ADVANCED TECHNIQUES TO DEVELOP ASPHALT MASTER CURVES FROM THE BENDING BEAM RHEOMETER

G.M. Rowe, M.J. Sharrock, M.G. Bouldin and R.N. Dongré

President, Abatech, Inc., Director, Abatech International, Ltd., Senior Scientific Advisor, Koch Materials Company, President, Dongré Laboratory Services, Inc.

Abstract. *From BBR data the relaxation modulus master curve of the binder is calculated. Shift factors were determined using an Arrhenius fit. Once the BBR creep compliance data was fitted to a master curve, the data was converted to a relaxation modulus master curve using Hopkins and Hamming procedure. Data from the Lasmont test road in Canada is analyzed using various methods and recommendations are made for master curve analysis of bonders with test data from the bending beam rheometer.*

Key words: *master curves, shift factors, low temperature, bending beam rheometer, asphalt binders*

Introduction

The Bending Beam Rheometer was introduced as a test method for asphaltic binders during the Strategic Highway Reserach Program (SHRP). This method of testing has been adopted in the provisional specification to determine binder stiffness at 60 seconds and the slope of the stiffness curve – log time versus log stiffness – the m-value, to grade asphalt binders. However, recent work has led to an alternate specification parameter being calculated, with data from the BBR being used to generate themal stress in the pavement structure. As part of the development work a considerable effort has been made to develop a robust procedure to determine master curves from the bending beam rheometer. Data is presented which has been analyzed using four procedures and recommendations are made with regard to the method of master curve analysis.

Background

The BBR was specially developed to overcome testing problems that can occur with other methods when testing stiff binders at cold temperatures. The testing mode of this equipment is illustarted schemically in Figure 1.

The test specimen is a slender beam of asphalt binder (125 x 12.5 x 6.25 mm) which is simply supported is loaded with a constant force at mid span. The deflection is monitored with time and this is used for calculation of the stiffness as a function of time using Equation 1.

$$S(t) = \frac{PL^3}{4bh^3\,\Delta(t)} \qquad (1)$$

where S(t) = Creep stiffness at time, t
(t = 60 seconds is used as standard)
P = Applied consatnt load, normally 100g
L = Distance between beam supports, 102 mm
b = Beam width, 12.5 mm
h = Beam thickness, 6.25 mm
Δ(t) = Deflection at time, t
(t = 60 seconds used as standard)

The stiffness and the slope of the stiffness curve (m-value) have been used in the Superpave specification as illustrated in Figure 2.

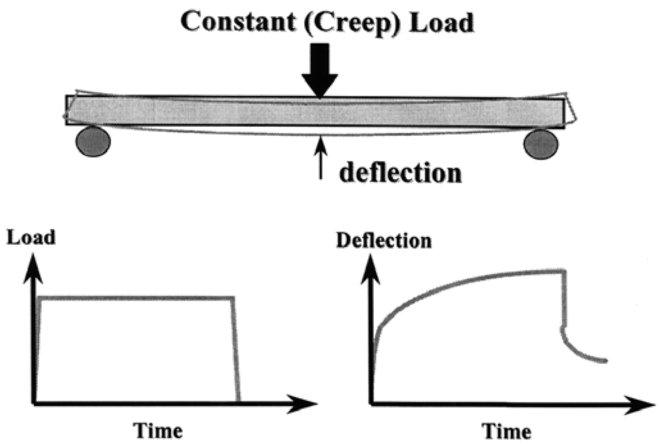

Figure 1. Bending Beam Rheometer

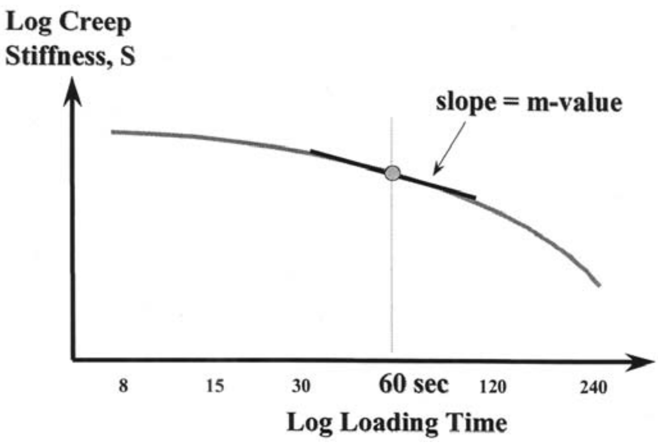

Figure 2. Determination of S(60) and m-value

The creep stiffness data from this test method has also been used to construct master curves using time-temperature superposition (Bahia et al., 1992)

Material Testing

During the development of the master curve analysis procedure test data was acquired on seven binders placed on the Lamont Test Road in Canada (Anderson, 1998). These binders varied considerably in their properties and provide a good range of properties to evaluate the models. The RTFO aged binders from sections 1, 4 and 7 from this project were examined. In addition, several modified binders have also been evaluated using the procedures described herein.

Analysed Method

The first step of the analysis is to create master curves of the relaxation modulus from the BBR data. As with all fitting procedures there is, of course, no single solution or recipe for generating the required data. A procedure has been selected because it provides numerical stability with the constraints of the testingh.

Isotherms of the apparenet stiffness, S(t), (1/compliances from BBR data) are used with best results are obtained by using multiple BBR isotherms.

To obtain shift factors BBR stiffness data at six loading times between 8 and 240s for everey temperature is shifted horizontaly on the log time axis to form a smooth curve with reasonable overlap. The shift factor needed to horozontally shift the BBR is numerically determined using Gordon and Shaw's method (1994).

The temperature dependency of the shift factors is modeled using the Arrhenius equation where a_1 is an asphalt dependent constant, Equation 2.

$$\ln(a_T) = a_1 \left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \quad (2)$$

The factor a_1 is the slope of the temperature dependency of the shift factor and can vary for differnet asphalt crude sources whilst modifiers do not appear to significantly affect its value. The reduced time, ξ is then determined by dividing the physical time by the shift factor.

$$\xi = \frac{t}{a_T} \quad (3)$$

In the next step the master curve of the BBR stiffness data, S (t) is fitted to a functional relationship before the relaxation modulus, E(t), is determined.

Various models have been evaluated for the fitting of master-curves. Christensen and Anderson (1992) proposed a form of model which two parameters are fitted with a known glassy modulus, as follows:

Christensen-Anderson (CA):

$$S(\xi) = S_{glassy}\,[1 + (\xi/\lambda)^{\beta}]^{-1/\beta} \quad (4)$$

S_{glassy} is a constant ($3*10^3$Mpa) and λ and β are fitted.

This type of the model enables the low temperature properties of asphalt binders to be modeled with reasonable accuracy. However, it should be noted that models of this form should not be applied to the total binder master curve since no change in the slope of [d log S(ξ) /d log (ξ)] is possible at higher temperatures (Stastna et al., 1997). This is because at long times $S(\xi) \approx S_{glassy}\,(\xi/\lambda)^{-1}$ and at short loading times $S(\xi) \approx S_{glassy}$.

Christensen-Andersen method can be considered to be restricted form of a more general equation proposed by Sharrock and Bouldin as follows:

Christensen-Anderson-Sharrock-Bouldin (CASB):

$$S(\xi) = S_{glassy}\,[1 + (\xi/\lambda)^{\beta}]^{-\kappa/\beta} \quad (5)$$

S_{glassy}, λ, β and κ are fitted.

In the CASB method four parametrs are fitted. However, while this method works well with data collected over a wide time range the limited data from the BBR the stiffness data is best fitted using only three-parameter model.

Typically BBR data generally covers only two decades of stiffness and loading time. Consequently, two additional three parametrs models are evaluated as follows:

Christensen-Anderson-Marasteanu (CAM) (Marasteanu and Anderson, 1999):

$$S(\xi) = S_{glassy}\,[1 + (\xi/\lambda)^{\beta}]^{-\kappa/\beta} \quad (6)$$

S_{glassy} is a constant ($3*10^3$Mpa) and λ, β and κ are fitted.

Christensen-Anderson-Sharrock (CAS):

$$S(\xi) = S_{glassy}\,[1 + (\xi/\lambda)^{\beta}]^{-1/\beta} \quad (7)$$

S_{glassy}, and are fitted.

In addition, the discrete spectrum model has been evaluated as part of this work.

Discrete spectrum (DS):

$$S(\xi) = S_{glassy} \sum_{i=1}^{n} S_i \,.\, e^{-\xi/\lambda_i} \quad (8)$$

In this method "n" is numerically optimized and the relaxation strenghts, g_i, relaxation times, λ_i, estimated.

The shifted BBR stiffness master curve is fitted to the model using a modified non-linear Marquadt-Levenburg least squares otimization.

An approximation to the relaxation modulus master curve is calculated using the algorithm of Hopkins and Hamming (1957). The Hopkins and Hamming algorithm provides a numerical solution to the convolution integral required to convert BBR creep stiffness (actually compliance, D (ξ), is first computed using the model parameters determined above, D (ξ) = $1/S_{BBR}(\xi)$) to relaxation modulus. The convbolution integral may bewritten as:

$$\int E(\xi)D(t-\xi)d\xi = t \quad (9)$$

The expression for calculateing each $E(t)$ at values of t midway between the values of t where $D(t)$ is known is as follows:

$$E(t_{n+\frac{1}{2}}) = \frac{t_{n+1} - \sum_{i=0}^{n-1} E(t_{i+\frac{1}{2}})[f(t_{n+1}-t_i) - f(t_{n+1}-t_{i+1})]}{f(t_{n+1}-t_n)} \quad (10)$$

where

$$f(t_{n+1}) = f(t_n) + \frac{1}{2}[D(t_{n+1}) + D(t_n)][t_{n+1} - t_n] \quad (11)$$

The initial value $f(t)$ at zero time is set as zero.

The E (ξ) data is then fitted using the model parameters. While this appears to be a complex and laborious effot to convert the compliances to true relaxation modulus, instead of taking the inverse and using it as relaxation modlus., Figure 3 illustrates the imporatnace of this step. Even for much less complex materails (as in this example PIB) the simple inversion does not fit the data very well when the material exhibits any real changes of the relaxation modulus, i.e., when the material becomes more viscous. Obviously, most asphalts exhibit significant changes of the modulus with increasing time (or temperature). Consequently, the resulting error is non-trivial.

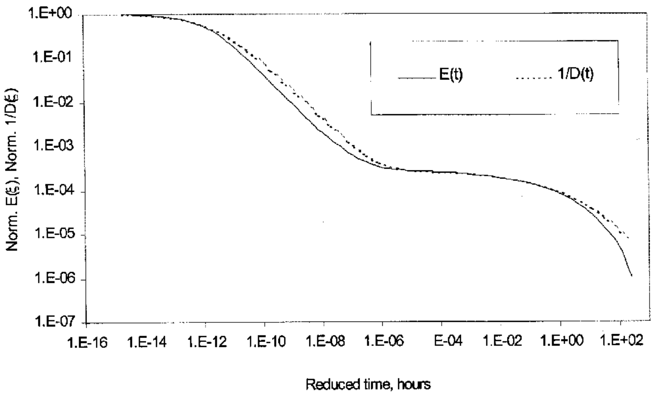

Figure 3. Comparison of Inverse Compliance to Relaxation Modulus for Polyisobutylene

Sensitivity Analysis

The results obtained with the three Lamont binders are given below for the model parameters using two and five isotherms in the analysis method. In addition the root mean square (rms) errors expressed in percent for each of the methods has been calculated as indicated below.

When five isotherms are present the lowest rms% error is obtained with the discrete spectrum method whereas when 2 isotherms are present then best results are obtained with the CAS method. The poorest method for the fitting is the CA method, which is expected since this is only a two-parameter model.

The functional form models such as the CA, CASB, CAM and CAS methods are all similar in that they model the entire shape of the master curve.

As previously mentioned in the CASB nethod it was recognized that the slope of the master curve at long loading times might not be equal to – 1 (for large times the slope becomes κ) and that the glassy modulus needs to be fitted since this does vary with binder source. Consequently, the flexibility of this model allows more complex materials to be modeled. However, with the limited range of data that is obtained from the BBR - typically 2 decades of loading time and a single decade of stiffness – it was determined that generally allowing three parameters to vary a good fit of the data can be obtained. Consequently, subsequent evaluations were limited to the three parameter functional form models.

Both the CAM and CAS methods are simplifications to the CASB method, which fit 3 parameters. The CAM method, like the CA method, fixes the glassy modulus at 3 GPa. Christensen and Anderson (1992) adopted this value based upon the large volume of historical data that suggests that this is an appropriate value of binder stiffness representing glassy behaviour.

However, other researchers such as Dickinson and Witt (1974) suggest that the glassy modulus can vary as a fundamental material property. In order to evaluate the significance of variation in glassy modulus the CAS model was evaluated.

From the initial analysis it appears that the CAS method fits the data with the highest level of accuracy. This is considered to have occured as a direct result of allowing variable glassy moduli values in this method. This was particularly evident with Lamont 1 dara set that is consistent with high glassy moduli.

The largest errors are associate with the Lamont 1 data. This data is plotted in Figures 4 and 5 for the two and five isotherm data respectively. It can be observed from these figures that all methods give very close fits that are nearly impossible to discern graphically.

The selection of the most appropriate method in part depends upon the analysis need of the engineer using the

Table 1. RMS Error in % obtained from master curve fit

Lamont Test Section	2 Isotherms				5 Isotherms			
	DS	CA	CAS	CAM	DS	CA	CAS	CAM
1	1.246	0.936	0.501	1.481	0.646	3.370	1.185	2.278
4	0.352	0.982	0.819	0.825	0.886	0.910	0.697	0.775
7	0.505	1.689	0.761	1.156	0.575	2.078	0.849	0.951
Mean	0.701	1.202	0.694	1.154	0.702	2.119	0.910	1.335
Rank	2	4	1	3	1	4	2	3

Table 2. Fitted model parameters

Lamont Test Section	Parameter	2 Isotherms			5 Isotherms		
		CA	CAS	CAM	CA	CAS	CAM
1	S_{glassy}	3000	4139.82	3000	3000	7970.31	3000
4	S_{glassy}	3000	3481.72	3000	3000	3470.19	3000
7	S_{glassy}	3000	4349.70	3000	3000	3831.12	3000
1	λ	9952.87	30792.98	128.49	19437.16	324839.95	280.88
4	λ	7303.23	12819.98	316.39	9028.26	13864.20	1051.45
7	λ	402.00	843.77	107.37	1370.62	2389.16	155.09
1	β	0.1539	0.1319	0.1689	0.1471	0.1020	0.1586
4	β	0.1586	0.1465	0.1692	0.1561	0.1458	0.1635
7	β	0.1878	0.1585	0.1931	0.1878	0.1663	0.1991
1	κ	1	1	0.6568	1	1	0.6681
4	κ	1	1	0.7271	1	1	0.8126
7	κ	1	1	0.8518	1	1	0.7794

Figures in bold indicate default values

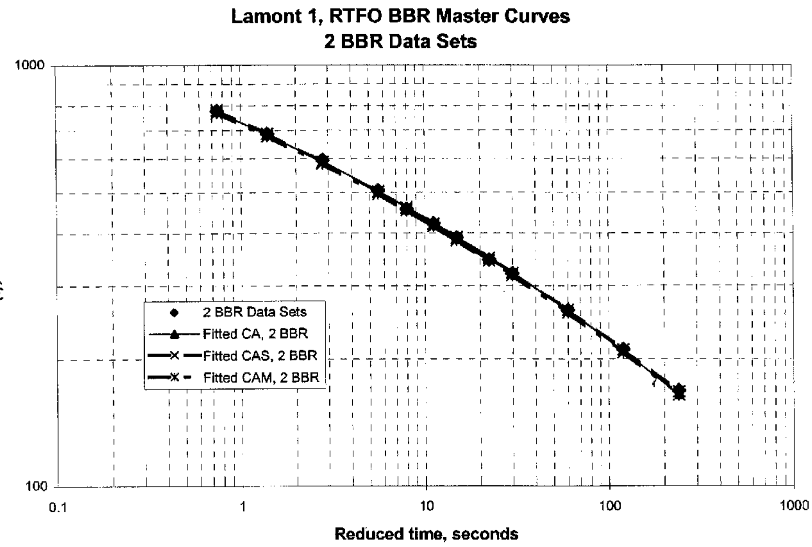

Figure 4: BBR master curve using 2 isotherms, Tref = - 24 °C

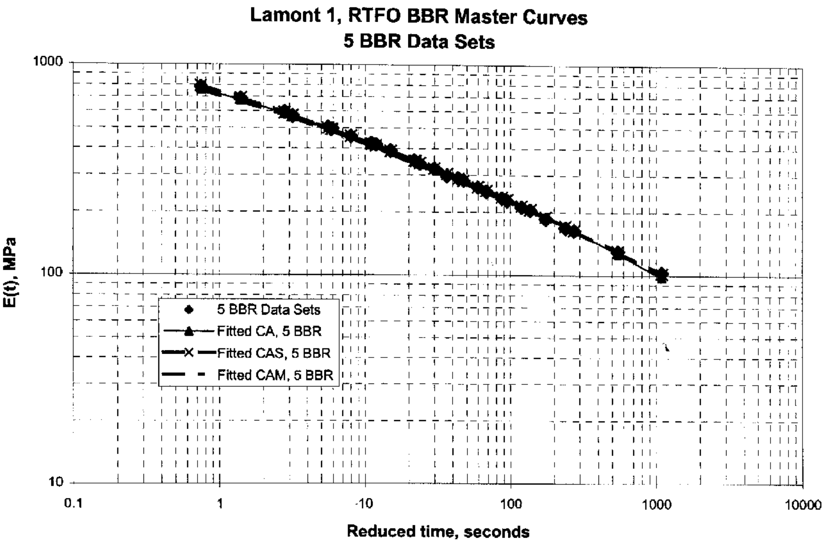

Figure 5. BBR master curve using 5 isotherms, Tref = -24 °C

results. For example if visco-elastic analysis is to be conducted then the *discrete spectrum* may be the preferred method since the relaxation strengths and times are used in the input to the analysis. The discrete spectrum method appears to be one of the most reliable methods for obtaining a good fit for the master curve parameters (see Figure 6 – Lamont Test Section 1, 5 Isotherms). However, with this method the results should not be extended beyond the data set since often non-physical behaviour is often obtained when the results are extrapolated as illustrated earlier.

To investigate the quality of fit further to the shape of the master curve an analysis of errors at different stiffness measurements has been made. Examples of this analysis are presented in Figures 7 and 8 for the Lamont 1 and 4 binder data sets. These two are illustrated since they represent the highest and lowest errors obtained with the functional form models. The percent error at each stiffness value has been determined and plotted versus the corresponding stiffness value. A moving average line (3 data points) has then been fitted through the data points. Data with no bias is represented by a horizontal line at the zero value or by a line close to the zero value.

From inspection of the two figures it can be observed that with Lamont 1 that both the CA and CAM methods under-predict the stiffness at high and low values of stiffness. In addition the CA over-predicts the stiffness at intermediate values of stiffness.

The CAS method produces the best fitting of the shape of the stiffness curve. Lamont 4 data set represents results that are

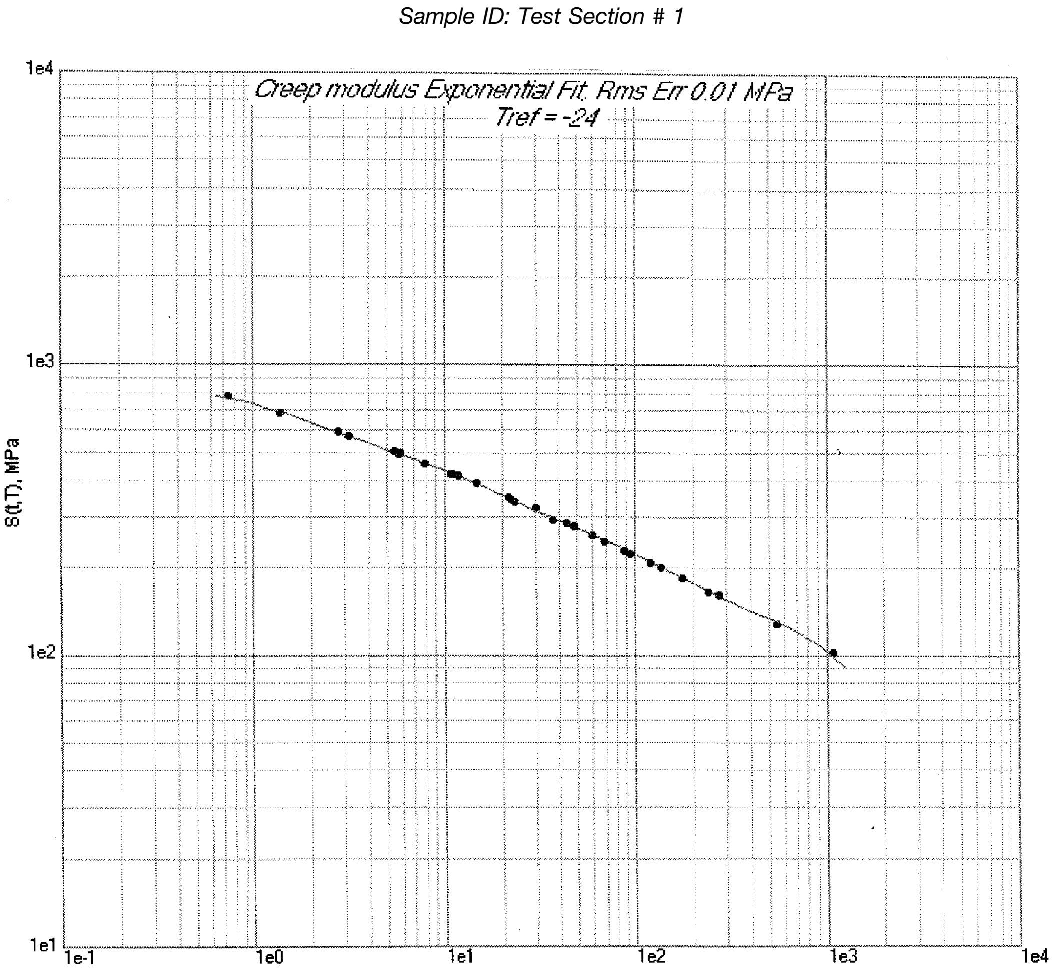

Figure 6. Discrete Spectrum Fit to Lamont 1, 5 Isotherms, Tref = -24 °C

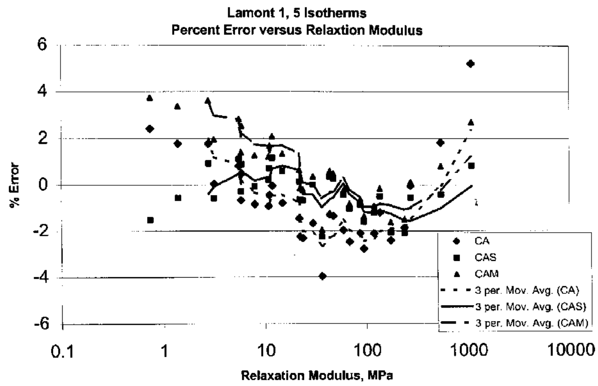

Figure 7. Bias Assessment in Master Curve Fit, Lamont 1, 5 Isotherms

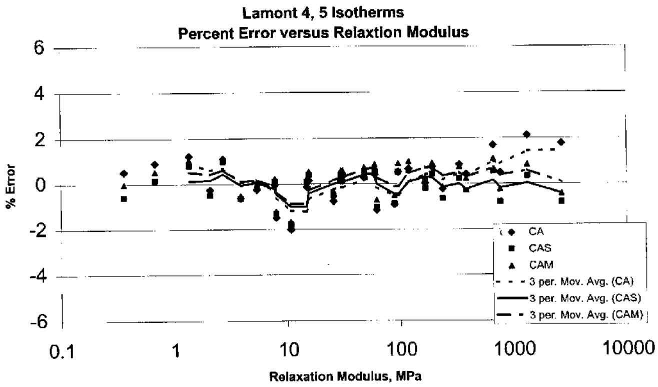

Figure 8. Bias Assessment in Master Curve Fit, Lamont 4, 5 Isotherms

close 3,000 MPa S_{glassy}, used by the CA and CAM methods. However, with this data set the CAS method also offers the least bias and produces the least error variation with stiffness. However, it should be noted that the "true" value of the glassy modulus may be significantly different to that obtained in this fitting process and the results reported for the CAS method should be regarded as a fitting parameter.

For specification purposes it has been proposed to gather the BBR data at the two Superpave temperatures which bracket S(60) = 300Mpa. The reference temperature is always the higher of the two temperatures (i.e. the test temperature where S(60s, T_{test} < 300Mpa). The BBR data at the reference tempersture is held stationary. This data is then used to compute thermal stresses in the pavement structure. Since the failure of pavement structures occurs close to these temperature it is postulated that the most important aspect of BBR stiffness master curves is the region between 100 MPa and 500 MPa stiffness.

A typical comparison of the relaxation modulus from the Lamont data sets – 5 isotherms versus 2 isotherms – yields ratio at 1, 10 and 100 seconds as follows:

Loading Time (seconds)	E(ξ) 2 Isotherms/E(ξ) 5 Isotherms
1	1.02
10	1.01
100	0.98

From inspection of this data it can be concluded that using two isotherms yields sufficiently accurate results compared to 5 isotherms which can then be used for thermal stress calculations. If more complete behaviour is required then further isotherms should be included in the analysis.

Conclusions

Four methods have been used to fit asphalt master curves at low temperatures. From analysis of binders supplied to the Lamont test road in Canada we are able to draw conclusions, as follows:

1. Overall the Discrete Spectrum fit appears to be the best method for fitting a master curve over a wide range of temperatures. However, this method cannot be used to extrapolate the data beyond the range over which it is collected.
2. The CAS method provides the best fit to the Lamont data from sections 1, 4 and 7 since it allows variation in the glassy modulus and the terminal slope which are fixed in other functional from methods evaluated.
3. Comparisons of 2 versus 5 isotherms to produce a master curve results in similar stiffness results at 1, 10 and 100 seconds reduced time. This enables two data sets to be used for thermal stress calculations.
4. Overall, the CAS method appears to be the best functional form for fitting BBR data with the data sets investigated to date. This method results in the lowest root mean square errors and the least bias in the test results.

The results presented in this paper have been based upon data obtained from the bending beam rheometer. The methods presented are suitable for this equipment and the temperature ranges considered. However, they should be used with caution at higher temperatures.

Acknowledgements

The authors would like to thank the following organizations for the encouragement with this work; Citgo Refining Company, ERGON, Enichem Elastomers Americas, Fina Oil and Chemical Company, Koch Materials Company, MTE Services Inc.,Shell Chemical Company and Ultra-Pave. Our sincere thanks go to all the staff at University of Calgary for their special support and assistance. Last but not least, we would like to thank Alberta Trans, and especially Jim Gavin, for their generous help in making the data and samples available.

References

Anderson, K., Further Investigation Concerning Low Temperature Cracking of Asphalt Pavements Using C-SHRP Test Roads, "Final Report, 1998.

Bahia, H.U., Anderson, D.A. and Christensen, D.W., The Bending Beam Rheometer: A Simple Device for Measuring Low Temperature Rheology of Asphalt Binders, Journal of the Association of Asphalt Paving Technologists, Volume 61, 1992, pp. 67–116.

Dickinson, E.J., and Witt, H.P., The Dynamic Shear Modulus of Paving Asphalts as a Function of Frequency, Transactions, Society of Rheology 18:4, 1974, pp 591-606.

Gordon/Shaw, Computer Programs for Rheologists, Hanser/ Gardner Pubs, 1994

Hopkins I. L. and Hamming R.W., On creep and Relaxation, Jour. Appl. Phys., Vol. 28, No.8, pp. 906, 1957.

Marasteanu, M. O., Anderson, D.A., Improved model for Bitumen Rheological Characterization, Eurobitume Workshop on Performance Related Properties for Bituminous Binders, Luxembourg, May 1999, paper no. 133.

Stastna, J. Zanzotto, L. and Berti, J., How Good are Some Rheological Models of Dynamic Materilas Function of Asphalt, Journal of the Association of Asphalt Paving Technologists, Volume 66, 1997, pp. 458–485.