



Exploring the Potential of Microalgae as an Alternative Aged Bitumen Rejuvenator

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Abstract

Ongoing efforts to phase out fossil fuel (crude oil) dependency is forcing the asphalt industry to evolve, i.e. to look for new sustainable, circular and biobased alternative product to replace bitumen (a crude oil product). In an effort to improve its sustainability the asphalt industry has perfected the asphalt recycling process. Whereby reusing old asphalt, simply by rejuvenating aged bitumen, allows the industry to reduce the use of fresh bitumen and in turn reduce environmental impact and improve sustainability of road construction and maintenance. However, the process requires use of light (crude) oils to rejuvenate Recycled Asphalt (RA) bitumen. In a further effort to remove fossil fuel-based oils in the asphalt recycling process, researchers have started to investigate alternative products, such as bio-oils as rejuvenation agents.

This study investigates use of biomaterials, namely: microalgae lipids (oils), microalgae biomass, soybean oil and palm oil, as rejuvenating agent. Their performance was evaluated against that of a commercial rejuvenator. A multi-scale material testing approach, that includes chemical, and mechanical evaluations, was employed to evaluate the effectiveness of the bio-oils and microalgae biomass as rejuvenators. Bio-oils and microalgae biomass were incorporated into RA bitumen at dosage of 3wt.%, with chemical changes analysed using Gel Permeation Chromatography (GPC), Fourier Transform Infrared Spectroscopy (FTIR), and chemical fractionation (SARA). Mechanical performance of the blends was assessed by employing needle penetration (pen) and softening point (Ring and Ball) tests. Performance of bio-oils and microalgae biomass were further assessed by including them into an asphalt mix containing 30% Recycled Asphalt (RA), where bio-rejuvenator content was 0.15wt%. The performance of the mixtures was evaluated through a testing programme that included: Indirect Tensile Stiffness Modulus (ITSM), Water Susceptibility, Wheel Tracking and the Thermal Stress Restrained Specimen Test (TSRST).

Findings highlight the potential of biomaterials, such as microalgae oils and microalgae biomass as a sustainable and effective agents for restoring the functional properties in asphalt mixtures. It also became clear that the rejuvenators do not fully restore the chemical composition of the bitumen, therefore more research is recommended into a framework to assess rejuvenation effectiveness on binder level.

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Highlights

1. Bio-oils and microalgae biomass function as effective asphalt rejuvenators, producing mixtures with strong durability performance.
2. Microalgae biomass, without microalgae oil extraction, showed clear potential as an asphalt rejuvenator.
3. The chemical properties and physical performance test of RA bitumen bio-oil blends did not show a standard trend. A better understanding of correlation of biomaterials in asphalt binders and their performance in asphalt mixes is needed.

Introduction

For over a century bitumen is a key constituent in an asphalt mix design and road construction [1, 2]. Bitumen binds the asphalt rock skeleton together and its visco-elastic properties gives the asphalt flexibility and resistance to high traffic loading and extreme weather conditions, such as, rain, ice, snow and heat [3]. Bitumen also has self-healing abilities [4, 5]. It is capable to repair (close) microcracks that appear after extreme traffic and environmental loading [6]. However, over time asphalt loses this healing (self-repairing) ability. During its service life molecules in bitumen evaporate, polymerize and oxidize and bitumen becomes brittle and loses its ability to self-repair [6, 7]. Over time cracks appear and lead to the pavement failure, requiring partial repair (patching) or in some extreme cases a full pavement replacement [8, 9]. However, the removal and replacement of an asphalt pavement does not mark the end of the asphalt material's service life.

Asphalt and road industry since 1970, have developed, optimised and perfected the asphalt recycling procedures [10, 11]. In some cases, the process is so efficient, allowing 100% asphalt recycling [12]. Asphalt recycling means reclaiming old material (Recycled Asphalt, RA) and combining it with fresh aggregates, bitumen (a crude oil product), and softer bitumen or a rejuvenating agent [10, 13]. The primary aim of the recycling process is to restore the properties of the aged asphalt mix, by reducing its brittleness [14]. If recycling percentages are low or the aging in the asphalt is moderate, recycling can be performed by introducing, only, a softer binder [13]. However, in case of a higher ageing degree or higher recycling percentages a rejuvenation agent is needed to restore the asphalt properties. The goal of this rejuvenation agent is to restore the original molecular structure of the aged (recycled) bitumen, by replacing its lost maltenes and saturants and break down agglomeration of molecules [15, 16]. To achieve that, a small amount of rejuvenator is added, between 3% - 6% of recycled asphalt bitumen weight, to the new asphalt mix [17-21].

Traditionally, oils originating from the crude oil distillation

are used as asphalt bitumen rejuvenators [22]. Nonetheless, in an effort to make the asphalt production more sustainable, renewable bio-based products are being studied [23]. Recent studies have shown that food-based by-products, such as vegetable oils, can function as asphalt rejuvenators [24-28]. However, dedicating agricultural land to grow crops for asphalt bitumen rejuvenator production, and diverting potential food resources toward asphalt production raises sustainability and ethical concerns in a world already facing increasing pressure on food supplies [29]. A more responsible approach would be to explore alternatives like non-edible biomass, which offers a promising renewable feedstock [25]. Biomass aligns with circular-economy principles by enabling the use of industrial by-products and secondary materials in the production of asphalt bio-binders and aged bitumen bio-rejuvenators [21, 25, 30, 31]. The wood byproducts, such as lignin and tall oil, are being well explored to date [23, 32, 33] and showed good performance [34, 35] and received good feedback (acceptance) by the road construction crews – as wood-based products have pleasant (woody) smell in comparison to the crude oil based products. However, demand on biopolymers, such as lignin, from competing industries [36], for example polymer industry, are making availability of lignin and tall oil for road construction challenging. According to Chisti [37], microalgae is only biomass source that is capable of displacing crude oil products. Microalgae stand out from conventional oil-producing crops due to their fast growth rate and high lipid content. Under typical cultivation conditions, microalgae can double their biomass within 24 hours [37]. Microalgae are known for their high lipid content, typically around 30 – 60 % dry weight, e.g. *Nannochloropsis Oceanica* [38]. However, with optimised cultivating technique the lipid content of some of the microalgae species, e.g. *Schizochytrium* sp., can be up to 77% dry weight [37].

Furthermore, microalgae cultivation and asphalt bio-binder/rejuvenator can be linked to the wastewater purification process to bring further environmental benefits [39]. Microalgae can effectively remove nitrate and phosphate from wastewater due to their high nutrient uptake and continuous photosynthetic activity. Since these wastewater-grown microalgae are not suitable for food, they can be used to produce materials for road construction [31, 40]. This creates an opportunity for the asphalt industry to adopt microalgae lipids as a more sustainable alternative to conventional crude oil-based bitumen rejuvenators. Chailleux et. al. [40, 41], Audo et. al. [42] and the BioRePavation project [43] demonstrated that lipids (oils) derived from microalgae can serve as an asphalt binder for both producing new asphalt mixtures and enhancing asphalt recycling processes. Tabaković et al. [21] demonstrated the potential of directly using microalgae biomass, as a rejuvenator for aged bitumen. This would be a promising step toward improving sustainability of microalgae use in asphalt production, as it

skips the energy demanding lipid extraction process, and offers an opportunity to match the current bitumen rejuvenator market price, which is less than 3 €/kg [44].

This study builds on Tabaković et. al. [21] where microalgae biomass and microalgae lipids performance as bitumen rejuvenators were investigated in comparison to a commercially available rejuvenator and two vegetable oils (palm oil and soybean oil). The study is split into two parts. The first part investigates effect of microalgae biomass, microalgae lipids and bio-oils on a bitumen blend. Here, microalgae biomass, microalgae lipids and bio-oils are used in order to rejuvenate aged bitumen. Performance of microalgae biomass, microalgae lipids and bio-oils were compared to a commercially available aged bitumen rejuvenator. The second part focuses on the use of microalgae biomass, microalgae lipids and bio-oils as rejuvenator of recycled asphalt bitumen within a full asphalt mix; SMA 11b. The performances of the asphalt mixtures containing microalgae biomass, microalgae lipids and bio-oils are also compared to a commercially available bitumen rejuvenator.

Materials

Bitumen, Rejuvenating Oils and Blends

Microalgae biomass (*Nannochloropsis oceanica* paste) was supplied by AlgaePARC laboratories at Wageningen University. The microalgae cultivation was carried out in accordance with Benvenuti et al. [45]. The microalgae lipids were subsequently extracted from the *Nannochloropsis oceanica* paste by Biobased and Circular Technologies department at TNO Petten.

Two additional bio-based oils were included in the study: Soybean Oil, sourced from Ademia Cosmetics, and Palm Oil, sourced from Cosmetics Natural Oils Ltd. A commercially available bio-based rejuvenator, Neomex® Hr was provided by the Latexfalt B.V. and fresh (neat) bitumen 70/100pen was provided by the Breedon Group Plc.

The ageing method and the blending procedure of aged bitumen and bio-oil rejuvenators are explained in the paper on which this works builds [21]. Five different blends were prepared using aged bitumen combined with four different rejuvenating oils (3% by weight), along with one additional blend incorporating microalgae biomass. The properties, namely: pen value and softening point, of neat and aged bitumen and prepared blends, containing aged bitumen and rejuvenating oils and microalgae biomass are summarised in Table 1. Pen values and softening point values indicate that rejuvenating oils in aged bitumen blend did not soften the aged bitumen sufficiently to restore the aged bitumen to the original values of the neat bitumen. These results indicate that for all used bio-oils, a higher amount of rejuvenator is needed to soften the bitumen to required softening point. However,

results do indicate that all rejuvenators have the ability to soften the aged bitumen. The palm oil blend shows the most effective softening of all blends with the highest pen value 68dmm and the lowest softening point 49.2°C.

Table 1: Needle penetration (pen) value of the 70/100pen bitumen with microalgae lipids and biomass as a rejuvenator.

	Penetration (dmm)	Average Softening Point (°C)
Sample	EN 1426: 2025	EN 1427:2015
70/100pen Neat Bitumen	86	46.0
70/100pen Aged Bitumen	43	53.1
70/100pen Aged Bitumen + Microalgae Lipids	53	50.5
70/100pen Aged Bitumen + Microalgae Biomass	45	53.0
70/100pen Aged Bitumen + Soybean oil	59	52.6
70/100pen Aged Bitumen + Palm oil	68	49.2
70/100pen (aged) + commercial bio-rejuvenator	59	50.2

Asphalt mix: SMA11b + 30% RAP

Reclaimed asphalt (RA) was obtained from a single source stockpile in Netherlands, supplied by Asphalt Production Amsterdam (APA). By obtaining RA from a single stockpile, the concern of the RA variability is eliminated. Three representative samples of 1kg of the RA were taken from the stockpile to analyse the RA material. Aged bitumen was recovered according to EN 12697-1:2005, the bitumen content was determined to be 4.1% by weight. The particle size distribution of the aggregates was determined in accordance with IS EN 12697-2:2002 and is presented in Table 2, alongside the aggregate distribution of the fresh aggregates. The RA grading results show that the RA is a continuously graded material. This enables the RA to partially replace a portion of each constituent of the fresh aggregates.

SMA 11b mix containing 30% RA was designed following EN 13108-5: 2006. Figure 1 presents the mix grading, which shows that the mix designs fall within the standard limits for target composition. The standard limits for target composition enabled us to optimise the particle size distribution for the mix designs, which in turn allowed the mixes to be designed as shown in Table 3. The grading limits are tight which resulted in higher percentages passing for aggregates below 10mm. The microalgae biomass, microalgae lipids and bio-oils are added to the asphalt mixtures in amounts of 0.15 % of total

Table 2: Aggregate Particle Size Distribution.

Sieve Size (mm)	Constituents					
	Bestone 8/11	Bestone 4/8	Sand (Bestone 0/2)	Wigro 0/0 Winterswijk	Backhouse dust 0/0 Productie	Recycled Asphalt
16	100.00	100.00	100.00	100.00	100.00	100.00
11	89.32	100.00	100.00	100.00	100.00	99.10
8	16.20	90.01	100.00	100.00	100.00	88.40
5.6	2.95	41.98	100.00	100.00	100.00	48.50
2	1.33	3.73	92.97	100.00	100.00	11.70
0.5	0.96	1.04	36.11	100.00	98.70	7.90
0.125	0.54	0.57	5.35	100.00	78.50	4.10
0.063	0.14	0.30	1.75	82.00	58.30	2.30

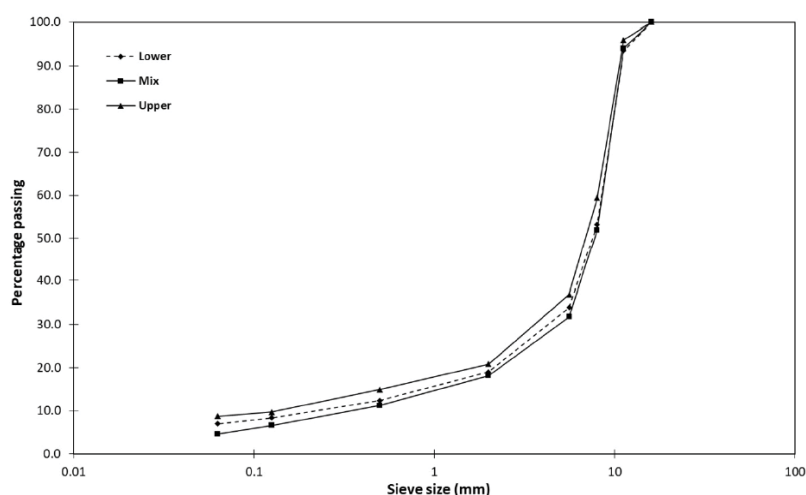


Figure 1: Mix Particle Size Distribution.

mix weight or 2.3% by weight of total binder (neat bitumen, RA bitumen and rejuvenator) weight. Using this mix design, asphalt test slabs of 50mm thick and 500x500mm were made in the laboratory.

Methods

Bitumen Test Methods

Gel Permeation Chromatography (GPC)

The GPC test, in accordance with EN ISO 13885-1:2020, and following the Tabaković et al. [31] procedure, was used to determine the molecular weight and size distributions of the bitumen + bio-oil/mass samples. The components, molecular size separation was achieved using three columns, (APC XT 45, 1.7µm, APC XT 200, 2.5µm and APC XT 450, 2.5µm). Tetrahydrofuran (THF) served as both the eluent and solvent for preparing solutions at approximate concentration 1.2 g/l, which were filtered through 13 mm, 0.45µm Milex FH syringe microfilter to remove insoluble material. The test column temperature was maintained at 35°C with an isocratic flow rate of 0.5ml/min. Detection was carried out using

a Photodiode Array Detector (PAD) (190- 450nm) and a Refractive Index Detector (RI), with the PDA at 254nm used for determining molecular weight.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR was used to assess the dominant chemical functional groups in the neat, aged and rejuvenated bitumen samples, following the protocol of Hofko et. al. [46]. All analyses were performed using a Perkin Elmer Universal ATR accessory over a wavenumber range of 4000 – 600 cm⁻¹, with a resolution of 4 cm⁻¹ and 24 scans. The carbonyl (C=O) and sulfoxide (S=O) indices were calculated to evaluate the rejuvenating effect of the bio-oils, microalgae biomass and commercial rejuvenator on aged bitumen. The functional groups indices are calculated following the Huang et al [47], via equation 1 and 2

$$I_{C=O}(\text{Carbonyl Index}) = \frac{\text{Area of peak limits 1635 to 1735 (Cm}^{-1}\text{)}}{\text{Area of peak limits 1349 to 1538 (Cm}^{-1}\text{)}} \quad \text{Equation 1}$$

$$I_{S=O}(\text{Sulfoxide Index}) = \frac{\text{Area of peak limits 980 to 1082 (Cm}^{-1}\text{)}}{\text{Area of peak limits 1349 to 1538 (Cm}^{-1}\text{)}} \quad \text{Equation 2}$$

Table 3: Mix Composition.

Mix Constituent	Mix proportion (%)
Bestone 8/11	49.9
Bestone 4/8	1
Sand (Bestone 0/2)	9.05
Filler - Wigro 0/0 Winterswijk	3.5
Filler – Backhouse dust 0/0 Productie	1
Dripping Inhibitor	0.3
RA (ZOAB PR saved 5/8 ARB)	30
RA bitumen rejuvenating oil	0.15
Bitumen (70/100pen)	5.1

SARA analyses

A SARA analyses was conducted to assess the colloidal stability of aged bitumen and rejuvenator blends. Because the molecular structures of heavy oils and bitumen are highly complex, accurate quantification of individual compounds is virtually impossible. Therefore, to characterise the chemical composition of bitumen, hydrocarbon group-type analysis is commonly applied [48]. Liquid Chromatography (LC), the core technique underlying SARA, separates bitumen into saturates, aromatics, resins, and asphaltenes based on the solubility behaviour. The resulting SARA fractions provide insight into blending compatibility, stability, fouling and coking tendency and overall bitumen stability [49, 50].

Asphalt mix test methods

Bulk density - and coring

The bulk density was carried out in accordance with EN 12697-6. Eight specimens were cored out of the test slab and left to dry for 24h. After drying specimen's dimensions and weight (m1) were recorded and dry density calculated. Specimens were immersed a water-bath at room temperature for 30 min. Once specimens were sufficiently saturated the mass of the saturated specimen (m2) while saturated were recorded. Table 4 summarises calculated specimen bulk density results.

The test programme was designed to comprehensively evaluate mechanical performance of asphalt mixtures. Table 5 summarises the mechanical tests, testing conditions and relevant European standards used in study.

Results

Binder blend

Molecular weight

Table 6 summarises GPC test results, presenting the number-average (Mn) and weight-average (Mw) molecular weights

for all bio-oils, microalgae biomass, commercial rejuvenator, neat bitumen, aged bitumen and rejuvenated aged blends. The initial observation shows that bio-oils, microalgae biomass and commercial rejuvenator have significantly lower Mw, comparing to neat, aged and rejuvenated bitumen blends. The results further show that ageing and addition of rejuvenating oils increases the molecular weight (Mw) of the bitumen blends. It was expected that molecular weight will increase with ageing, because of evaporation, polymerization and oxidation processes within the bitumen. However, it was not expected that rejuvenating oils both from microalgae and from standard commercial rejuvenating oil, will increase the blend molecular weight (Mw) especially as their Mw is lower than aged bitumen Mw. The polydispersity index (PDI), a measure of molecular weight broadness, is calculated using following equation:

$$PDI = \frac{M_w}{M_n} \quad \text{Equation 3}$$

The PDI for all five blends, including the neat bitumen, shows broad molecular dispersity (>2,0). All blends fall within a narrow range (2.69 – 2.76), suggesting consistent high molecular heterogeneity across the samples. However, the results show that the incorporating bio-oils or microalgae biomass, does not return the Mw and PDI values to those of the neat bitumen. In fact, they promote further increase in molecular weight and polydispersity, which could even be interpreted as increased ageing. It is likely that the blending process, executed at 160°C for 30 minutes, introduced additional bitumen ageing, contributing to the formation of higher molecular weight components in the blends. This apparent ageing effect due to the relatively long period at increased temperature during blending seems to be stronger compared to the addition of the lighter fractions from the bio-oils. However, mixing in asphalt plants is performed using powerful mixing equipment, and hence substantially shorter mixing times are applied in practice (10 to 30 seconds). Therefore, it is expected that this apparent ageing effect might be less in full scale application.

Functional Groups

The BRUKER software was used to correct base line for FTIR spectra comparison. The corrected base line spectra plots of neat, aged and rejuvenated bitumen blends at the wave number ranging from 600 cm⁻¹ to 4000 cm⁻¹ are shown in Figure 2. Aged bitumen and bio-rejuvenated blends display nearly the same functional groups, which is logical as the blends consist mainly of aged bitumen with only 3 % bio-oil. All samples show small peaks at 1031cm⁻¹ (S = O stretching) and distinct peaks at 1700cm⁻¹ (C= O stretching), the last one resulting from the break of the C = C bonds and generation of carbonyl during bitumen oxidation as a result of ageing.

Table 4: bulk density and void content values of SMA 11B mix containing 30% RAP and various rejuvenators.

Mix	Bulk density	Void content
	(Mg/m ³)	(%)
SMA 11B + 30% RAP – commercially available bio-rejuvenator (reference)	2.31	7.7
SMA 11B + 30% RAP – Microalgae lipids as rejuvenator	2.35	6.2
SMA 11B + 30% RAP – Microalgae biomass as rejuvenator	2.33	6.9
SMA 11B + 30% RAP – Soybean oil	2.28	8.9
SMA 11B + 30% RAP – Palm oil	2.31	7.7

Table 5: Mechanical tests for asphalt mixtures.

Test	Conditions	Standard
Indirect Tensile Stiffness Modulus (ITSM)	temp. 20°C	EN 12697-26
Water Sensitivity	-	EN 12697-12
Indirect Tensile Strength	temp. 15°C	EN 12697-23
Wheel Tracking (Rutting Test):	700N loading @ frequency 26.5cycles/min, for Nf 10,000 cycles, @ temp. 45 °C	EN 12697-22
Thermal Stress Restrained Specimen Test (TSRST)	Start temp. 20°C, end temp -40°C, duration 6 hours @ temp. gradient 8.5°C/hour.	EN 12697-46

Table 6: Mass distribution (daltons), of the rejuvenators and 70/100pen bitumen blends with varying rejuvenators.

Rejuvenator	Mn	Mw	PDI
Microalgae lipids	781	1005	1.3
Microalgae biomass	470	618	1.3
Soybean oil	605	913	1.5
Palm oil	963	1288	1.3
Commercial bio-rejuvenator	586	723	1.2
Blend	Mn	Mw	PDI
70/100pen Neat	841	1800	2.1
70/100pen (aged)	890	2186	2.5
70/100pen (aged) + Microalgae lipids	917	2533	2.8
70/100pen (aged) + Microalgae biomass	918	2479	2.7
70/100pen (aged) + Soybean oil	912	2486	2.7
70/100pen (aged) + Palm oil	-	-	-
70/100pen (aged) + commercial bio-rejuvenator	912	2457	2.7

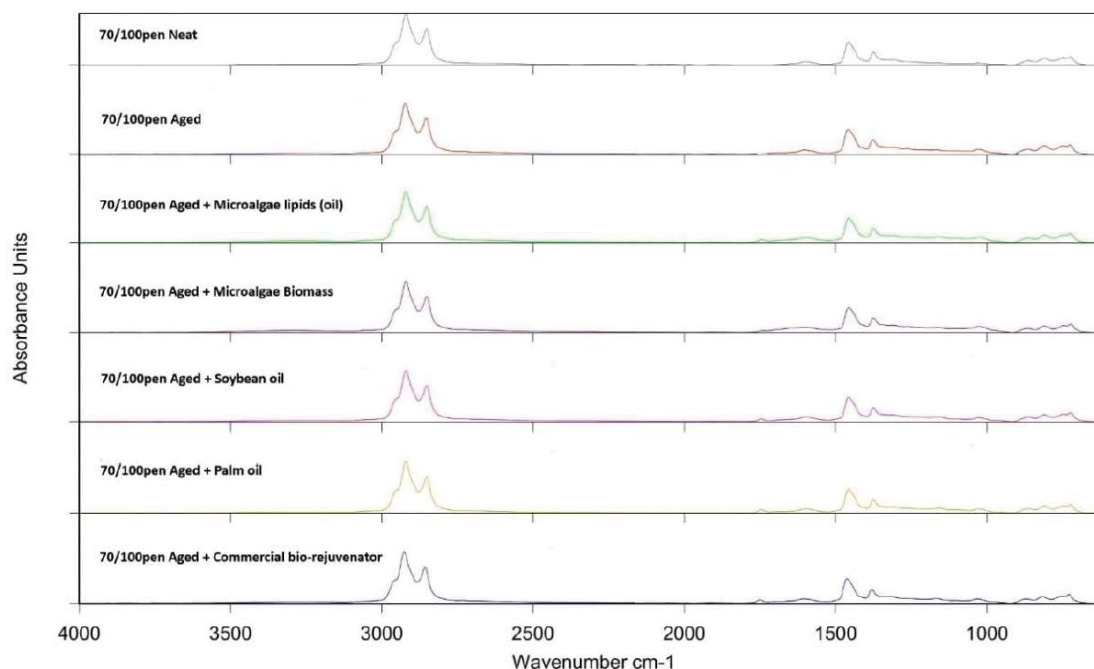


Figure 2: FTIR spectra of bitumen blends samples.

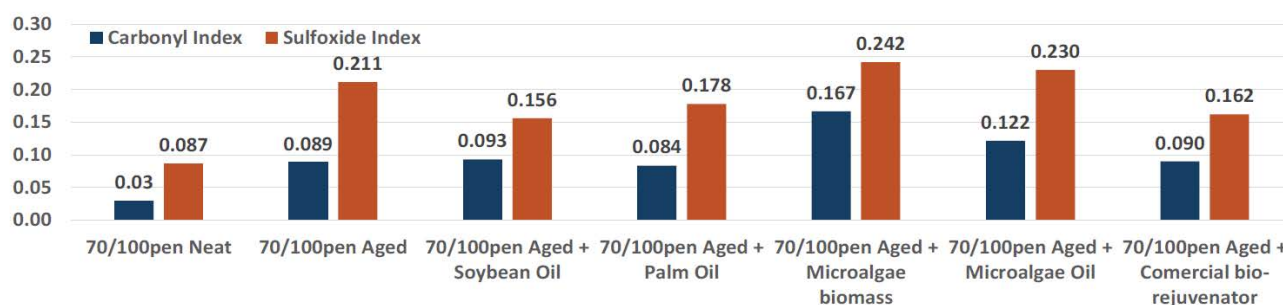


Figure 3: Carbonyl and Sulfoxide Indices for bitumen blends.

As it is not possible to quantify the differences in the specific aging peaks that relate to the carbonyl (C=O) and sulfoxide (S=O) peaks from the spectra presented in Figure 2, a quantified comparison is made using the carbonyl and sulfoxide indices, which are calculated according to Equation 1&2 from section 3.1. Figure 3 presents the carbonyl and sulfoxide indices for all blends. The graph clearly shows an upward trend in both indices with increasing bitumen ageing. The neat bitumen results show the lowest carbonyl and sulfoxide indices values. However, the results show an inconsistent trend across the rejuvenated blends. The blend containing Soybean oil shows a slight increase of carbonyl index but significant decrease in sulfoxide index compared to the aged bitumen without additions. Palm oil shows a decrease in both carbonyl and sulfoxide indices. Both microalgae oil and microalgae biomass blends shows significant increase in both indices. Whereas, the commercial bio-rejuvenator, similarly as Soyabean oil blend, shows only slight increase

in carbonyl index and a pronounced decrease in sulfoxide index. These indices, therefore, show no positive impact of both microalgae lipid (oil) on bitumen oxidation. However, in none of the blends the ageing level is restored to the neat values. This was to be expected, as the addition of a small percentage of bio-oil will not remove oxygen from the binder, it will mainly reduce the oxygen content by diluting it. It is less likely that oxidation reactions will be reversed.

Figure 4 illustrates the analysis of the SARA test results of the 70/100pen blends (neat and aged) containing the various bio-oil as aged bitumen rejuvenator. The results show that ageing increases the Resins and decreases Aromatics and Asphaltenes, while the Saturate fraction stays roughly the same. Addition of bio-oils slightly decreases the Saturates, and to a larger extend Aromatics, while the amount of Asphaltenes increases. The amount of Resins increase for all bio-oils, expect for palm oil.. The addition of bio-

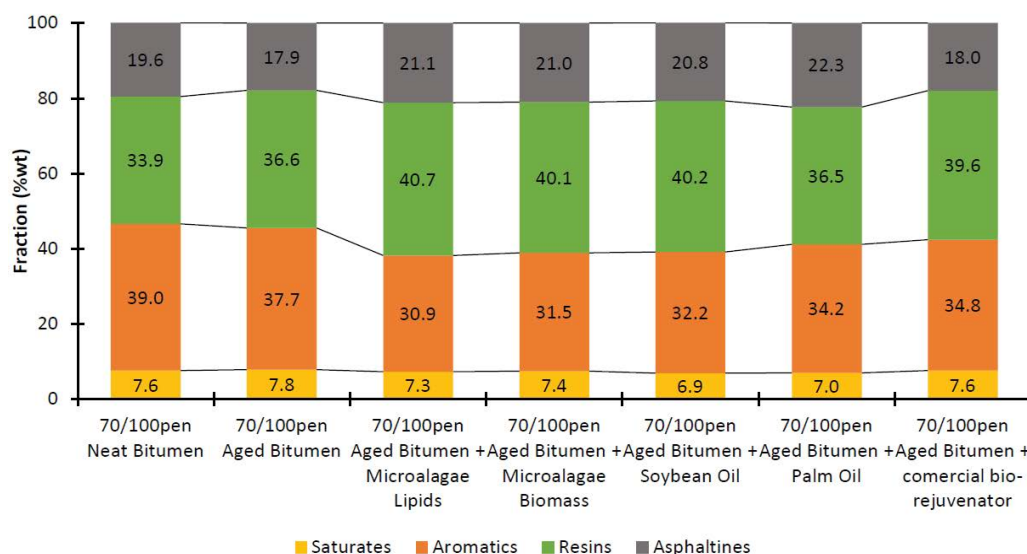


Figure 4: SARA fractions of the 70/100pen bitumen with microalgae lipids and biomass as a rejuvenator.

oils did not restore the initial structure of the bitumen, but actually changed it further from the neat bitumen profile. The commercially available rejuvenator results in the exact same percentages of saturates 7.6% as the neat bitumen, however the other fractions are also not restored to their original values.

Asphalt mix

Indirect Tensile Stiffness Modulus test

Table 7 summarises the indirect tensile stiffness modulus (ITSM) test results, at 15°C, of SMA 11B + 30%RAP with a commercial rejuvenator as reference, and various bio-based rejuvenators including microalgae lipids, and microalgae biomass. The results show that all the tests are passing EN 12687 – part 26 standard requirement. Results also show that the mix containing microalgae biomass as bitumen rejuvenator has lowest stiffness modulus at 1.6GPa. This was expected, as the biomass introduces more material that has a limited stiffness. The mix containing microalgae lipids demonstrates a stiffness that is close to the commercially available aged bitumen rejuvenator. Out of all bio-oils

the Soybean oil showed a stiffness recovery closed to the commercially available bio-rejuvenator.

Indirect Tensile Strength

Table 8 shows the indirect tensile strength test results of SMA 11B + 30%RAP with a commercial rejuvenator as reference, and various rejuvenators including microalgae lipids, and microalgae biomass. The results show very compatible IT strength of alternative rejuvenating agents including microalgae biomass. The mixtures containing microalgae biomass showed highest strength of 1.24MPa and mix containing soybean oil lowest strength of 1.01MPa.

Indirect Tensile Strength Ratio Test (ITSR)

The ITSR tests assesses the resistance of asphalt against moisture damage, by comparing the strength of a specimen subjected to water conditioning to a dry specimen (the value reported in the previous section). EN 12697-12:2018 requires that this ratio is at least 80%. The results are presented in Figure 5.

Table 7: Indirect Tensile Stiffness Modulus test results of SMA 11B mix containing 30% RAP and various rejuvenators.

Mix	Indirect Tensile Stiffness Modulus – ITSM (MPa)
SMA 11B + 30% RAP – commercially available bio-rejuvenator (reference)	2032
SMA 11B + 30% RAP – Microalgae lipids (oil)	1922
SMA 11B + 30% RAP – Microalgae biomass	1661
SMA 11B + 30% RAP – Soybean oil	1982
SMA 11B + 30% RAP – Palm oil	1809

Table 8: Indirect Tensile Strength test results of SMA 11B mix containing 30% RAP and various rejuvenators.

Mix	(MPa)
SMA 11B + 30% RAP – commercially available bio-rejuvenator (reference)	1.13
SMA 11B + 30% RAP – Microalgae lipids	1.13
SMA 11B + 30% RAP – Microalgae biomass	1.24
SMA 11B + 30% RAP – Soybean oil	1.01
SMA 11B + 30% RAP – Palm oil	1.14

The figure shows that each mix meets the requirement of 80%. This indicates that all mixtures exhibit a sufficient resistance to water damage. The results further show that all mixtures containing test bio-oils and microalgae biomass outperformed the control mix, incorporating the commercial bio-rejuvenator. The strongest performance was given by mix containing microalgae lipids with ITSR value of 112.2%. The mix containing microalgae biomass as a rejuvenator also performed well with ITSR value of 90.9%, which can be interpreted as an indication that the presence of the biomass does not have a very negative influence on the water sensitivity.

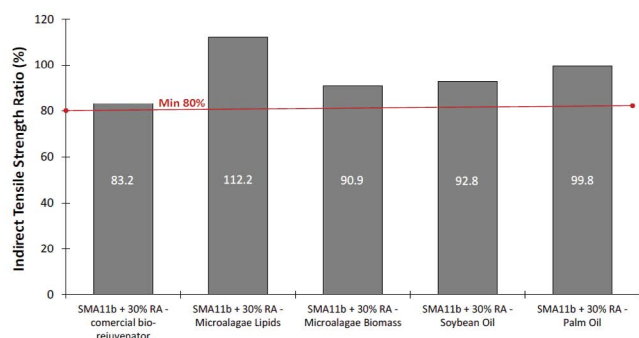


Figure 5: Asphalt mixes durability: Indirect Tensile Strength Ratio test results of SMA 11B mix containing 30% RAP and various rejuvenators.

Wheel Tracking

Table 9 shows the rut depth results from the wheel tracking test, at 10,000 wheel passing cycles. Results show that all mixtures meet the asphalt mix performance requirement. However, the mix containing microalgae biomass as rejuvenator demonstrated a high resistance to rutting, with a proportional rut dept of 7.3%. Which is 3.8% lower than mix containing commercial aged bitumen rejuvenator. The mix containing microalgae lipids as a rejuvenator also showed good resistance to rutting, with proportional rut dept of 8.2%. The best performing bio-oil was palm oil with rut dept of 3.7mm and proportional rut depth of 6.8%.

Thermal Stress Restrained Specimen Test (TSRST)

The TSRST test assesses how much stress builds up in an

asphalt specimen as a result of temperature reduction. This is important as restrained temperature loading can lead to damages in pavements. Figure 6 illustrates the TSRST test results. In the graph, the stress build up is shown with temperature reduction, the line ends when the specimen breaks, the temperature at which this happens is the critical temperature. The results show that for all materials the critical temperature is in the region between -19.6°C/1.13MPa for the mix containing Soybean oil and -25.63°C/1.71MPa for mix containing the Palm oil. Performance of both mixtures containing microalgae lipids (oil) and biomass were quite similar with failure temperature at -22°C and failure stress 1.42MPa. Results further indicate that all mixtures are able to withstand the standard temperature reduction up until -15°C showing a stress level ranging between 0.4 – 0.6 MPa.

Table 9: Rut depth measurement of SMA 11B mix containing 30% RAP and various rejuvenators.

Mix	Rut Depth @ 10,000 cycles (mm)	Proportional Rut Depth @ 10,000 cycles (%)
SMA 11B + 30% RAP – commercially available bio-rejuvenator (reference)	6.3	11.1
SMA 11B + 30% RAP – Microalgae lipids	4.4	8.2
SMA 11B + 30% RAP – Microalgae biomass	4	7.3
SMA 11B + 30% RAP – Soybean oil	4.4	7.9
SMA 11B + 30% RAP – Palm oil	3.7	6.8

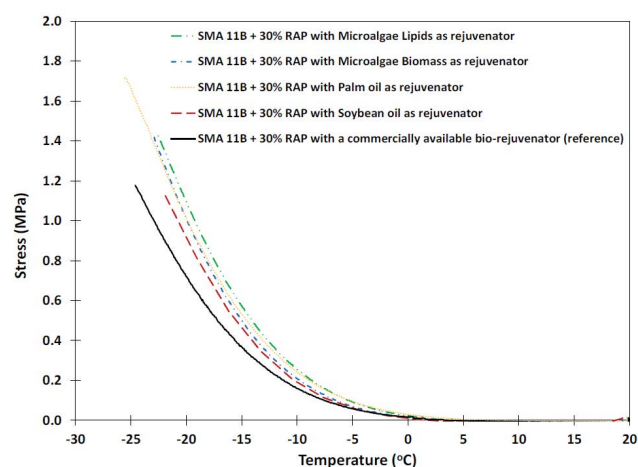


Figure 6: Temperature effect on of SMA 11B mix containing 30% RAP and various rejuvenators.

Conclusions

The goal of the study was to test initial properties and performance of aged bitumen and recycled asphalt that contains different types of bio-rejuvenating oils to assess if micro algae oil could be a good alternative for commercially available rejuvenators.

Results from the bitumen blends show that all studied rejuvenators, including the commercial one, are unable to reset the binder to its original state. Gel Permeation Chromatography (GPC) tests showed that all rejuvenated blends have a higher average molecular weight compared to both the fresh and the aged binder. FTIR characterisation, showed that both the carbonyl and sulfoxide indices remained high after rejuvenation. SARA test results show that the rejuvenators have impact on the chemical groups, however none of them are bringing the aged binder back to its original composition. The behaviour of the rejuvenated binders, assessed using the penetration value and the ring and ball temperature, showed that the addition the rejuvenator helped to soften the binder. However, all rejuvenators still resulted in a harder binder compared to the original fresh binder at the used dosage of 3%. The executed tests provide insight in how the rejuvenators influence the chemical characteristics and the behaviour of the binder. However, based on the results it is not possible to conclude on the expected performance of the binder when applied in an asphalt mix at industrial scale. Additional tests or insight are needed to assess the performance of a rejuvenator on binder level. In addition, it is also important to assess the impact of temperature and residence time during the blending process on the resulting binder characteristics.

When rejuvenated asphalt mixtures are evaluated, it becomes clear that the identified changes in the binder do have a positive influence on performance of the asphalt mixtures. The impact of the bio-oils and biomass rejuvenators on the asphalt performance varies between the performance indicator studied. The rejuvenators are able to decrease the mix stiffness. The indirect tensile strength is increased for the mix where microalgae biomass is added. Water resistance and wheel tracking test results showed good durability performance of all mixtures containing bio-rejuvenators. The TSRST results showed good performance of all mixtures in the same range as commercial rejuvenators.

In summary, the results show that microalgae-based rejuvenators (lipids and biomass) proved to be an effective rejuvenator. The regularly available bio-oils such as soybean oil and palm oil also perform well as a rejuvenator, however as they are part of the human food chain, it would be unethical to consider using these bio-oils in asphalt production. It is therefore worthwhile to explore growing algae in brown water, as it has been demonstrated that the algae oil and biomass

are effective as rejuvenator. In addition the cultivation in brown water also has potential for water purification as algae consume nitrogen during growth. Cultivation in brown water reduces the price, both financially and environmental, which would encourage acceptance of biomaterials in asphalt.

The results also indicate that microalgae biomass can function directly as a bitumen rejuvenator without requiring prior lipid (oil) extraction. If this is the case, this means that one production step can be left out, further reducing cost and environmental impact.

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