EVALUATION OF LOW TEMPERATURE PROPERTIES OF HMA MIXTURES

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ABSTRACT

The deterioration of flexible pavements due to low temperature cracking is a significant and costly problem in the State of Nevada. The Nevada Department of Transportation initiated several research efforts aimed at exploring Nevada's problem with this distress. The research evaluated several newly developed low temperature performance tests under Nevada's conditions. The goal of the research was to determine the applicability of the tests for characterizing the low temperature response of Nevada's asphalt binders and HMA mixtures. This paper summarizes Nevada's experience with the SHRP low temperature tests and specifications; highlighting the effectiveness of the Superpave PG binder grading system and Thermal Stress Restrained Specimen Test. The contribution of asphalt aging to Nevada's cracking problem is also included in the paper.

An investigation of the Superpave Performance Graded Binder tests has determined that the bending beam rheometer and the direct tension test correlate very well and it may not be necessary to run both tests as they are set up in the current Superpave specifications. The TSRST appears to provide the greatest value for evaluating low temperature properties of HMA mixtures. Findings from the research indicate that there are some significant correlations between the low temperature properties of asphalt binders and HMA mixtures if the mixtures are aged appropriately. This emphasizes the need to implement the appropriate conditioning procedure when low temperature cracking is used as part of the mix design and evaluation process. On the other hand, the research showed that when using polymer-modified asphalt binders, the low temperature grade of the asphalt binder maybe conservative enough where testing of the HMA mix may not be necessary.

INTRODUCTION

Low temperature cracking of hot mixed asphalt (HMA) pavements has been a serious concern to pavements/materials engineers for many years. The mechanism of low temperature cracking is very complex in nature due to the influence of material, structural and environmental conditions on the process. Significant research over the years has enhanced the understanding of this form of pavement distress, however changes in binder chemistry and loading conditions over the past 20 years has uncovered the need for more advance analysis. In 1987, the Strategic Highway Research Program (SHRP) was established with the intent of providing advanced technologies to address many of these issues. While SHRP researchers considered all forms of pavement distress, low temperature cracking received more than its share of attention. When the products of the SHRP research were released to the public in 1992 in the form of the Superpave system, several new tests became available allowing engineers and researchers to directly or indirectly evaluate the response of asphalt binders and/or HMA mixtures to low temperatures.

Nevada has historically experienced excessive low temperature cracking and other forms of pavement distress due to its unique climate. The extreme cold and warm temperatures in the region, lends itself well to rutting and low temperature cracking. These extreme conditions however place enormous pressure on material engineers who must use nontraditional techniques to combat both forms of distress. With the introduction of the Superpave system, engineers are now better equipped to evaluate pavement performance prior to construction.

BACKGROUND

Low temperature cracking of HMA pavements is a distress that affects many regions of the United States and Canada. The process is associated with volumetric changes in the HMA layer as the pavement temperature drops. If the pavement is unrestrained, the contraction associated with the drop in pavement temperature will not result in the development of tensile stresses. In reality however, friction developed between the HMA and base layers along with the infinite length, restrain the pavement from contraction and in return induce tensile stresses in the pavement (Jung and Vinson 1994a, Vinson et al. 1989). As the temperature continually drops, tensile stresses increase until a point where the stress equals the tensile strength of the mixture. At the temperature where tensile stress equals tensile strength, a crack develops through the HMA layer to relieve the stress.

The pattern of thermal cracking is transverse to the direction of traffic and typically spaced at regular intervals between 3m and 30m depending on the age, thickness and conditions of the pavement. Although initially harmless, with time these cracks can allow the transfer of water and fines in and out of the pavement, leading to performance problems and the eventual loss of pavement life.

Over the years, a number of test methods have been used to evaluate the response of asphalt binders and HMA mixtures to low temperature cracking. Many tests have been used directly to measure failure properties at low temperatures while others have been primarily used for modeling and prediction purposes. A review of the more common test methods is presented below.

The Superpave system introduced several new low temperature asphalt binder tests to the asphalt paving industry. Among the tests introduced were the bending beam rheometer (BBR) and the direct tension (DT) tester for measuring the rheological and fracture properties of asphalt binders at low temperatures.

The BBR is a creep test used to measure the rheological properties of asphalt binders at low temperatures. The test is performed through the application of a static load to the center of a simply supported beam. A time history of load and deflection is generated from the test which enables stiffness S(t) and its rate of change with loading time (m) to be determined through classical beam theory. The DT test was developed to measure the strength and failure strain of asphalt binders at low temperatures. The test is performed by subjecting a dogbone shaped specimen of the asphalt binder to a uniaxial tensile load while recording the stress/strain properties at failure.

In 1989, Vinson et al compiled a summary of the methods to evaluate the resistance of HMA mixtures to low temperature cracking (Vinson et al. 1989). The summary included the Indirect Diametral Tension Test, Direct Tension Test, Tensile Creep Test, Flexural Bending Test, Thermal Stress Restrained Specimen Test, C*-Line Integral Test, Three-Point Bend Specimen Test, and the Coefficient of Thermal Contraction Test. Each test was evaluated over a series of criterion with the Thermal Stress Restrained Specimen Test (TSRST) determined to exhibit the greatest potential for evaluating the low temperature cracking resistance of HMA mixtures. Although extensive research went into validating the TSRST, fundamental viscoelastic and fracture properties needed to predict performance under environmental and pavement conditions cannot be determined from the test. The TSRST test is performed by cooling a beam shaped specimen of HMA at a specified rate while restraining it from contracting. As the HMA is cooled, thermally induced tensile stresses develop in the specimen as a result of being restrained. When the induced tensile stress equals or exceeds the tensile strength of the mixture, failure occurs with the corresponding characteristics of fracture stress and fracture temperature.

Thermal cracking occurs at cold temperatures, when the aged asphalt binder which is already stiff, becomes brittle and loses its ability to dissipate stress through viscous flow. For this purpose, SHRP has adopted two asphalt binder aging procedures to reflect the contribution of short and long term aging to pavement performance. The rolling thin film oven test (RTFOT), a test first introduced in California 1959, was selected to simulate the short term volatilization and oxidative hardening of the asphalt binder. The RTFOT provides an aged asphalt binder that closely reflects the hardening experienced during the manufacture and construction of HMA. The pressure aging vessel (PAV) was made available to account for the effects of oxidative hardening on performance at intermediate and low temperatures. The test is performed by exposing RTFOT residue to high air pressure and temperature in the PAV. The PAV is speculated to simulate the oxidative aging equivalent to 5-10 years of service with the actual time frame found to be binder, temperature, and region specific (Bahia and Anderson 1995).

The selection of the HMA mixture aging protocol for Superpave was based on research performed at Oregon State University during the Strategic Highway Research Program (Bell 1994, Bell et al. 1994). Several short and long term aging tests procedures were evaluated using a series of mixture and binder related tests. For the short term aging research, conditioning of the loose mix using a forced draft oven aging and extended mixing process, was evaluated to determine its effectiveness. Long term aging was investigated by conditioning compacted samples using a similar forced draft oven aging procedure, a pressure oxidation procedure, and a triaxial cell aging method. At the conclusion of the investigation, the forced draft oven aging of the loose mixture for 4 hours at 135°C was recommended as a short term aging procedure. For long-term aging, both forced draft oven aging and low pressure oxidation were recommended for further use. For dense graded mixtures with stiff asphalt binders, oven aging for 5 days at 85°C was recommended while for open graded or soft asphalt binder mixtures, a low pressure oxidation for 5 days at 85°C was selected.

The first attempt to relate the Superpave asphalt binder properties to laboratory mixture performance was reported in SHRP-A-398 (SHRP 1994). A thermal cracking validation was performed by relating asphalt binder properties to TSRST test results conducted on HMA mixtures. A ranking of the asphalt binders using the BBR limiting stiffness temperature at 300MPa and direct tension ultimate failure strain at –26°C was found to compare favorably with the TSRST fracture temperature rankings. Similarly, linear regression relationships relating m-value, stiffness and ultimate strain at failure using both aged and unaged binders, to TSRST fracture temperature at short and long term aging conditions, were satisfactory for the most part. The exception to the rule was the ultimate failure strain at -26°C while did not correlate well with fracture temperature of both short and long term aged mixtures (Jung and Visnon 1994b).

Similar studies on the low temperature performance of polymer modified binders were performed by King et al (King et al. 1993). In testing of several RTFOT aged asphalt binders with a range of polymer concentrations, relationships between the bending beam rheometer limiting temperature and the TSRST fracture temperature were reported to be excellent. When similar relationships were developed with the direct tension, correlations were comparably worse. Therefore, if the TSRST is truly representative of thermal cracking, then the BBR limiting temperature is certainly a better single performance indicator than the direct tension limiting failure strain temperature. Even if this is the case, findings in the study still indicate that the direct tension provides value. When the BBR limiting temperature data were used to develop a relationship with direct tension limiting temperature data, the correlations provided some interesting trends. The polymers tended to reduce the limiting failure strain temperature more than they reduced the limiting stiffness temperature.

A preliminary evaluation of the relationships between specification properties and performance at low temperatures was performed during the SHRP research. Five test sites located in Alaska, Pennsylvania and Finland, along with research at the Frost Effects Research Facility of the U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL), were used to validate the TSRST as an accelerated low temperature performance test for HMA pavements (Kanerva et al. 1994). The research concluded that cracking behavior at four of the five test sites and the USACCREL, could be explained using the TSRST fracture temperature. Furthermore, the research suggested that it's possible to develop a model using the TSRST, field aging conditions and local temperature data to predict the development of cracking in all climates. This statement was confirmed following the development of models by Raad et al (Raad et al. 1998) to predict the low temperature cracking of unmodified and modified HMA mixtures in Alaska. Cracks spacing of Alaskan pavements were modeled as a function of age, predicted minimum air temperature, TSRST fracture temperature and TSRST fracture strength. Although the study was site specific and based on limited data, the correlations were very promising indicating the effectiveness of the TSRST as a low temperature prediction device.

In 1993, SHRP researchers reported on an extensive study to evaluate the low temperature properties of mixtures measured by the indirect tensile creep test at low temperature (ITLT) with field performance and binders properties (Lytton et al. 1993). The study concluded that the ITLT is suitable to predict field performance of asphalt mixtures subjected to low temperature cracking and the S and m parameters are suitable to measure the low temperature rheological properties of asphalt binders.

LOW TEMPERATURE PROPERTIES OF ASPHALT BINDERS

It is widely recognized that asphalt binder is the primary contributor to the resistance of low temperature cracking in HMA pavements. The level of resistance is largely controlled by the physical properties of the asphalt binder, which dictates the magnitude and extent of low temperature cracking. At low temperatures, asphalt binders behave in a brittle manner and lose their ability to absorb energy through viscous flow.

Presently the Superpave binder grading system uses the bending beam rheometer and the direct tension test to evaluate the low temperature properties of asphalt binders. The two tests have been specified in the Superpave binder grading system in recognition that the pre-failure properties of the BBR may not correlate well with true fracture properties experienced in the field. This has shown to occur in many polymer based asphalt binders, where the binder may exhibit high stiffness yet still poses a high strain tolerance. In instances where this is the case, the direct tension can be used as a supplemental test to the BBR if the asphalt binder stiffness is between 300 and 600 MPa and the creep rate remains greater than 0.300.

The data presented in this paper were collected from a testing plan conducted to evaluate the low temperature properties of several Nevada asphalt binders using the Bending Beam Rheometer and Direct Tension tests. The limiting temperatures of each binder based on the individual test parameters, was used as criterion for evaluation.

In a six-year span between 1993 and 1999, approximately 60 asphalt binders were graded using the Superpave Performance Binder Grading System. Of these, over 20 asphalt binders have complete low temperature characterizations. The remaining projects lack the direct tension results due to fundamental problems experienced with the testing equipment early in the program. Nevertheless, the 20 asphalt binders represent many core projects constructed around the state where the range of asphalt binders is typical of those used in Nevada. Although the majority of the asphalt binders were classified as AC-20P, AC-20, AC-20 with 25% Trinidad Lake Asphalt, AC-30, AC-30P and some performance graded binders were also represented in the study. Following testing of the asphalt binders, the limiting temperatures based on each of the three low temperature criteria, S(t), m-value, and failure strain was compiled and are presented in Table 1.

The limiting temperatures of the twenty asphalt binders based on the bending beam rheometer creep stiffness S(t) and creep rate m-value were first analyzed to determine if the direct tension was required to complete the grading. The current Superpave specification states that the direct tension is only required for creep stiffness values between 300MPa and 600MPa and creep rate values greater than 0.300 at the selected test temperature. Of the twenty asphalt binders analyzed, only one required testing using the direct tension test. Direct tension testing of the one binder did not introduce any change in binder grade.

The next area of interest was to determine if relationships exist between the two low temperature characterization tests (i.e. BBR and DT). A series of linear regression analyses were performed to determine if relations exist between the limiting temperatures determined based on the three design criterion. Three models were fit relating BBR S(t) to Direct Tension Failure Strain, BBR m-value to Direct Tension Failure Strain, and BBR S(t) to BBR m-value. The analysis was performed using the SAS macro REGRESS and the associated macro call files mldumreg.sas and mlrind.sas. Figures 1, 2, and 3, present the relationships with the effects of polymer modification included in the analysis through the use of an indicator variable. The significance of the relationships were found to be strong, $R^2 = 0.82$ to 0.86. The analysis of variance assumptions of normally distributed error, equal variance and absence of outliers and/or influential observations were all checked and satisfied. Equations relating the limiting temperatures based on the three design criterion are presented below,

$DTT = -3.333 + 0.813BBR\text{-}S(t)$ for neat & polymer modified AC (1)

$DTT = -5.984 + 0.703BBR\text{-}m\text{-}value$ for polymer modified AC (2a)

$DTT = -2.359 + 0.703BBR\text{-}m\text{-}value$ for neat asphalt cement (2b)

$BBR\ S(t) = 1.806 + 1.061BBR\text{-}m\text{-}value$ for polymer modified AC (3a)

$BBR\ S(t) = -9.230 + 0.541BBR\text{-}m\text{-}value$ for neat asphalt cement (3b)

It's worth noting from equation 1 that the relationship between direct tension limiting temperature and BBR limiting temperature based on stiffness is represented by a single equation for both neat and polymer-modified binders. While performing the analysis, it became evident that the effect of polymer modification on the relationship was insignificant, and the term was removed from the model. A scatter plot of the data presented in Figure 1, shows that the data are randomly scattered close to the line of equality, indicating that the BBR S(t) and direct tension limiting temperatures are providing similar results regardless of binder composition.

In equation 2 the effects of polymer modification on the relationship between BBR m-value and direct tension limiting temperatures can be noticed through a 3.5^{o}C improvement in low temperature resistance over the non-polymerized materials. Additionally, Figure 2 indicates the BBR m-value appears to be consistently more conservative than the direct tension at assigning the limiting temperature of non modified binders. A similar trend was experienced when the BBR m-value was compared with the BBR creep stiffness limiting temperatures. From Figure 3, the polymer modified asphalt binders plotted close to the line of equality while the five neat asphalt binders remained above the equality line. This once again shows, the criteria for

BBR m-value is most conservative at assigning limiting temperatures. Additional low temperature data from neat asphalt binders are needed to validate this statement.

A statistical analysis was conducted to assess whether the limiting temperatures determined by the three different methods (BBR-S(t), BBR-m-value, and DT) are statistically the same. Using a significance level of 0.05, the analysis concluded that the limiting temperatures determined by the three criteria are all the same. Since the majority of the projects included polymer-modified binders, this conclusion should be considered valid for polymer-modified binders only.

RESISTANCE OF HMA TO LOW TEMPERATURE CRACKING

The objective of this part of the research was to evaluate the low temperature properties of HMA mixtures at various aging conditions. In order to achieve this objective, the following mixtures were tested in the TSRST.

1) LMLC PAV – Lab Mixed Lab Compacted-Pressure Aging Vessel Binder
2) LMLC STOA – Lab Mixed Lab Compacted-Short Term Oven Aged Mix
3) LMLC LTOA – Lab Mixed Lab Compacted-Long Term Oven Aged Mix
4) FMLC – Field Mixed Lab Compacted (represents short term aged condition)
5) FMLC LTOA – Field Mixed Lab Compacted-Long Term Oven Aged Mix

It is well recognized that laboratory produced mixtures for some reason or another, often do not represent the field produced mixture. For this reason, lab and field produced mixtures were included in the study to see if low temperature properties are sensitive to mixture's origin.

A total of twenty-four projects constructed throughout Nevada over the past six years were tested in the TSRST to determine their response to low temperature cracking. Due to material availability, amendments to the testing plan and unforeseeable testing problems, only a partial factorial is available for analysis. Nevertheless, with all the obstacles encountered, thirteen of the twenty-eight contracts tested have completed matrices. All contracts consisted of a similar dense graded asphalt mixture with nominal maximum size aggregate of ¾" and percent passing #200 between 3 and 7%. Sixteen of the twenty-four projects contained an AC-20P binder, while the remaining projects consisted of AC-30, AC-30P, AC-20, AC-20+Trinidad Lake Asphalt, and several performance graded asphalt binders. Whenever possible, three replicates of each mixture condition were fabricated and tested. Fracture temperature and fracture stress were recorded directly from the TSRST and later used to test several hypotheses regarding the mixtures conditions. Table 2 summarizes the average values of the TSRST data generated in this research effort.

Impact of Mixture's Condition on Low temperature Properties

The objective of this part of the research was met by conducting statistical analyses to test the various hypotheses.

H_o: TSRST response variable for LMLC STOA and FMLC are the same: This hypothesis was established to determine if a difference existed in the low temperature response of short term aged mixtures produced in the laboratory and those produced in the field. Using fracture temperature and fracture stress as the response variables, eighteen contracts were investigated. The hypothesis that the fracture temperature of the two short term aging conditions are the same could not be rejected. As anticipated, we can conclude that the fracture temperature of short term aged mixtures produced in the lab and field, are statistically the same.

With fracture stress as the response variable, the hypothesis was re-tested and rejected. We can conclude that the fracture stress for the different short term aged mixtures is statistically different. On average, the field produced mix exhibited a 0.33MPa lower fracture stress under the short term aging conditions as compared to the lab produced mixtures.

H_0: TSRST response variable for LMLC STOA and LMLC LTOA are the same: This hypothesis was investigated to determine if the long and short term aging conditions of laboratory produced mixtures resulted in different low temperature properties. Using fracture temperature and fracture stress as the response variables, sixteen contracts were investigated. The hypotheses for both response variables were rejected, concluding that fracture temperature and fracture stress are not the same for short and long term aged LMLC mixtures. In the study the long term aging of the lab produced mixtures experienced on average 5.5°C warmer fracture temperature and 0.32MPa lower fracture stress than the short term aging.

H_0: TSRST response variable for FMLC and FMLC LTOA are the same: A similar hypothesis was developed to determine if the additional long term oven aging of the field produced mixtures resulted in different low temperature properties. Once again sixteen contracts were investigated with fracture temperature and fracture stress used as the criteria for testing the hypotheses. The hypothesis was rejected, concluding that the addition of long term oven aging produced a significant difference in fracture temperature of field produced mixtures. As anticipated, the long term oven aged mix on average experienced a 3.5°C warmer fracture temperature than the short term aged mix (FMLC).

Using fracture stress as the response variable, the difference in short and long term aging of field produced HMA was re-tested and could not be rejected. It can be concluded, based on this study, that aging of field produced mixtures has no statistical impact on fracture stress.

H_0: TSRST response variable for LMLC STOA and LMLC PAV are the same: This hypothesis was initiated to determine if the TSRST was sensitive enough to distinguish changes in asphalt binder conditions. Twenty four projects were investigated with fracture temperature and fracture stress used as the criteria for testing the hypotheses. The difference in fracture temperature and fracture stress was found significant. On average, the PAV condition experienced a 2.5°C warmer fracture temperature and a 0.62MPa lower fracture stress than the short term oven aged condition.

H_0: TSRST response variable for LMLC LTOA, FMLC LTOA and LMLC PAV are the same: This hypothesis was developed out of interest in determining if all long term aging processes have the same effect. Using fracture temperature and fracture stress as the response variables once again, fourteen contracts were investigated. The hypothesis that fracture temperature of the three long term aging systems were the same could not be rejected. The difference in fracture stress however was significant.

Although the findings of the five hypotheses as a whole are consistent with engineering judgement, caution should still be exercised due to some serious discrepancies in data generated by the TSRST. On ten of the twenty-seven projects investigated, the TSRST fracture temperature for the lab mixed lab compacted mixtures made with PAV-aged binder was very close if not colder than the LMLC or FMLC short term aged mixtures. A possible explanation for this is the PAV may not adequately simulate the aging conditions critical to low temperature cracking. In response to this, it's worth noting that all the discrepancies occurred on contracts consisting of polymer modified asphalt binders except for contract 2603 which contained a neat binder with 25% Trinidad Lake Asphalt. This may indicate that the PAV aging system and/or the TSRST has some limitations when used with polymer modified asphalt binders.

The recommendations of the hypotheses testing and comparing these recommendations with pavement engineering judgement showed that the fracture temperature is a more stable and reliable measure of the low temperature properties of HMA mixtures than the fracture stress. Combining these findings with the fact that the fracture temperature can be more directly applied to mixture's evaluation while the fracture stress data require further interpretation, makes the use of the fracture temperature a more attractive approach.

RELATIONSHIP BETWEEN ASPHALT BINDER PARAMETERS AND RFORMANCE IN THE TSRST

The objective of this part of the research was to compare the low temperature characteristics obtained from measurements of binders properties and those obtained from measurements on mixtures. Using data presented in the first and second parts of this paper, single variable linear regression models were developed relating TSRST fracture temperature at the various mixture conditions to limiting temperatures determined from the BBR and direct tension. Since the majority of the projects included polymer modified binders (15 out of 20), the regression analyses were conducted on the polymer modified mixtures only. It should be noted that the limiting temperatures of asphalt binders used in the regression analysis are based on actual test temperatures, which are 10°C warmer than the anticipated failure temperature. This constant shift in the temperature will not affect the forms of the relationships, however, a 10°C should be subtracted from the temperatures generated from the models in order to obtain the low temperature grade of the binder.

Without extensive discussion of each of the models, the relationships ranged from fair to extremely good, R^2 ranged from 53 to 90. To reword this, between 53 and 90% of the variability in TSRST fracture temperature can be accounted for in the limiting temperature of the asphalt binder. Table 3 compares the limiting temperatures based on binder testing and the TSRST fracture temperatures of the mixtures and Table 4 summarizes the models developed based on these data. All of the correlations with good levels of R^2 values (above 70%) were obtained when the binders properties are correlated to the properties of the long term aged mixtures. The BBR and DT properties are measured on asphalt binders that are subjected to long term aging. Attempting to relate the limiting temperatures determined on the long term aged binders with the fracture temperatures of unaged HMA mixtures did not result in good correlations due to the significant difference in the conditions of the binder. However, correlating the BBR and DT limiting temperatures with the fracture temperatures of the long term aged HMA mixtures resulted in good-excellent correlations. This emphasizes what is already a known fact that the resistance of the HMA mixture to low temperature cracking is mainly controlled by the conditions of the binder. In addition, such consistency gives the TSRST a great credibility in measuring the low temperature cracking resistance of HMA mixtures.

For the majority of the contracts evaluated, the critical low temperature assigned by the Superpave binder grading system was equal to or colder than the fracture temperature experienced under the five mixture conditions. This trend appears more consistent with the polymer modified asphalt binders indicating that the Superpave binder specification is conservative enough that the low temperature binder grade can be used to ensure performance. For the neat asphalt binders however, TSRST fracture temperatures were consistently warmer than the polymer-modified asphalt binders and the limiting temperatures based on Superpave binder specification appeared nonconservative in almost every instance. The findings are based on only a small numbers of neat binders, therefore a larger sample base is needed to confirm this statement.

CONCLUSIONS AND RECOMMENDATIONS

An investigation of the Superpave low temperature binder tests, suggest redundancies exist between the Bending Beam Rheometer and Direct Tension tests. The three test parameters of creep stiffness, creep rate, and failure strain were determined equally capable of establishing the low temperature grade of polymer modified asphalt binders. Inconsistencies experienced with neat asphalt binders however warrant the inclusion of the BBR creep rate (m-value) parameter, after it appeared sensitive to binder composition. Modifications to the performance graded binder specification are presently underway to help address these issues and hopefully provide better use of the Direct Tension

The continual use of the TSRST for the low temperature evaluation of lab and field produced mixtures subjected to long term oven aging is suggested. The fracture temperature is recommended to be used in determining the resistance of HMA mixtures to low temperature cracking since it provides a direct measure and it is more stable than the fracture stress. The LTOA of the HMA mixture appears to provide a better representation of aging experience in the field by accounting for the significant effects of asphalt, aggregate and aging interactions. Although the TSRST showed signs of inconsistency during the research, concern is minor since the discrepancies were limited to polymer modified binders under PAV-aged conditions. The data presented in this paper showed that determining the fracture temperature of the long term aged HMA mixtures is more appropriate than measuring the fracture temperature of HMA mixtures produced with PAV-aged binders.

The data generated in this study showed that the use of the limiting temperature measured on the asphalt binder results in a conservative low temperature grade for polymer-modified binders while it is unconservative for neat asphalt binders. Based on this finding, it is recommended that both the binder’s limiting temperature and the fracture temperature of the long term aged HMA mixture be determined to ensure good long term field performance.

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Table 1: Bending beam rheometer and direct tension limiting temperatures.

Contract	AC Grade	PG Grade	Polymer Modification	Limiting Temperature ©			Direct Tension Required ?
				BBR-S(t)	BBR-m-value	Direct Tension	
2480	AC-20P	PG58-28	Yes	-20.4	-18.9	-18.0	No
2491	AC-20P	PG52-16	Yes	-15.5	-16.2	-14.2	No
2501-B	AC-30	PG64-16	No	-18.0	-11.7	-17.0	No
2530	AC-20P	PG58-28	Yes	-20.4	-19.2	-22.7	No
2545	AC-20P	PG58-22	Yes	-14.0	-17.3	-13.5	No
2552	AC-20P	PG58-28	Yes	-21.7	-19.9	-20.8	No
2558-93	AC-20P	PG58-22	Yes	-14.2	-15.4	-14.5	No
2558-94	AC-20P	PG52-16	Yes	-14.1	-15.8	-14.3	No
2603	AC-20+TLA	PG70-16	No	-11.8	-7.5	-12.4	No
2604	AC-30	PG70-22	No	-16.3	-14.8	-14.8	No
2611-A	AC-20	PG64-16	No	-16.9	-12.5	-13.4	No
2611-B	AC-20P	PG64-28	Yes	-22.7	-23.8	-23.5	No
2617	AC-20P	PG52-22	Yes	-15.7	-17.2	-15.6	No
2622	AC-30P	PG70-22	Yes	-13.2	-12.4	-19.6	No
2704	AC-20P	PG58-28	Yes	-19.2	-19.6	-17.4	No
2711	AC-20P	PG58-22	Yes	-16.8	-18.5	-17.7	Yes
2825	Unknown	PG70-28	Yes	-21.2	-22.5	-20.4	No
2838	Unknown	PG64-34	Yes	-28.3	-28.1	-30.8	No
2880-A	Unknown	PG64-22	No	-17.1	-16.2	-17.6	No
2880-B	AC-20P	PG58-22	Yes	-14.1	-16.5	-17.2	No

Table 2: Low temperature properties of HMA mixtures measured by the TSRST.

Contract	LMLC STOA		LMLC LTOA		FMLC		FMLC LTOA		LMLC PAV	
	Fracture Stress (Mpa)	Fracture Temp (C)	Fracture Stress (Mpa)	Fracture Temp (C)	Fracture Stress (Mpa)	Fracture Temp (C)	Fracture Stress (Mpa)	Fracture Temp (C)	Fracture Stress (Mpa)	Fracture Temp (C)
2480	2.32	-38.4							0.80	-29.1
2491	1.79	-25.1			2.07	-17.6			0.92	-25.6
2501-A	1.38	-31.9	0.52	-18.9			0.73	-13.5	0.73	-26.3
2501-B	2.42	-34.8							0.8	-36.6
2530	1.49	-38.9	1.07	-30.1	1.56	-33.2	0.88	-31.9	0.34	-24.3
2545	1.91	-33.3	2.11	-26.4	1.91	-28.0	2.08	-26.4	0.73	-27.0
2552	2.74	-34.6			1.22	-38.7	0.86	-32.2	0.99	-33.2
2558-93	1.79	-20.9	2.64	-24.8					1.11	-30.3
2558-94	2.47	-32.3	2.07	-25.2	1.89	-33.4			0.81	-33.0
2603	0.30	-15.0	0.12	-17.6	0.53	-13.1	0.70	-13.3	0.20	-16.3
2604	1.05	-26.2	1.88	-15.1	0.59	-23.0	1.51	-19.3	0.76	-24.3
2611-A	0.80	-24.5							0.47	-17.5
2611-B	0.79	-32.5			1.07	-26.4			1.06	-34.5
2617	1.26	-30.9					3.17	-28.2	1.12	-30.5
2622	0.75	-34.1			1.46	-28.7	0.98	-29.8	0.73	-31.4
2704	2.54	-35.1	2.34	-28.0	2.38	-36.7	3.01	-31.7	2.56	-30.0
2711	3.84	-34.5	2.59	-28.0	2.32	-35.0	1.96	-27.8	2.47	-30.0
2742	0.80	-36.6	0.76	-34.1	1.36	-38.8	1.80	-40.4	1.58	-35.6
2825	2.40	-32.2	2.24	-26.4	2.81	-35.0	2.76	-32.6	2.14	-28.2
2838	4.70	-44.6	3.80	-37.6	2.82	-44.7	2.50	-40.5	2.24	-38.5
2880-A	2.36	-29.7	1.87	-24.2	1.94	-31.5	2.12	-26.4	2.11	-24.6
2880-B	2.23	-29.8	2.06	-28.0	2.35	-29.1	2.30	-25.9	2.85	-29.0
2880-C	2.32	-29.7	1.77	-23.9	1.81	-30.8	1.89	-26.6	1.34	-23.2
2880-D	2.45	-31.6	2.37	-27.9	1.96	-30.2	2.02	-26.6	1.84	-27.5

Table 3: Comparison of binders limiting temperatures and HMA mixtures fracture temperatures.

	Binder Limiting Temperature C	LMLC STOA Fracture Temp (C)	LMLC LTOA Fracture Temp (C)	FMLC Fracture Temp (C)	FMLC LTOA Fracture Temp (C)	LMLC PAV Fracture Temp (C)
2480	-18.0	-38.4				-29.1
2491	-14.2	-25.1		-17.6		-25.6
2530	-19.2	-38.9	-30.1	-33.2	-31.9	-24.3
2545	-13.5	-33.3	-26.4	-28.0	-26.4	-27.0
2552	-19.9	-34.6		-38.7	-32.2	-33.2
2558-93	-14.2	-20.9	-24.8			-30.3
2558-94	-14.1	-32.3	-25.2	-33.4		-33.0
2611-B	-22.7	-32.5		-26.4		-34.5
2617	-15.6	-30.9			-28.2	-30.5
2622	-12.4	-34.1		-28.7	-29.8	-31.4
2704	-17.4	-35.1	-28.0	-36.7	-31.7	-30.0
2711	-16.8	-34.5	-28.0	-35.0	-27.8	-30.0
2825	-20.4	-32.2	-26.4	-35.0	-32.6	-28.2
2838	-28.1	-44.6	-37.6	-44.7	-40.5	-38.5
2880-B	-14.1	-29.8	-28.0	-29.1	-25.9	-29.0

Table 4: Summary of regression models relating the fracture temperature of HMA mixture with the limiting temperature of binder.

Mixture TSRST Fracture Temperature, Y(C)	Binder Limiting Temperature, X(C)	Relationship	R^2 Value (%)
LMLC STOA	DT	Y = -16.795+0.875X	65
LMLC LTOA	DT	Y = -15.027+0.712 X	85
FMLC	DT	Y = -15.749+0.850X	55
FMLC LTOA	DT	Y = -13.357+0.873X	88
LMLC PAV	DT	Y = -21.808+0.448X	69
LMLC STOA	BBR-S(t)	Y = -22.156+0.636X	71
LMLC LTOA	BBR-S(t)	Y = -16.332+0.682X	78
FMLC	BBR-S(t)	Y = -19.581+0.683X	60
FMLC LTOA	BBR-S(t)	Y = -15.456+0.810X	90
LMLC PAV	BBR-S(t)	Y = -20.408+0.515X	64
LMLC STOA	BBR-m-value	Y = -12.836+1.085X	53
LMLC LTOA	BBR-m-value	Y = -14.607+0.745X	74
FMLC	BBR-m-value	Y = -11.410+1.072X	51
FMLC LTOA	BBR-m-value	Y = -15.840+0.784X	71
LMLC PAV	BBR-m-value	Y = -20.493+0.552X	59

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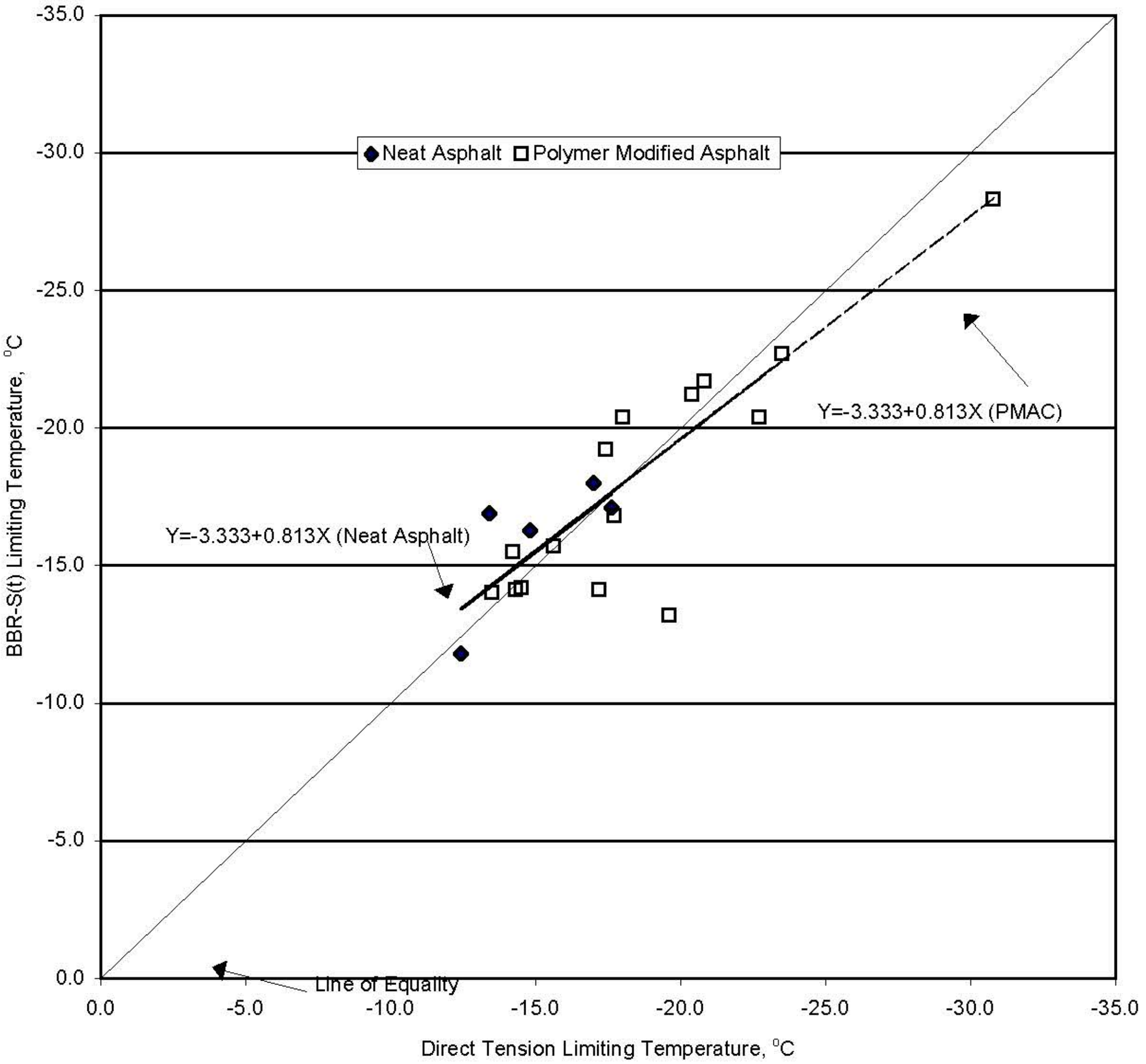

Figure 1. Relationship between BBR S(t) and DT limiting temperatures.

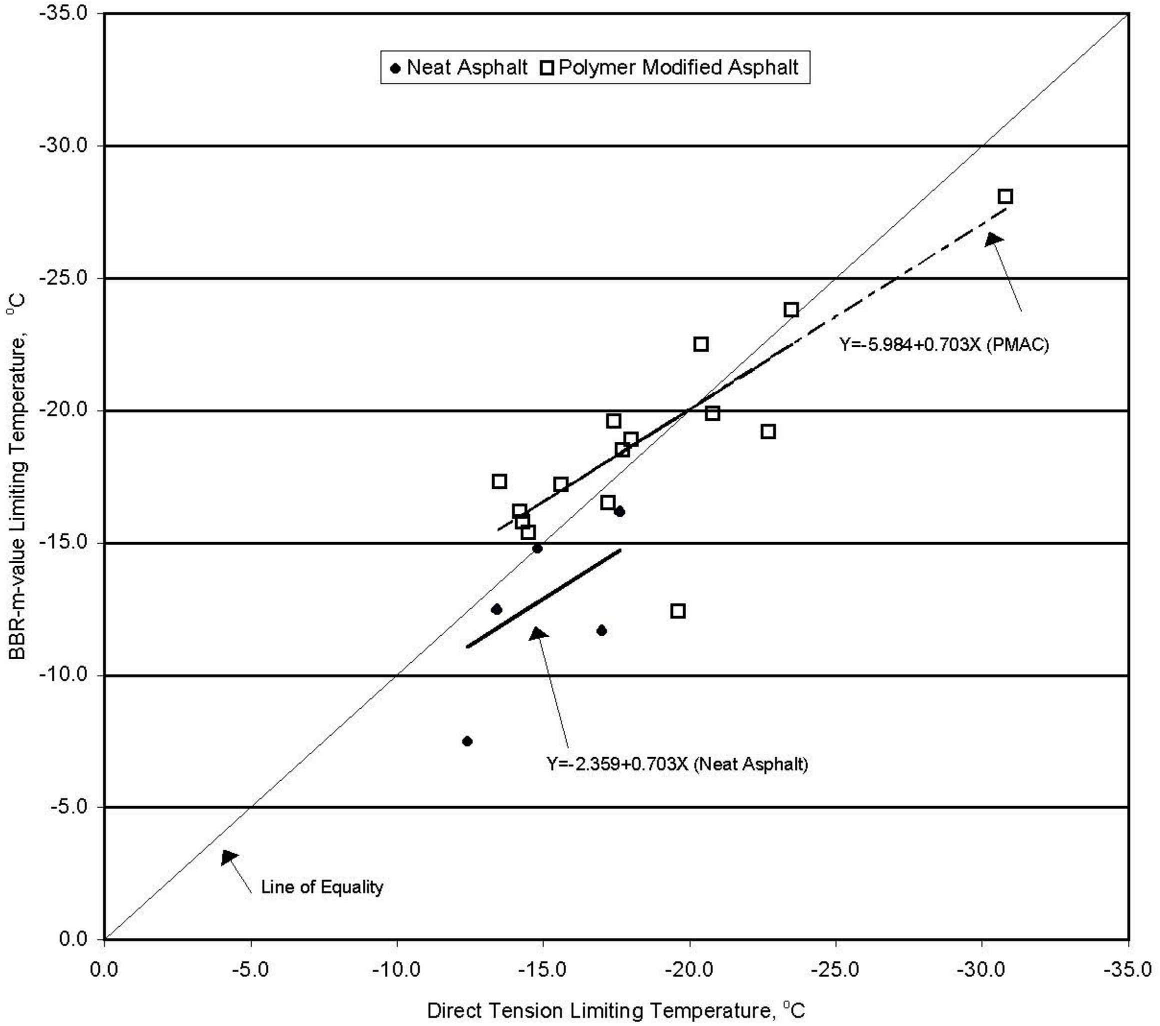

Figure 2. Relationship between BBR m-value and DT limiting temperatures.

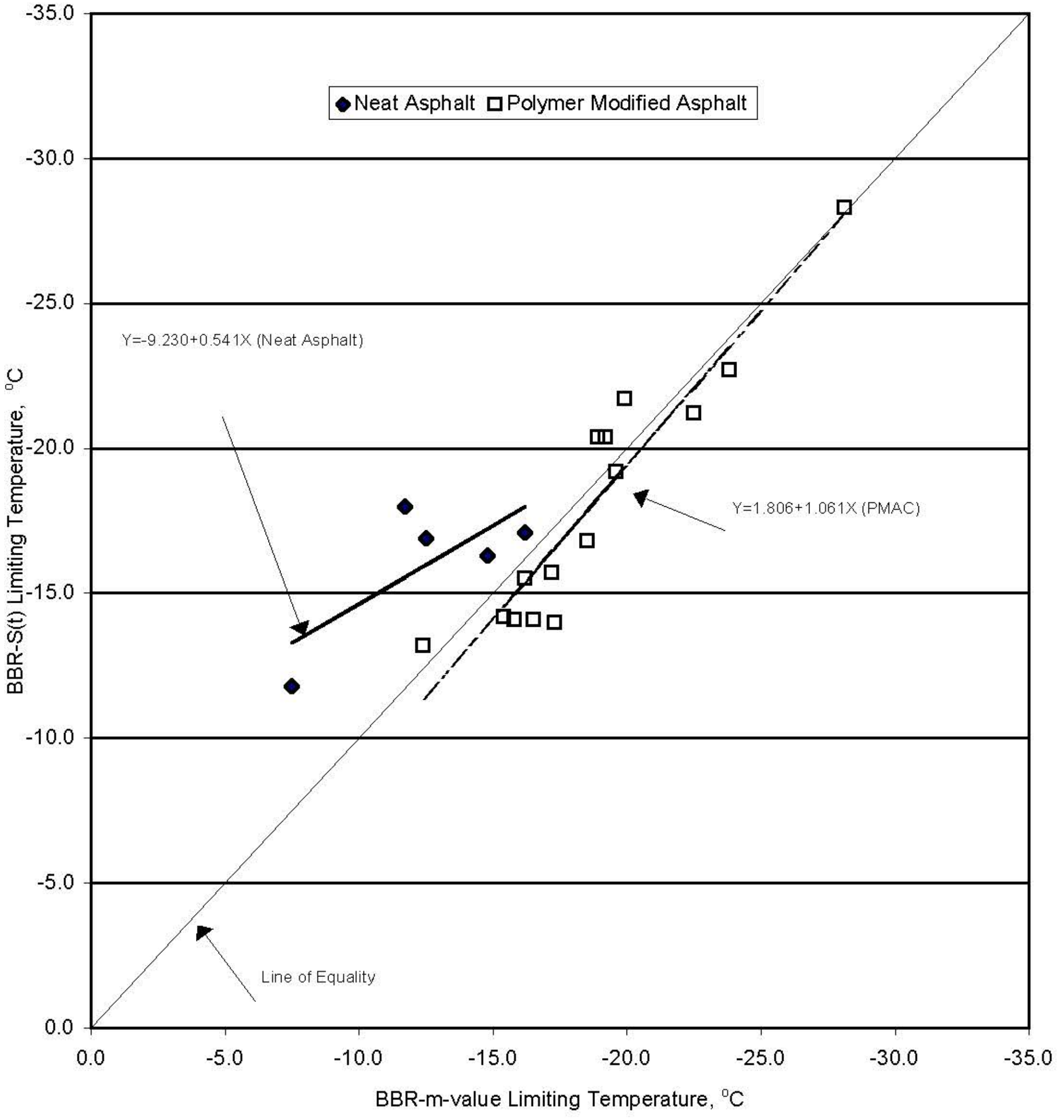

Figure 3. Relationship between BBR m-value and BBR S(t) limiting temperatures.