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UNIFYING ASPHALT RHEOLOGICAL DATA USING THE MATERIAL'S VOLUMETRIC-FLOW RATE

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Abstract

The material's volumetric-flow rate MVR (in cc / 10 minutes) through a predefined die under conditions of constant temperature and stress has been used for obtaining unified curves of fundamental rheological properties such as |G*|, G@ and |G*| / Sin * versus frequency in the case of six unmodified asphalts. It has been shown that there is a theoretical basis for the unification and that 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, rather than in research laboratories as is the case with 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.

Keywords : asphalt rheology, unified curves, viscoelastic parameters, flow measurement device, material's volumetric-flow rate

INTRODUCTION

Asphalts have been recognized as complex materials in terms of their constitution and their rheological behavior. It is generally accepted that asphalts form a colloidal system represented by a suspension of asphaltene micelles in a hydrocarbon solvent consisting of saturated paraffins, cycloparaffins and aromatic structures, whose functionality could vary from polar to non-polar and aliphatic to aromatic. Alternatively, asphalts are viewed as systems in which amphoteric chemical species, i.e. those containing strong acid and strong base components on the same compound, are dispersed in a non-polar matrix. In either case, it is this ability to form a colloidal system that lends asphalts their viscoelastic behavior. The interactions between the colloids lead to the formation of a temporary elastic network with reversible or partially reversible deformation depending on the deformation time.

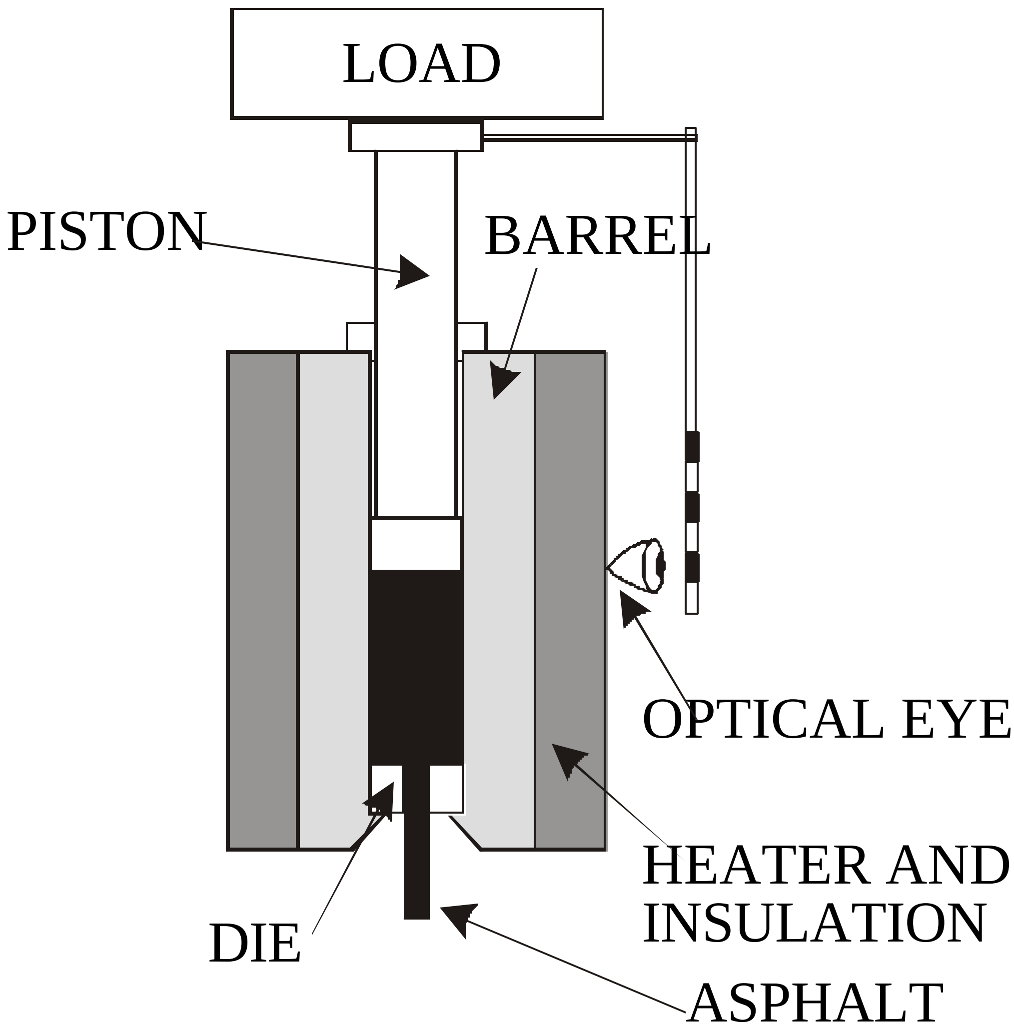
Asphalts find major use as binders in road paving applications as well as waterproof coatings in the roofing industry. The present focus is on paving asphalts though the concepts discussed in the subsequent paragraphs could easily be applied to the rheology of asphalts in roofing or other fields. Understanding the rheology of paving asphalts is important from 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. Secondly, understanding the rheology of the asphalt helps to properly mix the asphalt with the mineral aggregate at the appropriate temperature and to compact the composite material in place so that the final pavement can be prepared well and with ease. Thirdly, understanding asphalt rheology helps to determine 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. Asphalts on paved roads are subjected to a wide range of static and dynamic stresses at varying temperatures and under different environmental conditions. 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. Some of the works include (a) those that sought to study and recommend various important rheological parameters for asphalts (Anderson et al. 1994; Bahia and Anderson 1995; Hanson et al. 1995; Dongre et al. 1996), (b) those that modified the asphalts by air blowing, adding various chemicals or polymers and then studying the rheological properties (Nadkarni et al. 1985; Goodrich 1988; Shashidhar et al. 1995), (c) those that looked for proper equipment to perform fundamental rheological measurements (Wood and Miller 1960; Schweyer et al. 1976), (d) those that attempted to find methods for rapid rheological measurements (Griffin et al. 1957; Heukelom 1973; Stroup-Gardiner and Newcomb 1995), (e) those that searched for relationships between empirical tests and fundamental tests (Van der Poel 1954), (f) those that identified key rheological parameters as specifications to address major distresses in asphalt pavements (Anderson et al. 1994) under the Strategic Highway Research Program (SHRP) and so on. 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. Based on the findings of SHRP (a five-year $150 million dollar United States research effort established and funded under the 1987 Surface Transportation and Uniform Relocation Assistance Act), it was concluded that fundamental viscoelastic behavior of asphalts under different levels of stresses and temperatures needs to be understood 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 will be if one is able to identify a very simple, yet reasonably accurate rheological parameter that could be determined rapidly on equally simple, low cost instrument and then relate it to fundamental rheological data in such a way that viscoelastic parameters could be determined through mere calculation rather than actual experimentation. The present work attempts to bring this idealistic viewpoint to reality and shows a step-by-step procedure to attain this goal.

SIMPLE RHEOLOGICAL PARAMETER

The simple parameter chosen to give a good measure of the rheological characteristics of 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 Figure 1.

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).



This equipment is borrowed from the polymer industry where it is routinely used to measure the melt flow index of the polymers. 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 that of 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 an internal diameter of 2.095 " 0.005 mm.

A cursory look at the proposed method to measure the flow parameter may prompt some asphalt rheologists to recall earlier efforts (Schweyer and Buscot 1971; Schweyer et al. 1976) when a capillary rheometer was used for generating viscosity data. Initially (Schweyer and Buscot 1971), experiments were conducted at a constant rate of strain but later (Schweyer et al. 1976) a constant stress mode was employed for more rapid testing. The approach did not become popular because of the large shear stresses and strains that were produced during measurement. These could lead to spurious results under certain conditions of high stresses due to the elasticity of the material and in other cases, where experimentally correct data could be produced, the results could be outside the range of practical use because of the unreasonably high strain values.

Moreover, their attempt was to generate the entire shear stress versus shear rate data through the capillary rheometer.

In the present case, though a capillary die is used for flow rate measurement, the data is limited to one single value of MVR that is carefully controlled to lie within restricted bounds, thereby keeping the shear rates within acceptable limits. Moreover, the MVR data is collected only under a limited range of dead load conditions, thereby putting an upper bound on the stress level. If at all there are any deficiencies in the measuring technique, these are automatically annulled because the MVR is only used as a normalizing parameter.

DEFINITION OF MVR

The 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. It has been chosen to be consistent with the well-known rheological parameter used in polymer melt rheology, namely, the melt flow index MFI (Shenoy and Saini 1996), 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.

POSSIBLE SOURCES OF ERROR IN MVR DATA

Since the unification approach to be developed subsequently, relies on the MVR value, it is imperative to understand the possible sources of errors in MVR data and evaluate whether there is a need for any correction terms to be introduced during the development of the theoretical basis for unification. Some of the sources of errors in MVR data could be due to

a) kinetic energy effect, b) hydrostatic head of the fluid material above the die exit,

c) time-dependency of the flow, d) entrance and end corrections, and e) effective wall slip.

a) Kinetic energy effect : When the material moving through the barrel of the FMD suddenly encounters the capillary die, it begins to move quickly, resulting in a fall in pressure. This effect of kinetic energy change can be taken into account by replacing)P in the shear stress calculation by)P - c_FDv^2, where v is the average velocity of flow, D is the density of the material and c_F is a correction factor. If the MVR is kept to a low value, then the kinetic energy term attains very little significance and particularly so at higher loads. In the present case, it is recommended that the MVR be determined in such a way through the proper use of the correct dead load condition that its value is maintained to a reasonably low level, say between 1 to 50. Hence, it is assumed that this source of error will be insignificant.

b) Hydrostatic head of the fluid material above the die exit : Another source of possible error could be due to the hydrostatic pressure exerted by the fluid material in the barrel. In the present case, it is recommended that the measurement of MVR be taken only within fixed scribed markings on the piston, so that the piston head is always between 50 and 20 mm above the upper end of the die. Thus, almost the same hydrostatic head would exist for all tested materials, especially because they are all of nearly the same densities. It is also recommended that the dead weight for extrusion should lie between 0.1 - 20 kg, automatically creating a pressure much in excess of the hydrostatic head and hence would not allow this source of error to attain relevance.

c) Time-dependency of the flow : Another source of error that needs to be addressed is the time-dependence of the flow as it goes through the FMD. At a fixed temperature and applied pressure, the manifestation of this time dependent flow is the gradual rise in the output rate from the initial to a higher, steady state value. A rough calculation shows that the pressure drop increases from 78% to 100% of the applied pressure when the FMD goes from completely filled to empty. MVR is determined between fixed markings scribed around the center region of the piston and so the FMD does not truly go through the extreme cases of completely filled or empty barrel. The error introduced due to this time dependence of flow is therefore minimized. Further, this error is not of much concern because MVR is used in the unification approach only as a normalizing parameter firstly to create the unified curves and then secondly, to regenerate the fundamental rheological data back from them. Thus, any effective error would mutually cancel out.

d) <u>Entrance and end effects</u> : In the FMD, since the material flows from a wider reservoir into a capillary of short length in a converging stream and then immediately out in a diverging stream, the shear stress - shear rate values would need entrance and end effect corrections. Customary methods of incorporating these corrections are through the use of an effective capillary length popularly known as the Bagley correction for the shear stress and using the Rabinowitsch-Weissenberg correction for the shear rate. Both these corrections will not be incorporated in the theoretical development because MVR will be used only as a normalizing parameter first to get the unified curves and then to regenerate data. Hence, this source of error is not considered, as it would mutually cancel out when rheological data is regenerated from the unified curves.

e) <u>Effective wall slip</u> : It is known that when a material flows through a capillary, the high molecular weight portions tend to move away from the wall thereby leaving a thin layer of low molecular weight compounds over which the material slips through. This can be another source of error especially in materials that have a very wide molecular weight distribution or are, in general, inhomogeneous. Presently, this error is not accounted during the theoretical derivations for unification. As long as there is successful unification of data, this error can be ignored. However, in case, it is found that some particular materials fail to give proper unification and in case it is felt that the wall slip may be the possible cause of the failure, then this correction needs to be included. For the time being, however, this source of error is considered to be unimportant.

THEORETICAL BASIS FOR UNIFICATION

The equipment used for measurement of MVR as defined above would fall in the category of a circular orifice rheometer (Shenoy and Saini 1996). Hence the expressions for shear stress τ and shear rate $\dot{\gamma}$ in this equipment (on the assumption that the fluid is Newtonian as a first approximation) can be written in the following well-known conventional forms:

$$\tau = \frac{R_N F}{2\pi R_P^2 l_N} \qquad (1)$$

$$\dot{\gamma} = \frac{4Q}{\pi R_N^3} \qquad (2)$$

where nozzle radius R_N = 0.105 cm, piston radius R_P = 0.4737 cm, nozzle length l_N = 0.8 cm, force F = load L (kg)

X 9.807 X 10^5 dynes and the flow rate Q (cc/s) is related to MVR (cc/10min) as follows by definition.

$$Q = \frac{MVR}{600} \qquad (3)$$

Since the geometry of the measuring equipment is fixed as given above, Equations (1) and (2) can be reduced to give the following:

$$J/L = 9.13 \times 10^4 = \text{constant} \qquad (4)$$

and

$$u/MVR = 1.83 = \text{constant} \qquad (5)$$

Note that the constant has only geometric values and no material properties.

When the MVR value is generated under a specific load condition for a particular grade of asphalt at a given temperature, the shear stress and shear rate values corresponding to those test conditions can be obtained from Eqs. (4) and (5). At that very temperature, by changing the applied load, a different value of MVR can be generated which corresponds to a new set of shear stress and shear rate values. In this way, it is possible to generate the shear stress versus shear rate curve for the asphalt at that temperature. This curve, which may be generated through the flow measurement device (FMD), should correspond to the shear stress versus shear rate curve generated from any rheometer because the response of the material to stress should be independent of the type of measuring equipment. Generating the full flow curve from the FMD is meaningless, when more sophisticated equipments are available. However, any curve generated from a sophisticated equipment would have a point on it which corresponds to the shear stress and shear rate values from the FMD as given by equations (4) and (5). Thus, if the shear stress J versus shear rate u data from any rheometer were replotted as J/L versus u/MVR, then for all samples, the curves should pass through the co-ordinates of J/L = 9.13 x 10^4 and u/MVR = 1.83. This in effect, allows a vertical shift of the curves though division by L and a horizontal shift through division by MVR, thereby resulting in a superposition of the curves.

SHRP asphalt binder research findings have indicated that dynamic shear rheometer data are the preferred fundamental rheological properties of neat asphalts to relate to pavement performance for rutting at high temperatures. Hence, if a unification of rheological data is to be sought, then it is essential to develop a method to coalesce dynamic data in terms of the complex modulus |G*|, loss modulus G@, and parameter |G*|/Sin *.

Earlier investigations of rheological properties (at least for polymer melts) have shown that the data under dynamic conditions can be related to that obtained under steady shear within certain ranges of shear rates and frequencies (Cox and Mertz 1958; Pao 1957; Pao 1962; Spriggs 1965; Bogue 1966; Meister 1971). The empirical method suggested by Cox and Mertz (1958) for relating steady shear viscosity with the absolute value of complex viscosity O* is still the most attractive. According to the Cox-Mertz method,

O(u) = | O*|(T) at u = T (6)

The relationship simply indicates that for prediction purposes, the magnitude of complex viscosity is equal to that of shear viscosity at equal values of radial frequency T and shear rate u.

The relationship has been found to largely hold for flexible-chain thermoplastic melts, particularly in the lower and intermediate ranges of u and T. It can be assumed that this relationship would hold well in the lower and intermediate ranges of u and T for paving asphalts because they too are thermoplastic materials.

Using the fact that O = J/u and |O*| = |G*| / T by definition, the following expression is written.

J/u = |G*| / T at u = T (7)

Thus, the following equations corresponding to Eqs. (4) and (5) can be written.

|G*| / L = constant = 9.13×10^4 at u = T (8)

and

T/MVR = constant = 1.83 at u = T (9)

Thus, if the |G*| versus T data from the DSR are replotted as |G*| / L versus T/MVR, then for all samples, the curves will pass through the point with co-ordinates given by |G*| / L = 9.13×10^4 and T/MVR = 1.83. This in effect, allows a vertical shift of the curves through a division by L and a horizontal shift through a division by MVR, thereby resulting in a superposition of the curves.

Now in order to establish the relationship which is likely to give a unified curve for the other dynamic functions such as the loss modulus G'', it is necessary to use one of the theoretical models available in the literature (Pao 1957; Pao 1962; Spriggs 1965; Bogue 1966; Meister 1971). In the present case, the Spriggs (1965) model has been chosen for correlating the dynamic and steady state rheological characteristics. The choice is somewhat arbitrary as each model is known to have almost the same capability for prediction (Han 1976) and by no means indicates superiority of Spriggs (1965) model over the others. Based on the Spriggs (1965) model, the loss modulus G'' which is the dynamic function is expressed as follows:

$$G'' = \frac{\eta_0}{\lambda Z(\alpha)} \sum_{p=1}^{\infty} \frac{(\omega\lambda)^2}{p^{2\alpha} + (\omega\lambda)^2} \, p^{\alpha} \qquad (10)$$

whereas the shear stress τ which is the steady-state function is given as :

$$\tau = \frac{\eta_0}{c\lambda Z(\alpha)} \sum_{p=1}^{\infty} \frac{(c\dot{\gamma}\lambda)^2}{p^{2\alpha} + (c\dot{\gamma}\lambda)^2} \, p^{\alpha} \qquad (11)$$

where η_0, λ, α and $Z(\alpha)$ are model parameters and c is an arbitrary adjustable constant expressed in terms of an independent parameter ϵ as

$$c^2 = (2 - 2\epsilon - \epsilon^2) / 3 \qquad (12)$$

Comparing Eqs. (10) and (11) yields the following :

$$\tau = c^{-1} G'' \quad \text{at} \quad \omega = c\dot{\gamma} \qquad (13)$$

Thus, it is obvious from Eq. (13) that the dynamic loss modulus would be equivalent to the steady-state shear stress when shifted by an amount c. In order to determine the shift factor c, the procedure suggested by Spriggs (1965) needs to be followed, namely, of superimposing the plot of $O(u)/O_0$ versus cu on the plot of $O{:}(T)/O_0$ versus T. For example, a value of c = $/2/3$ has been found by Saini and Shenoy (1984) to correlate the dynamic and steady-state viscoelastic data for a particular grade of linear-low-density polyethylene over a wide range of frequencies and shear rates. Using Eq. (13) in Eqs. (4) and (5) the following equations can be written

$$G@ / L = \text{constant} \quad (14)$$

and

$$T/MVR = \text{constant} \quad (15)$$

Eqs. (14) and (15) again imply that a plot of G@ / L versus T/MVR on log-log scale should result in a unified curve, if arguments similar to those that were put forth earlier when discussing Eqs. (4) and (5) are followed. Knowing the inter-relationships between various dynamic material functions, unified curves can be expected for G:, tan *, and even |G*|/Sin * given the following.

$$G: = (|G^*|^2 - G@^2)^{0.5} \quad (16)$$

$$\tan * = G@ / G: \quad (17)$$

$$|G^*| / \sin * = (|G^*|)^2 / G@ \quad (18)$$

EXPERIMENTAL VERIFICATION

The theoretical development in the previous section has shown the possibility of unifying fundamental rheological data through the use of the material's volumetric-flow rate (MVR). In order to verify this, systematic experiments need to be done on a number of different asphalts that have widely different rheological characteristics. These have to be characterized on two different rheometers, one which gives the fundamental rheological properties in terms of the dynamic material functions and the other which gives the material's volumetric flow rate.

Equipment Used

(1) The Rheometrics Dynamic Shear Rheometer (DSR) was used for generating the dynamic data at three different temperatures of 46°C, 58°C and 70°C with a set of parallel plates of 25 mm diameter following the procedure given in the AASHTO provisional specifications (AASHTO 1993a). 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. In order 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 target strains were thus established and used in the frequency sweeps.

(2) The Kayeness Melt Indexer Model D4002 was used as the Flow Measurement Device (FMD) in order to measure the material's volumetric flow rate (MVR). The material's flow characteristic 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 hung off the top of the piston rod. Flags of different lengths are available such as 1/8", 1/4", ½" 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 were not taken on different samples. However, they were three measurements on the same sample and helped 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 for testing is heated in the oven to a temperature of 163°C so that it is in a pourable condition. Approximately 10 gms 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 predecided 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 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 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 gms. 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 50 in most cases.

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.

Materials Used

Six asphalts were chosen from among the SHRP Materials Reference Library asphalts to serve as representatives during the initial verification of the developed theory for unification. These were AAK-1, AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1. Their select properties are shown in Table 1. It can be seen that they cover a wide range of asphaltene content, a broad span of molecular weight, and a good spread of viscosity values. Each of these samples was 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 (AASHTO 1993b).

TABLE 1

Selected Details about the Asphalts Used

Asphalt ID	Source	Viscosity@140F, poise	Asphaltenes, %	Mol. Weight, daltons
AAK-1	Boscan	3256	20.1	860
AAA-1	Lloydminster	864	16.2	790
AAB-1	WY Sour	1029	17.3	840
AAD-1	California	1055	20.5	870
AAF-1	W Tx Sour	1872	13.3	840
AAM-1	W Tx Inter	1992	4.0	1300

UNIFICATION ATTEMPT

The first attempt to test the unification technique was with asphalt AAK-1. Figure 2 shows the |G*| versus T curves for three temperatures of 46°C, 58°C and 70°C which were generated from the DSR on original unaged, RTFOT and PAV aged AAK-1 samples.

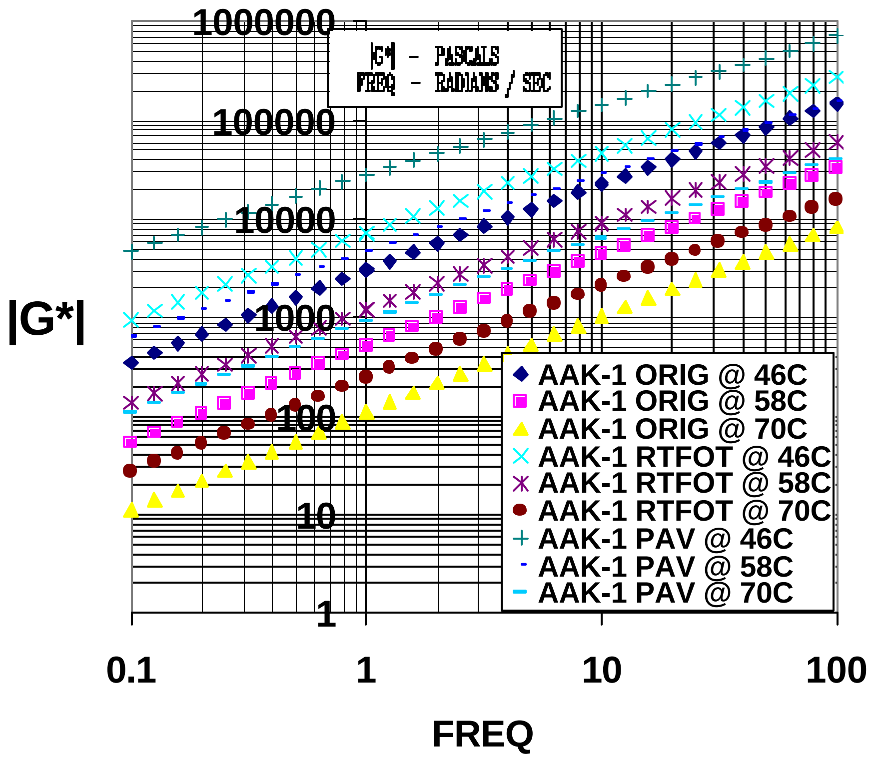


Figure 2 : Variation of the dynamic complex modulus |G*| with frequency T at three different temperatures of 46°C, 58°C and 70°C for asphalt AAK-1 in original, RTFOT and PAV forms.

Load versus MVR values obtained from the FMD for the AAK-1 samples at three identical temperatures are given in Tables 2 - 4.

TABLE 2

Load, MVR and n data for Original Unaged Samples

Asphalt ID	Temperature,°C	Load,kg	MVR,cc/10min	n
AAK-1	46	2.16	3.42	-
		5.00	7.74	-
	58	2.16	21.94	-
	70	2.16	102.20	-
AAA-1	46	2.16	15.71	0.981
	58	2.16	77.05	0.932
	70	0.32	43.62	0.971
AAB-1	46	3.06	13.26	0.912
	58	3.06	75.31	1.080
	70	0.32	35.86	0.978
AAD-1	46	5.00	24.56	1.000
	58	2.16	60.04	1.000
	70	1.00	101.53	1.000
AAF-1	46	5.00	7.64	1.060
	58	2.16	31.41	0.968
	70	1.22	75.27	1.030
AAM-1	46	2.38	6.29	0.893
	58	2.16	35.93	0.936
	70	0.32	23.20	0.984

TABLE 3

Load, MVR and n data for RTFOT Aged Samples

Asphalt ID	Temperature,°C	Load,kg	MVR,cc/10min	n
AAK-1	46	2.16	1.38	-
	58	2.16	9.43	-
	70	2.16	51.53	-
AAA-1	46	7.06	20.47	0.901
	58	1.00	15.23	0.938
	70	1.00	67.69	0.984
AAB-1	46	5.00	9.48	0.861
	58	3.06	36.81	0.924
	70	1.00	52.94	0.986
AAD-1	46	5.00	10.62	0.859
	58	1.00	10.34	1.020
	70	0.32	13.32	0.912
AAF-1	46	10.00	6.67	0.834
	58	5.00	26.58	1.020
	70	2.16	63.51	1.040
AAM-1	46	7.06	9.24	0.742
	58	3.06	25.54	0.871
	70	1.00	35.09	0.975

TABLE 4

Load, MVR and n data for PAV Aged Sample

Asphalt ID	Temperature,°C	Load,kg	MVR,cc/10min	n
AAK-1	46	2.16	0.23	-
	58	2.16	2.34	-
	70	2.16	12.54	-
AAA-1	46	10.00	6.64	0.691
	58	2.16	7.73	0.887
	70	1.00	16.32	0.864
AAB-1	46	10.00	4.32	0.671
	58	3.06	8.63	0.877
	70	1.00	14.16	0.954
AAD-1	46	10.00	4.73	0.716
	58	5.00	14.24	0.725
	70	2.16	26.34	0.691
AAF-1	46	10.00	1.07	0.752
	58	10.00	13.36	0.793
	70	2.16	16.06	0.899
AAM-1	46	10.00	3.80	0.600
	58	3.06	6.33	0.773
	70	2.16	22.06	0.818

Using corresponding values of load and MVR, the nine curves in Figure 2 were replotted to give a unified curve as shown in Figure 3. The 33 data points from each curve generated from the DSR were modified using a single data point from the FMD. A total of 297 data points have been unified into a single curve in Figure 3. Note that at 46°C temperature, the MVR value for the original unaged AAK-1 sample was determined at two different loads. It is immaterial which set is used for unification in Figure 3 as both give curves that superimpose.

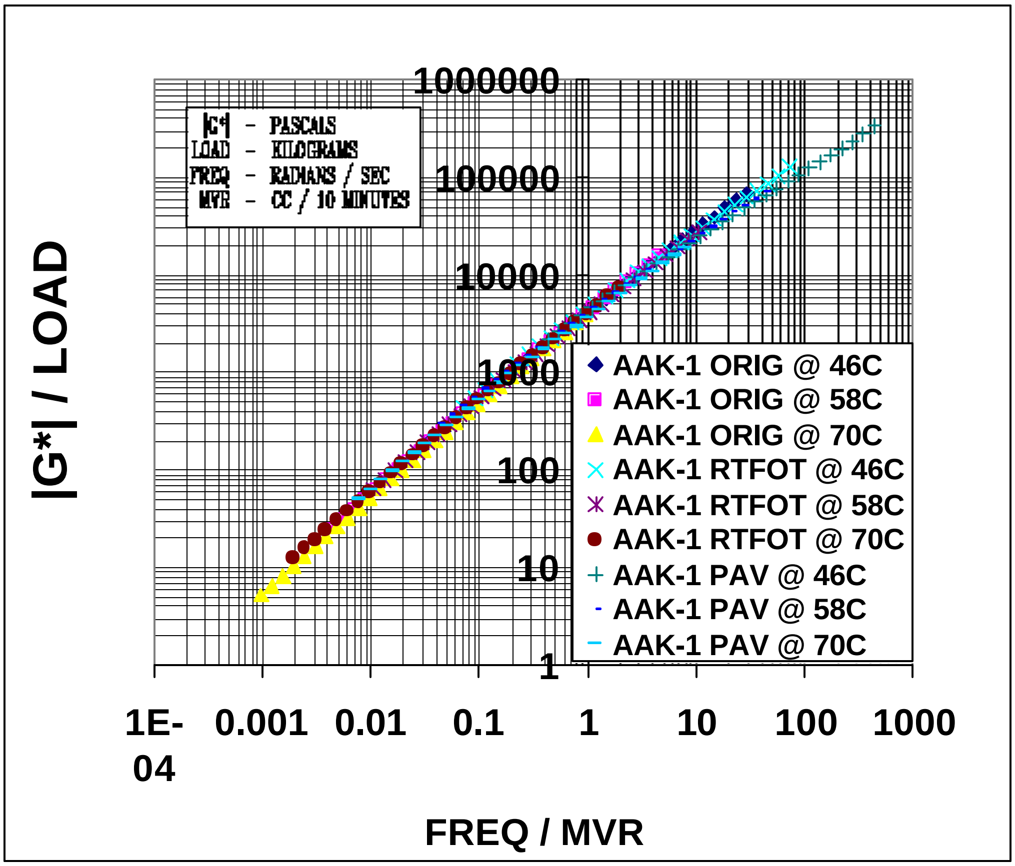


Figure 3 : Unified curve of the dynamic complex modulus |G*| with frequency T covering the temperature range of 46°C - 70°C for asphalt AAK-1 in original, RTFOT and PAV forms.

It was shown in the section on theoretical development that the unification should work for G@ versus T curves as well as the |G*| / Sin * versus T curves. This was tested for similar nine sets of curves like those shown in Figure 2 (i.e. for AAK-1 ORIG, RTFOT and PAV each at the three temperatures of 46°C, 58°C and 70°C). The results are shown in Figures 4 and 5.

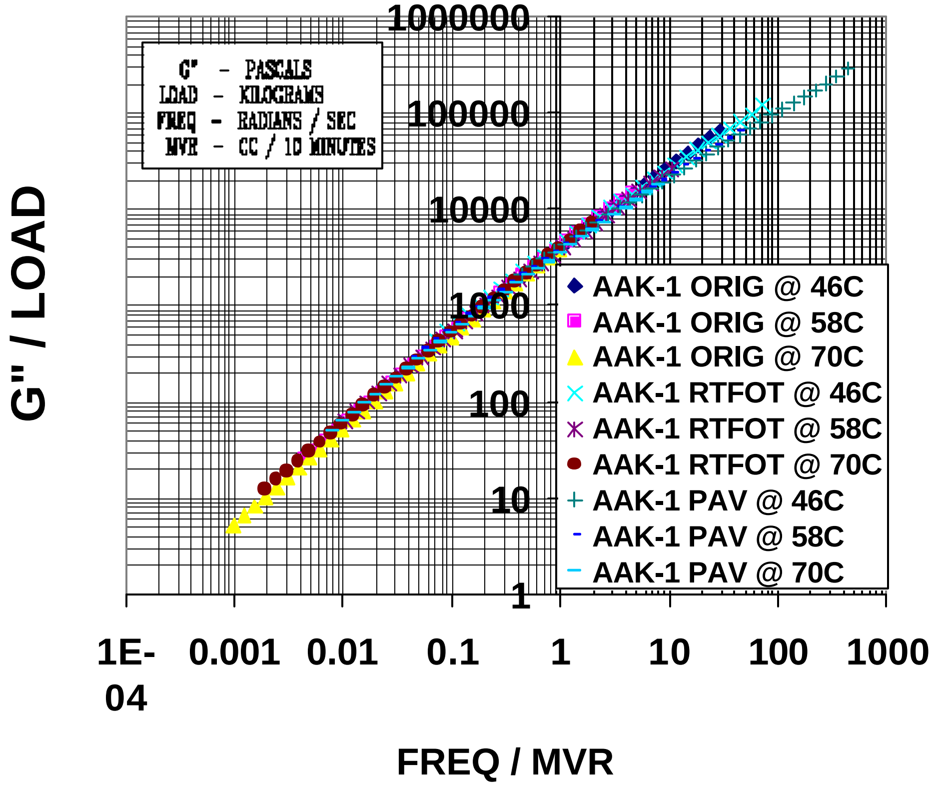


Figure 4 : Unified curve of the dynamic loss modulus G" with frequency T covering the temperature range of 46°C - 70°C for asphalt AAK-1 in original, RTFOT and PAV forms.

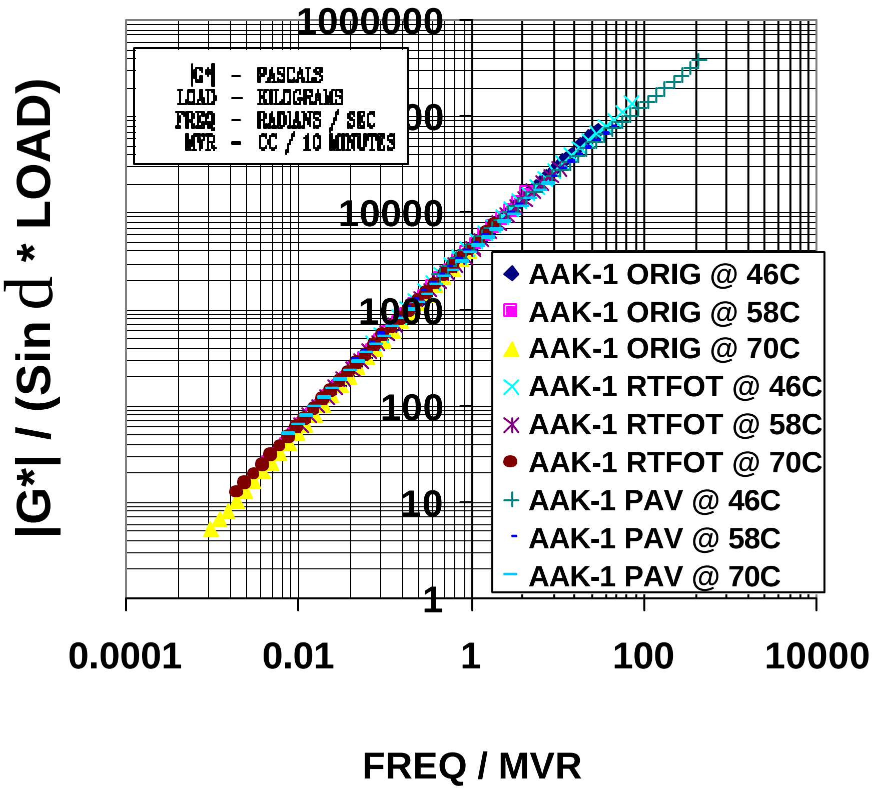


Figure 5 : Unified curve of the SHRP parameter |G*| / Sin * with frequency T covering the temperature range of 46°C - 70°C for asphalt AAK-1 in original, RTFOT and PAV forms.

IMPROVED REPRESENTATION

It was shown in the above section that there is basically just one single curve for the AAK-1 sample that is independent of the level of aging and also independent of temperatures, at least within the temperature ranges tested. Presently, the unified curve has a normalizing parameter for the y-axis (i.e., load), and another normalizing parameter for the x-axis (i.e., MVR). It would certainly be more beneficial to have the normalizing parameter all clubbed together on just one axis like the x-axis. This would make it much easier to regenerate fundamental rheological information and also to derive useful conclusions from the unified curves. An improved representation of the unification is therefore attempted. From the unified curve, the following equality can be written:

$$|G^*| / L = M \{T / MVR\} \qquad (19)$$

This is equivalent to stating that

$$J / L = M \{u / MVR\} \qquad (20)$$

where M represents a function. If the material is Newtonian in character then the relationship would be linear and one can write

$$J = O_0 \, u (L / MVR) \qquad (21)$$

where O_0 is the proportionality constant. The Newtonian viscosity of the sample is equal to O_0(L/ MVR), and can be calculated using the L and MVR values from the FMD at the particular temperature of interest. Eq. (21) would imply that a plot of J versus u(L/ MVR) would be unique and, therefore, in turn, a plot of |G*| versus T (L / MVR) would also unify provided the material is Newtonian. Transferring the L term from the left-hand-side to the right-hand-side cannot be done in this simple manner if the material is non-Newtonian. Asphalts are known to possess non-Newtonian characteristics and hence the relationships in Eqs. (19) and (20) are not linear. The non-linearity in the equations can be taken into account by using the Ostwald-de Waele power-law model (De Waele 1923; Ostwald 1925; Ostwald 1926) within small ranges of shear rates and frequencies. Within these ranges, Eq. (20) can be written as follows:

$$J / L = K_0 (u / MVR)^n \qquad (22)$$

where n is the power-law constant that is normally termed as the pseudoplasticity index or the shear susceptibility index and K_0 is the proportionality constant. The consistency index of the material is equal to K_0 (L/MVR^n) and can be calculated using the L and MVR values from the FMD at the particular temperature of interest. Based on Eq. (22), the following relationships can then be written

$$J = M \{u (L^{1/n} / MVR)\} \qquad (23)$$

and

$$|G^*| = M \{T (L^{1/n} / MVR)\} \qquad (24)$$

.

Eq. (24) then implies that a plot of |G*| versus modified frequency T ($L^{1/n}$ / MVR) should then give a unique curve.It also follows that G@ versus T ($L^{1/n}$ / MVR) and |G*| / Sin* versus T ($L^{1/n}$ / MVR) would each give a unique curve taking into account the non-Newtonian behavior of the material system. Since the load L and the MVR value are available from the flow measurement, it is only now necessary to devise a method to determine the n value in each case.

Determination of the n value

Since the J versus u curve and the |G*| versus T curve have continuously changing slopes for a non-Newtonian material, the value of n is constant only in short ranges of shear rates and frequencies. In that limited range, the power-law model can be fitted to the curve as follows:

$$J = K (u)^n \qquad (25)$$

Note that this is not the unified curve that is being considered but the curve that could be generated by simply changing the load conditions in the FMD as discussed earlier during the development of Eqs. (4) and (5). In the present context, the value of n has to be chosen in the range of shear stress and shear rate which corresponds closely to those applicable to the MVR value that is used for the normalizing process. Hence, in case the MVR value has been determined at a load L for a particular asphalt sample at a specific temperature, then two more MVR values are to be determined 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 L1) while the other is lower than L (i.e. L2). In order to get the value of n, Eq. (25) is re-written using Eqs. (4) and (5) as follows:

$$L1 = K\,(MVR1)^{n} \qquad (26)$$

and

$$L2 = K\,(MVR2)^{n} \qquad (27)$$

Solving Eqs. (26) and (27), the following equation can be written for estimating of the n value.

$$n = \log (L1/L2) / \log (MVR1/MVR2) \qquad (28)$$

VALIDATION AND CONFIRMATION

The unification approach has to be now validated and confirmed for a wide range of asphalts using the improved representation of the curves. In order to do this, a number of different asphalts were considered whose DSR data was generated. At the same time, MVR data was also obtained, and since in most cases the samples were expected to be non-Newtonian, the MVR data was obtained at more than one load condition in order to estimate the value of n. These values are shown in Tables 2 - 4 for AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1 asphalts, respectively. The collective data on all these asphalts were plotted as |G*| versus T $(L^{1/n} / MVR)$, G@ versus T $(L^{1/n} / MVR)$ and |G*| / Sin * versus T $(L^{1/n} / MVR)$ as shown in Figures 6-8.

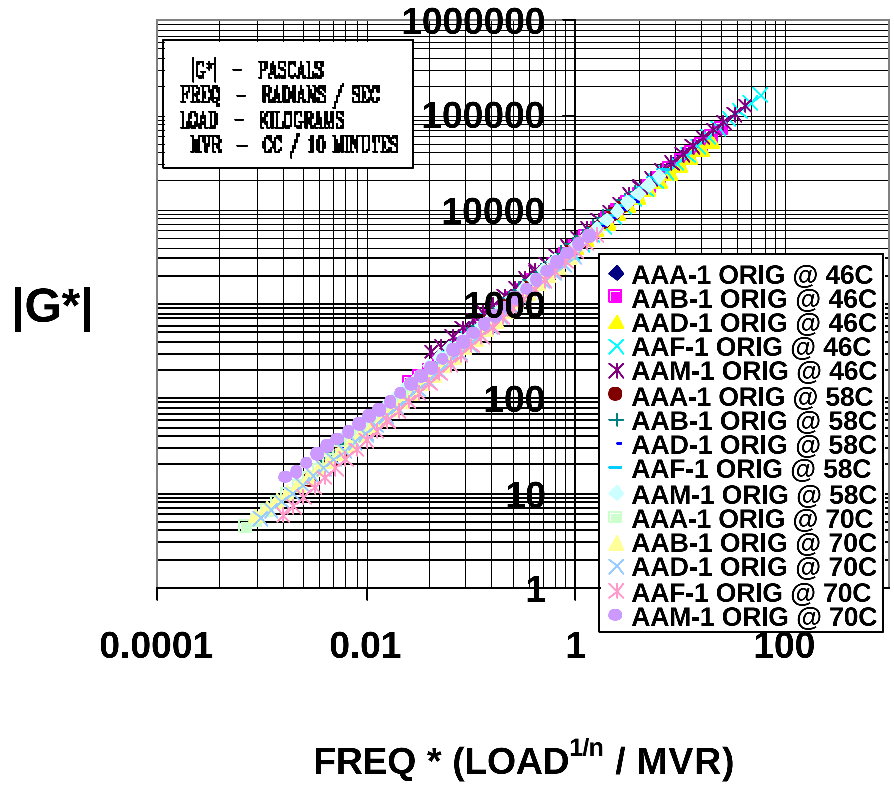


Figure 6(a) : Unified curve of the dynamic complex modulus |G*| with modified frequency $\mathrm{T}(L^{1/n}/MVR)$ covering the temperature range of 46°C - 70°C for five asphalts

(AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in original unaged forms.

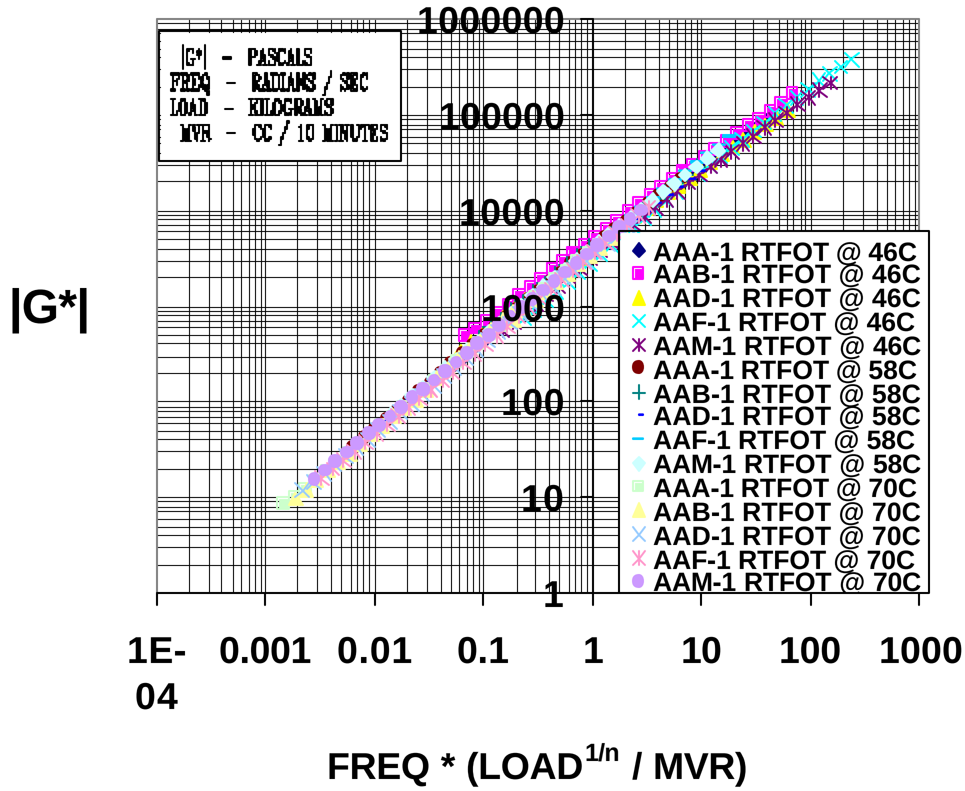


Figure 6(b) : Unified curve of the dynamic complex modulus |G*| with modified frequency $\tau(L^{1/n}/MVR)$ covering the temperature range of 46°C - 70°C for five asphalts

(AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in RTFOT aged forms.

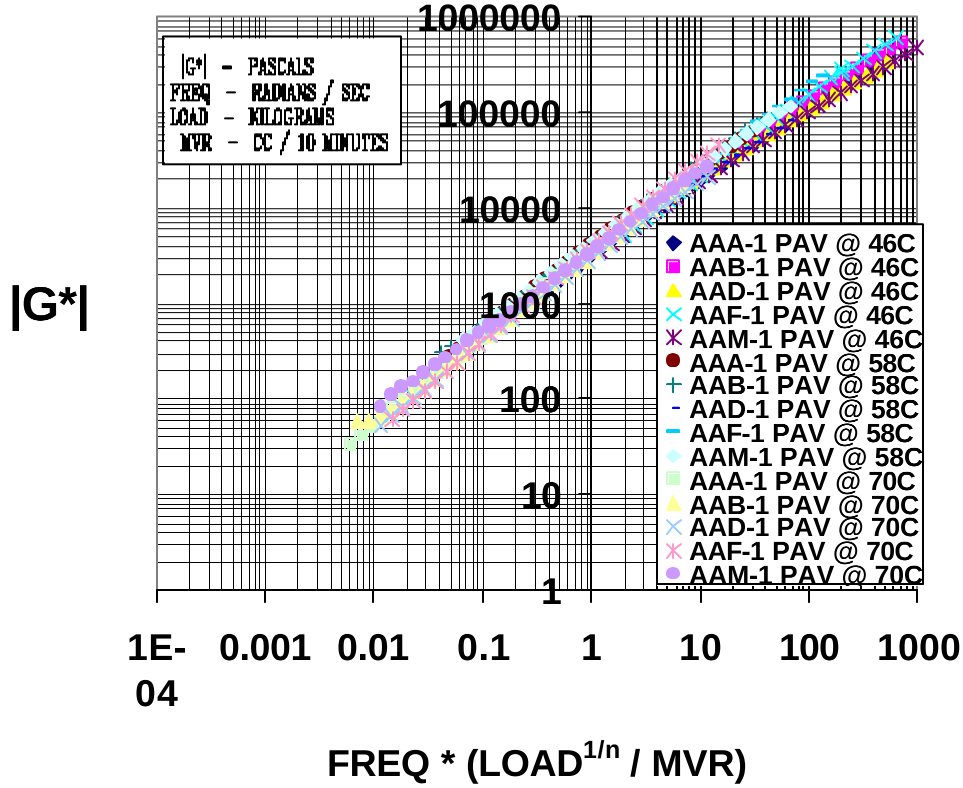


Figure 6(c) : Unified curve of the dynamic complex modulus |G*| with modified frequency $\mathsf{T}(L^{1/n}/MVR)$ covering the temperature range of 46°C - 70°C for five asphalts

(AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in PAV aged forms.

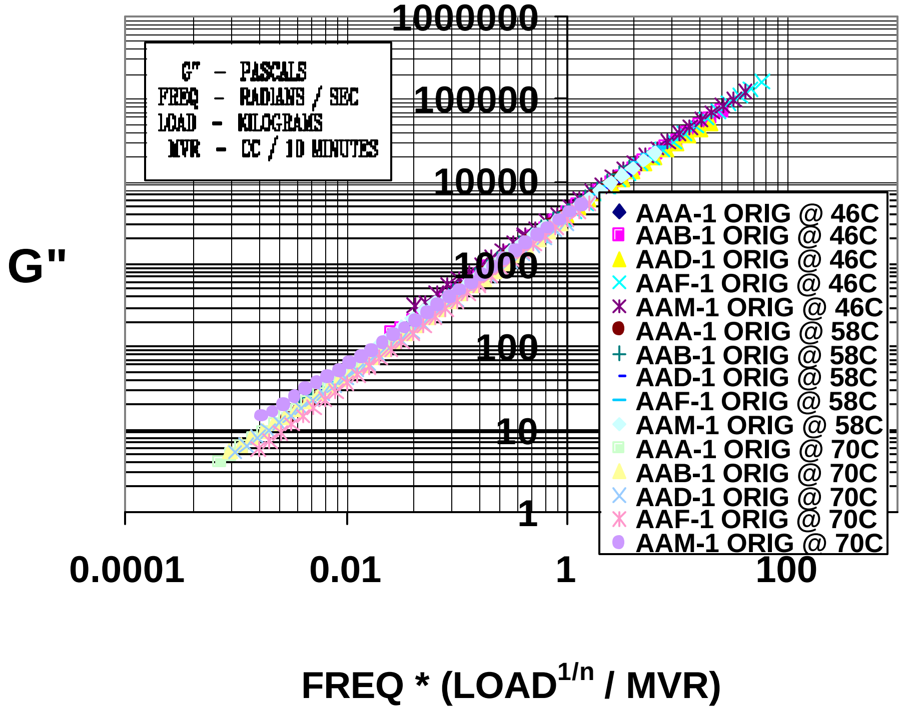


Figure 7(a) : Unified curve of dynamic loss modulus G" with modified frequency $\tau(L^{1/n}/MVR)$ covering the temperature range of 46°C - 70°C for five asphalts (AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in original unaged forms.

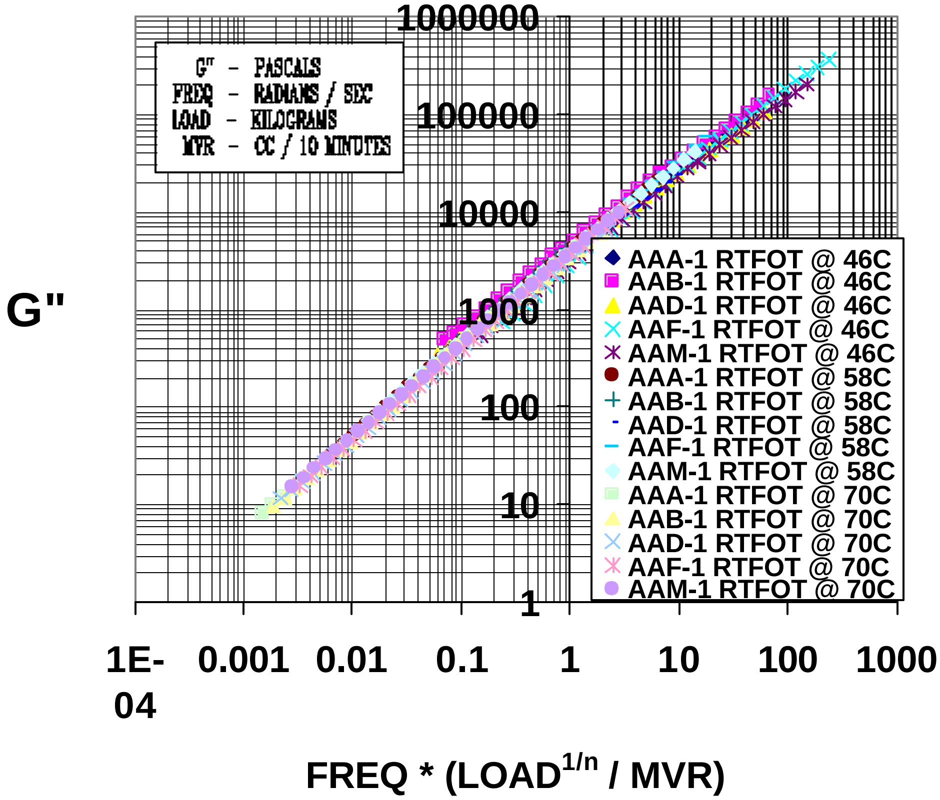


Figure 7(b) : Unified curve of dynamic loss modulus G" with modified frequency $\tau(L^{1/n}/MVR)$ covering the temperature range of 46°C - 70°C for five asphalts (AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in RTFOT aged forms.

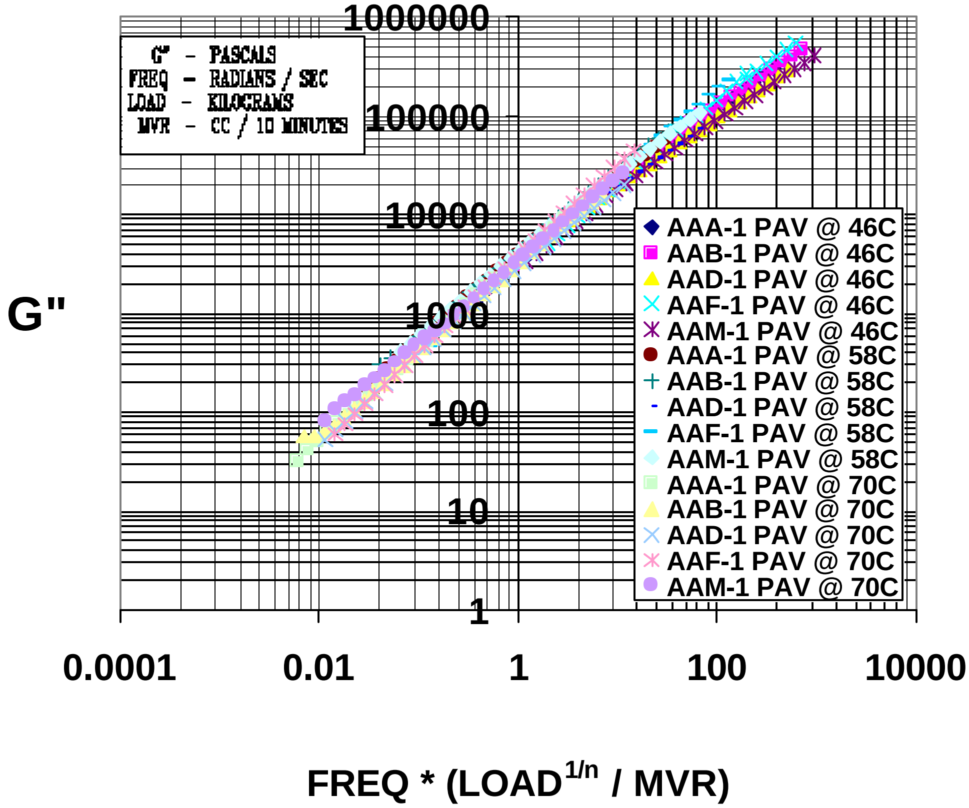


Figure 7(c) : Unified curve of dynamic loss modulus G" with modified frequency $T(L^{1/n}/MVR)$ covering the temperature range of 46°C - 70°C for five asphalts (AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in PAV aged forms.

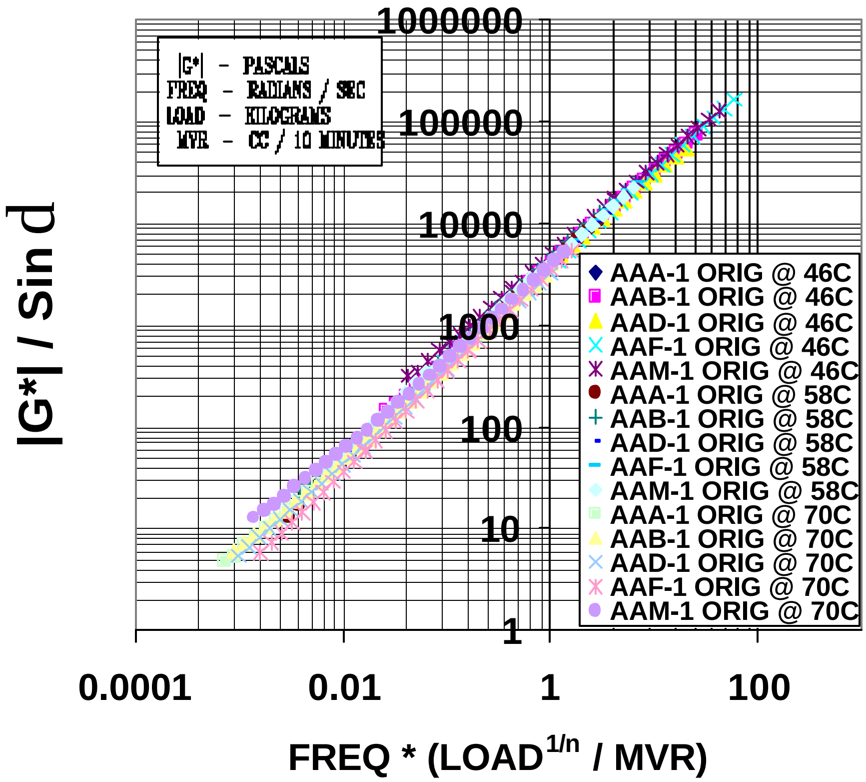


Figure 8(a) : Unified curve of the SHRP parameter |G*| / Sin * with modified frequency T($L^{1/n}$/MVR) covering the temperature range of 46°C - 70°C for five asphalts

(AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in original unaged forms.

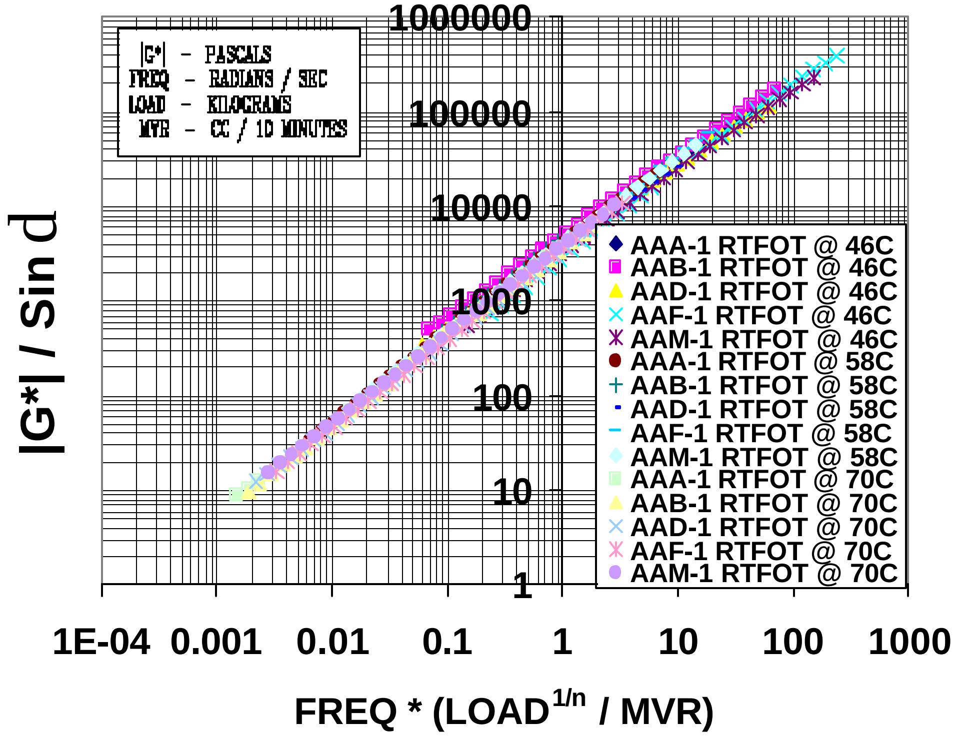


Figure 8(b) : Unified curve of the SHRP parameter |G*| / Sin * with modified frequency T($L^{1/n}$/MVR) covering the temperature range of 46°C - 70°C for five asphalts

(AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in RTFOT aged forms.

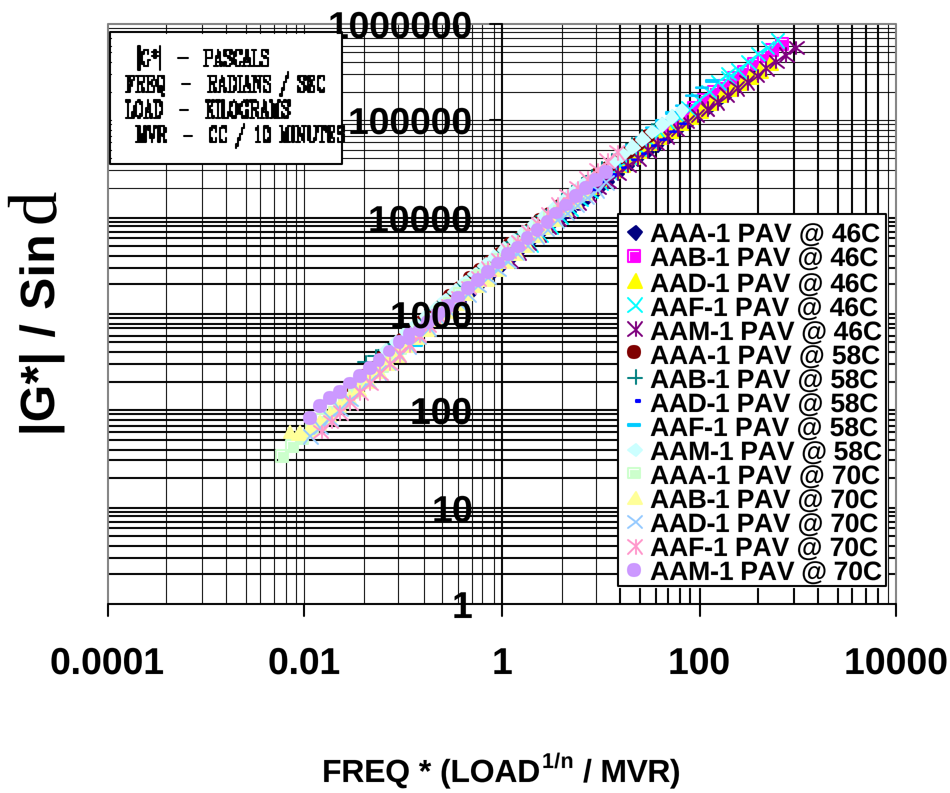


Figure 8(c) : Unified curve of the SHRP parameter |G*| / Sin * with modified frequency T($L^{1/n}$/MVR) covering the temperature range of 46°C - 70°C for five asphalts (AAA-1, AAB-1, AAD-1, AAF-1 and AAM-1) each in PAV aged forms.

It can be seen that the curves in Figures 6-8 are unique and independent of the type of asphalt as well as the temperature of measurement. Each unified curve 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). Different unified curves have been shown at different levels of aging i.e. (a) original unaged, (b) RTFOT aged and (c) PAV aged. This was done on account of two reasons. Firstly, to avoid clogging too much data on one curve and secondly because there was a slight but noticeable difference in PAV aged unified curve that would be otherwise lost if all data were plotted on one curve. It may be recalled that it was shown earlier through Figures 3 - 5 that the curves are unique independent of the level of aging. This was based on the data of only one asphalt, namely, AAK-1. When the other five asphalts were considered, it is found that the RTFOT aged data fell exactly on the original unaged sample data. However, the PAV aged data showed a slight deviation at the higher values of τ ($L^{1/n}$ / MVR). It is not clear whether this is an experimental artifact or whether truly the unified curve is different for PAV aged samples.

It can be seen that the unified curves show a band within which all the data points coalesce. It is important to estimate the bandwidth in order to get an idea about the error bounds of this technique. In order to do this, values of |G*| were noted for some typical τ ($L^{1/n}$ / 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 was found to be in the range of 3-16%. For the individual DSR measurements the error bound was calculated to be 6-13% and for the FMD measurements the error bound was calculated to be less than 2%. Thus, it is quite evident that the error bound range of 3-16 % in the unified curves is only a reflection of the errors in the original DSR data.

Figures 2-8 confirm that the unification technique works for at least six of the asphalts. A closer look at the selection of the six 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. Of course, this needs to be confirmed. However, that can be done over a period of time in future. Reinforcement of the unified curves with more data would help in outlining the final decisive shape of the curves. The main accent of the present paper 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, and this could be achieved through the analysis of rheological data on the six chosen asphalts. The unified curves of fundamental rheological data for all unmodified asphalts have many advantages and hence the beneficial implications of this unification are discussed next.

IMPLICATIONS OF THE UNIFIED CURVES

1) In the Superpave© binder performance grading system, there is a specification for minimum limit requirement of $|G^*|/\sin\delta$ ($\geq$ 1 kPa) for unaged asphalts and ($\geq$2.2 kPa) for RTFOT aged asphalts at a frequency of 10 radians/s, which is assumed to simulate traffic loading when vehicles are moving at 50 to 60 mph. From the unified curves given in Figs. 8(a) and 8(b), a value of $\omega\,(L^{1/n} / MVR)$ can be determined for these two specification limits as

$$\omega\,(L^{1/n} / MVR) = 0.245 \qquad (29)$$

(Minimum requirement for unaged unmodified asphalts)

$$\omega\,(L^{1/n} / MVR) = 0.55 \qquad (30)$$

(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:

$$(L^{1/n} / MVR) = 0.0245 \qquad (31)$$

(Minimum requirement for unaged unmodified asphalts)

$$(L^{1/n} / MVR) = 0.055 \qquad (32)$$

(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 different values, then no new data need to be generated. One could simply read out the new requirements corresponding to Eqs. (29) and (30) from Figs. 8(a) and (b). New research continually brings in new ideas and refinements of the specifications are not to be ruled out. New analysis 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. In fact, Eqs. (31) and (32) simply take on new values by using the new frequency in Eqs. (29) and (30).

2) The unified curves can be fitted with appropriate rheological equations so that predictions can be made in 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 $\omega\,(L^{1/n} / MVR)$ and $|G^*| / \sin\delta$ versus ω

($L^{1/n}$ / MVR) and for all unmodified asphalts. These equations would be directly useful to those who are modeling the performance of the asphalts and attempting to relate the performance characteristics with the chemistry and physical structure of the asphalts.

3) If a database which 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.

CONCLUDING REMARKS

The unification of fundamental rheological data for unmodified asphalts 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.

The FMD used for generating MVR data is a relatively simple and inexpensive piece of equipment and can be carried from place to place because of its relative light weight. 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.

When generating MVR data, a few important points should be borne in mind to assure accuracy.

1) The barrel, piston and die of the FMD should be meticulously cleaned before every measurement. Cotton swabs dipped in mineral spirits can be used for the barrel and the piston for scrubbing out the residual asphalt. The die can be dropped into a bowl of mineral spirits for about two minutes and then cleaned with a toothpick dipped in mineral spirits. The cleaning process may take five minutes but there is no compromise on getting the parts spotlessly clean.

2) When pouring hot asphalt 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 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 asphalts considered herein, it can 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.

3) The total time for experiment is quite small as can be seen from Table 5. However, care should be taken to maintain the MVR value between proper limits by a judicious choice of the load condition. Note that the testing time for 1.3 < MVR < 50 lies between 0.08 to 3.3 minutes, which is quite reasonable. It was found that for MVR . 0.2, the testing time was about 20 minutes and for MVR . 100, it was about 0.045 minutes using a Flag of 6.35 mm. In the former case, the flow is too slow while in the latter case the flow is too fast. Hence, it is recommended that the load condition should be chosen in such a way as to get MVR value between 1 and 50 when the Flag of 6.35 mm is used. By opting for a different Flag, these limits can be relaxed to a certain extent (for example, for MVR . 22 the flow time of about 0.2 minutes with Flag of length 6.35 mm can be increased to 0.8 minutes by using a Flag of length 25.4 mm).

TABLE 5

Details of the time required for generating MVR data

Activity	**Time, Minute(s)**
Sample weighing	1
Heating sample in oven @ 163°C	3
Pouring sample in FMD barrel	1
Temperature stabilization	10
Testing time for one MVR reading using Flag of 6.35 mm	
For MVR . 1.5	3.0
. 4.5	0.9
. 10	0.4
. 20	0.2
. 50	0.08
Time for remnant material to be discharged	3
Cleaning time	5

TABLE 6

Comparison between DSR and FMD

Considered Feature	DSR		FMD
Initial Equipment Cost	$ 35000	U	$5500*
Operational Cost	Power supply Air pressure Circulating water bath	U	Power supply only No air pressure No circulating water bath
Maintenance Cost	Complex Electronics Very high repair cost Expensive replacement parts Need for maintenance contract	U	Simple Electronics Little that can go wrong At best, die may need replacement ($60 each) No need for maintenance contract
Operator training	Complete day training is required in order to minimize errors during operation	U	Minimal or almost nil training is needed, thereby reducing the chances of error during operation
Experimental Ease	Not very easy to guess the strain levels to be used in a frequency sweep and hence extra data needs to be collected to make sure that obtained information is in the linear viscoelastic region	U	Not at all difficult to guess the load conditions in order to achieve MVR values between 1 and 50 to get most accurate data
	Replicate data has to be generated on a fresh sample for viscoelastic systems and needs an entire new run	U	Three MVR values are generated one after another for each sample loading.
Sample Preparation Time	U Heating the asphalt to 163°C and pouring in the silicone mold and cooling (about 5 minutes)	U	Heating the asphalt to 163°C and pouring into the barrel (about 5 minutes)

* Melt Flow Indexer Model D4002 from Kayeness (Morgantown, PA)

TABLE 6 (Continued)

Comparison between DSR and FMD

Considered Feature	DSR	FMD
Testing Time	Takes a long time to reach equilibrium temperature and the entire data generation takes over an hour without taking into account the time for establishing that the data is in linear viscoelastic range	U Equilibrates very quickly at all temperatures and the entire data generation takes only about 15 minutes (See Table 5 for details)
Specimen Size	U 1 gm (For one set of data)	10 gms (For three sets of data)
Variability of Output (% STD / AVG)	6 to 12	U 0.2 to 2.0
Data reduction method	Requires a computer and Windows '95 to run the software for calculation of various rheological functions	U Requires no computer as all calculations are done by the built-in software which does not require any other support program either
Information Obtained	U Extensive information on the basic rheological properties of asphalts can be got in terms of |G*|, G@, G=, etc.	U Only a single value of MVR at a fixed load L condition can be got. But this value can be related to all fundamental rheological properties generated from DSR
Mobility or Portability	Very heavy, Requires air pressure, Needs circulating water-bath and hence is not portable.	U Relatively light weight, Requires no air pressure, Needs no water-bath and thus is portable.

If the above points are borne in mind, it will be found that MVR data generated from the FMD is 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. 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. A comparison between DSR and FMD is shown in Table 6. It can be seen that the FMD beats out DSR on all counts except specimen size and the information obtained. While from the DSR, all fundamental rheological parameters can be obtained, the FMD can only give a single value measurement of MVR at a fixed load condition. However, in the foregone text, it has been shown how this single value can be correlated with each of the fundamental rheological parameters from the DSR. This new 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, and the equipment is portable could merit its use at the paving sites or at the refineries. The actual time for data generation is also very low as can be seen from Table 5, which gives the details of the time involved for getting three MVR readings on one asphalt. This makes the measurement particularly attractive.

ACKNOWLEDGMENTS

The author is extremely grateful to Ms Susan Needham for diligently generating all rheological data and also for providing inputs during the preparation of Table 6 wherein a comparison of the DSR and FMD was done. The author would also like to acknowledge the financial support provided by the Federal Highway Administration and National Research Council for the work.

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APPENDIX. NOTATION

a	model parameter in Eqs. (10) and (11)
c	arbitrary adjustable constant defined by Eq. (12)
c_F	correction term
‘	independent parameter in Eq. (12)
F	force (dynes, Newtons)
G*, G’, G”	complex modulus, dynamic storage modulus, dynamic loss modulus (Pa)
K	consistency index of a power-law fluid (gm.cm/s^{2-n})
K_0	proportionality constant
L	test load value used on the flow measuring device (kg)
L1	test load value lower than L used on the flow measuring device (kg)
L2	test load value higher than L used on the flow measuring device (kg)
l_N	nozzle length (cm, m)
MFI	melt flow index (gm / 10 min)
MVR	material’s volumetric-flow rate (cc / 10 min)
n	power-law index
ΔP	pressure drop (dynes/cm^2, Pa)
Q	flow rate (cc/s, m^3/s)
R_N ,R_P	nozzle radius, piston radius (cm, m)
v	average velocity of flow (cm/s, m/s)
Z(a)	model parameter in Eqs. (10) and (11)
δ	phase angle
u	shear rate (/s)
η, η*	steady shear viscosity, complex viscosity (poise, Pa.s)
η_0	proportionality constant
λ	model parameter in Eqs. (10) and (11)
ρ	density of the material (gm/cc, kg/m^3)
τ	shear stress (dynes/cm^2, Pa)
ω	frequency of oscillatory motion (radians/s)
Φ	represents the words “function of”