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FHWA BINDER ETG LOW TEMPERATURE TASK FORCE FINAL REPORT

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Contents

SUMMARY

The current Superpave specifications provide adequate performance prediction for many binders. One deficiency, however, is that by setting the m-value requirement in the specification, consideration of stiffness properties are overridden because most binders will generally fail the m-value at a higher temperature than by the stiffness, S(60). Another deficiency in the current Superpave specification is that the fracture properties such as failure stress or strain at failure are not required. What is needed is a comprehensive mechanistic model that equally considers both rheology and fracture properties of the asphalt binders at low service temperatures to control thermal cracking.

This report describes the development of a comprehensive mechanistic model that enables better prediction of the performance of asphalt binders at low service temperatures. Similar to the current practice the rheology data is obtained using the BBR except, the new model considers data at six loading times of 8 to 240 s. Instead of the current Superpave practice of using only the single point stiffness, S(60), and slope, m-value, the new model utilizes the full stiffness curve. The failure data obtained at two temperatures using the new direct tension

tester is required. Early versions of the direct tension test equipment did not yield satisfactory results, but the newly validated hardware is quite suitable for fast and reliable specification work.

The calibration work for the revised low-temperature specification is based on evaluations, of the Lamont test road in Alberta, Canada. Sections of this road, built in the summer of 1991, were constructed with seven different conventional and air-blown binders uniquely chosen to exhibit both very good and poor low-temperature performance. The binders from the test road were fully PG graded with the low temperature end varying from -22^0C to -40^0C. In addition, extensive binder tests were performed with DSR, BBR, and DTT to allow construction of complete modulus and failure master curves.

A performance model was developed to predict the critical cracking temperature (T_{cr}) of a binder in a pavement. From BBR data the relaxation modulus master curve of the binder is calculated.

Extensive work was done to evaluate the effects of variability in the coefficient of linear thermal expansion (α) and the glass transitions (T_g) of binders. Fortunately the effects can be simply accounted for. Shift factors were calculated using an Arrhenius fit. The convolution integral of the relaxation modulus is then integrated to estimate thermal stress in the binder as a function of temperature. This thermal stress was calculated using iterative numerical methods and was then compared to the fracture stress measured in the DTT to estimate the critical cracking temperature. The critical cracking temperature is where the thermal stress exceeds the failure stress.

Once the BBR creep compliance data was fitted to a master curve, the data was converted to a relaxation modulus master curve using the techniques of Hopkins and Hamming. After the relaxation modulus master curve was generated, the thermal stress was calculated via iterative numerical integration of the convolution integral, a three part process consisting of stress generation, stress relaxation, and summation of the stress. This process is described in detail.

Contents

Significant performance differences were observed in the field. Generally, the harder and low penetration grade asphalts exhibited higher critical failure temperatures and a higher crack frequency (#cracks/km). In the first step these field results were used to compare with the indirect tension test (IDT) results. For a reduced data set the IDT field data agreed well with performance. These results were then compared with the current Superpave binder specification. The current specification over-predicted the performance. In fact, in case of binder in section number 2 the current Superpave specification under-predicted the performance by 5^0C which is almost a full binder grade interval. The DTT failure strain criteria does not constitute a real solution either as it was also found to be biased towards over-predicting performance.

Best results were obtained using the predicted critical cracking temperatures determined using the new model. In six out of seven cases studied, the predictions agreed with the field performance ranges, i.e., the temperature ranges where the binders had failed on the test road. A statistical analysis of the performance comparison data set showed that the new proposed specification correctly predicted performance in 80% of the cases, whereas, the current Superpave specification and the DTT failure strain criteria were expected to fail the comparison with performance in 70 -85% of the cases. In addition, while the current Superpave specification fails to capture the benefits of many modifiers, the newly proposed specification based on critical cracking temperature captures the increased benefit of modifiers through their enhanced strength.

Comparison of the field performance and IDT results on mix retains, with the predicted failure temperature from the new procedure, shows excellent agreement and a reduced probability of failure. Thus, we propose adopting this procedure in-place of the current Superpave specification parameters.

Further field validation was provided by evaluating the Pennsylvania Test Road constructed in September 1976 in Elk County, PA just north of Wilcox. Two polymer modified asphalt binders that have been extensively used in Alberta and Alaska were also evaluated using the new procedure. The field performance data agrees very well with the performance predictions. However, the results indicate that buyers may want to adjust the specified grade in regions where rapid temperature drops are common to account for the increased cooling rates. Binder testing procedures were developed that are effective, efficient and ensure consistent quality. The proposed binder grading requires 2 BBR tests and a minimum of 2 DTT for determination of Tcr. The binder pre-qualification testing is based on 2 BBRs and 1 DTT to ensure that the critical cracking temperature is lower than the specification temperature Based on these results a new verification protocol is proposed. Typically, the proposed new verification test would be used by suppliers during production to maintain consistent quality of the pre-qualified product. The requirements of the verification test include a performance tolerance adjustment on strength and failure modulus, which allow for normal production and testing variations.

INTRODUCTION

Problem

The low-temperature transverse cracking in flexible pavements is a result of the combination of three distress mechanisms: 1) single event thermal cracking (SETC), 2) thermal fatigue (TF), and 3) load-associated thermal cracking (LATC). Out of the three, the single event thermal cracking is the most significant contributor to transverse cracking. The new Superpave binder specification does not discriminate among the various low temperature distress mechanisms. Instead, the stiffness and the slope from the Bending Beam Rheometer (BBR) creep data at a single loading time of 60s are used as surrogate rheological parameters to control pavement transverse cracking at low temperatures. The low-temperature performance, however, is a combination of rheological characteristics as well as fracture properties of the binder at service temperatures. Hence, a comprehensive model of low-temperature pavement performance must include rheological and fracture properties of the asphalt binder. This report describes the development of a comprehensive mechanistic model that enables better prediction of the performance of asphalt binders at low temperatures. To validate the model, low-temperature transverse cracking field data and material characteristics from the Lamont test sections in Canada were used. In this model, only single event thermal cracking is considered. Load induced and thermal cycling fatigue cracking were not included because the climate and traffic data indicate that single event thermal cracking was the predominant distress mechanism in the Lamont test sections.

Contents

Background

In the recent years significant progress has been made in capturing the true low temperature performance of *hot mix asphalt* (HMA). Hill's work demonstrates that for straight run, conventional *asphalt cements* (ACs) the tensile strength falls in a very narrow range and that binder stiffness can be used as a surrogate measure to predict *single event thermal cracking.* This was further substantiated by Deme et al.[2]. They found that the binder stiffness correlated very well with the low temperature performance of the Ste. Anne test sections.

The Pacific Coast User Producer Conference was the first group to attempt to incorporate actual field temperatures into a performance-related specification. To predict the low temperature stiffness the 4^0C penetration was introduced into the *Performance Based Asphalt* (PBA) specifications. Together with the existing specification limit for the 60^0C viscosity (the lower specification limit of the viscosity is based on the climatic regime in which the asphalt shall be used) this approach provided a crude approximation of McLeod's *Pen-I/is Number* (PVN)[3]. The Strategic Highway Research Program (SHRP) incorporated these concepts and improved them by measuring stiffness rather than predicting it using empirical test methods. SHRP further recommended that the stiffness should be measured using the more sophisticated test methods it developed. The *Bending Beam Rheometer*[4] (BBR) and the *Direct Tension Tester*[5] (DTT) were developed as significantly improved tools to evaluate binder rheology and fracture characteristics at low temperatures. One of the major differences of these new specification tests was that they were run near the expected actual lowest pavement temperature.

Note: The low temperature test are all run at a slightly higher temperature, T+?T. The temperature offset is selected to make the testing easier because we compensate/or the increased temperature by increasing the rate which results in decreased test times.

Current Superpave Low-Temperature Specification

In the current Superpave specification, data from both the BRR and the DTT are used. From the BBR data apparent stiffness (inverse compliance), S, is determined at a loading time of 60 seconds. From the same data the slope of the $\log_{10}$ stiffness versus $\log_{10}$ time, the m-value, is also calculated at 60 s. The temperature at which S(60) £ 300 MPa and m(60) ³ 0.3 is specified as the critical temperature + 10^0C. The fracture data (strain at fracture) from the DTT is used only conditionally in the current Superpave low-temperature specification. The failure strain limit of 1%, determined at an elongation rate of 1 mm/min, is used to control thermal cracking. Stress at failure (strength) is not used. This limit is only applicable when the stiffness, (S(60)), of binders at 60s, determined using the Bending Beam Rheometer (BBR), is between 300 MPa and 600 MPa. Accordingly, when stiffnesses are in this range and the binder can resist a strain of 1% or more without fracture, then the maximum creep stiffness requirement of 300 MPa is waived. The 'm ³ 0.3' criteria still must be met. This requirement was incorporated in the specification to accommodate the polymer modified bitumen binders which tend to be stiffer. *However, by* setting the in-value requirement in the specification the DTT results were de facto overridden because most binders would generally fail the in-value at a higher temperature than S(60). And even in those cases where Ts=300 > Tm=0.3 the m-value seldom reflected the field observed benefits of polymer modification. The reason for this discrepancy may be explained as follows. By setting the m-value (60) requirement in the specification, the low-temperature stiffness of the binders, S(60), becomes irrelevant. Consequently, the slope at a single point of 60s (the m-value) ranks the thermal cracking performance for most binders. The stiffness at 60s becomes unnecessary. For example, a binder with S(60) = 120 MPa is ranked the same as long as they both have m(60) = 0.3 at the given low grade temperature. Obviously, the binder with S(60) = 280 MPa will buildup thermal stresses that are greater than the binder with S(60) = 120 MPa while their m-value remains the same. So the only plausible explanation is that these two binders have strengths that are proportional to their S(60) stiffnesses. Failure strength data collected so far does not show a correlation between stiffness and strength. So strength must be considered explicitly along with rheology (S(60) and m-value(60)) to get an all inclusive and meaningful low-temperature binder specification.

Contents

Equation 1 $S(T,t) = S(T+?T,t/aT)$	Equation *2* $m(T,t) = d \log S/d \log t(T + ?T,t/aT)$
Equation 3 $e_f = f(T,de/dt)$	Equation 4 $?_f = f(T,de/dt)$

The DTT provides us with a tool to measure failure strain (e_f) and tensile strength $(?_f)$ of binders in a simple, reproducible and fast fashion. Nevertheless, the DTT, as developed during SHRP[5]was not fully implemented because the test equipment did not meet the required specifications and test procedures were not fully developed. An improved fluid based version[6] developed by the Federal Highway Administration's Office of Technology Applications (FHWA-OTA), was also found to have problems.
Some of the main issues in this regard were:

- *Temperature control and control type (fluid bath versus gas cooled chamber).*
- *Compliance.*
- Plexiglass End-Tab Compliance
- Machine Compliance
- *Rate control*
- *Silicone Rubber Molds were found to significantly affect fracture properties*
- *Alcohol, used as a cooling medium in the BBR, significantly affected Fracture properties*
- *Effective gage length equal to 26.66 mm used during SHRP is incorrect*

After these findings, a complete re-evaluation of the new DTT test method and related calculations was undertaken by the FHWA-OTA. This gave rise to three significant changes in the protocol for using the new Superpave DTT[7].

1. The silicone rubber molds used for producing bitumen test specimen have been replaced by specially designed aluminum molds.
2. Alcohol was replaced by a mixture of 43% potassium acetate and 57% de-ionized water as the cooling medium.
3. The effective gage length, Le, needed to compute accurate strains had to be changed to 33.8 mm from the current value of 26.66 mm based on the finite element analysis of the specimen geometry. These calculations were conducted by The Instron Corporation at their Boston, MA facility. A compliance value for the plastic end tabs was determined and included in calculations.
4. Plexiglass end-tabs (inserts) used to load the specimen are now replaced by specially designed end-tabs made from G-10 phenolic resin (glass-reinforced epoxy). End-tabs made from aluminum may also be used.

The Instron Corporation of Canton, MA incorporated the above improvements. The new DTT was thoroughly tested and an AASHTO test method reflecting the changes is now available[8]. The Utah Department of Transportation is currently successfully using this new Superpave DTT as a low-temperature specification requirement for all asphalt binders.

Contents