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Calculation of Shear Rate on Asphalt Binder in The Superpave Gyratory Compactor

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Abstract

Most modified asphalt binders show pseudoplastic characteristics and their viscosity values depend on shear rate. The calculation of compaction temperatures for Superpave gyratory compactors (SGCs) depends on viscosity measurements. Therefore, for modified asphalt binders, it is not possible to calculate the compaction temperatures without including the effect of shear rate in the SGC during viscosity measurements. Prior to this study, no experimental study on the calculation of shear rate in the SGC had been performed. The calculation of the shear rate in the SGC will make it possible to include the effect of shear rate during viscosity measurements. In this study, the shear rate inside the SGC was approximately 490 1/s. Standard error (SE) values of the estimates of shear rate values were calculated by the propagation of error method. The average value for SE was approximately 53 1/s.

Key words: Asphalt, Superpave, Superpave gyratory compactor, Viscosity, Mixing, Compaction, Shear rate.

Background

The Superpave gyratory compactor (SGC) is used to produce specimens for volumetric and mechanical property analyses. Throughout the compaction process, SGC keeps four factors that affect geometry and the movement of the specimen, under control to achieve uniform compaction. These factors are compaction pressure diameter of the specimen, number of gyrations per minute and compaction angle. Although these factors are very important, they are not sufficient for achieving uniform compaction. Other than these factors, the viscosity of asphalt binders plays a major role during compaction (Yildirim *et al.*, 2000).

Since the compaction of specimens prepared by binders with different grades does not vary, the resistance of the binder should be uniform throughout the compaction. Considering this fact, the Superpave mix design uses equiviscous compaction temperatures. According to Superpave mixture design, gyratory specimens are mixed and compacted at equiviscous binder temperatures corresponding to viscosities of 0.17 and 0.28 Pa.s, respectively. These viscosity values are specified in AASHTO TP4. In order to estimate the mixing and compaction temperatures for the Superpave mix design, a temperature-viscosity relationship for the binder should be developed as explained in ASTM D2493 (ASTM 2493, 1995).

Neither ASTM D2493 nor AASHTO TP4 includes the effect of shear rate in the calculation of compaction temperatures (Hensley and Parmer, 1998; Yildirim *et al.*, 2000). Exclusion of the effect of shear rate leads to the miscalculation of equiviscous temperatures, which eventually results in errors in the calculation of volumetric properties. At the same time, excluding the effect of shear rate in viscosity measurements results in very high compaction temperatures, sometimes above 160 °C. Heating the binder up to these high temperatures may oxidize the binder (Hensley and Parmer; 1998 and Shenoy; 2001).

Currently, researchers are trying to include the effect of shear rate in viscosity measurements for the calculation of equiviscous temperatures (Khatri and Bahia; 2001; Yildirim *et al.*, 2000). To achieve this, the shear rate value on the binders inside the SGC during compaction needs to be calculated.

It is important to understand the rheological behavior of asphalt binders at high temperatures to achieve proper compaction temperatures. Since most of the modified asphalt binders show pseudoplastic characteristics, it is not possible to develop a temperature-viscosity relation without including the effect of shear rate. Achieving equiviscous temperatures can be possible only by including the effect of shear rate in the SGC during viscosity measurements.

Objective

Compaction temperatures can be determined by estimating the relation between viscosity and temperature. Studies showed that most modified asphalt binders show pseudoplastic characteristic (Khatri and Bahia; 2001 and Yildirim *et al.*; 2000). For these materials, viscosity depends on shear rate (Levy, 1962). Therefore, for modified asphalt binders, the effect of shear rate should be included during viscosity measurements to calculate the compaction temperatures. Viscosity values should be calculated at the shear rates in the SGC, to achieve reliable compaction temperatures for an SGC.

No experimental study has been performed on the calculation of shear rate in the SGC. Thus, there was a need for this kind of study to understand the behavior of asphalt binders during compaction in the SGC. An experimental study was conducted with the objective of calculating the shear rate in the SGC. The results of this study are documented here.

Experimental Procedure

There are several factors affecting the bulk density values (G_{mb}) of a specimen. These are primarily gradation of the aggregate, aggregate type, viscosity of the asphalt binder, and the type of compactor. For any two specimens, if all factors affecting the G_{mb} are kept the same, the G_{mb} values for the two will also be the same. In this study, this idea was used for the calculation of shear rate inside the SGC.

In Figure 1, this approach is illustrated. First, two sets of specimens prepared by modified and unmodified asphalt binders will be compacted at different compaction temperatures in the SGC. Then the relation between the bulk density values (G_{mb}) and the compaction temperatures will be estimated for the two sets of specimens. It is hypothesized that the relationship between G_{mb}values and temperature will be as shown in Figure 1. The specimen prepared with unmodified asphalt and compacted at temperature A (Figure 1) will have the same G_{mb} value as the specimen prepared with modified asphalt binder and compacted at temperature B. This indicates that the viscosity value of the unmodified asphalt binder at temperature A is equal to the viscosity value of the modified asphalt binder at temperature B during compaction inside the SGC.

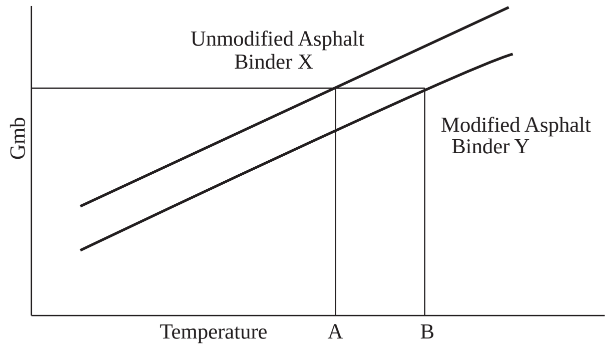

Figure 1. Temperature vs. G_{mb} relation for asphalt binders X and Y.

Since asphalt binder X is an unmodified asphalt binder, its viscosity at temperature A can be calculated easily. For asphalt Y, the relation between viscosity and shear rate can be estimated. Since the viscosity of asphalt binder X is known, the shear rate inside the SGC during compaction can be calculated. The equations representing the relation between shear rate and viscosity will be established at temperature A for the unmodified asphalt and at temperature B for the modified binder. The intersection point of these equations will give the shear rate inside the SGC during the compaction process. This approach is illustrated in Figure 2.

In this study, the relationship between compaction temperatures and G_{mb} values was estimated for eight different combinations. For each combination, one unmodified asphalt binder and one modified asphalt binder were used. Then the estimated relations for these binders were compared. Specimens were compacted using the SGC at five different temperatures and the corresponding G_{mb} values were calculated. Compaction temperatures are listed in Table 1. The same SGC was used throughout the experiment. Twenty specimens were prepared (two binders x five different temperatures x two replicates) for each test. The experiment was repeated for four different asphalt binders and two different mixes. Each of the modified asphalt binders was compared with two unmodified asphalt binders. The least squares method was used to estimate the relation between compaction temperatures and G_{mb} values. The model used for these estimations is y = a x ^{b}. In this model a and b are constants, y represents the G_{mb} values and x represents the compaction temperatures.

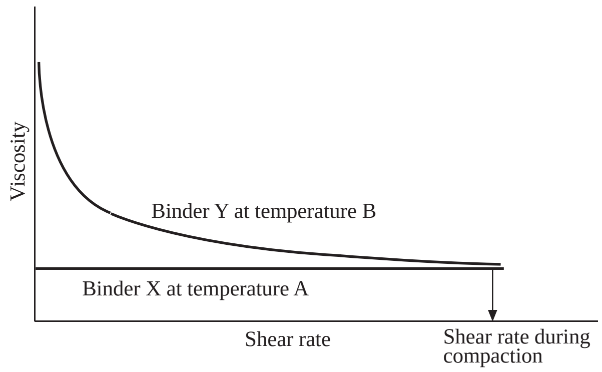

Figure 2. Shear rate vs. viscosity for binders X and Y.

In the next phase of this study, the relationship between shear rate and viscosity was estimated at the temperatures where the selected G_{mb} values are achieved by the modified and unmodified binders. The Brookfield viscometer was used for viscosity measurements. For each data point three measurements were completed. The average of these three data points was used to estimate the relation between shear rate and viscosity. The test temperatures for this phase are given in Table 2.

To estimate the relation between shear rate and viscosity, the Ostwald-de Waele power-law model was used. This is the most popular model to estimate the relation between shear rate and viscosity. The equation is given as $\eta = K\gamma^{n-1}$ where K and n values are constant (Reiner, 1960). "K" reflects the consistency index of the polymer. Higher values of K are an indicator of more viscous materials. n" is the power-law index giving a measure of the pseudeoplacticity, and higher values indicate more shear-thinning characteristics. In this model η" represents the viscosity and γ" represents the shear rate.

Table 1. Compaction temperatures for Mix 1 and Mix 2.

	Compaction temperatures				
MIX 1	55 °C	65 °C	75 °C	85 °C	95 °C
MIX 2	50 °C	60 °C	70 °C	80 °C	90 °C

Table 2. Temperatures for viscosity measurements.

	Test temperatures			
Modified 1	90 °C	91 °C	93 °C	
Modified 2	89 °C	91 °C	94 °C	95 °C
Unmodified 1	73 °C	78 °C	80 °C	83 °C
Unmodified 2	64 °C	68 °C	70 °C	71 °C

Materials

In this study, one Superpave mix (Mix 1) and one special mix (Mix 2) were prepared. A total of 80 specimens were produced (40 specimens x two mix designs). Specimens were individually batched and stored in plastic bags prior to use.

The first mix used for this study, Mix 1, was designed according to AASHTO PP28-95, *Standard Practice for Superpave Volumetric Design for HMA,* and met all the Superpave requirements. Mix 1 was a 12.5-mm coarse Superpave mix. A very similar mix was used to overlay a section of Business IH-35 in New Braunfels, Texas. Specimens prepared by Mix 1 were composed of 4550-g aggregate and 259-g asphalt binder. For this mix, the design asphalt content was selected at 4% air. The design asphalt binder content was 5.7%.

A special mix, Mix 2, was prepared to assist in evaluating the results. This mix was only composed of 4500-g natural sand with an asphalt binder content of 7%. No dust was used for this mix. For this mix only 35 gyrations were used to compact the specimen.

Two unmodified and two modified binders were selected. The modified asphalt binders were PG 76-22 and the unmodified asphalt binders were PG 64-22 and PG 52-28. The two unmodified asphalt binders used in this chapter, PG 64-22 and PG 52-28, are labeled as Unmodified 1 and Unmodified 2 respectively and the modified asphalt binders are labeled as Modified 1 and Modified 2.

For this study two types of aggregate were used: an angular and relatively porous crushedlime stone, and a rounded, smooth and relatively nonporous natural sand. Mix 1 was composed of 90% crushed limestone and 10 percent natural sand. Mix 2 was composed only of natural sand. Aggregate gradations of the mixes are given in Table 3.

The relationship between G_{mb}values and compaction temperatures was estimated for Mix 1 and Mix 2. For Mix 1, specimens were compacted at five different temperatures: 55 °C, 65 °C, 75 °C, 85 °C and 95 °C. For Mix 2, the temperatures used were 50 °C, 60 °C, 70 °C, 80 °C and 90 °C.

Compaction temperatures usually range from 80 °C to 155 °C (Asphalt Institute, 1989). However, for this research study, temperatures between 50 °C and 95 °C were used to better evaluate the effect of temperature on G_{mb}. At higher temperatures the viscosity of asphalt binder decreases; therefore, it becomes difficult to see the effect of compaction temperatures.

Table 3. Aggregate gradation of the mixes.

Sieve size	Cumulative % passing	Cumulative % passing
19	100	100
12.5	94	100
9.5	83	95
4.75	54	75
2.36	31	59
1.18	19	47
0.6	10	37
0.3	5	19
0.15	3	0
0.075	2	0

Results

The least squares method was used to estimate the relations between the compaction temperatures and G_{mb} values for modified and unmodified asphalt binders. Each relation between G_{mb} and compaction temperatures prepared by an unmodified asphalt binder was compared with those prepared by modified asphalt binders. An example comparison is presented in Figure 3. As expected, G_{mb} values rise with the latter because increasing temperature reduces mix resistance to compaction.

The relationship between G_{mb}values and compaction temperatures was estimated for one modified asphalt binder and for one unmodified asphalt binder in each comparison between the mixes. For each comparison a G_{mb} value was chosen. The G_{mb} values are listed in Table 4. Subsequently, the corresponding compaction temperatures were estimated using the selected G_{mb} value.

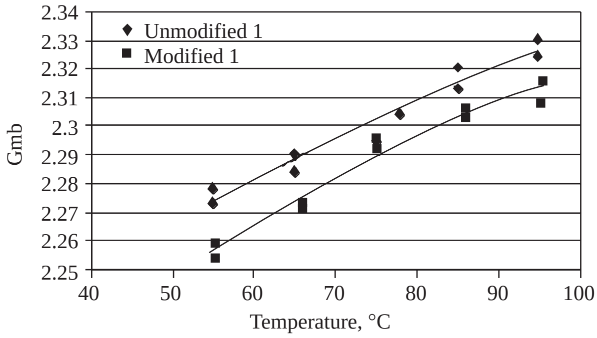

Figure 3. G_{mb} vs. temperature for Modified 1 and Unmodified 1 for Mix 1.

In Figure 3 the relationship between G_{mb} and compaction temperatures was estimated for the Modified 1 and Unmodified 1 asphalt binders. The G_{mb} value of 2.312 was selected. Using this G_{mb} value, corresponding compaction temperatures were estimated 93 °C for Modified 1 and 83 °C for Unmodified 1 asphalt binders. Therefore, it can be concluded that the viscosity of Modified 1 asphalt binder at 93 °C is equal to the viscosity of Unmodified 1 asphalt binder at 83 °C during compaction.

Table 4. Estimated Compaction Temperatures Delivering Equal G_{mb} Values.

Binders	Mix	G_{mb}	Compaction temperatures for G_{mb} value	
Modified 1 - Unmodified 1	1	2.312	Modified 1 93 °C	Unmodified 1 83 °C
Modified 1 - Unmodified 1	2	2.261	Modified 1 90 °C	Unmodified 1 80 °C
Modified 2 - Unmodified 1	1	2.308	Modified 2 94 °C	Unmodified 1 78 °C
Modified 2 - Unmodified 1	2	2.257	Modified 2 89 °C	Unmodified 1 73 °C
Modified 1 - Unmodified 2	1	2.312	Modified 1 93 °C	Unmodified 2 71 °C
Modified 1 - Unmodified 2	2	2.261	Modified 1 91 °C	Unmodified 2 68 °C
Modified 2 - Unmodified 2	1	2.310	Modified 2 95 °C	Unmodified 2 70 °C
Modified 2 - Unmodified 2	2	2.259	Modified 2 91 °C	Unmodified 2 64 °C

Figure 4 shows an example of the viscosity-shear rate relation for Modified 1 at 93 °C and for Unmodified 1 at 83 °C. As expected, unmodified asphalt binders showed Newtonian characteristics. Their viscosity values did not change much with increasing shear rate. On the other hand, modified asphalt binders showed shear thinning characteristics and their viscosity decreased with increasing shear rate. In Figure 4 the viscosity-shear rate relation was established for two selected binders. Afterward, the lines were extrapolated until an intersection was reached. At this intersection the viscosities are assumed to be equal. It can be concluded that the shear rate at the intersection is equal to the shear rate during compaction in the SGC. The estimated shear rates and their standard errors based on this concept are listed in Table 5.

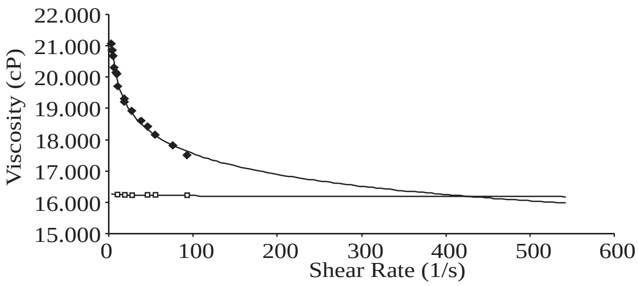

Figure 4. Example of estimation of shear rate during compaction.

Table 5 shows the estimated shear rates for each comparison. At the shear rates and temperatures listed in Table 5, asphalt binders are presumed to have the same viscosity. Similarly, the estimated G_{mb}-compaction temperature relations showed that at these temperatures, the viscosity values of these binders are the same during compaction. Since the viscosity of modified asphalt binders depends on both shear rate and temperature, having the same G_{mb} during compaction means that the estimates of shear rates during compaction are equal to those listed in Table 5.

In ASTM D2493, on the calculation of mixing and compaction temperatures, there is no shear rate specified. Currently, for viscosity measurements with the Brookfield viscometer, spindle numbers 27 and 20 RPM are used, which provide a 6.8 1/s shear rate. Table 5 indicates that the shear rate during compaction is much higher than this value. The shear rate estimates listed in Table 5 are between 399 and 638 1/s, with an average value of 487 1/s.

A numerical example for the calculation of shear rate is given below. This calculation is for the first row of Table 4.2 and is based on an intersection of two regression equations developed from data points in the two sets of tests.

Regression equation for Modified 1 at 93 °C: $\eta_1 = 22719\ \gamma_1^{-0.0561}$

Regression equation for Unmodified 1 at 83 °C: $\eta_2 = 16269\ \gamma_2^{-0.0010}$

(where γ = shear rate and η = viscosity)

The shear rate during compaction is denoted as γ and its associated viscosity is η. In Figure 4, at the intersection point, the following are assumed to hold:

Table 5. Estimated shear rates and their standard errors during compaction.

Compaction temperatures for G_{mb} values		Shear Rate (1/s)	SE (1/s)
Modified 1 93 °C	Unmodified 1 83 °C	429	29.17
Modified 1 90 °C	Unmodified 1 80 °C	399	29.80
Modified 2 94 °C	Unmodified 1 78 °C	556	37.00
Modified 2 89 °C	Unmodified 1 73 °C	416	36.45
Modified 1 93 °C	Unmodified 2 71 °C	433	71.70
Modified 1 91 °C	Unmodified 2 68 °C	503	38.33
Modified 2 95 °C	Unmodified 2 70 °C	638	100.55
Modified 2 91 °C	Unmodified 2 64 °C	523	80.87
Average		487	52.98

$\eta_1 = \eta_2 = \eta$, and

$\gamma_1 = \gamma_2 = \gamma$

$22719\ \gamma_1^{-0.0561} = 16269\ \gamma_2^{-0.0010}$

$\gamma = \gamma_1 = \gamma_2 = 429\ 1/s$ (Table 5, the first row)

Standard error (SE) values of the estimates of intersecting shear rates were calculated and are included in Table 5. To estimate the SE values for calculated shear rates, the propagation of error method (the delta method) was used (0).

$\eta = K\gamma^{\,n--1} \Rightarrow ln(\eta) = ln(K) + (n–1)\ ln(\gamma) \Rightarrow Y = A + BX$

where

$ln(\eta) = Y$

$ln(K) = A$

$(n\text{-}1) = B$, and

$ln(\gamma) = X$.

To calculate the intersection shear rate value ($X*$) the following function was used:

$X* = \frac{A1-A2}{B2-B1}$

Based on the fact that

$Y_1 = A_1 + B_1 X*$ for modified asphalt binder at temperature T_1,

$Y_2 = A_2 + B_2 X*$ for unmodified asphalt binder at temperature T_2.

Then the variance-covariance matrixes of the parameter estimates in these functions were calculated. The delta method was used to estimate the SE values for $X*$ as shown below

$VAR\ (X^*) = [dX^* / dc]' \sum [dX^* / dc]$

where

$[dX^* / dc]=[dX^* / dA1\ dX^* / dB1\ dX^* / dA2\ dX^* / dB2]$, and

$\sum$ is the variance-covariance matrix for the vector $[A_1, A_2, B_1, B_2]$.

The calculated SE values were for rectified functions. The delta method also was used to find the SE for the γ values via the following:

$SE_\gamma^2 \approx SE_x^2\ (f'(X^*))^2$

where

SE_γ is the standard error of γ,

SE_{X*} is the standard error of $X*$, and

$f(X^*) = exp\ (X^*)$.

A numerical example for both of the above described calculations is given below for Modified 1 at 93 °C and Unmodified 1 at 83 °C:

Given the estimated equation for Modified 1 at 93 °C:

$\eta_1 = 22719\ \gamma_1^{-0.0561}$

$ln(\eta_1) = ln(22719) + (-0.0561)\ ln(\gamma_1) = Y_1 = 10.031 + (-0.0561)\ X^*$

and that of Unmodified 1 at 83 °C: $\eta_2 = 16269\ \gamma_2^{-0.0010}$

$ln(\eta_2) = ln(16269) + (-0.0010)\ ln(\gamma_2) = Y_2 = 9.697 + (-0.0010)\ X^*$, and

$dX^* / dA_1 = 18.134$

$dX^* / dB_1 = -18.134$

$dX^* / dA_2 = -109.858$

$dX^* / dB_2 = 109.858$

The variance-covariance matrix ($\sum$) is estimated to be as follows:

1.2E-05	-4E-06	0	0
-4E-06	1.3E-06	0	0
0	0	2.3E-08	-8E-09
0	0	-8E-09	2.8E-09

$[dX^* / dc]' \sum [dX^* / dc] = 0.00468$

The variance of γ

$SE = \sqrt{851.3} = 29.17 sec^{-1}$ $Var\ (\gamma) = [exp\ X^*]^2$ $Var\ (X^*) = (429^2)\ (0.0046) = 851.3\ s^{-1}$

Thus, the SE of this estimate of the shear rate is 29.17 s^{-1}. This is not too large, relative to the range of shear rate values currently used.

Conclusions and Recommendations

This study focused on the calculation of the shear rate in the SGC. Although it is well known that the shear rate has a significant effect on high temperature viscosity values of modified binders, the shear rate value inside the SGC during compaction was not known. Calculation of the shear rate will make it possible to include the effect of shear rate during viscosity measurements. Therefore, the shear rate dependency of asphalt binder will be taken into account when determining mixing and compaction temperatures. In this study, shear rate inside the SGC was found to be approximately 490 1/s. SE values of the estimates of shear rate values were calculated by using the propagation of error method. The average value for SE was found to be approximately 53 1/s.

In this study it was observed that the compaction temperature has a significant effect on the G_{mb} value of a mix for both unmodified and modified asphalt binders. G_{mb} values decrease with increasing compaction temperature. This is an important indicator of the importance of compaction temperature for design. If the compaction temperature varies, the G_{mb} value, which is an important factor for design, varies as well, and this will affect all the results for design.

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