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HIGH TEMPERATURE PERFORMANCE GRADE SPECIFICATION OF ASPHALT BINDER FROM THE MATERIAL'S VOLUMETRIC-FLOW RATE

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ABSTRACT

Applying straightforward rheological principles, this article shows that the material's volumetric-flow rate MVR (in cc / 10 minutes) can be used to accurately determine the high temperature performance grade specification of paving asphalt binder. The MVR is easy to determine using a relatively inexpensive, user-friendly flow measurement device (FMD). On account of the simplicity in measurement, it may be routinely used for quality control / quality assurance purposes. It can also be used as a rapid product development / formulation tool.

RÉSUMÉ

En appliquant des principes rhéologiques simples, cette article montre que le débit volumétrique du matériau MVR (en cc / 10 minutes) peut être utilisé pour la détermination précise du grade performanciel de spécification à haute température des bitumes routiers. Le MVR est facilement déterminé en utilisant un système de mesure de débit (FMD) pratique et relativement bon marché. Compte tenu de la simplicité de l'essai, il peut être utilisé en routine à des fins de contrôle et d'assurance qualité. Cet essai peut également être utilisé comme un outil rapide d'aide à la formulation et au développement de produits.

1. INTRODUCTION

The fundamental viscoelastic behavior of asphalt binders under different levels of stresses and temperatures needs to be understood so that performance-related specifications can be developed to mitigate major pavement distresses [1], [2].

The Dynamic Shear Rheometer (DSR) was recommended [1] for determination of the viscoelastic properties of asphalt binders and for calculation of the high temperature performance-grade. Recently, it was shown [3], [4], [5], [6] that the material's volumetric-flow rate (MVR) determined using a simple flow measurement device (FMD) could lead to the unification of the curves of the fundamental viscoelastic data obtained from the DSR within the performance grade (PG) high temperature range for unmodified [3], [4] and modified [5] asphalt binders. Through the unified curves, it was established [3], [4], [5] that a parameter dependent on the MVR, the load condition L and the pseudoplasticity index n, could potentially be used for the estimation of the high temperature performance grade specification.

This paper explores the possibility of obtaining the high temperature PG specification from the MVR. The method is straightforward, fast and accurate and gives an alternative way for obtaining the specification temperature. Since the FMD is a simple inexpensive portable device, there is an added incentive to promote this technique for use on a routine basis for quality assurance of previously graded asphalt binders. It can also be effectively used during new product development when a target performance grade has to be prepared through blending of two grades of asphalt binders or adding polymers to asphalt binders.

2. MATERIAL'S VOLUMETRIC-FLOW RATE (MVR)

The MVR is defined as the volume of the material (in milliliters or cubic centimeters) that is extruded in 10 minutes through the capillary die of specific diameter and length of a closely defined flow measurement device (FMD) by applying pressure through dead weight under prescribed temperature conditions [3], [4], [5], [6]. This definition of MVR is rather an arbitrary one. It was chosen to be consistent with the well-known rheological parameter used in polymer melt rheology, namely, the melt flow index MFI [7], except that MFI is the weight extruded in 10 minutes while MVR is the volume extruded in 10 minutes. The volume-flow rate is more convenient to measure than the mass flow rate and does not require the knowledge of the density of the material in the calculations.

A schematic diagram of the FMD is shown in Figure 1. It is a simple, inexpensive equipment. The cylinder of the FMD is made of hardened steel and is fitted with heaters, insulated, and controlled for operation at the required temperature. The thermocouple is buried inside the instrument's barrel. The thermocouple and the associated temperature control electronics are calibrated against NIST traceable temperature probes by the equipment manufacturer. The heating device is capable of maintaining the temperature at 10 mm above the die to within "0.2°C of the desired temperature during the test. The temperature of the barrel, from 10 mm to 75 mm above the top of the die, is maintained within "1% of the set temperature (°C). All this is followed in strict compliance with the ASTM D1238 stipulations [8]. The piston is made of steel and the diameter of its head is 0.075" 0.015 mm less than that of the internal diameter of the cylinder, which is 9.5 mm. The material is extruded through a die made of hardened steel with an internal diameter of 2.095 " 0.005 mm.

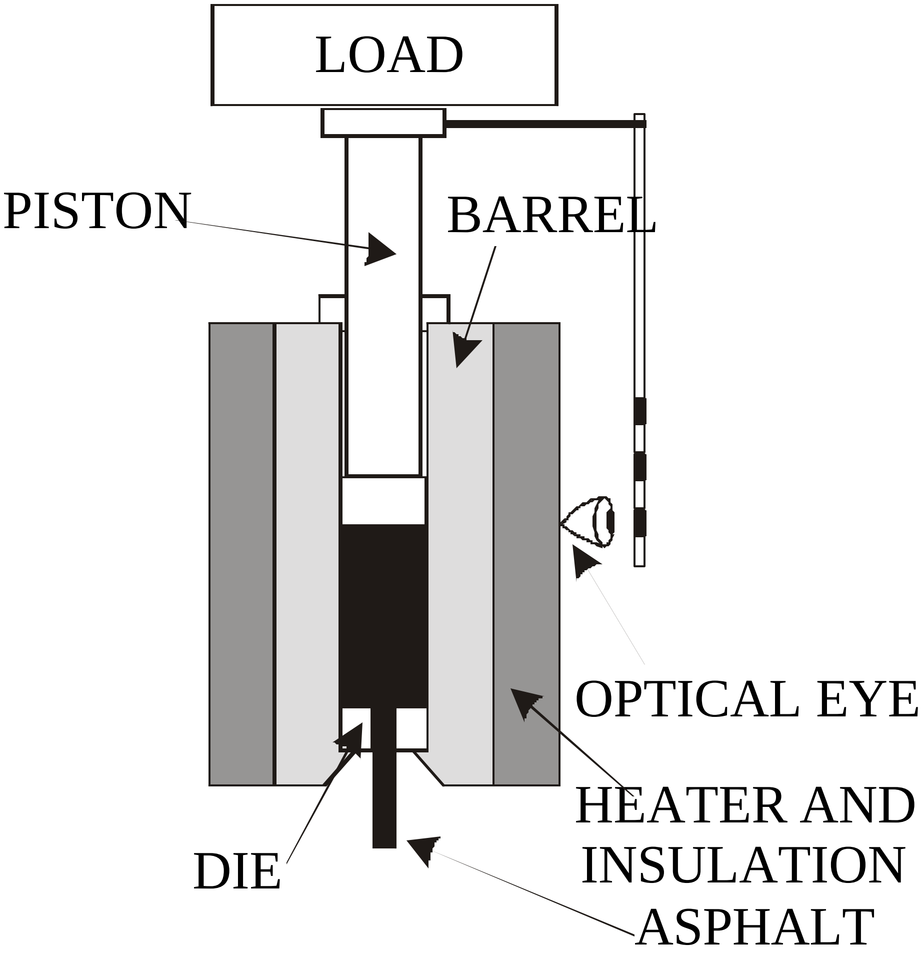

Figure 1: Schematic diagram showing the main parts of the Flow Measurement Device (FMD) that is used for determining the Material's Volumetric-flow Rate (MVR) [The barrel diameter = 9.5 mm and the die diameter = 2.095 mm, and the thermocouple (not shown in the diagram) is buried inside the barrel close to the die].

3. THEORETICAL BASIS

The collective data on all unaged asphalt binders, when plotted as complex modulus |G*| versus modified frequency T(L$^{1/n}$ / MVR), loss modulus G@ versus modified frequency T(L$^{1/n}$ / MVR) and Superpave parameter |G*| /sin * versus modified frequency T(L$^{1/n}$ / MVR), yield unified curves [3], [4], [5], [6]. Here * is the phase angle, L is the load and n is the power-law index corresponding to the slope of the load L versus MVR plot on a log-log scale. In the Superpave© binder performance grading system, there is a specification requirement of |G*|/sin* ($1kPa) for unaged asphalt binders at a frequency of 10 radians/s, which is assumed to simulate traffic loading when vehicles are moving at 30-36 kph. From the unified curve, a value of T(L$^{1/n}$ / MVR) was determined for |G*|/sin* = 1 kPa as

$$w\left(\frac{L^{1/n}}{MVR}\right) = 0.245 \qquad (1)$$

where frequency ω is in radians/s, load L is in kg, power-law index n is dimensionless and MVR is in cc/10min. Since a frequency of 10 radians/s has been chosen to simulate actual traffic conditions, the specification temperature would be the one when

$$\left(\frac{L^{1/n}}{MVR}\right) = 0.0245 \qquad (2)$$

where the load L is in kg, power-law index n is dimensionless and MVR is in cc/10min. In case the MVR value has been determined at the load L for a particular asphalt binder at a specific temperature, then it is necessary to determine two more MVR values at two other load conditions to estimate the value of n. The two load conditions are chosen in such a way that one is higher than L (i.e. say L_1) while the other is lower than L (i.e. say L_2). For example, if the MVR value has been determined at L = 2.16 kg, then it would be necessary to determine MVR value at L_1 = 3.06 kg and another at L_2 = 1.00 kg load. The following equation is used for estimation of the n value [3], [4], [5], [6].

$$n = \left(\frac{\log \frac{L_1}{L_2}}{\log \frac{MVR_1}{MVR_2}}\right) \qquad (3)$$

The MVR_1 and MVR_2 are the material's volumetric-flow rates at the two load conditions of L_1 and L_2.

4. EXPERIMENTAL DETAILS

In order to estimate the specification temperature corresponding to the frequency ω of 10 rad/s, it is necessary to determine the $L^{1/n}$/MVR at different temperatures, and then find the temperature at which $L^{1/n}$/MVR takes a value of 0.0245, when L is expressed in kg and MVR in cc/10 min. For verification purposes, the PG high temperature is also determined using the conventional method from Dynamic Shear Rheometer (DSR) data.

4.1 Equipment Used

The Melt Indexer Model D4002 from Kayeness (Morgantown, PA, USA) was used as the Flow Measurement Device (FMD) in order to measure the material's volumetric flow rate (MVR). The material's flow rate was assessed from the volumetric displacement with time based on the piston's downward movement. The piston's downward travel time was determined from a counter initiated by an optical sensor. The optical eye senses opaque flags on a transparent tape attached to the top of the piston rod. The transparent tape chosen was the one which had three 6.35 mm flags spaced at about 3.17 mm from each other, and three readings for MVR were obtained in one run of the sample at each temperature. The average of the three MVR readings was used in the calculation of the PG high temperature.

The FMD has a built-in computer that can be programmed to set up the experimental conditions. The temperature of MVR measurement and the load conditions are input into the system. Table 1 shows the choice of temperatures and load conditions that were used for previously graded asphalt binders in order to determine the continuous grading temperature.

TABLE 1

Load Conditions used for MVR Determination at Selected Temperatures

Temperature (°C)	**j Load L_1 (kg)**	**Load L (kg)**	**j Load L_2 (kg)**
PG (High Temp - 6°C)	3.060	2.160	1.225
PG (High Temp)	2.160	1.225	1.000
PG (High Temp + 6°C)	1.225	1.000	0.325

j Load L_1 and Load L_2 were used to determine the value of n in accordance with Eq. (3)

While the temperature of the FMD begins to rise toward the set temperature, the asphalt binder for testing is heated in the oven to a temperature of 163°C so that it is in a pourable condition. Approximately 10 g of asphalt binder are gradually poured in a thin continuous stream into the barrel of the FMD and the piston is put in place. When pouring hot asphalt binder into the barrel, care should be taken to pour in a thin uniform stream so that no air pockets are formed due to jerky filling. When air gets trapped in asphalt due to faulty pouring, the asphalt binder will not flow uniformly out of the die. In fact, an audible sound of a burst bubble will be heard when there is a discontinuity in the flow. Any reading taken during the time when such a sound is heard must be discarded, as it is erroneous. Based on the present experimental experience during generation of MVR data for asphalt binders considered herein, it could be said that the air entrapment may happen no more than 2% of the time. However, it is worth being aware of this in order to distinguish spurious readings from good ones.

The asphalt binder is then allowed to equilibrate with the set temperature. When the set temperature is reached, the buzzer sounds a signal and shows that the FMD is ready for MVR measurement. At this stage, the predecided load is placed on the piston and the flag with three black strips is placed on the extending piston arm. The asphalt binder begins to flow out of the die as soon as the load is placed. At that stage, the RUN signal is given to the FMD from the main panel of the equipment. Even though the run signal is given, the equipment does not start taking MVR readings until the first scribed mark on the piston is reached, which coincides with the point at which the optical eye shown in Figure 1 sees the first flag. Once the optical eye sees the first flag, the MVR is automatically and sequentially determined for all three flags. It takes only a few seconds for each flag to pass the optical eye.

The three MVR values corresponding to the three flags are automatically recorded by the FMD and then sent to a printer for final printout. The remnant material in the barrel after the MVR readings are recorded is allowed to drain out through the die. This takes about 2 to 5 minutes after which the load, the flag strip, and the piston are removed. The capillary die is removed from the equipment, dipped in a solvent, and cleaned thoroughly using cotton swabs and toothpicks. The piston and barrel are also cleaned with cotton swabs tied to specially designed plungers.

The Dynamic Shear Rheometer (DSR) from Rheometrics (Piscataway, NJ, USA) was used for generating the dynamic data at the three temperatures (given in Table 1) with a set of parallel plates of 25 mm diameter following the procedure given in the AASHTO provisional specifications [9]. The samples for the test were prefabricated using a silicone rubber mold. The rheometer and the temperature-controlled unit were operated through a personal computer and the data acquisition / analysis was done by using specialized software running under Windows ›95. The data were generated using a frequency sweep or a time sweep at a fixed frequency of 10 radians/s and low enough strain (10-12%) so as to be within the linear viscoelastic response range of the material.

4.2 Materials Used

Twelve different asphalt binders were chosen for this study. Ten of these included a PG52-34 (flux), a PG64-28 (base), a PG70-28 (unmodified high grade), a PG70-28 (air-blown) along with six other PG70-28 (polymer-modified grades), namely, Elvaloy, SBS_Linear-Grafted [SBS_L-G], SBS_Linear [SBS_L], SBS_Radial-Grafted [SBS_R-G], EVA and EVA_Grafted [EVA_G]. The PG numbers shown are based on the Superpave system description. All the asphalt binders were from the same source, namely, Venezuelan crude (blend of Boscan and Bachaquero). The PG70-28 (air-blown grade) was obtained by non-catalytic air-blowing of the PG52-34 (flux) while the polymer-modified grades were obtained by addition of various amounts of different polymers to the PG64-28 (base) or PG52-34 (flux) or mixture of the PG64-28 (base) and PG52-34 (flux) in different proportions so as to achieve the same performance grading. All these asphalt binders are part of the extensive ongoing polymer research program for the Accelerated Loading Facility (ALF) study at the Turner-Fairbank Highway Research Center. Two polymer-modified asphalt binders from the earlier ALF study were also included, namely, PG76-22 (Novophalt) and PG82-22 (Styrelf).

5. RESULTS AND DISCUSSION

For the experimental conditions outlined in Table 1, the values of the MVR were determined using the average of three readings from each run and the results are shown in Table 2. The last column in Table 2 shows the values of $L^{1/n}$ /MVR corresponding to each temperature.

TABLE 2

Load, MVR and n data for Original Unaged Samples

Binder ID	Temp. T,°C	Load L,kg	MVR cc/10min	Load L_1,kg	MVR_1 cc/10min	Load L_2,kg	MVR_2 cc/10min	n	$L^{1/n}$/MVR
Flux	46	2.160	23.41	3.060	31.47	1.225	11.40	0.902	0.1003
(PG52-34)	52	1.225	30.39	2.160	51.72	1.000	24.02	1.004	0.0403
	58	1.000	51.21	1.225	66.22	0.325	15.60	0.918	0.0195
Base	58	2.160	31.13	3.060	43.76	1.225	17.13	0.980	0.0705
(PG64-28)	64	1.225	36.98	2.160	61.95	1.000	28.25	0.981	0.0333
	70	1.000	56.99	1.225	76.59	0.325	19.27	0.962	0.0175
High	64	2.160	33.67	3.060	50.18	1.225	20.71	1.039	0.0623
(PG70-28)	70	1.225	40.04	2.160	76.07	1.000	34.21	0.964	0.0308
	76	1.000	68.13	1.225	84.68	0.325	21.10	0.955	0.0147
Air-Blown	64	2.160	23.15	3.060	46.88	1.225	16.08	0.859	0.1058
(PG70-28)	70	1.225	31.15	2.160	67.22	1.000	23.98	0.747	0.0421
	76	1.000	59.16	1.225	73.23	0.325	17.98	0.945	0.0169
Elvaloy	70	2.160	30.65	3.060	41.93	1.225	19.15	1.173	0.0629
(PG70-28)	76	1.225	35.84	2.160	59.01	1.000	27.40	1.004	0.0342
	82	1.000	45.60	1.225	61.12	0.325	16.45	1.011	0.0219

TABLE 2 (continued)

Load, MVR and n data for Original Unaged Samples

Binder ID	Temp. T,°C	Load L,kg	MVR cc/10min	Load L_1,kg	MVR_1 cc/10min	Load L_2,kg	MVR_2 cc/10min	n	$L^{1/n}$/MVR
SBS_L-G	64	2.160	14.92	3.060	29.19	1.225	11.47	0.996	0.1452
(PG70-28)	70	1.225	23.60	2.160	45.86	1.000	20.11	0.934	0.0527
	76	1.000	39.92	1.225	49.19	0.325	13.21	1.009	0.0251
SBS_L	64	2.160	19.63	3.060	28.70	1.225	9.72	0.846	0.1267
(PG70-28)	70	1.225	24.24	2.160	44.46	1.000	18.10	0.857	0.0523
	76	1.000	43.63	1.225	55.39	0.325	11.19	0.830	0.0229
SBS_R-G	64	2.160	12.88	3.060	19.06	1.225	6.82	0.890	0.1844
(PG70-28)	70	1.225	15.89	2.160	25.93	1.000	10.09	0.816	0.0807
	76	2.160	51.98	1.225	27.07	0.325	6.38	0.918	0.0445
EVA	64	2.160	93.60	3.060	121.43	1.225	39.04	0.810	0.0276
(PG70-28)	70	1.225	71.86	2.160	161.27	1.000	62.67	0.815	0.0179
	76	1.000	103.35	1.225	114.63	0.325	22.48	0.814	0.0097
EVA_G	64	2.160	96.14	3.060	132.97	1.225	36.37	0.709	0.0308
(PG70-28)	70	1.225	58.72	2.160	144.70	1.000	64.63	0.956	0.0211
	76	2.160	106.50	1.225	89.85	0.325	17.63	0.815	0.0094
Novophalt	70	2.160	27.75	3.060	53.53	1.225	11.82	0.609	0.1277
(PG76-22)	76	1.225	37.45	2.160	56.97	1.000	29.44	0.946	0.0394
	82	1.000	43.64	1.225	66.56	0.325	16.58	0.955	0.0229
Styrelf	76	2.160	16.41	3.060	22.09	1.225	6.90	0.790	0.1614
(PG82-22)	82	1.225	18.11	2.160	23.53	1.000	10.30	0.932	0.0687
	88	1.000	44.03	1.225	59.00	0.325	11.60	0.816	0.0227

The sets of values of $L^{1/n}$ /MVR versus 1/T(K) are plotted on a semi-logarithmic scale as shown in Figure 2 for a limited set of binders. The best line through the points is used for calculating the temperature at which the value of $L^{1/n}$ /MVR = 0.0245 when L is in kg and MVR is in cc/10 min, in order to satisfy the condition set up in Eq. (2). The specification temperatures calculated in this way are shown in column 2 of Table 3.

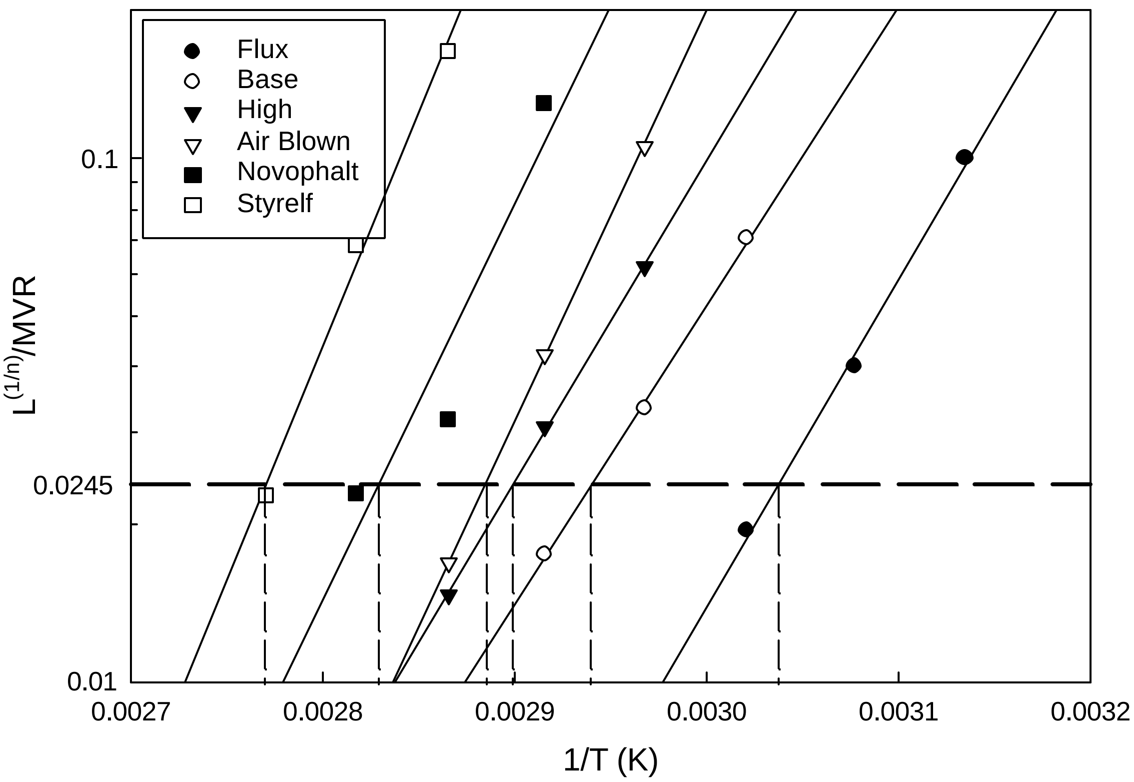

Figure 2: Variation of $L^{1/n}$/MVR versus 1/T on a semi-logarithmic plot using the average of three readings for the MVR at each temperature.

The data from the DSR is conventionally used for getting the high temperature PG number. This is done by plotting the value of |G*|/sin* versus 1/T(K) on a semi-logarithmic plot. The best line through the points is used for calculating the temperature at which the value of |G*|/sin* = 1 kPa in order to satisfy the condition set up by SHRP [1]. The specification temperatures calculated in this way are shown in column1 of Table 3.

TABLE 3
PG High Temperature Specifications Calculated by Different Methods

Binder ID	PG High Temperatures, °C @|G*|/sin* =1 kPa From DSR	@ $L^{1/n}$/MVR=0.0245 From FMD	@ MVR=50 for L=1.225 kg From FMD	From Eqn.(6)
	Column 1	Column 2	Column 3	Column 4
Flux (PG52-34)	55.84	56.08	55.82	56.02
Base (PG64-28)	67.62	66.91	66.48	66.50
High (PG70-28)	71.46	71.74	71.58	71.41
Air-Blown (PG70-28)	73.56	73.53	73.20	72.90
Elvaloy (PG70-28)	77.25	80.40	79.73	79.86
SBS_L-G (PG70-28)	75.65	75.87	76.22	76.14
SBS_L (PG70-28)	74.87	75.48	75.20	75.27
SBS_R-G (PG70-28)	74.51	80.98	81.16	81.62
EVA (PG70-28)	74.36	65.69	66.46	66.68
EVA_G (PG70-28)	73.27	66.98	68.05	68.13
Novophalt (PG76-22)	79.00	80.26	79.30	79.00
Styrelf (PG82-22)	87.00	87.83	87.29	87.05

A comparison of columns 1 and 2 of Table 3 shows that the specification temperatures obtained by the two methods match quite closely, with the exception of EVA and EVA_G and to some extent Elvaloy and SBS_R-G. Thus, the MVR has a good potential to be used for obtaining the PG high temperature. The MVR data measurement is very simple, and the FMD is relatively inexpensive. There are a number of other advantages in using the FMD instead of the DSR for the PG high temperature determination, which are all detailed elsewhere [3],[4],[5].

Even then, it is worth looking for further simplification of the method in obtaining the PG high temperature specification. Presently, the method relies on the determination of MVR at three different loads at each temperature. This means that, if three temperatures are used, nine data points are to be generated. Despite the fact that generating these nine data points is simple and quick, it is worthwhile exploring the possibility of reducing the experimentation by checking whether the same information could be generated using only three data points.

Data generation at three different loads was needed mainly to estimate the value of n. However, in the region of interest, the value of n hovers around the value of 0.9 to 1 in most cases. If, as an approximation, n is taken to be identically equal to 1 for the purposes of calculations, then there would be no need to generate MVR data at three different loads. Data at one selected load at each temperature would suffice. It is seen from Table 2 that the load of 1.225 kg is common for all the considered temperatures. Eq. (2) can be rewritten using n = 1 and L = 1.225 kg in order to get a new simplified condition for the PG high temperature specification with an easy-to-remember condition value for MVR of 50 cc/10 min.

$$MVR = \left(\frac{L^{1/n}}{0.0245}\right) = \left(\frac{1.225}{0.0245}\right) = 50cc/10\min \qquad (4)$$

In the simplified approach, the values of MVR for a load condition of 1.225 kg are plotted on a semi-logarithmic plot at the different temperatures as shown in Figure 3 for a limited set of binders. The best line through the points is used for calculating the temperature at which the value of MVR = 50 cc/10 min, in order to satisfy the condition set up in Eq. (4). The specification temperatures obtained by this simplified method are shown in column 3 of Table 3 and when compared with column 2 can be seen to give closely matching values. This shows that the error due to the approximations is negligible.

Even with the above simplified method, three temperature values are required in order to determine the best line on the plot of MVR versus temperature, before getting an estimate of the temperature at which MVR = 50 cc/10 min. It would be worthwhile to check whether MVR data taken at only two temperatures (one at grade temperature - 6^0C and the other at grade temperature + 6^0C) would suffice in getting good enough estimates of the PG high temperature specifications. The following equation is used to fit the straight lines in Figure 3.

$$\ln MVR_T = A + \frac{B}{T} \qquad (5)$$

where A and B are constants and MVR_T represents the MVR value at any temperature T. The two temperatures in degrees Kelvin (one at grade temperature - 6 and the other at grade temperature + 6) are designated as T_1 and T_2 and the MVR value at the high specification temperature T_{HS} is given the value of 50 cc/10 min. The three equations formed in this way are solved and an expression for T_{HS} is determined as follows, which can be used for the calculations of the high specification temperature in degrees Kelvin.

$$T_{HS} = \left(\frac{T_1 T_2(\ln MVR_{T_1} - \ln MVR_{T_2})}{T_1 \ln MVR_{T_1} - T_2 \ln MVR_{T_2} - (T_1 - T_2)\ln 50}\right) \qquad (6)$$

The PG high temperature is calculated as (T_{HS} - 273) in degrees Centigrade. The values calculated in this way are shown in column 4 of Table 3 and can be seen to match very well with the values shown in columns 2 and 3.

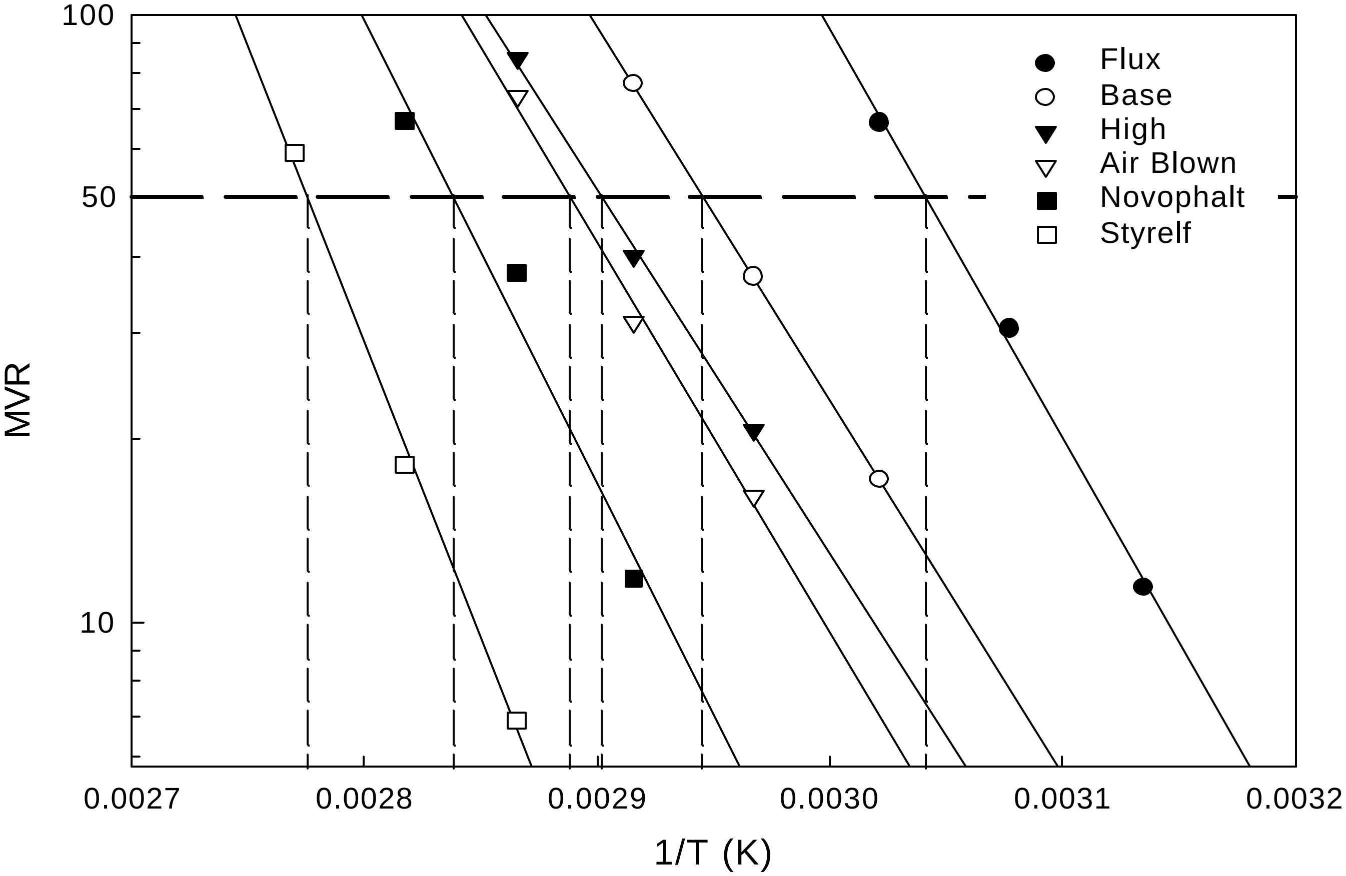

Figure 3: Variation of MVR versus 1/T on a semi-logarithmic plot using the average of three readings for the MVR at each temperature.

In order to check on the reproducibility of the PG high temperature calculations as described above, MVR data was determined three times on the same material using fresh sample each time at two temperatures and load L = 1.225 kg. The T_{HS} was then calculated for each sample using equation (6). This was done for two materials: (1) Base and (2) Styrelf. For each material, the calculated values of T_{HS} for three replicates are shown in Table 4. A similar exercise was carried out for two replicates on six asphalt binders (1) Elvaloy (2) SBS_L-G (3) SBS_L (4) SBS_R-G (5) EVA and (6) EVA_G. It can be seen that in all cases the values are in very close agreement.

TABLE 4

PG High Temperature Specifications Calculated using Replicates j j

Binder ID	**PG High Temperatures,°C from Eqn.(6)**			
	Replicate 1	**Replicate 2**	**Replicate 3**	**Avg**
Base (PG64-28)	67.08	67.18	67.42	67.23
Elvaloy (PG70-28)	79.86	80.15	-	80.01
SBS_L-G (PG70-28)	76.14	75.45	-	75.79
SBS_L (PG70-28)	75.27	75.46	-	75.36
SBS_R-G (PG70-28)	81.62	81.67	-	81.65
EVA (PG70-28)	66.68	68.00	-	67.34
EVA_G (PG70-28)	68.13	66.11	-	67.11
Styrelf (PG82-22)	86.27	86.16	86.25	86.23

j j The values given in the table are shown up to two decimal places only for making a comparison at a higher precision. In practice, all the values should be rounded off to the nearest integer.

6. CONCLUDING REMARKS

It has been shown that MVR can be very effectively used in determining the PG high temperature specification. The method relied on determining the temperature when $L^{1/n}$/MVR = 0.0245, when L is in kg and MVR is in cc/10 min, based on the Superpave© binder specification requirement of |G*|/sin* = 1 kPa for unaged asphalt binders at a frequency of 10 radians/s. Though |G*|/sin* parameter was found to relate to permanent deformation in the case of unmodified binders, it has been found not to correlate well in the case of polymer-modified binders [10-15]. 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 parameters |G*|/sin* so as to make it more sensitive to pavement performance [16-19].

One suggestion has been to use the zero-shear viscosity [10, 16], instead of the |G*|/sin* parameter. However, the method for the determination of zero-shear viscosity as proposed [16] is extremely time-consuming and hence, unlikely to be acceptable as a specification parameter unless zero-shear viscosity is determined by other simpler means. If at all, zero-shear viscosity becomes acceptable as a possible means of determining the rutting resistance of asphalt binders, the present recommendation based on MVR would still be a viable alternative. This is because it is known that shear viscosity is inversely proportional to MVR [7] and a relationship between zero-shear viscosity and MVR has been shown to hold well [7, 20].

The other suggestion [19] is to use the term |G* |/(1-(1/tan*sin*)), instead of the |G*|/sin* parameter, since it has been shown to be more sensitive to the variations in the phase angle *, and was found to describe the unrecovered strain in the asphalt binders more accurately, especially in the case of polymer-modified binders. It may be noted that in the present paper, equation (1) was obtained from the unified curve for the unmodified binders. Since for unmodified binders, the term |G*|/(1-(1/tan*sin*)) gives nearly the same PG values as those obtained by calculations using |G*|/sin*, equation (1) would hold even if the new specification is recommended for use. This means that the recommendations made in the present paper could still be followed and MVR could still be used for determining the PG high temperature specification. It may be used for continuous grading of previously graded asphalt binders or for first-time grading purposes.

When developing a new asphalt binder (either by blending two asphalt binders or adding polymers to asphalt binders or simply air-blowing neat asphalt binders) with a particular high temperature PG target in mind, there is often a need to check the specification temperature time and again to make sure whether the target has been met. In such circumstances, the use of MVR would greatly help. By running a small amount of sample through the FMD with a load of 1.225 kg, it can be checked whether the MVR value has reached the value of 50 cc/10 min at the target specification temperature. If not, it would mean that the modification step needs to continue.

The FMD used for generating MVR data is a relatively simple and inexpensive piece of equipment and can be carried from place to place (even to paving sites) because of 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 asphalt binders. All this makes the MVR an attractive parameter to be used for routine quality control as well as for new product development of asphalt binders.

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