plates and test setup.

3 RESULTS AND DISCUSSIONS

3.1 *Chemical analysis*

The FTIR spectra (enlarged image of the spectral region critical for bitumen ageing in Fig. 2) for the control (Ctrl) and treated (Treat) sections (A, B, C, and D) indicated that in-situ treatment did not result in formation of additional chemical functional groups. Strong unanticipated peaks (nitro compounds) at wavenumbers 1578 and 1540 cm^{-1} were observed but were also present in control specimens, confirming they were unrelated to treatment.

The average carbonyl and sulfoxide indices for each section (3 replicates per section, except for D, where 5 control and 2 treated replicates were tested) are shown in Figure 3. The results showed that the treated sections generally had lower carbonyls and sulfoxides than untreated sections, except for highways C and D, where the indices were similar. The unchanged indices for highways C and D can be attributed to factors such as localized binder oxidation differences before treatment and variability in agent penetration. Section C received a sealing agent, which primarily restricts moisture and oxygen ingress rather than reversing oxidation, leading to minimal changes in ageing indices. For both treated and untreated sections, sulfoxides formed in higher proportions than carbonyls due to higher reactivity of sulfur with oxygen compared to carbon. This aligns with previous studies indicating that carbonyl generation from bitumen ageing occurs slower than sulfoxide formation (Jing et al. 2019).

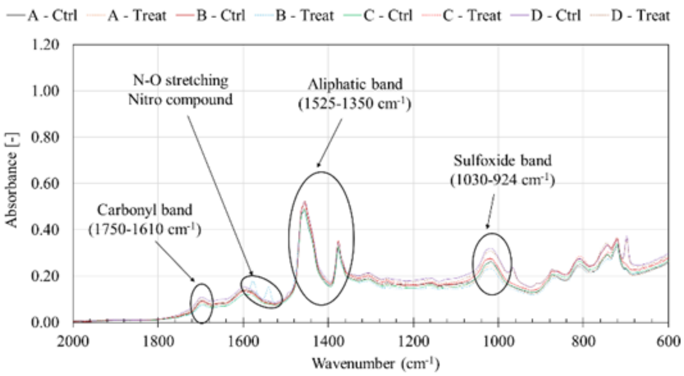

Figure 2. FTIR spectra of critical region for untreated and treated sections.

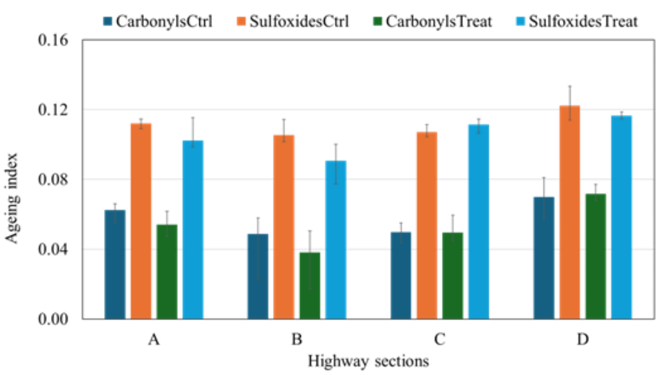

Figure 3. Carbonyl and sulfoxide indices for the four highway sections before and after in-situ treatment.

The FTIR spectra of in-situ treatment agents (confidential data not plotted) exhibited different peak intensities than the binders but similar wavenumbers to control and treated sections, suggesting a chemical composition similar to bitumen. This indicates that the treatments did not introduce new chemical bonds or functional groups but likely influenced the molecular arrangement of polar and non-polar components (Cavalli et al., 2018). The reduction in aging indices may also be due to the availability of additional fresh bitumen-like products following treatment. However, FTIR data alone is insufficient to confirm treatment effectiveness, and further research is needed using additional test methods to assess their impact on bitumen composition.

3.2 *Micro-computed tomography*

The peak histogram phase detection method was employed to detect the presence of treatment agents. A typical histogram of the treated sections is shown in Figure 4, which represents the distribution of greyscale values corresponding to different material phases in the ZOAB cores. Three distinct peaks with low (least X-ray attenuation), intermediate (moderate density), and high (highest X-ray attenuation) greyscale values were observed corresponding to air voids, asphalt mortar, and coarse aggregates, respectively. The histogram curves for treated ZOAB did not show any additional peaks that could indicate the presence of a distinct material phase. The possible reason for the non-appearance of surface treatment agents could be that they either diffused in the mortar or their density was similar to that of bitumen, which did not caused any dramatic changes in the density of treated mixtures. Further, no clear trends were observed in terms of void reduction across the depth of ZOAB and the application of treatment agents did not lead to reduction of air voids.

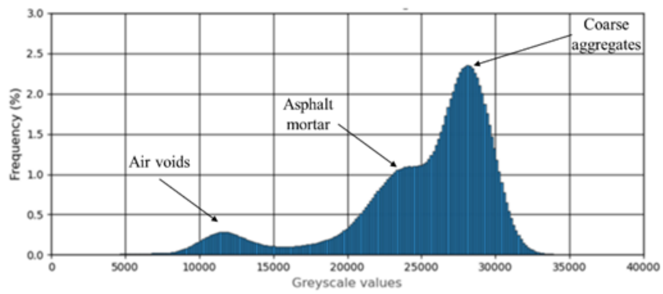

Figure 4. Greyscale histogram for treated sections.

3.3 *Rotating surface abrasion test*

The average aggregate loss (Figure 5) for treated sections was 67-82% lower than control. The variations in weight loss across sections can be linked to aging severity and treatment effectiveness. Sections with higher reduction in carbonyls and sulfoxides showed improved stone retention, with section B experiencing the highest reduction, followed by A and D. Note that the in-situ treatment did not introduce new chemical functional groups but likely diffused physically into the aged binder. This diffusion provided additional fresh binder, strengthening the mastic and bitumen bridges, restoring bitumen properties, and reducing mixture stiffness. Consequently, the binder-aggregate bond strength increased, leading to lower aggregate loss in treated mixtures. However, section C, treated with a sealing agent rather than a rejuvenator, deviated from this trend. The sealing agent functions as a moisture barrier rather than diffusing into the aged binder, explaining the not significant reduction in oxidation indicators. Despite this, it still contributed to improved stone retention by reducing moisture-related stripping effects.

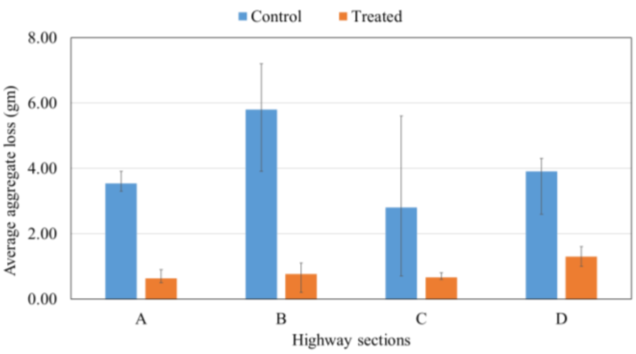

Figure 5. Average aggregate loss in the four highway sections before and after in-situ treatment.

4 CONCLUSIONS AND RECOMMENDATIONS

In this study, different investigations were undertaken to analyze the durability and raveling resistance of in-situ treated ZOAB mixtures. The major conclusions and recommendations are:

- FTIR analysis indicated that in-situ treatment reduced ageing indices by physically diffusing into binder without forming new chemical functional groups, indicating the preservation or restoration of binder properties.
- Micro-computed tomography detected no distinct material phases, indicating that treatment agents either diffused into the binder or had a density similar to bitumen, causing minimal changes within the mixtures.
- The in-situ rejuvenation reduced the aggregate loss by up to 82%, attributed to the reduced stiffness of the mixture.

Future research will focus on incorporating advanced performance characterization methods to better understand and quantify the effects of in-situ treatments on aged binder properties and pavement service life. In-situ treatment, already a mainstream pavement preservation technology in the Netherlands, is a promising method to extend asphalt service life, with potential for wider global adoption as a sustainable practice.

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