# LOW TEMPERATURE CRACKING PERFORMANCE OF WAX MODIFIED BITUMEN AND MIXTURE

P.K. Das
Div. of Highway and Railway Engineering, Royal Institute of Technology (KTH), Sweden
prabir.kumar@abe.kth.se
Y. Tasdemir
Engineering and Architecture Faculty, Bozok University, Turkey
yuksel.tasdemir@bozok.edu.tr
B. Birgisson
Div. of Highway and Railway Engineering, Royal Institute of Technology (KTH), Sweden
bjornbir@kth.se

## ABSTRACT:

The road construction phase is one of the source of emissions (greenhouse gases), which causes climatic changes. To decrease this emission and energy consumption, asphalt industry is getting more aware of the warm mix asphalt (WMA) technology as it reduces the mixing and compaction temperature. There are several types of additives generally used for producing WMA such as: Fischer-Tropsch (FT) paraffin, Asphaltan B, Aspha-min, Evotherm etc. Fatigue and rutting resistance of asphalt mixtures could be increased by using WMA mixtures. On the other hand, the behavior of WMA mixtures in low temperature cracking is not completely clear yet. The main objective of this paper is to study the effect of commercial wax on low temperature cracking with the help of fracture mechanics.

In this study, bitumen was modified with 4% Asphaltan B as a WMA additive. Bitumen properties were determined by conventional test methods, dynamic mechanical analysis and bending beam rheometer test whereas the mixture properties investigated by Superpave InDirect Tensile (IDT) test device and Thermal Stress Restrained Specimen Test (TSRST). The similar results were obtained from both Superpave IDT and TSRST. According to the test results, the addition of wax shows a minor negative effect. This minor difference between modified and unmodified mixture is very small, so it could be within the test repeatability limit.

Keywords: Warm mix asphalt, Superpave IDT, Low temperature cracking.

## 1. INTRODUCTION

In recent years, environmental awareness such as global warming and emissions has been increasing rapidly. Road construction and maintenance is one of the sources of extensive air pollution. Warm Mix Asphalt (WMA) is one of the effort to keep the environment green, originated in Europe. The most common technology of producing WMA is using commercial wax (FT-paraffin, Asphaltan B, aspha-min, etc) in asphalt. This wax modification helps to reduce the high mixing and compaction temperatures of regular hot mix asphalt (HMA) [1]. The lower mixing and compaction temperature leads to reduce air-pollution caused due to emission and fumes. Also, the short-term aging of bitumen during the mixing process may be controlled considerably. Furthermore, wax modification shows other advantages in such as widen the winter paving window and facilitate

applications, such as airport runway construction, where rapid opening to traffic is essential.
Though WMA presents an opportunity for the asphalt industry to improve its construction efficiency and environmental stewardship but there are some other important concerns as well, like log-term performance of the pavement, mix design, cost benefits, control of mixing process, etc. Early research and marketing efforts have primarily concerned on the environmental benefits and not as much on how the pavement will function under environmental and traffic loading. In the last decade, the effects of waxes on bitumen properties and mixture performance have been discussed for fatigue cracking, rutting, moisture damage [2-6] and a bit on low temperature cracking but more research is needed on those long term performance. Recently, experiments were carried out on WMA performance against moisture damage and fracture resistance under Swedish condition [7]. After getting positive response on fracture resistance and moisture performance, a study on low temperature cracking behavior of WMA was carried out as a continuous part of the project. This paper illustrate the low temperature performance of WMA in long cold winter and specifically how countries like Sweden, with such conditions, can benefit from this technology.

In this study, Hot Mix Asphalt (HMA) fracture mechanics framework along with the Energy Ratio (ER) was used as a tool to analyze the fracture resistance of the mixtures. The main feature of the HMA fracture mechanics framework is threshold concept developed at the University of Florida. Roque and Birgisson [8-11] performed comprehensive studies to characterize the crack initiation and crack growth of asphalt mixtures. As an outcome of these studies, they developed a viscoelastic fracture mechanics-based framework for predicting the cracking performance of asphalt mixtures by using the Superpave IDT test (resilient modulus test, creep compliance and indirect tensile strength). The main concept of the HMA fracture mechanics is that no single property is not quite enough to predict the cracking performance of a given asphalt mixture. In addition, a model is required that uses all of these fundamental mixture properties. This model was extended to identify a substitute property that combines the features of the HMA fracture mechanics framework with field experience, i.e. the Energy Ratio (ER) [10].

The primary objective of this research is to find out how warm mix asphalt performs in low temperature. In the process of answering that question both bitumen properties and mixture properties was investigated thoroughly. The low temperature performance of wax modified bitumen was evaluated using Bending Beam Rheometer (BBR) test and Dynamic Shear Rheometer (DSR) test along with conventional tests. Superpave IDT tests were conduct on the basis of HMA fracture mechanics and Thermal Stress Restrained Stress Test (TSRST) was used to investigate the low temperature cracking behavior of the asphalt mixtures.

## 2. EXPERIMENTAL DETAILS

### 2.1. Bitumen and additives

Bitumen of penetration grade 70/100 was modified by using commercial wax Asphaltan B (4% by weight), which is denoted wax AB. Asphaltan-B is an organic additive in the form of waxes. Asphaltan-B is a combination of nonglyceride long-chain carboxylic acid esters, free long chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins. It is a fossilized plant wax with a melting point is 82 to 95 °C [12].

The following test methods were used to analyze bitumen: softening point (EN 1427), penetration at 25°C (EN 1426), Brookfield viscosity at 135 °C and 165°C (ASTM D442), force ductility at 10°C (EN 13589, EN 13703). The results from conducted tests are summarized in Table 1. Adding of wax reduced Brookfield viscosity, which may lead to low mixing and compaction temperature of asphalt pavement. This wax modified bitumen also showed stiffening effect by increasing softening point and decreasing penetration value.

Table 1 – Characteristics of bitumen used in this study

| Bitumen | Penetration (dmm) | Softening point (°C) | Brookfield Viscosity (mPas) | | Forced Ductility at 10 °C (Nm) | Penetration Index |
|---|---|---|---|---|---|---|
| | | | at 135 °C | at 165 °C | | |
| Unmodified 70/100 | 81 | 46 | 345 | 101 | 1.38 | -1.1 |
| + 4% wax AB | 52 | 85 | 263 | 82 | 3.54 | 5.1 |

2.2. Asphalt mixtures

Asphalt mixtures were prepared in reference to ABT11 in the Swedish technical directive [13] which is dense graded asphalt concrete with a maximum aggregate size of 11mm. In this study, crushed aggregate were used obtained from Örebro query in Sweden. The mineralogy of that aggregate contains 44% Quarts, 20% K-feldspar, 28% Plagioclase and 7% Biotite, Epidote and Opaque. Chlorite also presents less than 1%. The particle size distributions of aggregates are shown in Fig. 1.

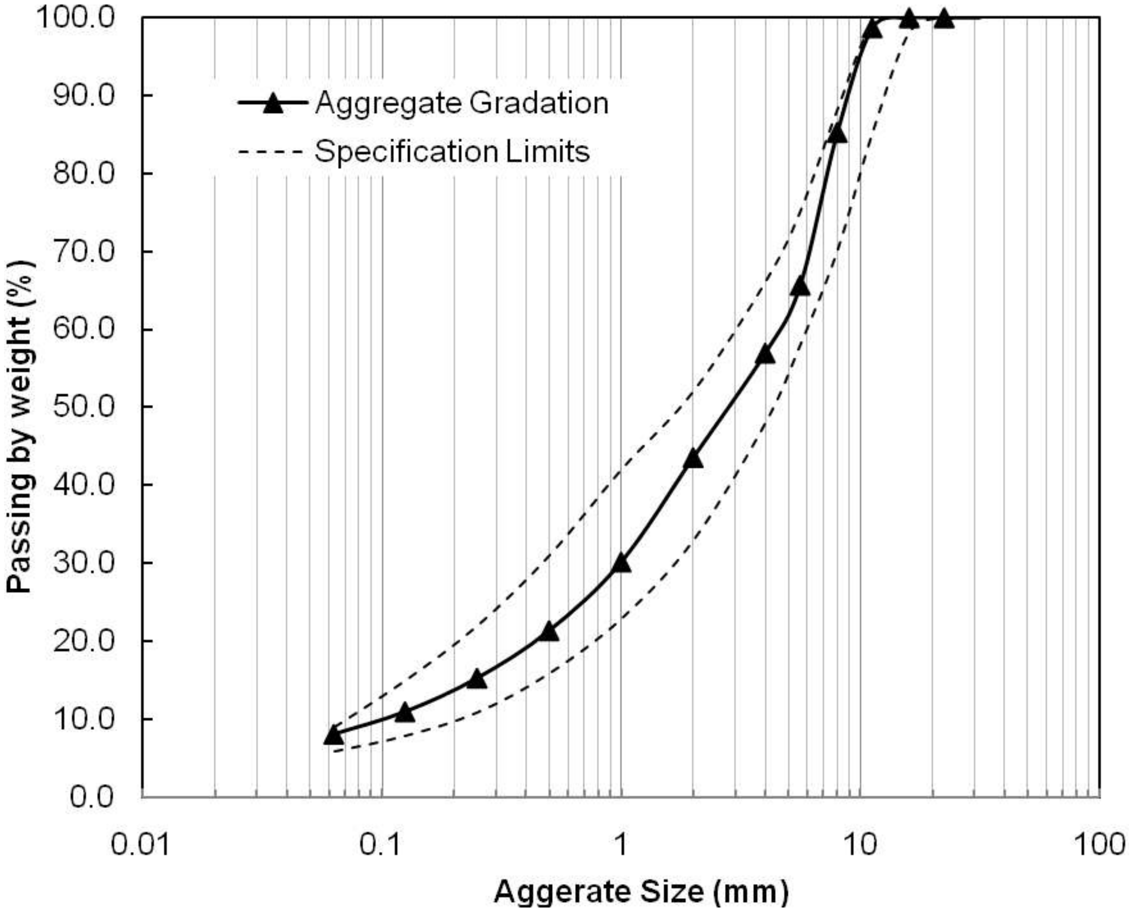

Figure 1 – Particle size distribution of the aggregates used and limits according to ABT11

Control mixture (mix-C) was produced by using unmodified 70/100 bitumen while wax modified mixture (mix-AB) was produced by using wax AB modified bitumen. The bitumen content was used 6.4% by weight for mixing. The temperature for mixing was 155 °C and compaction was 135 °C. Compaction of each specimen was done using a Superpave gyratory compactor. The target air void content of compacted specimen (150 mm diameter and 100 mm thickness) was 7±1% (by volume). For each type of mixture, total eight specimens were prepared, among those six for Superpave IDT test at 0 and -20 °C, three specimens for each temperature and two specimens for thermal stress restrained specimen test (TSRST) for evaluating low temperature performance of the mixtures.

## 2.3. Test Methods — Bitumen

### 2.3.1. *Dynamic Mechanical Analysis (DMA)*

Rheological parameters of bitumen such as complex shear modulus (G*) and phase angle (δ) were determined by using a strain-controlled rheometer (RDA II, Rheometrics). Both the unmodified and wax modified bitumen were tested at four different temperatures (10, 0, -10 and -20 °C). At each temperature, a frequency sweep was performed over range of 0.1 to 100 Hz. In all tests, parallel plates with 8 mm diameter and 1.5 mm gap were used. The measured parameters were used to construct complex modulus and phase angle master curves.

### 2.3.2. *Creep tests using Bending Beam Rheometer (BBR)*

Creep tests were conducted at three different low temperatures (-12, -18 and -24 °C) by following an AASHTO standard test method [14]. Creep stiffness (S) and creep rate (m) were determined at several loading times ranging from 8 to 240 seconds. Creep compliance was calculated from creep stiffness as they are reciprocal. Dynamic modulus was predicted from creep compliance by using linear viscoelastic theory. The calculated parameters were used to establish dynamic modulus master curves to analyze the propensity of wax additives to thermal cracking.

## 2.4. Test Methods — Asphalt Mixture

### 2.4.1. *Superpave InDirect Tensile (IDT) test*

The Superpave IDT test is a combination of three different tests i.e. Resilient modulus ($M_R$), Static creep and Strength test from which the following properties were determined: resilient modulus, creep compliance, tensile strength, fracture energy limit (FE), and dissipated creep strain energy limit (DCSE). The tests were performed following the procedure developed by Roque and Buttlar [15-16]. An HMA fracture mechanics framework [10-11] was used to compute Energy Ratio (ER) by combining those properties listed above. The experiments were performed at 0 and -20 °C to evaluate low temperature fracture performance. Three specimens were tested for every mixture and average approach was used to obtain material properties representative for each mixture.

### 2.4.2. *Tensile Stress Restrained Specimen Test (TSRST)*

In TSRST, rectangular specimens (38mm x 38mm x 140mm) were glued with two aluminum plates, and then mounted in a load frame. Tests were performed according to AASTHO TP-10-93 specification [17], where temperature reduced at a rate of 10 °C/h.

Thermally induced stress in the specimen were measured with the changing temperature. Finally, fracture occurred when thermally induced stress exceeded its strength.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

As asphalt mixture stiffness at low temperature is primarily depend on the stiffness of bitumen so the rheological properties of bitumen was investigated. Also the mixture functional and fracture properties at low temperature also studied. In the following sections, functional performance after bitumen modification with Asphaltan-B (wax AB) at low temperature are discussed and compared.

### 3.1. Rheological effects at low temperature using DMA and BBR

Dynamic modulus of bitumen depends on temperature and loading frequency. The temperature and frequency dependent characteristics of bitumen can be captured in a single composite curve, by using time-temperature superposition (or time-temperature equivalence) principle. The principle states that linear viscoelastic material properties obtained at different temperatures can be superimposed to a single curve at a reference temperature, which is called master curve. In a master curve, the performance of a material at low temperature is the same as that under short loading times or fast loading rates.

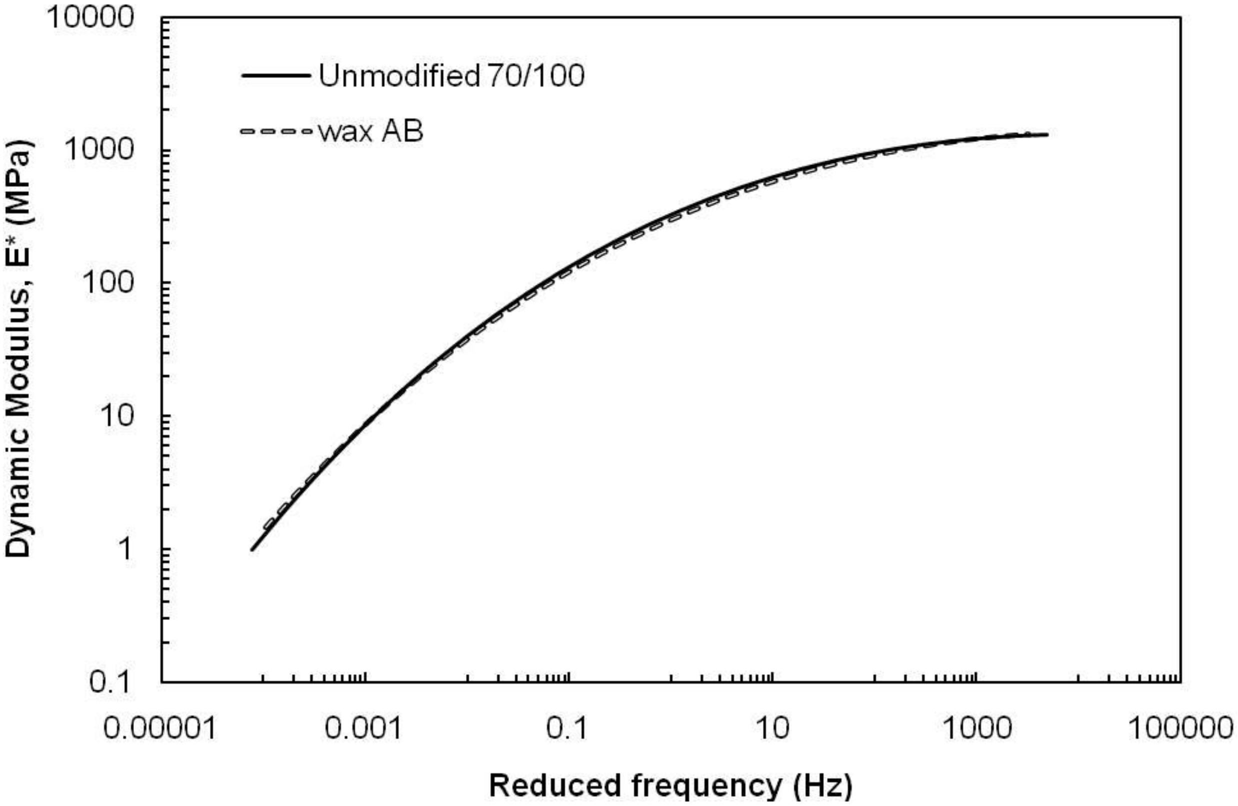

Figure 2 – Master dynamic modulus curves at reference temperature -10 °C from DSR

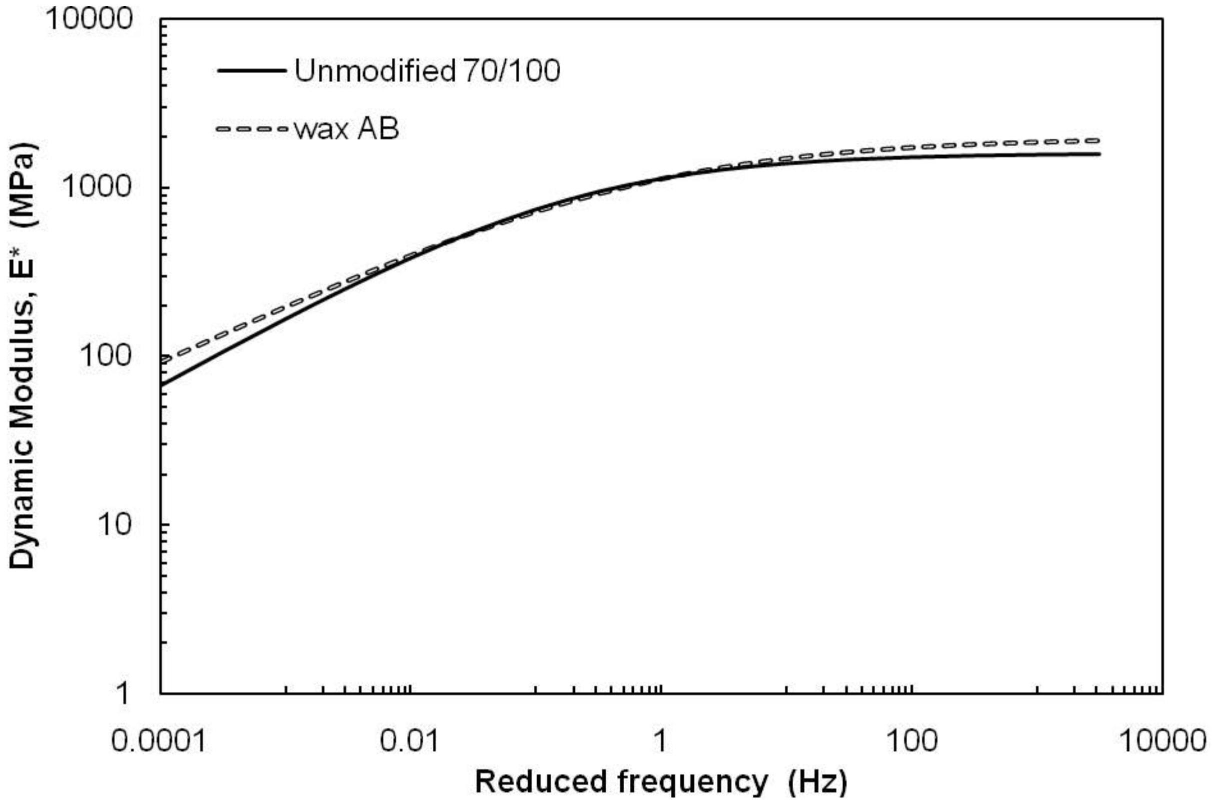

Figure 3 – Master dynamic modulus curves at reference temperature -10 °C from BBR

Dynamic modulus master curves are constructed at reference temperature -10 °C from DSR and BBR test results, which are depicted in figure 2 and 3 respectively. As mentioned above, in the master curve high frequency represents low temperature and vice versa. As expected, the dynamic modulus increases as the loading frequency increases; that is lowering down the temperature. At low temperature the wax modification exhibit a bit stiffer behavior compared with unmodified bitumen, in BBR it become more noticeable.

The creep stiffness (S) and slope of the stiffness curve (m-value) obtained from BBR tests are shown in table 2. Increasing stiffness means the thermal stresses developed in the pavement due to low temperature also increase and thermal cracking become more likely. On the other hand, decreasing m-value indicates declining the rate of stress relaxation which also increases the probability of thermal cracking. According to SHRP, a lower limit temperature (LST at which S = 300MPa or LmT at which m=0.3) can be determined from BBR test results. The results showed that due to wax modification, in all temperatures creep stiffness is higher and m-value is lower than the unmodified bitumen, except at -24 °C, which supports LST and LmT values as well.

Table 2 – BBR test results of bitumens used in the asphalt mixtures

| Bitumen | Creep Stiffness, S (MPa) / m-value | | | LST | LmT |
|---|---|---|---|---|---|
| | at -12 °C | at -18 °C | at -24 °C | (°C) | (°C) |
| Unmodified 70/100 | 150 / 0.40 | 414 / 0.30 | 832 / 0.21 | -16 | -18 |
| + 4% wax AB | 182 / 0.32 | 421 / 0.27 | 796 / 0.21 | -16 | -15 |

## 3.2. Mixture fracture performance at low temperature using Superpave IDT

To evaluate fracture properties of mixture after wax modification, Superpave IDT tests were conducted at 0 and -20 °C on both control mixture (mix-C) and mixture modified by wax Asphaltan B (mix-AB). All the fracture parameters obtained from these tests are summarized in table 3.

Table 3 – Summary of fracture parameters obtained from Superpave IDT tests

| Mixture ID | Test Temp. (°C) | MR (GPa) | Tensile Strength, $S_t$ (MPa) | Creep Rate (x $10^{-3}$) @ 1000s | EE (KJ/m$^3$) | FE (KJ/m$^3$) | DCSE$_f$ (KJ/m$^3$) | Energy Ratio (ER) |
|---|---|---|---|---|---|---|---|---|
| mix-C | 0 | 13.61 | 2.57 | 5.71 | 0.25 | 2.72 | 2.47 | 0.74 |
| mix-AB | | 13.35 | 2.58 | 2.48 | 0.25 | 2.52 | 2.27 | 1.57 |
| mix-C | -20 | 24.66 | 3.10 | 0.023 | 0.20 | 0.42 | 0.22 | 7.40 |
| mix-AB | | 22.90 | 3.25 | 0.019 | 0.23 | 0.43 | 0.20 | 7.50 |

Note. – In the table the control mixture denoted as mix-C and wax-AB modified mixture is denoted as mix-AB

Resilient modulus (MR) represents elastic stiffness of the material. In low temperature more the elastic stiffness means the materials become more plausible to thermal cracking. The results at both 0 and -20 °C temperature show that after wax modification the mixture has a little less elastic stiffness which may implies no negative effect on elastic stiffness.

According to HMA fracture mechanics, creep rate represents rate of damage in tension. As can be seen, the measured creep rate at 1000sec is lower for wax modified mixtures, indicating low rate of damage in tension at low temperature. Interestingly, after wax modification dissipated creep stain energy at failure decreased which indicates a lower fracture energy threshold. However, the difference between these two values is minor at -20 °C, which is considered as low temperature.

It can be also seen from table 3, with the lowering temperature from 0 to -20 °C, the difference in DCSE limit become lower which means in low temperature WMA may response similar like control mixture. By comparing all the parameters in table 3, it can be conclude that each and every parameter shows same trend in both 0 and -20°C, which shows test consistency as well.

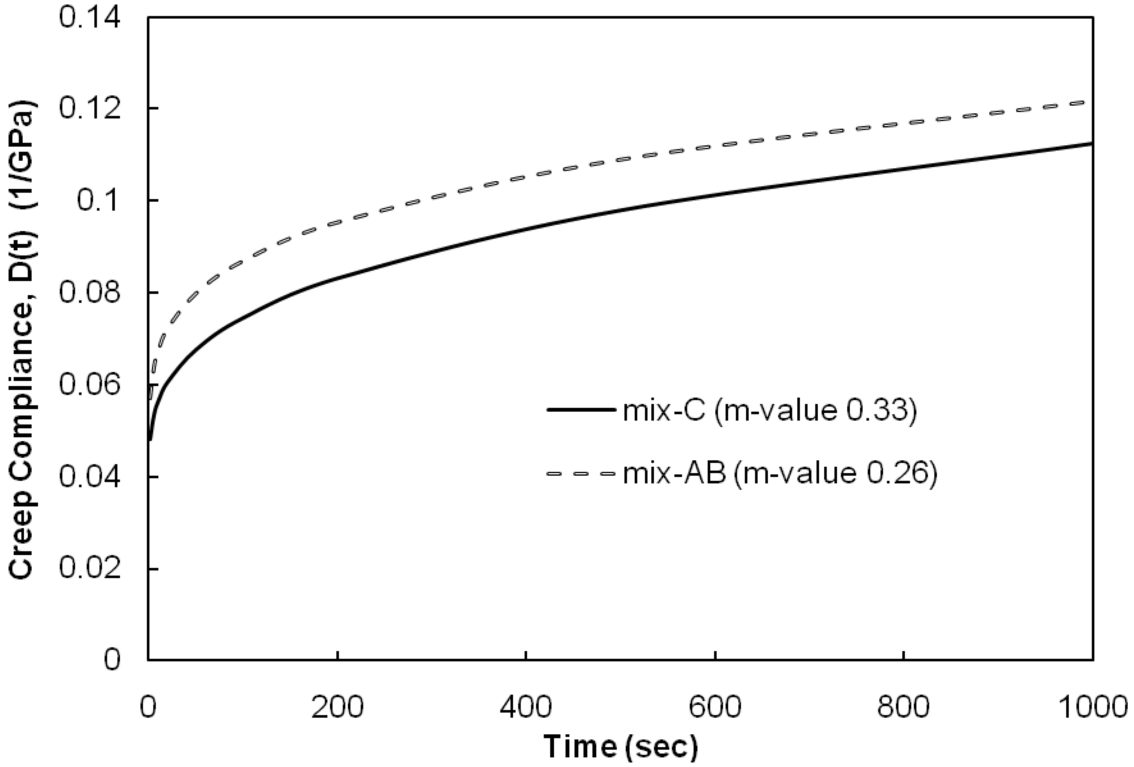

Figure 4 – Power law model of creep compliance at -20 °C

The relationships between the time dependent strain and applied stress are obtained from the conducted creep tests, shown in figure 4. The creep test results are presented in the form power law model of creep compliance. Creep compliance is an essential parameter to evaluate thermal cracking performance as it directly controls the magnetite of thermal stress development in the pavements. The creep compliance curve of mix-AB varied slightly from the control mixture, indicating minor negative effect of wax modification.

As per HMA fracture mechanics framework [10-11], a single parameter study is not quite enough so in order to get combined effect, the fracture resistance characterized by Energy Ratio (ER) was calculated. The ER values are shown in table 3 and it can be seen that energy ratio of WMA at 0 °C is significantly higher than the control mixture. This higher value of ER clearly indicates the fracture resistance of WMA is better than control mixture at 0 °C. To investigate the fracture resistance of WMA at a lower temperature, the tests were also conducted at -20 °C. The results showed that ER value of WMA is still slightly higher than the control mixture. However, this increment is too less that it can be within the test repeatability limit. This implies that wax modification may not show any negative effect on fracture performance at low temperature, minimum WMA will show similar fracture resistance as like control mixture.

### 3.3. Low temperature fracture performance using TSRST

The thermal stress restrained specimen tests (TSRST) were conducted to determine the low temperature cracking of asphalt mixtures. This method gave better field prediction according to a previous study [18]. As shown in figure 5, thermally induced stress increases relatively slow with the decreasing temperature, which is due to the relaxation of the specimen. After crossing a certain temperature (transition temperature), the thermally induced stress is not relaxed and is almost linearly increased until fracture of the specimen. The temperature at which specimen failed is recognized as fracture temperature and the strength is fracture strength. As can be seen, the fracture temperature is low for unmodified mixture by 1°C, but this difference is not that much severe because ±1°C is within the precision limit of the TSRST test.

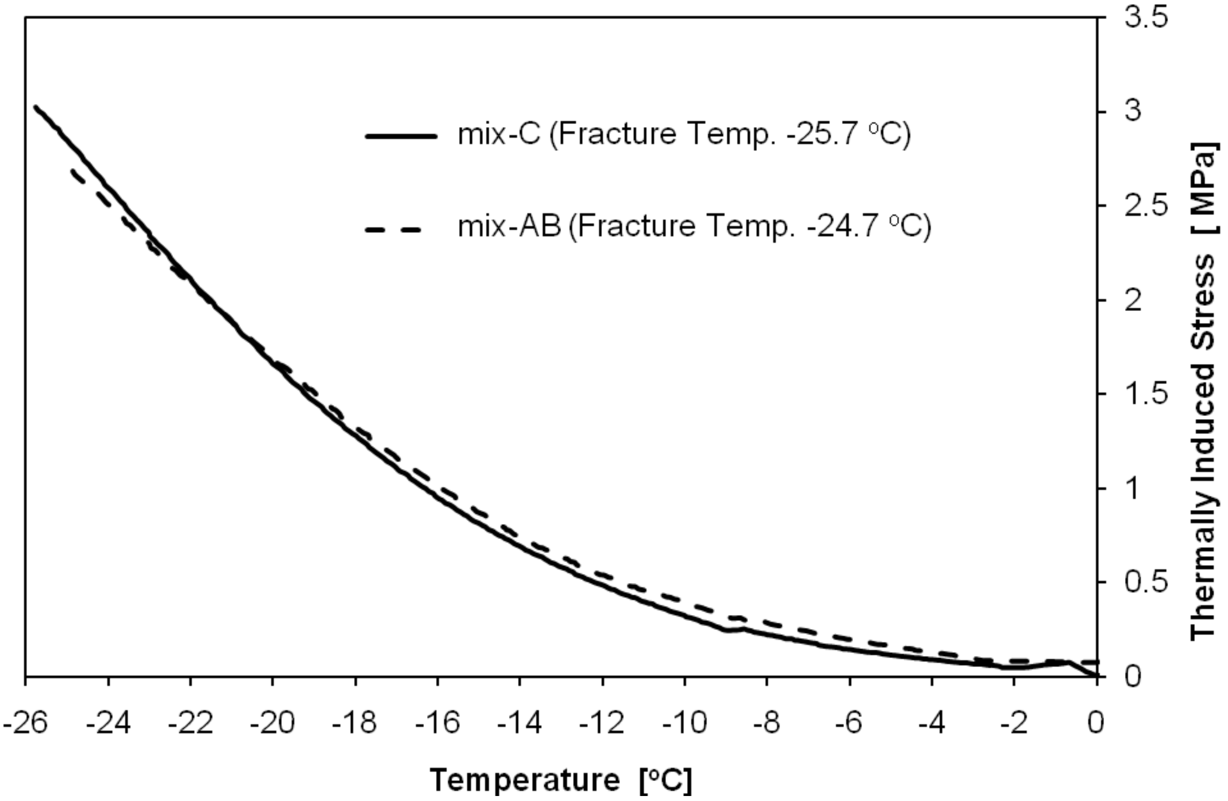

Figure 5 – Fracture temperature of different mixture obtained from TSRST

## 4. SUMMARY AND CONCLUSIONS

Low temperature performance of wax modified bitumen and asphalt was carried out by conducting a number of experiments. The stiffening effect of this modification on bitumen was evaluated by conventional tests (penetration, softening point and forced ductility) and rheological effects were evaluated by Brookfield viscosity, DSR and BBR tests. Whereas, fracture performance of WMA was found out by using key parameters such as creep compliance, elastic energy, dissipated creep strain energy and fracture energy. Particularly, HMA frame work along with energy ratio also studied to find out low temperature performance of WMA. In addition, to support these results TSRST test were also conducted as this test gives better field prediction. After analyzing the results, the key findings are summarized below:

- Addition of 4% wax (by weight) decreases in penetration while softening point and forced ductility increases, showing a clear stiffening effect.

- Wax modification shows a clear viscosity drop which is known as flow improving impact, can be observed from Brookfield viscosity test at 135 and 165 °C. Lower viscosity means it gets stiffer as shown in conventional tests which may lead to a lower mixing and compaction temperature than HMA.

- The dynamic modulus master curve obtained from the DSR and BBR, it can be seen that at high frequency (i.e., in low temperature) this additional wax also shows stiffening effect, which is more noticeable from BBR test results.

- According to HMA fracture mechanics WMA shows better cracking resistance at 0°C, as the energy ratio is more than double compared with the control mixture. The ER value of WMA is relatively high as the rate of creep at 1000sec is quite low for WMA which indicates low rate of damage.

- According to Superpave IDT results, wax modification lowers the dissipated creep energy threshold ($DCSE_f$) while interestingly the rate of creep in tension decreased. Both control and WMA mixture show similar energy ratios at -20 °C, as per HMA fracture mechanics it indicates no negative effect in fracture resistance at low temperature.

- In TSRST fracture temperature of WMA increases only 1 ºC than the control mixture. However, this increase is within the test repeatability limit, implying no major negative impact on low temperature crack susceptibility, which supports Superpave IDT and BBR test results as well.

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