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Influence of material factors on the determination of dynamic moduli and associated prediction models for different types of asphalt mixtures

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ABSTRACT

In a Mechanistic-Empirical (ME) pavement design system, the dynamic modulus is used to characterise asphalt mixtures, which are affected by many factors including environmental conditions and material properties. This study examined twenty types of asphalt mixtures containing nine types of bituminous binders that are commonly used for construction of road pavements in Norway. The objective of the study was to investigate the relationship between material factors and dynamic modulus. The dynamic moduli of asphalt mixtures were experimentally determined employing cyclic indirect tensile tests and were modelled with master curves implementing the sigmoidal function. The rheological properties of bitumen were characterised using a dynamic shear rheometer. The viscosity was simulated using a temperature-based log-linear relationship and the complex modulus was obtained based on the modified Huet-Sayegh model. The grey relational analysis revealed the correlation existing between the material factors and the dynamic modulus. A prediction model was established using a Multiple Linear Regression (MLR). The results indicate that the dynamic modulus of asphalt mixtures is greatly affected by the following parameters ranked in order of decreasing significance: viscosity and complex modulus of the binder, void filled with bitumen, air void content, bitumen penetration and softening point. Based on the MLR model, the correlation between the dynamic modulus and the bitumen viscosity and complex modulus fit well with Coefficient of Determination (R^2) $\geq$ 0.901. The determination of the sigmoidal function parameters to predict the dynamic modulus had good reliability with $R^2 \geq 0.973$. This study contributes to the development of an accurate and convenient method to predict the dynamic moduli of asphalt mixtures based on the material factors for a ME pavement design system.

1. Introduction

Asphalt pavement is widely used in highways, urban roads and airport runways due to the advantages of comfortable driving, low noise, anti-skid and short construction period, etc. [1–3]. Over the past decades, road construction in Norway has been dominated by an empirical design approach. With increasing traffic volumes, axial loads and new materials being used in road construction, the Norwegian Public Roads Administration (NPRA) is working together with Swedish Transport Administration (TV), Swedish National Road and Transport Research Institute (VTI) and Norwegian University of Science and Technology (NTNU) on a project called "VegDim" with the aim of developing and implementing a Mechanistic-Empirical (ME) pavement design system and to create a material database for Norwegian materials [4]. The ME pavement design approach provides a unified basis for the design of flexible pavements. Based on this method, the performance of a road is affected by a number of different factors, e.g., management systems, construction materials, structural design, environmental conditions, traffic type and volume [5,6]. In this regard, the dynamic modulus is important for asphalt material characterisation and generally determined by Cyclic Compression Test (CCT) or Cyclic Indirect Tensile Test (CITT) performed at different loading frequencies and temperatures

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[7–10]. Since the wearing and binder courses in Norway are commonly around 40 mm, the dimension of core samples derived from fields can meet the requirement of CITT (i.e. a diameter of 100 mm and a thickness of 40 mm) instead of CCT (i.e. a diameter of 100 mm and a height of 150 mm). Thus, the CITT was used in this study. However, the dynamic modulus test requires sophisticated devices and well-trained operational skills. Furthermore, the procedure is time-consuming and needs a cumbersome amount of the material to be tested. Therefore, the establishment of correlations between the properties of asphalt material factors and corresponding dynamic moduli is useful to make a reasonably accurate prediction of dynamic modulus for ME pavement design system.

In the ME pavement design guide, the prediction of the dynamic modulus for an asphalt mixture is based on the physical, rheological and mechanical properties of bituminous binder (e.g., viscosity, penetration, content), aggregates (e.g., grading curve) and asphalt mixture itself (e.g., air void) in the Witczak 1-37A model for the Level 2 and Level 3 conditions [11]. This model was further developed by incorporating the complex modulus of binder and the binder phase angle in the NCHRP 1-40D protocol, which was called Witczak 1-40D model [12]. Christensen et al. [13] used the Hirsch model to evaluate the dynamic modulus by taking into account bitumen stiffness and void characteristics of asphalt mixtures. Based on the Hirsch model, Al-Khateeb et al. [14] developed a simpler form of the model to overcome the problem of inaccurate prediction at high and low temperatures. Sakhaeifar et al. [15] developed two models based on the viscoelastic and time–temperature superposition principles to predict the dynamic moduli at a wide range of temperatures (e.g., −10, 4.4, 37.8 and 54.4 °C) named global and simplified global models. Although these models were established based on hundreds of asphalt mixture types in the United States, the materials in different regions of the world exhibit different properties [16–18].

In addition, the determination of the factors affecting dynamic modulus has received more attention from researchers. Shu et al. [19] developed a new micromechanical model based on the particulate-filled composite theory to predict the dynamic modulus of asphalt mixtures. The results showed that the stiffer binder, lower binder content and lower air void content lead to a higher dynamic modulus. Zhang et al. [20] analysed the influence of some material factors on the dynamic modulus by using grey relational analysis and established a prediction model to simulate the dynamic modulus based on the material parameters. The softening point of bitumen and the air void content of the asphalt mixture were highly correlated with the dynamic modulus. A regression model of dynamic modulus was proposed based on the loading rate and material parameters; results show that a higher Coefficient of Determination (R^2) was found for the conditions of the Chinese province Jilin compared to the outcomes of Witczak model. Whereas the viscosity and complex modulus of bitumen changing with different environmental conditions were not considered in this research. Bi et al. [21] compared the master curves of different types of asphalt mixtures to find the correlation between binder/mastic properties and dynamic modulus. The results indicated that the type of bitumen and the filler-to-binder ratio had a clear effect on the dynamic modulus, whereas the dynamic modulus of asphalt mixtures with different types of aggregates and fillers showed an insignificant difference. Moreover, there was a good correlation between the bitumen/mastic complex modulus and the dynamic modulus of asphalt mixtures. Previous studies mainly investigated several material factors in developing prediction models, while few studies provide a model for the dynamic modulus prediction considering all aspects of the material properties.

Therefore, a prediction model adopted for Norwegian materials, which comprehensively considers the material influence on dynamic modulus of asphalt mixtures, has not been investigated. To contribute to this research gap, this work aims to investigate the influence of material factors (i.e., maximum aggregate size, binder content, rheological properties of bitumen, bulk density and void characteristics of asphalt mixtures) on the dynamic modulus and establish an innovative prediction model for Norwegian asphalt mixtures.

In this research, the 20 types of asphalt mixtures commonly used for the construction of Norwegian roads were investigated. The dynamic moduli of the asphalt mixtures were determined by using the CITT. A regression model of the experimental data was developed based on the sigmoidal function. The bitumen viscosity was measured by the plate method and the experimental data were fitted to a temperature-dependent log-linear relationship. The bitumen complex modulus was obtained by performing a frequency sweep test using a Dynamic Shear Rheometer (DSR) and modelled based on the modified Huet-Sayegh formulation. The grey relational analysis was used to evaluate the degree of influence that each material factor (i.e., maximum aggregate size, binder content, rheological properties of bitumen, bulk density and void characteristics of asphalt mixtures) exerted on the dynamic modulus. The relationship between bitumen viscosity, bitumen complex modulus and dynamic modulus of asphalt mixtures was investigated and a prediction model for the master curve parameters was established. Statistical analysis was used to estimate the quality of the model. The results reveal the correlation between dynamic modulus and material factors and thus provide an accurate and convenient method to predict the dynamic modulus for use in the ME pavement design system.

2. Materials and methods

2.1. Materials

2.1.1. Bitumen

Three types of bitumen commonly used for Norwegian roads were investigated. The first type included bituminous binders with penetration of 70 – 100, 160 – 220 and 330 – 430 (0.1 mm at 25 °C). The second type was Polymer Modified Bitumen (PMB) with penetration of 65 – 105 (0.1 mm at 25 °C) and softening point higher than 60 °C. The third type comprised soft bitumen with viscosity values equal to 1500, 3000, 6000, 9000 and 12000 mm^2/s at 60 °C named V1500, V3000, V6000, V9000 and V12000, respectively. The physical properties of the investigated binders are shown in Table 1 and fulfil the requirements set by EN 12,591 [22]. The bitumen 70/100 and 160/220 were supplied by Veidekke company (Trondheim, Norway), and the other types were provided by Nynas company (Göteborg, Sweden).

2.1.2. Rock aggregates

Two types of aggregates were used in this study. The first type was a crushed rock from the Vassfjell area and supplied by Franzefoss company (Heimdal, Norway). This material is characterised by very good mechanical properties and is largely used for road construction in the central part of Norway [26,27]. The second type of aggregates used in this study was natural gravel and supplied by Forset Grus company (Tanem, Norway). This material has a poorer mechanical performance and is used for low-volume roads. The resistance to wear (abrasion value and Micro-Deval coefficient) and fragmentation (Los Angeles value) of the aggregates are specified in Table 2. The strength of the crushed rock aggregates fulfils the requirements set by the Norwegian pavement design code “N200” for high Annual Average Daily Traffic (AADT) of around 15 000 [28]. For asphalt mixtures used for roads with a lower AADT, 30 % to 50 % fine aggregates consist of natural gravel.

2.2. Specimen fabrication

In this study, the 20 asphalt mixture types, mostly used for Norwegian roads were investigated. They included five kinds of grading and nine types of bitumen. In terms of grading, they included Asphalt Concrete (AC), Stone Matrix Asphalt (SMA), Soft Asphalt (MA) for the low traffic volume road, Asphalt Gravel (AG) for the base layer and Asphalt Crushed Stone (AP) with a high air void content also for the base layer. All asphalt mixtures were prepared in the laboratory based on the average values of the upper and lower limits of the grading curves set by

Table 1
Physical properties of bitumen.

Bitumen type		Penetration at 25 °C [0.1 mm]		Softening point [°C]		Dynamic or kinematic viscosity at 60 °C [Pa·s or mm²/s]	
		EN 1426 [23]		EN 1427 [24]		EN 13,702 [25]	
		Value	Specification	Value	Specification	Value	Specification
Neat bitumen	70/100	92	70 – 100	46.0	43 – 51	235.7 Pa·s	≥ 90 Pa·s
	160/220	189	160 – 220	38.1	68 – 43	102.6 Pa·s	≥ 30 Pa·s
	330/430	–	–	–	–	44.5 Pa·s	≥ 12 Pa·s
PMB	65/105–60	88	65 – 105	62.6	≥ 60	391.8 Pa·s	–
Soft bitumen	V1500	–	–	–	–	1708 mm²/s	1000 – 2000 mm²/s
	V3000	–	–	–	–	2815 mm²/s	2000 – 4000 mm²/s
	V6000	–	–	–	–	5450 mm²/s	4000 – 8000 mm²/s
	V9000	–	–	–	–	8990 mm²/s	6000 – 12000 mm²/s
	V12000	–	–	–	–	14036 mm²/s	8000 – 16000 mm²/s

Table 2
Resistance to wear and fragmentation of rock aggregates.

Strength property	Abrasion value EN 1097-9 [29]	Micro-Deval coefficient EN 1097-1 [30]	Los Angeles value EN 1097-2 [31]
Crushed rock	7.8	14.2	18.2
Natural gravel	17.3	17.3	27.7

the Norwegian pavement design code “Nr. 670” [32] and the Optimum Binder Contents (*OBC*) determined by the Marshall mix design method [33]. The grading curves and the *OBC* of the 20 asphalt mixture types are given in Table 3.

Based on the grading curves and *OBC*, all asphalt mixture specimens were prepared according to the procedure shown in Fig. 1. The bitumen and aggregates were preheated at the conditioning time and temperature in accordance with EN 12697-35 [34]. After preheating process, the bitumen and aggregates were mixed in a continuously heated blender for 3 – 5 min to obtain the asphalt mixtures. The asphalt mixture was poured into a preheated mould to prepare asphalt slabs with dimensions 305 mm × 305 mm × 57 mm using a roller compactor. This device compressed the asphalt slab according to four sequences with the table moving velocity of 250 ± 100 mm/s and applying pressures of 2 bar, 4 bar, 6 bar and 0 bar, respectively [35]. Each stage consisted of four passes and vibration was used during the last passes of the fourth stage to ensure adequate compaction. Moreover, a 3 mm resin plate was placed at the bottom of the mould to protect the mould during the following sample coring operations. From the compacted slab, specimens with a diameter of 100 mm and a height of 40 mm were cored and cut from the asphalt slabs [36]. At least four testing specimens were obtained from each asphalt plate. The density and void characteristics including Air Void Content (V_a), Voids in the Mineral Aggregate (*VMA*) and Voids Filled with Bitumen (*VFB*) of testing specimens are given in Table 4.

2.3. Characterisation of material properties

2.3.1. Viscosity of bitumen by DSR rotational plate method

The dynamic viscosity of the bitumen was determined by a DSR based on the plate method [25,39]. The bitumen samples were placed between two 25 mm diameter plates. The rotation was conducted at a shear rate of 10 rad/s and a shear strain of 1 %. The shear stress was measured by the DSR. Based on Newton’s internal friction law, the dynamic viscosity was calculated by Eq. (1).

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{1}$$

where η is the dynamic viscosity, τ is the shear stress and $\dot{\gamma}$ is the shear rate. The viscosity test was performed at 40 °C, 60 °C, 80 °C and 100 °C to assess the relationship between viscosity and temperature. The bitumen types 70/100, 160/220, 330/430 and PMB were tested at 60 °C, 80 °C and 100 °C, while the soft bitumen of V1500, V3000, V6000, V9000 and V12000 were investigated at 40 °C, 60 °C and 80 °C. The testing temperatures were selected to ensure the bitumen behaviour

Table 3
Used grading curves and *OBC* of asphalt mixtures.

Mixture code	Passing percentage [%]									*OBC* [%]
	22.4 mm	16 mm	11.2 mm	8 mm	4 mm	2 mm	1 mm	0.25 mm	0.063 mm	
AC 11–70/100		100	95	70	47.5	33.5	25.5	12.5	7.5	5.1
AC 11–160/220		100	95	77	56	41.5	31.5	15	7.5	5.2
AC 11–330/430		100	95	77	56	41.5	31.5	15	7.5	5.8
AC 11-PMB		100	95	70	47.5	33.5	25.5	12.5	7.5	5.2
AC 16–70/100	100	95	71	58		31.5	24.5	13.5	8	4.9
AC 16–160/220	100	95	76	65		35.5	24.5	12.5	5.5	5.0
AC 16–330/430	100	95	76	65		35.5	24.5	12.5	5.5	5.6
AC 16-PMB	100	95	71	58		31.5	24.5	13.5	8	4.9
SMA 11–70/100		100	95	55.5	37.5	26		16	11	5.3
SMA 11-PMB		100	95	55.5	37.5	26		16	11	5.3
SMA 16–70/100	100	95	56	37		22.5		13.5	10	5.1
SMA 16-PMB	100	95	56	37		22.5		13.5	10	5.2
MA 11-V1500		100	94.5	79.5	60	43.5	34	17	6	4.3
MA 11-V6000		100	94.5	79.5	60	43.5	34	17	6	4.2
MA 16-V3000	100	92.5	80.5		46	31	21	8	5	4
MA 16-V9000	100	92.5	80.5		46	31	21	8	5	4.2
MA 16-V12000	100	92.5	80.5		46	31	21	8	5	4.2
AG 16–70/100	100	95	75			35.5		12.5	6	4.7
AG 16–160/220	100	95	75			35.5		12.5	6	4.6
AP 16–70/100	100	95	45	34.5		17		6.5	5	2.8

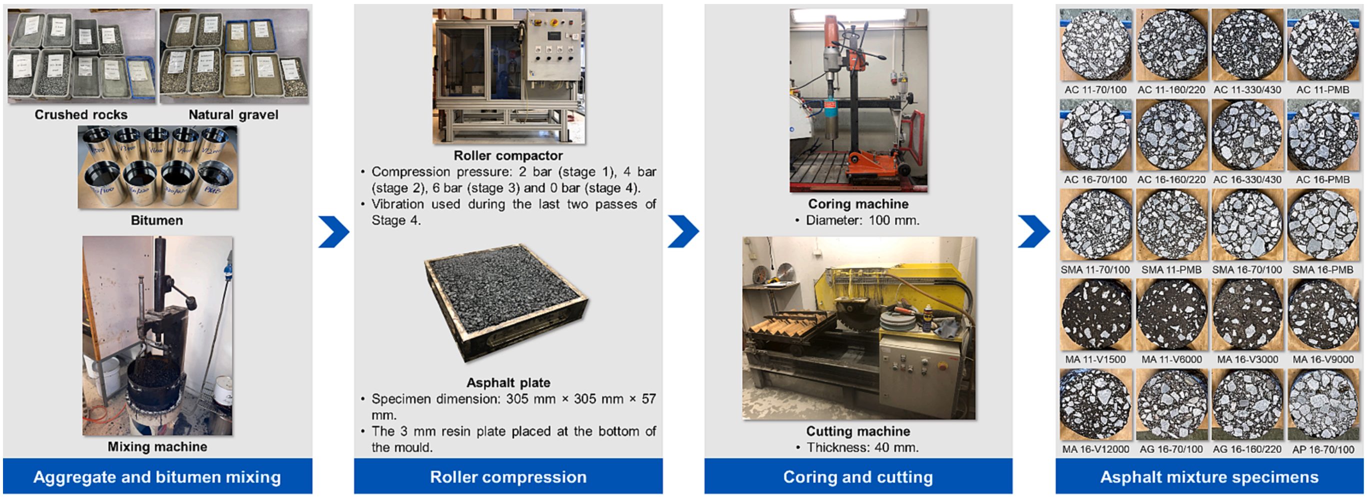

Fig. 1. Specimen preparation procedure.

Table 4
Density and void characteristics of testing specimens.

Mixture code	Density [Mg/m^3]	V_a [%]	*VMA* [%]	*VFB* [%]
	EN 12697-6 [37]	EN 12697-8 [38]		
AC 11-70/100	2.655	3.5	16.9	79.1
AC 11-160/220	2.557	3.0	16.1	81.7
AC 11-330/430	2.539	2.7	17.2	84.6
AC 11-PMB	2.684	2.3	16.1	85.7
AC 16-70/100	2.686	2.9	16.0	81.7
AC 16-160/220	2.647	2.8	15.9	82.6
AC 16-330/430	2.574	4.4	18.7	76.4
AC 16-PMB	2.697	2.5	15.6	83.8
SMA 11-70/100	2.597	5.2	18.8	72.5
SMA 11-PMB	2.676	2.3	16.4	85.8
SMA 16-70/100	2.650	3.9	17.3	77.5
SMA 16-PMB	2.689	2.3	16.2	85.6
MA 11-V1500	2.684	3.7	15.6	76.4
MA 11-V6000	2.635	5.7	17.0	66.3
MA 16-V3000	2.629	6.3	17.2	63.1
MA 16-V9000	2.631	6.0	17.3	65.1
MA 16-V12000	2.594	7.4	18.5	60.2
AG 16-70/100	2.563	7.9	19.9	60.0
AG 16-160/220	2.565	8.1	19.7	59.2
AP 16-70/100	2.430	15.8	22.6	30.0

within the Linear Viscoelastic (LVE) range. Three replicate specimens were tested for each type of bitumen and the mean value of dynamic viscosity was assessed, i.e., a total of 27 specimens were tested.

The kinematic viscosity is calculated as the dynamic viscosity divided by the bitumen density, which varies from 980 kg/m^3 to 1 010 kg/m^3 for the binders selected in this study. The kinematic viscosity expressed in mm/s^2 is therefore close to 1 000 times the associated dynamic viscosity expressed in Pa·s.

2.3.2. Complex modulus of bitumen by DSR frequency sweep method

The complex modulus of bitumen was also determined using the DSR by performing measurements at different loading frequencies and temperatures [40]. The bitumen samples were placed between two parallel plates with a diameter of 10 mm and a gap of 2 mm at low temperatures (<30 °C) and with a diameter of 25 mm and a gap of 1 mm at high temperatures (≥30 °C). The test temperatures ranged from −10 °C to 80 °C with intervals of 10 °C. The frequency was swept logarithmically down from 400 rad/s to 0.1 rad/s. The shear strain was controlled to keep all bitumen within the LVE range. The shear strain of the bitumen 70/100, 160/220, 330/430 and PMB was 1 %. The shear strain of the soft bitumen of V1500, V3000, V6000, V9000 and V12000 was 1 % and 2 % for temperatures lower or higher than 30 °C, respectively. The average results derived from the three replicate specimens were presented for a total of 54 samples that were tested.

2.3.3. Dynamic modulus by CITT method

The CITT was performed by a servo-pneumatic universal testing machine applying a controlled harmonic sinusoidal load. Two Linear Variable Differential Transformers (LVDT) were located on each side in the horizontal direction to obtain the corresponding deformation. The testing temperatures and frequencies vary from region to region according to local climatic and traffic conditions. In the United States, the testing temperatures of −12, 4, 21, 38 and 54 °C the testing frequencies from 0.1 Hz to 25 Hz are adopted based on the ME pavement design guide [11]. In Australia, the testing was carried out at four temperatures of 5, 20, 35 and 50 °C and six frequencies of 0.1, 0.5, 1, 5 10 and 25 Hz [16]. However, in Norway, the dynamic modulus of asphalt mixtures at low temperatures is of more concern. Thus, lower temperatures of −15, −10, 0, 15 and 30 °C and the frequencies of 0.1, 0.3, 1, 3, 5 and 10 Hz in accordance with EN 12697–26 were selected for the dynamic modulus test in this study [41]. The applied loads were adjusted to make sure that the initial horizontal strain amplitude was in a range comprised between 50 and 100 με for each testing frequency and temperature; this requirement ensured that the asphalt mixture specimens were in the LVE range. The dynamic modulus of the asphalt mixtures was determined based on the deviator stress and strain in the horizontal direction, and was calculated by the formula [42,43].

$$|E^*| = \frac{P}{t\Delta H}(\nu + 0.27) \tag{2}$$

where $|E^*|$ is the dynamic modulus, P is the vertical harmonic sinusoidal load, ν is the Poisson's ratio, t is the thickness of the asphalt mixture samples and ΔH is the horizontal deformation. To reduce random variation, four replicate samples were tested and the average values of the dynamic modulus were calculated; overall, a total of 80 CITT specimens were tested.

2.4. Master curve approach

2.4.1. Master curve construction for bitumen complex modulus

The master curve is constructed according to the time–temperature superposition principle by shifting the experimental results based on a selected reference temperature [44], which aims at predicting the stiffness for a wider frequency and temperature ranges than the tested ones. In this research, the Modified Huet-Sayegh (MHS) model was used to describe the master curve of bitumen expressed as [45,46]:

$$G^*(\omega) = \left\{ \left[G_0 + \frac{G_\infty - G_0}{1 + \delta_1 (i\omega\tau_1)^{-m_1} + \delta_2 (i\omega\tau_2)^{-m_2}} \right]^{-1} - \frac{i}{\eta_3 \omega} \right\}^{-1} \quad (3)$$

where $G^*(\omega)$ is the complex modulus, ω is the angular frequency, G_0 and G_∞ are the complex moduli at the infinitesimal and infinite frequencies, respectively, τ_1 and τ_2 are time constants for the parabolic dashpots and m_1, m_2, δ_1 and δ_2 are model parameters. The number of parameters can be decreased using one time constant $\tau = \tau_1 = \tau_2$. The Willian, Landel and Ferry (WLF) equation was used to shift the measured values based on the reference temperature of 15 °C given in Eq. (4) [47].

$$\log[\alpha(T)] = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)} \quad (4)$$

where $\alpha(T)$ is the shift factor, T is the testing temperature, T_r is the reference temperature and C_1 and C_2 are the model parameters. The fitting result was obtained by calculating the minimum error between the measured and modelled value.

2.4.2. Master curve construction for asphalt mixture dynamic modulus

The sigmoidal function was used to construct the master curve for the asphalt mixtures described in the ME pavement design guide [11], which also had better goodness of fit for the Norwegian AC and SMA mixtures [48], expressed as:

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(f)}} \quad (5)$$

where $|E^*|$ is the dynamic modulus, f is the frequency, δ and $\delta + \alpha$ are the dynamic moduli at the infinitesimal and infinite frequencies, respectively and β and γ are the model parameters. The WLF equation (Eq. (4)) was also used to shift the measured value based on the same reference temperature of 15 °C. The fitting result was calculated by minimizing the error between the measured and modelled values.

2.5. Grey relational analysis method

The grey relational analysis is a statistical technique, which is mainly used to elaborate the closeness of the relationship between main factors and sub-factors in a system as well as to evaluate the degree of influence that each sub-factor exerts on the main factor [49]. In recent research, it has been applied in the field of bituminous binders [50,51]. In this study, the grey relational analysis method was used to investigate the degree of influence that each material parameter (i.e., maximum aggregate size, binder content, rheological properties of bitumen, bulk density and void characteristics of asphalt mixtures) had on the dynamic modulus of asphalt mixtures. In total, there were m material parameters and n sets of data. The ith material parameters can be expressed as x_{ij}, where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$.

Since the numerical values of the material parameters are in different ranges, the min–max value method was used for the dimensionless processing of variables by Eq. (6).

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \; for \; i = 1, 2, \ldots, m \; and \; j = 1, 2, \ldots, n \quad (6)$$

where X_{ij} is the comparability sequence from 0 to 1, $\min(x_{ij})$ is the minimum value of the x_{ij} matrix and $\max(x_{ij})$ is the maximum value of the x_{ij} matrix. The dynamic modulus sequence was defined as the reference sequence X_{0j}. The difference between material parameter sequence, X_{ij}, and reference sequence, X_{0j}, is $\Delta_{ij} = |X_{0j} - X_{ij}|$. The grey relational coefficient is used to determine how close X_{ij} is to X_{0j}, which can be calculated by Eq. (7).

$$\gamma(X_{0j}, X_{ij}) = \frac{\min(\Delta_{ij}) + \zeta \max(\Delta_{ij})}{\Delta_{ij} + \zeta \max(\Delta_{ij})} \; for \; i = 1, 2, \ldots, m \; and \; j = 1, 2, \ldots, n \quad (7)$$

where $\gamma(X_{0j}, X_{ij})$ is the grey relational coefficient, $\min(\Delta_{ij})$ is the minimum value of Δ_{ij} matrix, $\max(\Delta_{ij})$ is the maximum value of Δ_{ij} matrix and ζ is the resolution coefficient between 0 and 1 to reflect the difference in the correlation and the value of 0.3 is selected in this study [20]. The grey relational grade between the ith material parameter sequence, X_i, and the dynamic modulus sequence, X_0, can be then calculated by Eq. (8).

$$\gamma(X_0, X_i) = \frac{1}{n} \sum_{j}^{n} \gamma(X_{0j}, X_{ij}) \text{ for } i = 1, 2, \ldots, m \quad (8)$$

where $\gamma(X_0, X_i)$ is the grey relational grade between 0 and 1, and the closer its value is to 1, the better the correlation between the material parameter and the dynamic modulus.

3. Results and discussion

3.1. Analysis of material properties

3.1.1. Viscosity-temperature curve of bitumen

The viscosities of the nine types of bitumen are presented in Fig. 2, with PMB being associated with the highest values in the range of 40 °C to 100 °C due to the network structure of the polymer in the bitumen [46,52]. Soft bitumen has the lowest viscosity, which presents a flow state at room temperature. The neat bitumen is characterised by average values, and its viscosity decreases as the penetration increases. The log value of viscosity is linear with temperature, as shown in Table 5. All R^2 are higher than 0.989, which indicates almost perfect fits. Therefore, the viscosity of the bitumen at a given temperature can be predicted by the linear regression model, which is used as a material factor influencing the dynamic modulus of asphalt mixtures.

3.1.2. Complex modulus master curve of bitumen

The complex moduli of the nine types of bitumen are shown in Fig. 3. The complex modulus of neat bitumen is higher than the one of soft bitumen. In terms of neat bitumen, the values of complex modulus decreased with increasing penetration. Regarding the soft bitumen, the values of complex modulus decreased with decreasing viscosity. The complex modulus of PMB is lower than the one of neat bitumen at high frequencies (low temperatures) and higher than that of neat bitumen at low frequencies (high temperatures). This is connected that the polymer increases the flexibility of the binder at low temperatures and the network structure of the polymer provides the elasticity in neat bitumen at high temperatures [53,54]. The MHS model and WLF equation parameters of nine bitumen are given in Table 6. The results display good goodness of fit as all R^2 values are higher than 0.968. Therefore, the complex modulus of bitumen at an arbitrary condition can be obtained by the master curves and used as a material factor for evaluating the dynamic modulus.

3.1.3. Dynamic modulus master curve of asphalt mixtures

The dynamic modulus master curves of asphalt mixtures were constructed using the sigmoidal function and the WLF equation based on the measured values of dynamic modulus at different frequencies and temperatures as shown in Fig. 4. Furthermore, Fig. 4 also documents that the dynamic modulus master curves of asphalt mixtures containing the bitumen types belonging to the same group (i.e., neat, PMB, soft) are relatively close. Moreover, the order of dynamic modulus of asphalt mixtures with different bitumen was in accordance with that of the viscosity and complex modulus of corresponding bitumen under the same testing conditions. This can be explained considering that the viscoelastic behaviour of asphalt mixture is highly determined by the rheological properties of bitumen [7–10]. The fitting parameters of both sigmoidal function and WLF equation are given in Table 7. All results display a high goodness of fit $R^2 \geq 0.973$. Since the viscosity of soft

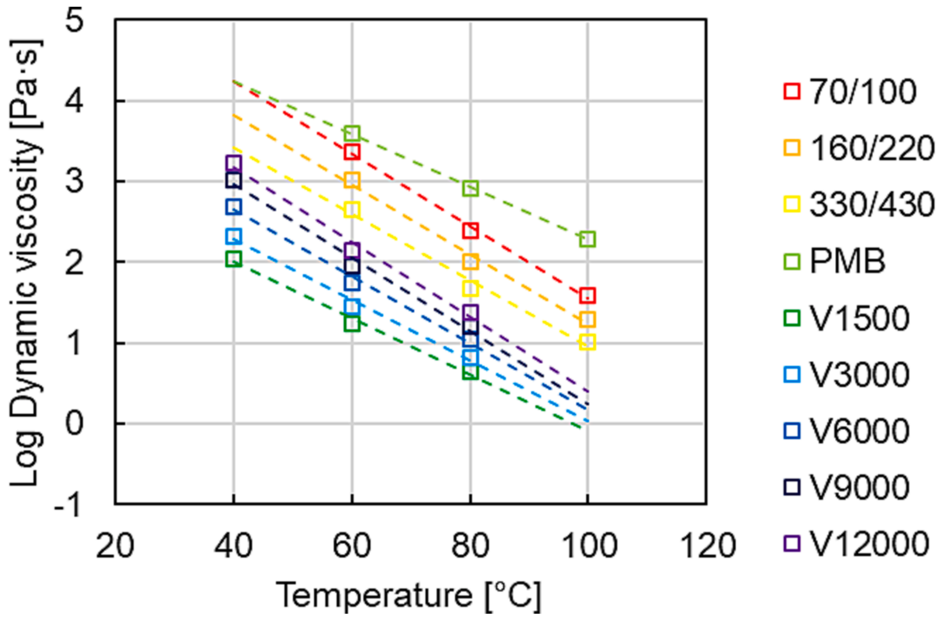

Fig. 2. Viscosity of bitumen.

Table 5
Linear regression of viscosity, η, with temperature, T.

Bitumen		Linear regression equation	R^2
Neat bitumen	70/100	$\log(\eta) = -0.0448 \cdot T + 6.0315$	0.997
	160/220	$\log(\eta) = -0.0430 \cdot T + 5.5481$	0.992
	330/430	$\log(\eta) = -0.0408 \cdot T + 5.0483$	0.989
PMB	65/105–60	$\log(\eta) = -0.0325 \cdot T + 5.5327$	0.999
Soft bitumen	V1500	$\log(\eta) = -0.0348 \cdot T + 3.3888$	0.992
	V3000	$\log(\eta) = -0.0376 \cdot T + 3.7867$	0.991
	V6000	$\log(\eta) = -0.0411 \cdot T + 4.2923$	0.991
	V9000	$\log(\eta) = -0.0454 \cdot T + 4.7810$	0.991
	V12000	$\log(\eta) = -0.0461 \cdot T + 5.0168$	0.991

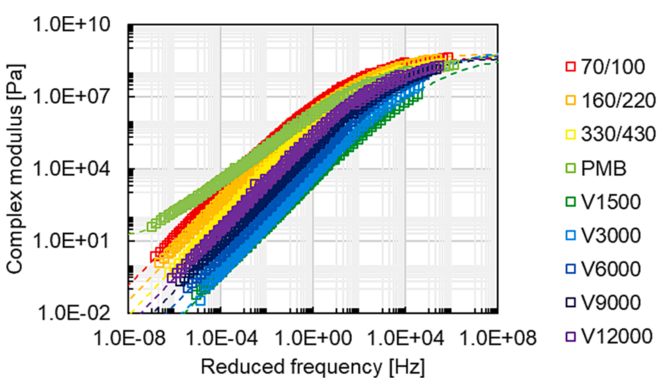

Fig. 3. Complex modulus of bitumen.

bitumen is very small at high temperatures, the dynamic modulus of the corresponding asphalt mixtures varies at high temperatures (≥15 °C) resulting in an R^2 lower than the ones of other mixtures.

3.2. Grey relational analysis of material factors

In this research, only bitumen 70/100, 160/220 and PMB are characterised by the following parameters of the penetration at 25 °C, $Pen_{25\,^\circ C}$, and softening point tested in the water, $T_{R\&B}$. Thus, the grey relational grad was assessed regarding the correlation between the dynamic modulus of asphalt mixtures and the following available material parameters: maximum aggregate size, P_{max}, binder content, B, bitumen viscosity, $\eta(T)$, bitumen complex modulus, $|G^*|(T,f)$, asphalt mixture density, ρ_{mix}, V_a, VMA and VFB. The bitumen viscosity and complex modulus obtained at the same testing conditions adopted for the evaluation of the dynamic modulus are calculated according to the regression and MHS models illustrated in Section 3.1.1 and Section 3.1.2, respectively. The 20 asphalt mixtures were analysed and their dynamic moduli were measured for 30 combinations of frequencies and temperatures for neat bitumen and PMB and 24 combinations for soft bitumen. Thus, the grey relational analysis was conducted for a total of 570 sets of data leading to the result shown in Fig. 5. The grey relational degree is ranked as follows in descending order: $|G^*|(T,f)$, $\eta(T)$, VFB, V_a, $\eta_{60\,^\circ C}$, B, ρ_{mix}, P_{max}, and VMA. The result indicates that the dynamic modulus is greatly affected by the bitumen complex modulus and its viscosity as the two corresponding factors are higher than 0.7, followed by the void characteristics of VFB and V_a with values of 0.595 and 0.592. Other factors, such as bitumen properties and binder content, have a relatively low effect on the dynamic modulus since their values range from 0.428 to 0.562. On the one hand, this outcome can be explained considering that the rheological properties of bitumen dominate the viscoelastic behaviour of asphalt mixtures. On the other hand, the factors of bitumen complex modulus and viscosity, resembling dynamic modulus, change with frequency and temperature, whereas others are not dependent on these two conditions and therefore do not vary, e.g., VFB, V_a, $\eta_{60\,^\circ C}$, B, ρ_{mix}, P_{max}, and VMA.

Considering the effect of $Pen_{25\,^\circ C}$ and $T_{R\&B}$, 13 asphalt mixtures with these two parameters were selected for the grey relational analysis; the corresponding 390 sets of data were analysed. The results are presented in Fig. 6, which are similar to the findings already reported in Fig. 5. The effect of $Pen_{25\,^\circ C}$ and $T_{R\&B}$ on the dynamic modulus of asphalt mixtures are close to $\eta_{60\,^\circ C}$, and are ranked according to the descending order: $|G^*|(T,f)$, $\eta(T)$, VFB and V_a.

The results of grey relational analysis illustrate that the most influential factor in the determination of the dynamic modulus of asphalt mixtures is represented by the rheological properties of the bitumen, which change with frequency and temperature. The void characteristics of VFB and V_a as well as $\eta_{60\,^\circ C}$, $Pen_{25\,^\circ C}$ and $T_{R\&B}$ of the binders are the other parameters exerting the largest influence.

Table 6
MHS model and WLF equation parameters of complex modulus.

Bitumen		MHS model								WLF equation		R^2
		G_0	G_∞	τ	m_1	m_2	δ_1	δ_2	η_3	C_1	C_2	
Neat bitumen	70/100	4.51×10^{-2}	3.52×10^{8}	6.30×10^{-3}	0.55	1.00	15.04	1.00	1.00×10^{50}	13.44	108.37	0.968
	160/220	4.01×10^{-103}	5.59×10^{8}	9.16×10^{-4}	0.45	1.00	12.57	1.00	9.97×10^{49}	14.23	125.06	0.994
	330/430	3.54×10^{-97}	5.82×10^{8}	2.18×10^{-4}	0.34	1.00	13.25	6.55	3.60×10^{50}	11.26	100.32	0.985
PMB	65/105–60	1.62×10^{1}	3.48×10^{9}	3.35×10^{-6}	0.22	0.70	29.03	5.59	1.00×10^{300}	13.53	104.01	0.984
Soft bitumen	V1500	1.09×10^{-6}	3.30×10^{8}	1.76×10^{-6}	0.49	1.00	10.11	1.00	3.24×10^{49}	8.34	100.91	0.991
	V3000	2.15×10^{-16}	7.70×10^{8}	9.86×10^{-7}	0.48	1.00	7.17	1.00	1.83×10^{49}	7.53	92.78	0.988
	V6000	3.23×10^{-163}	5.22×10^{8}	6.83×10^{-6}	0.5	1.00	7.98	1.00	8.64×10^{105}	9.34	102.05	0.987
	V9000	1.60×10^{-205}	3.71×10^{8}	3.22×10^{-5}	0.48	0.99	9.00	1.00	9.98×10^{49}	9.6	92.97	0.984
	V12000	5.46×10^{-281}	3.99×10^{8}	1.17×10^{-4}	0.5	1.00	12.42	1.04	1.10×10^{50}	10.95	99.83	0.978

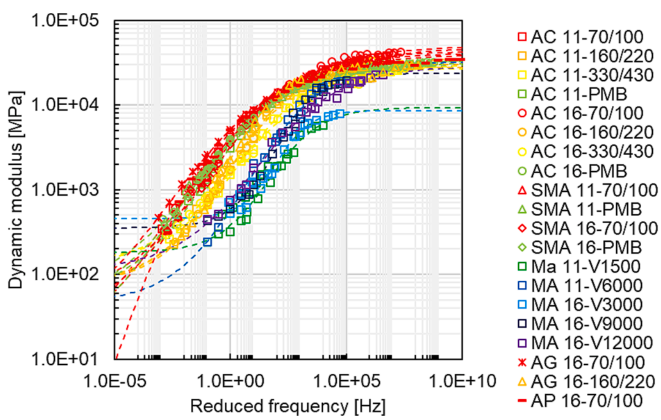

Fig. 4. Dynamic modulus master curves of asphalt mixtures.

3.3. *Correlation between bitumen viscosity, bitumen complex modulus and dynamic modulus of asphalt mixtures*

Based on the results of the grey relational analysis, the correlation between bitumen viscosity, bitumen complex modulus and dynamic modulus of asphalt mixtures was investigated. As shown in Fig. 4, the dynamic modulus of asphalt mixtures containing the different types of bitumen belonging to the same group is relatively close. Therefore, the asphalt mixtures were divided into nine types according to the type of bitumen. Based on the experimental data of the asphalt mixture dynamic modulus and the modelling data of the viscosity and complex modulus of the bitumen, Multiple Linear Regression (MLR) was performed to evaluate the correlation. The MLR model is given in Eq. (9).

$$\log[|E^*|(T,f)] = a_1 \cdot \log[\eta(T)] + a_2 \cdot \log[|G^*|(T,f)] + a_3 \quad (9)$$

where $|E^*|(T, f)$ is the dynamic modulus at different temperatures and frequencies, a_1, a_2 and a_3 are model parameters. $\eta(T)$ and $|G^*|(T, f)$ are obtained as illustrated in Section 3.1.1 and Section 3.1.2, respectively.

The model parameters are displayed in Table 8 and the results are illustrated in Fig. 7. All nine bitumen types have a good fit with $R^2 \geq 0.901$. The value of *Sig.* is the p-value, which indicates the significance of the independent variable in the model. The lower p-value shows the greater significance of the variable. Analysis of Variance (ANOVA) is used to verify the significance of the model. As shown in Table 8, the p-

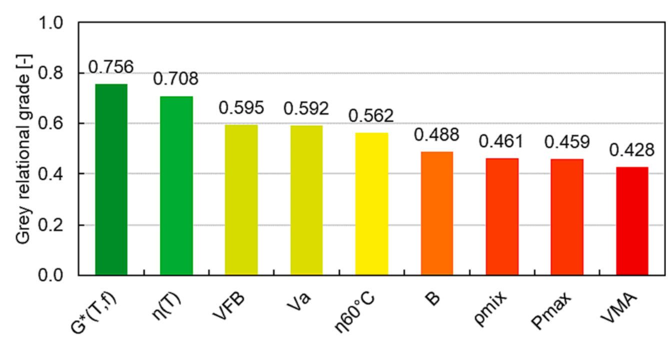

Fig. 5. Grey relational grade of material parameters except $Pen_{25\,^\circ C}$ and $T_{R\&B}$.

Table 7
Fitting parameter of sigmoidal function and WLF equation for dynamic modulus.

Mixture code	Sigmoidal function				WLF equation		R^2
	δ	α	β	γ	C_1'	C_2'	
AC 11–70/100	0.72	3.97	−0.98	0.38	17.87	123.47	0.999
AC 11–160/220	1.89	2.60	−0.09	0.63	9.39	82.16	0.995
AC 11–330/430	2.16	2.27	0.23	0.64	10.33	79.76	0.988
AC 11-PMB	1.74	2.73	−0.59	0.57	12.14	86.34	0.994
AC 16–70/100	0.90	3.80	−0.92	0.42	13.20	92.23	0.991
AC 16–160/220	1.87	2.67	−0.08	0.63	8.51	77.17	0.990
AC 16–330/430	2.02	2.46	0.07	0.50	11.60	83.09	0.990
AC 16-PMB	1.76	2.77	−0.65	0.49	11.40	74.07	0.997
SMA 11–70/100	1.40	3.21	−0.71	0.49	12.30	92.50	0.999
SMA 11-PMB	0.85	3.69	−1.04	0.42	9.94	69.26	0.998
SMA 16–70/100	1.74	2.89	−0.46	0.53	12.24	91.17	0.998
SMA 16-PMB	1.59	2.91	−0.78	0.51	12.20	83.56	0.997
MA 11-V1500	2.26	1.71	1.47	0.89	1.11	41.09	0.973
MA 11-V6000	1.65	2.86	0.45	0.61	5.50	70.76	0.977
MA 16-V3000	2.66	1.28	2.53	1.31	1.85	44.84	0.994
MA 16-V9000	2.55	1.83	1.97	1.02	18.41	167.42	0.980
MA 16-V12000	2.05	2.41	0.63	0.56	33705.31	180907.61	0.990
AG 16–70/100	1.17	3.43	−1.06	0.42	23.02	149.73	0.997
AG 16–160/220	1.91	2.53	−0.28	0.76	4.91	50.67	0.981
AP 16–70/100	−4.86	9.43	−2.26	0.36	8.20	57.47	0.996

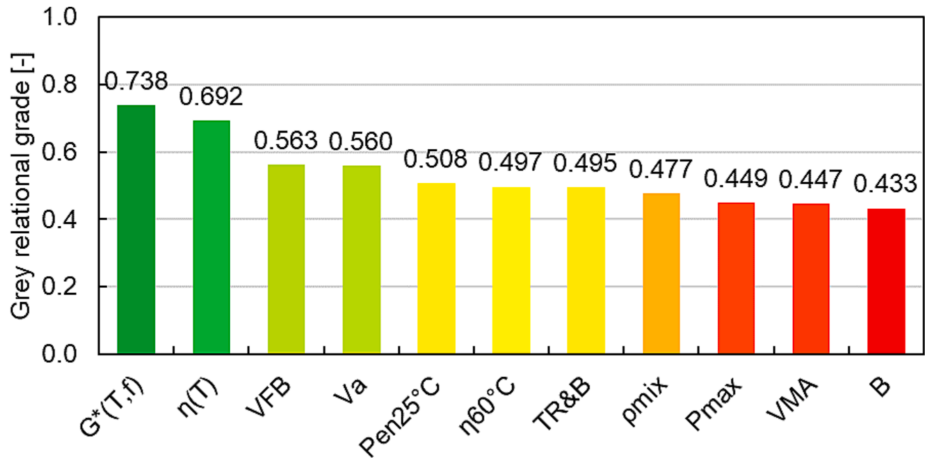

Fig. 6. Grey relational grade of material parameters containing $Pen_{25\ ^\circ C}$ and $T_{R\&B}$.

Table 8
MLR model parameters of Eq. (9) calculated for the nine bitumen types.

Bitumen type		Coefficient						ANOVA		Model summary
		a_1	*Sig.*	a_2	*Sig.*	a_3	*Sig.*	*F*	*Sig.*	R^2
Neat bitumen	70/100	0.041	0.057	0.463	0.000	6.385	0.000	7614.192	0.000	0.989
	160/220	0.086	0.039	0.452	0.000	6.212	0.000	2309.521	0.000	0.982
	330/430	0.300	0.000	0.320	0.000	6.385	0.000	2269.337	0.000	0.988
PMB	65/105–60	−0.009	0.837	0.501	0.000	6.442	0.000	4041.070	0.000	0.986
Soft bitumen	V1500	−0.131	0.411	0.336	0.000	38.213	0.000	95.217	0.000	0.901
	V3000	0.111	0.369	0.259	0.000	7.453	0.000	124.104	0.000	0.922
	V6000	0.024	0.719	0.429	0.000	6.858	0.000	1095.766	0.000	0.991
	V9000	0.093	0.437	0.407	0.000	6.511	0.000	285.341	0.000	0.965
	V12000	0.258	0.019	0.370	0.000	6.128	0.000	364.748	0.000	0.972

values of a_2 are all 0, reflecting the significance of bitumen complex modulus in the model. Whereas the p-values of a_1 are from 0 to 0.837, and neat bitumen shows a lower value than the other bitumen. This result indicates that the effect of viscosity on dynamic modulus depends on bitumen types. The ANOVA results indicate that the models for all bitumen have a good correlation with the test results. The R^2 of soft bitumen is more variable when compared to neat bitumen and PMB. This might be caused by the relatively unstable test results of the asphalt mixtures containing the soft bitumen, causing fluctuations, especially at high temperatures [55]. Nevertheless, the dynamic modulus of asphalt mixtures can be predicted with high reliability by the viscosity and complex modulus of the bitumen for certain loading frequency and temperature conditions. This method can save testing time and the required materials for performing the dynamic modulus test.

3.4. Dynamic modulus prediction model by master curve parameter modelling

Although the method illustrated in Section 3.3 can well predict the dynamic modulus of asphalt mixtures, it is necessary to assess the viscosity and complex modulus of bitumen, which are evaluated by means of laboratory devices requiring highly specialized equipment and well-trained operating skills. While the dynamic modulus varies with loading frequency and temperature, some other material parameters (i.e., P_{max}, B, $\eta_{60\ ^\circ C}$, ρ_{mix}, V_a, VMA, VFB, Pen and $T_{R\&B}$) do not vary. The sigmoidal function fits the dynamic modulus well and its fitting parameters are also fixed for one material. Thus, the material parameters can be used to predict the fitting parameters of the sigmoidal function and thus estimate the dynamic modulus. In this case, the selected material parameters were P_{max}, B, $\eta_{60\ ^\circ C}$, ρ_{mix}, V_a, VMA, VFB, Pen and $T_{R\&B}$, while δ, α, β and γ were chosen as the fitting parameters of sigmoidal function. The MLR was also used to find the correlation between material parameters and fitting parameters of sigmoidal function as expressed in Eq. (10) in two ways: one for the material parameters without Pen and $T_{R\&B}$ (Eq. (10.1)) and another one for all obtained material parameters (Eq. (10.2)).

For material parameters without Pen and $T_{R\&B}$

$$\delta,\alpha,\beta\ and\ \gamma = b_1\cdot P_{\max} + b_2\cdot B + b_3\cdot\eta_{60^\circ C} + b_4\cdot\rho_{mix} + b_5\cdot V_a + b_6\cdot VMA + b_7\cdot VFB + b_8 \tag{10.1}$$

For material parameters with Pen and $T_{R\&B}$

$$\delta,\alpha,\beta\ and\ \gamma = b_1^{'}\cdot P_{\max} + b_2^{'}\cdot B + b_3^{'}\cdot Pen_{25\ ^\circ C} + b_4^{'}\cdot T_{R\&B} + b_5^{'}\cdot\eta_{60\ ^\circ C} + b_6^{'}\cdot\rho_{mix} + b_7^{'}\cdot V_a + b_8^{'}\cdot VMA + b_9^{'}\cdot VFB + b_{10}^{'} \tag{10.2}$$

where $b_{1\text{-}10}'$ and $b_{1\text{-}8}$ are the regression parameters and all material parameters are in the international system of units. The MLR model parameters of Eq. (10) are given in Table 9. The results indicate that there is a good fit between parameters δ, α, β and material parameters. The correlation between γ and material parameters is relatively poor. This reflects the γ is less affected by the material properties. Nevertheless, in the MLR model with material parameters containing Pen and $T_{R\&B}$, the R^2 of γ is also as high as 0.837, showing a certain dependence of γ on the material parameters. Furthermore, in this MLR model, the variables of $\eta_{60\ ^\circ C}$ and V_a were excluded. This is due to the small correlation between $\eta_{60\ ^\circ C}$ and fitting parameters of master curve, which can also be verified by small values of b_3 for the MLR model without Pen and $T_{R\&B}$. The variable of V_a is excluded due to a higher variance inflation factor, which is caused by the correlation between V_a, VMA and VFB.

The dynamic modulus of the asphalt mixtures predicted by the sigmoidal function fitted with the material parameters and Witczak 1-

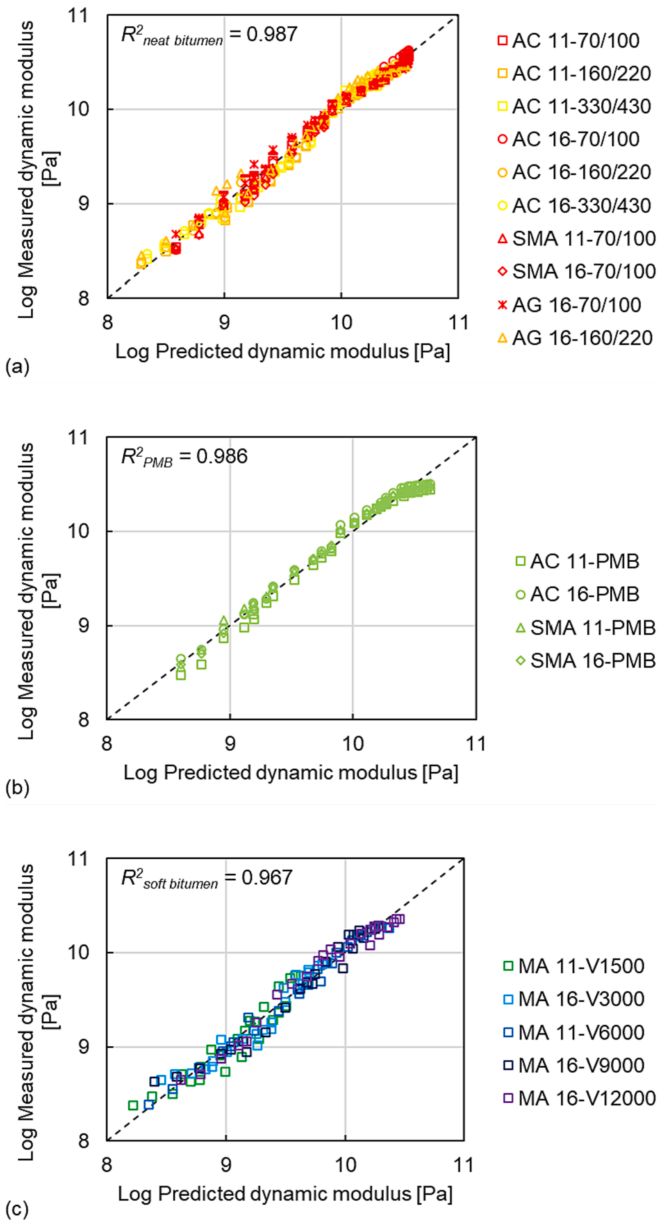

Fig. 7. Results of multiple linear regression of Eq. (6): (a) Neat bitumen, (b) PMB and (c) Soft bitumen.

37A, Witczak 1-40D, Hirsch, Al-Khateeb, global and simplified global models for comparison are shown in Fig. 8. The R^2 of the MLR without and with *Pen* and $T_{R\&B}$ are 0.973 and 0.993, respectively, which can reasonably predict the dynamic modulus for more types of asphalt mixtures [20]. The soft bitumen displays a lower R^2 than the other types, especially at low frequencies (high temperatures). This can be interpreted by taking into consideration the small contribution of soft bitumen to the elasticity of the asphalt mixture at high temperatures. In this condition, the stiffness is provided mainly by the aggregate skeleton, thus defining estimated actual stiffness, which deviates from the dynamic modulus predicted by the material parameters. Compared with the Witczak 1-37A (R^2 = 0.707), Witczak 1-40D (R^2 = 0.926), Hirsch (R^2 = 0.815), Al-Khateeb (R^2 = 0.814), global (R^2 = 0.906) and simplified global (R^2 = 0.891) models, the prediction results of the MLR model in this research shows a better fit. Furthermore, the empirical model of Witczak 1-40D is more suitable for Norwegian asphalt mixtures.

For each type of asphalt mixture, Fig. 9 shows that the MLR model

Table 9
MLR model parameters of Eq. (10).

Master curve parameter		Coefficient																				ANOVA		Model summary
		b_1	*Sig.*	b_2	*Sig.*	b_3	*Sig.*	b_4	*Sig.*	b_5	*Sig.*	b_6	*Sig.*	b_7	*Sig.*	b_8	*Sig.*					*F*	*Sig.*	R^2
MLR without *Pen* and $T_{R\&B}$	δ	0.129	0.049	−4.738	0.350	0.001	0.564	−0.018	0.193	−5.533	0.026	−0.647	0.001	2.580	0.234	99.76	0.027					24.08	0.000	0.934
	α	−0.145	0.069	8.730	0.171	−0.001	0.615	0.028	0.119	7.176	0.021	0.646	0.003	−4.188	0.124	−118.0	0.033					17.12	0.000	0.909
	β	0.118	0.039	−14.79	0.004	0.000	0.856	−0.038	0.006	−7.602	0.002	−0.303	0.029	6.063	0.005	121.9	0.004					16.30	0.000	0.905
	γ	0.024	0.271	−2.481	0.175	0.000	0.831	−0.007	0.160	−1.303	0.117	−0.063	0.234	0.970	0.207	24.66	0.104					2.906	0.050	0.629
		b_1'	*Sig.*	b_2'	*Sig.*	b_3'	*Sig.*	b_4'	*Sig.*	b_5'	*Sig.*	b_6'	*Sig.*	b_7'	*Sig.*	b_8'	*Sig.*	b_9'	*Sig.*	b_{10}'	*Sig.*	*F*	*Sig.*	R^2
MLR with *Pen* and $T_{R\&B}$	δ	0.107	0.163	8.187	0.005	125.7	0.029	0.062	0.041	–	–	0.011	0.119	–	0.942	−0.575	0.027	−2.375	0.038	11.52	0.571	43.01	0.000	0.984
	α	−0.110	0.176	−8.242	0.006	−150.0	0.020	−0.074	0.029	–	–	−0.010	0.156	–	0.963	0.576	0.034	2.3655	0.048	−7.046	0.744	38.06	0.000	0.982
	β	0.036	0.430	1.248	0.302	72.37	0.041	0.005	0.724	–	–	0.001	0.828	–	0.683	−0.064	0.613	−0.294	0.608	−0.714	0.955	9.808	0.012	0.932
	γ	0.005	0.728	0.093	0.799	31.67	0.013	0.005	0.314	–	–	0.001	0.636	–	0.678	−0.002	0.954	0.024	0.893	−2.381	0.562	3.669	0.086	0.837

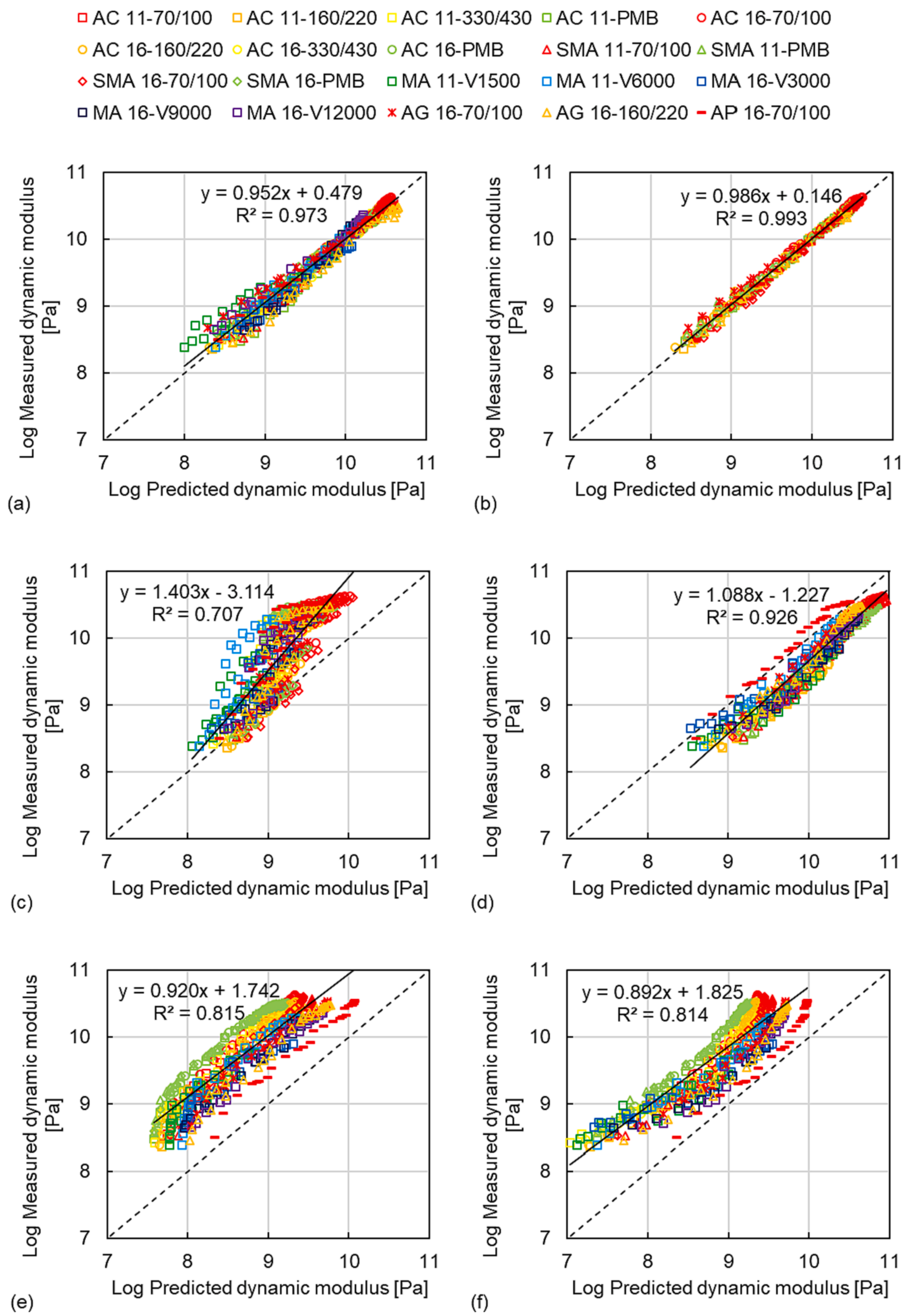

Fig. 8. Comparison between the predicted and measured dynamic modulus: (a) MLR model without *Pen* and $T_{R\&B}$, (b) MLR model with *Pen* and $T_{R\&B}$, (c) Witczak 1-37A model, (d) Witczak 1-40D model, (e) Hirsch model, (f) Al-Khateeb model, (g) Global model and (h) Simplified global model.

offers a better fit for stiffer bitumen. This relates to the larger variation in the dynamic modulus test for the asphalt mixtures containing soft bitumen. In summary, the dynamic modulus of asphalt mixtures can be predicted based on the material parameters by this MLR model.

4. Conclusions

In this study, the dynamic modulus was measured using the cyclic indirect tensile test for the 20 kinds of asphalt mixtures containing nine types of bitumen that are mostly used for Norwegian roads and corresponding master curves were constructed. The influence of different material factors (i.e., maximum aggregate size, binder content, rheological properties of bitumen, bulk density and void characteristics of asphalt mixtures) on the dynamic modulus was investigated. New prediction models for the dynamic modulus of asphalt mixtures were proposed based on the experimental test data. The testing results are used to create a database of asphalt materials for the "VegDim" project and the findings can be incorporated into the development of a ME pavement

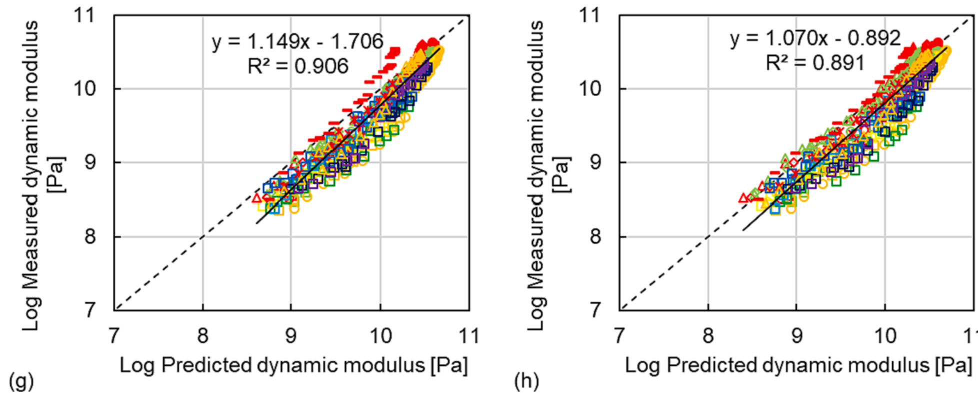

Fig. 8. (*continued*).

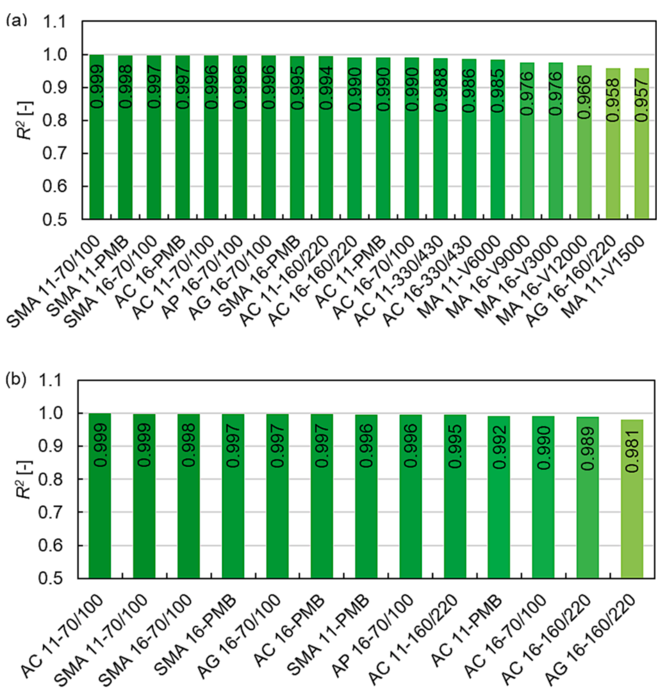

Fig. 9. Goodness of fit R^2 for each type of asphalt mixture: (a) MLR model without *Pen* and $T_{R\&B}$ and (b) MLR model with *Pen* and $T_{R\&B}$.

design for Norwegian conditions. The conclusions are summarised as follows.

- Regarding the nine types of bituminous binders, a log-linear relationship was used to model the relationship between viscosity and temperature, whereas the complex modulus was modelled based on the modified Huet-Sayegh formulation. As for the 20 types of asphalt mixtures, their dynamic moduli were modelled by using the sigmoidal function. The reliability associated with all the formulations was good showing Coefficient of Determination (R^2) $\geq$ 0.968.
- According to the grey relational analysis results, the dynamic modulus of asphalt mixtures is greatly affected by the viscosity and complex modulus of bitumen, followed by the void characteristics of void filled with bitumen and air void content, and then by the bitumen penetration and softening point.
- The dynamic moduli of asphalt mixtures containing the same bitumen type were close. The order of dynamic modulus of asphalt mixtures was in accordance with that of the viscosity and complex modulus of corresponding bitumen under the same testing conditions. The correlation between the dynamic modulus and bitumen viscosity and complex modulus was established by Multiple Linear Regression (MLR). The prediction model had the goodness of fit values $R^2 \geq 0.901$.
- The prediction model of the fitting parameters of the sigmoidal function had a good correlation with $R^2 \geq 0.973$ and asphalt mixtures with stiffer bitumen showed a better fit. This value was higher than the corresponding R^2 obtained for the other empirical prediction models. Moreover, this method accurately predicts the dynamic modulus of asphalt mixtures without involving the rheological properties of bitumen. This can reduce the tedious testing of bituminous rheological properties when predicting the dynamic modulus of asphalt mixtures.

The MLR results for master curve parameters show that some material factors have a significant influence on the prediction model for some asphalt mixtures, while they have little effect on other asphalt mixtures. Therefore, the types of material factors can be further optimised for a specific asphalt mixture to improve the accuracy of the prediction model and reduce the workload in future studies. In addition, since the current specification in many regions is based on a cyclic compression test for the circular cylinder to measure the dynamic modulus of asphalt mixtures, further research can focus on the difference and connection between compressive and indirect tensile modes in dynamic modulus results for optimising the prediction model.

CRediT authorship contribution statement

Hao Chen: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft. **Rabbira Garba Saba:** Project administration, Resources, Writing – review & editing, Supervision. **Gang Liu:** Methodology, Writing – review & editing, Supervision. **Diego Maria Barbieri:** Investigation, Writing – review & editing. **Xuemei Zhang:** Investigation, Writing – review & editing. **Inge Hoff:** Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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