Drift og vedlikehold
Teknologi Drift og vedlikehold
Teknologi Drift og vedlikehold
21.03.2024

Statens vegvesen

Aldring av bituminøse bindemidler

Felt- og laboratorieundersøkelser og utvikling av aldringsmodeller

STATENS VEGVESENS RAPPORTER Nr. 968

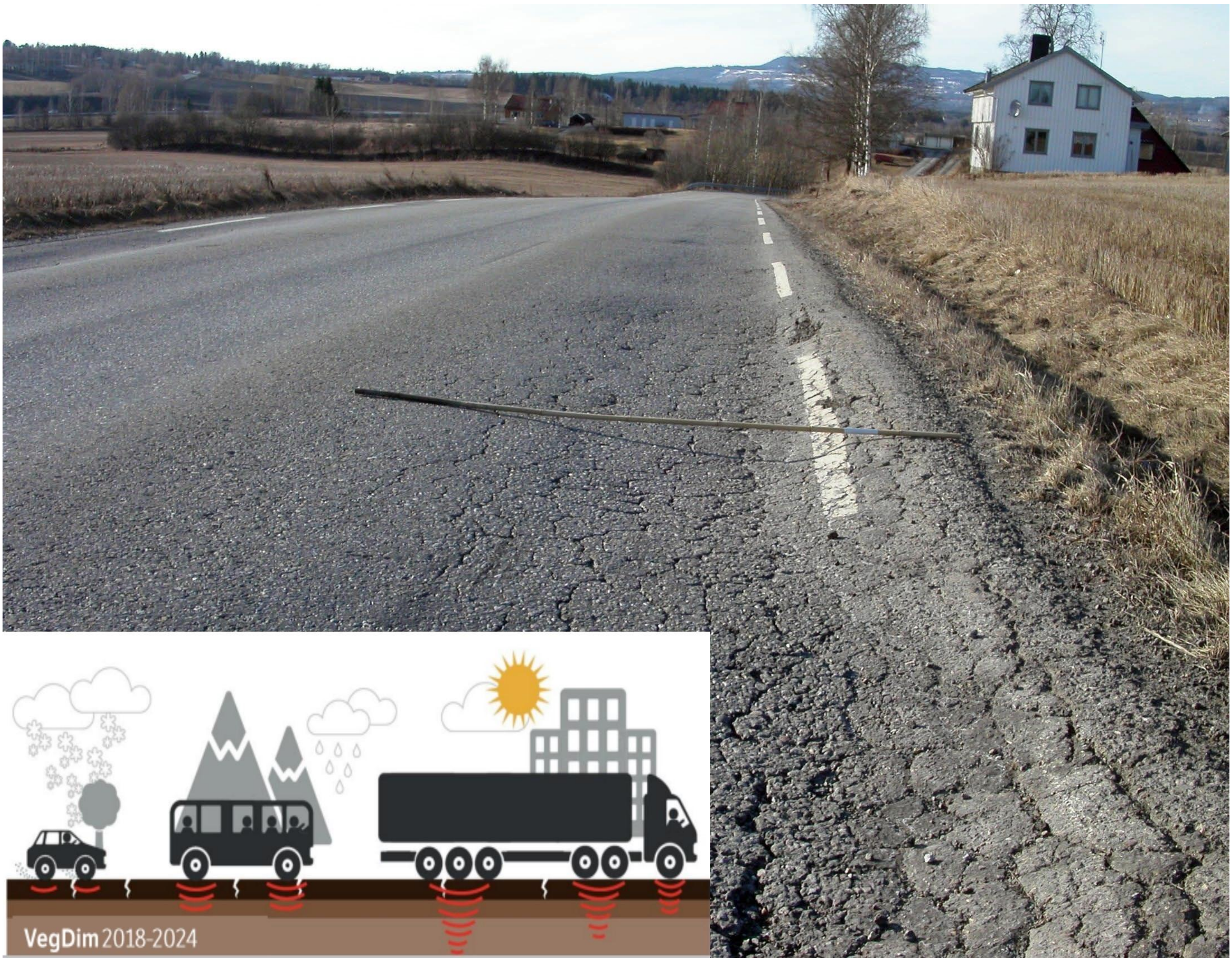


Foto: T. Haugødegård, Illustrasjon: Michelle G. Stoltenberg

Tittel
Aldring av bituminøse bindemidler

Undertittel
Felt- og laboratorieundersøkelser og utvikling av aldringsmodeller

Forfatter
Xuemei Zhang

Avdeling
Teknologi Drift og vedlikehold

Seksjon
Teknologi Drift og vedlikehold

Prosjektnummer
VVC 13480

Rapportnummer
968

Prosjektleder
Brynhild Snilsberg

Godkjent av
Rabbira Garba Saba

Emneord
Bitumen, aldring, klima, trafikk, dekkealder

Sammendrag
Denne studien hadde som mål å undersøke aldring av bituminøse bindemidler under norske forhold, og å utvikle aldringsmodeller for bitumen basert på dekkealder, trafikklast og klima. Åtte veistrekninger med ulike dekkealder ble valgt ut og undersøkt der asfaltprøver ble tatt fra slitelagene og data om klima og trafikk for hver av strekningene samlet inn. To type bindemidler (70/100 og PmB) ble ekstrahert fra felt-prøvene og ble testet i laboratoriet for å bestemme egenskapene til bindemidlene. Basert på testresultatene ble det etablert enkle aldringsmodeller som kan brukes til å estimere aldring ut ifra noen utvalgte materialparameterer.

Title
Ageing of bituminous binders

Subtitle
Field and laboratory investigation and development of ageing models

Author
Xuemei Zhang

Department
O&M Technology

Section
O&M Technology

Project number
VVC 13480

Report number
968

Project manager
Brynhild Snilsberg

Approved by
Rabbira Garba Saba

Key words
Bitumen, ageing, climate, traffic, pavement age

Summary
The objectives of this study were to investigate ageing of bituminous binders under Norwegian conditions and to develop ageing models for bitumen based on pavement age, traffic loading and climate effects. Asphalt samples were taken from eight road sections with varying pavement age, and traffic and climate data for these sections were collected. Two binder types (70/100 and PmB) were extracted and tested in the laboratory to determine their properties. Based on the results of the laboratory test, simple ageing models that can be used to estimate ageing using some selected material parameters were developed.

Antall sider 28

Pages 28

Preface

This report is the result of a research cooperation between Civil and Environment Engineering department at Norwegian university of science and technology (NTNU) and Norwegian Public Roads Administration (NPRA) and forms part of NPRA's research and development program, VegDim.

This research project started in April 2022 and was inspired by Xuemei Zhang's publication on ageing of bitumen. The first 8 months from April 2022 to December 2022 were used to collect the service conditions of the selected road sections and test field and reference samples. Another three months were applied to analyse the test data and build up ageing model of bitumen under Norwegian conditions. The entire project was, throughout all its phases, a close cooperation between the NTNU and the Road technology group of Operations and Maintenance division within the NPRA.

Some of results obtained during the project work were discussed and published as two international journal papers, which are listed as Appendix in the report. This report gives an overview of the conducted work and analyses of all important results that were produced until April 2023.

The results obtained in this project can be used in the development and calibration of the new pavement design program VegDim, which will be used as pavement structural design and analysis system to optimize road pavement structures under Norwegian and Swedish conditions.

Contents

1. INTRODUCTION

The ageing of bitumen is the most typical concern in the field of pavement engineering. Ageing of bitumen can be induced by many factors such as oxygen, high temperature, moisture, chemicals, and ultraviolet radiation during service period [1-3]. In general, the hardness and brittleness of bitumen are increased after ageing, and the adhesion and cohesion are degraded after ageing [4-6]. The changes in bitumen properties lead to brittle and loose asphalt mixture which are prone to various cracks [7]. Thus, bitumen ageing is an essential factor for most distress on asphalt pavement, including weathering, ravelling, transverse cracking, and fatigue cracking [8]. The more severe the bitumen ageing, the higher the risk of distress development. In the field, the combination of all potential influencers results in deterioration and shorter service life of asphalt pavements.

Therefore, the main objective of this project was to investigate the relationship between bitumen properties and service time, traffic, and climate under Norwegian conditions. Taking bitumen aging development into consideration in pavement design for Norwegian roads can improve the accuracy of the lifespan predication model.

To achieve this goal, eight road sections selected from various roads were analysed. The traffic, climate, and service time of the eight road sections were summarised. The properties of the extracted bitumen from the eight road sections were compared with unaged reference bitumen to develop an ageing model of bitumen under Norwegian conditions. Moreover, the dynamic moduli of core samples in the field were evaluated and analysed in comparison with asphalt mixtures made in the laboratory.

2. THE ROAD SECTIONS

2.1 Location and structure of the eight road sections

Detailed information on the eight road sections is shown in Table 1. The road sections are located on roads EV6, Fv33, EV16, Rv16. The service time varies from 4 years to 13 years. Two bitumen types were used for paving the road sections: neat bitumen with Pen 70/100 and polymer-modified bitumen (PMB). Most road sections were paved with asphalt concrete (AC) including AC 11 and AC 16, whereas Ev6-7 section was paved with AC 11 and SMA 11. The aggregate gradations of AC 11, AC 16 and SMA 11 are shown in Figure 1.

Table 1. Information of the eight road sections

Section code	Location	Paving/Coring year	Service time	Bitumen type	Mix type
Ev16 (Kongsvinger)	Ev16 S62D1	2015/2021	6	PMB 65/105	AC 11
Ev6-1 (Espa)	Ev6 S27D1	2015/2021	6		AC 16
Ev6-2 (Espa nord)	Ev6 S28D1	2012/2021	9		AC 16
Ev6-5	Ev6, S65D1	2009/2022	13	PMB 40/100	AC 11
Fv33 (Langslett)	Fv33 S5D1	2017/2021	4	70/100	AC 11
Rv3 (Åsta)	Rv3 S6D1	2014/2021	7		AC 11
Ev6-4	Ev6, S64D1	2012/2022	10		AC 11
Ev6-7	Ev6, S67D1	2011/2022	11		SMA/AC 11

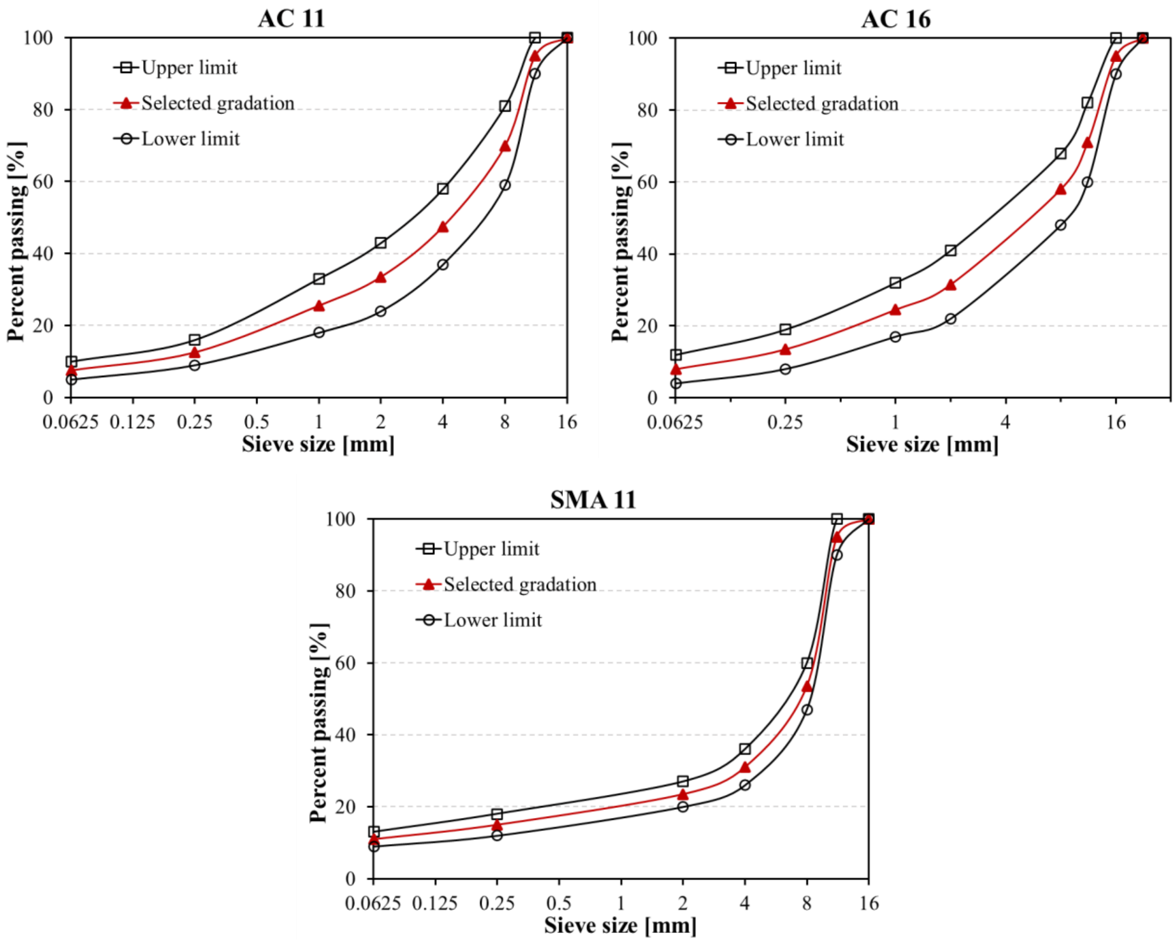


Figure 1. Aggregate gradation of AC-11, AC 16 and SMA-11

2.2 Climate and traffic information

The climate information including temperature and precipitation for the eight road sections was obtained from Norsk KLIMA servicesenter. The annual temperatures from 2009 to 2021 of the road sections are shown in Table 2. Based on the annual temperature, the mean annual temperature ($\overline{T}$), for each section was calculated and shown Table 2.

Table 2. Temperature data of the eight road sections

Section code	2009	2010	2011	2012	2013	2014	2015
Ev16 (Kongsvinger)	-	-	-	-	-	-	6.3 ℃
Ev6-1 (Espa)	-	-	-	-	-	-	6.2 ℃
Ev6-2 (Espa nord)	-	-	-		4.9 ℃	6.9 ℃	6.2 ℃
E6-5	4.1 ℃	1.7 ℃	4.9 ℃	3.3 ℃	3.9 ℃	5.5 ℃	4.9 ℃
Fv33 (Langslett)	-	-	-	-	-	-	-
Rv3 (Åsta)	-	-		-	-	4.7 ℃	3.9 ℃
Ev6-4	-	-	-	2.9 ℃	3.7 ℃	5.4 ℃	4.7 ℃
Ev6-7	-	-	4.9 ℃	3.3 ℃	3.9 ℃	5.5 ℃	4.9 ℃
Section code	2016	2017	2018	2019	2020	2021	$\bar{T}$
Ev16 (Kongsvinger)	5.8 ℃	5.6 ℃	6.1 ℃	5.8 ℃	7.9 ℃	5.4 ℃	6.1 ℃
Ev6-1 (Espa)	5.8 ℃	5.6 ℃	6.0 ℃	5.4 ℃	7.7 ℃	5.3 ℃	6.0 ℃
Ev6-2 (Espa nord)	5.8 ℃	5.6 ℃	6.0 ℃	5.4 ℃	7.7 ℃	5.3 ℃	6.0 ℃
Ev6-5	4.2 ℃	4.0 ℃	4.4 ℃	4.3 ℃	5.4 ℃	4.0 ℃	4.0 ℃
Fv33 (Langslett)	-	4.9 ℃	5.7 ℃	5.3 ℃	7.0 ℃	5.2 ℃	5.6 ℃
Rv3 (Åsta)	3.2 ℃	2.7 ℃	3.6 ℃	3.2 ℃	5.2 ℃	2.8 ℃	3.7 ℃
Ev6-4	4.1 ℃	3.9 ℃	4.4 ℃	4.1 ℃	5.0 ℃	3.8 ℃	4.2 ℃
Ev6-7	4.2 ℃	4.0 ℃	4.4 ℃	4.3 ℃	5.4 ℃	4.0 ℃	4.5 ℃

The annual precipitation (P) of the selected road sections was collected and presented in Table 3 together with the mean annual precipitation.

Table 3. Precipitation data of the eight road sections

Section code	2009	2010	2011	2012	2013	2014	2015
Unit				mm			
Ev16（Kongsvinger)	-	-	-	-	-	-	750.6
Ev6-1 (Espa)	-	-	-	-	-	-	853.5
Ev6-2 (Espa nord)	-	-	-	697.9	718.0	976.1	853.5
Ev6-5	681.8	720.6	914.7	830.4	744.6	563.3	670.7
Fv33 (Langslett)	-	-	-	-	-	-	-
Rv3 (Åsta)	-	-	-	-	-	896.5	794.6
Ev6-4	-	-	-	538.3	505.0	430.1	506.6
Ev6-7	-	-	-	821.5	682.2	655.7	717.5
Section code	2016	2017	2018	2019	2020	2021	$\bar{P}$
Unit				mm			
Ev16 (Kongsvinger)	588.7	717.6	535.4	814.3	925.9	593.3	703.7
Ev6-1 (Espa)	661.6	800.8	619.7	921.4	869.9	543.2	752.87
Ev6-2 (Espa nord)	661.6	800.8	619.7	921.4	869.9	543.2	766.21
Ev6-5	793	924	683.8	806.3	927	881.8	780.15
Fv33 (Langslett)	-	644.8	520.5	810.1	688.9	497.7	632.40
Rv3 (Åsta)	651.2	748.9	618.6	928.3	773.4	713.9	746.99
Ev6-4	567.2	619.7	498.1	540.3	603.6	535.5	534.44
Ev6-7	914.5	1008.4	751.6	896.9	1023	1041.4	851.27

Traffic data of the eight road sections, including AADT and heavy vehicle percentage, was obtained from Vegkart and presented in Table 4.

Table 4. Traffic data of the eight road sections

Road section	AADT	Percentage of heavy vehicles [%]
Ev16 (Kongsvinger)	8621	14
Ev6-1 (Espa)	14330	18
Ev6-2 (Espa nord)	14300	18
Ev6-5	5432	27
Fv33 (Langslett)	2700	10
Rv3 (Åsta)	5195	22
Ev6-4	5600	16
Ev6-7	5132	26

3. BITUMEN PROPERTY

3.1 Reference bitumen

To compare the ageing degree of bitumen from the field samples, two types of reference bitumen were studied, that is a polymer-modified bitumen (PMB) with Pen 65/105 and a neat bitumen with Pen 70/100. The physical properties of the two types of bitumen are presented in Table 5.

Table 5. Basic properties of the two types of bitumen

Binder	Penetration [0.1 mm]	Softening point [°C]
70/100	71	48.2
PMB	79	64.6
Standard	EN 1426:2015	EN 1427:2015

3.2 Extracted bitumen from the field asphalt mixture samples

3.2.1 Field asphalt mixture samples

Core specimens were drilled from road sections as shown in Figure 2. The specimens had a diameter of 100 mm and a thickness of 40 mm for dynamic modulus test. Some of the specimens had a thickness of 30 mm due to thinner asphalt layer. The asphalt mixture samples were then heated and mashed into pieces for further extraction test.

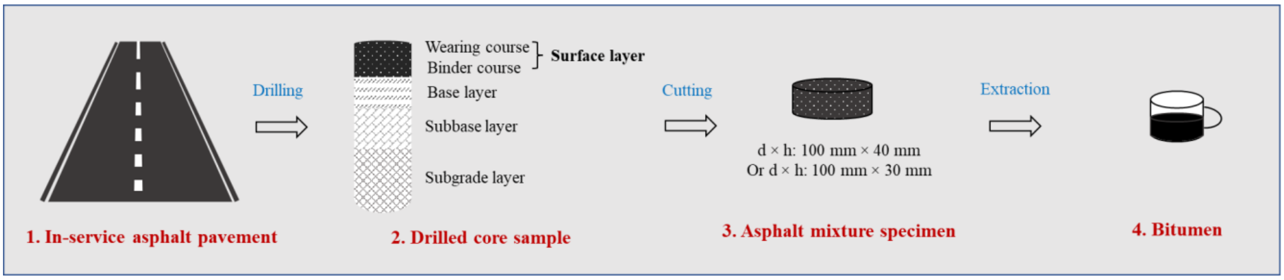


Figure 2. The process of field core samples

The extraction process includes two stages: separation of aggregate and bitumen and extraction of bitumen from dichloromethane in accordance with EN 12697-3 [9]. After the extraction process, bitumen samples were heated at 110 °C until the constant weight is achieved and then kept at room temperature for more than one week to avoid extra solvent in bitumen.

3.2.2 Bitumen properties characterisation

The stiffness and consistency of bitumen are normally characterised by softening point and penetration tests using ring and ball method and needle penetration method respectively [10, 11]. Two replicates and three measurements are tested for each bitumen specimen, and the mean value is used for analysis.

The chemical structure of bitumen is generally determined by the comprised groups which can be detected by Nicolet 8700 Fourier transform infrared (FTIR) radiation spectrometer with an attenuated total reflectance (ATR) accessory. The development of the chemical structure of bitumen over service life is identified by the infrared spectra tested by FTIR-ATR. Both quantitative and qualitative analyses were performed in this study in terms of the transmittance of peaks and chemical group indices.

The rheological properties of bitumen are characterised by conducting Dynamic Shear Rheometer (DSR) test. In order to study the development of bitumen properties over a range of temperatures and frequencies, the frequency sweep mode is applied for the DSR test. The specimen was tested at the frequencies of 0.1-400 rad/s and the temperatures of 30-80 °C with an interval of 10 °C for master curve construction. Moreover, this study aimed to investigate the ageing properties of bitumen under Norwegian conditions which is a cold climate. Thus, testing for the low to medium temperature rheological properties of bitumen is conducted using a plate of 8 mm at temperature ranges of 5 °C to 30 °C.

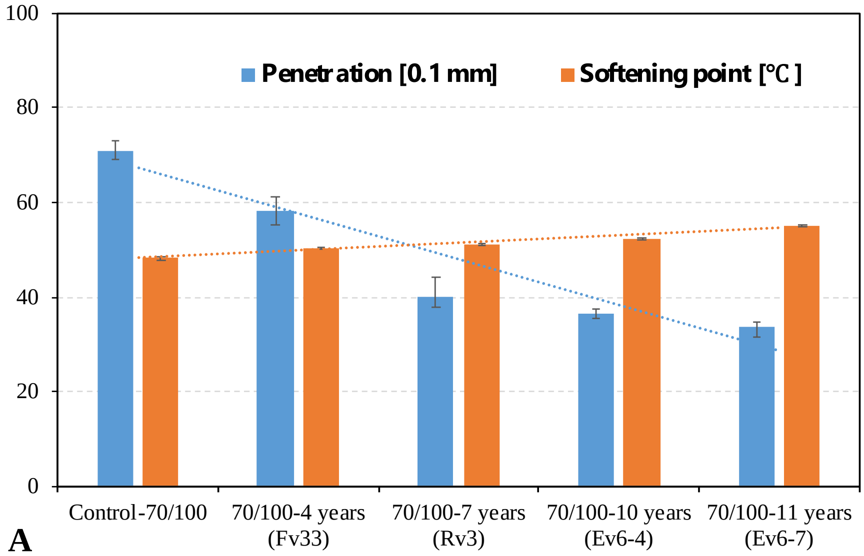
High-temperature performance grade (PG) reflects the stiffness and the rutting resistance of bitumen. PG value of bitumen specimen is measured by DSR using Smart Performance Grade template. The frequency is set to 10 rad/s, and the temperature is set starting from 64 ℃. The temperature keeps increasing until the rutting factor is smaller than 1 kPa, which demonstrates that the test fails. As a result, the failure temperature and rutting factor at tested temperatures are obtained.

3.3 Test results for the field and reference bitumen

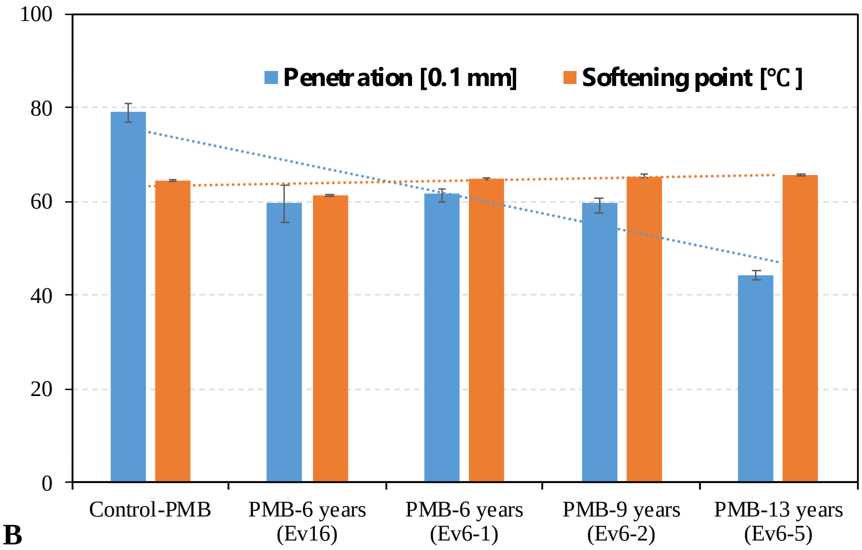
3.3.1 Physical properties of bitumen

The softening point and penetration of bitumen from different road sections are shown in Figure 3. The obvious changing trend of penetration is found for both 70/100 and PMB, that is the penetration value decreases with service time. The bitumen becomes stiffer as the result of of ageing, moisture immersion and traffic loading over service time. Inversely, the softening point of 70/100 increases with increasing service time under external Norwegian conditions. However, the softening point of PMB shows a slightly different behaviour, the value decreases in the short-term and increases afterwards. This result is consistent with Wu and Zhang's results, which is connected with the the intense degradation of the SBS modifier whthin PMB [12, 13]. In all, there is a linear correlation between pavement service time and penetration of both PMB and 70/100 and the softneing point of 70/100. Besides, the degree of change is more significant for 70/100 than that for PMB, indicating a greater ageing resistant of PMB.

`



A



B

Figure 3. Penetration and softening point of bitumen

3.3.2 Chemical properties of bitumen

As can be seen in Figure 4, oxidation of bitumen typically results in increased oxygen-containing functional groups detected by FTIR test, such as carbonyl and sulfoxide that are respectively located at 1700 cm^{-1} and 1030 cm^{-1} [9]. Besides, the butadiene double bond (C=C) of PMB is generally analysed for evaluating the ageing degree due to its specific oxidative reaction [3]. It is observed that the C=O and S=O peaks of both 70/100 and PMB sharpen over road service time, while the C=C of PMB decreases with increasing service time. These results follow the ageing effects on bitumen. To quantitatively evaluate the ageing degree of bitumen after distinct service time, the ageing indices are calculated following Eq (1), (2) and (3), where the CI, SI, and CCI are the ageing indices of carbonyl, sulfoxide, and butadiene groups, respectively.

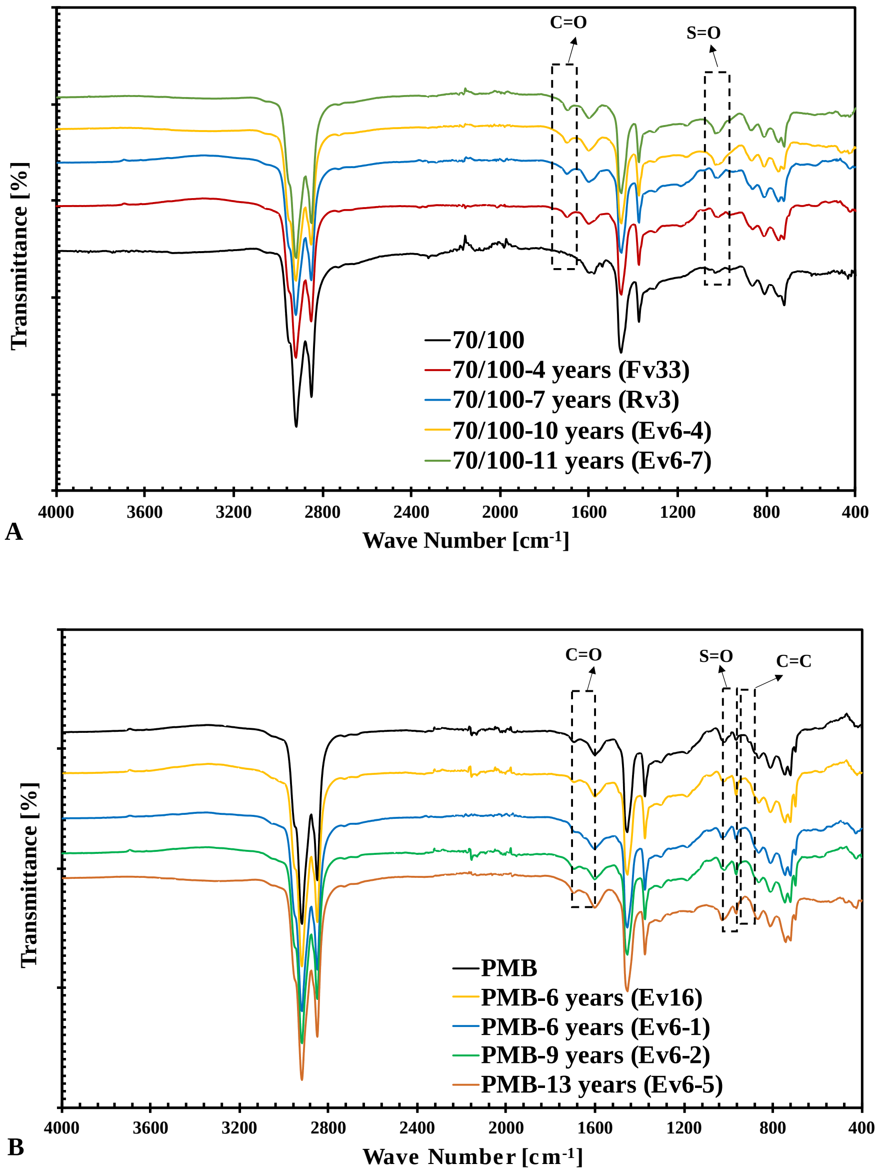


Figure 4. The FTIR spectra of all bitumen (A: 70/100; B: PMB)

$$SI = \frac{\textit{Area of the sulphoxide band centered around } 1030\ cm^{-1}}{\sum \textit{Area of the spectral bands between } 2000 \textit{ and } 1030\ cm^{-1}} \quad (1)$$

$$CI = \frac{\textit{Area of the carbonyl band centered around } 1700\ cm^{-1}}{\sum \textit{Area of the spectral bands between } 2000 \textit{ and } 1030\ cm^{-1}} \quad (2)$$

$$CCI = \frac{\textit{Area of the butadiene group centered around } 966\ cm^{-1}}{\sum \textit{Area of the spectral bands between } 2000 \textit{ and } 1030\ cm^{-1}} \quad (3)$$

The calculated SI, CI and CCI are displayed in Figure 5. It is clear that SI and CI increase with service time to different degrees, and SI index is more sensitive to service time than CI index. This result is in line with most studies [14, 15]. In contrast, the CCI value is negatively related with road section service time. These results indicate that longer service time induces severe oxidation of bitumen for both 70/100 and PMB. By comparing the CI and SI of the two bitumen, one can see that PMB is less affected by the service conditions.

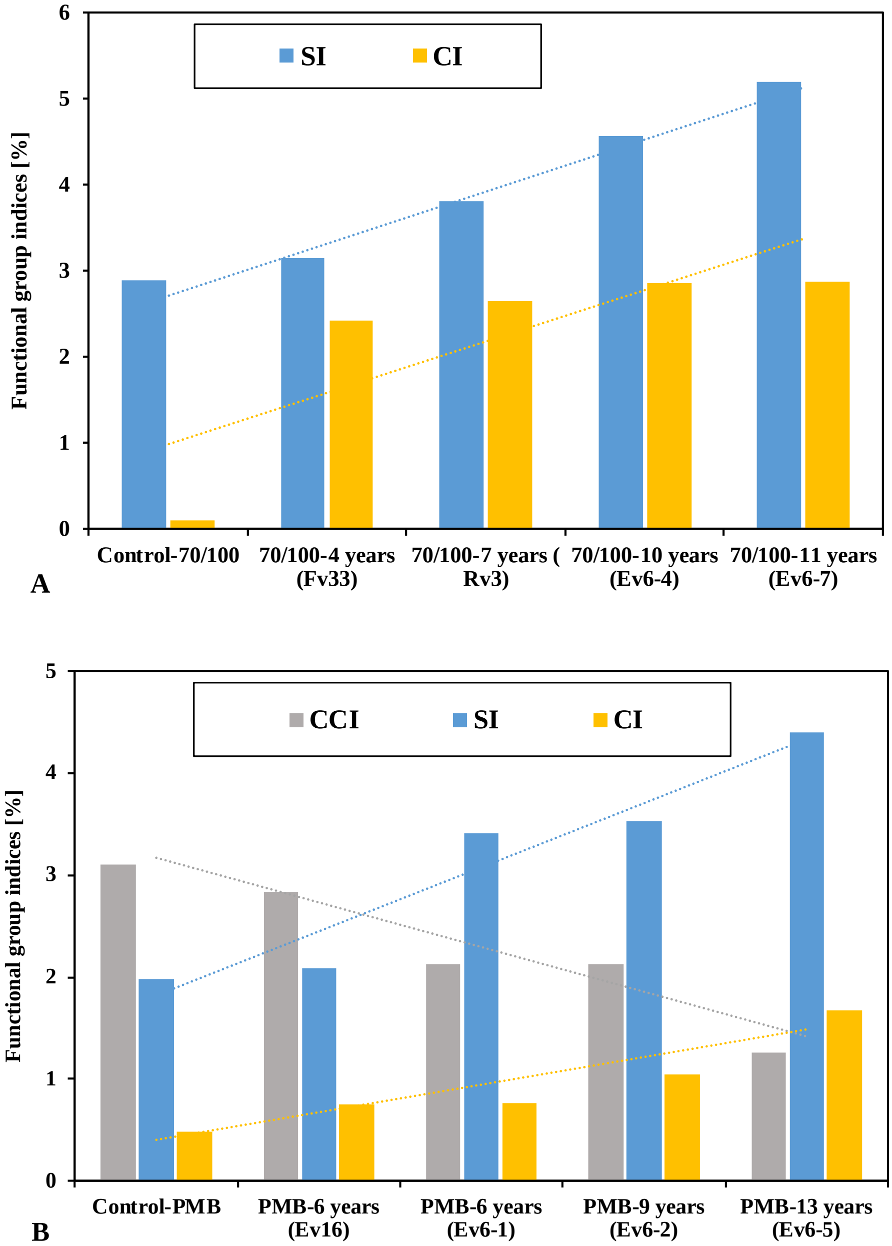


Figure 5. Ageing indices of all bitumen (A: 70/100; B: PMB)

3.3.3 Low to medium temperature rheological properties of bitumen

The low to medium temperature rheological properties of extracted bitumen and reference bitumen are characterised by complex modulus and phase angle at temperature range of 5-

30 °C. The results are shown in Figure 6. It demonstrates that the complex modulus of all bitumen specimens increases over service time, while the phase angle decreases over service time, indicating increasing degree of ageing of bitumen with increasing service time. This result is in line with the ageing results simulated in laboratory [16].

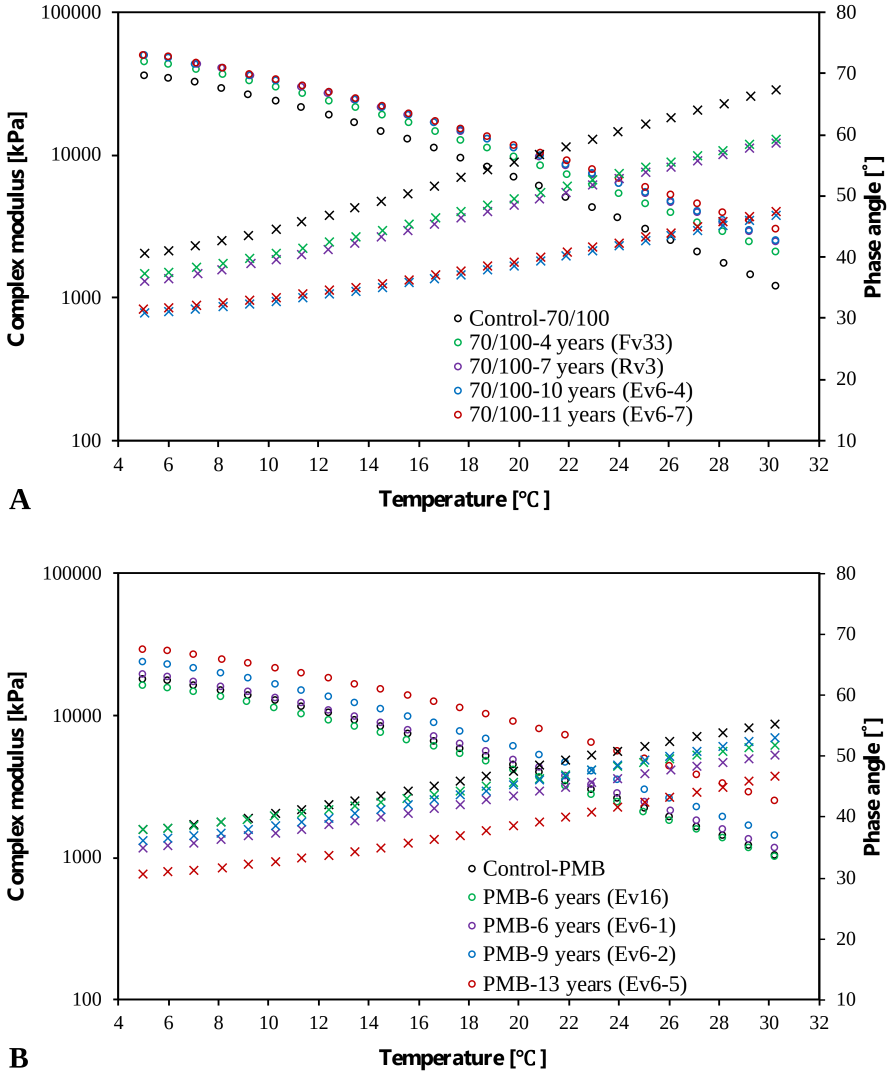


Figure 6. Complex modulus and phase angle of all bitumen (A: 70/100; B: PMB)

3.3.4 Master curve of bitumen

The complex modulus and phase angle master curves of both field bitumen and reference bitumen are illustrated in Figure 7. After several service years, the visco-elastic ratio (the ratio of viscous behaviour and elastic behaviour) is significantly influenced for PMB and 70/100. The complex modulus increases with increasing service time, whereas the phase angle decreases over service time, demonstrating a more elastic material after several years in service.

This trend agrees with the outcomes for penetration, ageing indices and low to intermediate temperature rheological properties, resulting in a linear correlation between complex modulus/phase angle and service time.

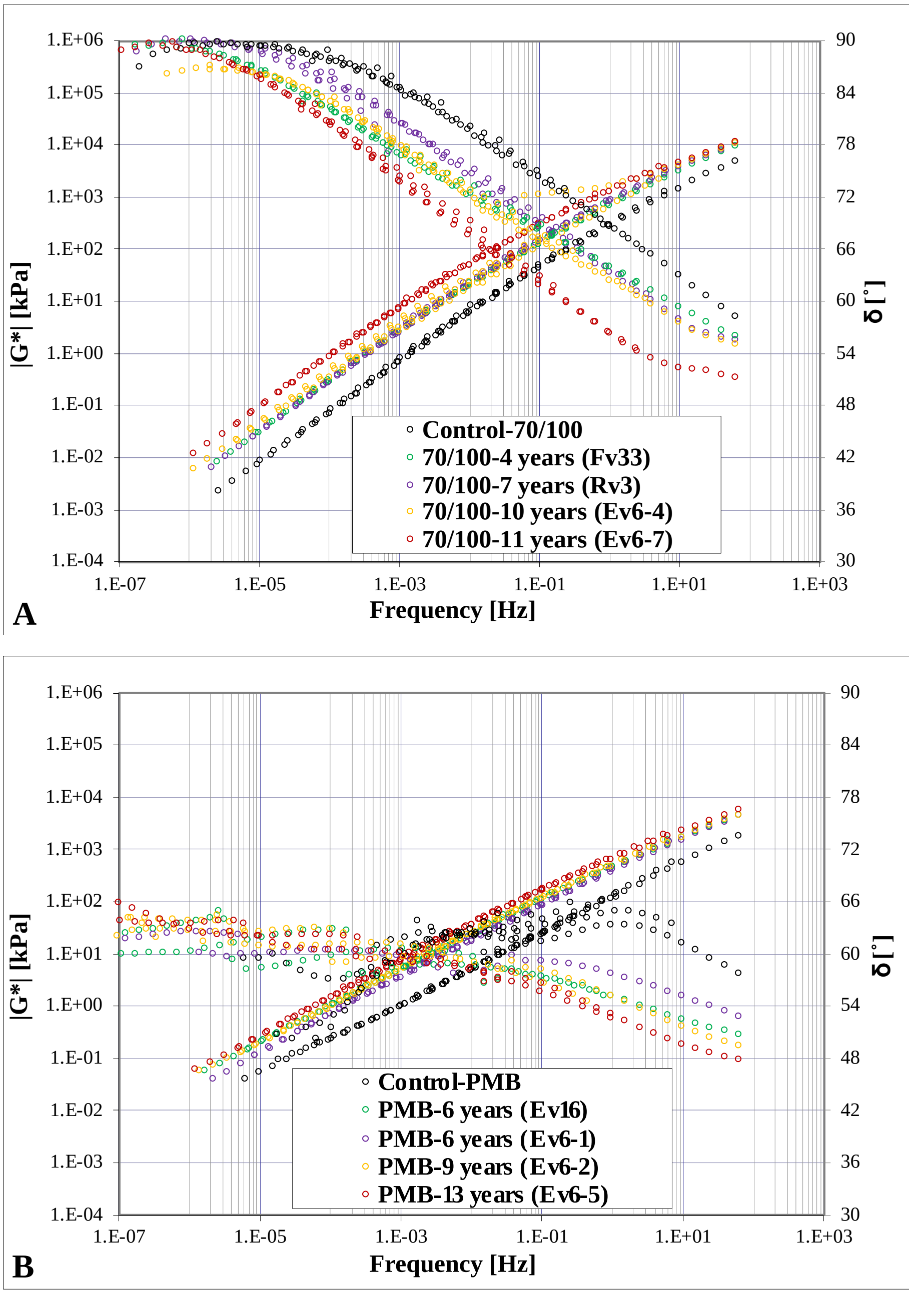


Figure 7. The master curve of all bitumen (A: 70/100; B: PMB)

3.3.5 Performance grade of bitumen

The PG value, rutting factor ($G^*/\sin\delta$) and pass temperature are listed in Table 6. Rutting factor indicates the ability of bitumen to resist rutting, a higher rutting factor presents better rutting resistance. The PG value and pass temperature of bitumen increases with increasing service time. As shown in Table 6, the rutting factor at fixed temperature of bitumen increases over service time under ambient service conditions. These findings indicate a stiffer bitumen with better rutting resistance is obtained after long serving period.

Table 6. The PG, pass temperature and rutting factor of all bitumen

Bitumen	Rutting factor [kPa]						Pass temperature [℃]
	58 ℃	64 ℃	70 ℃	76 ℃	82 ℃	88 ℃	
Control-70/100	1.72	0.78	/	/	/	/	62.1
70/100-4 years	/	4.61	2.1	1.01	0.19	/	76.1
70/100-7 years	/	3.94	1.76	0.84	/	/	74.6
70/100-10 years	/	4.33	1.96	0.93	/	/	75.4
70/100-11 years	/	7.75	3.37	1.54	0.73	/	79.5
Control-PMB	/	3.83	2.08	1.21	0.74	/	78.3
PMB-6 years	/	5.54	3.08	1.75	1.03	0.61	82.3
PMB-6 years	/	6.63	3.5	1.96	1.15	0.69	83.6
PMB-9 years	/	7.06	3.85	2.16	1.24	0.72	84.3
PMB-13 years	/	9.08	4.78	2.59	1.45	0.83	86.0

4. AGEING MODEL

In this chapter, penetration, softening point, pass temperature, complex modulus at temperature ranges of 10-80 ℃ with an interval of 10 ℃, rutting factor at 64 ℃, SI, CI, and CCI were selected as bitumen properties applied for ageing model construction. Bitumen type, service time, annual average daily traffic (AADT), heavy vehicle ratio (HVR), annual average temperature (AAT) and annual average precipitation (AAP) were chosen as service conditions of asphalt pavement for modelling.

4.1 Correlation between all selected parameters

By analysing the reference bitumen and extracted bitumen under different conditions by SPSS software, the correlation between bitumen property factors and service conditions was obtained and shown in Table 7. The closer the Pearson Correlation to -1 or 1, and the closer the Sig. (2-tailed) to 0, the greater the correlation. The negative and positive values of Pearson Correlation indicate the negative and positive correlation between two variables, respectively. It can be observed that most bitumen properties are highly related to service time, HVR and AAP, and are also slightly correlated with bitumen type and AAT. For example, longer service time results in the reduction in penetration and CCI index value, and the increase in complex modulus, rutting factor and SI index value. In contrast, AADT is rarely related to tested bitumen properties. The above results imply that service time, heavy vehicle and precipitation influence bitumen properties significantly, and the influences of bitumen type and pavement external temperature can also not be ignored, while AADT has limited effects on bitumen properties. Moreover, at higher temperatures (40-80 ℃), complex modulus is highly related to bitumen type and AAP, which is in line with the significant difference between neat bitumen and PMB at higher temperatures [17, 18].

Table 7. the correlation between bitumen properties and service conditions

Bitumen factor	Correlation Parameter	Bitumen type	Service time	AADT	HVR	AAT	AAP
Softening point	Pearson Correlation	-0.956**	0.237	0.551	0.219	0.430	0.209
	Sig. (2-tailed)	0.000	0.510	0.099	0.543	0.288	0.562
Penetration	Pearson Correlation	-0.454	-0.836**	-0.135	-0.831**	0.904**	-0.700*
	Sig. (2-tailed)	0.187	0.003	0.710	0.003	0.002	0.024
Passing temperature	Pearson Correlation	-0.923*	0.605	0.661*	0.612	0.414	0.668*
	Sig. (2-tailed)	0.026	0.064	0.038	0.060	0.308	0.035
G* at 10°C	Pearson Correlation	0.903**	0.333	-0.362	0.328	-0.745*	0.214
	Sig. (2-tailed)	0.000	0.346	0.305	0.335	0.034	0.552
G* at 20°C	Pearson Correlation	0.759*	0.542	-0.273	0.525	-.846**	0.367
	Sig. (2-tailed)	0.011	0.106	0.446	0.120	0.008	0.297
G* at 30°C	Pearson Correlation	0.612	0.655*	0.007	0.585	-0.665	0.491
	Sig. (2-tailed)	0.060	0.040	0.984	0.075	0.072	0.149
G* at 40°C	Pearson Correlation	0.345	0.700*	0.147	0.816**	-0.480	0.763*
	Sig. (2-tailed)	0.329	0.024	0.685	0.004	0.229	0.010
G* at 50°C	Pearson Correlation	0.150	0.779**	0.279	0.877**	-0.374	0.846**
	Sig. (2-tailed)	0.680	0.008	0.435	0.001	0.361	0.002
G* at 60°C	Pearson Correlation	-0.170	0.820**	0.460	0.890**	-0.106	0.889**
	Sig. (2-tailed)	0.639	0.004	0.181	0.001	0.803	0.001
G* at 70°C	Pearson Correlation	-0.523	0.740*	0.591	0.777**	0.202	0.804**
	Sig. (2-tailed)	0.121	0.014	0.072	0.008	0.631	0.005
G* at 80°C	Pearson Correlation	-0.763*	0.573	0.630	0.588	0.369	0.634*
	Sig. (2-tailed)	0.010	0.084	0.051	0.074	0.368	0.049
G*/sinδ (64 °C)	Pearson Correlation	-0.475	0.794**	0.489	0.778**	0.048	0.765**
	Sig. (2-tailed)	0.165	0.006	0.151	0.008	0.910	0.010
SI	Pearson Correlation	0.427	0.804**	0.149	0.759*	-0.714*	0.565
	Sig. (2-tailed)	0.218	0.005	0.682	0.011	0.047	0.088
CI	Pearson Correlation	0.611	0.615	-0.066	0.611	-0.748*	0.560
	Sig. (2-tailed)	0.061	0.059	0.856	0.060	0.033	0.092
CCI	Pearson Correlation	.[c]	-0.922*	-0.350	0.930*	0.876	-0.712
	Sig. (2-tailed)	0.000	0.026	0.564	0.022	0.124	0.178

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
b. Cannot be computed because at least one of the variables is constant.

4.2 Ageing model construction

Based on the characterisation of bitumen properties over service time adopted to local conditions, the relationship between bitumen properties and external conditions can be considered as linear correlations. Therefore, the ageing model was established based on the following equations:

$$\text{When } n=0,\ A_n=A_0 \quad (4)$$

$$\text{when } n\neq 0,\ A_n=A_0+B(\text{bitumen type, service time, AADT, HVR, AAT and AAP}) \quad (5)$$

Where A_n is the bitumen properties of in-service pavement after n years servicing; n means service time, the unit is year; A_0 is the initial properties without ageing; B is the additional changes in bitumen properties due to the external service condition of bitumen, including the value of bitumen type, AADT, service time, HRV, AAT and AAP. Bitumen type in this study was defined as scale input, where 1 represents PMB and 0 represents 70/100.

By conducting the linear regression of bitumen properties as a function of bitumen type, service time, AADT, HVR, AAT and AAP, the corresponding models are shown in Table 8, as well as the goodness of fit (R^2). All models have excellent goodness of fit as all R^2 excesses 0.94.

Table 8. Ageing models

Property	R^2	Model
Penetration	0.966	Penetration = 78.623-13.401Bitumen type - 0.437Service time-216.348HVR - 2.531AAT + 0.064AAP
Softening point	0.993	Softening point = 52.775 - 8.773Bitumen type - 0.375Service time + 137.438HVR + 4.631AAT - 0.037AAP
Pass temperature	1.000	Pass temperature = 69.0.13 - 5.857Bitumen type + 0.314Service time + 43.607HVR + 2.854AAT - 0.005AAP
G* (10℃)	0.987	G* = 7609.810 + 14715.059Bitumen type + 1176.164Service time + 0.15AADT - 93022.532HVR - 4368.908AAT + 31.89AAP
G* (20℃)	0.977	G* = 3628.460 + 3222.315Bitumen type + 382.77Service time - 0.03AADT - 18025.759HVR - 1144.335AAT + 7.209AAP
G* (30℃)	0.973	G* = -1992.829 + 1010.343Bitumen type - 42.617Service time - 0.026AADT + 23020.128HVR + 776.133AAT - 8.664AAP
G* (40℃)	0.993	G* = -635.987 + 103.714Bitumen type - 8.618Service time - 0.011AADT + 2608.089HVR + 103.646AAT - 0.27AAP
G* (50℃)	0.993	G* = -115.137 + 13.409Bitumen type - 1.554Service time - 0.003AADT + 548.255HVR + 22.871AAT - 0.071AAP
G* (60℃)	0.994	G* = -18.846 + 0.019Bitumen type - 0.211Service time - 0.001AADT + 111.354HVR + 5.027AAT - 0.015AAP
G* (70℃)	0.997	G* = -1.551 - 1.189Bitumen type - 0.008Service time + 21.431HVR + 1.075AAT + 0.002AAP
G* (80℃)	0.998	G* = 0.612 - 0.761Bitumen type - 0.001Service time - 5.653E-5AADT + 5.530HVR + 0.287AAT - 0.001AAP
Rutting factor	0.998	Rutting factor = -5.229 - 1.669Bitumen type + 0.362Service time + 16.613HVR + 1.710AAT + 0.002AAP
SI	0.948	SI = -3.761 + 1.69Bitumen type + 0.071Service time + 1.458E-5AADT + 30.908HVR + 0.974AAT - 0.009AAP
CI	0.996	CI= -0.311 + 1.483Bitumen type + 0.099Service time - 1.562E-5AADT - 2.033HVR - 0.131AAT
CCI	1.000	CCI = 15.322 + 3.432E-5AADT - 0.018AAP

To verify the accuracy of the ageing models, the predicted bitumen properties calculated from ageing models of Table 8 and the measured bitumen properties are compared in Figure 8 (PMB) and Figure 9 (70/100). As presented in Figure 9, the bitumen properties, especially physical properties, PG parameters, and rheological properties, can be predicted by their corresponding ageing models by inputting bitumen type, service time, AADT, HVR, AAT and AAP. In contrast, the three predicted indices presented in Figure 8E are slightly different from the measured ageing index value but within reasonable variation range. These results verify the high accuracy of the ageing models.

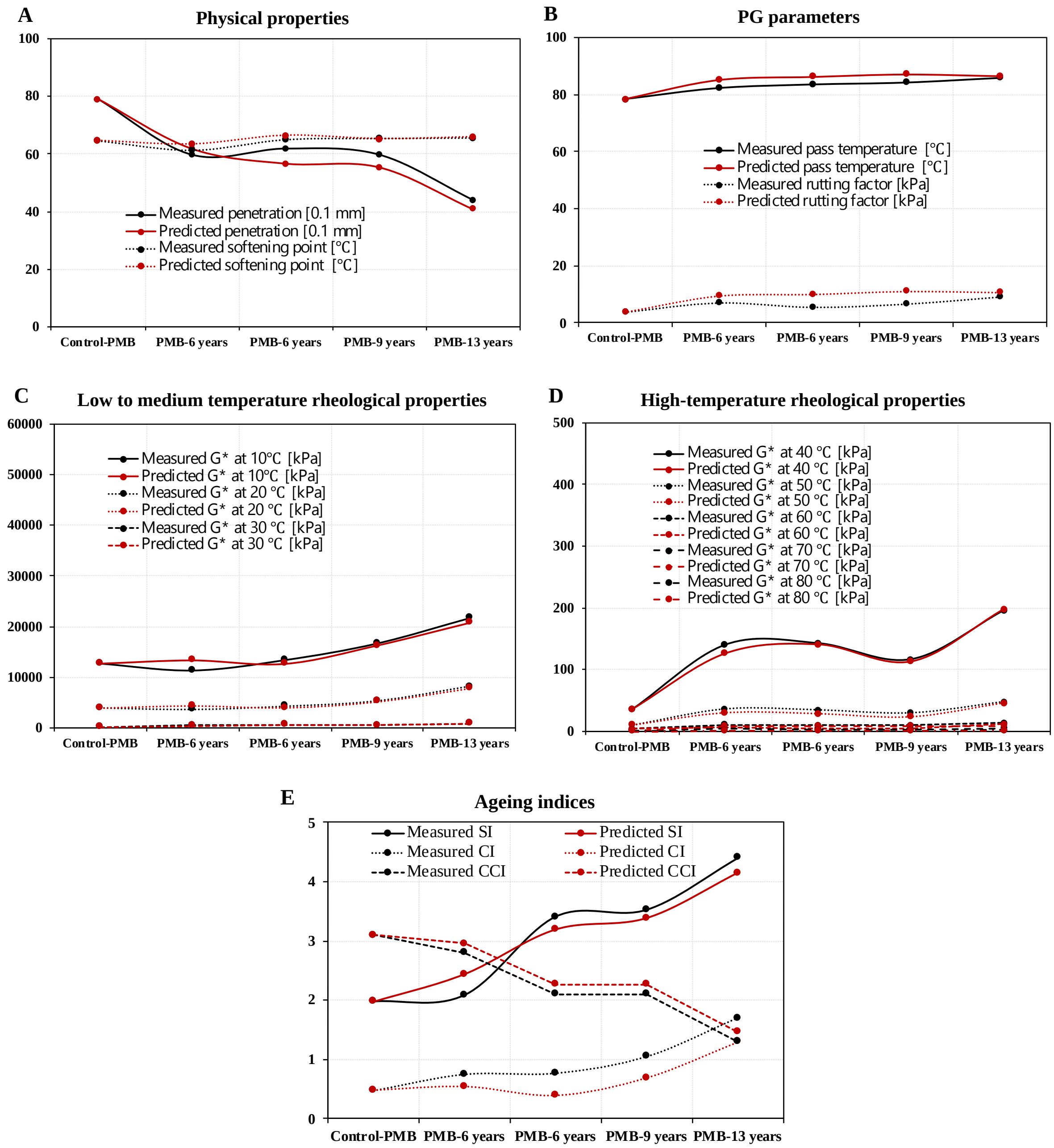


Figure 8. The comparison between measured data and predicted data by ageing models for PMB

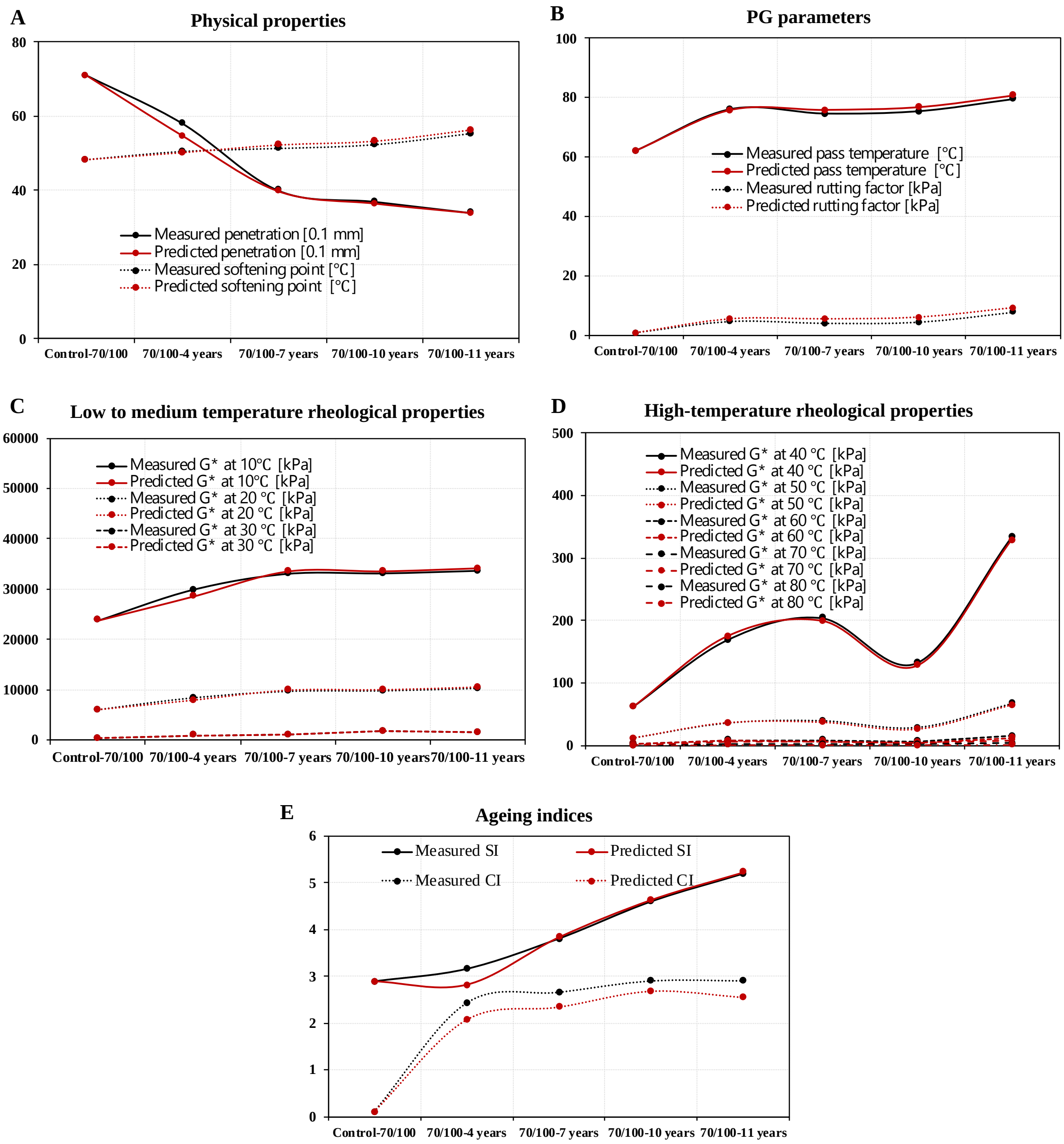


Figure 9. The comparison between measured data and predicted data by ageing models for 70/100

5. DYNAMIC MODULUS OF ASPHALT MIXTURE

The dynamic modulus of field asphalt mixture samples and three reference asphalt mixtures (AC11-PMB, AC11-70/100, AC16-PMB) were evaluated and shown in Figure 10. As observed for PMB mixtures, the slopes of serviced section curves are flatter than the reference mixture (AC11-PMB), indicating a weaker susceptibility to frequency or temperature. With respect to the performance at lower frequencies, the dynamic modulus increases until 6-year-service time for AC11-PMB mixtures, and the dynamic modulus decreases afterward. Regarding AC16-PMB mixtures, the dynamic moduli are hardly influenced by short service time. Besides, the dynamic moduli of the four road sections are similar but smaller than the reference AC11-PMB and AC16-PMB at higher frequencies. Thus, service time and ambient environment influence the dynamic modulus of mixture at lower frequencies and higher temperatures more significantly, which agrees with Nobakht's study [40]. Moreover, the stiffness almost keeps slightly increasing or unchanged until 9 years of servicing under the function of traffic compaction and asphalt mixture ageing, whereas the stiffness after 9 years servicing decreases due to the occurrence of cracks.

In terms of 70/100 mixtures, the slopes of 70/100-4 years (Fv33) and 70/100-7 years (Rv3) sections are lower than the reference mixture (AC11-70/100), and this result can be interpreted by a more stable asphalt mixture state caused by ageing. With the prolonged service time, the dynamic modulus decreases over service time at all tested frequencies, and the slope of 70/100-11 years is the lowest among all 70/100 mixture specimens. This changing trend in the dynamic modulus of 70/100 road sections is the same as that of PMB road sections. However, comparing the variations in dynamic modulus, road sections made by AC-11 70/100 are more severely influenced by the service condition and service time compared to road sections made by AC-11 PMB. This result is connected with the better performance of PMB.

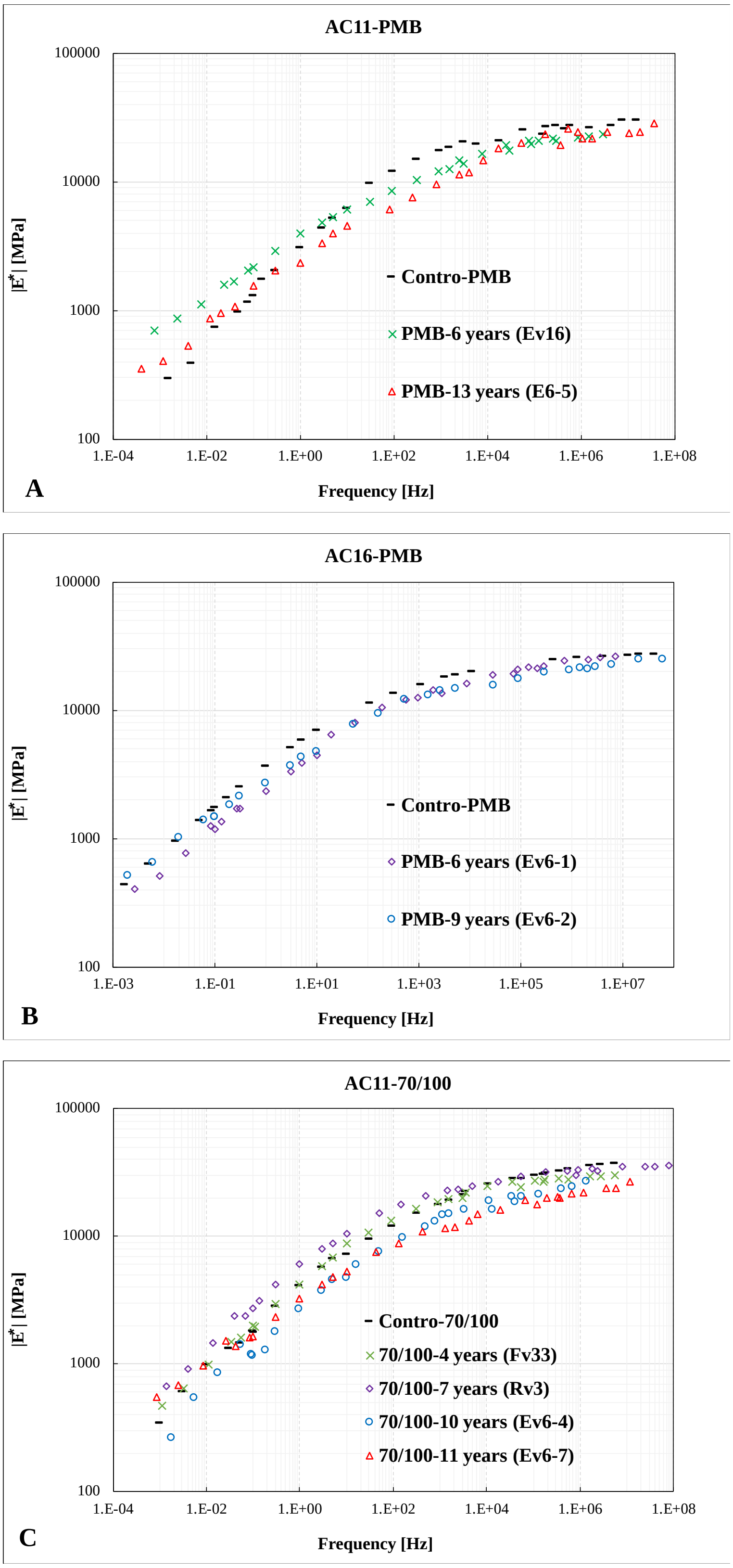


Figure 10. Dynamic moduli of field and laboratory samples (A: AC-11 PMB; B: AC-16 PMB; C: AC-11 70/100)

6. CONCLUSIONS

The project evaluated properties of bitumen extracted from in-service pavements. The evaluated bitumen had different initial material properties, road service time, climatic and traffic conditions. Tests for original/unaged bitumen provided an overview over the performance of two reference bitumen for comparison. Thus, the physical, chemical, and rheological properties and performance grade of both the extracted bitumen and reference bitumen were analysed. In comparison with reference bitumen, the softening point, ageing indices (SI and CI), complex modulus, rutting factor and pass temperature of extracted bitumen increases over pavement service time in general, and the penetration, CCI index and phase angle decrease over service time regardless of bitumen type. The relationship between changes in bitumen properties and service time is nearly linear. Thus, linear ageing models for bitumen properties based on bitumen type, service time, annual average daily traffic, heavy vehicle ratio, annual average temperature and annual average precipitation were proposed to predict the bitumen performance under different service conditions without coring and extraction and presented in Table 8. The bitumen properties predicted by ageing models are in agreement with the tested bitumen properties in laboratory, indicating excellent goodness of fit and high accuracy of the ageing models. Besides, the changes in dynamic modulus of asphalt mixtures are attributed not only the bitumen ageing but also the fractures inside asphalt mixture structure, which induces the increased value in the beginning and decreased value afterwards.

7. REFERENCES

[1] C. Baek, B.S. Underwood, Y.R. Kim, Effects of Oxidative Aging on Asphalt Mixture Properties, Transportation Research Record (2296) (2012) 77-85.

[2] Y. Li, J. Feng, S. Wu, A. Chen, D. Kuang, Y. Gao, J. Zhang, L. Li, L. Wan, Q. Liu, Review of ultraviolet ageing mechanisms and anti-ageing methods for asphalt binders, Journal of Road Engineering (2022).

[3] X. Zhang, I. Hoff, H. Chen, Characterization of various bitumen exposed to environmental chemicals, J Clean Prod (2022) 130610.

[4] X.H. Lu, U. Isacsson, Effect of ageing on bitumen chemistry and rheology, Constr Build Mater 16(1) (2002) 15-22.

[5] R. Zhai, P. Hao, Research on the impact of mineral type and bitumen ageing process on asphalt-mineral adhesion performance based on molecular dynamics simulation method, Road Mater Pavement 22(9) (2021) 2000-2013.

[6] L. Ma, A. Varveri, R. Jing, S. Erkens, Comprehensive review on the transport and reaction of oxygen and moisture towards coupled oxidative ageing and moisture damage of bitumen, Constr Build Mater 283 (2021) 122632.

[7] O. Sirin, D.K. Paul, E. Kassem, State of the art study on aging of asphalt mixtures and use of antioxidant additives, Advances in Civil Engineering 2018 (2018).

[8] Y.H. Huang, Pavement analysis and design, 1993.

[9] X.M. Zhang, H. Chen, D.M. Barbieri, B.W. Lou, I. Hoff, The classification and reutilisation of recycled asphalt pavement binder: Norwegian case study, Case Studies in Construction Materials 17 (2022).

[10] CEN (European Committee for Standardization). 2015. Bitumen and bituminous binders—Determination of needle penetration. EN 1426: 2015. Brussels, Belgium: CEN.

[11] CEN (European Committee for Standardization). 2015. Bitumen and bituminous binders—Determination of needle penetration. EN 1426: 2015. Brussels, Belgium: CEN.

[12] S.P. Wu, L. Pang, L.T. Mo, Y.C. Chen, G.J. Zhu, Influence of aging on the evolution of structure, morphology and rheology of base and SBS modified bitumen, Constr Build Mater 23(2) (2009) 1005-1010.

[13] D.M. Zhang, H.L. Zhang, C.J. Shi, Investigation of aging performance of SBS modified asphalt with various aging methods, Constr Build Mater 145 (2017) 445-451.

[14] Z.G. Feng, S.J. Wang, H.J. Bian, Q.L. Guo, X.J. Li, FTIR and rheology analysis of aging on different ultraviolet absorber modified bitumens, Constr Build Mater 115 (2016) 48-53.

[15] J. Lamontagne, P. Dumas, V. Mouillet, J. Kister, Comparison by Fourier transform infrared (FTIR) spectroscopy of different ageing techniques: application to road bitumens, Fuel 80(4) (2001) 483-488.

[16] X. Zhang, I. Hoff, Comparative Study of Thermal-Oxidative Aging and Salt Solution Aging on Bitumen Performance, Materials 14(5) (2021) 1174.

[17] L.Y. Shan, X.F. Qi, X.L. Duan, S. Liu, J. Chen, Effect of styrene-butadiene-styrene (SBS) on the rheological behavior of asphalt binders, Constr Build Mater 231 (2020).

[18] S. Hassanpour-Kasanagh, P. Ahmedzade, A.M. Fainleib, A. Behnood, Rheological properties of asphalt binders modified with recycled materials: A comparison with Styrene-Butadiene-Styrene (SBS), Constr Build Mater 230 (2020).

8. APPENDIX

Based on this report, two papers were produced regarding the dynamic modulus of asphalt mixture and ageing model for bitumen and shown as follows:

(1). Xuemei Zhang, Hao Chen*, Rabbira Garba Saba and Lisa Tronhuus Hannasvik. Lateral and longitudinal variations in dynamic modulus of asphalt pavement: surface layer and base layer. Construction and Building Materials 2023, 381: 131304.

https://www.sciencedirect.com/science/article/pii/S0950061823010176

(2). Xuemei Zhang, Rabbira Garba Saba, Hao Chen*, Inge Hoff, Jianan Liu, Lei Zhang, Fusong Wang. Research on asphalt surface layer performance over service time and establishment of ageing model for in-service bitumen under Norwegian conditions. Case Studies in Construction Materials, Vol. 20, 2024.

https://www.sciencedirect.com/science/article/pii/S2214509523010057?via%3Dihub

Statens vegvesen
Pb. 1010 Nordre Ål
2605 Lillehammer

Tlf: (+47) 22 07 30 00

firmapost@vegvesen.no

ISSN: 1893-1162

vegvesen.no

Tryggere, enklere og grønnere reisehverdag