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Experimental Study of Compression-Tension Asymmetry in Asphalt Matrix under Quasi-static and Dynamic Loads via an integrated DMA-based Approach

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Abstract

This research presents an experimental approach to study the mechanics of asphalt matrix, a crucial component in asphalt concrete, consisting of asphalt binder, fine aggregates and filler. Understanding its response is essential to guide and improve the new designs in advanced asphalt concrete. The proposed approach makes use of the dynamic mechanical analysis (DMA) to execute a variety of quasi-static and dynamic tests under tension and compression. Uniaxial tests reveal a remarkable compression-tension asymmetry of the asphalt matrix in terms of stiffness and strength. The peak stress and stiffness can be 5 and 3 times, respectively, larger under compression than in tension. Both properties strongly depend on the strain rate, albeit stiffness and peak stress in compression are more sensitive than in tension. A straightforward equation for the creep rupture envelop is derived by performing creep tests at different stress levels. Amplitude and frequency sweep tests and fatigue-recovery test are performed to explore the inherent self-healing capabilities of asphalt matrix at room temperature. Doubling the regularity of resting periods significantly helps to regain the stiffness and it leads to a 4-times extension of the fatigue life.

Keywords: asphalt matrix, visco-elasto-plasticity, compression-tension asymmetry, dynamic mechanical analysis, strain-rate dependency, self-healing

1. Introduction

Asphalt concrete, also known as asphalt mixture, is the most widely used material for pavements. It is a heterogeneous multiphase composite, mainly containing asphalt binder, aggregates and filler, where aggregates work as the skeleton to bear loading and asphalt binder is the adhesive to maintain the whole structure. Since asphalt pavement undergoes repetitive traffic loads under different climatic conditions, it is of great importance to understand the mechanical behavior and failure mechanism of asphalt materials.

Different laboratory tests have been designed to investigate the rheological properties of asphalt materials related to different aspects of pavement performance. To determine the rheological parameters of asphalt binder, the dynamic shear rheometer (DSR) is commonly used by applying shear loads in different conditions [1]. According to the standard AASHTO TP101-12 [2], frequency sweep test and amplitude sweep test performed on DSR can determine the rheological parameters

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and the damage characteristics of asphalt binder, respectively [3-6]. With the frequency sweep test at very low strain amplitude, the two key parameters, namely complex shear modulus (G^*) and phase angle (δ) can be measured to evaluate the resistance of asphalt binder to shear deformation in the linear visco-elastic region. The amplitude sweep test can help to distinguish the linear and the nonlinear visco-elastic regions of asphalt binder. Additionally, as an improved method mentioned in AASHTO TP70 [7], the multiple stress creep-recovery test (MSCR) is used to characterize the mechanical behavior of binder in the nonlinear region and evaluate its potential for permanent deformation (e.g., rutting) [8,9]. With regard to asphalt concrete, various quasi-static tests and dynamic tests are designed to characterize its rheological behavior. According to AASHTO TP79 [10] and TP107 [11], the visco-elastic and damage parameters can be determined via dynamic modulus tests and cyclic direct tension tests on the Asphalt Material Performance Tester (AMPT), respectively [12, 13]. Besides, quasi-static and dynamic uniaxial tests in both tension and compression can be conducted by using the MTS machine [14]. Moreover, other types of test have been conducted to evaluate the visco-elastic and the damage behavior of asphalt concrete. With the aid of a new machine invented by Kazakhstan Highway Research Institute, the tensile creep tests were conducted on asphalt concrete at different temperature to determine the long-term strength [15]. Relaxation tests at different temperature and cyclic tests at different temperature and loading frequency were conducted in indirect tension to investigate the visco-elastic behavior and the effect of loading time, loading frequency and temperature on the Poisson's ratio of asphalt concrete [16].

Along with the experimental research, the finite element method (FEM) has been proved as a useful tool to verify and predict the mechanical behavior of asphalt materials from the numerical point of view [17,18]. For the sake of simplicity, asphalt concrete is usually simulated as a homogeneous material [19, 20]. However, the discontinuity of asphalt concrete cannot be ignored since factors like the nonlinear behavior of matrix, the distribution of air voids, the shape and distribution of aggregates and the strength of the matrix-aggregate interface can considerably affect its macro-mechanical response. Thus, it is of great importance to reveal the internal structure of asphalt concrete and study the damage evolution and crack propagation process qualitatively and quantitatively. Taking into account both calculation time and accuracy, researchers started to consider asphalt concrete as a three-phase composite formed by coarse aggregates, asphalt matrix and air voids to investigate the visco-elastic behavior and the failure mechanism in detail [21-24]. Here, asphalt matrix, is a homogeneous blend of asphalt binder, fine aggregates (passing a 2.36-mm [8#] sieve) and filler. Compared with asphalt binder, asphalt matrix has rheological characteristics more similar to asphalt concrete due to its solid-like behavior. In consideration of the experimental and the numerical aspects, namely the identification of material properties and the construction of numerical model, asphalt matrix is found to be a better choice for the rheological analysis associated with pavement performance. It is worth mentioning that an asphalt matrix specimen is much smaller than its equivalent asphalt concrete specimen, which means the same amount of asphalt matrix tests requires much less material than asphalt concrete. However, there are no specifications or standard tests for asphalt matrix. By referring to the standard test for asphalt concrete, some researchers utilized MTS to perform compressive creep test on cylindrical asphalt matrix specimens at different stress level and temperature to obtain the visco-elastic parameters [25]. Inspired by the testing technique for asphalt binder, researchers also use DSR for the characterization of asphalt matrix by applying different load in torsion, where the specimen is usually obtained by coring or cutting a cylindrical compacted sample with a standard dimension [26-28]. DSR only allows for torsion tests.

However, the quasi-static and the dynamic tests in compression and tension can be conducted by using the dynamic mechanical analysis (DMA) [29].

In addition, researches have found that asphalt binder has the capability of self-healing after failure, which means it is able to repair the micro-damage caused by loading after a certain resting period [30, 31]. Numerous studies have proved that asphalt concrete also has this self-healing capability [26,32,33]. By introducing resting periods during loading, asphalt concrete can regain partial strength after damage. Thus, it is necessary to consider self-healing while studying asphalt matrix. A good understanding of the self-healing capability of asphalt matrix can help to improve the mix design of asphalt concrete, which is crucial for prolonging the lifespan of asphalt pavements.

In order to comprehensively understand the behavior of asphalt concrete and properly guide the test for its constitutive study, this research studies the mechanical properties of asphalt matrix via different quasi-static and dynamic tests. This paper is organized as follows. Section 2 describes the basic material properties. In Section 3, the fabrication procedure of the specimen and the test setup are introduced in detail. Section 4 and Section 5 deal with the experimental analysis of the quasi-static and the dynamic behaviors of asphalt matrix, respectively. The conclusion of this study is finally summarized in the last section.

2. Material composition

PEN 70 asphalt binder is used for all the samples in this research, and its basic properties can be found in Table 1.

Table 1: Three basic indices of #70 asphalt binder.

Index	Test result	Grade
Penetration ($\times 10^{-1}$ mm)	63.47 ± 0.33	60-80
Softening point ($^{\circ}\text{C}$)	49.5 ± 0.3	44-54
Ductility at 10°C (cm)	>150	>100
Density (g/cm^3)	1.03 ± 0.02	-

Limestone aggregate is used to prepare the asphalt matrix. The optimum asphalt-aggregate ratio for AC-13 is first determined as 4.5 wt%, based on which the optimum asphalt-fine aggregate ratio for asphalt matrix is calculated as 14.63 wt%. The aggregate gradation and the corresponding density of fine aggregates are listed in Table 2. Before the preparation of the specimen, the weight of asphalt and each aggregate fraction are determined according to the specimen dimension, as well as the asphalt-aggregate ratio and the density of each component.

Table 2: Aggregate gradation and corresponding density.

Sieve size (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-13 Gradation (Passing percentage %)	100	96	72.9	40.6	30.7	22.7	15.4	11.3	7.7	5.5
Aggregate density (g/cm^3)					2.68	2.64	2.63	2.63	2.63	2.75

3. Specimen preparation and Test setup

In this section, the preparation process of the asphalt matrix specimen is described and the testing machine used for the quasi-static and the dynamic tests mentioned in the following sections is introduced.

3.1. Specimen preparation

Cylindrical specimens with the dimension of $\phi 150 \text{ mm} \times 60 \text{ mm}$ are fabricated by a Superpave gyratory compactor (TIPTOP ICT-250) complying with the procedure described in AASHTO T312 [34]. The designed density of asphalt matrix (2.22 g/cm^3) is achieved.

A cylindrical specimen with a much smaller size is required for the following mechanical tests due to the limited measurement range of the testing equipment (max normal force = 50 N). Taking into account the maximum size of the aggregate, the critical slenderness ratio to prevent buckling and the difficulty of the manufacture process, the dimension of the cylindrical specimen is finally determined as $\phi 10 \text{ mm} \times 40 \text{ mm}$. Cylindrical specimens with the thickness of 40 mm are cut from the big cylindrical sample by removing 10 mm from the top and bottom surfaces, respectively. A drilling machine is used, where the water-cooled bit drill with an inner diameter of 10mm is designed for the coring. A cutting speed of 480 rpm is chosen for the drilling to prevent high temperatures caused by friction. After the coring process, specimen with the aimed dimension is finally obtained. In order to attach this specimen to the testing machine, couples of steel caps were specially designed, as it is shown in Fig. 1(a). Every cap is mechanized and shaped as half rectangle and half cylinder. The cylindrical part is glued to the specimen ends by using epoxy resin for tension tests. This cap shape allows for an accurate fit into the solid rectangular fixtures (SRF). Fig. 1(b) shows a steel mold designed to ensure the alignment of the specimen during the adhesive bonding process, as shown in Fig. 1(c).

Figure 1: (a)Steel caps; (b)Alignment mold; (c)Adhesive bonding of tabs aligned by the mold.

3.2. Testing machine

Anton Paar MCR702 MultiDrive is a versatile rheometer equipped with an additional lower drive unit which enables it to work as the combination of DSR and DMA (see Fig. 2). This machine can perform quasi-static and dynamic tests not only in torsion but also in compression and tension. Two parallel plates are used for compression tests. In tension tests, the specimen glued with two

caps is attached to the machine by using a pair of SRF clamps. As for the measurements of the machine, the frequency ranges from 0.01 to 100 Hz, the accuracy of the displacement measurement is 0.01 μm , and the normal force ranges from 0.005 to 50 N. Moreover, the maximum normal force of MCR702 can reach 50 N which is almost two times that the force of a normal DMA. All tests in this study are conducted at room temperature (25°C).

Figure 2: Anton Paar MCR702.

4. Quasi-static tests

In this section, the loading conditions of the uniaxial constant strain rate tests, the creep tests and the creep-recovery tests are explained and the results of each test are given and analyzed.

4.1. Uniaxial loading at different strain rates

Uniaxial loading tests at constant strain rate are conducted. Seven strain rates, namely 1.25, 2.5, 3.75, 5, 6.25, 7.5 and 8.75 ($\times 10^{-4} \text{ s}^{-1}$) are chosen for the tension tests, while only the first four strain rates are used for the compression tests due to the limitation of the machine's maximum normal force.

Fig. 3 shows the representative stress-strain curves at the four strain rates, where the asymmetric behavior between compression and tension is clearly observed. The Young's modulus (E_c and E_t) is calculated as the slope of the initial straight part of the curve, which is within the elastic limit. It should be noted that the curve at the very beginning of the loading is not taken into account in the calculation due to the transient instability caused by the machine. The ultimate strength (σ_c and σ_t) and the corresponding strain (ε_c and ε_t) are measured at the peak of the loading curve.

It is worth noting that the mechanical behavior of asphalt matrix varies considerably at different strain rates in both compression and tension. A clearer relationship between strain rate and different material parameters within the chosen range of strain rate can be seen in Fig. 4: the Young's modulus and the ultimate strength are positively linear correlated with the strain rate while the strain value at the peak almost remains unchanged in both compression and tension cases. The fitted linear correlation coefficients are listed in Table 3. The physical meanings of A and B are connected to the dynamic viscosity of asphalt matrix, which can show the effect of the strain rate on the Young's

modulus and the ultimate strength of asphalt matrix, respectively. The result shows that C is noticeably smaller than A and B, which indicates that, compared with the Young's modulus and the ultimate strength, the strain value at the peak load is remarkably less sensitive to the strain rate.

Figure 3: Stress-strain curves at different strain rates under compression and tension.

Figure 4: E, peak stress and strain at different strain rates in compression and tension.

Table 3: Comparison of the linear correlation coefficients between compression and tension.

Equation	Param	Unit	Compression	Tension	Ratio C/T
$E = E_0 + A\dot{\epsilon}$	E_0	MPa	1.075	0.497	2.2
	A	MPa·s	3180	340	9.3
$\sigma_b = \sigma_{b0} + B\dot{\epsilon}$	σ_b	MPa	0.230	0.065	3.5
	B	MPa·s	560	24	23.3
$\epsilon_b = \epsilon_{b0} + C\dot{\epsilon}$	ϵ_b	mm/mm	0.231	0.158	1.5

Additionally, the ratio between the compressive and the tensile coefficients indicates that the asymmetric behavior of the material is not negligible. The result shows that the strength of asphalt matrix is higher when under pressure, which suggests that the plastic flow of the material can be affected by hydrostatic pressure. Therefore, considering the complex loading condition on the pavement, we should design specific compression or tension tests for the purpose of more accurate evaluation and prediction of the material properties.

The final states of the damaged specimens after being loaded at the highest and the lowest strain rate are shown in Fig. 5. The shear band can be seen in the specimens after compressive loading, which is due to the plastic yielding and flow. Besides, necking can be observed before fracture when the specimen is under tensile loads, during which the cross-section area decreases.

Figure 5: Specimens after loading at $1.25 \times 10^{-4} \text{ s}^{-1}$ and $5 \times 10^{-4} \text{ s}^{-1}$.

4.2. Creep test

Under long-term stress, asphalt material can deform continuously and result in failure, even when the stress is below the yield strength. The creep process consists of three stages: (i) the primary stage, (ii) the secondary stage and (iii) the tertiary stage. During the primary stage, material deformation increases creep resistance, and thus the creep rate decreases until it reaches the minimum value. The creep rate remains constant during the secondary steady stage until reaching a critical point where the corresponding stress is defined as creep rupture stress. This point represents the initiation of the tertiary stage in which the material degrades. During this stage, the creep rate increases rapidly, accelerating the internal damage progression until the total failure.

A creep rupture envelope curve is commonly used to predict the ultimate lifetime of a material. Since creep test is costly and time consuming and the designed life of the material can be too long to be measured in lab tests, the envelope can be very helpful for the evaluation and further prediction of the material response and for a safe design. The creep rupture envelope is usually displayed as a log-log plot of creep rupture stress as a function of failure time, which tends to be linear on this coordinate scheme [35, 36]. Once the required working time of the material is given, a safe stress

can be determined according to the creep rupture envelope. Similarly, with a known load, the ultimate service life of the material can be predicted.

To study the creep behavior of asphalt matrix, creep tests at six loading levels (10, 20, 25, 30, 40 and 50 N for compression; 2.5, 5, 10, 20, 30 and 40 N for tension) are conducted.

Figure 6: Creep curves in compression.

Figure 7: Creep curves in tension.

Fig. 6 and Fig. 7 show the creep curves for compression and tension, respectively. The critical failure point is determined by fitting the creep curve and obtaining the second inflection point on its second derivative. The creep rupture stress and the corresponding failure time at the critical point of each creep curve are obtained. It is worth noting that in the compressive creep tests, the material still does not enter the tertiary creep stage after 6000 s under a load of 10 N. Therefore, the determination of the creep rupture envelope can help to save testing time. The creep rupture envelope (see Fig. 8) is obtained by fitting the critical points with the function $\log(\sigma) = a \log(t) + b$ and the fitted coefficients are given in Table 4. The determined envelop curve can help to evaluate and predict the long-term creep properties of asphalt matrix.

Figure 8: Creep rupture stress (envelopes) versus time.

Table 4: The fitted coefficients of the creep rupture envelope curve.

Coefficients	a (MPa/s)	b (MPa)
Compression	-0.307	0.420
Tension	-0.578	-0.037

4.3. Creep-recovery test

A stress σ_0 is instantaneously applied on the material at $t = 0$, kept constant for t_0 seconds and then removed at $t = t_0$. The total recoverable (elastic) strain is defined as $\varepsilon_e = \varepsilon_{ie} + \varepsilon_{ve}$, where ε_{ie} is the instantaneous elastic strain when the stress σ_0 is just applied and ε_{ve} is the visco-elastic strain. The latter one is a time-dependent deformation before the stress is removed. The instantaneous elastic strain is immediately recovered once the material is unloaded, while the visco-elastic part is recovered with a certain retardation due to the viscosity. The irrecoverable permanent strain ε_p is mainly caused by viscous flow and damage. Creep-recovery test can provide very useful information about the material's nonlinear visco-elastic properties.

A series of creep-recovery tests under different loads (5, 10, 20, 35, 30 and 40 N) are conducted. The specimen is loaded for 200 s and then unloaded for 800 s, and the average creep-recovery curves are shown in Fig. 9. It can be seen that only partial creep strain is recovered in each case. As the creep load increases, both the total creep strain and the irrecoverable strain increase significantly.

Figure 9: Creep recovery curves.

In order to get a quick and comprehensible assessment of the visco-elastic response of this asphalt matrix, the linear one-dimensional and isotropic Kelvin-Voigt (K-V) model is adopted. It consists of a Hookean elastic spring and a Newtonian dashpot connected in parallel, whose constitutive model is expressed as:

$$\sigma = E\varepsilon + \eta\dot{\varepsilon} \quad (1)$$

where E is the Young's modulus of the linear spring and η is the viscosity of the dashpot.

Since the recovery process starts at $t = t_0$ where the load is removed, Eq. (1) can be represented as $0 = E\varepsilon + \eta\dot{\varepsilon}$. By solving this equation, the remained elastic strain during recovery can be represented as $\varepsilon(t) = Ce^{-(t-t_0)/(\eta/E)}$, where C is the recoverable strain (ε_e) and η/E is the retardation time (t_R). Thus, the expression of the recovery curve is obtained:

$$\varepsilon(t) = \varepsilon_e e^{-(t-t_0)/t_R} + \varepsilon_p \quad (2)$$

The coefficients of Eq. (2) are fitted to follow the experimental results in Fig.9. The relationships between creep stress and different parameters (i.e., ε_e , ε_p and t_R) are shown in Fig. 10. It can be seen that both the recoverable and irrecoverable strains are positively correlated with the creep stress, and the irrecoverable strain increases quite significantly with the increase of the creep stress. The strain curves can be fitted with a linear equation: $\varepsilon = a\sigma + b$, the results of which are given in Table 5. The slope (a) of $\varepsilon_p - \sigma$ is almost 40 times that of $\varepsilon_e - \sigma$, indicating that the irrecoverable strain is considerably more sensitive to the creep stress. Moreover, the change in t_R^{-1} is almost negligible.

Figure 10: Inelastic and elastic strain-stress curves.

Table 5: The fitted coefficients of the strain-creep stress curves.

Coefficients	a (MPa ⁻¹)	b (-)
ε_p	0.53	0.014
ε_e	0.015	0.003

5. Dynamic tests

In this section, amplitude sweep tests, frequency sweep tests and fatigue-recovery tests are conducted and the testing results are analyzed. All the dynamic tests are conducted by using a sinusoidal load under compression and tension. With the aid of the dynamic tests, the two rheological parameters, namely the complex modulus (E^*) and the phase angle (δ) measured in tension can be determined:

$$E^* = E' + iE'' \quad (3)$$

$$\delta = \tan^{-1}\left(\frac{E''}{E'}\right) \quad (4)$$

where E' is the storage modulus, representing the the energy stored in the recoverable elastic part, E'' is the loss modulus, characterizing the amount of energy dissipated in the viscous part, which is irrecoverable, i is the imaginary unit number, and the phase angle δ ranges from 0° to 90° .

5.1. Strain amplitude sweep test

Amplitude sweep test can determine the linear visco-elastic region (LVE), within which the complex modulus of the material is almost constant. The limiting strain (ε_L) of LVE is obtained where the storage modulus deviates from the LVE plateau with a tolerance of 10% [37].

In the strain amplitude test, the strain increases linearly from 0.01% to 100% and the frequency

(f) is kept constant. Here, three frequencies, 0.1, 1 and 10 Hz are chosen. It is worth mentioning that due to the limitation of the normal force and the displacement of the DMA device, the test might be terminated before the aimed maximum strain is reached.

The results of the amplitude sweep test are given in Fig. 11. The plateau storage modulus (E') and the loss modulus (E'') within LVE, as well as the limiting strain ε_L values at the frequency of 0.1, 1 and 10 Hz are listed in Table 6. It is noteworthy that the limiting strain of LVE is only valid for the applied frequency. In addition, the material is stiffer at a higher loading frequency, and the corresponding ε_L is smaller, which is a clear feature of rate-dependent materials.

Figure 11: Strain amplitude sweep curves.

Table 6: Parameters at different loading frequencies.

f (Hz)	E' (MPa)	E'' (MPa)	ε_L
0.1	10.6 ± 1.3	24.5 ± 2.5	$0.10\% \pm 0.02\%$
1	52.6 ± 3.3	107.1 ± 5.6	$0.049\% \pm 0.06\%$
10	157.9 ± 4.2	325.4 ± 7.8	$0.037\% \pm 0.07\%$

5.2. Frequency sweep test

Strain-controlled frequency sweep tests in tension are conducted at different strain amplitude (i.e., 0.1%, 0.5% and 1%). The frequency increases from 0.1 to 10 Hz in each test.

The result of the frequency sweep test at different strain level is shown in Fig. 12, where the phase angle δ is plotted on a semi-logarithmic scale as a function of the frequency. Three repetitions of the frequency sweep test seem to be sufficient to quantitatively catch the feature of the dynamic behavior of asphalt matrix. The average percentage error of each parameter in case of $\varepsilon = 0.1\%$, 0.5% and 1%, respectively, is calculated and listed in Table 7.

Table 7: Percentage error of parameters at different loading amplitude.

Loading Amplitude	$\varepsilon_{E'}$	$\varepsilon_{E''}$	ε_{δ}
0.1%	4.09%	2.91%	0.43%
0.5%	3.54%	2.83%	0.28%
1%	5.03%	3.66%	0.81%

Figure 12: Frequency sweep curves at different strain rates.

As the strain amplitude increases from 0.1% to 1%, both of the storage modulus and the loss modulus decrease, indicating the increasing accumulation of dissipative micro-mechanism. Additionally, the phase angle increases when the strain amplitude is larger, which can be explained by the increasing energy dissipation, indicating that the material behavior is, in general, more viscous. It can be noticed that in each test, the loss modulus is larger than the storage modulus and the phase angle is larger than 45° , which indicates that the material behaves like a fluid in the testing condition [38, 39]. Additionally, in case of $\varepsilon = 1\%$, the slight increase in the phase angle at 10 Hz is caused by frictional heating.

Figure 13: Generalized Maxwell model.

A generalized Maxwell model is adopted for the asphalt matrix. Fig. 13 shows the schematic representation of the generalized Maxwell model which consists of a spring and several spring-dashpot branches (also known as Maxwell elements) connected in parallel [40]. The equivalent

frequency domain approximation for the tensile modulus is written in terms of a Prony series expansion [41].

$$E^*(\omega) = E_\infty + \sum_{i=1}^{N_b} \frac{E_i \omega t_{Ri} i}{1 + \omega t_{Ri} i} \quad (5)$$

where E_∞ is the equilibrium modulus of the generalized Maxwell model, referring to the static response when the spring-dashpot branched are fully relaxed, E_i is the tensile modulus of the i th elastic spring, t_{Ri} is the relaxation time of the i th dashpot, N_b is the number of the spring-dashpot branches in the generalized Maxwell model and ω (in radians) is the frequency of the load ($\omega = 2\pi f$).

Least-squares method is adopted to fit Eq. (5) to the $\tan \delta$ -frequency data at the strain amplitude of 0.1%, where $\tan \delta$ is the dissipation factor. The equilibrium modulus E_∞ is determined as 0.01 MPa via relaxation test. The generalized Maxwell model with different numbers of Maxwell branches (N_b) are tried for the fitting. The results in Fig. 14 show that the fitting result can match the experimental data to a great extend when $N_b = 5$, with the sum of squared residuals $R^2 = 0.0006$. The fitted parameters of the generalized Maxwell model with 5 Maxwell branches are presented in Table 8. Five relaxation times are considered in this model. It is worth mentioning that when E_∞ increases by 50 %, the change of fitted t_{Ri} values are less than 1 %, indicating that the sensitivity of relaxation time to E_∞ is very low during fitting.

Figure 14: Fitted $\tan \delta$ -frequency curves using the generalized Maxwell model with different N_b .

Table 8: The fitted parameters of the generalized Maxwell model for the asphalt matrix.

i	1	2	3	4	5
E_i (MPa)	11455.3	1.005	0.256	0.101	0.0355
t_{Ri} (s)	2.54×10^{-6}	0.0156	0.0637	0.234	0.974
E_∞ (MPa)	0.01				

It can be seen from the result that the stiffness and the relaxation responses change over a wide

range of timescales. The dashpot in series with the spring in each Maxwell branch has different relaxation time, leading to the rate-dependent change in the stiffness of the material. To be more precise, when the loading rate is slower, the dashpot with shorter relaxation time flows faster, leading to less contribution of the connected spring to the total stiffness of the material. On the other hand, under higher loading rate, the dashpots react slower, and thus the spring in each branch can contribute more to the whole model, resulting in a higher total stiffness. The characterization of the material properties can help us to understand how asphalt matrix behaves under different loading conditions. Moreover, the determination of the material model is very relevant for numerical modelling of asphalt matrix and asphalt concrete in further research.

5.3. Fatigue-recovery test

In real condition, asphalt pavement mainly undergoes intermittently dynamic wheel loads. According to the results in Fig. 9, only a small amount of visco-elastic strain can be recovered, indicating that, compared to the visco-elastic property, self-healing plays a more important role in the recovery of material properties. Since the micro-damage caused by wheel loads can be recovered after a certain resting period due to the self-healing capability of asphalt, it is important to figure out how the duration of the resting period can affect its healing efficiency.

A cyclic sinusoidal load $\sigma = \sigma_0 \sin(2\pi ft)$ is applied to the asphalt matrix specimen, where σ_0 is the amplitude of the load and f is the loading frequency. It is worth mentioning that the frequency 10 Hz is adopted in the fatigue analysis to align with the frequency of a vehicle axle-hop on asphalt pavement [42]. Besides, σ_0 is set as 0.5 MPa just to ensure that it is large enough to cause micro-damage during loading. The loading time (LT) is set as 30 s and the recovery time (RT) is set as 0, 30 and 60 s, respectively, in the fatigue-recovery tests. Here, the resting interval of 0 s indicates the normal fatigue test without resting period.

Figure 15: Fatigue-recovery curves (RT=0, 30, 60 s).

Figure 16: Changes in the normalized norm of complex modulus during the loading cycles (RT=0, 30, 60 s).

The stiffness of the fatigue damaged specimen can recover after a certain resting period. With multiple times recovery, the fatigue life of asphalt matrix is significantly increased as shown in Fig. 15. Fig. 16 shows the relation between loading cycles and normalized norm of complex modulus ($|E^*|/|E_0^*|$), where $|E^*| = \sqrt{E'^2 + E''^2}$ and E_0^* is the initial complex modulus. When $|E^*|/|E_0^*|$ decreases by 40 % and 60 %, the corresponding loading cycles are summarized in Table 9. In case of $|E^*|/|E_0^*| = 0.6$, the loading cycles for RT=30 s and 60 s are about 3 and 8 times larger than that without resting, respectively. When $|E^*|/|E_0^*| = 0.4$, the loading cycles for RT=30 s and 60 s are about 3.5 and 4 times larger than that for RT=0 s, respectively. The result indicates that longer recovery time can help to slow down the general degradation of the material in the beginning of the loading, for example, when cycles ≤ 1000 , the general degradation for the RT=60 s case is about 2 times slower than that for the RT=30 s case. However, the recovery time shows less effect on self-healing with the increase of loading cycles (e.g., cycles ≥ 6000).

Table 9: The corresponding loading cycles at $|E^*|/|E_0^*| = 0.6$ and 0.4.

$ E^* / E_0^* $	RT (s)	Cycles
0.6	0	850
	30	2400
	60	6900
0.4	0	1750
	30	6600
	60	7340

In addition, the decreasing rate of the storage modulus and the loss modulus at each loading interval is obtained. The average decreasing rate is calculated by Eq. (6) and listed in Table 10.

$$D_{E'} = \frac{\sum_{i=1}^N D_{E'}^i}{N}$$

$$D_{E''} = \frac{\sum_{i=1}^N D_{E''}^i}{N}$$
(6)

where $D_{E'}^i$ and $D_{E''}^i$ are the decreasing rate of storage modulus and loss modulus at the i th loading interval, denoting the degradation rate of material after each healing period, and N is the total number of the loading intervals.

Table 10: The average decrease rate of E' and E'' with different RT.

RT (s)	0	30	60
$D_{E'}$ (MPa/s)	0.444	0.868	0.874
$D_{E''}$ (MPa/s)	0.965	1.502	1.837

Figure 17: Modulus decreasing rate (RT=0, 30, 60 s).

As shown in Fig. 17, before the unstable propagation of damage, the decreasing rate of the modulus decreases with the increase of total loading time. In addition, both $D_{E'}$ and $D_{E''}$ are higher when the recovery time is longer.

Lissajous curve [43], namely stress-strain hysteresis loop, is also used to analyze the rheological behavior of materials. As shown in Fig. 18 (a) and (b), the Lissajous curve is a straight line when the material is purely elastic, while it is a circle if the material is purely viscous. An ellipse curve indicates that the material has visco-elastic behavior (Fig. 18 (c)). Besides, a distorted ellipse curve shows nonlinear visco-elastic behavior.

Figure 18: Schematic representation of Lissajous curve.

The area of the ellipse curve represents the dissipated energy density (u^d):

$$u^d = \int \sigma(\epsilon) d\epsilon \quad (7)$$

which is related to the (viscous) loss modulus (E'') of the material.

Figure 19: Stress-strain hysteresis loops.

The Lissajous curves at the end of every loading interval (30 s) for each fatigue-recovery tests are presented in Fig. 19 (the first five intervals are shown). When the recovery time is longer, a slower increase in the area of the Lissajous curve can be observed. The dissipation ratio (DR) is used to quantitatively analyze the effect of recovery time, which is defined as:

$$DR = \frac{u_k^d - u_0^d}{u_0^d} \times 100\% \quad (8)$$

where u_0^d is the dissipated energy density of the first circle and u_k^d is the dissipated energy density of the k th circle ($k=0, \dots, N$).

The relationship between DR and loading time for different RT cases is shown in Fig. 20. It can be seen that DR increases linearly with the increase of loading time. The increasing rate (slope) of the curves are calculated as 0.64 %/s, 0.23 %/s and 0.05 %/s for the case of RT=0 s, 30 s and 60 s, respectively.

Figure 20: Stress-strain hysteresis loops.

To better investigate the self-healing effect and determine proper healing indices, tests with more complex loading conditions (e.g., different combination of loading time and recovery time) need to be conducted. The self-healing effect of asphalt matrix will be quantitatively analyzed in our further research.

6. Conclusions

This study presents a collection of mechanical tests to characterize the quasi-static and dynamic response of an asphalt matrix using PEN 70 asphalt binder at room temperature. Only one single machine (DMA) has been used to carry out all the tests. The proposed experimental setup is proved feasible for the experimental characterization of this material, which is commonly used in the production of asphalt concrete. A total of six tests, including three quasi-static and three dynamic tests, have been conducted. On the basis of this study, the following conclusions can be drawn.

Quasi-static tests:

(1) In the uniaxial tests at different strain rates, full stress-strain curves till total failure are obtained. The result denotes that the asphalt matrix is a visco-elasto-plastic material which exhibits a notorious asymmetric behavior between compression and tension under different strain rates. Both the stiffness and the strength of asphalt matrix present a clear linear dependency with the strain rate within the range $1.25\text{-}8.75 \times 10^{-4} \text{ s}^{-1}$.

(2) With the aid of creep tests at different stress levels, the creep rupture envelop curves of asphalt matrix in both compression and tension can be obtained, which show a linear dependency with loading time on the log-log coordinate scheme. This can help to evaluate and predict the long-term creep behavior of asphalt matrix, so as to guide the further material design and optimization of asphalt concrete with the aid of numerical methods.

(3) By fitting the creep-recovery curves, the elastic strain ε_e and the permanent strain ε_p are proved to be linearly correlated with the creep stress. Compared to the recoverable strain, the permanent strain is far more sensitive to the creep stress.

Dynamic tests:

(4) The LVE region of asphalt matrix can be determined by amplitude sweep tests. The

measured limiting strain (ε_L) of LVE is only valid for the applied frequency. Moreover, at a higher loading frequency (e.g., 10 Hz), the plateau complex modulus is higher but the ε_L is smaller, indicating that asphalt matrix is stiffer but can degrade sooner.

(5) In the frequency sweep tests, asphalt matrix shows a fluid-like behavior at room temperature when the loading frequency is within 0.1-10 Hz, as the phase angle is always larger than 45° . The maximum phase angle increases from 72° to 73.5° when the strain amplitude changes from 0.1 % to 1 %, in which case the material behavior is more viscous. The generalized Maxwell model consisting of a linear spring and five Maxwell branches connected in parallel can be used to describe the rate-dependent behavior of asphalt matrix, which is also required for further modelling research.

(6) The result of fatigue-recovery tests show that asphalt matrix has the capability of self-healing. The fatigue life of asphalt matrix can be multiplied by 4 by introducing resting periods between loading intervals. When increasing the recovery time, asphalt matrix can regain higher modulus. This, however, will decrease faster during the following loading period. Thus, frequent resting periods are necessary for increasing the self-healing efficiency.

Asphalt matrix contains the most relevant mechanical features to understand the behavior of asphalt concrete, i.e., rate-dependent compression-tension asymmetry, visco-elasto-plasticity and self-healing. In other words, the analysis on the behavior of asphalt matrix from different aspects can help to understand how asphalt concrete is affected by different factors like strain/stress level, loading frequency, loading type, resting time, etc.

However, it is worth mentioning that with regard to self-healing analysis, a more detailed testing scheme should be designed to determine and characterize proper self-healing indices. The self-heating effect at high loading rate/frequency might cause a local increase of plastic dissipation, which requires a further study with the aid of a thermographic camera. In addition, the effects of temperature, conditioning of samples, different material compositions need to be investigated, and nonlinear loading is required for a better understanding of the nonlinear behavior of the material.

On the basis of this study, more experimental analysis of the self-healing capability of asphalt matrix will be conducted as further research. Moreover, the constitutive model of asphalt matrix will be further developed and incorporated in a big asphalt concrete model for the evaluation and prediction of its global response. The development of the numerical model of asphalt matrix and asphalt concrete considering visco-elasto-plastic and self-healing properties is being carried out in our ongoing research.

CRedit author statement

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Reference

- [1] AASHTO T315: Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (dsr). Standard; American Association of State Highway and Transportation Officials, Washington, DC; 2012.
- [2] AASHTO TP101: Estimating damage tolerance of asphalt binders using the linear amplitude sweep. Standard; Recuperado el 12; 2014.
- [3] Lei Z, Tian-shuai L, Fei G, Yi-qiu T. Rheological and physical properties of asphalt mixed with warm compaction modifier. *Construction and Building Materials* 2016; 123:309-16.
- [4] Wang C, Chen Y, Cao W. A chemo-rheological approach to the healing characteristics of asphalt binders under short-and long-term oxidative aging. *Construction and Building Materials* 2019; 221:553-61.
- [5] Mirzaaghaeian E, Modarres A. Rheological properties of bituminous mastics containing chemical warm additive at medium temperatures and its relationship to warm mix asphalt fatigue behavior. *Construction and Building Materials* 2019;225(1):44-54.
- [6] Shan L, Qi X, Duan X, Liu S, Chen J. Effect of styrenebutadiene-styrene (sbs) on the rheological behavior of asphalt binders. *Construction and Building Materials* 2020; 231:117076.
- [7] AASHTO TP70: Standard method of test for multiple stress creep recovery (mscr) test of asphalt binder using a dynamic shear rheometer (dsr). Standard; American Association of State Highway and Transportation Officials, Washington, DC; 2009.
- [8] Soenen H, Blomberg T, Pellinen T, Laukkanen O. The multiple stress creep-recovery test: a detailed analysis of repeatability and reproducibility. *Road Materials and Pavement Design* 2013; 14(1):2-11.
- [9] Hassanpour-Kasanagh S, Ahmedzade P, Fainleib AM, Behnood A. Rheological properties of asphalt binders modied with recycled materials: A comparison with styrene-butadiene-styrene (sbs). *Construction and Building Materials* 2020;230:117047.
- [10] AASHTO TP79: Standard method of test for determining the dynamic modulus and ow number for hot mix asphalt (hma) using the asphalt mixture performance tester (ampt). Standard; American Association of State Highway and Transportation Officials, Washington, DC; 2009.
- [11] AASHTO TP107: Determining the damage characteristic curve of asphalt concrete from direct tension cyclic fatigue tests. Standard; American Association of State Highway and Transportation Officials, Washington, DC; 2014.
- [12] Diaz L, Archilla A. From testing to design: An easy way use and interpret the results from the asphalt mixture performance tester (ampt). *International Journal of Pavement Research and Technology* 2013;6(5):52738.
- [13] Keshavarzi B, Kim Y. A viscoelastic-based model for predicting the strength of asphalt concrete in direct tension. *Construction and Building Materials* 2016; 122:721-7.
- [14] Koohi Y, Lawrence J, Luo R, Lytton R. Complex stiffness gradient estimation of field-aged asphalt concrete layers using the direct tension test. *Journal of materials in civil engineering* 2012;24(7):832-41.
- [15] Iskakbayev A, Teltayev B, Yestayev K, Abu B. Long-term strength of asphalt concrete and its applications. *Construction and Building Materials* 2020; 244:118325.
- [16] Islam M, Faisal H, Tarefder R. Determining temperature and time dependent poisson's ratio of

asphalt concrete using indirect tension test. Fuel 2015; 146:119-24.

[17] Yin A, Yang X, Gao H, Zhu H. Simulation of crack propagation in asphalt concrete using an intrinsic cohesive zone model. Engineering Fracture Mechanics 2012; 92:40-55.

[18] Hossain M, Tarefder R. Identifying damage in asphalt matrix materials surrounding an aggregate particle. Construction and Building Materials 2013; 49:536-46.

[19] Song S, Paulino G, Buttlar W. Simulation of crack propagation in asphalt concrete using an intrinsic cohesive zone model. Journal of Engineering Mechanics 2006; 132(11):1215-23.

[20] Aragão F, Hartmann D, Kim Y, Da Motta L. Mesostructural damage simulation of asphalt mixture using microscopic interface contact models. Transportation Research Record 2014; 2447(1):42-50.

[21] Dong Z, Gong X, Zhao L, Zhang L. Mesostructural damage simulation of asphalt mixture using microscopic interface contact models. Construction and Building Materials 2014; 53:665-73.

[22] Wimmer J, Stier B, Simon J, Reese S. Computational homogenization from a 3d finite element model of asphalt concrete-linear elastic computations. Finite Elements in Analysis and Design 2016;110:43-57.

[23] Huang W, Zhang X, Yin Y. An image-based finite element approach for simulating viscoelastic response of asphalt mixture. Advances in Materials Science and Engineering 2016;2016:1-11.

[24] Zhang Y, Leng Z. Quantification of bituminous mortar ageing and its application in ravelling evaluation of porous asphalt wearing courses. Materials & Design 2017; 119:1-11.

[25] Ye Y, Yang X, Chen C. Experimental researches on viscoelastoplastic constitutive model of asphalt mastic. Construction and Building Materials 2009;23(10):3161-5.

[26] Kim Y, Little D, Lytton R. Fatigue and healing characterization of asphalt mixtures. Journal of Materials in Civil Engineering 2003;15(1):75-83.

[27] Reinke G, Glidden S, Herlitzka D, Jorgenson J. Laboratory investigation of hma performance using hamburg wheel tracking and dsr torsional creep tests. Journal of ASTM International 2005;2(10):1-32.

[28] Caro S, Beltrán D, Alvarez, A.E., Estakhri C. Analysis of moisture damage susceptibility of warm mix asphalt (wma) mixtures based on dynamic mechanical analyzer (dma) testing and a fracture mechanics model. Construction and Building Materials 2012; 35:460-7.

[29] Menard K, Menard N. Dynamic mechanical analysis. Encyclopedia of Analytical Chemistry: Applications, Theory and Instrumentation 2006; 1-25.

[30] Little D, Lytton R, Williams D, Chen C. Microdamage healing in asphalt and asphalt concrete, volume 1: microdamage and microdamage healing, project summary report. Tech. Rep. FHWA-RD-98-141; Research report 7229; Turner-Fairbank Highway Research Center; 2001.

[31] Bhasin A, Palvadi S, Little D. Influence of aging and temperature on intrinsic healing of asphalt binders. Transportation research record 2011; 2207(1):70-8.

[32] Raithby K, Sterling A. The effect of rest periods on the fatigue performance of a hot-rolled asphalt under reversed axial loading and discussion. Association of Asphalt Paving Technologists Proc 1970; 33:134-52.

[33] Daniel J, Kim Y. Laboratory evaluation of fatigue damage and healing of asphalt mixtures. journal of materials in civil engineering. Journal of Materials in Civil Engineering 2001;13(6):434-40.

[34] AASHTO T312: Standard test method for dynamic young's modulus, shear modulus, and poisson's ratio by impulse excitation of vibration. Standard; American Association of State Highway

and Transportation Officials, Washington, DC; 2014.

[35] Lampman S. Characterization and failure analysis of plastics. Asm International; 2003.

[36] McKeen L. The effect of creep and other time related factors on plastics and elastomers. Elsevier; 2009.

[37] ASTM. ASTM D7175: Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer; 2008.

[38] Barnes H, Hutton J, Walters K. An introduction to rheology. Elsevier; 1898.

[39] Christensen D, Mensching D, Rowe G, Anderson R, Hanz A, Reinke G, et al. Past, present, and future of asphalt binder rheological parameters: Synopsis of 2017 technical session 307 at the 96th annual meeting of the transportation research board. Transportation Research Circular 2019;(E-C241).

[40] Roylance, D. Engineering viscoelasticity. Department of Materials Science and Engineering–Massachusetts Institute of Technology, Cambridge MA; 2001(2139): 1-37.

[41] Sain T, Meaud J, Yeom B, Waas A, Arruda E. Rate dependent finite strain constitutive modeling of polyurethane and polyurethane-clay nanocomposites. International Journal of Solids and Structures 2015; 54:147-55.

[42] Cebon D. Handbook of Vehicle-Road Interaction. Swets & Zeitlinger; 1999.

[43] Mezger T. The rheology handbook: for users of rotational and oscillatory rheometers. Vincentz Network GmbH & Co KG; 2006.