Material's Volumetric-Flow Rate (MVR) as a Unification Parameter in Asphalt Rheology and Quality Control / Quality Assurance Tool for High Temperature Performance Grading

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Abstract

Rheological data of unmodified and polymer-modified asphalts are conventionally obtained from dynamic mechanical characterization and expressed in terms of sets of curves showing the variation of viscoelastic properties with frequency. Using the conventional melt flow indexer, the material's volumetric-flow rate *MVR* (in cm^3 / 10 minutes) through a predefined die under conditions of constant temperature and stress when obtained for the same asphalts, shows a direct relationship with the dynamic data. The *MVR* value helps in unifying the sets of dynamic data curves of $|G^*|$, G'' and $|G^*|/\sin\delta$ versus frequency in the case of unmodified asphalts, polymer-modified asphalts and asphalt mastics. The unification technique has a sound theoretical basis and the unified curves have far-reaching implications. Since *MVR* is so simple to determine quite accurately on a relatively inexpensive, easy-to-use flow measurement device (*FMD*), this parameter can be generated on paving sites or at refineries, if needed, rather than in research laboratories as is the case with the fundamental rheological parameters. The *MVR* can then be used as an excellent indicator of the fundamental rheological parameters through the use of the unified curves. The *MVR* can be utilized to accurately determine the currently used high temperature performance grade specification of paving asphalt. On account of the simplicity in obtaining this specification value from the *MVR*, it may be routinely used for quality control / quality assurance purposes. It can also be used as a rapid product development / formulation tool.

Zusammenfassung

Die rheologische Daten von unmodifizierten und durch Polymere modifizierte Asphalte werden üblicherweise mittels dynamisch-mechanischer Charakterisierung erhalten und dann als Kurvenschar, welche die Änderung der viskoelastischen Eigenschaften bei verschiedenen Frequenzen zeigen, dargestellt. Für die gleichen Asphalte kann aber auch die volumetrische Fliessrate (MVR), welche in einem konventionellen Melt Flow Indexer mit definierter Düse bei konstanter Temperatur und Schubspannung gemessen wird, mit den dynamischen Daten korreliert werden. Der MVR-Wert wird hierbei benutzt, um die frequenzabhängigen dynamischen Daten für $|G^*|$, G'' und $|G^*|/\sin\delta$ für modifizierte und unmodifizierte Asphalte und Asphaltharze zu normieren. Diese Normierungstechnik basiert auf einen theoretischen Hintergrund und die normierten Kurven haben weitreichende praktische Konsequenzen. Der MVR-Wert kann sehr einfach und genau mit preiswerten und einfach zu bedienenden Flow Measurement Devices (FMD) vor Ort oder in Raffinerien bestimmt werden, anstatt in Forschungslabors durch aufwendige rheologische Versuche. Der MVR-Wert kann sodann mittels der normierten Kurven als ein hervorragender Indikator für fundamentale rheologische Parameter herangezogen werden. Zudem kann er benutzt werden um die gegenwärtig verwendete "High Temperature Performance Grade" Anforderungen von Strassenasphalt präzise zu bestimmen. In Anbetracht der Einfachheit, mit welcher diese Spezifikation anhand des MVR-Wertes bestimmt werden kann, könnte dieses Verfahren routinemässig zur Qualitätskontrolle und Qualitätsbürgschaft ebenso zur schnellen Produktentwicklung verwendet werden.

Résumé

Les données rhéologiques d'asphaltes non modifiés et modifiés par ajoût de polymère sont obtenues de manière conventionnelle à partir de la caractérisation mécanique en régime dynamique, et exprimées en terme d'ensembles de courbes, qui montrent la variation fréquentielle des propriétés viscoélastiques. En utilisant l'"indexer" conventionnel d'écoulement de fondu, le taux d'écoulement volumétrique (MVR) du matériau (en cm3/10 minutes) à travers une ouverture prédéfinie et sous des conditions de température et pression constantes, montre une relation directe avec les données dynamiques. La valeur du MVR aide à unifier l'ensemble des courbes dynamiques pour |G*|, G'' et |G*|/sind en fonction de la fréquence, obtenues pour les asphaltes non modifiés, modifiés par ajonction de polymère et pour les asphaltes mastics. La technique d'unification découle d'une approche théorique et les courbes unifiées possèdent des implications profondes. Comme le MVR est simple à déterminer assez précisement avec un appareil de mesure d'écoulement relativement bon marché et facile à utiliser, ce paramètre peut être obtenu dans les raffineries ou directement sur les sites de pavage, si besoin est, plutôt que dans les laboratoires de recherche, comme cela est le cas lorsqu'on veut obtenir les paramètres rhéologiques fondamentaux. Le MVR peut alors être utilisé comme un excellent indicateur des paramètres rhéologiques fondamentaux, par l'intermédiaire des courbes unifiées. Le MVR peut être utilisé pour déterminer de manière précise les spécifications usuelles de catégorie de performance haute temperature de l'asphalte de dallage. A cause de la simplicité avec laquelle la valeur de spécification peut être obtenue à partir du MVR, ce dernier peut être utilisé de manière routinière pour des problèmes de contrôle de qualité/assurance qualité. Il peut également être utilisé comme un outil rapide pour la formulation/le développement de produit.

Key words: Asphalt rheology, unified curves, flow measurement device, material's volumetric-flow rate, viscoelastic parameters, Superpave specification parameter, rutting resistance, aging

1 INTRODUCTION

Knowledge of the rheology of paving asphalts is important from several different viewpoints. Primarily, it is useful as a control tool to distinguish between various asphalts from different crude sources and which are refined using different processes. A survey identifies more than 120 different crude sources in the United States, and the crude is processed by one of four major refining methods [1]. Secondly, around 94% of the highways in the United States are surfaced with an asphalt / mineral-aggregate mixture [2]. Understanding asphalt rheology is important for properly mixing the asphalt with the mineral aggregate at the appropriate temperature and compacting the composite material in place so that the final pavement can be prepared well and with ease. Thirdly, understanding asphalt rheology is necessary for determining how their rheological properties relate to the distresses in the pavements after the lay down process and after years of service. There is no denying that performance related criteria are most important because if a distress is prevented or at least alleviated, then economic savings are gigantic.

Components of the asphalt can be crystalline solids or amorphous solids or liquids, depending on the temperature and thermal history. In addition, under typical usage, the asphalt is exposed to oxygen and moisture for long periods over potentially wide temperature ranges. These conditions cause continuing changes in the asphalt chemical composition and hence in the rheological properties. Asphalt on paved roads is subjected to a wide range of static and dynamic stresses at varying temperatures and under different environmental conditions. Hence it is essential to develop a good insight into the rheological properties of the asphalts covering a wide range of shear rates over an equally broad range of temperatures and under simulated environmental conditions.

With enough important reasons to understand the rheology of asphalts, it is not surprising that there has been a lot of attention given to this subject over the years with respect to unmodified asphalts [3 - 49] and polymer-modified asphalts [40, 41, 48, 50-81]. Asphalts in road paving applications are often modified [68, 69] through the use of small amounts (4-8 wt %) of polymers and there are more than 20 listed reasons [59, 68] for such modification. Whatever be the reason for the addition of polymers to asphalts, their presence changes the rheological characteristics of the original base asphalt. The rheology of polymer-modified asphalts has received considerable attention over the years [40, 41, 48, 50-81]. The references cited herein are by no means exhaustive and should in no way be considered as only the most important ones relating to asphalt rheology. They have been selected at random with a view to make allusions to the various aspects that researchers have focused their attention on when studying the rheological properties of asphalts. The works include:

- those that sought to study and recommend various important rheological parameters for asphalts [13, 18 - 20, 24, 26, 43-46, 49],
- those that modified the asphalts by air blowing, adding various chemicals or polymers, and then studying the rheological properties [40, 41, 47, 48, 50-81],
- those that looked for proper equipment for fundamental rheological measurements [15, 33],
- those that attempted to find methods for rapid rheological measurements [10, 17, 31, 47],
- those that searched for relationships between empirical tests and fundamental tests [9], and
- those that identified key rheological parameters as specifications to address major dis-

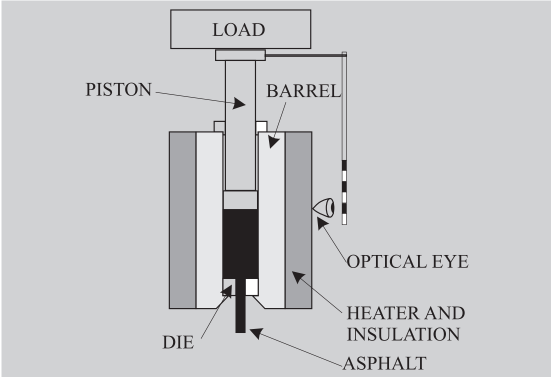


Figure 1: Schematic diagram showing the main parts of the Flow Measurement Device (FMD) that is used for determining the Material's Volumetric-Flow Rate (MVR).

tresses in asphalt pavements [44] under the Strategic Highway Research Program - SHRP (a five-year $150 million dollar United States research effort established and funded under the 1987 Surface Transportation and Uniform Relocation Assistance Act).

The rapid rheological measurements normally give information on the consistency of the asphalts but do not provide all the fundamental rheological knowledge about the material. The findings of SHRP indicate that understanding the fundamental viscoelastic behavior of the asphalts under different levels of stresses and temperatures is absolutely crucial for performance-related specifications to address major pavement distresses. The equipment that provide the fundamental rheological information have a constraint in that they cannot easily be taken to the field or on-site, normally require highly trained operators, and are also relatively much more expensive. An improved situation is the one in which a simple yet reasonably accurate rheological parameter is used instead. It is important that this parameter relates to fundamental rheological data and can be determined rapidly on a simple, low cost instrument.

2 SIMPLE RHEOLOGICAL PARAMETER

The simple parameter that is chosen [82-85] to give a good measure of the rheological characteristics of the asphalt is the material's volumetric-flow rate (*MVR*) that is determined through a closely defined flow measurement device (*FMD*), whose main parts are shown in Fig. 1. This equipment, namely the melt flow indexer, is borrowed from the polymer industry where it is routinely used to measure the melt flow index of the polymers [86]. The cylinder of the flow measurement device 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. The piston is made of steel and the diameter of its head is 0.075 ± 0.015 mm less than the internal diameter of the cylinder, which is 9.5 mm. Extrusion of the material is done through a die made of hardened steel with internal diameter of 2.095 ± 0.005 mm.

2.1 DEFINITION OF MVR

The Material's Volumetric-Flow Rate (*MVR*) is defined as the volume of the material (in milliliters or cubic centimeters) that is extruded in 10 minutes through the die of specific diameter and length as described above by applying pressure through dead weight under prescribed temperature conditions. This definition is rather an arbitrary one but has been chosen to be consistent with the well-known rheological parameter used in polymer melt rheology, namely, the melt flow index MFI [86], 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.

3 FLOW MEASUREMENT DEVICE

The Flow Measuring Device (*FMD*) in order to measure the material's volumetric-flow rate (*MVR*) that was used [82, 83, 85] was Kayeness [87] Melt Indexer Model 4002. The material's flow characteristic is assessed from the volumetric displacement with time based on the piston's downward movement. The piston's downward travel time is determined from a counter initiated by an optical sensor. The optical eye senses opaque flags on a transparent tape hung off the top of the piston rod. Flags of different lengths are available such as 1/8", 1/4", 1/2" and 1". Multiple flags are also available. In the present case, the transparent tape chosen was the one which had three 1/4" flags spaced at about 1/8" from each other. Such a multiple flag was advantageous to use because three readings for *MVR* could be obtained in one run of the sample. These may not be exact replicates, as they are not taken on different samples. However, they are three measurements on the same sample and help to identify any bad data.

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. While the temperature of the *FMD* begins to rise towards the set temperature, the asphalt is heated in the oven to a temperature of 163°C in order to increase its fluidity so that it can be poured with ease. Approximately 10 grams of asphalt are gradually poured in a thin continuous stream into the barrel of the *FMD* and the piston is put in place. The asphalt is then allowed to equilibrate with the set temperature. This takes from 10 to 15 minutes depending upon the set temperatures, the temperature of the poured asphalt, and the quantity of the asphalt that finally sits in the barrel. 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 pre-decided weight is placed on the piston and the flag with three black strips is placed on the extending piston arm.

Asphalt begins to flow out of the die as soon as the load has been 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 sees the first flag. It takes about 8 to 10 minutes for the scribed mark to reach the point when the measurement starts. This time is, of course, variable and can be shortened by pouring less asphalt into the barrel. In the present case, this time is maintained at a value between 8 to 10 minutes because the poured asphalt material was always around 10 grams. Once the optical eye sees the first flag, the *MVR* is automatically determined for all three flags sequentially. It takes a few seconds for each flag to pass the optical eye. This time is also variable, because it is dependent upon the viscosity of the asphalt. Lower viscosity asphalts flow in shorter times. The flow time also decreases with increasing loads. In the present case, the *MVR* data was taken under such load conditions as to maintain the *MVR* values to be between 1 and 100.

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 entire cleaning process takes about 5 minutes.

3.1 DYNAMIC SHEAR RHEOMETER

The Rheometrics Dynamic Shear Rheometer (DSR) was used [82, 83, 85, 88] for generating the dynamic data at different temperatures ranging from 46°C to 70°C with a set of parallel plates of 25 mm diameter following the procedure given in the AASHTO provisional specifications [89]. The samples for the test were prefabricated using a silicone rubber mold. To maintain a specific constant temperature, the samples were completely immersed in temperature-controlled water that was circulated throughout the test by a pump-equipped water bath. The rheometer and the temperature-controlled unit were operated through a personal computer and the data acquisition / analysis was done using specialized software running under Windows ’95.

The data were generated using a frequency sweep covering a range from 0.1 radians/s to 100 radians/s with 33 data points. It was essential to establish that the generated data is within the linear viscoelastic range of response. The values of the viscoelastic functions are independent of the applied stress amplitudes within the linear range of response, but the moduli begin to show a decrease with increasing stress when the response gets into the non-linear range. To identify the border between the two regimes of response, a few experiments were initially conducted using different stress levels to watch the strain levels when the response changes from linear to non-linear. The established target strains are used in the frequency sweeps.

Figure 2a (left above): Unified curve of the SHRP parameter |G|/sin δ with modified frequency ω(L$^{1/n}$/MVR) covering the temperature range of 46°C - 70°C for five asphalts (AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in original unaged forms.*

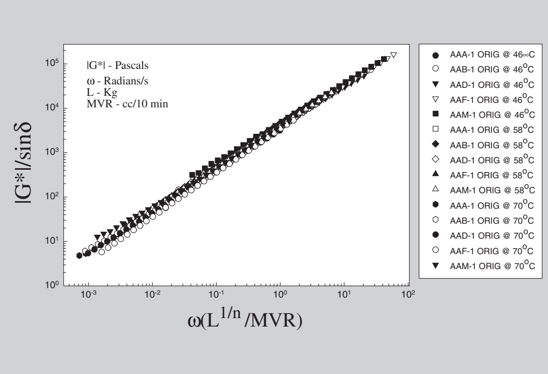


Figure 2b (right above): Unified curve of the SHRP parameter |G|/sin δ with modified frequency ω(L$^{1/n}$/MVR) at temperatures of 52°C and 64°C for five asphalts (AAA-2, AAB-2, AAC-2, AAD-2 and AAF-2) each in original unaged form.*

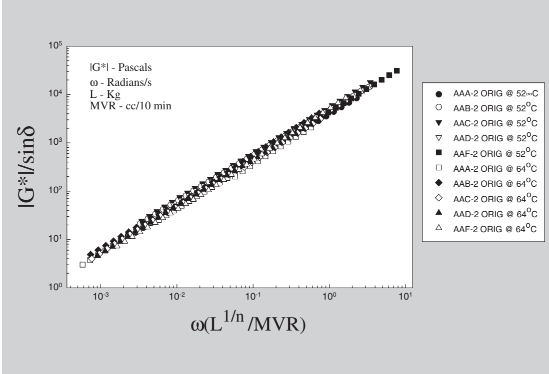
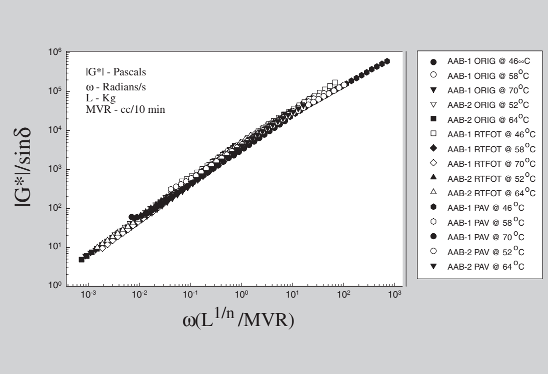


Figure 3 (left below): Unified curve of the SHRP parameter |G|/sin δ with modified frequency ω(L$^{1/n}$/MVR) at temperatures of 46°C, 58°C and 70°C for asphalt AAB-1 as well as at temperatures of 52°C and 64°C for asphalt AAB-2, each in original unaged and (RTFOT & PAV) aged forms.*



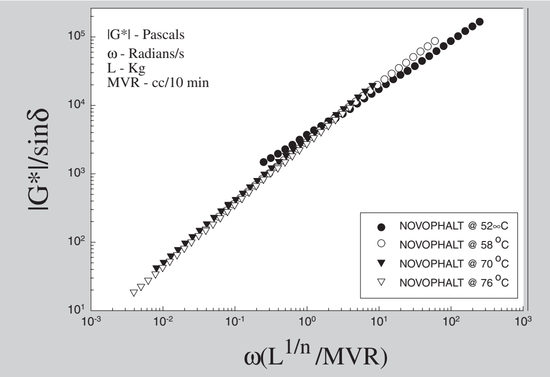
4 UNIFIED CURVES

The equipment used for measurement of *MVR* as defined above falls in the category of a circular orifice rheometer [86]. Through a systematic theoretical analysis [82-84] of flow through a circular orifice rheometer, it has been shown that *MVR* can be related to the fundamental rheological properties, namely, |*G**|, *G”* and |*G**|/sin δ that are determined from the Dynamic Shear Rheometer (DSR). When plots of |*G**|, *G”* and |*G**|/sin δ versus frequency ω are replotted on a modified frequency scale $\omega\, L^{1/n}/MVR$, then unified curves could be obtained for each of the rheological parameters |*G**|, *G”* and |*G**|/sin δ. In case the *MVR* value has been determined at a load *L* for a particular asphalt sample 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. L_2). For example, if the *MVR* value has been determined at say 2.16 kg, then it would be necessary to determine *MVR* value at say 3.06 kg and another at say 1.00 kg. load. In order to get the value of n, the following equation is used, where MVR_1 and MVR_2 are the two values at L_1 and L_2, respectively:

$$n = \frac{\log \dfrac{L_1}{L_2}}{\log \dfrac{MVR_1}{MVR_2}} \qquad (1)$$

4.1 UNMODIFIED ASPHALTS

Five asphalts from among the SHRP Materials Reference Library asphalts were chosen [82] to serve as representatives during the initial verification of the developed theory for unification. These were AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1 from the dash-1 series. For further confirmation of the unification technique, five more asphalts were chosen [83] from among the SHRP Materials Reference Library asphalts. These were AAA-2, AAB-2, AAC-2, AAD-2 and AAF-2 from the dash-2 series. This was done with the idea of covering a wide range of asphaltene content, a broad span of molecular weight, and a good spread of viscosity values. Each of these samples were tested in their original unaged form and then again after aging using the rolling thin film oven test (RTFOT) at 163°C for 85 minutes and in the pressure aging vessel (PAV) at 100°C for 20 hours in accordance with the AASHTO provisional standard procedure [90]. The unified |*G**|/sin δ curve for original unaged unmodified asphalts for the dash-1 series is shown in Fig. 2a while the dash-2 series is shown in Fig. 2b. It can be seen that the curves in Fig. 2 are unique and independent of the type of asphalt as well as the temperature of measurement. The unified curve in Fig. 2a has a total of 495 data points (i.e. 99 data points for each of the five asphalts: AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1). The unified curve in Fig. 2b has a total of 330 data points (i.e. 66 data points for each of the five asphalts: AAA-2, AAB-2, AAC-2, AAD-2 and AAF-2). It should be noted that the unified curve in Fig. 2 basically superimpose on each other though one is for dash1 type asphalts at temperatures of 46°C, 58°C, 70°C and the other is for dash2 type asphalts at temperatures of 52°C, 64°C. Similar unified curves are obtained for |*G**| as well as *G”* for all unmodified unaged asphalts. Based on the theoretical development, the unification should hold independent of



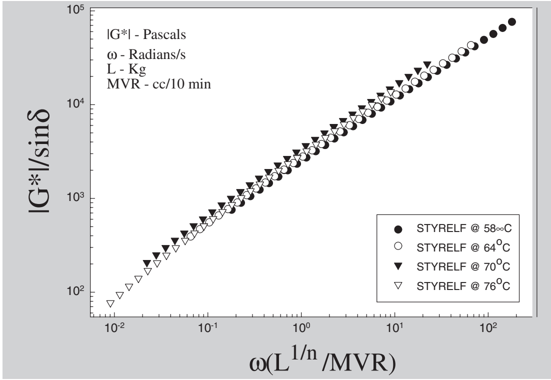


Figure 4 (left): Unified curve of the SHRP parameter |G|/sin δ with modified frequency ω($L^{1/n}$/MVR) covering temperature range of 52°C - 76°C for Novophalt original unaged sample.*

Figure 5 (left): Unified curve of the SHRP parameter |G|/sin δ with modified frequency ω($L^{1/n}$/MVR) covering temperature range of 58°C - 76°C for Styrelf original unaged sample.*

whether the sample is in the original unaged form or RTFOT/PAV aged form. Unified curves were, indeed, obtained for |*G**|, *G"* and |*G**|/sin δ for RTFOT and PAV aged unmodified asphalts [82]. The other check was to see whether the dash1 and dash2 grades of asphalt from one source formed a unified curve. In order to view this, AAB-1 data at 46°C, 58°C and 70°C were plotted along with AAB-2 data at 52°C and 64°C as shown in Fig. 3. When other pairs of dash1 and dash2 were considered, the results were similar and hence, they have not been shown here.

4.2 POLYMER-MODIFIED ASPHALTS

The two polymer-modified asphalts chosen for testing the efficacy of unification were those that were used in the Accelerated Loading Facility (ALF) experiment [91] at the Turner-Fairbank Highway Research Center of the Federal Highway Administration. These were Novophalt and Styrelf:

i. Novophalt (PG76-22) is manufactured by Advanced Asphalt Technologies (AAT), Sterling, VA. The base asphalt used for the ALF Novophalt is AC-10. The asphalt is mixed with a certain amount (probably about 6.5%) of low-density polyethylene (unknown grade as the information is proprietary). The material is run through a high shear mixer at about 145°C and then fed back into the mixer and run again to get a better dispersion. The final mixed material is not stabilized and tends to separate if correct handling procedures are not followed.

ii. Styrelf (PG82-22) is presently 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 styrene-butadiene (SB) is added to it. Sulfur is added for the reactions to occur in order to achieve chemical links with asphaltenes and other reactive species in the asphalt.

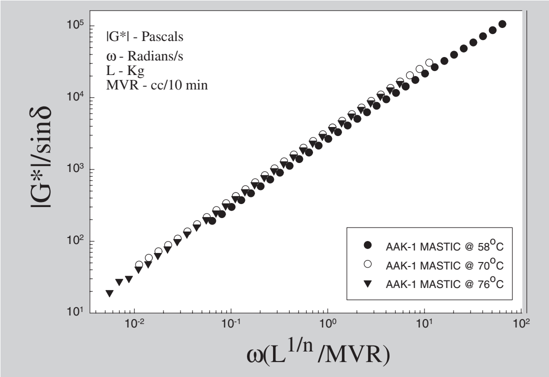
The idea of unification has been extended [85] to polymer-modified asphalts, specifically, Novophalt and Styrelf. It has been shown that unified curves can be obtained for each polymer-modified asphalt (for example, as in Fig. 4 shown for Novophalt) using the same method that was used for unmodified asphalts.

It must be noted that Novophalt is an unstablized system and hence it is naturally difficult to get reproducible rheological data. Whenever DSR data is obtained on two different Novophalt samples, there is a considerable variation in the rheological characteristic even if all other conditions (such as temperature of measurement, the plate diameters, frequency range of measurements, etc.) are maintained the same. One would have expected this to cause a problem in the unification; however, it does not. The unification is based on getting DSR data and *FMD* data on rheologically identical samples. This is achievable if care is taken to pour the sample for the DSR and the *FMD* measurement from the same container at around the same time and the same temperature. When such care is taken, the sample measured on the DSR and the *FMD* are rheologically identical and they will then unify elegantly on the curve. In case a replicate is taken and the two DSR data do not match, it will be found that the *MVR* data on the replicate will also be offset accordingly in such way that the data will unify. This is because the term *($L^{1/n}$/MVR)* will take care of the corresponding changes.

Based on the theoretical development, it is evident that the unification should hold independent of the type of polymer-modified asphalt being considered, though of course each different type of polymer-modified asphalt may have its own unified curve. In order to confirm this, the polymer-modified asphalt Styrelf is considered. Again, the 33 data points from each curve generated from the DSR were modified using a single data point from the *FMD*. A total of 132 data points have been unified into a single curve in Fig. 5. The same procedure when applied to |*G**| and *G"* data for Novophalt and Styrelf also gave unified curves.

4.3 ASPHALT MASTICS

"Asphalt mastics" is the term used to designate asphalts containing suspended fillers. The word 'filler' in this context refers to that fraction of mineral dust passing the 200-mesh sieve or par-



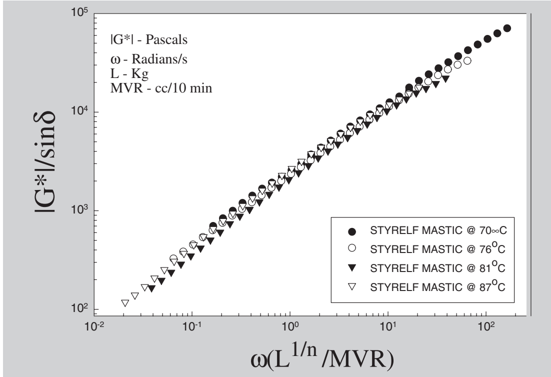


Figure 6 (left): Unified curve of the SHRP parameter $|G^*|/\sin\delta$ with modified frequency $\omega(L^{1/n}/MVR)$ covering temperature range of 58°C - 76°C for AAK1 mastic unaged sample.

Figure 7 (right): Unified curve of the parameter $|G^*|/\sin\delta$ with modified frequency $\omega(L^{1/n}/MVR)$ covering temperature range of 70°C - 87°C for Styrelf mastic unaged sample.

ticles smaller than 75 µm. The two asphalts chosen for checking the applicability of unification [92] were 1.) an unmodified asphalt AAK1 from the Material's Reference Library and 2.) a polymer-modified asphalt Styrelf from the Accelerated Loading Facility (ALF) study [91] at Turner-Fairbank Highway Research Center of the Federal Highway Administration:

i. The asphalt mastics were prepared by mixing 30 volume percent of diabase with the binder. The choice of using 30 volume percent of diabase to prepare the asphalt mastic was based on the fact that the fines passing 200 mesh work out to about 27-28% by volume of the binder in most fully graded aggregate systems.

ii. Measured quantity (97.98 g) of binder was heated to 163°C for 80 minutes. At the same time, measured quantity (102.52 g) of diabase (to make 30 volume percent mastic) was also heated to the same temperature for 80 minutes. The binder was removed from the oven and stirred for 1 minute at 600 rpm with a mechanical stirrer. Then the heated diabase powder was added to it and it was further stirred for 2 minutes at 600 rpm. The mixture was then poured into silicon molds to make samples for the DSR and also poured into the *FMD* to get the *MVR* data.

In Figs. 6 and 7, the 33 data points for each curve generated from the DSR were modified using a single data point from the *FMD*. A total of 99 data points have been unified into a single curve in Fig. 6 and a total of 132 data points have been unified into a single curve in Fig. 7. Applying the same procedure to G'' and $|G^*|$ data for AAK1 mastics and Styrelf mastics, also gave unified curves.

5 DISCUSSION OF THE RESULTS

Figs. 2 and 3 confirm that the unification technique works for at least ten different unmodified asphalts. A closer look at the selection of the ten asphalts indicates that they span a wide range of viscosity levels, have varied asphaltene content, varied wax content as well as high to low molecular weights. When such a wide spectrum of differences can be unified by the suggested approach, it may not be too unrealistic to expect that all unmodified asphalts would fall on the same curve.

Figs. 4 and 5 confirm that the unification technique works for at least two polymer-modified asphalts. The polymer-modified asphalts chosen in this study are different in many respects. Firstly, they are not made from the same base asphalt. Secondly, whereas one is modified using a thermoplastic homopolymer - low-density polyethylene, the other is modified using a block copolymer - styrene butadiene styrene. The rheological behaviors of the modifiers in their pure melt form are radically different [86] and hence their presence in the asphalt depicts quite different rheological characteristics. Despite these diversities, it has been shown that the unification approach works well in both cases. It may therefore, not be unrealistic to expect that the unification technique would in general be applicable to all polymer-modified asphalts. Of course, this needs to be confirmed, and can be done over a period of time in future.

Figs. 6 and 7 confirm that the unification technique works for at least two asphalt mastics. In the mastic study, the two binders chosen AAK1 and Styrelf are representative of an unmodified asphalt and a polymer-modified asphalt, respectively. It might thus be reasonable to expect that the unification technique will work well for any asphalt mastic, provided of course the system analyzed stringently follows the definition of the asphalt mastic as given earlier. The mastic must be formed by suspended filler in the asphalt, implying that it should not be a settling or unstable suspension. To confirm that the unification technique would not work when handling settling, unstable suspensions, experiments were carried out with two more mastics. One used the unmodified asphalt AAF1 and the other used the polymer-modified asphalt Novophalt. Both these binders formed settling, unstable suspensions and an attempt to unify the curves did fail in both cases. Thus, when developing unified rheological curves for asphalt mastics, it is important to first make sure that a non-settling, stable suspension is being handled.

Reinforcement of the curves with more data and further refinement of the curves to reduce the error bounds can be accomplished to finally establish the decisive shapes of the unified curves. Based on the theoretical analysis [82, 83, 85, 92], it is not surprising that unified curves could be obtained for unmodified asphalts, polymer-modified asphalts and mastics. This is because the theoretical equations, which support the unification, are not dependent on the type of material characterized on the DSR and the *FMD*, and hence applicable to a variety of systems [86, 93].

The main accent of the unification work [92] was essentially to establish the unification technique and suggest the methodology that needs to be followed in order to achieve proper unification based on good theoretical foundations. This could be achieved through the analysis of rheological data on the ten chosen unmodified asphalts, two representative polymer-modified asphalts and two selected asphalt mastics. The unified curves of fundamental rheological data have many advantages. Hence the beneficial implications of this unification are discussed next.

5.1 IMPLICATIONS OF THE UNIFIED CURVES

The implications of the united curves are:

i. In the Superpave © binder performance grading system, there is specification for a minimum limit requirement of $|G^*|/\sin\delta$ (= 1 kPa) for unaged asphalts and (= 2.2 kPa) for RTFOT aged asphalts at a frequency of 10 radians/s to simulate traffic loading when vehicles move at 50-60 mph. From the unified curves given in Figs. 2 - 5, a value of $\omega\,(L^{1/n}/MVR)$ was determined for the first specification limit as

$$\omega \frac{L^{1/n}}{MVR} = 0.245 \tag{2}$$

(Minimum requirement for unaged unmodified asphalts and polymer-modified asphalts–Novophalt and Styrelf)

A value of $\omega\,(L^{1/n}/MVR)$ was determined for the second specification limit as

$$\omega \frac{L^{1/n}}{MVR} = 0.55 \tag{3}$$

(Minimum requirement for RTFOT aged unmodified asphalts)

Since a frequency of 10 radians/s has been chosen to simulate actual traffic conditions, the requirements can be rewritten as follows:

$$\frac{L^{1/n}}{MVR} = 0.0245 \tag{4}$$

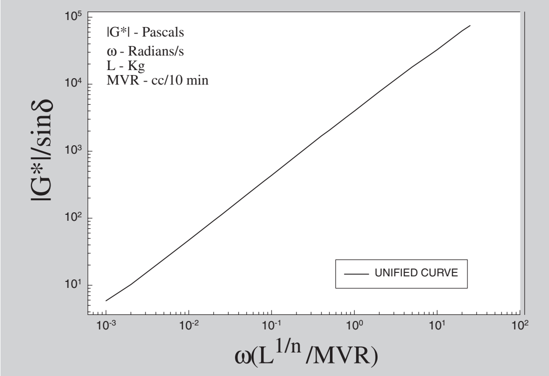
(Minimum requirement for unaged unmodified asphalts and polymer-modified asphalts–Novophalt and Styrelf)

$$\frac{L^{1/n}}{MVR} = 0.055 \tag{5}$$

(Minimum requirement for RTFOT aged unmodified asphalts)

The implicit advantage of the unification technique is that, if at all the Superpave © binder specifications are changed from the present 1 kPa and 2.2 kPa to some other values, then no new data need to be generated. One could simply read out the new requirements corresponding to Eqs. 2 and 3 from the unified plots. New research continually brings in new ideas, and refinements of the specifications are not to be ruled out. New analyses or traffic conditions in the future could warrant the imposition of a higher frequency than 10 radians/s in the specifications. With the unified curves available, there would be no need to again generate fresh data. Eqs. 4 and 5 simply take on new values by using the new frequency in Eqs. 2 and 3.

ii. The unified curves can be fitted with appropriate rheological equations so that predictions can be made in the future, not by reading values from the plots, but by simple mathematical calculations. These rheological equations will give unique relationships between $|G^*|$ versus $\omega\,(L^{1/n}/MVR)$, G'' versus $\omega\,(L^{1/n}/MVR)$, $|G^*|/\sin\delta$ versus $\omega\,(L^{1/n}/MVR)$, and so on for all unmodified asphalts. These equations would be directly useful to those



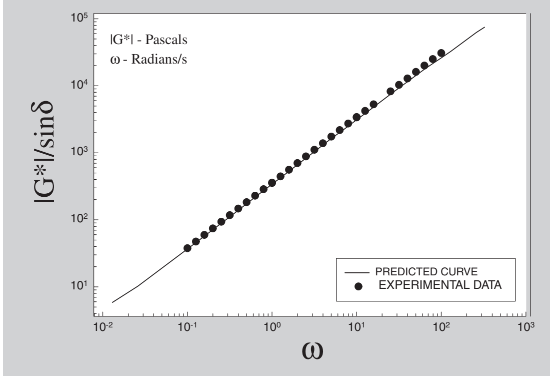


Figure 8 (left): Unified curve of the SHRP parameter |G|/sin δ with modified frequency $\omega(L^{1/n}/MVR)$ at temperatures of 46°C - 70°C for unmodified original unaged asphalts.*

Figure 9 (right): Comparison of the predicted curve and experimental data for the SHRP parameter |G|/sin δ with frequency ω at temperature of 52°C for unmodified original unaged asphalt AAF2.*

who are modeling the performance of asphalts and attempting to relate the performance characteristics with their chemistry and physical structure.

iii. If a database that includes all-important parameters of asphalts is to be developed, then the unified curves will greatly reduce the amount of data that are needed to be stored in the information base. In fact, for all unmodified asphalts, the complete rheological data will be capsuled in just one single curve corresponding to each fundamental material function.

5.2 ERROR BOUNDS AND CONFIDENCE LIMITS

The unified curves show a band within which all data points coalesce. It is important to estimate the bandwidth in order to get an idea about the error bounds of this technique. To do this, values of $|G^*|$ were noted for some typical ω $(L^{1/n}/MVR)$ values for each set of data. From these data, the minimum, maximum, average and standard deviations were calculated. The percentage error considering all cases for unmodified asphalts were seen to be in the range of 3-16% and for polymer-modified asphalts to be in the range of 7-20%. The error bounds for individual DSR measurements were found to be 6-12% for unmodified asphalts and 7-22% for polymer-modified asphalts. For the *FMD* measurements, the error bounds were found to be 0.2-2% for unmodified asphalts and 1-4% for polymer-modified asphalts. It is quite evident that the error bound range of 3-16 % for unmodified asphalts and 7-20% for polymer-modified asphalts in the unified curves is more of a reflection of errors in the original DSR data.

Whether the error comes from the *FMD* or DSR or both measurements, it is important to check what effect this error would have on the Superpave © binder specifications if estimates were obtained from the unified curves. From Fig. 2a at $|G^*|/\sin\delta$ (= 1 kPa), the minimum, average and maximum values of $\omega(L^{1/n}/MVR)$ were estimated from the bandwidth as 0.21, 0.245 and 0.28. It may be recalled that 0.245 is the value used in Eq. 2. Thus, at ω = 10 rad/s, the minimum, average and maximum values of $(L^{1/n}/MVR)$ were calculated as 0.021, 0.0245 and 0.028, respectively. The values of temperatures corresponding to these $(L^{1/n}/MVR)$ values were estimated using an Arrhenius relationship. For AAA-1 ORIG, for example, temperatures obtained are 60.9, 59.8 and 58.8 corresponding to $(L^{1/n}/MVR)$ equal to 0.021, 0.0245 and 0.028. It can be seen that the temperature difference between the minimum and maximum is only about 2 degrees. This means that if the unified curve were used for PG grading, it would be perfectly okay even with the existing bandwidth as it will correctly estimate the appropriate grade and not jump a grade.

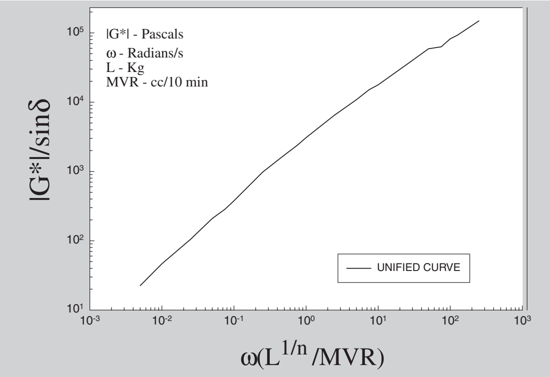
5.3 PREDICTING VISCOELASTIC DATA FROM UNIFIED CURVES

The idea behind developing the unified curves is to get a method for predicting viscoelastic parameters without actually generating DSR data. In order to check whether this is possible, the following steps need to be followed.

5.3.1 UNMODIFIED ASPHALTS

From Fig. 2a, the average values of the viscoelastic parameter $|G^*|/\sin\delta$, at different values of modified frequency ω $(L^{1/n}/MVR)$ are obtained. Using these values, the unified curve for unmodified original unaged asphalts is drawn as shown in Fig. 8. Using these predicted unified points, it is now possible to estimate the $|G^*|/\sin\delta$ values at different frequencies for any unmodified asphalt at any temperature between 46°C - 70°C when *MVR* value at a convenient load, *L*, and the parameter, *n*, are known.

In order to check the predictability, unmodified asphalt AAF-2 is chosen. It should be noted that this asphalt was not used when the unified curve was formed in Fig. 2a. Asphalt AAF-2 is a West Texas Sour with a viscosity of 867 poise @ 140°F and has about 13% asphaltenes. The test temperature is chosen as 52°C. At this temperature, for original unaged AAF-2, the *MVR* is determined to be 12.97 cm^3/10min at load *L* = 1 kg and



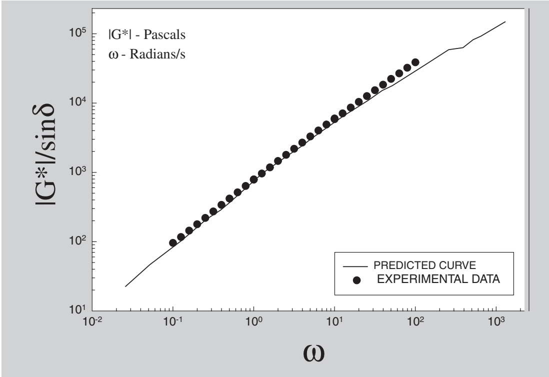


Figure 10 (left): Unified curve of the SHRP parameter $|G^*|/\sin\delta$ with modified frequency $\omega(L^{1/n}/MVR)$ at temperatures of 52°C - 76°C for polymer-modified unaged asphalt - Novophalt.

Figure 11 (right): Comparison of the predicted curve and experimental data for the SHRP parameter $|G^*|/\sin\delta$ with frequency ω at temperature of 64°C for polymer-modified unaged asphalt - Novophalt.

the value of n is determined from two other *MVR* measurements as equal to 0.925. Thus a value of $(L^{1/n}/MVR)$ is calculated as 0.077. Using this value in Fig. 8, the variation of $|G^*|/\sin\delta$ parameter is calculated and shown by the solid line in Fig. 9. Actual DSR data are plotted on the same figure. The match between predicted curve and experimental data is seen to be good.

A similar exercise is carried out for PAV-aged asphalt AAF-2 at 52°C, and the match between predicted curve and experimental data was found to be excellent [83]. For confirmation of predictability, the same calculations were done for asphalt AAB2 that was RTFOT-aged. This time the test temperature was chosen as 64°C. Again, the match between the predicted curve and experimental data was found to be excellent [83].

5.3.2 POLYMER-MODIFIED ASPHALTS

For polymer-modified asphalts, the predictability procedure is illustrated for Novophalt data. From the unified curve in Figure 4, the average values of the $|G^*| / \sin\delta$ parameter were obtained at different values of modified frequency ω $(L^{1/n}/MVR)$. Using these values, theoretical unified curve was drawn as shown in Fig. 10. From this theoretical unified curve, it is now possible to estimate $|G^*|/\sin\delta$ values at different frequencies for Novophalt at any temperature between 52°C - 76°C when the *MVR* value at a convenient load, *L*, and the parameter, *n*, are known.

In order to check the predictability, Novophalt data at 64°C is chosen. It should be noted that data at this temperature was not used when the unified curve was formed in the first place. At this temperature of 64°C, the *MVR* is determined to be 80.17 cm^3/10min at load $L = 10$ kg and the value of n is determined from two other *MVR* measurements as equal to 0.84. Thus a value of $(L^{1/n}/MVR)$ is calculated as 0.193. Using this value, the variation of $|G^*|/\sin\delta$ is calculated and shown by the solid line in Fig. 11. Actual DSR data are plotted on the same figure and the match between predicted curve and experimental data is seen to be good.

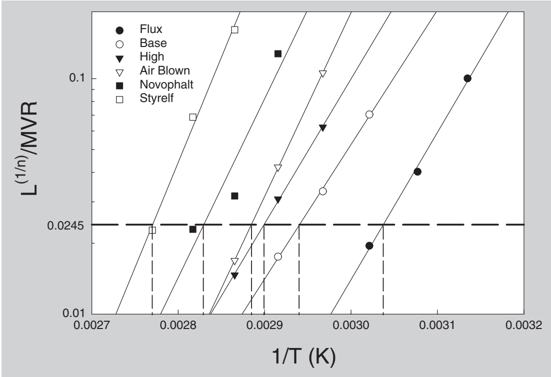
5.4 HIGH TEMPERATURE PG SPECIFICATION FROM THE MVR

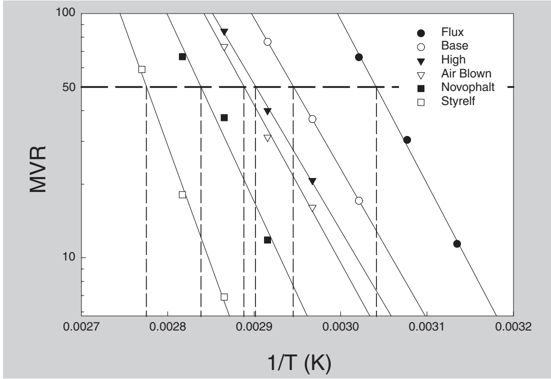
This section explores the idea of obtaining the high temperature PG specification from the *MVR*. The method is straightforward, fast and accurate and gives an alternative way for obtaining the specification temperature. Since the *FMD* is a simple inexpensive portable device, there is an added incentive to promote this technique for use on a routine basis for quality assurance of previously graded asphalt. 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 asphalts or adding polymers to asphalt.

In order to estimate the specification temperature, 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. For verification purposes, the PG high temperature is also determined using the conventional method from Dynamic Shear Rheometer (DSR) data. A total of twelve asphalts were chosen for this study. Ten of these included a PG52-34 (flux), a PG64-22 (base), a PG70-22 (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 asphalts 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 PG64-22 (base) or PG52-28 (flux) or mixture of the PG64-22 (base) and PG52-28 (flux) in different proportions so as to achieve the same performance grading. These asphalts were chosen for this study since they 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 asphalts from the earlier ALF study

Figure 12 (left): Variation of $L^{1/n}/MVR$ versus 1/T on a semi-logarithmic plot for select asphalts.

Figure 13 (right): Variation of MVR versus 1/T on a semi-logarithmic plot for select asphalts.





were also included, namely, PG76-22 (Novophalt) and PG82-22 (Styrelf). The sets of values of $L^{1/n}/MVR$ versus 1/T (K) were plotted on a semi-logarithmic scale as shown in Figure 12 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 in order to satisfy the condition set up in Eq. 4.

The above procedure 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, which was chosen to be *L* = 1.225 kg. Eq. 4 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.

$$MVR = \frac{L^{1/n}}{0.0245} = \frac{1.225}{0.0245} = 50 \tag{6}$$

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 Fig. 13 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, in order to satisfy the condition set up in Eq. 6.

The specification temperatures obtained by this simplified method, when compared with earlier method was found to give closely matching values, showing that the error due to the approximations was 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. It would be worthwhile to check whether *MVR* data taken at only two temperatures (one at grade temperature - 6°C and the other at grade temperature + 6°C) would suffice in getting good enough estimates of the PG high temperature specifications, using the following equation.

$$T_{HS} = \frac{T_1 T_2 (\ln MVR_{T_1} - \ln MVR_{T_2})}{T_1 \ln MVR_{T_1} - T_2 \ln MVR_{T_2} - (T_1 - T_2)\ln 50} \tag{7}$$

where 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 designed as T_1 and T_2 and the *MVR* value at the high specification temperature T_{HS} is given the value of 50. The PG high temperature is calculated as (T_{HS} - 273) in degrees Centigrade. 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 Eq. 7. This was done for two materials i. Base and ii. Styrelf. For each material, the calculated values of T_{HS} for three replicates were found to be in very close agreement.

The data from the DSR using the time sweep is presently used for determining the high temperature PG number. This is done by plotting the average value of $|G^*|/\sin\delta$ over the time of measurement 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 $|G^*|/\sin\delta$ = 1 kPa in order to satisfy the condition set up by SHRP.

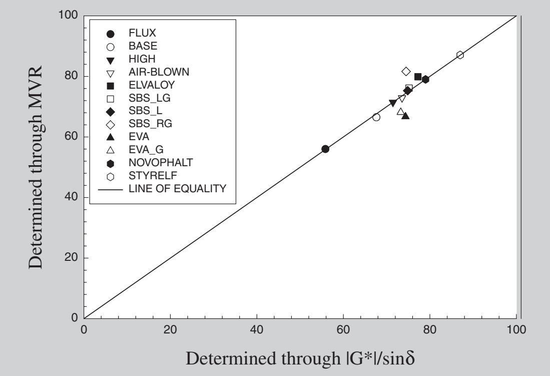


Figure 14: Comparison between the high temperature PG determined through MVR and that determined through |G|/sin δ.*

The specification temperatures obtained by all four methods were compared and the values were found to match quite closely. Figure 14 shows the goodness of the comparison between the high temperature PG determined through *MVR* and that determined through $|G^*|/\sin\delta$.

6 CONCLUDING REMARKS

The unification of fundamental rheological data for unmodified asphalts, polymer-modified asphalts and asphalt mastics provides a rather powerful tool to reduce subsequent experimentation and to ease the generation of rheological information in the future. It also provides the possibility of introducing new specification parameters that have the advantage of being easy to determine and at the same time being more flexible to changes, in case such a need for a specification change is felt in the future.

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, based on the Superpave © binder specification requirement of $|G^*|/\sin\delta$ = 1 kPa for unaged asphalts at a frequency of 10 radians/s. Though $|G^*|/\sin\delta$ parameter was found to relate to permanent deformation in the case of unmodified asphalts, it has been found not to correlate well in the case of polymer-modified asphalts [95-100]. 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 $|G^*|/\sin\delta$ so as to make it more sensitive to pavement performance [101-104].

One of the suggestions has been to use the zero-shear viscosity [95, 101], instead of the $|G^*|/\sin\delta$ parameter. However, the method for the determination of zero-shear viscosity as proposed [101] 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* [86] and a relationship between zero-shear viscosity and *MVR* has been shown to hold well [86, 105].

Repeated creep and recovery test for binders (RCRB) is being suggested by Bahia et al. [97] 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 0.3 kPa for a 1-second duration (loading time) followed by a 9-second recovery period (rest period) for 100 cycles. Bouldin et al. [102,103] have utilized the RCRB as proposed by Bahia et al. [97] to evaluate the relative rut resistance of test binders. The generated experimental data was then used by Bouldin et al. [103] to develop a semi-empirical model to refine the current Superpave high temperature specification parameter $|G^*|/\sin\delta$. The proposed refinement to the Superpave specification parameter as done by Bouldin et al. [103] involves five empirical fitting parameters that are likely to change if more data are analyzed, or if experimental data of the replicates are 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 a general equation that would be applicable at all times.

Shenoy [104] 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 [104] for %-unrecovered strain is as follows:

$$\%\gamma_{unr} = \frac{100\sigma_o}{|G^*|}\left(1 - \frac{1}{\tan\delta\sin\delta}\right) \tag{8}$$

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

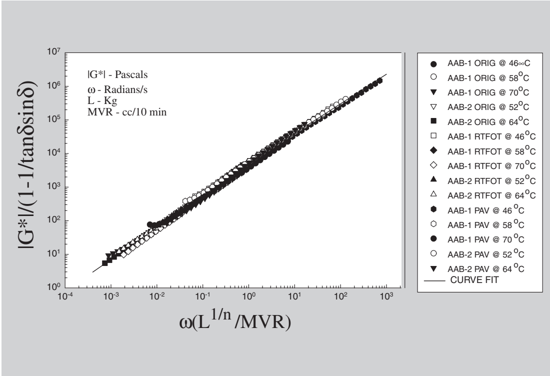


Figure 15 (left above): Unified curve of the new specification parameter $|G^*|/(1 - (1/\tan\delta \sin\delta))$ with modified frequency $\omega(L^{1/n}/MVR)$ at temperatures of 46°C, 58°C and 70°C for asphalt AAB-1 as well as at temperatures of 52°C and 64°C for asphalt AAB-2, each in original unaged and (RTFOT & PAV) aged forms.

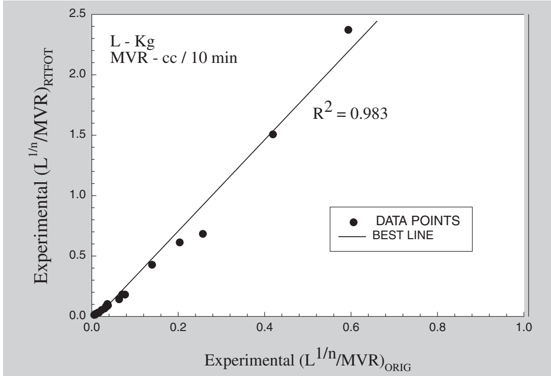


Figure 16a (right above): Plot of the shift factor $L^{1/n}/MVR$ for RTFOT-aged asphalts versus the original unaged asphalts.

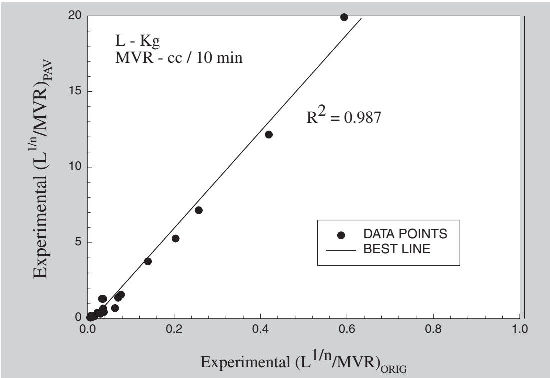


Figure 16b (left below): Plot of the shift factor $L^{1/n}/MVR$ for PAV-aged asphalts versus the original unaged asphalts.

$$\frac{|G^*|}{\left(1-\dfrac{1}{\tan\delta\sin\delta}\right)} \tag{9}$$

Shenoy [104] suggests the above term as the new specification parameter, instead of $|G^*|/\sin\delta$. The high specification temperature is specified as the temperature at which the term given by Eq. 9 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 the same specification temperatures for unmodified binders as predicted under the earlier Superpave specification system. Any new specification parameter or its refinement should maintain the specification value for unmodified binders while providing a better means of specification for modified binders.

Using the new specification parameter given by Eq. 9, unified curve can be obtained for all cases in a manner similar to those in Figs. 2-7 which were established for $|G^*|/\sin\delta$. As an example, unified curves for the new specification parameter are shown in Fig. 15 for the unmodified asphalt systems used in Fig. 3. Any unified curve can be fitted by an appropriate rheological model as done by Shenoy [106]. Since Figure 15 covers a very large range of modified frequency $\omega L^{1/n}/MVR$, the curve is split into two parts and appropriate constitutive equations of the power-law form are fitted to each part. Then the two equations are combined to give a composite model covering the entire range of data. The form of the model suggested by Shenoy [106] is given below:

$$\left[\frac{|G^*|}{1-\dfrac{1}{\tan\delta\sin\delta}}\right]=\frac{A_1(\omega L^{1/n}/MVR)^{B_1}}{[1+\{(A_1/A_2)^{2/(B_1-B_2)}(\omega L^{1/n}/MVR)^2\}]^{(B_1-B_2)/2}} \tag{10}$$

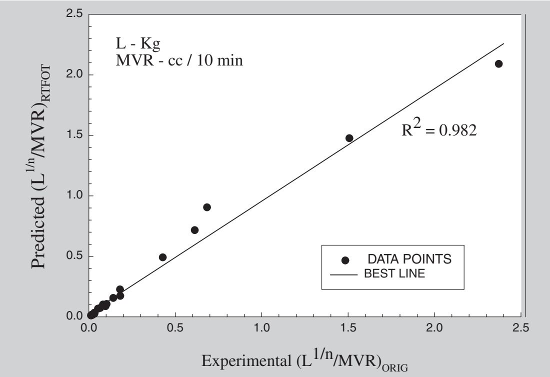
Using values of A_1 = 4850, B_1 = 0.947, A_2 = 5212 and B_2 = 0.881 gave good agreement with the data points in Figure 15 resulting in the following equation:

$$\left[\frac{|G^*|}{1-\dfrac{1}{\tan\delta\sin\delta}}\right]=\frac{4850(\omega L^{1/n}/MVR)^{0.95}}{[1+0.114(\omega L^{1/n}/MVR)^2]^{0.033}} \tag{11}$$

Though the curve in Fig. 15 shows only data for AAB-1 and AAB-2, this curve is unique [82, 83] for all original unaged as well as RTFOT and PAV-aged unmodified asphalts within the temperature range of 46° - 70°C. Thus Eq. 11 is valid for all original unaged as well as RTFOT and PAV-aged unmodified asphalts within the temperature range of 46° - 70°C.

One of the advantages of this unification is that if a relationship is established between the shift factors $L^{1/n}/MVR$ for the aged asphalts with those of the unaged asphalts, then there would be no need in the future to even age the asphalts in the laboratory for estimating the rheological changes due to aging. Fig. 16. show the variation of $(L^{1/n}/MVR)_{RTFOT}$ with $(L^{1/n}/MVR)_{ORIG}$ and $(L^{1/n}/MVR)_{PAV}$ with $(L^{1/n}/MVR)_{ORIG}$. The best line through the points is drawn using the following equations and can be seen to show a correlation coefficient R^2 of greater than 0.98.

$$(L^{1/n}/MVR)_{RTFOT} = 14e^{-0.03T}(L^{1/n}/MVR)_{ORIG}$$
$$(L^{1/n}/MVR)_{PAV} = 475e^{-0.06T}(L^{1/n}/MVR)_{ORIG} \tag{12}$$



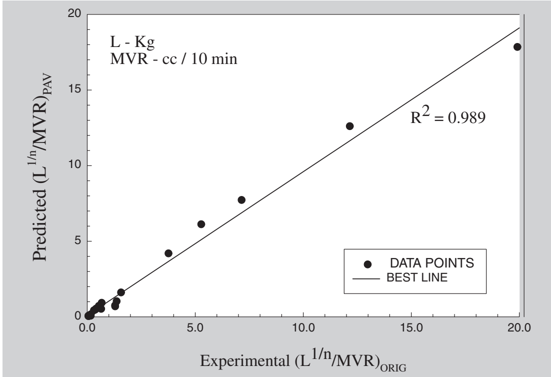
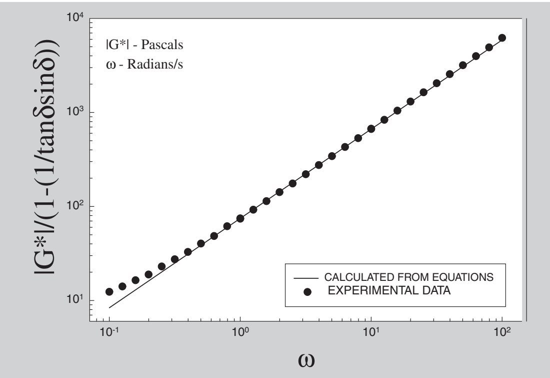


Figure 17a (left above): Plot of the shift factor $L^{1/n}/MVR$ predicted through Eq. 12a versus the experimental data for RTFOT-aged asphalts.

Figure 17b (right above): Plot of the shift factor $L^{1/n}/MVR$ predicted through Eq. 12b versus the experimental data for PAV-aged asphalts.



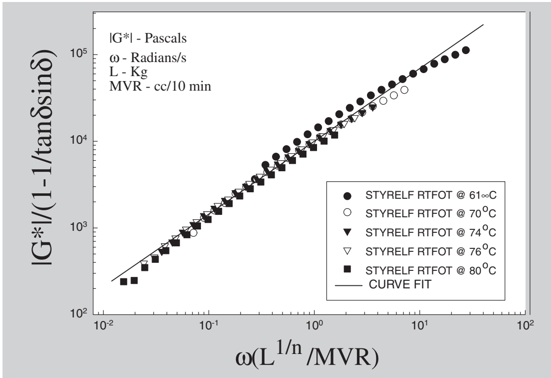


Figure 18 (left below): Comparison of the predictions from calculations with experimental data for the new specification parameter $|G^*|/(1 - (1/\tan\delta \sin\delta))$ versus frequency ω at temperature of 70°C for RTFOT-aged AAA-1 sample.

Figure 19 (right below): Unified curve of the new specification parameter $|G^*|/(1 - (1/\tan\delta \sin\delta))$ with modified frequency $\omega(L^{1/n}/MVR)$ covering temperature range of 58°C - 76°C for Styrelf RTFOT-aged sample.

where *L*, *n* and *MVR* are, respectively, the applied load (kg), the power-law index and the material's volumetric-flow rate (cc/10 min) at the temperature of interest T (°C). The subscripts ORIG, RTFOT and PAV designate the aging conditions of the tested sample, namely, the original unaged, the RTFOT and PAV-aged, respectively. Fig. 17 show how the predictions from Eq. 12 compare with actual experimental data.

The actual aging of the asphalt in the laboratory can thus be eliminated if the above approach is followed for estimating the rheological properties [106]. In fact, Eq. 11 along with Eq. 12a can be used for obtaining the variation of the new specification parameter for the RTFOT-aged asphalt from the value of the shift factor for the original unaged sample as shown in Fig. 18. It can be seen that the calculations based on Eqs. 11 and 12a give good prediction of the experimental data. The same approach can be followed to get an estimate of the rheological properties of the PAV-aged asphalt from the original unaged sample by using Eqs. 11 and 12b.

The fitting of appropriate rheological models to the unified curves has other advantages too. Combining the model with Eq. 8 can give an estimate of the %-unrecovered strain. This has a great deal of relevance to polymer-modified asphalts that show a high degree of elasticity and wherein the %-unrecovered strain is much less than the total strain during deformation. To demonstrate how this can be done, the unified curve of the polymer-modified asphalt – Styrelf for the new specification parameter is chosen as shown in Fig. 19. The following model of the power-law form is used for fitting the data.

$$\left[\frac{|G^*|}{1-\dfrac{1}{\tan\delta\sin\delta}}\right] = A_1(\omega L^{1/n}/MVR)^{B_1} \tag{13}$$

Note that this is a simpler version of equation (10) and is applied on account of the narrower range of the modified frequency $\omega L^{1/n}/MVR$ covered by the data. Using the values of A_1 = 10 and B_1 = 0.84 when $|G^*|$ is expressed in kPa in Eq. 13 and combining it with Eq. 8 for a value of τ_O = 0.3 kPa gives the following:

$$\%\gamma_{unr} = \frac{3}{\left(\omega L^{1/n}/MVR\right)^{0.84}} \tag{14}$$

Eq. 14 can now be used for estimating the %-unrecovered strain using the appropriate values of *L*, n and *MVR* obtained from the *FMD*. Figure 20 shows the plot of the estimated $\%\gamma_{unr}$ versus the actual experimental values determined from a creep recovery test using a loading time t = 1/ω. The correlation coefficient of R^2 = 0.983 demonstrates the excellent relationship.

Thus, it can be seen that the term $L^{1/n}/MVR$ can be effectively used for estimating the %-unrecovered strain and the high tempera-

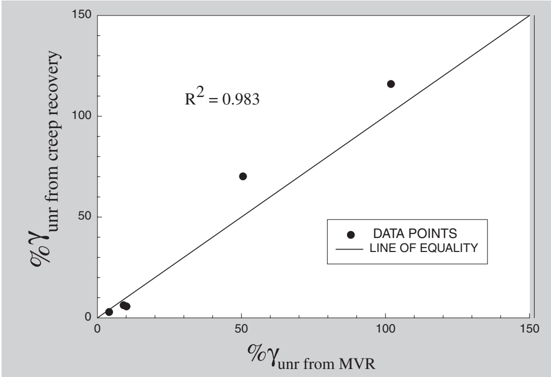


Figure 20 : Comparison of the %-unrecovered strain obtained from creep recovery experimental data with that obtained by calculations using MVR data from the FMD.

ture PG values through the refined new specification parameter given by Eq.9. It may be noted that Eq. 4 was obtained from the unified curve for the unmodified asphalts. Since for unmodified asphalts, Eq. 9 would give nearly the same PG values as those obtained by calculations using $|G^*|/\sin\delta$, Eq. 4 would hold even if the new specification is recommended for use. This means that the recommendations made in the present work 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 or for first-time grading purposes. Future research may show that the recommendations may even relate to actual high temperature performance.

When developing a new asphalt binder (either by blending two asphalts or adding polymers to asphalt or simply air-blowing neat asphalts) 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 at the target specification temperature. If not, it implies that the modification step needs to continue. The *FMD* that is used for the generation of *MVR* data is a relatively simple, inexpensive piece of equipment and can be carried from place to place because of its relative lightweight. It neither needs any arrangements for air pressure nor requires a circulating water-bath to maintain a constant temperature environment. 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. It was found that *MVR* data generated from the *FMD* was very highly reproducible. In fact, in terms of repeatability of data, the *FMD* performs better than DSR. There are a number of other benefits in using the *FMD* [82, 83, 85, 92]. The evaluation of the benefits of the *FMD* are based on a number of factors such as initial equipment cost, operational cost, maintenance cost, operator training requirements, experimental ease, testing time, specimen size, variability of output, data reduction method, information obtained, and mobility or portability.

It was found that the *FMD* beats out DSR on most counts except specimen size and the information obtained. While from the DSR, all fundamental rheological parameters can be obtained, the *FMD* gives a single value measurement of *MVR* at a fixed load condition. However this single value can be correlated with each of the fundamental rheological parameters from the DSR. The unification technique thus upgrades the simple flow rate parameter to a level of high utility. The fact that the *FMD* is a relatively inexpensive equipment, operational costs are low, *MVR* data generation requires minimal training and the output has low level of variability, no calibration is needed, and the equipment is portable merits its use at the paving sites or at the refineries. The actual time for data generation is also very low. 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, and would serve as an excellent “Purchase Guide” specification for the user / producer of paving asphalts.

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