Laboratory Evaluation of Deurex-Modified Asphalt

Shengfeng Yang[1]; Kezhen Yan[2]; Weili He[3]; and Haibing Wang[4]

Abstract: The ability of Deurex natural sugar cane wax to reduce the blending and compaction temperatures of warm-mix asphalt renders it a promising technology in pavement construction to reduce CO_2 emissions and save energy. This new warm-mix additive might revolutionize pavement construction and warm-mix asphalt production by introducing a new class of mixtures with excellent environmental performance. The goal of this study was to evaluate the feasibilities and benefits of the incorporation of Deurex into asphalt binders. Deurex was blended into asphalt at contents of 1, 3, 5, and 7%, and the following tests were performed: physical properties, performance grade, multiple stress creep recovery, frequency sweep, separation, differential scanning calorimetry (DSC), and Fourier transform infrared rheometer (FTIR). The test results showed that the increase in Deurex significantly reduces the viscosity of asphalt binders, implying that a decrease in the blending and compaction temperatures of asphalt mixtures can be achieved during pavement construction. In addition, the tests showed that the addition of Deurex increases complex modulus (G^*), rutting factor ($G^*/\sin\delta$), average percentage recovery, and phase angle, and reduces nonrecoverable creep compliance and phase angle. It is suggested that Deurex-modified binders are less subject to permanent deformation at high temperature. Moreover, DSC analyses showed that Deurex has little effect on asphalt thermal properties. Further, FTIR analyses showed that chemical reactions might happen during the mixing of Deurex and asphalt. Overall, the good performance of Deurex-modified asphalt showed its potential as a new additive in warm-mix asphalt manufacture. **DOI: 10.1061/(ASCE)MT.1943-5533.0002111.**

Author keywords: Viscosity; Deurex; Rheological properties; Asphalt.

Introduction

Environmental pollution on a global scale has brought to light the urgent need for new resource-conserving and environment-friendly technologies and processes. In this context, warm-mix asphalt (WMA) technologies offer promising potential. Indeed, WMAs can decrease the blending and compaction temperatures of asphalt mixtures, thereby reducing the carbon emissions and energy consumption inherent in asphalt pavement construction (Xiao et al. 2012). It is estimated that more than 50 WMA technologies have been developed worldwide, involving three approaches (Omari et al. 2016; Punith et al. 2011; Xiao et al. 2011, 2012): the injection of water to produce a foaming effect; the addition of organic additives such as Sasobit and Deurex (Deurex Company, Elsteraue, Germany); and the addition of chemicals such as Aspha-Min.

The mixing and compaction temperatures of WMA mixtures are 10–30°C less than those of conventional hot-mix asphalts (HMAs) (Ali et al. 2014; Sangsefidi et al. 2016; Tan et al. 2012). These lower temperatures significantly reduce emissions of greenhouse gases and poisonous chemicals (Punith et al. 2011; Sangsefidi et al. 2016; Tan et al. 2012; Xiao et al. 2012) and the volatilization of harmful composites in the asphalt. Furthermore, it is suggested that they enhance the long-term durability of asphalt mixtures by reducing short-term aging (Ahmed et al. 2012; Arega et al. 2011; Banerjee et al. 2012). Many researchers have proved similar or better rheological and technical properties of WMA mixtures compared with conventional HMA mixtures (Almeida-Costa and Benta 2016; Arega et al. 2011; Omari et al. 2016; Punith et al. 2011).

Deurex, produced in Germany, is extracted from sugar cane and has a hybrid chemical structure of sugarcane wax and long-chain aliphatic hydrocarbons (Deurex 2015). This structure, similar to the wax and long-chain aliphatic polymethylene hydrocarbon structure in Sasobit, comprises the core components of warm-mix additives that achieve viscosity reduction in asphalt binders. Compared with Sasobit, which is produced from coal gasification (Hurley and Prowell 2005), Deurex, obtained from sugarcane, does not contain any dangerous ingredients according to Deurex Directive 1999/45/EC (Deurex 2015), which means that it is environmentally friendly, easy to use, and economically feasible.

In this study, the physical properties, rheological performance, and chemical characteristics of asphalt binders containing five different percentages of Deurex were investigated. The testing procedures of penetration, softening point, ductility, viscosity, performance grade, multiple stress creep recovery, frequency sweep, separation, and differential scanning calorimetry (DSC) were carried out to assess the characteristics of Deurex-modified asphalt binders.

Materials and Physical Properties

A 60/80-pen (70#) asphalt binder (equivalent to PG64-16 asphalt binders obtained from PG Grading according to the Superpave performance grade) was adopted as the base (neat) asphalt in this study; its properties are provided in Table 1. Technical data for Deurex (Fig. 1) are provided in Table 2.

The base asphalt was first heated to 140 ± 5°C in an electric oven until it flowed fully. Then Deurex was added at 0, 1, 3, 5, and 7%, and the resulting mixtures were stirred thoroughly in a

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Note. This manuscript was submitted on February 16, 2017; approved on June 15, 2017; published online on November 8, 2017. Discussion period open until April 8, 2018; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561.

Table 1. Properties of Base Binder

Binder testing	Specification	Test temperature	Values	Specification
Penetration (0.1 mm)	60–80	25°C	74.7	ASTM D5 (ASTM 2013)
Softening point (°C)	43+	—	48.1	ASTM D36 (ASTM 2012)
Ductility (cm)	40+	15°C	1,315	ASTM D113 (ASTM 2007)

Fig. 1. Deurex

Table 2. Deurex Technical Data

Technical properties	Description	Method
Color	Olive green	—
Viscosity (140°C)	40 mPa	DIN EN ISO 3104
Density (23°C)	0.98–1.02 g/cm^3	DIN EN ISO 1183
Dropping point[a]	125–135°C	DGF M-III3
CAS number[b]	142583-61-7 sugar cane wax	—

Note: The test methods are European Standard.
[a]Dropping point = temperature at which materials like wax that do not have a melting point pass from semisolid to liquid under specific test conditions.
[b]CAS = chemical abstracts service number: a unique number identifying a specific chemical substance in a database.

high-shear mixer at 4,000 revolutions per minute (rpm) for 30 min at 150 ± 5°C. During the mixing, the Deurex flowed and dissolved completely in the asphalt. The control group (0% Deurex) was similarly stirred to achieve the same mixing effect.

The general conventional properties of the Deurex-modified binders, including penetration at 25°C and softening point and ductility at 15°C, were measured according to ASTM D5 (ASTM 2013), ASTM D36 (ASTM 2012), and ASTM D113 (ASTM 2007) standards. The effects of Deurex on these properties are shown in Fig. 2. Figs. 2(a and c) show that an increase in Deurex resulted in a decrease in penetration and ductility. When the Deurex content was less than 3%, the influence of ductility was considerable. An increase from 0 to 3% decreased penetration and ductility by approximately 20 (from 74.7 to 61.2) and

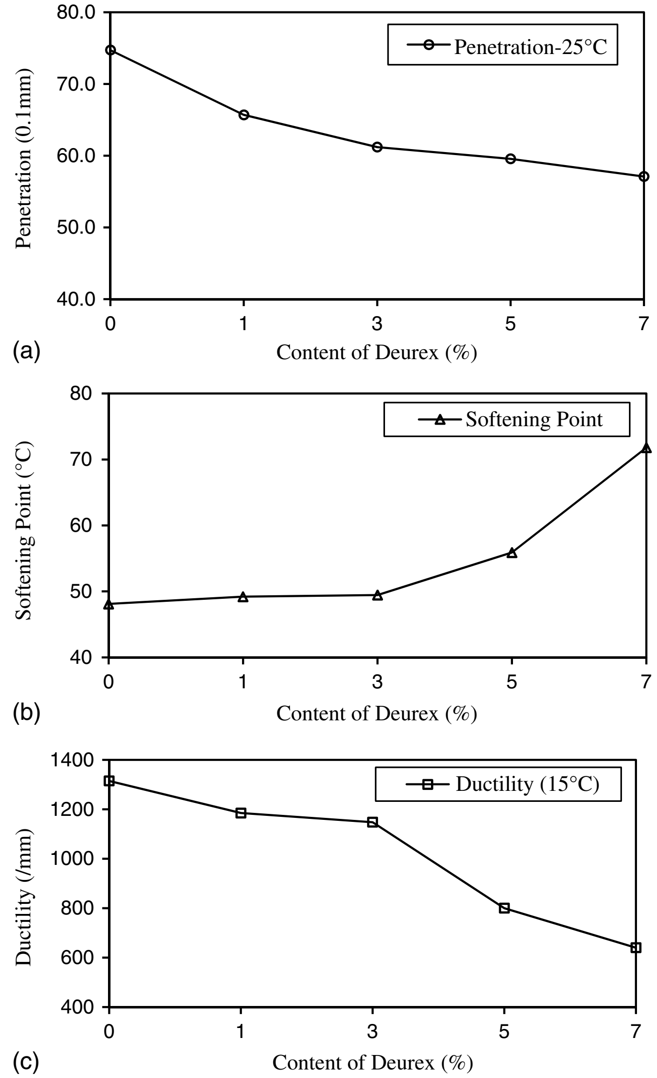

Fig. 2. Conventional properties of Deurex-modified asphalt binder: (a) penetration at 25°C; (b) softening point; (c) ductility at 15°C

12.6% (from 1,315 to 1,148), respectively. Fig. 2(b) shows that the softening point increased with an increment of Deurex from 1 to 7%. It could be derived from these results that the addition of Deurex improved the temperature performance of the modified asphalt binders and decreased their low-temperature cracking.

Rotational Viscosity Test

Following AASHTO T316 (AASHTO 2013), a Brookfield rotational viscometer (Shanghai Changji Geological Instrument, Shanghai, China) (No. -21 spindle) was used to test the viscosity of both base and Deurex-modified asphalt binders (8.5-g asphalt specimens) at 105, 120, 135, 150, and 175°C. Fig. 3 shows the variation in RV values for the Deurex-modified asphalt binders at the specified percentage increments of Deurex. From the results, it can be seen that the addition of Deurex had an obvious impact on viscosity reduction at 105, 120, and 135°C, and that an increase in Deurex from 0 to 3% led to sharp declines in viscosities at 105, 120, and 135°C (approximately 31.4, 25.8, and 25.4%, respectively). However, at 150 and 175°C, viscosity changed little, indicating that the Deurex-modified binders began to show similar fluid properties. It could be concluded that, at more than 1%, Deurex efficiently reduced asphalt viscosity.

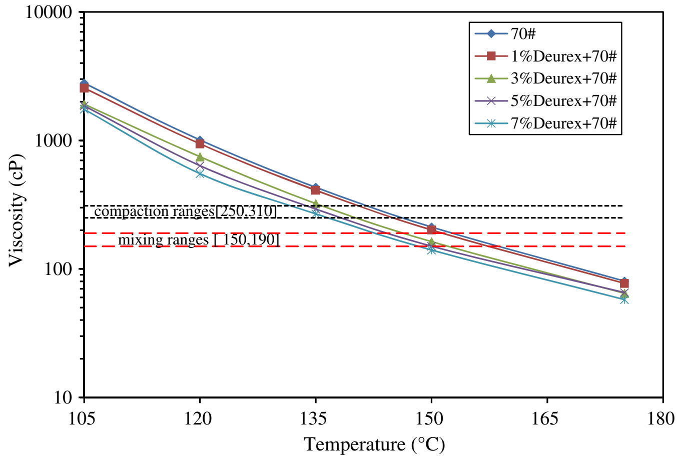

Fig. 3. Rotational viscosity test

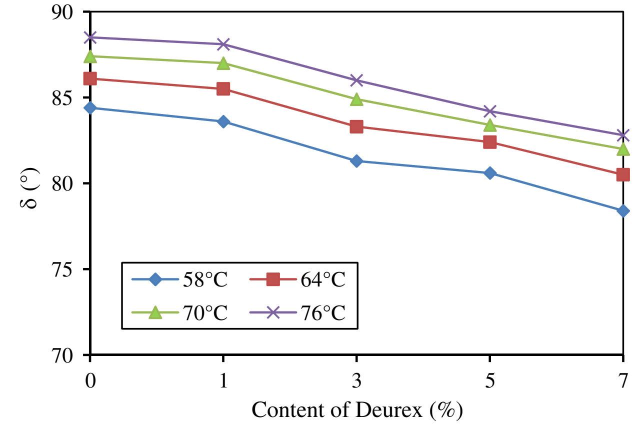

Fig. 5. Phase angle δ

Performance Grade

Asphalt grading is mainly designed to determine the high-, intermediate-, and low-temperature conditions at which a binder performs without failure or damage (Samy 2013). High- and intermediate-temperature grades were obtained from a dynamic shear rheometer (DSR) test following AASHTO T315-08 (AASHTO 2008b); the low-temperature grade was obtained from a bending beam rheometer (BBR) test following AASHTO T313-08 (AASHTO 2008a).

DSR Test

A dynamic shear rheometer was used to exert a shearing stress on a thin unaged asphalt specimen sandwiched between two parallel oscillatory plates of 25-mm diameter with a gap of 1 mm between them. The test was performed at a constant strain of 12%, a constant frequency of 10 rad/s (1.59 Hz), and test temperatures of 58, 64, 70, and 76°C. Through experimentation, complex shear modulus G^* (an indicator of overall stiffness or resistance to deformation under load) and phase angle δ (a measure of viscoelasticity) were measured automatically by *Rheoplus* software.

As shown in Fig. 4, all binders exhibited an increase in G^* with an increase in Deurex at all test temperatures, suggesting that the incorporation of Deurex improved the permanent deformation of the asphalt binders. In addition, G^* decreased as the testing temperature increased. Phase angle δ at different contents of Deurex at four temperatures is shown in Fig. 5. Obviously, the addition of Deurex significantly reduced δ, indicating a transformation of the elastic characteristics of the asphalt.

After measuring G^* and δ, the rutting factor $G^*/\sin\delta$ could be obtained. Rutting factor $G^*/\sin\delta$ is applied to determine high-temperature stiffness or rutting resistance of asphalt binders. A minimum value of 1.0 kPa for unaged asphalt binders at a designated test temperature is specified by Superpave. As shown in Fig. 6, $G^*/\sin\delta$ exhibits a rising curve similar to that for G^*. It is seen that, at 58, 64, and 70°C, $G^*/\sin\delta$ values for all additive contents met the minimum requirement except that of the original binder at 70°C. Meanwhile, it was found that the asphalt binders at 76°C failed to meet the minimum requirement of 1.0 kPa. Consequently, Fig. 6 indicates that the addition of Deurex affected the rutting factor of the control binder.

Asphalt pavement binder is prone to aging when the light oil in it volatizes and is oxidized during the binder's service life. The aged asphalt binder gradually acquires elastic-solid properties that easily bring about fatigue damage to asphalt pavement under repeated traffic loads. In addition, long-term oxidative aging owing to the large size of the binder molecules (i.e., asphaltene) affects complex shear modulus and phase angle, causing the binder to harden. Thus, $G^*\sin\delta$ (fatigue factor) can be used to explain the fatigue cracking resistance of asphalt pavement at an intermediate service temperature.

In this test, the rolling thin-film oven test + pressurized aging vessel (RTFO + PAV) residue samples were sandwiched between two 8-mm oscillatory plates with a gap of 2 mm to investigate the

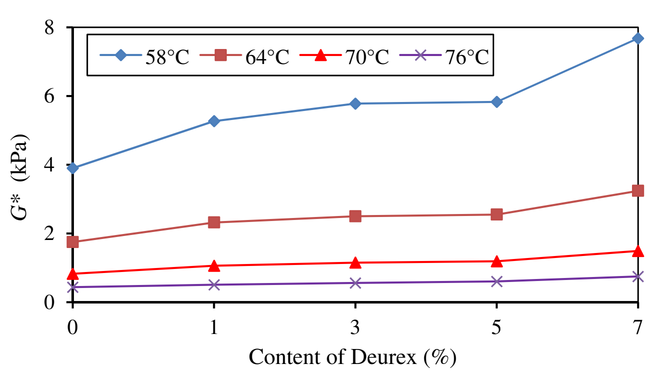

Fig. 4. Complex shear modulus G^*

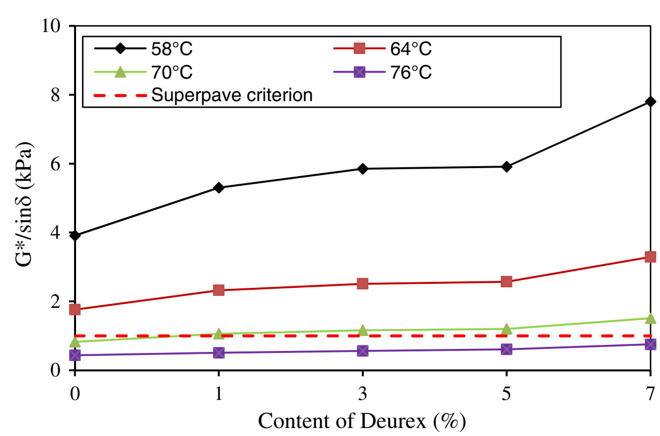

Fig. 6. Rutting factor $G^*/\sin\delta$

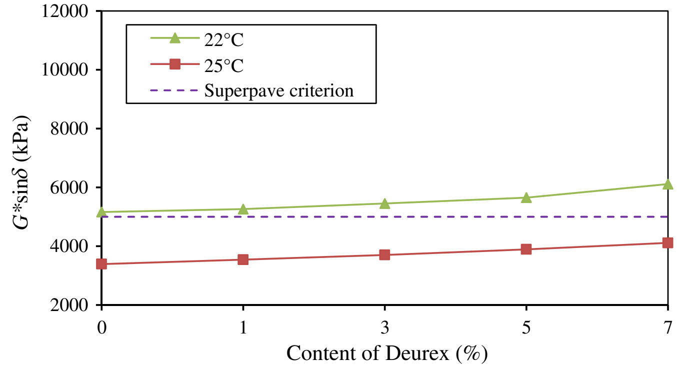

Fig. 7. $G^* \sin\delta$ values for RTFO + PAV aged WMA binders

intermediate-temperature grade for determining $G^* \sin\delta$. The tests were started at 22°C with a constant frequency of 10 rad/s (1.59 Hz) and a constant strain of 1%. Fig. 7 presents the effects of Deurex on $G^* \sin\delta$. The dotted line represents the minimum value of 5,000 kPa specified by Superpave. As shown, the aged Deurex-modified binders at the two test temperatures exhibited a consistent increasing trend for $G^* \sin\delta$. Deurex had a slight effect on the fatigue factor because its percentage increments resulted in diminutive increases in $G^* \sin\delta$ (from 3,390 to 4,410 kPa and less than 5,000 kPa). Thus, it reduced the fatigue property of the conventional binders but had no effect on the aged binder intermediate-temperature grade.

BBR Test

The BBR test was used to assess the low-temperature creep properties of asphalt binders by measuring parameters of creep stiffness and *m* values. Creep stiffness was measured through 60-s seating loading (980 ± 50 mN) at 10°C above the low-temperature grade designation for asphalt binders. The *m* value represents the changing rate of creep stiffness with time, which is an important indicator of stress relaxation characteristics of viscoelastic materials. In order to control low-temperature cracking, AASHTO M320 (AASHTO 2015) requires that creep stiffness be lower than 300 MPa and that *m* be higher than 0.3 for RTFO + PAV residues.

The results of the BBR test at −6 and −12°C are shown in Fig. 8. It can be seen that the increase in Deurex content resulted in an increase in creep stiffness but a decrease in *m* value at −6 and

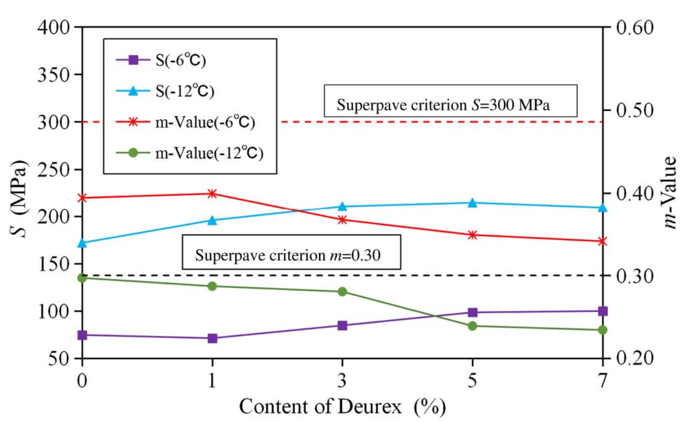

Fig. 8. Creep stiffness (*S*) value and *m* value variations with changes in additive content at −6 and −12°C

−12°C. The peak creep stiffness value (214.7 MPa) was less than 300 MPa, meeting the AASHTO M320 requirement. The *m* values at −6°C were higher than 0.3, but those at −12°C were lower and thus failed to meet the requirement. When the Deurex content increased from 0 to 3%, the *m* values at −6 and −12°C decreased slightly, by 6.82 and 5.58%, respectively. However, when the content increased to 7%, the decrements of *m* values at −6 and −12°C were relatively high, at 13.4 and 21.1%, respectively. Therefore, it could be concluded that when the mixing proportion exceeded 3%, Deurex exerted an obvious impact on the asphalt binders' stress relaxation.

Frequency Sweep Test

Research has found that the dynamic modulus (E^*) of HMA mixtures can decrease as much as tenfold when loading frequency is reduced from 10 to 0.01 Hz (Hossain 2011). In this study, the corresponding G^* value of the modified asphalt binders exhibited a similar trend of frequency dependency. In practice, traffic speed exerts a significant effect on the rutting potential of newly constructed pavement. It is said that the shearing frequency in DSR tests can be associated with traffic conditions, which means that performance under load at specific speeds is expressed at a corresponding frequency (Hossain 2011). Generally, frequencies between 10^{-1} and 10^2 rad/s are used to simulate normal vehicle traffic on pavement.

Another element affecting pavement rutting is temperature. Generally, a high surface temperature causes the softening of asphalt mixtures, eventually resulting in a larger deflection in the pavement under certain loading conditions. Thus pavement deflection is influenced by the combination of vehicle speed and surface temperature. For this reason, a frequency sweep test using DSR was performed on the asphalt binder specimens to simulate traffic speed and atmospheric temperature.

The test was performed on 25-mm parallel plates with a 1-mm gap between them at 58°C with frequencies ranging 100–0.1 Hz. Fig. 9 shows that five binders with various contents of Deurex exhibited consistent increasing G^* and decreasing δ with increasing frequency. What is more, it can be seen that the addition of Deurex resulted in increased complex modulus and decreased phase angle at all frequencies, suggesting that Deurex causes an increase in $G^*/\sin\delta$ and improves rutting resistance. However, even though the phase angles decreased as frequency increased, all of them were greater than 70°. This suggests that the obvious viscosity would cause rutting at different traffic speeds.

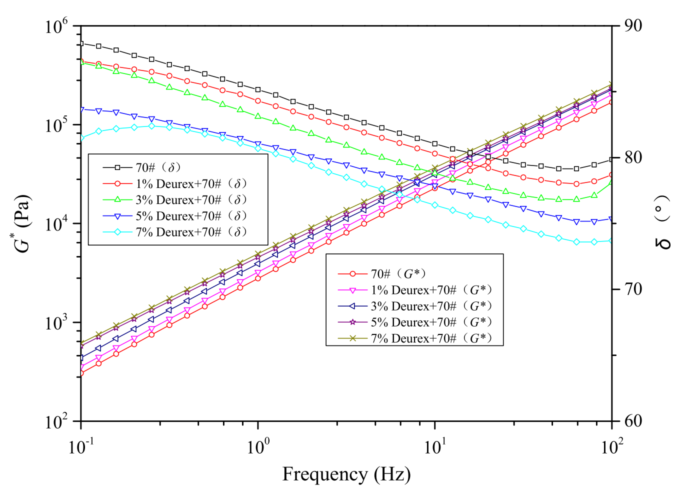

Fig. 9. Frequency sweep test

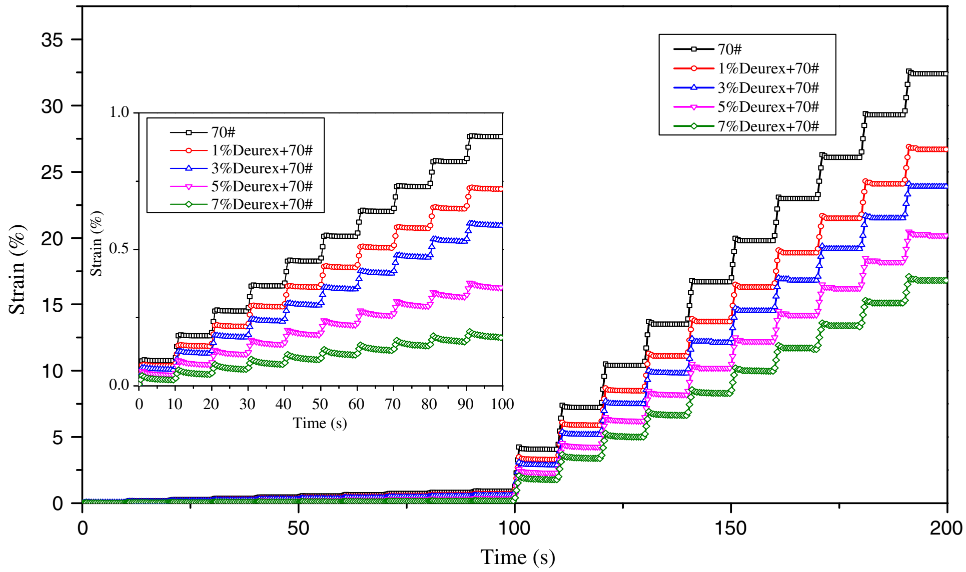

Fig. 10. MSCR test at 58°C

Multiple Stress Creep Recovery Test

The multiple stress creep recovery (MSCR) test is designed to identify the elastic response in asphalt binders and the change in response at different stress levels (0.1 and 3.2 kPa) while being subjected to 10 cycles of creep stress (1.0-s duration per cycle) and recovery (9.0-s duration per cycle). The MSCR test was performed on the RTFO-aged binder using the DSR at temperatures of 52, 58, 64, and 70°C according to ASTM D7405 (ASTM 2010). Nonrecoverable creep compliance and average percentage recovery (designated $R100$ and $R3200$) were the desired parameters obtained from the MSCR test to evaluate the elasticity of Deurex-modified binders. Nonrecoverable creep compliance ($J_{nr3.2}$) is an important indicator of permanent deformation resistance of an asphalt pavement under repeated traffic loads (Soenen et al. 2013; Zoorob et al. 2012). The $R100$ and $R3200$ were applied to measure the ability of a sample to return to its previous sharp under repeated stretch and relaxation.

The creep recovery cycle curves of the base and Deurex-modified asphalt binders at 58°C obtained from the MSCR test are shown in Fig. 10. It can be seen that the binders with Deurex have lower accumulated strain, meaning that the Deurex enhanced the elastic response of the binder at high temperature. It can also be seen that the accumulated strain of the binders significantly decrease with increasing Deurex. This suggests that Deurex-modified binders would be less subject to permanent deformation at high temperature and less liable to rutting compared with neat asphalt.

Fig. 11 shows the $R100$ and $R3200$ of the Deurex-modified binders at temperatures ranging 64–70°C. It indicates similar trends for all binders with temperature increases. In addition, $R100$ and $R3200$ increased with the addition of Deurex at all test temperatures, indicating the ability of Deurex to enhance recovery. Moreover, compared with the $R100$ value for each binder, the $R3200$ value was lower in all cases, which might be attributed to a slight nonlinear elasticity and a weaker capacity for recovery. Finally, the $R3200$ values for the 0–3% Deurex-modified asphalt reached zero at the test temperature of 70°C, implying a viscous characteristic of this binder.

In Fig. 12, nonrecoverable creep compliance ($J_{nr3.2}$) is shown for all contents of Deurex at four test temperatures. All binders exhibited similar increased $J_{nr3.2}$ with rising test temperatures, but showed decreased $J_{nr3.2}$ with increasing Deurex content for each test temperature. Such results suggest that Deurex can significantly reduce the permanent deformation of pavement under repeated traffic loads.

Thermal Stability and Thermal Analysis

The difference in solubility and density between Deurex and binder causes phase separation in the asphalt binder during thermal storage (Galooyak et al. 2011). Given the nature of sugar cane wax and the long-chain aliphatic hydrocarbon components of Deurex (Gandhi 2008), it was necessary to investigate the effects on asphalt binders of wax crystallization and melting. Separation and DSC tests, two effective tools to investigate the thermal properties and behavior of modified asphalt binders, were chosen for this study (Ge et al. 2016; Yu et al. 2016; Zhang et al. 2015).

The storage stability, or separation, test was performed on all contents of Deurex in the modified binders according to ASTM D7173 (ASTM 2014). A sample was preheated in an oven at 163 ± 5°C and stirred thoroughly in a mixer. It was then poured into vertical tubes for 50 ± 0.5 g and the tubes were sealed and kept in an oven at 163 ± 5°C for 48 ± 1 h. Finally, the tubes were placed in a freezer at −10 ± 10°C. After cooling fully, the tubes were cut into three equal portions and the softening points of the upper and bottom parts were measured according to ASTM D36 (ASTM 2012).

The results for the Deurex-modified binders are provided in Table 3, which indicates that the softening points of the top and bottom parts of the test specimens were less than 2.2°C even at the maximum mixing proportion of 7% Deurex. It can be concluded that Deurex-modified asphalt has excellent thermal storage stability and miscibility.

In the overall consideration of viscosity reduction, high- and low-temperature performance, fatigue factor, and economic benefit, 3% appears to be the optimum Deurex content. Therefore, the 3% Deurex-modified asphalt and the base asphalt were chosen for the DSC test to compare thermal behavior. In the test, 7–10-mg samples were poured into aluminum pans, which were placed in the differential scanning calorimeter (DSC) at normal temperature (22.5°C) and purged with dry nitrogen gas for 15 min. The temperature was then ramped up to 800°C at a constant rate of 10°C/min. The experimental data resulting from this heating processing were collected and analyzed by a software.

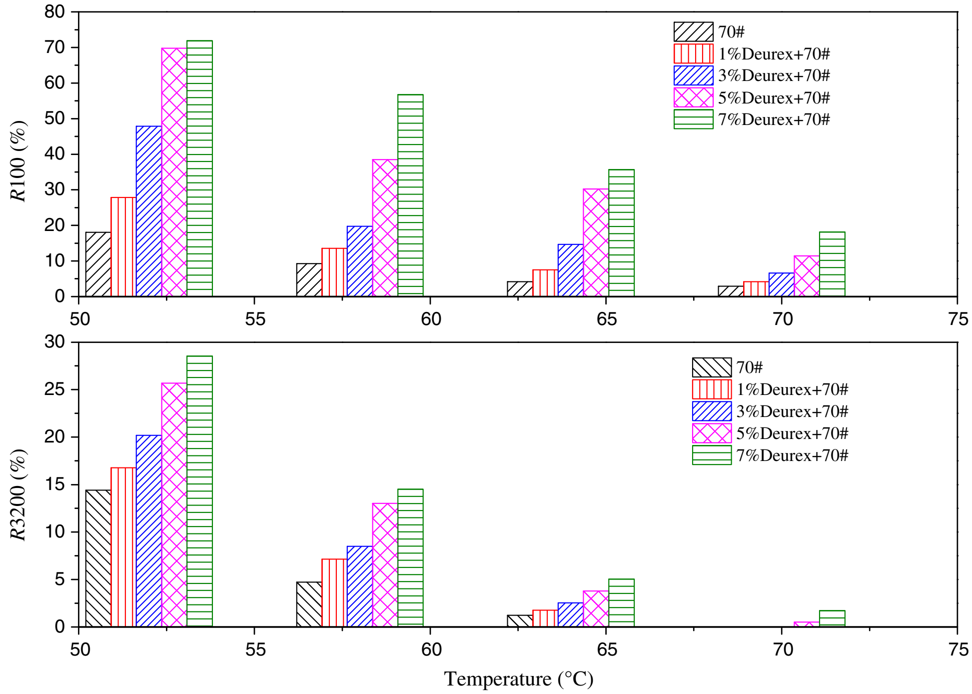

Fig. 11. Variations in $R100$ and $R3200$ with changes in additive content at four test temperatures

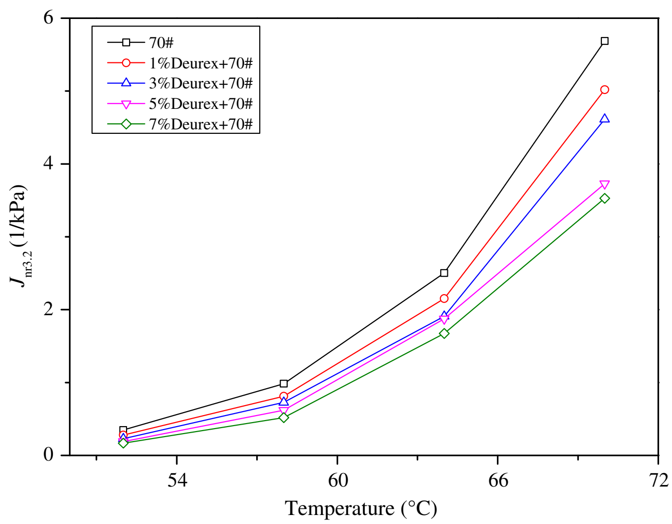

Fig. 12. Variations in nonrecoverable creep compliance ($J_{nr3.2}$) with changes in additive content at four test temperatures

Table 3. Storage Stability of Deurex-Modified Binders

Sample	SP top (°C)	SP bottom (°C)	ΔSP (°C)
Base binder	49.6	48.6	1.0
1% Deurex + 70#	57.4	58.2	−0.9
3% Deurex + 70#	61.1	61.6	−0.6
5% Deurex + 70#	65.4	65.9	−0.5
7% Deurex + 70#	72.1	73.1	−1.0

Note: SP = softening points; ΔSP = difference between the softening points of the upper and bottom parts.

Fig. 13 shows the Tg-DSC heating cycle (NETZSCH Group, Selb, Germany) from room temperature to 800°C for binders with and without Deurex [thermogravimetric analyzer (Tg) and differential scanning calorimetry (DSC) form a set of measure system].

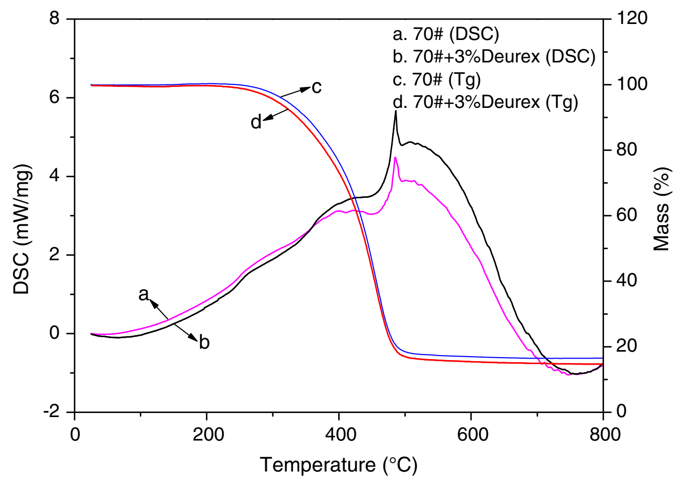

Fig. 13. Tg-DSC curves for binders with and without Deurex

As can be seen, the Tg-DSC curves show similar fluctuation for binders with and without Deurex. The heat flow and mass loss of the Deurex-modified asphalt show no obvious change compared with the base asphalt as the temperature increases, suggesting that Deurex does not influence asphalt binder thermal properties. In addition, Fig. 13 indicates only one rapid mass loss stage in the temperature range of 260–485°C, which was related to binder decomposition. Moreover, the DSC curves of two samples show a sharp and strong endothermic peak at 485°C, which could be attributed to the combustion of the binders.

FTIR Analysis

Fourier transform infrared analysis is a powerful method for identifying functional groups in liquid and solid substances. Infrared

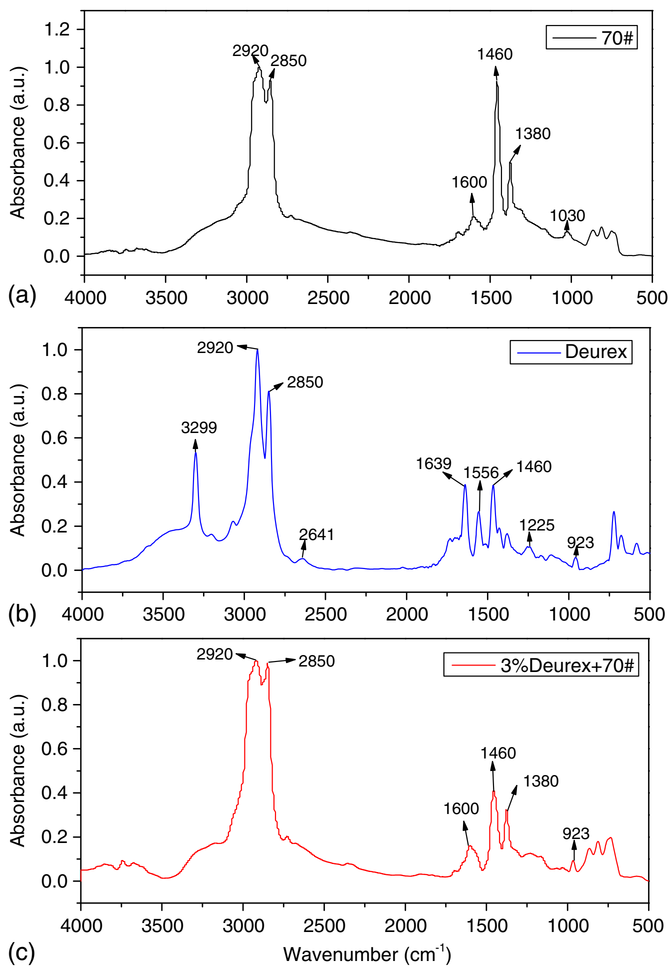

Fig. 14. FTIR analysis: (a) base asphalt; (b) Deurex; (c) 3% Deurex-modified asphalt

spectroscopy determines the covalent bonds in molecules or the vibration of lattice crystals by analyzing the infrared light absorbed by them. Because absorption by different kinds of bonds depends on the intensity and frequency of the light absorbed, the unique chemical characteristics can be identified (Gandhi 2008; Xiao et al. 2012).

The FTIR scans of the base asphalt, Deurex, and the Deurex-modified asphalt (3% Deurex) are shown in Figs. 14(a–c). The broad peaks between 2,800 and 3,200 cm^{-1} represent the aliphatic C-H stretching of alkane with strong intensity (Hossain et al. 2013). Such broad peaks also occurred in the Deurex scans, as shown in Fig. 14(b), resulting from the major elements of Deurex—carbon, hydrogen, and oxygen (as shown in its CAS code)—which are the same as those of the base asphalt. The FTIR absorbances (peak heights) at 1,639, 1,556, and 1,460 cm^{-1} are indicators of saturated fatty acid C═O stretch, aromatic ring C═C, and bending of CH_2 and CH_3, respectively. A weak peak at 923 cm^{-1} is an indicator of C─O─C.

In Figs. 14(a and c), peaks at 1,600, 1,460, and 1,380 cm^{-1} stand for aromatics, CH_3, and CH_2, respectively. The broad peaks between 2,800 and 3,200 cm^{-1} in Fig. 14(c) are the same as in Figs. 14(b and c), representing alkane. However, compared with that in Fig. 14(a), the peak at 923 cm^{-1} in Fig. 14(b) also exists in the spectrum of asphalt after the addition of Deurex. Nevertheless, compared with those in Figs. 14(a and b), in Fig. 14(c) the absorbance peak at 1,030 cm^{-1}, representing S═O (sulfoxide), and that at 1,556 cm^{-1}, representing aromatic ring C═C, disappear. This indicates that the chemical reaction might happen during the mixing of Deurex and asphalt.

Conclusions

Based on conventional, Superpave, and microcosmic tests on Deurex-modified asphalt binders, the major findings from this study are as follows:

- The addition of Deurex resulted in an increase in softening point and penetration; however, ductility decreased when Deurex was increased; it can be concluded that Deurex enhances high-temperature binder performance but degrades low-temperature performance; further, because Deurex reduced the viscosity of the tested asphalt binders at different percentages, it is concluded that it can be used as a new kind of warm-mix additive;
- The values of $G/^* \sin\delta$ and $G^* \sin\delta$ rose with increasing Deurex content; suggesting that Deurex improves the rutting resistance of asphalt binders but slightly reduces their fatigue performance at intermediate temperatures; low-temperature cracking resistance was slightly impaired after adding Deurex in terms of lower m values; however, the low-temperature grade of Deurex-modified asphalt binders was the same as that of the base asphalt binder, indicating that the addition of Deurex just slightly reduced the modified binders' low-temperature performance;
- The frequency sweep test showed that, when Deurex was increased, the G^* value increased but phase angles decreased at all frequencies, indicating enhanced rutting resistance of the Deurex-modified binders under loads at different traffic speeds;
- The addition of Deurex resulted in an increase in average percentage recovery ($R100$ and $R3200$) and a consistent reduction in strain and $J_{nr3.2}$ at all test temperatures; this suggests that Deurex can significantly improve permanent deformation resistance under repeated traffic loads;
- In the overall consideration of viscosity reduction, high- and low-temperature performance, fatigue factor, and economic benefit, 3% appears to be the optimum Deurex mixing content;
- The similar trend of two Tg-DSC curves shows that Deurex has little effect on the thermal properties of asphalt; and
- The FTIR analysis showed that chemical reactions might occur during the mixing of Deurex and base asphalt according to the disappearance of peaks at 1,030 and 1,556 cm^{-1}.

This study investigated only the physical and rheological properties and the microstructures of Deurex-modified asphalt binders. Additional mixture research supplemented with field validation is strongly recommended in future work.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (Nos. 51278188 and 50808077), the Project of Young Core Instructor Growth from Hunan Province, and the Project for Young Teacher Growth of Hunan University. The authors are sincerely grateful for this financial support.

References

AASHTO. (2008a). "Standard method of test for determining the flexural creep stiffness of asphalt binder using the bending beam rheometer (BBR)." *AASHTO T313-08*, Washington, DC.

AASHTO. (2008b). "Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)." *AASHTO T315-08*, Washington, DC.

AASHTO. (2013). “Standard method of test for viscosity determination of asphalt binder using rotational viscometer.” *AASHTO T316*, Washington, DC.

AASHTO. (2015). “Performance-graded asphalt binder.” *AASHTO M320*, Washington, DC.

Ahmed, E. I., Hesp, S. A. M., Samy, S. K. P., Rubab, S. D., and Warburton, G. (2012). “Effect of warm mix additive’s and dispersants on asphalt rheological, aging, and failure properties.” *Constr. Build. Mater.*, 37, 493–498.

Ali, A., Abbas, A., Nazzal, M., Alhasan, A., Roy, A., and Powers, D. (2014). “Workability evaluation of foamed warm-mix asphalt.” *J. Mater. Civ. Eng.*, 10.1061/(ASCE)MT.1943-5533.0000904, 04014011.

Almeida-Costa, A., and Benta, A. (2016). “Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt.” *J. Cleaner Prod.*, 112, 2308–2317.

Arega, Z., Bhasin, A., Motamed, A., and Turner, F. (2011). “Influence of warm-mix additives and reduced aging on the rheology of asphalt binders with different natural wax contents.” *J. Mater. Civ. Eng.*, 10.1061 (ASCE)MT.1943-5533.0000315, 1453–1459.

ASTM. (2007). “Standard test method for ductility of bituminous materials.” *ASTM D113*, West Conshohocken, PA.

ASTM. (2010). “Standard test method for multiple stress creep and recovery (MSCR) of asphalt binder using a dynamic shear rheometer.” *ASTM D7405*, West Conshohocken, PA.

ASTM. (2012). “Standard test method for softening point of bitumen (ring-and-ball apparatus).” *ASTM D36*, West Conshohocken, PA.

ASTM. (2013). “Standard test method for penetration of bituminous materials.” *ASTM D5*, West Conshohocken, PA.

ASTM. (2014). “Standard practice for determining the separation tendency of polymer from polymer modified asphalt.” *ASTM D7173*, West Conshohocken, PA.

Banerjee, A., Smit, A. D., and Prozzi, J. A. (2012). “The effect of long-term aging on the rheology of warm mix asphalt binders.” *Fuel*, 97, 603–611.

Deurex. (2015). “Directive 1999/45/EC.” ⟨www.deurex.com/waxes/⟩ (Jun. 15, 2015).

Galooyak, S. S., Dabir, B., Nazarbeygi, A. E., Moeini, A., and Berahman, B. (2011). “The effect of nanoclay on rheological properties and storage stability of SBS-modified bitumen.” *Pet. Sci. Technol.*, 29(8), 850–859.

Gandhi, T. (2008). “Effects of warm asphalt additives on asphalt binder and mixture properties.” Ph.D. dissertation, Clemson Univ., Clemson, SC.

Ge, D. D., Yan, K. Z., You, Z. P., and Xu, H. B. (2016). “Modification mechanism of asphalt binder with waste tire rubber and recycled polyethylene.” *Constr. Build. Mater.*, 126, 66–76.

Hossain, M. Z. (2011). “Evaluation of rheological properties of asphalt binders for pavement design applications.” Ph.D. dissertation, Univ. of Oklahoma, Norman, OK.

Hossain, Z., Lewis, S., Zaman, M., Buddhala, A., and O’Rear, E. (2013). “Evaluation for warm-mix additive-modified asphalt binders using spectroscopy techniques.” *J. Mater. Civ. Eng.*, 10.1061/(ASCE)MT .1943-5533.0000562, 149–159.

Hurley, G. C., and Prowell, B. D. (2005). “Evaluation of Sasobit for use in warm-mix asphalt.” *Rep. No. 05-06*, National Center for Asphalt Technology, Auburn, AL.

Omari, I., Aggarwal, V., and Hesp, S. (2016). “Investigation of two warm mix asphalt additives.” *Int. J. Pavement Res. Technol.*, 9(2), 83–88.

Punith, V. S., Xiao, F. P., and Amirkhanian, S. N. (2011). “Effects of moist aggregates on the performance of warm mix asphalt mixtures containing non-foaming additives.” *J. Test. Eval.*, 39(5), 847–857.

Rheoplus [Computer software]. Anton Paar, Graz, Austria.

Samy, S. K. P. (2013). “Effects of warm mix additives and disperants on rheological, aging and failure properties of asphalt cements.” M.S. dissertation, Queen’s Univ., Kingston, ON.

Sangsefidi, E., Mansourkhaki, A., and Ziari, H. (2016). “Effect of aggregate gradation on permanent deformation behavior of a warm mix asphalt.” *Mater. Test.*, 58(7–8), 678–688.

Soenen, H., Blomberg, T., Pellinen, T., and Laukkanen, O. V. (2013). “The multiple stress creep-recovery test: A detailed analysis of repeatability and reproducibility.” *Road Mater. Pavement Des.*, 14, 2–11.

Tan, Y. Q., Guo, M., Xu, H. N., and Zhang, R. (2012). “Comparative study on laboratory performance of hot- and warm-mix asphalt mixtures.” *J. Test. Eval.*, 40(5), 715–723.

Xiao, F. P., Punith, V. S., and Amirkhanian, S. N. (2012). “Effects of non-foaming WMA additives on asphalt binders at high performance temperatures.” *Fuel*, 94(1), 144–155.

Xiao, F. P., Punith, V. S., Putman, B., and Amirkhanian, S. N. (2011). “Utilization of foaming technology in warm-mix-asphalt mixtures containing moist aggregates.” *J. Mater. Civ. Eng.*, 10.1061/(ASCE)MT .1943-5533.0000297, 1328–1337.

Yu, H. Y., Leng, Z., and Gao, Z. M. (2016). “Thermal analysis on the component interaction of asphalt binders modified with crumb rubber and warm mix additives.” *Constr. Build. Mater.*, 125, 168–174.

Zhang, H. L., Zhu, C. Z., Yu, J. Y., Shi, C. J., and Zhang, D. M. (2015). “Influence of surface modification on physical and ultraviolet aging resistance of bitumen containing inorganic nanoparticles.” *Constr. Build. Mater.*, 98, 735–740.

Zoorob, S. E., Castro-Gomes, J. P., Oliveira, L. A. P., and O’Connell, J. (2012). “Investigating the multiple stress creep recovery bitumen characterisation test.” *Constr. Build. Mater.*, 30, 734–745.