The International Journal of Pavement Engineering, Vol. 3, (2002)

Estimating the Unrecovered Strain during a Creep Recovery Test from the Material's Volumetric-flow Rate (MVR)

AROON SHENOY

Senior Research Fellow
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101
Tel: (202) 493 3105
Fax: (202) 493 3161
E-mail: aroon.shenoy@fhwa.dot.gov

Abstract

The ineffectiveness of the Superpave specification parameter $|G^*|/\sin\delta$ in capturing the high temperature performance of paving asphalts, especially some polymer-modified ones, has led researchers to seek other possible parameters that may relate to rutting resistance better. Some researchers suggested a repeated creep and recovery test as a means to obtain a new rutting parameter, while other researchers suggested a refinement to the existing Superpave specification parameter. A new parameter defined as $|G^*|/(1-(1/\tan\delta\sin\delta))$ was previously derived from first principles and proposed as a refined Superpave specification parameter for future use. This new parameter was shown to essentially give the same information as that obtained through a repeated creep and recovery test.

The present work demonstrates a simpler method to obtain the unrecovered strain during a repeated creep and recovery test and uses the material's volumetric-flow rate (MVR) to get this information. While the repeated creep and recovery test as well as the $|G^*|/(1-(1/\tan\delta\sin\delta))$ parameter are obtained from the Dynamic Shear Rheometer (DSR), the MVR is obtained from a simple Flow Measurement Device (FMD). The FMD is a relatively inexpensive portable piece of equipment with low operational costs, and, through minimal training, the MVR data can be generated with a low level of variability. Thus, the proposed method of estimating the unrecovered strain during a repeated creep and recovery test from the MVR is greatly advantageous.

Keywords : Superpave specification parameter, repeated creep, creep recovery, rutting resistance, asphalt rheology, material's volumetric-flow rate, flow measurement device

INTRODUCTION

The Superpave specification parameter |G*|/Sin δ for high temperature performance grading of paving asphalts has not been found to be satisfactory in rating various binders, especially some polymer-modified ones, for their rutting resistance [Phillips and Robertus (1996), Stuart and Mogawer (1997), Bahia et al. (1999), Chabert et al. (1999), Mazé and Brûlé (1999), Collop and Khanzada (1999), Desmazes et al. (2000), Bouldin et al. (2000, 2001), Shenoy (2001a)]. The failure of this parameter has been demonstrated through field data during the Accelerated Loading Facility (ALF) testing at the Turner-Fairbank Highway Research Center by Stuart and Mogawer (1997) and also through laboratory testing during the National Co-operative Highway Research Program (NCHRP) Project 9-10 by Bahia et al. (1999). This has been the driving force for researchers to seek other possible parameters which may relate to rutting resistance better and also to search for ways to refine the existing parameter |G*|/Sin δ so as to make it more sensitive to pavement performance.

The repeated creep and recovery test for binders (RCRB) has been suggested by Bahia et al. (1999) as a possible means to estimate the rate of accumulation of permanent strain in the binders. The RCRB test protocol consists of applying a creep load of 300 Pa for a 1-second duration (loading time) followed by a 9-second recovery period (rest period) for 100 cycles in a Dynamic Shear Rheometer (DSR). Bouldin et al. (2000, 2001) utilized the RCRB as proposed by Bahia et al. (1999) to evaluate the relative rut resistance of test binders. The generated experimental data was then used by Bouldin et al. (2001) to develop a semi-empirical model to refine the current Superpave high temperature specification parameter |G*|/Sin δ also obtained from the DSR.

The proposed refinement to the Superpave specification parameter as done by Bouldin et al. (2001) involved five empirical fitting parameters that would change if more data are analyzed, or if experimental data of the replicates were used instead of those on the original samples. In other words, the expression suggested by them by force-fitting experimental data cannot be truly treated as an equation with general validity.

Shenoy (2001a) has shown that it is possible to provide a refinement to the Superpave high temperature specification parameter simply by following first principles and deriving the methodology through basic concepts rather than by force-fitting experimental data. The expression given by Shenoy (2001a) for %-unrecovered strain is as follows:

$$\%\gamma_{unr} = \frac{100\sigma_0}{|G^*|}\left(1 - \frac{1}{\tan\delta \sin\delta}\right) \text{-------------------} (1)$$

where γ_{unr} is the unrecovered strain, σ_0 is the applied stress in Pa, |G*| is complex modulus in Pa, and δ is the phase angle in radians.

To minimize the unrecovered (or permanent) strain, the following term needs to be maximized.

$$\frac{|G^*|}{\left(1-\frac{1}{\tan d \sin d}\right)} ----------------------------- (2)$$

Shenoy (2001a) has suggested the above term as the new specification parameter, instead of |G*| /sin *. The high specification temperature is specified as the temperature at which the term given by expression (2) takes a value of 1 kPa for the original unaged binder and a value of 2.2 kPa for the RTFOT aged binder. The values of 1 kPa for the original unaged binder and 2.2 kPa for the RTFOT aged binder have been retained because only then the equation would predict around the same specification temperatures for unmodified binders as predicted under the earlier Superpave specification system.

Whether the unrecovered strain is obtained through a repeated creep and recovery test or through equation (1) using frequency sweep data, the rheological information has to be generated from the Dynamic Shear Rheometer (DSR). Recently, Shenoy (2000a, 2000b, 2001b, 2001c) has shown that all the fundamental rheological data obtained in frequency sweep during oscillatory shear from the DSR can be unified using the material's volumetric-flow rate (MVR) determined from the Flow Measurement Device (FMD).

OBJECTIVE

The purpose of the present work is to show that the unrecovered strain during a repeated creep and recovery test can be estimated directly from the MVR when the unified curve is used. The method of estimation is demonstrated through the analysis of the rheological data for one particular polymer-modified asphalt chosen as a case study. Limiting the work to one particular polymer-modified asphalt was done on purpose so that the methodology does not get lost among the multitude of graphs and tables that would have otherwise been present if a large number of binders were used in this study. Moreover, when developing the relationship between creep recovery and |G*|/(1-(1/tan δ sin δ)), over 30 asphalt binders were analyzed in the earlier work [Shenoy (2001a)], and in validating the unification technique over 20 asphalt binders were used in the previous work [Shenoy (2000a, 2000b, 2001b, 2001c, 2001d)]. The present work basically establishes the connection between the creep recovery and the unification parameter through the unified curve of |G*|/(1-(1/tan δ sin δ)). Hence, using a single polymer-modified asphalt in this study was thought to be sufficient for outlining the methodology. The outlined procedure can, however, be used for all asphalts, irrespective of whether they are unmodified or modified with different polymers.

EXPERIMENTAL DETAILS

Binder Used

The binder chosen as case study for the present work is a thermoplastic elastomer (TPE) - modified asphalt - Styrelf. This was used in the Accelerated Loading Facility (ALF) experiment [Stuart and Izzo (1999)] at the Turner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA).

Styrelf is manufactured by Koch Materials, Wichita, KS. The base asphalt used for Styrelf is AC-20. This asphalt is first blown to AC-40 grade and then around 6% styrene-butadiene (SB) is added to it. Sulphur is added for the reactions to occur in order to achieve chemical links with asphaltenes and other reactive species in the asphalt. Under the original Superpave performance grading system, Styrelf grades as PG82-22.

Equipment Used

The Styrelf samples for each experiment were tested after aging using the rolling thin film oven test (RTFOT) at 163°C for 85 minutes. The performed experiments were creep (followed by recovery) and the frequency sweep on the Rheometrics constant stress dynamic shear rheometer (DSR) at five different temperatures (61°C, 70°C, 74°C, 76°C, 80°C). The creep experiments were performed under a fixed imposed stress F_0 of 0.3 kPa and (a) using 1-second loading time followed by a 9-second recovery time and (b) using 10-second loading time followed by a 90-second recovery time.

The frequency sweep data were generated at five different temperatures (61°C, 70°C, 74°C, 76°C, 80°C) using a set of parallel plates of 25 mm diameter following the procedure given in the AASHTO provisional specifications (AASHTO 2000). The samples for the test were prefabricated using a silicone rubber mold. The data were generated for a frequency range from 0.1 radians/s to 100 radians/s. It was made certain that all generated data were within the linear viscoelastic range of response.

The Kayeness Melt Indexer Model D4002 was used as the Flow Measurement Device (FMD) in order to measure the material's volumetric flow rate (MVR) at five different temperatures (61°C, 70°C, 74°C, 76°C, 80°C). The material's flow characteristic is assessed from the volumetric displacement with time based on the piston's downward movement. At each temperature and each load conditon, three readings for MVR were obtained in one run of the sample, and the average was used. Only the average values are shown in Table 1. The data were generated under different load conditions in order to calculate the value of the power-law index n and the shift factor $L^{1/n}$/MVR following the procedure established earlier [Shenoy (2000a, 2000b, 2001b, 2001c, 2001d)]. The values obtained for the RTFOT-aged Styrelf samples are shown in Table 1.

TABLE 1: Load, MVR and n data for RTFOT Aged Styrelf Samples

Temperature, T °C	Load, L_1 kg	MVR_1 cc/10min	Load, L_2 kg	MVR_2 cc/10min	Load, L kg	MVR cc/10min	n	$L^{1/n}$/MVR
61	14.90	12.18	10.00	7.26	14.90	12.18	0.771	2.733
70	10.00	24.80	5.00	9.99	7.06	18.18	0.762	0.715
74	10.00	46.68	5.00	19.49	7.06	32.76	0.794	0.358
76	7.06	12.18	2.16	9.87	5.00	26.97	0.858	0.242
80	7.06	69.63	2.16	17.65	5.00	41.40	0.863	0.156

RESULTS AND DISCUSSION

Rheological data obtained from the DSR frequency sweep can be expressed in terms of the complex modulus |G*|, loss modulus G" and the SHRP parameter |G*|/sin δ versus the frequency ω curves. The flow data from the FMD are expressed in terms of the MVR under specific load conditions L as given in Table 1. When this information is used to form a shift factor $L^{1/n}$/MVR calculated in Table 1, the DSR data can be reorganized to give unified |G*|, G" and the SHRP parameter |G*|/sin δ versus the modified frequency ω $L^{1/n}$/MVR curves as shown by Shenoy (2000a, 2000b, 2001b, 2001c). The unification technique applies even to the refined Superpave specification parameter |G*|/(1-(1/tan δ sin δ)), and a unified curve for the RTFOT-aged Styrelf data over the entire range of temperature 61°C-80°C can be obtained as shown in Figure 1.

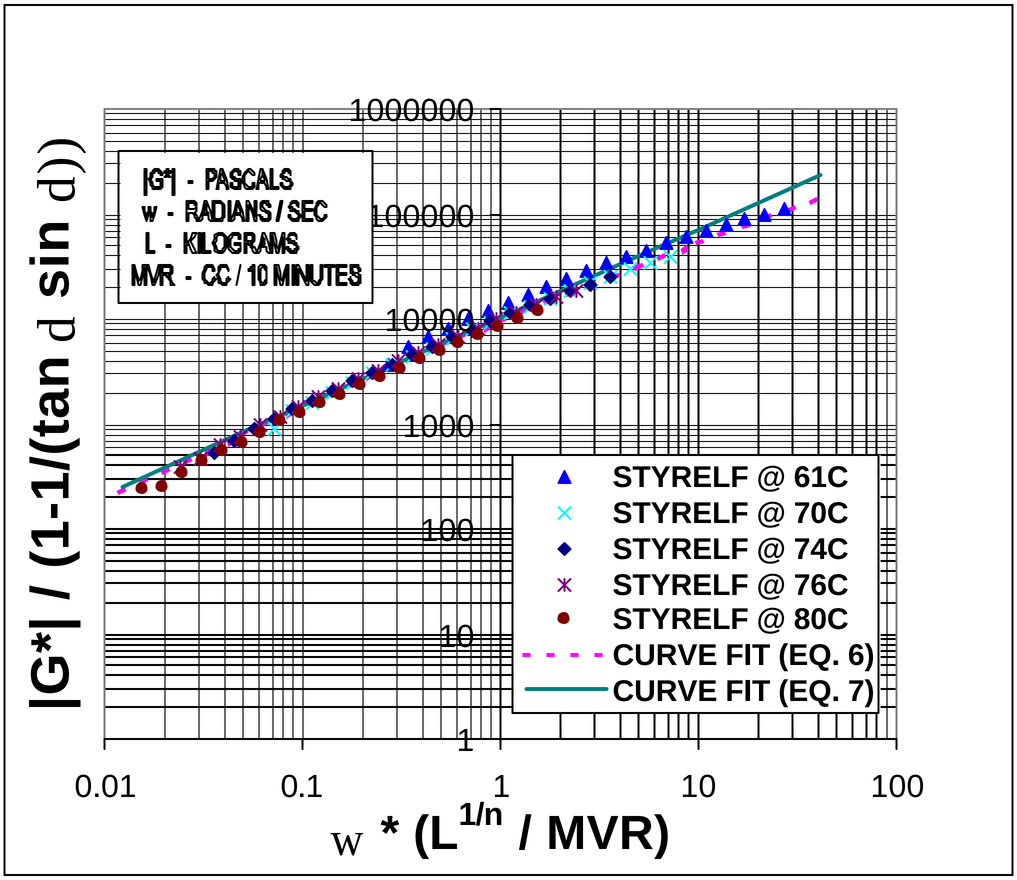

Figure 1: Unified curve of the new specification parameter |G*|/(1-(1/tan δ sin δ)) with modified frequency covering temperature range of 61°C – 80°C for RTFOT-aged Styrelf sample.

In order to use the unified curve for prediction purposes, the curve in Figure 1 needs to be fitted by an appropriate rheological model. When the data points cover a very large range of modified frequency $\omega L^{1/n}$/MVR, it is beneficial to first split the modified frequency range into two parts, then fit appropriate constitutive equations to each part, and later combine these two equations to give a composite model covering the entire range of data. The approach followed the lines of the General Rheological Model that was formulated to cover the entire range of the viscosity versus shear rate curves [Shenoy and Saini (1996)]. It is assumed that the points in the figure fit a power-law model of the following form in the two ranges of $\omega L^{1/n}$/MVR.

$$\frac{|G^*|}{\left(1-\frac{1}{\tan d \sin d}\right)} = A_1 (wL^{1/n} / MVR)^{B_1} \qquad for \qquad 0.0001 < wL^{1/n} / MVR < 1 ----- (3a)$$

$$\frac{|G^*|}{\left(1-\frac{1}{\tan d \sin d}\right)} = A_2 (wL^{1/n} / MVR)^{B_2} \qquad for \qquad 1 < wL^{1/n} / MVR < 1000 ----- (3b)$$

where A_1, A_2 and B_1, B_2 are coefficients and exponents, respectively, ω is the frequency in radian/s, L is the load in kg, MVR is the material's volumetric -flow rate in cc/10min, and n is the power index. The following equation that was developed and discussed in earlier work [Shenoy (2000a, 2000b, 2001b, 2001c, 2001d)] is used for determining the value of n.

$$n = \frac{\log \frac{L_1}{L_2}}{\log \frac{MVR_1}{MVR_2}} ------------------------------------ (4)$$

where MVR_1 and MVR_2 are the material's volumetric -flow rate (cc/10min) at the two loads of L_1 and L_2 (kg), respectively.

The particular form of Equation (3) was selected for its simplicity. The coefficients and exponents can be calculated by fitting the best line through the data points on a log-log plot. In order to fit the entire range of data in the figure, the two expressions in Equations (3a) and (3b) are combined through the following form along the lines of the General Rheological model discussed in Shenoy and Saini (1996).

$$\left[\frac{|G^*|}{\left(1-\frac{1}{\tan d \sin d}\right)}\right]^N = [A_1 (wL^{1/n} / MVR)^{B_1}]^N + [A_2 (wL^{1/n} / MVR)^{B_2}]^N ---------- (5)$$

The power index N is determined by trial to be equal to $2/(B_2-B_1)$. The rearranged form of the Equation (5) is thus written as follows.

$$\left[\frac{|G^*|}{\left(1-\frac{1}{\tan d \sin d}\right)}\right]=\frac{A_1(wL^{1/n}/MVR)^{B_1}}{[1+\{(A_1/A_2)^{2/(B_1-B_2)}(wL^{1/n}/MVR)^2\}]^{(B_1-B_2)/2}}----------(6)$$

The above equation that is derived from Equations (3) and (5) is basically valid over the modified frequency range $0.0001 < \omega L^{1/n}/MVR < 1000$. It can be seen in Figure 1 that the modified frequency range is much narrower since $0.01 < \omega L^{1/n}/MVR < 30$. In such circumstances, a simpler form of the rheological model would do a good enough job, and the following form is chosen in the present case to cover the narrower modified frequency range of $0.01 < \omega L^{1/n}/MVR < 30$.

$$\frac{|G^*|}{\left(1-\frac{1}{\tan d \sin d}\right)}=A\ (wL^{1/n}/MVR)^{B} \qquad for \qquad 0.01<wL^{1/n}/MVR<30-----(7)$$

Combining the above Equations (6) and (7) with Equation (1) gives

Full form of the equation

$$\%g_{unr}=\frac{100s_0[1+\{(A_1/A_2)^{2/(B_1-B_2)}(wL^{1/n}/MVR)^2\}]^{(B_1-B_2)/2}}{A_1(wL^{1/n}/MVR)^{B_1}}-------------(8a)$$

Simplified form of the equation

$$\%g_{unr}=\frac{100s_0}{A(wL^{1/n}/MVR)^{B}}--------------------------------(8b)$$

The curve fit based on Equation (6) was found to give good agreement with the data points shown in Figure 1 using values of A_1 =10763, B_1 = 0.877, A_2 = 9937 and B_2 = 0.718, and represents the dashed line in Figure 1; while the curve fit based on Equation (7) was found to give good agreement with the data points shown in Figure 1 using values of A =10000 and B = 0.84, and represents the solid line in Figure 1. Using these values of A_1, B_1, A_2, B_2, A, B and the applied load σ_0 value of 300 Pa gives the following equations.

Full form of the equation

$$\%g_{unr} = \frac{2.787[1 + 2.737(wL^{1/n} / MVR)^2]^{0.079}}{(wL^{1/n} / MVR)^{0.877}} \text{------------} (9a)$$

Simplified form of the equation

$$\%g_{unr} = \frac{3}{(wL^{1/n} / MVR)^{0.84}} \text{------------} (9b)$$

Equation (9) can now be used for estimating the %-unrecovered strain using the appropriate values of L, n and MVR obtained from the FMD as given in Table 1. Figure 2 shows the plot of the estimated $\%\gamma_{unr}$ versus the actual experimental values determined from a creep recovery test given in Table 2 for a loading time t = 1/ ω. If the creep loading was for a duration of 1 second, then the value of ω = 1 radians/s was used and if the creep loading was for a duration of 10 seconds, then the value of ω = 0.1 radians/s was used in Equation (9). It was found that the best line through the data points in Figure 2 showed excellent correlation coefficient R^2 = 0.98, using the full form of the equation, namely, Equation (9a) and an excellent correlation coefficient R^2 = 0.983, using the simplified form of the equation, namely, Equation (9b).

TABLE 2: Creep recovery data from the DSR for RTFOT Aged Styrelf Samples

Temperature, T °C	Stress duration, t seconds	Unrecovered strain, γ_{unr} %
61	10	6.3
70	1	2.9
74	10	70.2
76	1	5.7
80	10	116.0

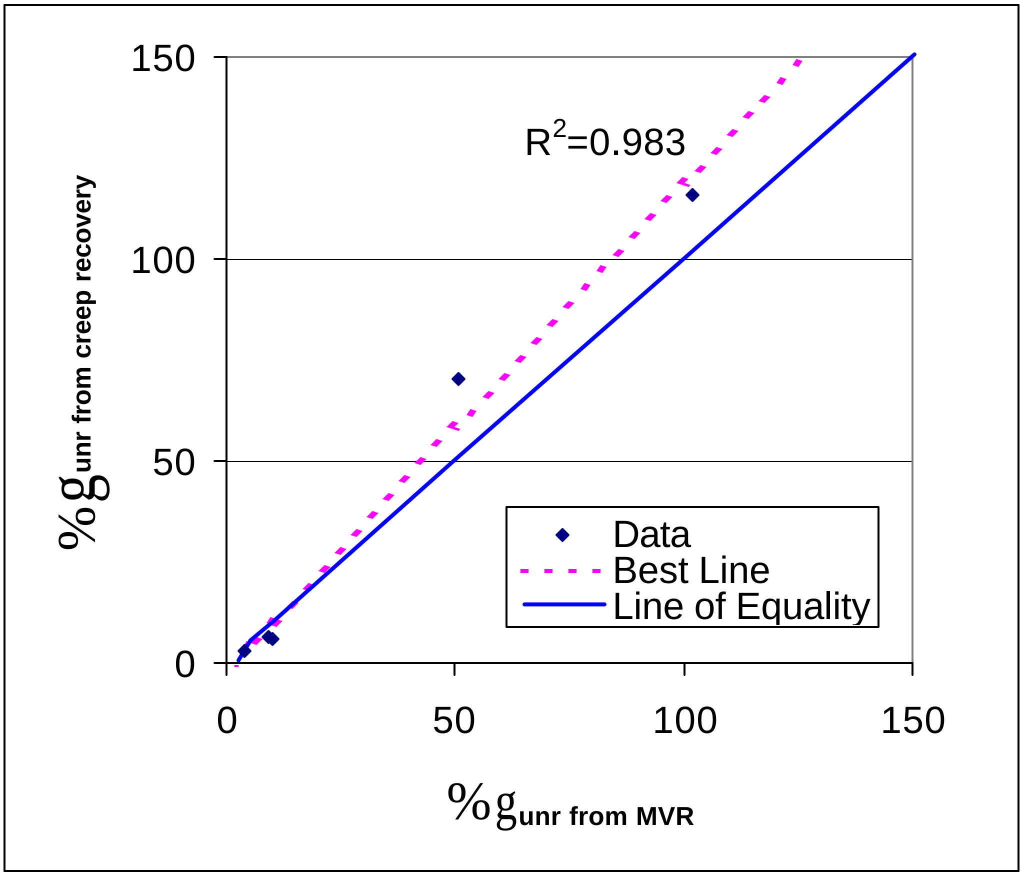

Figure 2: Comparison of the %-unrecovered strain obtained from creep recovery experimental data with that obtained by calculations through Equation (9) using MVR data from the FMD.

CONCLUDING REMARKS

The present work establishes a procedure to estimate the unrecovered strain during a creep recovery test from the material's volumetric-flow rate (MVR). The method involves the use of the unified curve for the new Superpave specification parameter $|G^*|/(1-(1/\tan\delta \sin\delta))$. The unified curve is unique for each type of polymer-modified asphalt. Hence, once such a curve is established for the polymer-modified asphalt under investigation, there is no further need to generate more data from the DSR. An appropriate rheological model fit to the unified curve gives the variation of the new Superpave specification parameter $|G^*|/(1-(1/\tan\delta \sin\delta))$ and the modified frequency ($\omega L^{1/n}/MVR$). A correlating equation giving the relationship between the %-unrecovered strain and the modified frequency term allows the estimation of the %-unrecovered strain.

The steps that are needed in order to get the %-unrecovered strain estimates are as follows:

1) The MVR_1, MVR_2 and MVR values (cc/10min) of the RTFOT-aged sample are determined at three different load conditions L_1, L_2 and L (kg) at the temperature of interest T (°C).
2) Equation (4) that was developed and discussed in earlier work [Shenoy (2000a), (2000b), (2001b)] is used for determining the value of n.
3) The term ($L^{1/n}$/MVR) is determined.
4) The unified curve is fitted with the rheological model given by Equation (6) if the full form of the equation is used and A_1, B_1, A_2, and B_2 are determined; on the other hand, the unified curve is fitted with the rheological model given by Equation (7) if the simplified form of the equation is used and values of A and B are determined.
5) Equation (9) is used for estimating the %-unrecovered strain after using the appropriate value of ω and σ_0. If %-unrecovered strain is desired at a loading time of 't' and applied stress of 'σ', then ω=1/t and $\sigma_0 = \sigma$ is to be used in Equation (9).

The entire procedure to obtain the %-unrecovered strain of aged asphalts by following steps 1-5 would take only fraction of the time that would otherwise have been needed if one were to go through the process of actually generating creep recovery test data. Since the present method relies on the MVR to generate the necessary rheological information from the unified curves, there are a number of added advantages [Shenoy (2000a), (2000b), (2001b)]. The MVR is simple to determine quite accurately from the FMD. The FMD is a simple, inexpensive piece of equipment that can be carried from place to place (even to paving sites) due to its lightweight. It neither needs any arrangements for air pressure nor requires a circulating water-bath to maintain a constant temperature environment. It does need a 120V power source. Since this equipment was originally built for taking polymer melt data at high temperatures (125°C – 300°C), it has an excellent temperature control system with variations of about 0.1°C, especially in the temperature range applicable to paving asphalts. With such extensive benefits, the procedure outlined in this work should be attractive enough for routine use in estimating the rutting resistance potential of any unmodified or polymer-modified asphalt.

Acknowledgements

The author is grateful to Ms Susan Needham for generating the rheological data on the DSR and the FMD. The author would also like to acknowledge the financial support given by the Federal Highway Administration and the National Research council for this work.

References

American Association of State Highway and Transportation Officials (2000) "Method for determining the rheological properties of asphalt binder using a Dynamic Shear Rheometer (DSR)." AASHTO Provisional Standard Designation TP5-98: Washington D. C.

Bahia, H. U., Zeng, M., Zhai, H. and Khatri, A. (1999) "Superpave protocols for modified asphalt binders", *Fifteenth quarterly progress report for NCHRP Project 9-10*: Washington D.C.

Bouldin, M. G., Dongré, R., Zanzotto, L. and Rowe, G. M. (2000) "The application of visco-elastic models to predict the relative performance of binders for grading purposes", *Proceedings of 2nd Eurasphalt & Eurobitume Congress*, Barcelona, Spain, Book 1, pp. 74-82.

Bouldin, M. G., Dongré, R. and D'Angelo, J. (2001) "Proposed refinement to the Superpave high temperature specification parameter for performance graded binders", *Paper presented at the 80th annual meeting of the Transportation Research Board*, January 7-11, Washington D. C.

Chabert, D., Triquigneaux, J-P. and Vaniscote, J-C. (1999) "Rheology of elastomer binders and rutting resistance of bituminous mixes", *Proceedings of the Eurobitume Workshop 99*, Paper No. 028.

Collop, A. C. and Khanzada, S. (1999) "Permanent deformation in idealised bituminous mixtures and bitumen properties", *Proceedings of the Eurobitume Workshop 99*, Paper No. 124.

Desmazes, C., Lecomte, M., Lesueur, D. and Phillips, M. (2000) "A protocol for reliable measurement of zero-shear-viscosity in order to evaluate the anti-rutting performance of binders", *Proceedings of 2nd Eurasphalt & Eurobitume Congress*, Barcelona, Spain, Book 1, pp. 202-211.

Mazé, M. and Brûlé, B. (1999) "Relationship between rheological properties of modified binders and hot mixtures rutting", *Proceedings of the Eurobitume Workshop 99*, Paper No. 044.

Phillips, M. C. and Robertus, C. (1996) "Binder rheology and asphaltic pavement permanent deformation; the zero-shear viscosity", *Presented at the Eurasphalt & Eurobitume Congress*.

Shenoy, Aroon (2000a) "Validating the generality and predictive ability of unified rheological curves for unmodified paving asphalts", *Construction and Building Materials*, 14, pp. 325-339.

Shenoy, Aroon (2000b) “Developing unified rheological curves for polymer-modified asphalts Part I. Theoretical analysis, *Materials and Structures*, 33, pp. 425-429; Part II. Experimental verification, *Materials and Structures*, 33, pp. 430-437.

Shenoy, Aroon (2001a) “Refinement of the Superpave specification parameter for performance grading of asphalt”, *Journal of Transportation Engineering*, 127 (5), pp. 357-362.

Shenoy, Aroon (2001b) “Unifying asphalt rheological data using the Material’s Volumetric-flow Rate”, *J. Materials in Civil Engineering*, 13 (4), pp. 260-273.

Shenoy, Aroon (2001c) “Material’s Volumetric-flow Rate (MVR) as a unification parameter in asphalt rheology and QC/QA tool for high temperature performance grading”, *Applied Rheology*, 10 (6) pp. 288-306.

Shenoy, Aroon (2001d) “High temperature performance grade specification of asphalt binder from the material’s volumetric-flow rate”, *Materials and Structures*, 34.

Shenoy, A. V. and Saini, D. R. (1996) “Thermoplastic Melt Rheology and Processing”, Marcel Dekker, Inc., N. Y.

Stuart, K. D. and Izzo, R. P. (1999) “Hot mix asphalt pavement construction report for the 1993-2000 FHWA Accelerated Loading Facility report”, FHWA-RD-99-083 Report to the FHWA.

Stuart, K. D. and Mogawer, W. S. (1997). “Validation of asphalt binder and mixture tests that predict rutting susceptibility using FHWA Accelerated Loading Facility”, *Proc. AAPT*, 66, pp. 109-152.