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Development of Alternative Parameters to Evaluate the Temperature Susceptibility of Asphalt Binders

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Abstract: The penetration test is a simple and commonly used test method to evaluate the temperature susceptibility of asphalt binders. In this study, the penetration index (*PI*) of six different asphalt binders was experimentally measured and quantified. Based on the data analysis from this study, it was found that the *PI* calculated in accordance with the Chinese specifications is highly dependent on the test temperature, test specifications, and analysis model. These factors introduce errors into the estimation of the temperature susceptibility of the asphalt binders. The dynamic shear rheometer (DSR) and the bending beam rheometer (BBR) tests were utilized to evaluate the temperature susceptibility of asphalt binders at the intermediate-high and low temperature ranges, respectively. The results indicated that the storage modulus estimated using the DSR and the stiffness measured using the BBR were more reliable temperature susceptibility parameters than the *PI*. In consideration of these findings, the variation rate of the common logarithm of the storage modulus and stiffness were thus proposed as the standard parameters in lieu of the *PI* to characterize the temperature susceptibility of asphalt binders.

Key words: *Asphalt binder; Bending beam rheometer; Dynamic shear rheometer; Penetration index; Temperature susceptibility.*

Introduction

Temperature susceptibility, defined as the change in consistency, stiffness, or viscosity as a function of temperature [1], is an important rheological property of the asphalt binder. Phang and Fromm [1] showed that temperature susceptibility of the asphalt binder can be related to the compaction, rutting, and cracking performance of an asphalt pavement. An asphalt binder with lower temperature susceptibility ensures better pavement performance, particularly in terms of high temperature permanent deformation and rutting. Therefore, it is of prime importance to have reliable and accurate methods to evaluate and characterize the temperature susceptibility of asphalt binders.

Numerous evaluation methods have been proposed to characterize the temperature susceptibility of asphalt binders, for example the Penetration Index (*PI*) [2], the Penetration Ratio (*PR*) [3], the Penetration-Viscosity Numbers (*PVN*) [4], the Viscosity-Temperature Susceptibility (*VTS*) [5, 6], the Temperature of Equivalent Stiffness (*TES*) [3], and the Bitumen Test Data Chart (*BTDC*) [7, 8]. These indexes are determined based on penetration, softening point, and breaking point measurements, which are traditional and empirical properties of the asphalt binder. Currently, the *PI* is being used in China as a quality control measure of the asphalt binders. To calculate the *PI*, a regression analysis using three or more penetration values and their corresponding temperatures is often used. The regression coefficient is applied to verify the reliability of the test data. However, concerns regarding the use of the *PI* as a temperature susceptibility parameter have been recently addressed [9-12].

Other rheological evaluation methods have been recently developed with the application of different rheometers, namely the Dynamic Mechanical Analysis (DMA) [13, 14], the Dynamical Shear Rheometer (DSR) [15, 16], and the Bending Beam Rheometer (BBR) [15]. Because the test temperature range for these rheometers is wider than that for the traditional test apparatus such as the penetration test, the indices measured with these new rheometers are considered to more favorably reflect the true temperature susceptibility of the asphalt binders; and thus their preference.

Based on the foregoing discussions, the objectives of this study were to explore the validity of the *PI* and to evaluate the temperature susceptibility of the asphalt binders at different temperature zones using the DSR and the BBR.

Materials and Test Methods

Six penetration-graded paving asphalt binders (labeled A to F) produced from five crude sources (Orimulsio, Venezuela; Gudao, China; Huanxiling, China; Suizhong 36-1, China; Kelamayi, China) were chosen in this study, which were straight run products. Selected properties for these asphalt binders are listed in Table 1.

Penetration Test

Seven temperatures: 5, 10, 15, 20, 25, 30, and 35°C were selected for the penetration test, which was performed in accordance with the ASTM D5: Standard Test Method for Penetration of Bituminous Materials [17]. The penetrometer equipment used in this study was a PNR-10 Penetrometer manufactured by Petrotest Co. of Germany.

DSR Test

For DSR test measurements, a SR-5 rheometer manufactured by

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Table 1. Properties of the Asphalt Binders Used in This Study.

Asphalt Binder	Crude Source	Penetration Grade	Penetration (25°C,100*g*,5*s*)/*dmm*	Ductility (15°C)/*cm*	Softening Point /°C	Wax % (Distillation Method)
A	Orimulsio	AH-90	85	>150	47.5	1.6%
B	Gudao	A-100	86	>150	46.2	2.6%
C	Huanxiling	AH-90	99	>150	45.2	2.2%
D	Huanxiling	AH-130	134	>150	41.8	2.3%
E	Suizhong 36-1	AH-90	85	>150	50.7	1.6%
F	Kalamayi	AH-90	85	>150	48.1	1.5%

Rheometric Scientific Inc. was used. The tests were performed according to the AASHTO T 315 standard: Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer [18]. The selected test temperatures were: 7, 10, 13, 16, 19, 22, 25, 28, 46, 52, 58, and 64°C. For the lower to intermediate test temperatures (from 7 to 28°C), a parallel plate with an 8*mm* diameter and a 2*mm* gap between plates was used, while for the higher temperatures (46°C and above), the selected plate had a diameter of 25*mm* and the gap between plates was 1*mm*. All test measurements were conducted at a frequency of 10 *rad/s* in a strain controlled loading mode. As per AASHTO T 315 standard test procedure, a strain level of 12% was applied at the higher test temperatures (46°C and higher) while as strain level of 1% was selected for the lower to intermediate test temperatures (i.e., 28°C and lower).

The primary output data from the DSR test is the complex modulus, G^*, and the phase angle, δ. The complex modulus is defined as the ratio of the peak stress to the peak strain and it is a measure of the overall resistance of the asphalt binder to deformation. The phase angle is the difference between the time occurrence of the peak stress and the peak strain in an oscillatory deformation and it is a measure of the viscoelastic character of the material. With G^* and δ, the storage modulus G' (= $G^* \cdot \sin\delta$), the loss modulus G'' (= $G^* \cdot \cos\delta$), and the rutting parameter ($G^*/\sin\delta$) can then be easily calculated.

BBR Test

Creep tests were carried out by using BBR equipment manufactured by Cannon Instrument Company. AASHTO T 313 standard: Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer [19] was the test method utilized for the BBR tests conducted in this study. The selected test temperatures were -12, -15, -18, -21, -24, and -27°C. During BBR testing, an asphalt beam with dimensions of 125×12.5×6.25*mm* in length, width, and thickness, respectively, was immersed in a constant temperature water-bath. The preconditioning time at minimum temperature for the asphalt-beam specimen in the water-bath was 60*mins*. A 100*g* vertical load was then applied at the midpoint of the asphalt beam specimen and vertical deflections were subsequently measured as a function of time. The creep stiffness, S, and the creep rate, m, of the asphalt-beam samples were determined from the bending stress and strain at a loading time of 60*s*.

Results and Discussion

Penetration Test

Penetration measurements acquired at the different test temperatures for every asphalt binder are listed in Table 2. The PI value was calculated according to the JTJ052-2000 standard specification [20] as follows:

Firstly, plot $\log P$ versus T curve and fit it using the following equation:

$$\log P = AT + K \quad (1)$$

where; P - Penetration, *dmm*; T - Testing temperature, °C; A – Slope of the regression line, named penetration temperature index; K - Constant.

Secondly, the PI for each asphalt binder was then calculated using the following equation [2]:

$$PI = \frac{30}{1+50A} - 10 \quad (2)$$

Note that the standard needlepoint length for the penetration test is about 64*dmm*. When the penetration is less than 64 units, its value will be affected by the needlepoint length. By contrast, however, if the penetration is more than 64 units this effect can be ignored [21]. Hence, based on the penetration threshold value of 64*dmm*, three types of combinations of the test temperatures were selected to check the validity of the calculated PI:

1. temperatures in which the PI values were all greater than 64*dmm*: (25, 30, and 35°C),
2. temperatures in which the PI values were all less than 64*dmm*: (5, 10, and 15°C) and (5, 10, 15, and 20°C), and a mixture of temperatures in which both PI values are higher and/or lower than 64*dmm*: (15, 25, and 30°C), (10, 15, 20, and25°C), (20, 25, 30, and 35°C), and (5, 10, 15, 20, 25, 30, and 35°C).

Table 2. Penetration Test Results for All Asphalt Binders at Different Test Temperatures (*dmm*).

Asphalt Binder	$P_{5°C}$	$P_{10°C}$	$P_{15°C}$	$P_{20°C}$	$P_{25°C}$	$P_{30°C}$	$P_{35°C}$
A	7	14	26	47	85	142	244
B	6	10	18	40	85	118	263
C	7	14	28	51	99	180	313
D	9	17	34	70	134	228	>350
E	7	13	25	46	86	150	260
F	10	18	29	49	85	138	219

Table 3. Penetration Temperature Index, *A*, Penetration Index, *PI*, and R^2, for the Combined Penetration Test Results Determined at Different Temperatures.

Item	A	B	C	D	E	F
$A_{5,10,15℃}$	0.0561	0.0522	0.0582	0.0585	0.0524	0.0462
$PI_{5,10,15℃}$	-2.1156	-1.6898	-2.3274	-2.3567	-2.7127	-0.9366
$R^2_{5,10,15℃}$	0.997	0.999	1.000	0.999	0.999	0.996
$A_{25,30,35℃}$	0.0458	0.0488	0.0500	/[a]	0.0481	0.0411
$PI_{25,30,35℃}$	-0.8815	-1.2791	-1.4286	/[a]	-1.1894	-0.1800
$R^2_{25,30,35℃}$	0.999	0.991	0.999	/[a]	1.000	0.999
$A_{15,25,30℃}$	0.0500	0.0556	0.0542	0.0553	0.0522	0.0454
$PI_{15,25,30℃}$	-1.4286	-2.0635	-1.9138	-2.0319	-1.6898	-0.8236
$R^2_{15,25,30℃}$	0.999	0.991	0.999	0.997	0.999	0.999
$A_{5,10,15,20℃}$	0.0546	0.0566	0.0564	0.0595	0.0530	0.0456
$PI_{5,10,15,20℃}$	-1.9571	-2.1671	-2.1466	-2.4528	-1.7808	-0.8537
$R^2_{5,10,15,20℃}$	0.998	0.996	0.999	0.999	0.999	0.999
$A_{20,25,30,35℃}$	0.0475	0.0518	0.0526	0.0511	0.0499	0.0432
$PI_{20,25,30,35℃}$	-1.1111	-1.6435	-1.7355	-1.5612	-1.4163	-0.5036
$R^2_{20,25,30,35℃}$	0.999	0.996	0.998	0.997	0.999	0.998
$A_{10,15,20,25℃}$	0.0519	0.0618	0.0557	0.0601	0.0541	0.0450
$PI_{10,15,20,25℃}$	-1.6551	-2.665	-2.074	-2.5093	-1.9028	-0.7692
$R^2_{10,15,20,25℃}$	1.000	0.996	0.999	0.999	1.000	0.999
$A_{5\text{-}35℃}$	0.0510	0.0558	0.0547	0.0572	0.0520	0.0477
$PI_{5\text{-}35℃}$	-1.5493	-2.0844	-1.9679	-2.228	-1.6667	-0.7264
$R^2_{5\text{-}35℃}$	0.998	0.995	0.999	0.9998	0.999	0.999
ΔPI [b]	1.230	0.999	0.900	0.948	1.523	0.757

[a] Values could not be obtained because the penetration value of asphalt D at 35°C was not available.
[b] ΔPI, calculated according to Eq. (3), shows the max gap value of *PI* at different temperature zones.

The values of *A*, *PI*, and coefficients of determination, R^2, for each test temperature combination are presented in Table 3. It can be observed from the table that the regression coefficients of all six asphalt binders are considerably high in magnitude; some are even equal to 1.000. This is indicative of a good correlation between log*P* and *T*, and is also representative of relatively good test data. However, the resulting *PI* values for most of the asphalt binders are different for each test temperature combination, indicating that the same asphalt binder has different *PI* values at different temperature zones, i.e., the *PI* appears to be temperature dependent. Moreover, if the maximum difference between the *PI* values is calculated as:

$$\Delta PI = PI_{max} - PI_{min} \tag{3}$$

where; PI_{max} - maximum value of *PI* in seven temperature zones; PI_{min} - minimum value of *PI* in seven temperature zones; ΔPI - maximum difference of *PI* in seven temperature zones.

The differences of *PI* also vary for different asphalt binders from 0.757 for type F asphalt binder through 1.523 for type E asphalt binder as presented in Table 3, which indicates that if the temperature susceptibility of one asphalt binder is evaluated using penetration values at different temperatures, the result will differ significantly.

The model used to calculate *PI* (Eq. (2)) can be used to explain these variations. It should be noted that a slight change of *A* (i.e., one unit change) will get multiplied 50 times, which will result in a substantial difference in the computed *PI* value. In other words, slight measurement errors can be easily magnified by the analysis model presented in Eq. (2); which has a net impact of the appropriate interpretation of the results. Additionally, the allowable variation range specified by the penetration test itself can also be another source of errors for the *PI* results. Take for instance asphalt binder A with penetrations values of 26, 85, and 142*dmm* at 15, 25, and 30°C, respectively (Table 1). According to the ASTM D5 standard [17], when a penetration value is less than 50, the maximum difference between the highest and the lowest penetration can not exceed 2*dmm*; when the penetration value is equal to or greater than 50 units but less than 150 units, the maximum difference between the highest and the lowest penetration can not exceed 4*dmm*. Therefore, based on the standard requirements, the variation range for asphalt binder A penetration at 15, 25, and 30°C are between 24 and 28*dmm*, 81 and 89*dmm*, and 138 and 146*dmm*, respectively. If the penetration value at 25°C is fixed, and the penetrations at 15 and 30°C modified following the mentioned guidelines, different values of *PI* can be obtained, as shown in Fig. 1. Based on these results, it is apparent that even for the same asphalt binder, the allowed variations in penetration values result in values of *PI* of (-1.747) and (-0.977), and a ΔPI of 0.77, respectively.

The fact that there is no guide for what can be considered as a reasonable or allowable *PI* value for different asphalt binders at different temperature zones may result in a poor asphalt binder selection. Obtaining a high regression coefficient value in the *PI* calculation does not guarantee the best asphalt binder selection. As demonstrated previously, the *PI* value is affected by the specification of the test method and the analysis model.

Temperature Susceptibility Index at Intermediate-High Temperatures

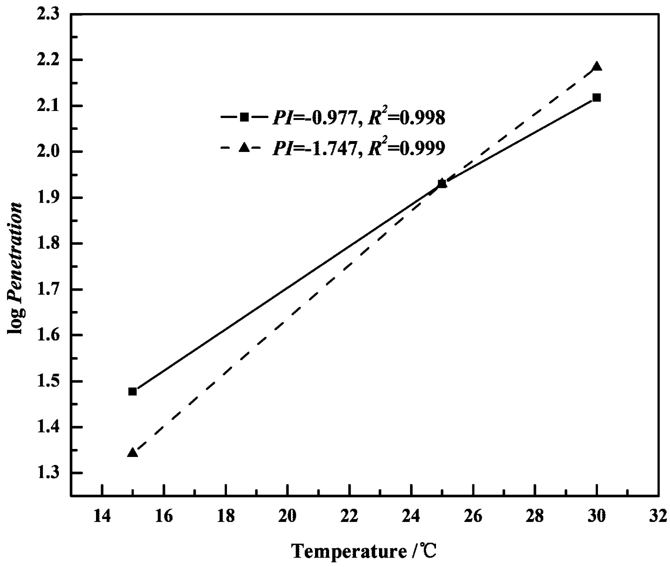

Fig. 1. Change of *PI* Value for Asphalt Binder A Resulting from Applying the Standard Variation Range.

The DSR test was used to characterize the viscous and elastic behavior of the asphalt binders using G^* and δ at different temperatures. The relationship between complex modulus and temperature can be established using the DSR test, which can then be related to the temperature susceptibility of the asphalt binder. DSR data of six asphalt binders are given from Tables 6 to 11, as shown in Appendix.

It was found that the common logarithm of G^*, $G^*/\sin\delta$, G', and G'' for each asphalt binder had a strong relationship with the test temperatures when the following equation was applied:

$$\log G = (GA)(T) + C_1 \quad (4)$$

Where; $\log G$ - Common logarithm of G^*, $G^*/\sin\delta$, G' or G'' in each case, *kPa*; T - Temperature, °C; GA - Slope of the regression line, denoted as modulus index; C_1 - Constant.

The value of GA can be used to characterize the temperature susceptibility of the asphalt binder; the higher the absolute value of GA, the more temperature susceptible the asphalt binder is at the intermediate-high temperature zone. Table 4 lists the GA values, R^2, and temperature susceptibility ranking (1 being the least susceptible and 6 the most susceptible) for the six asphalt binders included in this study using all four parameters: G^*, $G^*/\sin\delta$, G', and G''. Asphalt binder F has the lowest temperature susceptibility on the basis of the four parameters. The temperature susceptibility ranking for the six asphalt binders is consistent for all the parameters, except for asphalt binders C and E, as well as B and D for the $GA_{G^*/\sin\delta}$ parameter. However, these two values are very close to each other.

The absolute values of $GA_{G'}$ are higher than those of the other three indices and also there is a significantly greater difference in the $GA_{G'}$ magnitude among the asphalt binders. This indicates that the storage modulus of asphalt binder is the most sensitive parameter at the intermediate-high temperature zone; and would thus be the best temperature susceptibility indicator for the asphalt binders within this temperature domain. On this basis, the $GA_{G'}$ is thus proposed as a standard temperature susceptibility index in this temperature zone in lieu of the *PI* value.

Temperature Susceptibility Index at Low Temperatures

Because the traditional tests do not provide a direct method to evaluate the temperature susceptibility of asphalt binders at temperatures below freezing, the susceptibility is only predicted from other indices such as the *PI* and *PVN*. However, there exist some inherent errors due to the extrapolation of the calculations and several subjective factors in the test measurements. The BBR test method proposed by Strategic Highway Research Program (SHRP) offers a good way to measure the property of asphalt binders at low temperatures. Creep stiffness, *S*, which is a measure of how the asphalt binders resist constant loading and creep rate, *m*, which is the slope of log stiffness versus log time curve at any time (a measure of how the asphalt binder stiffness change with loading) were obtained using the BBR. The change of *S* and *m* with temperature can reflect the temperature susceptibility of the asphalt binder. Stiffness and *m* data of six asphalt binders are given in Tables 12 and 13, respectively, as shown in Appendix. Similar to Eq. (4), the following equations can be obtained:

$$\log S = (SA_s)(T) + C_2 \quad (5)$$

$$m = (SA_m)(T) + C_3 \quad (6)$$

where; $\log S$ - Common logarithm of *S*, *MPa*; *m* -creep rate; *T* - Temperature, °C; SA_S - Slope of the regression line, denoted as Stiffness index; SA_m - Slope of the regression line, denoted as the *m* index; C_2 -Constant; C_3 -Constant.

A higher absolute value of SA_S means that the stiffness of the asphalt binder increases quickly with a decrease in the temperature, a phenomenon that will tend to promote pavement cracking at low temperatures. On the other hand, a higher SA_m value indicates that the *m*-value increases rapidly with a drop in the temperature; which indicates a better relaxation ability of the asphalt binder and a consequent reduced probability of low temperature cracking in the pavement. Therefore, a lower SA_S value and a higher SA_m value will relate to a better performance of the asphalt binder in the low temperature zone. The values of SA_S, SA_m, R^2, and the rank order of temperature susceptibility for the six asphalt binders evaluated in this study are given in Table 5.

Table 5 shows that the rank orders of temperature susceptibility for the six asphalt binders are different according to the values of SA_S and SA_m, respectively. However, it is generally noticed that the absolute values of SA_S are higher than those of SA_m for all the six asphalt binders. This means that a change of temperature has more effect on the stiffness than on the *m*-value; namely the stiffness is more sensitive to temperature than *m*-value. Also the difference in magnitude among the SA_S values is more significant than that among the SA_m values, thus the SA_S Parameter would be judged as a better indicator of temperature susceptibility. Hence, a different array of asphalt binders can be effectively compared and the temperature susceptibility easily ranked through these large differences in the SA_S values (in magnitude). On this basis, the SA_S is proposed as the temperature susceptibility index in low temperature zone. On

Table 4. Slope, *GA*, R^2, and Ranking of the Asphalt Binders According to Their Temperature Susceptibility.

Asphalt Binder	GA_{G^*}	R^2	Ranking	$GA_{G^*/\sin\delta}$	R^2	Ranking	$GA_{G''}$	R^2	Ranking	$GA_{G'}$	R^2	Order
A	-0.0671	0.998	2	-0.0683	0.997	2	-0.0658	0.999	2	-0.0847	0.998	2
B	-0.0758	0.997	5	-0.0804	0.994	6	-0.0718	0.997	5	-0.0963	0.996	5
C	-0.0690	0.995	4	-0.0700	0.994	3	-0.0680	0.996	4	-0.0926	0.997	4
D	-0.0767	0.979	6	-0.0777	0.977	5	-0.0758	0.980	6	-0.1010	0.986	6
E	-0.0687	0.997	3	-0.0701	0.996	4	-0.0673	0.998	3	-0.0895	0.999	3
F	-0.0583	0.996	1	-0.0605	0.996	1	-0.0572	0.998	1	-0.0712	0.997	1

Table 5. Stiffness Iindex, SA_S, *m* Index, SA_m, R^2, and Ranking of the Asphalt Binders According to Their Temperature Susceptibility.

Asphalt Binder	SA_S	R^2	Ranking	SA_m	R^2	Ranking
A	-0.0672	0.981	4	0.0212	0.997	5
B	-0.0447	0.989	1	0.0090	0.995	1
C	-0.0571	0.994	2	0.0196	0.994	4
D	-0.0695	0.987	5	0.0234	0.993	6
E	-0.0655	0.991	3	0.0192	0.996	3
F	-0.0771	0.989	6	0.0188	0.985	2

comparative basis, asphalt binder B has the lowest temperature susceptibility (i.e., the least temperature sensitive) while asphalt binder F is the most temperature sensitive among the list (i.e., the worst). However, the rank order of the temperature susceptibility at the low temperature zone was found to be different from that at the intermediate-high temperature zone, according to the $GA_{G'}$ value.

Correlation between *PI*, $GA_{G'}$, and SA_S

According to JTJ052-2000 [20], *PI* is used to characterize the temperature susceptibility of asphalt binder. On the basis of above discussion, $GA_{G'}$ and SA_S were proposed to describe the temperature susceptibility of asphalt binder at the intermediate-high temperature zone and low temperature zone, respectively. Hence, it is needed to know if *PI* has some correlations with each of them. The linear correlation method was used to analyze the relation between *PI* (determined from three penetrations at 15, 25, and 30°C) and $GA_{G'}$ and SA_S. It was found that there is a good linear correlation between *PI* and $GA_{G'}$, in which the R^2 reaches 0.961. This may be due to the similar temperature zone that these two values were determined. However, the R^2 for linear correlation between *PI* and SA_S is only 0.518, which indicates that there is no significant relation between these two parameters for the six asphalt binders. Nevertheless, more data will be needed to verify this.

Conclusions

Penetration index (*PI*) is affected by the selected temperature zone, the penetration test specifications, and the analysis model. Higher regression coefficients obtained in the *PI* analysis cannot guarantee the best asphalt binder selection since some level of uncertainties still exists when trying to predict the temperature susceptibility of the asphalt binder using the *PI*.

$GA_{G'}$ of the asphalt binder, which obtained from the DSR test is proposed to characterize the temperature susceptibility at the intermediate-high temperature zone and has the potential to replace the *PI*. The SA_S of the asphalt binders, which is obtained from the BBR test, is proposed as the temperature susceptibility index in low temperature zone. According to the $GA_{G'}$ and SA_S values, the rank order of temperature susceptibility for six asphalt binders were found to be different. However, more laboratory research supplemented with field validation and a different array of asphalt binders is strongly recommended to validity the findings of this study.

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Appendix

Table 6. DSR Rheological Parameters of Asphalt Binder A.

Temperature °C	G^* kPa	$\delta°$	$G^*/\sin\delta$ kPa	G' kPa	G'' kPa
7	8.57E+03	54.4	1.05E+04	4.99E+03	6.97E+03
10	4.96E+03	59.1	5.78E+03	2.55E+03	4.26E+03
13	3.27E+03	61.6	3.71E+03	1.56E+03	2.87E+03
16	1.73E+03	65.9	1.90E+03	7.06E+02	1.58E+03
19	9.53E+02	69.4	1.02E+03	3.35E+02	8.92E+02
22	6.05E+02	71.3	6.39E+02	1.94E+02	5.73E+02
25	3.60E+02	74.8	3.73E+02	9.44E+01	3.47E+02
46	16.6	82.3	16.8	2.22	16.5
52	7.02	84.0	7.06	0.73	6.98
58	3.16	85.3	3.17	0.26	3.15
64	1.07	87.3	1.07	0.05	1.07

Note: data at 28 °C was not generated.

Table 7. DSR Rheological Parameters of Asphalt Binder B.

Temperature °C	G^* kPa	$\delta°$	$G^*/\sin\delta$ kPa	G' kPa	G'' kPa
7	1.52E+04	33.5	2.75E+04	1.27E+04	8.40E+03
10	1.01E+04	36.5	1.70E+04	8.12E+03	5.87E+03
13	8.27E+03	36.7	1.39E+04	6.63E+03	4.94E+03
16	4.03E+03	44.5	5.74E+03	2.87E+03	2.82E+03
19	2.18E+03	50.4	2.83E+03	1.39E+03	1.68E+03
22	1.17E+03	51.6	2.18E+03	7.27E+02	1.34E+03
25	5.95E+02	68.8	6.38E+02	2.15E+02	5.55E+02
28	3.50E+02	72.8	3.66E+02	1.03E+02	3.34E+02
46	14.3	80.3	14.5	2.41	14.1
52	5.55	83.0	5.59	0.68	5.51
58	2.37	84.9	2.38	0.21	2.36
64	1.11	86.4	1.11	0.07	1.11

Table 8. DSR Rheological Parameters of Asphalt Binder C.

Temperature °C	*G** *kPa*	δ°	*G*/sinδ* *kPa*	*G'* *kPa*	*G"* *kPa*
7	9.22E+03	56.7	1.10E+04	5.06E+03	7.71E+03
10	5.06E+03	62.6	5.70E+03	2.33E+03	4.50E+03
13	3.58E+03	64.5	3.96E+03	1.54E+03	3.23E+03
16	1.75E+03	69.4	1.87E+03	6.16E+02	1.64E+03
19	9.16E+02	73.3	9.57E+02	2.63E+02	8.78E+02
22	5.84E+02	75.0	6.04E+02	1.51E+02	5.64E+02
25	2.90E+02	78.6	2.96E+02	5.73E+01	2.84E+02
28	1.85E+02	80.3	1.88E+02	3.12E+01	1.82E+02
46	12.6	85.6	12.7	0.97	12.6
52	5.25	87.0	5.26	0.27	5.25
58	2.34	88.0	2.34	0.08	2.34
64	1.11	88.7	1.11	0.03	1.11

Table 9. DSR Rheological Parameters of Asphalt Binder D.

Temperature °C	*G** *kPa*	δ°	*G*/sinδ* *kPa*	*G'* *kPa*	*G"* *kPa*
7	1.52E+04	59.5	1.77E+04	7.71E+03	1.31E+04
10	8.24E+03	65.4	9.07E+03	3.43E+03	7.49E+03
13	5.64E+03	67.3	6.11E+03	2.18E+03	5.20E+03
16	1.15E+03	72.2	1.21E+03	3.52E+02	1.10E+03
19	5.83E+02	75.7	6.01E+02	1.44E+02	5.65E+02
22	3.72E+02	77.3	3.82E+02	8.18E+01	3.63E+02
46	7.38	86.8	7.39	0.41	7.37
52	3.21	87.8	3.22	0.12	3.21
58	1.92	88.2	1.92	0.06	1.92

Note: data at 25, 28, and 64°C were not generated.

Table 10. DSR Rheological Parameters of Asphalt Binder E.

Temperature °C	*G** *kPa*	δ°	*G*/sinδ* *kPa*	*G'* *kPa*	*G"* *kPa*
7	9.17E+03	53.8	1.14E+04	5.42E+03	7.40E+03
10	5.91E+03	57.3	7.03E+03	3.19E+03	4.97E+03
13	3.69E+03	60.6	4.24E+03	1.81E+03	3.22E+03
16	2.21E+03	63.8	2.47E+03	9.76E+02	1.99E+03
19	1.30E+03	66.7	1.41E+03	5.14E+02	1.19E+03
22	7.48E+02	69.5	7.99E+02	2.62E+02	7.01E+02
25	4.17E+02	72.1	4.38E+02	1.28E+02	3.97E+02
28	2.18E+02	74.8	2.26E+02	5.72E+01	2.10E+02
46	14.5	83.5	14.6	1.64	14.4
52	6.26	85.3	6.28	0.51	6.24
58	2.85	86.7	2.85	0.16	2.84
64	1.35	87.9	1.35	0.05	1.35

Table 11. DSR Rheological Parameters of Asphalt Binder F.

Temperature °C	*G** *kPa*	δ°	*G*/sinδ* *kPa*	*G'* *kPa*	*G"* *kPa*
7	6.58E+03	51.1	8.45E+03	4.13E+03	5.12E+03
10	4.13E+03	54.9	5.04E+03	2.37E+03	3.37E+03
13	2.83E+03	56.5	3.40E+03	1.56E+03	2.36E+03
16	1.17E+03	60.4	1.97E+03	5.78E+02	1.49E+03
19	1.02E+03	63.5	1.14E+03	4.55E+02	9.12E+02
22	6.74E+02	65.1	7.43E+02	2.84E+02	6.12E+02
25	3.80E+02	68.5	4.08E+02	1.39E+02	3.54E+02
28	2.50E+02	70.6	2.65E+02	8.30E+01	2.36E+02
46	26.7	77.5	27.3	5.78	26.1
52	12.1	79.8	12.3	2.14	12.0
58	5.8	81.9	5.86	0.82	5.74
64	2.93	83.6	2.95	0.33	2.92

Table 12. Creep Stiffness Modules of Asphalt Binders (*MPa*).

Asphalt Binder	Temperature, °C					
	-12	-15	-18	-21	-24	-27
A	94.3	163	314	490	624	994
B	180	246	378	513	642	828
C	157	222	344	562	790	1.05E+03
D	79.2	150	258	435	594	899
E	94.8	161	276	450	619	910
F	54.2	77	164	300	448	694

Table 13. Creep Velocity of Asphalt Binders.

Asphalt Binder	Temperature, °C					
	-12	-15	-18	-21	-24	-27
A	0.502	0.452	0.370	0.308	0.253	0.188
B	0.319	0.294	0.258	0.234	0.213	0.183
C	0.462	0.411	0.351	0.272	0.226	0.178
D	0.524	0.469	0.376	0.332	0.238	0.181
E	0.494	0.416	0.372	0.308	0.259	0.198
F	0.503	0.481	0.396	0.358	0.285	0.234