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Case study

The classification and reutilisation of recycled asphalt pavement binder: Norwegian case study

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ABSTRACT

With increased demand of asphalt pavement and limited binder and aggregate supply, the reutilisation of Recycled Asphalt Pavement (RAP) has gained more attention in pavement engineering from the environmental, sustainable, and economic views. Given this background, this study aims to classify and reutilise the recycled asphalt binder collected from Norwegian fields used for new asphalt pavement. For this purpose, three RAP binders (namely RAP-1, RAP-2, and RAP-3) extracted from the recycled asphalt pavement were categorised into two types of asphalt binders by comparing them with fresh asphalt binder 70/100 and long-term aged asphalt binder in terms of the physical, chemical, rheological, and mechanical properties. The specific treatments for the two types of RAP binder were proposed: Direct application of RAP-1 and RAP-2 binders as a replacement for fresh asphalt binder; and restoring RAP-3 binder by 4% rejuvenator to the same level as a fresh asphalt binder. Finally, the feasibility of three treated RAP binders for asphalt pavement was evaluated by analysing asphalt mixture performance. The results suggested that the three RAP binders can be applied to new asphalt pavements after proper treatments.

1. Introduction

Exposure to the sunlight, extreme temperature, moisture, and oxygen can age asphalt pavement, resulting in a brittle and fragile asphalt binder [22,24]. The asphalt pavement with aged asphalt binder has insufficient ability to resist permanent deformation, fatigue cracking, and moisture damage, resulting in a large number of waste asphalt mixtures, namely recycled asphalt pavement (RAP) [2, 11]. However, recycled asphalt pavement still contains valuable asphalt binder and aggregates, which should be carefully treated or reused. Thus, the reuse of RAP is one of the primary concerns for current asphalt pavement technology from the environmental and economic perspectives [4,10]. Moreover, asphalt binder is the by-product of petroleum, therefore, it is a non-renewable resource with high cost. These facts make road administration aware that recycling RAP binders can conserve energy and lower expenses [1]. Many policies were published to promote the reuse of RAP binders. For example, Norway has committed to recycle a large amount of waste from construction projects according to the European Economic Agreement (EEA), and the reuse of road materials is also included

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[13]; the US Department of Transportation also appealed to reuse the oxidised asphalt binder in newly constructed asphalt pavement [9,21].

A large number of researchers also made many efforts to properly reuse RAP binders since 1973 [6,9,12,25,27]. The asphalt binder properties can be reversible if proper measurements are taken. The addition of rejuvenators in aged asphalt binder is one of the effective methods. Rejuvenating agents that increase the reuse of RAP, reduce the waste aged asphalt binder and restore the binder performance are of significant interest. The commonly used rejuvenators are waste oil, plant oil, engineered products and refinery base oils [3,8,15]. Many literatures have reported that the addition of different rejuvenators can enhance the distinct properties of aged asphalt binder. For instance, a bio-based rejuvenator is able to alleviate the mechanical properties of aged asphalt binder [5]; The animal fat rejuvenator was found to improve the low-temperature, thermal stability, and fatigue cracking resistance of aged asphalt binder [16]; Waste wood alleviated the stiffness of aged asphalt binders by increasing the viscous components within the aged binder [30]; Engineered rejuvenator restored the ability of mixtures with aged asphalt binder to resist rutting, moisture damage, fatigue cracking, and fracture [7]. There are two theories explaining the rejuvenation effect on recycled asphalt binder: fraction adjustment theory and compatibility theory [36]. The fraction adjustment theory refers to the addition of specific components within aged asphalt binder provided by rejuvenators, and the compatibility theory is based on thermodynamics that relies on a decreased solubility parameter between the fractions of asphalt binder that is acquired after regeneration [14]. Above all, adding a rejuvenator in aged asphalt binder ensures the sustainable development of pavement engineering and reduces resource consumption, gas emissions (VOCs), and overall costs.

Large quantities of researchers have conducted the long-term ageing of asphalt binder in the laboratory to simulate the practical situation in the field [26,29]. Even though the asphalt binder in the laboratory can simulate the behaviour of asphalt binder aged in the field, there is still a gap between them due to the complex service circumstance of asphalt pavement [32,36]. Therefore, this study collected recycled asphalt binder from the field for the subsequent investigations. Besides, there are various asphalt binders for Norwegian roads. For example, 70/100 and polymer modified asphalt binder are the most commonly used asphalt binders. The former type is normally applied for roads with low-traffic volume, and the latter type is mostly used for high-volume roads. The asphalt binders with higher penetration or lower viscosity, such as 160/220, 330/430 and soft asphalt binder (V1500 and V3000), are widely applied for low degree roads or base layer of pavements. The RAP is normally obtained from quarries where different asphalt binder types might mix. Thus, the recycled asphalt binder extracted from RAP varies significantly.

This study aims to classify and utilise the collected recycled asphalt binder from fields as a replacement of fresh asphalt binder for asphalt pavement. The collected and extracted asphalt binder from RAP was firstly classified into different types of asphalt binder on the basis of its chemical, physical, rheological, and mechanical properties. Distinct measurements were implemented to various asphalt binders for further application in asphalt pavement. Finally, the application of treated recycled binders was evaluated based on the binder and asphalt mixture performance. The findings from the study give a reference to the utilisation of the recycled asphalt binder on newly constructed asphalt pavements.

2. Materials and methods

2.1. Materials

2.1.1. Asphalt binder

In this study, three types of Recycled Asphalt Pavement (RAP) entitled as RAP-1, RAP-2, and RAP-3, the blend of different roads in Norway, were collected from two quarries. The two quarries are located at Heimdal, Norway and Tanem, Norway, respectively. The RAP binder was obtained by the extraction test, and their properties are tested and shown in Table 1. Moreover, fresh asphalt binder with penetration of 70/100 and PAV (pressure ageing vessel) aged asphalt binder were studied as references. 70/100 binder was supplied by the Veidekke company, and PAV binder was obtained by ageing 70/100 binder in accordance with EN 14769:2012.

2.1.2. Asphalt mixture

The asphalt mixture used in this research is AC-11, which is normally used for the surface layer of asphalt pavement. The aggregate degradation of AC-11 is designated as the average value of upper limit and lower limit and shown in Table 2. The optimum binder content was 5.1% for the AC-11 mixtures determined by the Marshall mix design. The testing mixture specimens were prepared by a gyratory compactor with a pressure of 380 kPa and the gyratory angle of 17 mrad to obtain the samples with a diameter of 100 mm and

Table 1
Properties of recycled asphalt binder.

Binder	Penetration	Softening point	Viscosity at 60 °C	Source
Unit	0.1 mm	°C	Pa s	
Specification	EN 1426:2015	EN 1427:2015	EN 13702:2018	
70/100	78	46.6	243	Veidkke company
RAP-1	93	46.0	263	Quarry 1
RAP-2	83	45.8	355	Quarry 2
RAP-3	42	53.4	611	Quarry 2
PAV binder	41	57.6	687	Laboratory

Table 2
Aggregate gradation of AC-11.

Sieve [mm]	Upper limit	Lower limit	Selected gradation
16 mm	100	100	100.0
11.2 mm	100	90	95.0
8 mm	81	59	70.0
4 mm	58	37	47.5
2 mm	43	24	33.5
1 mm	33	18	25.5
0.25 mm	16	9	12.5
0.063 mm	10	5	7.5

a height of 60 mm according to EN 12697–31. To ensure sufficient compaction, the 80 designed gyrations were applied for the AC-11 mixtures. Four parallel samples were manufactured for each type of asphalt mixture.

For the asphalt mixture samples used in this study, the aggregate type and binder content are the same. Only the binder type is different to analyse the effect of binder on asphalt mixture performance.

2.2. Experimental methods

2.2.1. Research plan

The experimental plan of this study and performance assessment of asphalt binders and mixtures are shown in Fig. 1. Firstly, three RAP binders were extracted from RAP. The three RAP binders were classified into two types for further reuse depending on their physical, rheological, and mechanical properties, namely: (1) the type similar to fresh 70/100 binder (RAP-1 and RAP-2 binders) and (2) the type that severely aged (RAP-3 binder). Thus, different reuse methods for two kinds of binders were implemented: the former can be directly used as a replacement of 70/100 binder; the latter was restored to the rejuvenated binder having similar properties to the fresh 70/100 binder. Finally, the asphalt mixtures prepared with RAP-1, RAP-2, and rejuvenated RAP-3 binders were compared with those that prepared with fresh 70/100 binder to confirm proper stiffness of binders in the asphalt mixture.

2.2.2. Extraction process

The extraction process was carried out to obtain a RAP binder for further reutilisation and tests. It includes two sections: separation of RAP binder and aggregates following EN 12697–1 and extraction of binder from dichloromethane following EN 12697–3. After the two processes, the RAP binder specimens were heated at 110 ℃ until the weight stopped changing. This process aims to remove the excessive solvent in a binder. To ensure the uniform properties of the RAP binder, the samples were mixed and stirred together at 140 ℃ for 20 mins before further tests.

2.2.3. Rejuvenated asphalt binder preparation

For the aged asphalt binder, adding a rejuvenator is an effective method to restore the asphalt binder properties to fresh binder. In this research, the rejuvenator was provided by the company Kraton, which is a by-product of the paper industry. The rejuvenating process is shown in Fig. 2 [35]. The extracted asphalt binder was preheated at 130 ℃ for 1 h to semi-fluid. The calculated dosage of rejuvenator was added into the asphalt binder evenly and stirred at room temperature for 10 mins. The stirred asphalt binder mixing rejuvenator was then put back into the heating cabinet at 130 ℃ for 10 mins. The rejuvenating process is completed after five cycles.

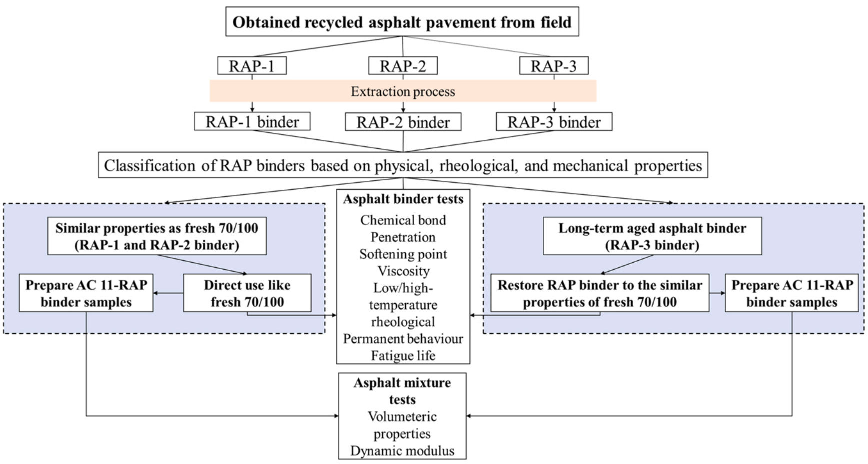

Fig. 1. Research plan and test methods.

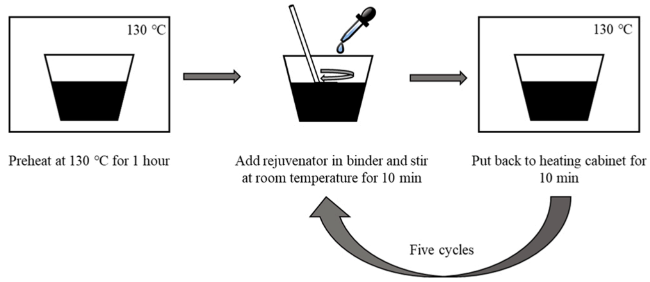

Fig. 2. Preparation of rejuvenated asphalt binder.

2.2.4. Asphalt binder tests

2.2.4.1. Fourier transform infra-red test. The chemical bond of asphalt binder, especially two ageing chemical bonds, was characterised by Nicolet 8700 Fourier Transform Infra-red Radiation (FTIR) spectrometer with the Attenuated Total Reflectance (ATR) accessory. The scan range is from 400 cm^{-1} to 4000 cm^{-1} with a resolution of 4 cm^{-1}. Each specimen was tested three times, and the FTIR spectrum with the largest absorbance peaks was selected and analysed. The FTIR spectra and functional group indices were used to characterise the chemical structure of the asphalt binder from the qualitative and quantitative perspectives, respectively.

2.2.4.2. Traditional binder tests. The penetration at 25 ℃, softening point, and viscosity at 60 ℃ of the binder were measured according to EN 1426:2015, EN 1427:2015, and EN 13702:2018. Three measurements were tested for penetration test, and two replicates were tested for softening point and viscosity tests. The mean value of each parameter was analysed. The three parameters are fundamental indicators characterising the physical properties of the asphalt binder.

2.2.4.3. Bending beam rheometer test. The low-temperature rheological properties of the asphalt binder were evaluated by Bending Beam Rheometer (BBR) at − 18 ℃ based on EN 14771:2012. The specimen used for the BBR test was made to 6.4 ± 0.1 mm high, 12.7 ± 0.25 mm wide, and 127 ± 5 mm long. The creep rate (m-value) and creep stiffness (S) were determined according to Eqs. (1) and (2). The m-value and S at 60 s were used for characterising the creep and relaxation performance. Two replicates were run for each binder, and the mean value was applied as the final result.

$$S_m(t) = \frac{PL^3}{4bh^3\delta(t)} \quad (1)$$

$$m(t) = \left|\frac{dlog[S(t)]}{dlog(t)}\right| \quad (2)$$

where P is the test load at time t, N; L is the distance (102 mm) between two supports; b is the width (12.7 mm) of the asphalt binder sample; h is the thickness (6.4 mm) of the asphalt binder sample; $\delta(t)$ is the measured deflection at time t, mm.

2.2.4.4. Dynamic shear rheometer test. The dynamic shear rheometer test was conducted to characterise the rheological and mechanical properties of asphalt binders. Two samples were prepared for each type of test, and the mean value of the two results was applied for the final analysis.

The high-temperature rheological properties of the asphalt binder were evaluated using the complex modulus and phase angle tested by a dynamic shear rheometer according to EN 14770. The test was conducted at a frequency of 10 rad/s in the temperature range of 30–80 ℃ with an interval of 1 ℃. The specimen thickness and diameter are 1 mm and 25 mm, respectively.

The permanent deformation behaviour of the asphalt binder was characterised by the multiple stress creep recovery (MSCR) test at 60 ℃ following EN 16629. Two stress levels, 3.2 kPa and 0.1 kPa, and ten loading-recovery (1–9 s) cycles for each stress level were adopted to evaluate the non-recoverable creep compliance (J_{nr}) and percent recovery (%R) of binders.

The fatigue behaviour of the asphalt binder was evaluated by the Linear Amplitude Sweep (LAS) test based on AASTHO TP 101–12. The test temperature was selected as 25 ℃ for this study. There are two steps for the LAS test: frequency sweep at a constant strain of 0.1% with a range of frequency from 0.2 to 30 Hz, and amplitude sweep at a constant frequency of 10 Hz with an increasing strain from 0.1% to 30%. The fatigue failure is defined as a 35% reduction in the initial modulus, and the fatigue life is then calculated using Eq. (3).

$$N_f = A(\gamma_{max})^{-B} \quad (3)$$

where γ is the designated strain level, A and B are viscoelasticity related coefficients of asphalt binder.

2.2.5. Asphalt mixture tests

2.2.5.1. Air voids content test. The air voids content is the basic parameter of asphalt mixture, which should be in the range of 2.5–5.5% for AC mixtures in accordance with the design criteria [18] and can be applied to characterise the volumetric properties of asphalt mixtures. In this study, the air voids content of AC 11 specimens was calculated using the bulk and maximum specific gravities according to EN 12697–8.

2.2.5.2. Cyclic indirect tensile test. The cyclic indirect tensile test was carried out to analyse the dynamic modulus of asphalt mixtures in accordance with EN 12697–26, which is a mandatory input of pavement design. The samples with the dimension of 100 mm diameter and 40 mm height were cut from the gyratory specimens for the cyclic indirect tensile test. The test was conducted at frequency of 1 Hz and a wide range of temperatures (−15 °C, −10 °C, 0 °C, 15 °C, and 30 °C). Based on the obtained dynamic modulus over a range of temperature, the stiffness of mixture samples was characterised.

3. Results and discussions

3.1. Classification of recycled binder

Three RAP binders obtained from the field were evaluated and classified into different types by comparing with the fresh 70/100 asphalt binder and PAV aged binder based on chemical, physical, rheological, and mechanical properties.

3.1.1. Chemical structure of asphalt binder

Observing the FTIR spectra of the asphalt binder shown in Fig. 3A, there is no additional peaks but apparent changes in two specific peaks are located at 1030 cm^{-1} and 1700 cm^{-1}. A lack of additional peak means the asphalt binder is not the variation of the polymer modified binder but the virgin binder. The two peaks respectively indicate the sulfoxide group and carbonyl group, which are the typical factors indicating the oxidative degree of the asphalt binder [33]. Obviously, two peaks of three RAP binders were enhanced compared to fresh 70/100 binder to different degrees. This result explained that the RAP binders apparently aged along the service period by the external environment. Several factors are known to age binder, such as oxygen, ultraviolet radiation, and chemicals [23, 34]. However, the three RAP binders showed various ageing degrees due to the service life and service circumstance of recycled asphalt pavement.

To quantitatively evaluate the oxidative degree of different asphalt binders, the sulfoxide index (SI) and carbonyl index (CI) were calculated following Eqs. (4) and (5) [28,31].

$$SI = \frac{A_{1030}}{A_{1456}} \tag{4}$$

$$CI = \frac{A_{1700}}{A_{1375}} \tag{5}$$

where $A_{1030/1456/1700/1375}$ is the integral area of sulfoxide group cantered around 1030 cm^{-1}, 1456 cm^{-1}, 1700 cm^{-1}, and 1375 cm^{-1}.

Fig. 3B shows the sulfoxide index and carbonyl index of different asphalt binders. The sulfoxide index and carbonyl index of RAP-1 have similar values to a fresh 70/100 binder. The carbonyl index of the RAP-2 binder was closer to 70/100 binder instead of the PAV aged binder, and the sulfoxide index of the RAP-2 binder was similar to the PAV aged binder rather than 70/100 binder. Moreover, the

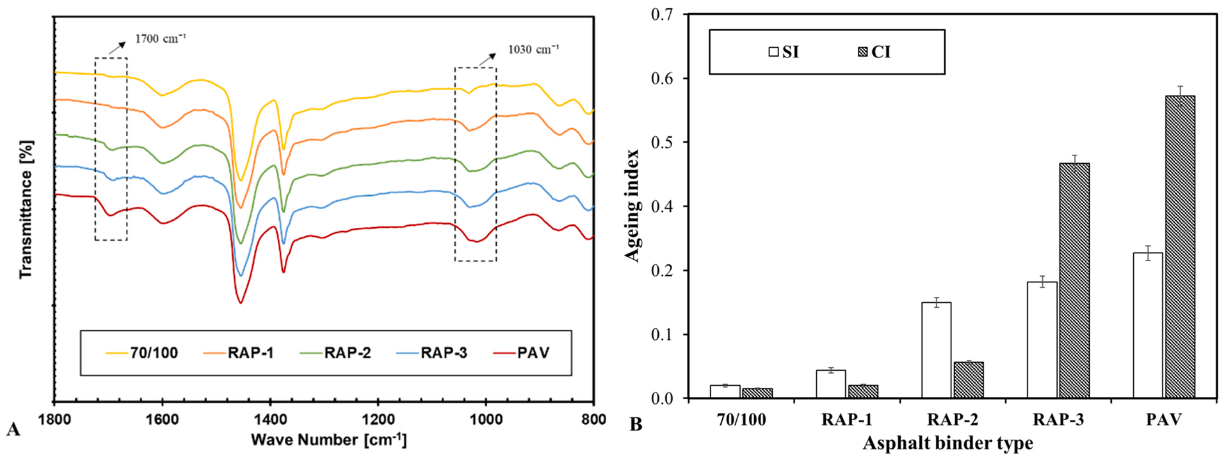

Fig. 3. The FTIR spectrum (A) and ageing index (B) of asphalt binder.

two indices of the RAP-3 binder were around 80% of that of the PAV binder, which were far higher than that of the RAP-1 and RAP-2 binders. These phenomena relate to the severe ageing of the RAP-3 binder, the slight ageing of RAP-1 and RAP-2 binders, and the complicated components within the recycled binder. Therefore, by integrating the two indices together, arranging the binders by their oxidative degree in descending order: PAV binder, RAP-3 binder, RAP-2 binder, RAP-1 binder, and 70/100 binder.

3.1.2. Physical properties of asphalt binder

The physical properties of the asphalt binder were characterised by its penetration (Fig. 4A), softening point (Fig. 4B), and viscosity (Fig. 4C). As the figures showed, the RAP-1 binder showed indistinguishable values of softening point and viscosity with 70/100 binder and a slight increase in penetration, indicating similar stiffness, high-temperature stability and flow resistance with reference 70/100 binder. RAP-2 binder also has similar physical properties as fresh asphalt binder (70/100). The results imply that RAP-1 and RAP-2 binders might be the aged high penetration binder or the blend of aged binder with high penetration and aged 70/100 binder. Besides, RAP-3 exhibited similar physical properties as PAV aged binder and significant variation as 70/100 binder, which could be the aged 70/100 binder. The physical properties of various binders can be the indications of their chemical structures (two ageing indices), that is, asphalt binder with higher ageing indices tends to be stiffer and more stable.

3.1.3. Rheological properties of asphalt binder

3.1.3.1. Low-temperature rheological properties. The low-temperature rheological properties conducted by the BBR test at − 18 °C were evaluated by two parameters: stiffness and m-value. Based on the definition of two parameters, the asphalt binder with lower stiffness and a higher m-value is recognised to have better low-temperature rheological properties. As Table 3 presented, it is obviously observed that RAP-1 and RAP-2 binders had slightly lower stiffness and higher m-value compared to 70/100 binder, while the RAP-3 binder had a distinct difference with 70/100 binder but similar S(t) and m-value values with the PAV binder. These results demonstrate that RAP-1 and RAP-2 binders show close low-temperature rheological properties to the fresh binder (70/100). In contrast, the RAP-3 binder has severe low-temperature performance similar to PAV aged binder.

3.1.3.2. High-temperature rheological properties. In order to investigate the response of various binders at high temperatures, the dynamic shear rheometer test at a temperature range of 30–80 °C was performed. The complex modulus and phase angle at 30–80 °C are depicted in Fig. 5. As the figure shows, RAP-1 and RAP-2 binders showed a slight difference compared to 70/100 binder but an apparent difference with PAV aged binder, presenting lower complex modulus and higher phase angle than 70/100 binder. In comparison, the RAP-3 binder showed a significant increment in complex modulus and decrement in phase angle than 70/100 binder but similar curves to the PAV binder. The above results indicate that RAP-1 and RAP-2 binders have the rheological properties comparable with unaged 70/100 binder, and the RAP-3 binder showed nearly the same rheological properties as PAV aged binder. These changes in the rheological properties of asphalt binder are in line with chemical and physical properties.

The results from the rheological properties of the asphalt binder verify that RAP-1 and RAP-2 binders are the results of the aged binder with a higher penetration degree, while the RAP-3 binder tends to be the aged binder of 70/100.

3.1.4. Mechanical properties of asphalt binder

3.1.4.1. Permanent deformation resistance. Fig. 6A presents the strain response at two loading modes (0.1 kPa and 3.2 kPa) over time from the MSCR test. As can be seen, the strain of all specimens increased with time and loading. It is also observed that RAP-3 and PAV binder curves were significantly lower than 70/100, RAP-1, and RAP-2 binder curves at two loading modes, representing minor strain responding to applied loading of RAP-3 and PAV binders and considerable strain of 70/100, RAP-1, and RAP-2 binders. Moreover, RAP-1 and RAP-2 binders showed similar strain curves and slightly smaller strain than 70/100 binder, while the RAP-3 binder curve

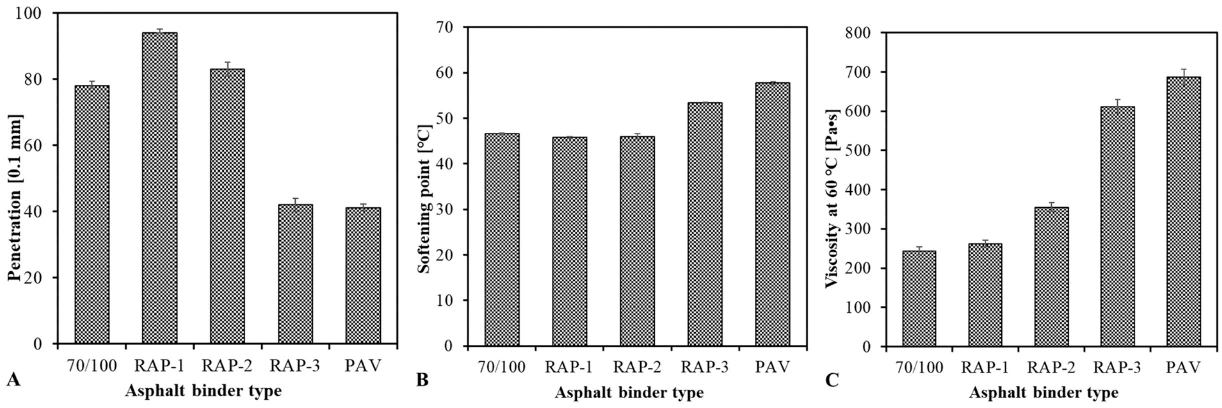

Fig. 4. Three physical parameters of asphalt binder.

Table 3
BBR parameters of asphalt binder at − 18 °C.

Asphalt binder	S (t) [MPa]	m-value
70/100 binder	126.0	0.32
RAP-1 binder	72.7	0.39
RAP-2 binder	62.9	0.42
RAP-3 binder	298.0	0.27
PAV binder	319.0	0.26

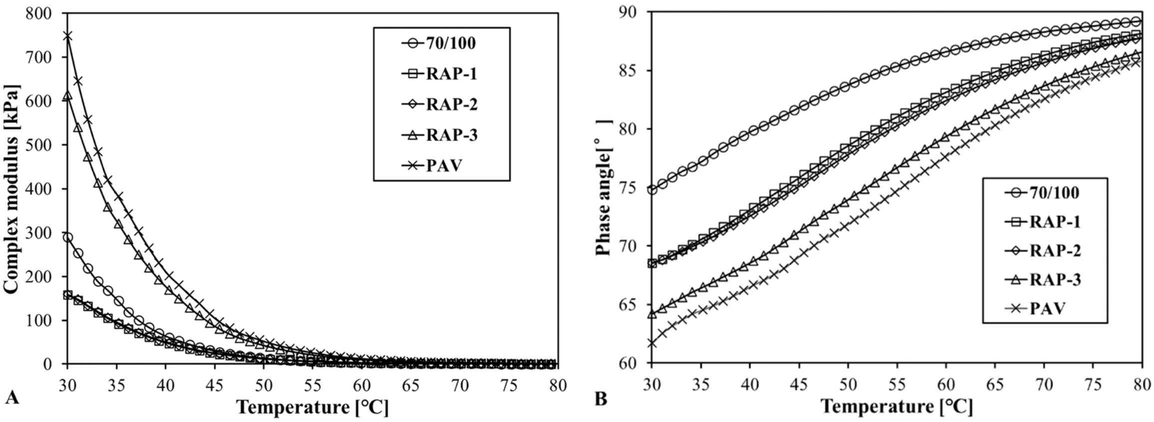

Fig. 5. Complex modulus (A) and phase angle (B) of asphalt binder.

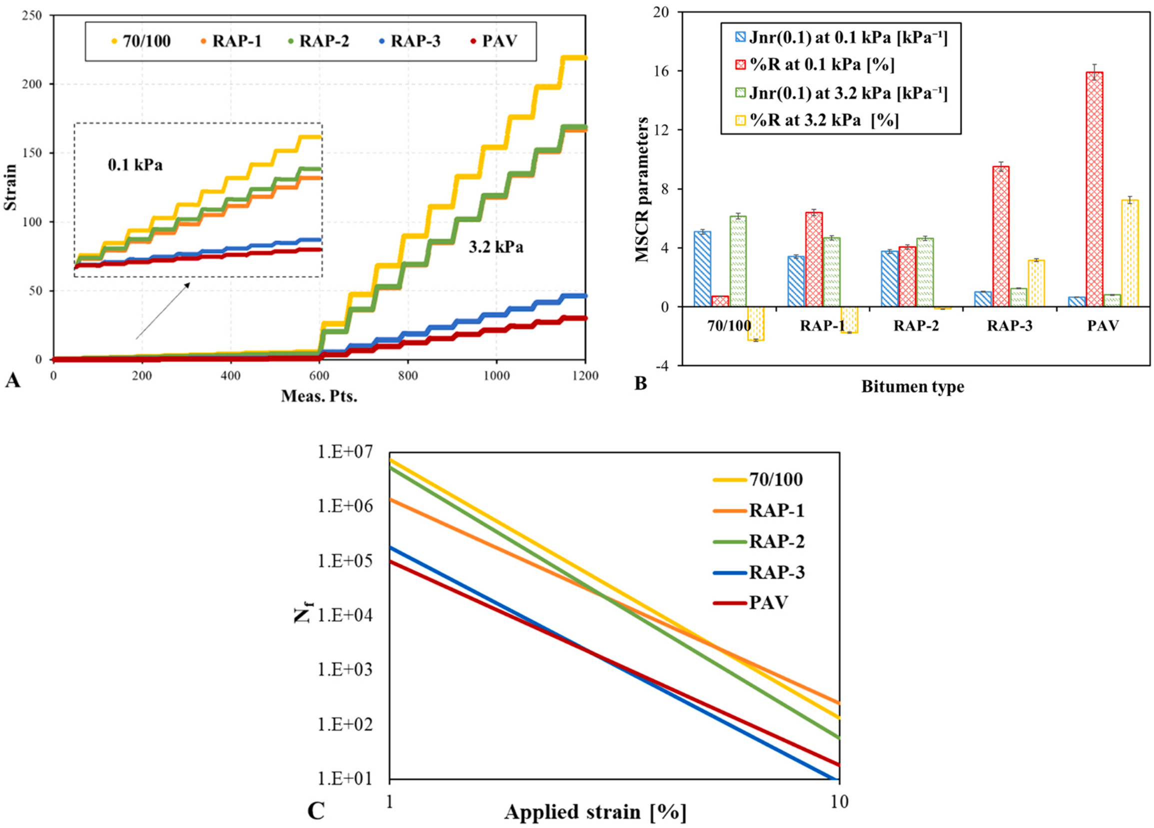

Fig. 6. Strain response (A), MSCR parameters (B), and Fatigue life (N_f) (C) of asphalt binder.

was close to the PAV binder curve. These results represent that RAP-1 and RAP-2 binders have similar strain responses as 70/100 binder. The small difference in strain response is originated from the oxidation of RAP binders during the servicing period. The RAP-3 binder was severely oxidated to a similar level with the long-term ageing in the laboratory.

Two factors of asphalt binder at 0.1 kPa and 3.2 kPa obtained from the MSCR test, non-recoverable creep compliance (J_{nr}) and percentage recovery (%R), were plotted in Fig. 6B. The non-recoverable creep compliance (J_{nr}) is defined as a non-recovered strain

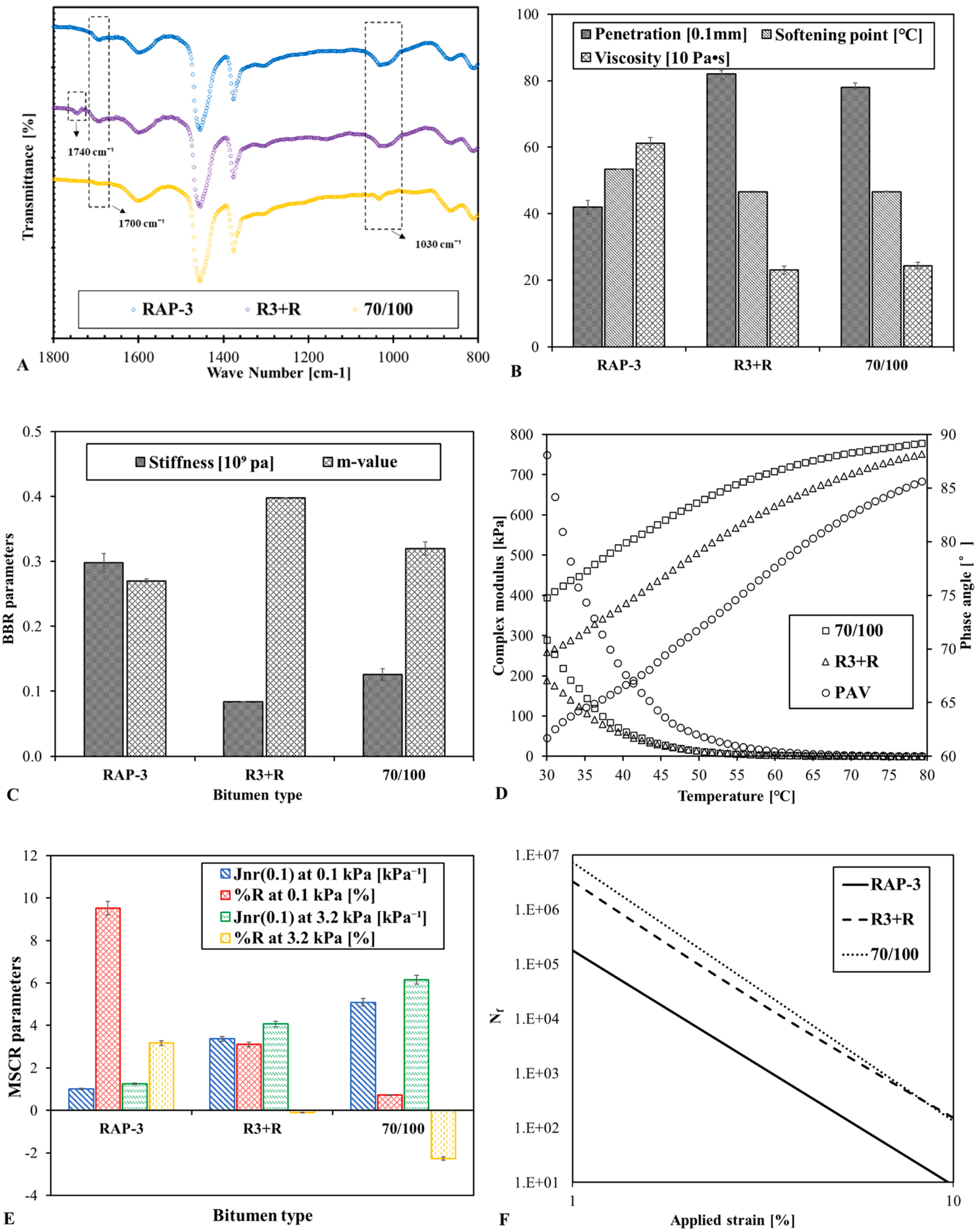

Fig. 7. The performance parameters of RAP-3 before and after rejuvenation: FTIR spectra (A), physical properties (B), BBR parameters (C), complex modulus and phase angle (D), MSCR parameters (E) and N_f (F).

divided by an applied stress, indicating the rutting resistance of the asphalt binder. The %R is calculated as the recovered strain divided by the total stain, indicating the recovery ability of the asphalt binder. Thus, higher non-recoverable creep compliance exists typically with a lower percentage recovery, resulting in an insufficient resistance of asphalt binder to permanent deformation.

As shown in Fig. 6B, RAP-1 and RAP-2 binders showed similar values in $J_{nr}(0.1)$ and $J_{nr}(3.2)$, and some variation in %R at both 0.1 kPa and 3.2 kPa, indicating similar rutting resistance and some difference in recovery ability of the two asphalt binders. The difference in recovery ability is consistent with the high-temperature rheological properties results, which can be interpreted by the severe oxidation analysed from the chemical structure. Regarding the RAP-3 binder, similar $J_{nr}(0.1)/J_{nr}(3.2)$ and %R(0.1)/%R(3.2) values compared to the PAV binder were found, resulting in similar rutting resistance and recovery ability with PAV aged binder. This phenomenon is contributed to the similar oxidative degrees of the two binders.

3.1.4.2. Fatigue resistance. The fatigue performance of the asphalt binder was characterised by the LAS test using fatigue life. Fatigue life (N_f) is defined as the number of loading cycles until fatigue failure. Longer fatigue life illustrates better fatigue resistance of the asphalt binder. Fig. 6C plots the fatigue life of various asphalt binders over applied strain. A general tendency can be seen: the fatigue life decreases with the increasing strain. However, the descending degrees were different due to the various chemical structures and ageing degrees of the asphalt binder. It should be noted that RAP-1 and RAP-2 curves tended to merge with 70/100 curve and be far away from RAP-3 and PAV curves, which indicates that RAP-1 and RAP-2 binders present similar fatigue resistance as 70/100 binder. Moreover, the slopes of RAP-1 and RAP-2 curves were lower than that of 70/100 binder, indicating the weaker strain sensitivity of RAP-1 and RAP-2 binders. The weakened strain sensitivity of the asphalt binder is an indication of oxidation. Besides, the fatigue life of RAP-3 and PAV binders were closed to each other, although the changing trends over strain were different. This result shows that the RAP-3 binder has similar fatigue resistance behaviour to a long-term aged binder, which validates the long-term oxidation of recycled asphalt pavement. The smaller slope of the RAP-3 binder is an indication of a less severe ageing degree concluded from SI and Ci indices and asphalt binder properties compared with the PAV binder.

Generally, from the results presented in this section, it can be stated that RAP-1 and RAP-2 binders have similar performance to a fresh binder, including chemical structure, physical properties, rheological properties, and mechanical properties. In contrast, the RAP-3 binder shows similar behaviours in chemical structure, physical, rheological and mechanical properties as the PAV aged binder. These results can be explained as RAP-1 and RAP-2 might be recycled from the lower traffic road with softer binder, and RAP-3 might be the aged 70/100 binder. The conclusion can be summarised that RAP-1 and RAP-2 binders have the possibility to be used as 70/100 binders when constructing an asphalt pavement, while RAP-3 is a typical RAP binder after long-term oxidation.

3.2. The reutilisation of three recycled binders

3.2.1. The pre-process of RAP binders

3.2.1.1. RAP-1 and RAP-2 binders. Results in Chapter 3.1 indicate that RAP-1 and RAP-2 binders have the sufficient ability to replace fresh 70/100 for asphalt pavements according to physical, chemical, rheological and mechanical properties, although there is a slight difference in elasticity. Thus, the two RAP binders are recommended to be directly used for asphalt mixture like fresh 70/100 binder.

3.2.1.2. RAP-3 binder. RAP-3 binder, distinct from the other two binders, is the aged binder to have similar properties as PAV aged binder, which means RAP-3 binder is hardly replaced as a 70/100 binder in terms of chemical, physical, rheological and mechanical properties. Thus, refreshing the RAP-3 binder to similar properties as the fresh binder (70/100) would be a significant measurement for binder reuse. Therefore, the RAP-3 binder was restored by a 4% rejuvenator determined by the empirical double-logarithmic formula and calibration in terms of penetration, softening point and viscosity parameters [35]. After the rejuvenation, the refreshed asphalt binder (R3 +R) was compared with the reference binder (70/100). The chemical, physical, rheological, and mechanical properties of rejuvenated RAP-3 were studied.

Fig. 7 shows the chemical, physical, low/high-temperature rheological, and mechanical properties of the RAP-3 binder before and after the rejuvenation, as well as the reference binder (70/100). By adding a 4% rejuvenator, the two peaks of the sulfoxide group and carbonyl group weakened slightly, and a new peak indicating the rejuvenator component that appeared in the R3 +R binder. The FTIR spectra indicate that the rejuvenation can alter the chemical structure of the asphalt binder in a physicochemical way, demonstrating a C-O group indicating rejuvenators located at 1740 cm^{-1} [34]. However, the sulfoxide and carbonyl groups of R3 +R showed a few changes after rejuvenation, which indicates that the functional indices are not definitely positively related to the physical, rheological, and mechanical properties in this study due to the complex and blended components. The penetration, softening point, and viscosity of the RAP-3 binder were restored to similar values of 70/100 binder with a minimal error (5%, 0%, and 5.5%). The S(t) and m-value were decreased and increased to the relative values as the reference binder. The complex modulus and phase angle of the RAP-3 binder were reduced and increased to some degrees. J_{nr} and N_f of the RAP-3 binder were refreshed to the similar values of fresh binder, while %R was barely restored. The improvement in binder performance is in line with other researchers' results [20]. The above results illustrate that the physical, low-temperature and high-temperature rheological, rutting and fatigue resistance of the RAP-3 binder are refreshed to a similar level as the fresh binder (70/100) with acceptable distinctions. Thus, R3 +R as a component for asphalt mixture has initially sufficient performance in an external service environment.

3.2.2. The reutilisation of RAP binders for asphalt mixture

For further verification, the feasibility of RAP-1, RAP-2 and rejuvenated RAP-3 (R3 +R) binders (100%) on asphalt mixtures were also studied by the air voids and dynamic modulus analyses. The asphalt mixtures with 70/100 binder and PAV binder were studied as the reference.

The effect of RAP binders on air voids content of mixtures is shown in Table 4. The air voids of mixtures fabricated by RAP-1 and RAP-2 binders were slightly higher than 70/100 mixture, and the increase is still within the reasonable range. However, RAP-3 mixture had a relatively higher air void content compared to the 70/100 mixture and similar air void content to PAV mixture, which can be interpreted by its low adhesion capacity. After the rejuvenation, the air void content of the R3 +R mixture is 0.3% lower than that of 70/100 mixture, which is lower than the maximum repeatability (0.4%) according to EN 12697–8. These results demonstrate that RAP-1, RAP-2, R3 +R mixtures can meet the requirement of fresh mixtures and exhibit comparable volumetric properties after proper treatments. It also verifies that the similar asphalt binder performance would result in similar volumetric properties of asphalt mixtures.

The dynamic moduli of 70/100, RAP-1, RAP-2, RAP-3, R3 +R, and PAV mixtures over temperature were shown in Table 4. It can be observed that different changing tendencies in stiffness are found for the five mixtures. The RAP-1 and RAP-2 mixtures had similar stiffness to the reference mixture both at high and low temperatures. This result agrees with the binder properties, which means similar binder performance leads to similar asphalt mixture stiffness, which is also proven by Olard [19]. In contrast, RAP-3 mixture behaved distinguishably in stiffness compared to the 70/100 mixture at higher temperatures (15 ℃ and 30 ℃), resulting in a higher dynamic modulus and stiffer mixture samples. This big distinction was alleviated by the rejuvenator as the R3 +R mixture (RAP-3 after rejuvenation) showed similar stiffness as the 70/100 mixture. However, the RAP-3 mixture presented similar dynamic modulus values as PAV mixtures, which is in line with the binder properties. Besides, the similar dynamic moduli of 70/100, RAP-1, RAP-2, RAP-3, R3 +R, and PAV mixtures at − 15 ℃ originates from the stiffer behaviour of all types of mixtures at lower temperatures, and this result is consistent with Nobakht's study [17]. In comparison with the dynamic modulus at low temperatures, the dynamic modulus at higher temperatures reflects the binder performance better. The above results indicate that RAP-1, RAP-2 and R3 +R mixtures have similar characteristics under loading as the 70/100 mixture. Thus, the utilisation of the three recycled binders on asphalt mixtures was demonstrated to be feasible.

The air voids and dynamic modulus results of the three RAP binders fulfiling the bituminous properties are also verified to guarantee the required volumetric property and proper stiffness of asphalt mixture. Hence, the three RAP binders, RAP-1, RAP-2, and R3 +R, were validated for asphalt pavement as 70/100 binders.

4. Conclusions

In the present work, the main purpose was to classify and recycle the RAP binders as a replacement for fresh asphalt binders that are used for new asphalt pavement. Some summarised findings can be drawn as follows.

By comparing RAP binders and the reference binders, three RAP binders were classified into two types of binders: the binder having similar properties to 70/100 binder (RAP-1 and RAP-2), and the aged binder (RAP-3) being similar to PAV aged binder.

Based on the properties of the three RAP binders, two treatments were made to reuse the RAP binders: direct application of RAP-1 and RAP-2 binders as a replacer of 70/100 binders; restoring the RAP-3 by rejuvenator to a similar level as fresh 70/100 binder.

The three treated RAP binders were proven to fulfil the 70/100 binder performance, and their mixtures were found to behave comparably to the 70/100 mixture. The results concluded that the three treated RAP binders can be used for newly constructed asphalt pavement like 70/100 binder.

The data quality, consistency, statistical variability, and repeatability of the laboratory tests in this study were controlled well in a reasonable range. The application of these RAP binders as a replacement for fresh 70/100 binders will help road administration and industry with asphalt binder recycling. Moreover, the findings in the study contribute to more possibilities for recycled asphalt pavement binder. However, the asphalt binder extraction process requires a lot of energy and cost and the conclusions obtained from this study are only suitable for the pavement with neat bitumen. Above all, this study assorted and reused the RAP binders for asphalt pavement, which is one of the best waste managements for bituminous materials. Further research could focus on the in-field performance of treated RAP binders, the improvement of RAP mobilisation for further in-field application and extraction technology.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

Table 4
Air voids and dynamic modulus of asphalt mixtures.

Mixture type	Temperature	70/100 mixture	RAP-1 mixture	RAP-2 mixture	R3 +R mixture	RAP-3mixture	PAV mixture
Air void [%]		4.4	4.7	4.9	4.5	5.4	5.5
Dynamic modulus [MPa]	-15 ℃	29,550.9	29,148.2	28,982.8	29,424.1	30,834.0	31,097.3
	-10 ℃	29,242.5	29,487.2	29,094.5	23,946.4	29,755.9	29,823.7
	0 ℃	16,471.9	17,275.9	17,220.9	13,252.7	18,165.0	18,599.2
	15 ℃	3434.9	3277.1	3165.0	3246.0	5524.1	5696.6
	30 ℃	1277.7	1555.0	1244.2	1096.2	1799.2	2103.3

influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] F.H. Administration, Demonstration Project 39—Asphalt Recycling, in: F.H. Administration (Ed.), Washington, DC, 1978–1983.
[2] T.B. Alam, M. Abdelrahman, S.A. Schram, Laboratory characterisation of recycled asphalt pavement as a base layer, Int. J. Pavement Eng. 11 (2) (2010) 123–131.
[3] T. Bai, Z.A. Hu, X. Hu, Y. Liu, L. Fuentes, L.F. Walubita, Rejuvenation of short-term aged asphalt-binder using waste engine oil, Can. J. Civ. Eng. 47 (7) (2020) 822–832.
[4] R. Cao, Z. Leng, S.-C. Hsu, Comparative eco-efficiency analysis on asphalt pavement rehabilitation alternatives: hot in-place recycling and milling-and-filling, J. Clean. Prod. 210 (2019) 1385–1395.
[5] M.C. Cavalli, M. Zaumanis, E. Mazza, M.N. Partl, L.D. Poulikakos, Effect of ageing on the mechanical and chemical properties of binder from RAP treated with bio-based rejuvenators, Compos. B Eng. 141 (2018) 174–181.
[6] A. Copeland, Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice, Federal Highway Administration, Office of Research, United States, 2011.
[7] M.A. Elseifi, L.N. Mohammad, S.B. COOPER III, Laboratory evaluation of asphalt mixtures containing sustainable technologies, Asph. Paving Technol. (2011) 227–244.
[8] Y. Fang, Z. Zhang, J. Yang, X. Li, Comprehensive review on the application of bio-rejuvenator in the regeneration of waste asphalt materials, Constr. Build. Mater. 295 (2021), 123631.
[9] A. FHWA, Study of the Use of Recycled Paving Materials: A Report to Congress, FHWA-RD-93-417, Federal Highway Administration (FHWA), Washington, DC, 1993.
[10] M.I. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resour. Conserv. Recycl. 104 (2015) 224–238.
[11] B. Huang, X. Shu, G. Li, Laboratory investigation of portland cement concrete containing recycled asphalt pavements, Cem. Conc. Res. 35 (10) (2005) 2008–2013.
[12] M. Hugener, D. Wang, A. Cannone Falchetto, L. Porot, P. Kara De Maeijer, M. Orešković, M. Sa-da-Costa, H. Tabatabaee, E. Bocci, A. Kawakami, B. Hofko, Recommendation of RILEM TC 264 RAP on the evaluation of asphalt recycling agents for hot mix asphalt, Mater. Struct. 55 (2) (2022) 1–9.
[13] Kontrollordningen For Asfaltgjienvinning (KFA), Blandeprosedyre for Rejuvenator, 2020. ⟨https://www.asfaltgjenvinning.no/resources/files/infoskriv/KFA_Blandeprosedyre_for_rejuvenator.pdf⟩. (Accessed 28 September 2020).
[14] D. Kuang, W. Liu, Y. Xiao, M. Wan, L. Yang, H. Chen, Study on the rejuvenating mechanism in aged asphalt binder with mono-component modified rejuvenators, Constr. Build. Mater. 223 (2019) 986–993.
[15] T.B. Moghaddam, H. Baaj, The use of rejuvenating agents in production of recycled hot mix asphalt: a systematic review, Constr. Build. Mater. 114 (2016) 805–816.
[16] N. Nciri, T. Shin, N. Kim, A. Caron, H. Ben Ismail, N. Cho, Towards the use of waste pig fat as a novel potential bio-based rejuvenator for recycled asphalt pavement, Materials 13 (2020) 1002.
[17] M. Nobakht, M.S. Sakhaeifar, Dynamic modulus and phase angle prediction of laboratory aged asphalt mixtures, Constr. Build. Mater. 190 (2018) 740–751.
[18] Norwegian Public Roads Administration (NPRA), Guildelines Asphalt 2019, 2019.
[19] F., Di Olard, H. Benedetto, B. Eckmann, J.P. Triquigneaux, Linear viscoelastic properties of bituminous binders and mixtures at low and intermediate temperatures, Road Mater. Pavement Des. 4 (1) (2003) 77–107.
[20] A. Ongel, M. Hugener, Impact of rejuvenators on aging properties of bitumen, Constr. Build. Mater. 94 (2015) 467–474.
[21] F. Pahlavan, A. Hung, E.H. Fini, Evolution of molecular packing and rheology in asphalt binder during rejuvenation, Fuel 222 (2018) 457–464.
[22] R. Polo-Mendoza, G. Martinez-Arguelles, L.F. Walubita, F. Moreno-Navarro, F. Giustozzi, L. Fuentes, T. Navarro-Donado, Ultraviolet ageing of bituminous materials: a comprehensive literature review from 2011 to 2022, Constr. Build. Mater. 350 (2022), 128889.
[23] R. Tauste, F. Moreno-Navarro, M. Sol-Sánchez, M. Rubio-Gámez, Understanding the bitumen ageing phenomenon: a review, Constr. Build. Mater. 192 (2018) 593–609.
[24] L.F. Walubita, M. Ling, L.M.R. Pianeta, L. Fuentes, J.J. Komba, G.M. Mabrouk, Correlating the asphalt-binder MSCR test results to the HMA HWTT and field rutting performance, J. Transp. Eng. Part B: Pavements 148 (3) (2022) 04022047.
[25] D., Cannone Wang, A. Falchetto, K.H. Moon, C. Riccardi, J. Pei, Y. Wen, Artificially prepared reclaimed asphalt pavement (RAP)—an experimental investigation on re-recycling, Environ. Sci. Pollut. Res. 26 (35) (2019) 35620–35628.
[26] J. Yu, Y. Guo, L. Peng, F. Guo, H. Yu, Rejuvenating effect of soft bitumen, liquid surfactant, and bio-rejuvenator on artificial aged asphalt, Constr. Build. Mater. 254 (2020), 119336.
[27] M. Zaumanis, R.B. Mallick, R. Frank, Evaluation of different recycling agents for restoring aged asphalt binder and performance of 100% recycled asphalt, Mater. Struct. 48 (2015) 2475–2488.
[28] H. Zhang, D. Zhang, Effect of different inorganic nanoparticles on physical and ultraviolet aging properties of bitumen, J. Mater. Civ. Eng. 27 (2015) 04015049.
[29] J. Zhang, C. Sun, P. Li, H. Jiang, M. Liang, Z. Yao, X. Zhang, G. Airey, Effect of different viscous rejuvenators on chemical and mechanical behavior of aged and recovered bitumen from RAP, Constr. Build. Mater. 239 (2020), 117755.

[30] R. Zhang, Z. You, H. Wang, X. Chen, C. Si, C. Peng, Using bio-based rejuvenator derived from waste wood to recycle old asphalt, Constr. Build. Mater. 189 (2018) 568–575.
[31] S. Zhang, H. Hong, H. Zhang, Z. Chen, Investigation of anti-aging mechanism of multi-dimensional nanomaterials modified asphalt by FTIR NMR and GPC, Constr. Build. Mater. 305 (2021), 124809.
[32] X. Zhang, H. Chen, D.M. Barbieri, I. Hoff, Laboratory evaluation of mechanical properties of asphalt mixtures exposed to sodium chloride, Transp. Res. Rec. (2022), 03611981221082579.
[33] X. Zhang, H. Chen, I. Hoff, The mutual effect and reaction mechanism of bitumen and de-icing salt solution, Constr. Build. Mater. 302 (2021), 124213.
[34] X. Zhang, I. Hoff, H. Chen, Characterization of various bitumen exposed to environmental chemicals, J. Clean. Prod. (2022), 130610.
[35] X. Zhang, T. Fidai, I. Hoff, B.O. Lerfald, H. Chen, Determination of rejuvenator proportion within the recycled bitumen: empirical doublelogarithmic formula and calibration, J. Mater. Civ. Eng., 2022 (In press).
[36] T. Zhou, L. Cao, E.H. Fini, L. Li, Z. Liu, Z. Dong, Behaviors of asphalt under certain aging levels and effects of rejuvenation, Constr. Build. Mater. 249 (2020), 118748.