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Low and Intermediate Temperature Evaluation of Asphalt Binders through Dynamic Shear Rheometer

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13. Abstract

The low-temperature properties of asphalt binder play a critical role in the behavior and performance of flexible pavements. Since the 1990s, the Bending Beam Rheometer (BBR) has been the standard instrument for characterizing these properties. However, BBR testing requires time-consuming sample preparation and extensive equipment maintenance. Despite advancements in asphalt binder characterization and more efficient testing processes, the conventional BBR is still primarily used for low-temperature characterization. Recently, new methods using a Dynamic Shear Rheometer (DSR) have been developed to assess the low-temperature performance characteristics of asphalt binders. This study compared conventional BBR test results with two DSR-based methods: the Incremental Creep at Low Temperature (iCCL) and the Ultra-Thin Film Oven (UTFO) methods, developed by Pavement Systems LLC and the Western Research Institute (WRI), respectively. The results of the DSR low-temperature grades are practically similar to the low-performance grade from the BBR; however, an

Analysis of Variance (ANOVA) on the continuous grades reveals a significant difference between the two approaches. Ultimately, this research finds that the reliability of the WRI, iCCL, and UTFO methods is limited within conventional low-temperature grades (between -22°C and -25°C) and deviates further from BBR results as the temperature grade decreases.

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Abstract

The low-temperature properties of asphalt binder play a critical role in the behavior and performance of flexible pavements. Since the 1990s, the Bending Beam Rheometer (BBR) has been the standard instrument for characterizing these properties. However, BBR testing requires time-consuming sample preparation and extensive equipment maintenance. Despite advancements in asphalt binder characterization and more efficient testing processes, the conventional BBR is still primarily used for low-temperature characterization. Recently, new methods using a Dynamic Shear Rheometer (DSR) have been developed to assess the low-temperature performance characteristics of asphalt binders. This study compared conventional BBR test results with two DSR-based methods: the Incremental Creep at Low Temperature (iCCL) and the Ultra-Thin Film Oven (UTFO) methods, developed by Pavement Systems LLC and the Western Research Institute (WRI), respectively. The results of the DSR low-temperature grades are practically similar to the low-performance grade from the BBR; however, an Analysis of Variance (ANOVA) on the continuous grades reveals a significant difference between the two approaches. Ultimately, this research finds that the reliability of the WRI, iCCL, and UTFO methods is limited within conventional low-temperature grades (between -22°C and -25°C) and deviates further from BBR results as the temperature grade decreases.

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Implementation Statement

This research assessed alternative methods for the low-temperature performance grading of asphalt binders. Currently, low-temperature grading relies on the Bending Beam Rheometer (BBR). However, this study demonstrates that the Dynamic Shear Rheometer (DSR) can be implemented as a faster and more efficient alternative. Although DSR provides a convenient technique for low-temperature grading, practitioners must account for the data variation between the two devices. Ultimately, this study recommends that agencies evaluate and adopt these DSR-based methods according to their specific operational needs and required levels of accuracy.

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Introduction

The grading system for asphalt binders improved from penetration into a more detailed version of viscosity through the early 1960s. After roughly 30 years, the Performance Grading (PG) system was developed to address the rising need for improved characterization of asphalt binders. It has been over 25 years since the AASHTO M 320 [1] and AASHTO T 313 [2] standards were implemented. While additional test methods have been implemented for high-temperature characterization, low-temperature characterization has been conducted with the Bending Beam Rheometer (BBR), with no change through these years. The lack of novel testing methods has caused significant issues for the low-temperature properties [3]. Environmental and traffic-induced stresses, along with the application of recycled materials (e.g., RAP and RAS), are degrading the low-temperature performance of asphalt binders [4].

The Bending Beam Rheometer (BBR) evaluates low-temperature binder performance by measuring stiffness from the center deflection of an asphalt beam under load, while the m-value is determined from the beam's relaxation behavior. This test requires extensive calibration and maintenance, as well as time-consuming specimen preparation. Operational challenges associated with the BBR, combined with the increasing use of modified binders and additives, have prompted state agencies to seek alternative methods for determining low-temperature performance grades. Many of these alternative approaches rely on the Dynamic Shear Rheometer (DSR), an instrument that is already widely available to agencies, suppliers, and contractors.

Agencies are also motivated toward innovative asphalt binder characterization methods due to increasing modification of the asphalt binder. Asphalt binder is subjected to many additive modifications due to performance enhancements or cost improvements. These changes can occur in the refinery or plant before mixing with aggregate, but may still require additional testing due to changes during production. BBR testing requires considerable time for preparation and cannot be performed in the limited plant production timeline; therefore, alternative methods may be adopted to meet production timelines.

The Dynamic Shear Rheometer (DSR) is used to evaluate a material's resistance to deformation under shear forces induced by torsional loading. Traditionally, the DSR has been employed to characterize asphalt binders at high and intermediate temperatures. Because binder viscosity varies significantly with temperature, DSR specimen geometry is selected to remain within the torsional limits of the device. As testing temperature decreases, asphalt binder viscosity increases, requiring smaller specimen geometries to ensure accurate measurements and avoid exceeding instrument limits. Figure 1 illustrates the different spindle sizes commonly used to represent standard asphalt binder specimen dimensions

Figure 1. 4mm, 8mm, and 25mm DSR spindles

Research has been performed on the capability of the 4mm and 8mm DSR samples in predicting the low-temperature behavior of asphalt binders [5] [6] [7] [8]. Western Research Institute (WRI) has pioneered a method to determine the stiffness of asphalt binders at low temperatures based on the parameters derived from a master-curve of asphalt binders at low to intermediate temperatures [9].

Pavement Systems LLC has developed an 8mm method called Incremental Creep at Low-Temperature (iCCL) to address the difficulties of the sample preparation and timeliness of the BBR testing. iCCL determines the low-temperature characteristics of the asphalt binder through a constant sheer (creep) load in increments at low temperatures. The Minimum Strain Rate (MSR) is determined from the strain rate versus the time of 60 sec. The Pavement Systems LLC software measures the MSR to continuous low-temperature performance grade from BBR internally [3]. Pavement Systems LLC has further expanded their method and developed another test method. The Ultra-Thin Film Oven (UTFO) test has the same mechanism and preparation as iCCL; however, in this method, asphalt binders can be tested in their original state without any RTFO and PAV aging.

Objective

The primary objective of this research was to evaluate the effectiveness of newly proposed methods (iCCL, UTFO, and WRI) for the low-temperature performance grading of asphalt binders by comparing them against the conventional Bending Beam Rheometer (BBR) test. Ultimately, this study aimed to determine whether these alternative methods can provide reliable, efficient, and practical options for binder characterization that could potentially enhance or replace traditional BBR testing.

Scope

To achieve this objective, the research focused on comparing key performance indicators between the testing methods, specifically stiffness and thermal cracking resistance. The study's material scope included a diverse, representative sample of both modified and unmodified asphalt binders and additives. These materials were sourced directly from producers throughout Louisiana to ensure the findings are highly applicable to the state's current infrastructure and paving practices

Background

Low and intermediate temperature performance grading of asphalt binders requires the use of several specialized equipment, such as, the Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), ductilometer, Pressure Aging Vessel (PAV), and the Rolling Thin Film Oven (RTFO). In recent years, national research activities have focused on the reduction of equipment, time, material, and effort required to determine the low and intermediate temperature properties of asphalt binders.

Waleed et al. developed a method to predict low-temperature binder properties using DSR frequency sweep tests conducted on twelve asphalt binders at temperatures between 0 and 25°C with an 8-mm parallel plate geometry. Frequency-domain data were converted to time-domain responses and transformed from shear to bending behavior using linear viscoelastic theory. A model was used to construct master curves of storage and loss moduli, from which flexural creep stiffness and m-values were predicted through inverse Laplace transformation. The predicted BBR parameters, S(60) and m(60), showed strong agreement with measured BBR results, demonstrating the feasibility and accuracy of the proposed DSR-based approach [10].

Buchner et al. investigated the applicability of the 4-mm DSR geometry for low-temperature binder characterization and identified significant challenges associated with specimen preparation due to the very small sample size and limited compatibility of existing equipment for trimming specimens to such dimensions [11]. To address these issues, they proposed a top-trimming (TT) apparatus and preparation method to improve specimen fabrication and handling. To evaluate repeatability, ten repetitions of the temperature–frequency sweep (T–f sweep) were conducted for each asphalt binder, involving three different operators and two different DSR instruments. The results for the 50/70 and 25/55-55 binders showed reasonable repeatability for this preliminary research using the 4-mm geometry. The coefficient of variation across all temperature and frequency combinations ranged from 11% to 19%, with the potential for improvement through more systematic temperature control of the trimming tool. When results from a single operator were considered, variability was reduced to as low as 6%. The study did not include a direct comparison with results from the widely adopted BBR test, limiting its applicability for validating the method against established low-temperature performance metrics.

Kommidi evaluated three DSR-based methods for predicting low-temperature binder performance: the WRI, NCHRP, and UNL approaches [5]. These methods differ primarily in their calculation procedures and viscoelastic modeling frameworks. The research concluded that the WRI method performed well overall but was highly dependent on the specific binder dataset used for calibration. The NCHRP method showed strong potential, demonstrating a good linear correlation between DSR-predicted stiffness and slope values and the corresponding BBR measurements. While creep stiffness predictions were generally accurate, the slope (m-value) was consistently underpredicted. The UNL mechanistic approach was found to be both rigorous and mechanically sound, providing effective predictions of BBR parameters. To further improve accuracy, Kommidi proposed separate shift factors for creep stiffness and slope predictions, which resulted in satisfactory agreement with experimental BBR results [12].

Recent research from Pavement Systems, LLC introduces two new tests (iCCL and UTFO) that determine low-temperature binder grades using a single instrument. These methods can analyze standard binder, and potentially mastic extracted from a core, in a single test run, significantly reducing both preparation and testing time. Researchers report several key advantages to this streamlined approach, including enhanced laboratory safety through the elimination of hazardous coolants, solvents, and pressurized air. Furthermore, the automated testing procedures reduce manual technician labor and offer faster turnaround times, completing sample preparation and testing in approximately 30 minutes per sample. The method provides a continuous low-temperature performance grade from a single test with improved repeatability, requires only a small amount of binder (≈30 mg), and simplifies cleaning and equipment maintenance. Additionally, it enables rapid PG determination using original binder, making it an effective screening tool [3]. These methods require online data transfer from the device to Pavement Systems, LLC analysis system for results to be computed and sent back.

Current mix extraction processes do not allow qualitative testing on latex / crumb-rubber modified binders extracted from asphalt mix. Additionally, in recent years, the asphalt binder industry has investigated substitutes of styrene-butadiene-styrene (SBS) and styrene-butadiene rubber (SBR) as modifiers in asphalt binders. Among these substitutes are elastomers, such as recycled ground tire rubber and plastomers, such as Ethene-Vinyl-Acetate (EVA) and Polyethylene (PE). Other modifiers include sulfur additives and polyphosphoric acid (PPA). It is commonly believed that elastomers, such as SBS perform better than plastomers and other modifiers. Therefore, there is a pressing need to identify and characterize the modifier type in asphalt binder. The current Superpave PG grading system does not address polymer identification and aging-related polymer degradation issues. [13] Several testing methods have been proposed to improve the characterization of asphalt binders. The iCCL test was developed to evaluate a binder's resistance to thermal cracking and to determine its low-temperature grade, both with and without modifiers. Additionally, the iRLPD test was introduced to measure the fatigue cracking resistance of mastic asphalt binders containing RAP/RAS, REOB, WMA, rejuvenators, rubber, and other additives [14].

This research evaluated alternative approaches for testing and specifying the low- and intermediate-temperature performance of asphalt binders using the Dynamic Shear Rheometer (DSR). The evaluated approaches were based on methods proposed by the Western Research Institute (WRI) and Pavement Systems, which aim to address limitations associated with the conventional Bending Beam Rheometer (BBR) test.

A range of asphalt binders produced and used in the state of Louisiana were analyzed using these DSR-based methods. The resulting low- and intermediate-temperature performance parameters were then compared with those obtained from the currently adopted BBR test. This comparison was conducted to assess the effectiveness, reliability, and practicality of the alternative methods in predicting binder performance and to evaluate their potential for use in Louisiana specifications.

Methodology

Experimental Plan

Twenty asphalt binders were collected at various times from multiple suppliers throughout Louisiana and evaluated for this study. Table 1 shows the quantities of the samples provided by each producer and their corresponding performance grades.

Table 1. List of samples

Sample Source	Number of Samples	Performance Grade of the Samples
Ergon	5	67-22
	1	70-22
	2	70-22m*
	3	76-22m
Hunt	1	58-28
	1	67-22
	1	76-22m
Marathon	2	67-22
Martin	3	67-22
	1	67-22E
	1	67-22H
	3	70-22m
	4	76-22m
Valero	3	58-22
	1	70-22m
	1	76-22m
Henderson	1	67-22
	1	70-22
	1	76-22
In-house modified Marathon with Isocyanate additive	2	67-22

*m: styrene-butadiene-styrene (SBS) modified

Sample Preparation

WRI Method

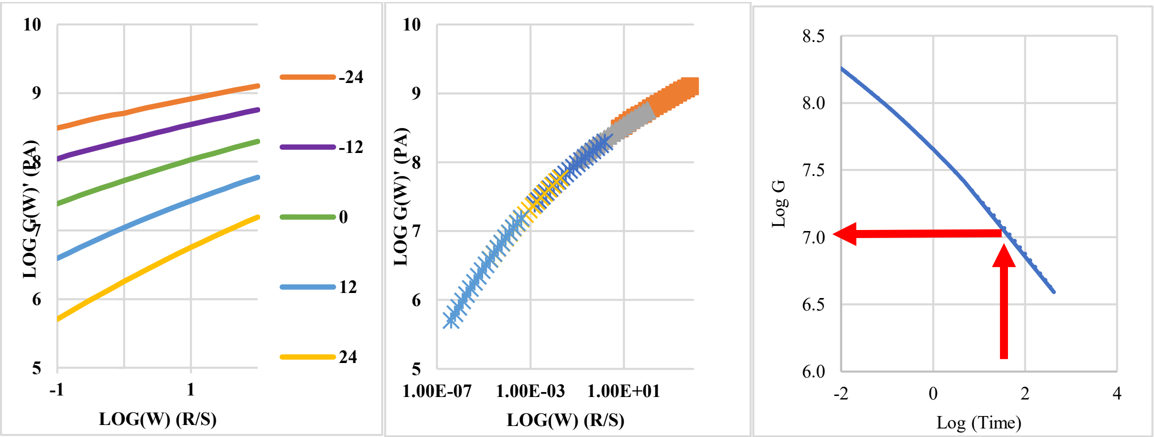
Sample preparation for the 4-mm DSR with the WRI method was similar to that of conventional DSR testing at high temperature [15]. However, initial testing showed that any pre-stress tension will alter the test results; therefore, extra dwell time (8 min. at 90˚C) was adopted to eliminate any stresses stored in the specimen during preparation.

In this method, isothermal frequency sweep curves were developed by testing asphalt binder samples over a frequency range of 0.1 to 100 Hz at temperatures of –24°C, –12°C, 0°C, 12°C, and 24°C. The resulting isotherms were then shifted horizontally using temperature-dependent shift factors to construct a continuous master curve in accordance with time–temperature superposition principles.

Two master curves were developed in this approach, each corresponding to a reference temperature located above and below the anticipated binder performance grade. These master curves were subsequently transformed into logarithmic master curves, which enable interpolation and extrapolation of stiffness values. Using the logarithmic master curve, the binder stiffness was determined at a loading time of t = 60 s, consistent with BBR analysis. In addition, the first derivative of the logarithmic stiffness curve is used to calculate the corresponding slope (m-value) at t = 60 s.

Figure 2 illustrates the overall workflow of the WRI method used to determine the low-temperature performance grade of asphalt binders.

Figure 2. Summary of WRI analysis process



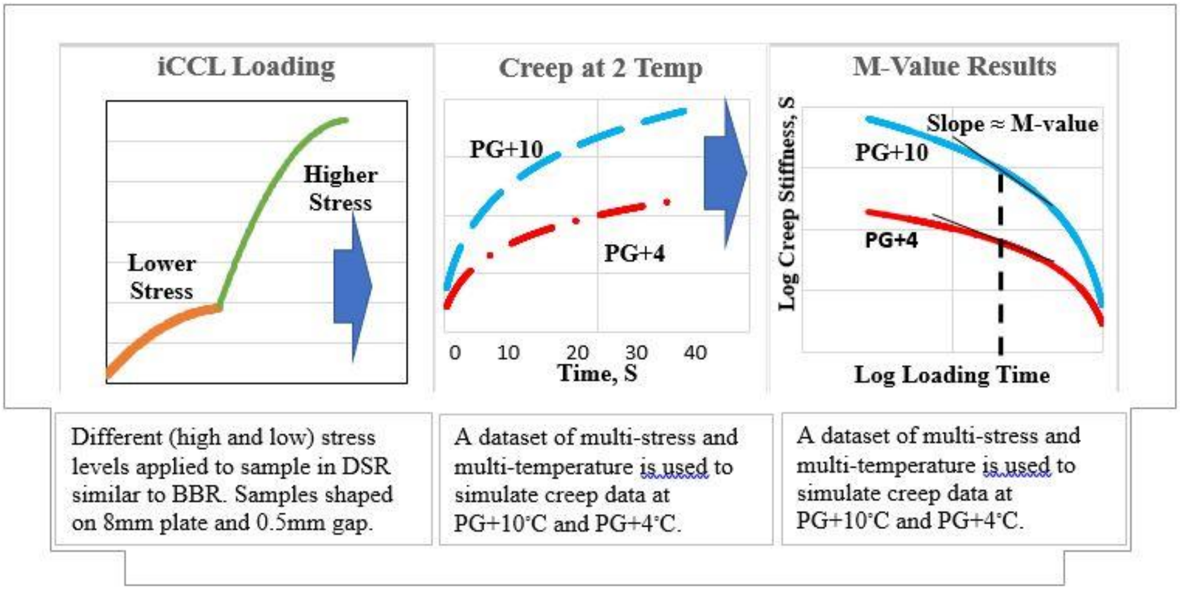
iCCL and UTFO Methods

According to the procedure defined by Pavement Systems LLC, similar sample preparation processes are used for the iCCL and UTFO methods. An asphalt binder was prepared with a weight of 0.031-0.038 grams. The sample was sandwiched between an 8mm plate and spindle with no trimming and a 0.5mm gap. Prior to testing, the sample was conditioned at 90˚C for five min. to eliminate the pre-stress forces. The DSR device used for iCCL has a mechanical gearing system, which is distinct from typical DSR devices that use air-bearings.

The UTFO procedure is nearly identical to that of the iCCL. However, UTFO uses the original asphalt binder, while iCCL is performed on the PAV aged samples. The UTFO procedure goes through a conditioning phase (closed-chamber high-temperature treatment) that aims to simulate the rolling thin film oven (RTFO) procedure.

The iCCL method employs a cyclic stepwise loading process consisting of 0.1 seconds of loading followed by 0.9 seconds of relaxation, as illustrated in Figure 3. During the test, the responses from mechanical gear DSR shown in Figure 4, transferred by DSR software directly to Pavement Systems, LLC [16]. The company collects and analyzes the response data, returning the results to the user as a correlated stiffness and m-value. The specific correlation algorithm used to generate these values is proprietary and not disclosed to the user.

Figure 3. iCCL results process [11]



Different (high and low) stress levels applied to sample in DSR similar to BBR. Samples shaped on 8mm plate and 0.5mm gap.

A dataset of multi-stress and multi-temperature is used to simulate creep data at PG+10˚C and PG+4˚C.

A dataset of multi-stress and multi-temperature is used to simulate creep data at PG+10˚C and PG+4˚C.

Figure 4. Anton Paar MCR 72 with mechanical gear system and Bending Beam Rheometer

BBR

BBR testing (shown in figure 4) was performed in accordance with AASHTO T 313 at two different temperatures, one above and one below the known performance grade. Two sets of the m-values and stiffness were determined and analyzed for low-temperature grading [2]. The continuous low-temperature grade was determined for each sample so that the m-value that would meet the 0.300 threshold and the stiffness would meet the 300 MPa specification. Based on the results, the low-temperature grade of all the samples evaluated in this study were found to be controlled by the m-value (negative ΔT_c).

Discussion of Results

In this study, the low-temperature performance grade was determined for each testing method based on the standard criteria for stiffness and m-value. To ensure a comprehensive analysis and avoid wide 6°C increments, continuous grades were also considered for the analysis. The continuous grades and PG grades for each method are shown in Table 2.

Table 2. Continuous and standard performance grades

Sample	WRI			UTFO			iCCL			BBR		
	Continuous	St.Dev.	PG	Continuous	St.Dev.	PG	Continuous	St.Dev.	PG	Continuous	St.Dev.	PG
1	-25.35	1.27	-22	-25.53	0.38	-22	-25.03	0.51	-22	-23.31	0.15	-22
2	-22.48	0.40	-22	-25.00	0.26	-22	-22.07	0.55	-22	-22.35	0.14	-22
3	-22.42	1.08	-22	-23.93	0.75	-22	-23.37	0.21	-22	-22.47	0.54	-22
4	-31.65	1.38	-28	-32.10	0.17	-28	-32.90	0.10	-28	-29.86	0.12	-28
5	-28.68	0.66	-28	-31.67	0.06	-28	-32.97	0.23	-28	-28.84	0.06	-28
6	-25.75	0.78	-22	-25.10	0.10	-22	-23.30	0.35	-22	-24.09	0.19	-22
7	-24.62	0.90	-22	-25.63	0.42	-22	-23.03	0.51	-22	-22.57	0.01	-22
8	-33.29	1.36	-28	-33.07	0.21	-28	-35.07	0.06	-28	-32.57	0.49	-28
9	-24.67	0.74	-22	-26.23	0.45	-22	-26.80	0.20	-22	-23.54	0.21	-22
10	-30.43	1.78	-28	-31.80	0.40	-28	-30.50	0.35	-28	-29.21	0.05	-28
11	-24.14	1.35	-22	-25.73	0.38	-22	-24.83	0.70	-22	-22.90	0.11	-22
12	-23.82	2.09	-22	-24.73	0.25	-22	-24.53	0.21	-22	-23.22	0.15	-22
13	-23.12	0.91	-22	-25.80	0.10	-22	-25.50	0.30	-22	-23.44	0.00	-22
14	-26.57	0.64	-22	-26.53	0.38	-22	-25.83	0.35	-22	-24.85	0.03	-22
15	-26.63	0.22	-22	-22.63	0.15	-22	-24.40	0.44	-22	-22.62	0.30	-22
16	-26.32	0.62	-22	-23.37	0.57	-22	-22.63	0.06	-22	-21.60	0.34	-16
17	-26.45	0.28	-22	-26.40	0.17	-22	-25.60	0.46	-22	-25.62	0.09	-22
18	-24.58	0.76	-22	-24.73	0.31	-22	-23.97	0.80	-22	-23.13	0.11	-22
19	-28.67	0.27	-28	-25.73	0.38	-22	-25.93	0.67	-22	-25.05	0.11	-22
20	-27.15	1.27	-22	-31.13	0.31	-28	-29.20	0.36	-28	-26.12	0.14	-22
21	-26.06	0.62	-22	-26.87	0.15	-22	-25.80	0.17	-22	-24.61	0.09	-22
22	-24.72	0.29	-22	-24.67	0.40	-22	-23.47	0.15	-22	-23.68	0.15	-22
23	-23.55	0.56	-22	-24.43	0.50	-22	-22.60	0.36	-22	-22.92	0.61	-22
24	-25.67	1.23	-22	-25.47	0.38	-22	-25.37	0.29	-22	-23.68	0.23	-22

Sample	WRI			UTFO			iCCL			BBR		
	Continuous	**St.Dev.**	**PG**	**Continuous**	**St.Dev.**	**PG**	**Continuous**	**St.Dev.**	**PG**	**Continuous**	**St.Dev.**	**PG**
25	-26.01	1.46	-22	-26.30	0.26	-22	-23.63	0.15	-22	-23.31	0.28	-22
26	-23.18	0.72	-22	-26.30	0.17	-22	-24.67	0.12	-22	-23.92	0.58	-22
27	-25.03	0.76	-22	-26.17	0.35	-22	-24.17	0.25	-22	-24.17	0.22	-22
28	-31.82	1.03	-28	-27.17	0.38	-22	-28.20	0.17	-22	-26.79	0.14	-22
29	-22.95	0.38	-22	-24.00	0.46	-22	-24.63	0.15	-22	-22.00	0.00	-22
30	-23.39	0.59	-22	-23.63	0.38	-22	-23.90	0.10	-22	-22.98	0.55	-22
31	-24.84	0.78	-22	-25.33	0.35	-22	-26.30	0.10	-22	-23.85	0.09	-22
32	-28.28	0.86	-28	-27.60	0.26	-22	-26.47	0.38	-22	-26.98	1.08	-22
33	-23.90	1.60	-22	-26.70	0.26	-22	-25.97	0.65	-22	-22.17	0.20	-22
34	-27.19	0.95	-22	-26.70	0.26	-22	-25.70	0.44	-22	-25.49	1.21	-22
35	-24.21	0.75	-22	-26.13	0.64	-22	-24.33	0.67	-22	-23.78	0.53	-22
36	-29.57	0.28	-28	-27.17	0.51	-22	-26.40	0.46	-22	-26.00	0.12	-22
37	-23.89	1.21	-22	-26.90	0.92	-22	-25.73	0.49	-22	-23.88	0.13	-22
38	-24.33	0.39	-22	-27.13	0.29	-22	-27.80	0.26	-22	-25.59	0.31	-22
Avg. St. Dev.*	**1.44**			**0.84**			**0.97**			**1.11**		

*Avg.: Average, St.: Standard, Dev.: Deviation

From Table 2, Sample 16 has a lower PG compared to the DSR methods. Further, Samples 19, 32, and 36 have BBR results similar to the iCCL and UTFO results, while Sample 20 has BBR results that only match the WRI result. According to the samples in this study, the proposed DSR methods matched the BBR low temperature PG grade in 34 of the 38 binders evaluated (89%). The average standard deviation for each test procedure was determined by averaging the standard deviations from each sample set by test method. The average standard deviation shows the UTFO has the lowest variability, followed by iCCL, BBR and WRI, respectively.

Table 3 presents a delta analysis of the samples evaluated in this study. The delta was determined by subtracting the low temperature continuous grade determined by BBR from that of the three DSR methods respectively. A positive delta indicates a “warmer” BBR continuous grade with respect to the corresponding DSR method. The table shows the average delta for each of the test methods evaluated. The average low temperature continuous grade of the three DSR based methods were within 1.3 to 1.9°C of the low-temperature continuous grade determined through BBR. These results indicate that practitioners can expect practically similar continuous low temperature grade and performance grade results from the DSR methodologies when compared to the BBR.

Table 3. Continuous grades Delta analysis

Delta from BBR							
Sample	**WRI**	**UTFO**	**iCCL**	**Sample**	**WRI**	**UTFO**	**iCCL**
1	2.0	2.2	1.7	20	1.0	5.0	3.1
2	0.1	2.7	-0.3	21	1.5	2.3	1.2
3	0.0	1.5	0.9	22	1.0	1.0	-0.2
4	1.8	2.2	3.0	23	0.6	1.5	-0.3
5	-0.2	2.8	4.1	24	2.0	1.8	1.7
6	1.7	1.0	-0.8	25	2.7	3.0	0.3
7	2.1	3.1	0.5	26	-0.7	2.4	0.8
8	0.7	0.5	2.5	27	0.9	2.0	0.0
9	1.1	2.7	3.3	28	5.0	0.4	1.4
10	1.2	2.6	1.3	29	0.9	2.0	2.6
11	1.2	2.8	1.9	30	0.4	0.6	0.9
12	0.6	1.5	1.3	31	1.0	1.5	2.5
13	-0.3	2.4	2.1	32	1.3	0.6	-0.5
14	1.7	1.7	1.0	33	1.7	4.5	3.8
15	4.0	0.0	1.8	34	1.7	1.2	0.2
16	4.7	1.8	1.0	35	0.4	2.4	0.5
17	0.8	0.8	0.0	36	3.6	1.2	0.4
18	1.5	1.6	0.8	37	0.0	3.0	1.9
19	3.6	0.7	0.9	38	-1.3	1.5	2.2

	Delta from BBR		
	WRI	**UTFO**	**iCCL**
Avg. Delta	1.4	1.9	1.3
Min Delta	-1.3	0.0	-0.8
Max Delta	5.0	5.0	4.1

As shown in the table above, five of the 38 samples (highlighted) exhibit differences between the BBR and alternative method results that are large enough to alter the final performance grade. Among these five samples, only one was graded as -16°C by the BBR due to modification effects. The remaining samples were graded as -22°C by the BBR, whereas the alternative methods classified them as -28°C. These samples originated from different suppliers, and no consistent trend or common characteristic was observed among them.

Table 4 presents a shift factor analysis of the samples evaluated in this study. The shift factor was determined by dividing the low temperature continuous grade determined by BBR from that of the three DSR methods respectively. Therefore, a shift factor <1 indicates a “warmer” BBR continuous grade with respect to the corresponding DSR method. As shown in the table, the average shift factor for the three DSR methodologies ranges between 0.93 and 0.95. Practitioners may use this framework to develop relationships to estimate the low temperature continuous grading of the BBR while conducting the DSR methodologies.

Table 4. Continuous grades shift factor analysis

Shift from BBR							
Sample	**WRI**	**UTFO**	**iCCL**	**Sample**	**WRI**	**UTFO**	**iCCL**
1	0.92	0.91	0.93	20	0.96	0.84	0.89
2	0.99	0.89	1.01	21	0.94	0.92	0.95
3	1.00	0.94	0.96	22	0.96	0.96	1.01
4	0.94	0.93	0.91	23	0.97	0.94	1.01
5	1.01	0.91	0.87	24	0.92	0.93	0.93
6	0.94	0.96	1.03	25	0.90	0.89	0.99
7	0.92	0.88	0.98	26	1.03	0.91	0.97
8	0.98	0.98	0.93	27	0.97	0.92	1.00
9	0.95	0.90	0.88	28	0.84	0.99	0.95
10	0.96	0.92	0.96	29	0.96	0.92	0.89
11	0.95	0.89	0.92	30	0.98	0.97	0.96
12	0.97	0.94	0.95	31	0.96	0.94	0.91
13	1.01	0.91	0.92	32	0.95	0.98	1.02
14	0.94	0.94	0.96	33	0.93	0.83	0.85
15	0.85	1.00	0.93	34	0.94	0.95	0.99
16	0.82	0.92	0.95	35	0.98	0.91	0.98
17	0.97	0.97	1.00	36	0.88	0.96	0.98
18	0.94	0.94	0.96	37	1.00	0.89	0.93
19	0.87	0.97	0.97	38	1.05	0.94	0.92

	Shift from BBR		
	WRI	**UTFO**	**iCCL**
Avg. Shift	0.95	0.93	0.95
Min Shift	0.82	0.83	0.85
Max Shift	1.05	1.00	1.03

In Figure 5, the continuous grades from the WRI, UTFO, and iCCL methods are compared with the BBR results.

Figure 5. Continuous grade results of the DSR methods vs BBR

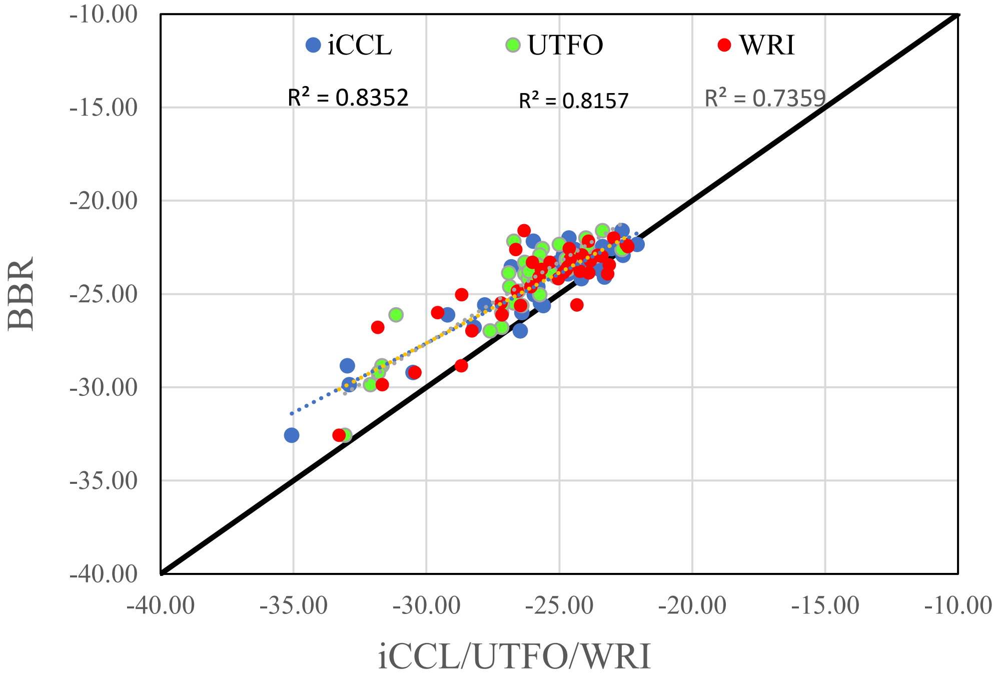


Figure 5 shows that the majority of the data points fall above the X = Y line, indicating that the BBR method is a more conservative method (i.e. the BBR continuous grade is typically "warmer" than that of the DSR results). Therefore, for a known BBR result, the corresponding DSR result is expected to be colder (i.e., a larger negative value). An analysis of the trend-lines reveals that the iCCL exhibits the strongest positive correlation ($R^2 = 0.84$) with the BBR, followed by UTFO and WRI, respectively [17].

Statistical Analysis of Results

An Analysis of variance (ANOVA) was conducted using the Duncan Multiple Comparison Test (MCT) procedure on the results of the continuous grade through SAS software to determine the statistical differences between the BBR and proposed methods. ANOVA was performed to identify statistically significant differences among the average continuous grades from the 4 test methods. When significant differences were detected, the Duncan Multiple Comparison Test (MCT) was applied to group the means. Results assigned the same Duncan group are not statistically different, while results in different groups indicate significant differences at the selected confidence level.

Each DSR sample had three different continuous grades from three replicates, and the BBR had four continuous grades by randomly assigning two results from two replicates at higher grades and two results at lower grades. Table 5 shows the results of the statistical grouping from the Duncan MCT. Significant differences are shown with different letters, considering a significance level (alpha) of 0.05. Homogeneity of variance was confirmed using Levene’s test within each sample type.

Table 5. ANOVA analysis of the asphalt binder samples

Duncan MCT Grouping									
Sample	**BBR**	**iCCL**	**UTFO**	**WRI**	**Sample**	**BBR**	**iCCL**	**UTFO**	**WRI**
1	A	B	B	C	20	A	B	B	B
2	A	B	A	C	21	A	C	B	B
3	A	A	B	A	22	A	B	A/B	A/B
4	A	A	C	B	23	A/B	A	C	B
5	A	B	A/B	C	24	A	B	B	A
6	A	A/B	B	B	25	A	A	C	B
7	A	A	B	B	26	A	C	D	B
8	B	A	C	C	27	A	B	B	A
9	A	B	A	A	28	B	D	C	A
10	A	B/C	C	A/B	29	A/B	A	A/B	B
11	A	A/B	B	A	30	A	B	A	C
12	A	C	C	B	31	B	A/B	A/B	A
13	A	B	C	C	32	A	A	B	A
14	A	A	A	A	33	A	C	C	B
15	A	A/B	B	A/B	34	A	B	C	B
16	A	B	B	B	35	B	B	A	A/B
17	A	C	B/C	B	36	A	A	B	B
18	A	B	C	A	37	A	A	B	C
19	A	B	C	A	38	A	A	B	B

Based on the ANOVA results, the percentage of instances with a statistical difference between the BBR results and the proposed testing methods was determined.. The continuous grade comparison shows that the WRI method was statistically different for 58% of the comparisons. The UTFO method was statistically different for 76% of samples tested, while the iCCL procedure resulted in a statistical difference in 58% of the comparisons. The presence of statistical significance is controlled by the sample average and standard deviation. Because these methods are highly repeatable (indicated by low standard deviations), even small, practically insignificant differences become statistically significant. However, as previously stated, when evaluating the low-temperature Performance Grade (PG) using standard 6°C increments, the procedures determined a similar grade for 89% of the comparisons.

Conclusions

Based on the experimental results of the asphalt binders in this study, the low-temperature grade determined from the DSR methods were compared to the results from the BBR testing. These testing methods were evaluated in several different ways: practicality of final PG grades, variability of the results, correlation of the results, and statistical analysis of the continuous grades. Based on these analyses, the following conclusions were drawn:

- Results indicate that practitioners can expect practically similar continuous low temperature grade and performance grade results from the DSR methodologies when compared to the BBR.
- The average low temperature continuous grade of the three DSR based methods fell within 1.3 to 1.9°C of the low temperature continuous grade determined through BBR.
- The average shift factor for the three DSR methodologies ranges between 0.93 and 0.95. Practitioners may use this framework to develop relationships to estimate the low temperature continuous grading of the BBR while conducting the DSR methodologies.
- Statistical analysis, through ANOVA, showed that the majority of samples indicated statistically significant continuous grading differences when DSR methods are compared to BBR results. The WRI and iCCL methods showed the least instance of differences (58%), followed the UTFO method (76%).
- While statistical differences in continuous grades were significant in many of the samples, the proposed methods were able to practically and accurately determine the low-temperature grade of the asphalt binder, agreeing with the BBR-determined grade in 89% of the samples evaluated.
- The BBR resulted in a warmer continuous grade in the majority of the samples evaluated. Therefore, the BBR result is more conservative when compared to DSR methods.

Operational Conclusions

Additional operational considerations were noted and summarized in Table 6 below:

Table 6. Operational comparison

	WRI	iCCL	UTFO
Test Time	6 hr (after PAV)	0.5 hr	1 hr
Device	Air-bearing DSR	Mechanical DSR	Mechanical DSR
Complexity	Easy but time consuming	Easy, fast	Easy, moderate duration
Analysis	Advanced, user analyzed	Advanced, proprietary software (black box), cannot verify	Advanced, proprietary software (black box), cannot verify

Recommendations

Based on the results of this study, DSR methods aim to predict the BBR results based on correlations through different methods. While the results show acceptable and practical correlation, statistical analyses differ. Further, if these methods are applied for low-temperature performance grade, they need to be thoroughly investigated. Based on the results of this study, it is recommended that practitioners can use these alternative testing methods for low temperature verifications of low temperature performance grade.

Acronyms, Abbreviations, and Symbols

Term	**Description**
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
cm	centimeter(s)
DOTD	Louisiana Department of Transportation and Development
DSR	Dynamic Shear Rheometer
FHWA	Federal Highway Administration
iCCL	Incremental Creep at Low-Temperature
in.	inch(es)
lb.	pound(s)
LTRC	Louisiana Transportation Research Center
m	meter(s)
SAS	Statistical Analysis Software ver. 9.4
UTFO	Ultra-Thin Film Oven

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Appendix

Table 7. Raw data

Sample	4mmWRI	UTFO	iCCL	BBR	Sample	4mmWRI	UTFO	iCCL	BBR
1	-25.12	-25.7	-24.6	-23.50	20	-28.28	-31.4	-28.8	-26.00
	-26.71	-25.1	-24.9	-23.29		-27.41	-31.2	-29.5	-26.00
	-24.21	-25.8	-25.6	-23.32		-25.77	-30.8	-29.3	-26.24
	.	.	.	-23.13		.	.	.	-26.24
2	-22.32	-24.8	-21.7	-22.51	21	-25.81	-27	-25.9	-24.57
	-22.93	-25.3	-21.8	-22.27		-26.77	-26.9	-25.9	-24.51
	-22.19	-24.9	-22.7	-22.41		-25.61	-26.7	-25.6	-24.72
	.	.	.	-22.21		.	.	.	-24.65
3	-21.75	-23.9	-23.3	-22.00	22	-24.48	-25.1	-23.3	-23.87
	-23.66	-23.2	-23.2	-22.97		-24.64	-24.3	-23.6	-23.66
	-21.84	-24.7	-23.6	-22.00		-25.05	-24.6	-23.5	-23.70
	.	.	.	-22.91		.	.	.	-23.50
4	-30.16	-32.2	-32.9	-30.00	23	-23.17	-24.9	-22.7	-23.62
	-31.93	-31.9	-32.8	-29.85		-24.2	-23.9	-22.2	-22.48
	-32.87	-32.2	-33	-29.86		-23.29	-24.5	-22.9	-23.24
	.	.	.	-29.71		.	.	.	-22.35
5	-28.58	-31.7	-32.7	-28.89	24	-26.28	-25.3	-25.7	-23.70
	-29.38	-31.6	-33.1	-28.89		-26.47	-25.2	-25.2	-23.97
	-28.07	-31.7	-33.1	-28.79		-24.25	-25.9	-25.2	-23.40
	.	.	.	-28.79		.	.	.	-23.64
6	-26.45	-25.1	-22.9	-24.32	25	-25.25	-26.5	-23.5	-23.65
	-24.91	-25	-23.5	-24.18		-27.69	-26.4	-23.6	-23.42

Sample	4mmWRI	UTFO	iCCL	BBR	Sample	4mmWRI	UTFO	iCCL	BBR
	-25.9	-25.2	-23.5	-24.00		-25.09	-26	-23.8	-23.18
	.	.	.	-23.88		.	.	.	-23.00
7	-25.43	-26.1	-22.6	-22.57	26	-23.25	-26.5	-24.6	-24.40
	-23.65	-25.3	-22.9	-22.57		-23.86	-26.2	-24.8	-23.40
	-24.77	-25.5	-23.6	-22.58		-22.43	-26.2	-24.6	-24.44
	.	.	.	-22.58		.	.	.	-23.43
8	-33.52	-33	-35	-32.96	27	-25.51	-25.8	-23.9	-23.97
	-34.51	-33.3	-35.1	-33.04		-25.43	-26.2	-24.4	-24.34
	-31.83	-32.9	-35.1	-32.09		-24.15	-26.5	-24.2	-24.00
	.	.	.	-32.21		.	.	.	-24.38
9	-25.08	-26.2	-26.8	-23.78	28	-30.69	-27.6	-28.1	-26.93
	-23.82	-26.7	-27	-23.44		-32.08	-26.9	-28.4	-26.88
	-25.12	-25.8	-26.6	-23.63		-32.7	-27	-28.1	-26.70
	.	.	.	-23.31		.	.	.	-26.64
10	-32.16	-32.2	-30.9	-29.24	29	-22.81	-24.1	-24.5	-22.00
	-28.61	-31.8	-30.3	-29.16		-22.65	-23.5	-24.8	-22.00
	-30.52	-31.4	-30.3	-29.26		-23.38	-24.4	-24.6	-22.00
	.	.	.	-29.18		.	.	.	-22.00
11	-24.49	-26	-24.9	-22.81	30	-22.91	-23.2	-23.8	-22.52
	-25.29	-25.9	-25.5	-23.00		-23.22	-23.8	-23.9	-23.50
	-22.65	-25.3	-24.1	-22.81		-24.05	-23.9	-24	-22.49
	.	.	.	-23.00		.	.	.	-23.42
12	-23.49	-24.5	-24.3	-23.25	31	-25.74	-25.3	-26.4	-23.87
	-26.06	-25	-24.6	-23.04		-24.35	-25.7	-26.3	-23.96
	-21.91	-24.7	-24.7	-23.41		-24.44	-25	-26.2	-23.75

Sample	4mmWRI	UTFO	iCCL	BBR	Sample	4mmWRI	UTFO	iCCL	BBR
	.	.	.	-23.18		.	.	.	-23.84
13	-24.11	-25.8	-25.2	-23.44	32	-27.63	-27.5	-26.3	-27.92
	-22.31	-25.7	-25.5	-23.44		-29.26	-27.9	-26.2	-27.92
	-22.93	-25.9	-25.8	-23.44		-27.96	-27.4	-26.9	-26.07
	.	.	.	-23.44		.	.	.	-26.02
14	-27.29	-26.1	-26.2	-24.88	33	-23.17	-27	-25.3	-22.35
	-26.34	-26.7	-25.5	-24.88		-22.8	-26.6	-26.6	-22.00
	-26.07	-26.8	-25.8	-24.82		-25.74	-26.5	-26	-22.35
	.	.	.	-24.82		.	.	.	-22.00
15	-26.59	-22.5	-24.2	-22.87	34	-26.55	-26.9	-25.9	-26.73
	-26.86	-22.8	-24.9	-22.36		-26.74	-26.4	-26	-24.77
	-26.43	-22.6	-24.1	-22.89		-28.28	-26.8	-25.2	-26.27
	.	.	.	-22.37					-24.18
16	-25.61	-23.2	-22.6	-21.36	35	-24.43	-26.5	-23.9	-23.62
	-26.61	-22.9	-22.7	-21.90		-23.38	-26.5	-25.1	-23.19
	-26.74	-24	-22.6	-21.25		-24.83	-25.4	-24	-24.44
	.	.	.	-21.89		.	.	.	-23.88
17	-26.67	-26.3	-25.2	-25.74	36	-29.28	-27.6	-26.5	-25.94
	-26.13	-26.6	-25.5	-25.65		-29.6	-27.3	-26.8	-25.87
	-26.55	-26.3	-26.1	-25.60		-29.84	-26.6	-25.9	-26.13
	.	.	.	-25.51		.	.	.	-26.07
18	-24.43	-24.4	-23.2	-23.26	37	-24.98	-27.9	-26.3	-24.03
	-23.91	-25	-24.8	-23.09		-24.1	-26.1	-25.4	-23.82
	-25.4	-24.8	-23.9	-23.16		-22.59	-26.7	-25.5	-23.94
	.	.	.	-23.00		.	.	.	-23.73

Sample	4mmWRI	UTFO	iCCL	BBR	Sample	4mmWRI	UTFO	iCCL	BBR
19	-28.78	-25.3	-26.7	-25.00	38	-23.99	-27.3	-28.1	-25.95
	-28.36	-26	-25.6	-24.91		-24.24	-26.8	-27.6	-25.63
	-28.87	-25.9	-25.5	-25.18		-24.76	-27.3	-27.7	-25.55
	.	.	.	-25.09		.	.	.	-25.21