Moisture susceptibility of Warm-Mix-Asphalt in a changing climate: incorporating top-down cracking and fracture mechanics approach

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Paper prepared for presentation
at the CLIMATE CHANGE CONSIDERATIONS FOR GEOTECHNICAL AND PAVEMENT MATERIALS ENGINEERING Session

of the 2015 Conference of the
Transportation Association of Canada
Charlottetown, PEI

Abstract:

Over the next decade, climate changes may cause an increase in precipitation in some areas of Canada, including Ontario. In such areas, moisture damage can be one of the major causes of premature degradation of asphalt pavements. Failure of asphalt pavements due to moisture damage causes a considerable expenditure of funds for repair and rehabilitation every year. Traditionally moisture damage of the asphalt mixtures is evaluated by tensile strength ratio between dry and wet condition, which is not sufficient to conclude the moisture damage performance. Also, the results from the majority of conventional tests do not correlate well with the observed field performance. In order to overcome these difficulties, the varying effects of moisture damaged on wax modified asphalt mixture properties were investigated by using Superpave IDT creep, resilient modulus and strength tests. Moreover, fracture mechanics approach has also been utilized to characterize the moisture susceptibility of the asphalt mixture performance.

In recent years, with the increasing concerns of global warming and increasing emissions, the asphalt industry has been using commercial waxes in asphalt mixtures to lower its emissions by reducing the mixing and compaction temperatures. Thus, in this study, PG 58-22 asphalt binder was modified by two types of commercial waxes (FT-paraffin and Asphaltan B) and mixed with two types of crushed granite aggregates, which were used to investigate the moisture damage potential of the wax modified asphalt mixtures.

This paper provides a summary of the evaluation test set up and obtained results. It was found that the warm mix asphalt mixtures have a higher moisture damage ratio (MDR) of Energy Ratio compared to unmodified mixtures, clearly indicating the higher fracture resistance than the control mixtures. Moreover, the results obtained from moisture damage ratio in terms of the number of load repetition required to grow a fixed crack (MDR_N); also confirms the wax modified mixtures have a better crack initiation and growth resistance even after conditioning. The analyses of the obtained results, thus, indicate that warm mix asphalt could be a greener solution to the climate change and towards a durable pavement infrastructure.

Keywords: Warm-mix asphalt, Moisture damage; Fracture mechanics; Superpave IDT

1. Introduction

In recent years, with increasing concerns of global warming and emissions, the warm-mix asphalt technology (WMA) utilizing commercial waxes has become a growing alternative to conventional hot-mix asphalt (HMA). This wax modification helps to reduce the mixing and compaction temperature of the asphalt mixture, which reduces fuel costs and emissions (D'Angelo et al., 2008). Furthermore, wax modification shows other advantages in construction and maintenance phase, such as longer paving seasons, longer hauling distances, reduced wear and tear of the plants and ability to open the site to traffic sooner. Commercial waxes are normally used as a flow improver (Hurley and Prowell, 2006) and most commonly used waxes are Fischer Tropsch-paraffin (FT-paraffin), Asphaltan B, aspha-min etc. Asphalt binder itself is a very complicated and temperature dependent material, while wax in it shows even more complex behavior. This wax modification not only helps environmentally by reducing temperature, but may also affect the distresses of the pavement caused by traffic loading and environmental effects, such as: fatigue cracking, rutting, low temperature performance, moisture damage etc.

Over the next decade, climate changes may cause an increase in precipitation in some areas of Canada, including Ontario. In such areas, moisture damage can be one of the major causes of premature degradation of the asphalt pavements. The moisture infiltration into the asphalt weakens of the cohesive bond in the asphalt mastic particles (the combination of asphalt binder and filler is known as asphalt mastic), furthermore, weakens the aggregate-asphalt mastic adhesive bond. Due to the pumping effect, which is a continuous action of the moisture and traffic loading, the aggregates in the wearing asphalt course start losing the asphalt film coating and consequently, remove from the surface prematurely. These two damage phenomena are known as stripping and raveling, respectively. Once stripping and raveling start, they rapidly progress into a more severe degradation of the wearing surface and leads to the appearances of 'potholes' (Emery and Seddik, 1997). The time between stripping and forming potholes is rather quick, sometimes potholes may appear overnight. The potholes cause safety and uncomfortable driving issues, thus needed to be repaired quickly and therefore, increases the maintenance costs of the road authorities, which is ultimately the taxpayer's money.

In the past, a number of test procedures had been developed to evaluate the moisture damage potential of asphalt mixtures. The most commonly used procedures include Tensile Strength Ratio, Duriez test, SSAT test and others (Solaimanian et al., 2003). All of these moisture susceptibility tests evaluate the effects of water damage in the laboratory by measuring the relative change of a single parameter before and after conditioning (such as: tensile strength ratio, resilient modulus ratio, complex modulus ratio and so on.). These tests are normally simple and easy to perform but they do not provide enough explanations for the causes of moisture damage and also the results from the majority of these tests do not correlate well with the field performance. In order to overcome these difficulties, during the last decades, new analytical approaches by considering multiple parameters were developed to characterize moisture damage (Birgisson et al., 2003; Masad et al., 2006). These new methodologies are based on thermodynamics, fracture mechanics, continuum damage mechanics, surface energy and/or micro-mechanics approaches (Caro et al., 2008). Since the environmental benefits of using WMA are well accepted, the long term performance, particularly the moisture susceptibility of the WMA has been investigated in this study by incorporating top-down cracking and fracture mechanics approach.

2. Hot-mix asphalt fracture mechanics to evaluate moisture damage

"HMA Fracture Mechanics" developed by Zhang et al. (2001) can be able to describe the fracture properties of HMA mixtures. It is a fundamental framework that can predict the micro- and macro-damage in mixtures resulting by changes in the viscoelastic properties of mixtures, as well as strength and stiffness. In this framework, the development of macro-cracks at any time during either crack initiation or propagation described by lower and upper thresholds: Dissipated Creep Strain Energy ($DCSE_f$) limit and Fracture Energy (FE), respectively. DCSE limit is associated with continuous repeated loading and FE corresponds to that threshold required to fracture the mixture with a single load application (Birgisson et al., 2006). Once the energy threshold is exceeded, non-healable macro-cracks develop and propagate along the mixture.

The rate of damage growth blow the energy threshold is governed by the creep properties of the mixture. The creep compliance of the mixture can be fitted by the following power function:

$$D(t) = D_0 + D_1 t^m \qquad (1)$$

The power law parameters D_0, D_1 and m can be obtained from creep tests. Based on the concepts and HMA fracture model, dissipated creep strain energy (DCSE limit) and the creep strain rate (m-value and D_1) are the key parameters to control the cracking performance of asphalt mixtures.

A typical stress-strain response is shown in Figure 1. As can be seen, the dissipated creep strength energy ($DCSE_f$) can be determined by deducting from fracture energy (FE) to elastic energy (EE). Fracture energy is the area under the stress-strain curve to the failure strain.

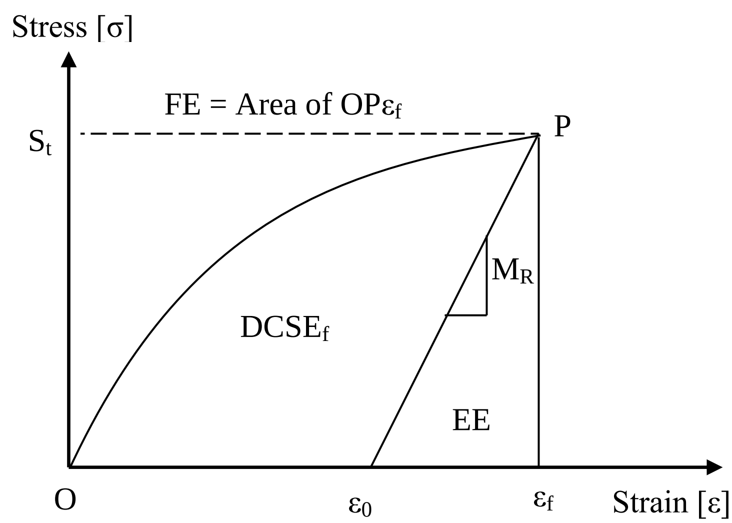

Figure 1. Graphical illustration of lower and upper threshold (Das et al., 2012a)

The fracture performance of the mixtures cannot be defined by using only one parameter such as tensile strength, resilient modulus or m-value. For this reason, to evaluate the fracture performance correctly, researchers (Roque et al., 2004) introduced a dimensionless parameter called Energy Ratio (*ER*) into the HMA fracture mechanics model. This parameter can be used as a measure of the fracture resistance of mixtures and expressed by the following equation:

$$ER = \frac{DCSE_f}{DCSE_{\min}} = \frac{a \times DCSE_f}{m^{2.98} D_1} \tag{2}$$

$$a = 0.0299\sigma^{-3.1}(6.36 - S_t) + 2.46 \times 10^8 \tag{3}$$

where $DCSE_f$ is the dissipated creep strain energy limit (KJ/m^3) and $DCSE_{min}$ is minimum dissipated creep strain energy (KJ/m^3) for adequate fracture performance. $DCSE_{min}$ is a function of the creep compliance power law parameters (m and D_1). For a known maximum tensile stress in the asphalt layer, $DCSE_{min}$ can be calculated by the tensile stress (σ) of the asphalt layer (psi) and the tensile strength (S_t) of the material (MPa). For a good field performance of the mixture $ER>1$ is required. Generally, higher *ER* indicates better fracture resistance of the mixture.

Birgisson et al. (2003) used the concept of *ER* into moisture damage ratio (*MDR*) to evaluate the moisture damage in asphalt mixtures. The multiple-parameter *MDR* is an analytically-based function to quantify damage by combining more than one material property, also considering both dry and wet conditions. This parameter can be used to evaluate the loss of resistance to fracture in asphalt mixtures due to moisture damage. The multiple-parameter presented by the authors can be expressed as:

$$MDR_{ER} = \frac{ER_w}{ER_d} = \frac{f(\sigma, S_t, D_t, m, DCSE_f)_w}{f(\sigma, S_t, D_t, m, DCSE_f)_d} \tag{4}$$

Birgisson et al. (2003) utilized the fatigue model for asphalt mixtures proposed by Zhang et al. (2001) to integrate the varying effects of moisture damage on key mixture properties into a single number (ratio of the number of cycles to failure after and before conditioning) that reflects the change in the cracking performance of the mixture due to water conditioning. The number of cycles (N) is a performance function required to generate a crack of 1in. (25.4 mm) under cyclic loading conditions using the Superpave IDT. According to threshold concept, crack growth occurs when the accumulated dissipated creep strain energy equals to the threshold *DCSE*. In order to calculate the number of cycles to grow 25.4 mm long crack, it is necessary to calculate the dissipated creep strain energy per cycle (*DCSE/cycle*). The following equation can be used to calculate the *DCSE/cycle*:

$$DCSE/_{cycle} = \frac{1}{20}\sigma_{avg}{}^2 D_1 m\,(100)^{m-1} \tag{5}$$

where σ_{avg} is a field parameter representing average stress in the zone of interest, and m and D_1 are the same parameters as described in Eq. 1. Since *DCSE/cycle* is known, the number of cycles to reach the *DCSE* limit can be determined. This multiple-parameter *MDR* can also be used to represent the moisture damage and can be expressed as:

$$MDR_N = \frac{N_{conditioned}}{N_{unconditioned}} = \frac{f(\sigma_{avg}, D_{1_w}, m_w, DCSE_{f_w})}{f(\sigma_{avg}, D_{1_d}, m_d, DCSE_{f_d})} \tag{6}$$

3. Materials and methods

3.1. Asphalt binder and wax additives

In this study, PG 58-22 asphalt binder was used as control binder and denoted as O. The binder was modified by using two types of commercial waxes, FT-paraffin obtained from Sasol Wax GmbH and Asphaltan B obtained from Romonta GmbH. The FT-paraffin and Asphaltan B waxes are denoted as wax S and wax MW, respectively. The binder-wax mixture was prepared in the laboratory with 4% addition of wax by weight of binder. The sample was then heated up to 155ºC. The samples were then placed in preheated shaker blocks and homogenized by shaking for 90 seconds.

3.2. Aggregate and asphalt mixtures

Dense graded asphalt concrete mixtures with the maximum aggregate size of 16 mm were prepared. The measured particle size distributions of the aggregates used are shown in Figure 2. The binder contents were 6.2% for AG1 and 6.4% for AG2 by weight. The mixtures were compacted in a Superpave gyratory compactor to target air void content of 7±1% by volume.

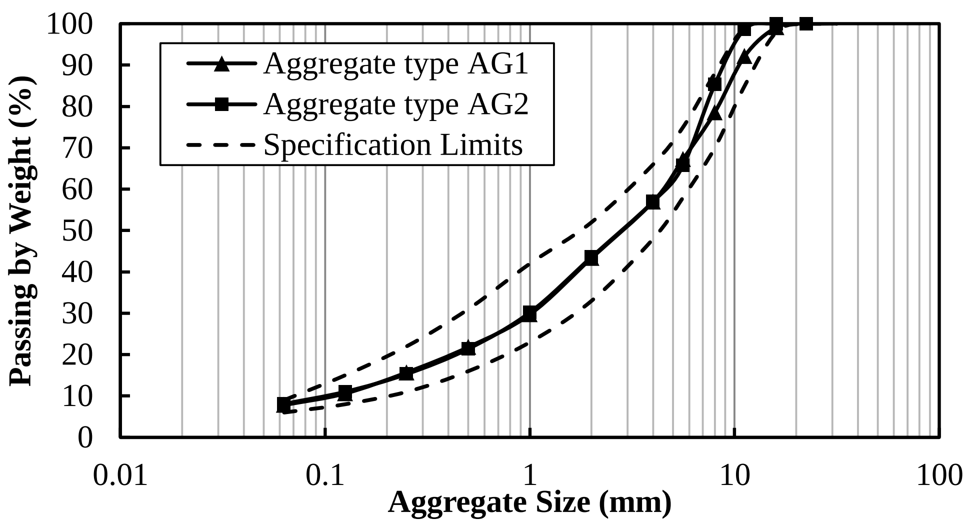

Figure 2. Aggregate gradation in asphalt mixtures

The temperature for mixing control mixture was 155ºC and the compaction temperature was 135ºC. While, the wax S and wax MW modified asphalt mixtures were mixed and compacted 10ºC and 15ºC reduced temperatures than the control one, respectively. The compacted specimens were extruded from molds and allowed to cool at room temperature for 24 hours. For each mixture, six specimens (three conditioned and three unconditioned for Superpave IDT test) were prepared and air voids were measured, among those three specimens were then subjected to saturation according to the AASHTO T-283 procedure. Once the target saturation level was achieved, the specimens were placed in a 60ºC water bath for 24 hours. After completing the moisture conditioning, the conditioned mixtures were allowed to drain for 48 hours at room temperature. Then, the conditioned and unconditioned specimens were cut with a wet saw into 50 mm thick specimens with a diameter of 150 mm. Finally, the conditioned-cut specimens were placed in an environmental chamber at 25ºC and allowed to equilibrate to constant humidity for 2 days before testing in the Superpave IDT test.

3.3. Superpave IDT test

The Superpave IDT tests were conducted according to the AASHTO TP9 specification to measure the resilient modulus, the static creep and the tensile strength. The experiments were carried out at 0ºC, which is fairly critical temperature under cold climate conditions. In these tests, cylindrical specimens with 150 mm in diameter and 50 mm in thickness were used. The experimental setup of the Superpave IDT test is shown in Figure 3.

Figure 3. The experimental setup of the Superpave IDT test

Two strain gauges (with a length of 38.1 mm) were placed at the center of the specimen to measure vertical and horizontal deformations during loading. To take into account the 3D effects, correction factors are needed to correct the measured horizontal and vertical deformation to fit the deformation in a flat plane. The average strain is the value obtained from correction factors divided by the gauge length. Finally, center correction factors are used to correct the strain values at the center of the specimen. The detail information about the test procedures can be found at Birgisson et al. (2006).

Resilient modulus test: The resilient modulus and Poisson's ratio were determined from the resilient modulus test. The ratio of the applied stress to the recoverable strain under applied repeated loads is known as resilient modulus. The resilient modulus test was conducted in the load control mode by applying a repeated haversine waveform load to the specimen for a 0.1 second, followed by 0.9 seconds rest period, resulting in horizontal strain within the range of 200 to 300 micro-strains.

Static creep test: As creep compliance is a function of time-dependent strain over stress, the time-dependent behavior of asphalt mixture can be represented by the creep compliance curve. Moreover, it can be used to evaluate the rate of damage accumulation in asphalt mixtures. The creep compliance test was conducted by applying a constant load for 1000 seconds, resulting in horizontal strain within the range of 200 to750 micro-strains. If the horizontal deformation was more than 180 micro-inches at 100 seconds, the load was immediately removed from the specimen and before reloading at a lower load level specimen was allowed to recover for a minimum of five minutes. Three mixture parameters (D_0, D_1 and *m*-value) can be obtained from creep compliance tests. D_0 describes the instantaneous elastic response; D_1 provides ideas about the initial portion of the creep compliance curve, while *m*-value expresses the longer-term portion of the same curve. An asphalt mixture with a low m-value exhibits a low rate of damage accumulation (Kim et al., 2003).

Indirect tensile strength test: The IDT strength test was conducted to determine the strength and failure strain of the sample in a displacement control mode by applying a constant rate of 50.8 mm/min until the specimens were failed. With the stress-strain response, the dissipated creep strength energy ($DCSE_f$) was determined by deducting from fracture energy (*FE*) to elastic energy (*EE*). Fracture energy is the area under the stress-strain curve to the failure strain (as shown in Figure 1). Strength tests were conducted in a displacement control mode and used to determine fracture parameters such as: tensile strength, failure strain, fracture energy and dissipated creep strain energy.

4. Results and discussions

4.1. Binder Mixtures

Conventional tests were performed to determine the modified and unmodified asphalt binder characteristics. These included softening point, penetration and force ductility tests. The effects of adding FT-paraffin (wax S) and Asphaltan B (wax MW) are reported in Table 1. The addition of both waxes increased softening point and decreased penetration, which indicates the stiffening effect. Wax S showed the largest stiffening effects. Dynamic viscosity at 135ºC and 165ºC was reduced by the addition of wax S and wax MW. This reduced viscosity due to wax S and wax MW modification resulted in decreasing mixing and compaction temperature by 10ºC and 15ºC compared to the control one, respectively. This would lead to the green solution by lowering emission and energy consumption. The force ductility test result generally represents the cohesion and homogeneity of the test sample. By analyzing the force ductility test results, it was observed that the deformation energy increased due to the addition of wax in asphalt binder, which again indicates the stiffing effect.

Superpave binder testing was performed by utilizing the results from bending beam rheometer (BBR) and dynamic shear rheometer (DSR). For controlling the low temperature cracking propensity according to Superpave binder specifications, BBR creep stiffness must not exceed 300 MPa and the m-value must be limited to at least 0.3. The limit stiffness temperature (LST) at which S=300 MPa and limit m-value temperature (LmT) at which m=0.3 were determined by analyzing BBR test results. It was observed that the limit temperatures were somewhat affected by the addition of wax. The highest limit stiffness temperature (-15°C) as well as highest m-value limit temperature (-13°C) of control samples was registered for the binder containing Wax S. Based on these results, the performance grade of control binder was found to be PG 58-22. Adding wax S and wax MW changed the grading to PG 64-22, indicating an improvement on the rutting criteria without compensating the thermal cracking performance.

Table 1. Asphalt binder test results before and after modification

Characteristics	**Units**	**Reference binder**	**Reference + 4% wax S**	**Reference + 4% wax MW**
Softening Point	^{o}C	46	89	85
Penetration	dmm	81	45	52
Brookfield visc. at $135^{0}C$	mPas	345	270	263
Brookfield visc. at $165^{0}C$	mPas	101	80	82
Force Ductility	Nm	1.38	4.03	3.54
LST from BBR	^{0}C	-16	-15	-16
LmT from BBR	^{0}C	-18	-13	-15
DSR, $G^*/\sin\delta$ at 64, unaged (min. 1.00)	kPa	1.12	1.07	1.51
DSR, $G^*/\sin\delta$ at 58/64 C, RTFO aged (min. 2.20)	kPa	4.74/2.07	nd/2.25	nd/3.29
DSR, $G^* \sin\delta$ at 22/25 C, PAV aged (max. 5000)	kPa	3008/nd	nd/1666	nd/2153
Binder grade		PG 58-22	PG 64-22	PG 64-22

nd: not determined

4.2. Asphalt mixtures

The effects of moisture damage on the fracture resistance of the asphalt mixtures were evaluated and a summary of the mixture fracture properties obtained from the Superpave IDT is shown in Table 2. The results obtained after conditioning is denoted by C.

It can be observed that in case of creep properties m, D_1 and creep compliance @1000 seconds, after conditioning the moisture susceptibility of wax modified mixtures is less than the mixtures with the control binder. The results clearly indicate that irrespective of the aggregate types, the cohesive properties of wax modified asphalt mixtures increased compared to the unmodified one. The Fracture energy and *DCSE* limit provide preliminary insight on how the mixture will respond under loading. As shown in Table 2, fracture energy and $DCSE_f$ decreased after conditioning for all mixtures. This indicates the fracture resistance of the asphalt mixtures reduced due to the moisture conditioning, indicating cohesive damage due to the presence of moisture. In comparison with different mixtures presented in Table 2, wax MW modified asphalt mixture showed the highest fracture resistance capacity after conditioning.

Table 2. Summary of mixtures fracture properties before and after moisture conditioning

Sample ID	Resilient Modulus, M_R (GPa)	D_1 (1/GPa)	*m*-value	Tensile Strength, S_t (MPa)	Fracture Energy (KJ/m^3)	$DCSE_f$ (KJ/m^3)	*D(1000)* (1/GPa)	Energy Ratio, *ER*
AG1-O	12.95	0.0920	0.629	2.40	2.51	2.27	7.17	0.93
AG1-O-C	8.40	0.0492	0.786	1.05	0.42	0.35	11.34	0.17
AG1-MW	13.22	0.0449	0.562	2.47	1.98	1.73	2.25	2.01
AG1-MW-C	12.11	0.0396	0.609	1.85	0.93	0.79	2.74	0.92
AG1-S	14.97	0.0332	0.598	3.01	2.33	2.02	2.13	2.44
AG1-S-C	13.66	0.0490	0.576	1.72	0.66	0.55	2.70	0.62
AG2-O	13.61	0.1316	0.616	2.57	2.72	2.47	9.34	0.74
AG2-O-C	12.60	0.1171	0.722	1.56	0.84	0.74	17.20	0.18
AG2-MW	13.35	0.0584	0.613	2.58	2.70	2.27	4.12	1.57
AG2-MW-C	12.02	0.0580	0.569	1.89	1.03	0.88	3.03	0.86
AG2-S	13.87	0.0395	0.610	2.48	1.88	1.65	2.74	1.76
AG2-S-C	13.65	0.0621	0.567	1.63	0.74	0.64	3.20	0.61

Figure 4 represents the moisture damage ratio (i.e., conditioned/unconditioned) of tensile strength obtained from Superpave IDT for all mixtures. As seen from the figure, tensile strength decreased from the unconditioned to conditioned specimen for all the mixtures, implying the presence of damage in the mixtures. The moisture damage ratio of the tensile strength of wax modified mixtures has been always higher compared to the mixtures with the control binder, as shown in Figure 4, which indicates also the benefit of using waxes in the mixtures. Mixtures with wax MW modified binder have shown the highest effect (more than 0.7 or 70%) that indicates the anti-stripping behavior.

Figure 5 represents the creep rate of all the mixtures before and after conditioning. The mixtures with unmodified binder are mostly moisture damaged as the creep rate is too high compared to other mixtures shown in Figure 5. The creep rate indicates how fast the materials loose the fracture resistance under loading. It is clearly visible from the creep rate in 1000 seconds, additional of wax dramatically increase the fracture resistance of the mixture even after conditioning.

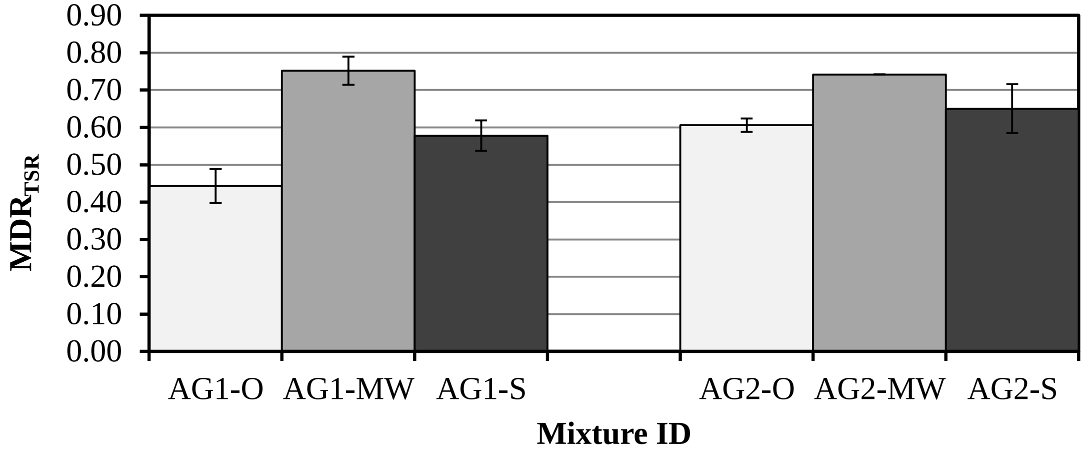

Figure 4. Moisture damage ratio of tensile strength for different mixtures

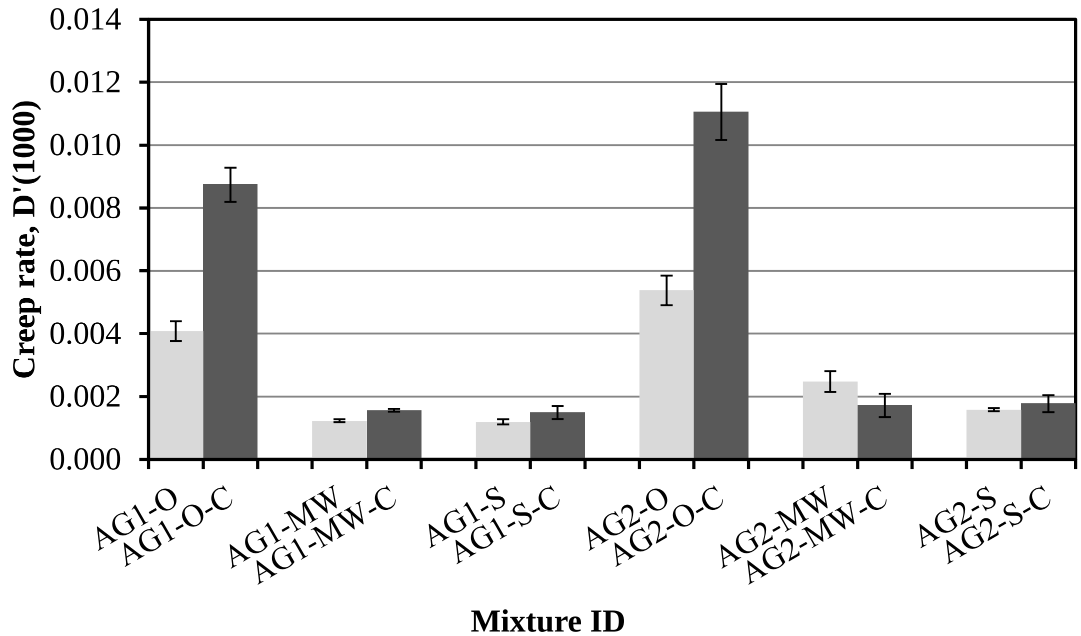

Figure 5. Creep rate of different unconditioned and conditioned mixtures

Any of these single parameters are not able to provide enough evidence to conclude about the fracture resistance of the mixtures. Hence, energy ratio (ER) has been utilized in this study, which is known to be capable of detecting changes in the fracture properties of the mixtures (Birgisson et al., 2006). The energy ratio concept is more reasonable to characterize the cracking resistance of asphalt mixtures than $DCSE_f$ because it takes into account both the energy required to fracture and the dissipated energy accumulation in the mixtures under loading condition. In Table 2, the decreasing of ER represents how the fracture resistance of the mixtures affected by the moisture damage. Figure 6 represents the MDR of energy ratio for all the mixtures. The mixtures with wax modified binder shows higher MDR_{ER} compared to unmodified mixtures, clearly indicating the higher fracture resistance than the control mixtures.

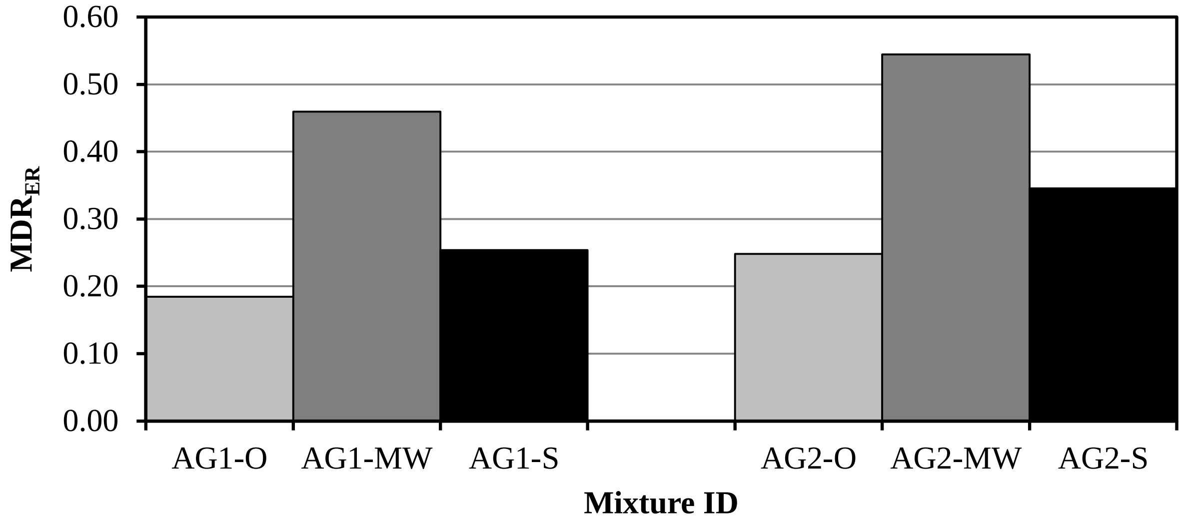

Figure 6. Moisture damage ratio of ER for different mixtures (Das et al., 2012b)

To evaluate the effects of moisture damage in mixtures using an HMA fracture mechanics framework, the ratio of the number of cycles requires for growing a 25.4mm long crack under cyclic loading conditions in the Superpave IDT test is calculated for after and before conditioning. The results are shown in Figure 7. The reduction in the number of cycles to failure due to conditioning is a measure of the reduction in the fracture resistance of the mixtures due to moisture damage. It can be seen that the wax modified asphalt mixtures show better performance to the control mixture, in terms of the number of cycles need to fail. In consistence with the above findings, irrespective of the aggregate types, wax MW shows the largest effect in the mixtures.

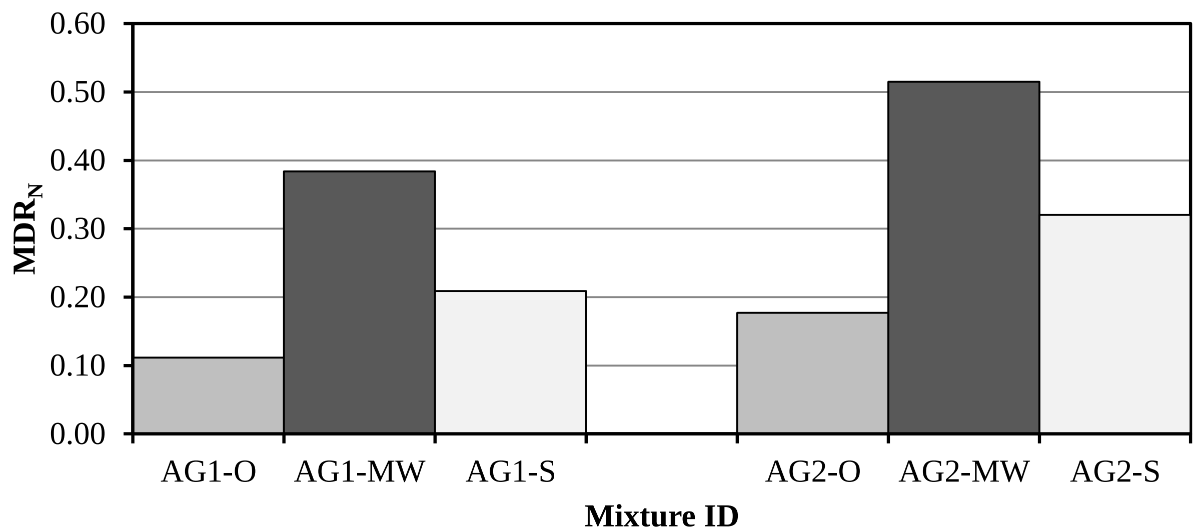

Figure 7. Moisture damage ratio of the number of cycles to failure for after and before conditioned of the mixtures

5. Conclusions

A throughout fracture resistance investigation has been conducted to investigate the moisture damage susceptibility of typical commercial wax modified asphalt mixtures. Key fracture properties were evaluated, such as creep compliance, elastic energy, dissipated creep strain energy, and fracture energy. Moreover, the HMA fracture mechanics framework with the energy ratio (ER) parameter was used to represent the fracture resistance of the mixtures studied. The analyses of the results lead to the following conclusions:

- Dynamic viscosity at 135°C and 165°C was reduced by the addition of FT-paraffin (wax S) and Asphaltan B (wax MW). The reduced viscosity results the decreasing of mixing and compaction temperature of the mixture nearly 10°C and 15°C, respectively, which leads lower emission and lower energy consumption.

- Based on DSR and BBR results, it may be concluded that both of the wax modified binders have higher rutting resistance at high temperatures than the unmodified binder without compensating the thermal cracking performance.

- The fracture energy and $DCSE_f$ decreased after conditioning for all mixtures. The decrement of fracture energy and $DCSE_f$ after conditioning is less for wax modified mixtures. The conditioned Asphaltan B wax modified mixtures showed highest fracture resistance compared with the others, indicating the required energy to fracture mixtures increases with the addition of wax.

- The moisture damage ratio of the tensile strength of wax modified mixtures has been always higher compared to the mixtures with the control binder, which also indicates the benefit of using warm mix asphalt. Asphaltan B wax modified mixtures showed the highest value (more than 70%), reflecting the anti-stripping behavior.

- A single parameter such as fracture energy, $DCSE_f$ and tensile strength is not enough to conclude about the mixture fracture resistance of the mixtures. The energy ratio concept is more reasonable to characterize the cracking resistance of asphalt mixtures than $DCSE_f$ because it takes into account both the energy required to fracture and the dissipated energy accumulation in the mixtures. The decreasing of *ER* due to the conditioning represents how the fracture resistance of the mixtures affected by the moisture damage. The warm mix asphalt showed a higher moisture damage ratio of *ER* compared to unmodified mixtures, clearly indicating the higher fracture resistance than the control mixtures.

- The reduction in the number of cycles to failure due to conditioning is a measure of the reduction in the fracture resistance of the mixtures due to moisture damage. It can be seen that the addition of wax showed better performance in terms of the number of cycle needs to failure compared to the control mixture.

The analyses of the obtained results, thus, indicate that warm mix asphalt could be a greener solution to the climate change and towards a durable pavement infrastructure.

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