Exploration of alternatives of elastic recovery and conventional fatigue tests of modified binders

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Abstract

For characterizing polymer modified binders, different state Departments of Transportation (DOTs) use a variety of laborious and empirical Performance Grade (PG) “Plus” test methods such as elastic recovery (ER) and tenacity. However, the effects of elastomeric and/or plastomeric polymers are not been accurately identified through these conventional tests. The main research goal of this study is to recommend alternative test method(s), which can be pursued by using a, commonly available, dynamic shear rheometer (DSR). To this end, efficacies of test methods such as multiple stress creep recovery (MSCR), elastic recovery using a DSR (ER-DSR), linear amplitude sweep (LAS), and binder yield energy test (BYET) were explored in this study. Also, a viscoelastic continuum damage (VECD) model was developed to characterize the fatigue cracking of asphalt binders. Two types of polymer modified binders from ten sources approved by the Arkansas Department of Transportation (ARDOT) and Texas Department of Transportation (TXDOT) were evaluated in the laboratory. Test results and analyses suggest that without risking the suppliers or users, either the ER-DSR or MSCR test can be a good replacement of the ER test method. A new ER-DSR binder grading system has been proposed. Among the selected fatigue tests, the BYET results were found to be highly related to fatigue damage.

Keywords: PG Plus binder; Elastic Recovery ER; MSCR; ER-DSR; LAS; BYET

1. Introduction

Uses of polymer modified asphalt binders have been extensively increased in pavement engineering due to their high resistance against permanent deformation (rutting and shoving), fatigue cracking, thermal cracking, stripping, and temperature susceptibility [1–2]. Existing performance grade (PG) test methods have been developed only to characterize unmodified asphalt binders; they are not suitable to determine the mechanical properties of a polymer-modified binder beyond its linear viscoelastic range [3–5]. Different state and local highway agencies use different PG plus (PG+) test techniques such as elastic recovery (ER) and tenacity to capture the presence of polymers, but there is no uniform parameter to characterize polymer-modified asphalt binders. Besides, the specification parameters and acceptable limits vary largely among agencies as they have been adopted and practiced by engineering judgments instead of

the asphalt binders’ mechanical performance. The Arkansas Department of Transportation (ARDOT) uses a laborious and empirical ER method (American Association of State Highway Transportation Officials (AASHTO) T 301: Elastic Recovery Test of Bituminous Materials by Means of a Ductilometer) [6] to characterize polymer modified binders. There are currently no uniform guidelines (e.g., aging condition or test temperature) to conduct the ER test and acceptance criteria among transportation agencies around the world.

Many state agencies follow AASHTO M320 “Standard Specification for Performance-Graded Asphalt Binder” to characterize PG asphalt binders [7]. However, applicability of AASHTO M320 specification for polymer-modified asphalt binders has been questioned by both industry and state highway agencies. AASHTO M332 “Performance-Graded Asphalt Binder Using the Multiple-Stress Creep-Recovery (MSCR) Test” [8] has been suggested as a substitution of AASHTO M320 [9]. The MSCR test was developed improve understanding of the presence of polymers in asphalt binders. The MSCR test can provide information on both mechanistic performance and polymeric formulation of the asphalt binder. MSCR parameters such as the percent recovery (%R) and the non-recoverable creep compliance (J_{nr}) exhibit a better relationships with permanent deformation [10]. MSCR %R is a measure of how much the sample returns to

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its original state after being repeatedly strained and relaxed. J_{nr} is a measure of the amount of residual strain left in the specimen after repeated creep and recovery cycles, relative to the amount of stress applied. The test is performed by applying a repeated haversine load for one-second followed by a nine-second relaxation period under initial application of low stress of 0.1 kPa followed by increased stress to 3.2 kPa. The J_{nr} value at 3.2 kPa can be used to classify the modified asphalt binders and designate traffic conditions that are represented by standard (S), heavy (H), very heavy (V), and extreme (E) [9–12], as shown in Table 1.

Multiple researchers reported that the MSCR test has the ability to eliminate the conventional ER test through the %R parameter [9–12]. The conventional MSCR test is conducted at the high pavement temperature for the climatic zone, whereas the conventional ER test is typically conducted at 25°C. In addition to the MSCR test method, researchers around the world have introduced other test methods. For instance, Clopotel and Bahia [3] proposed a new technique to determine ER using the dynamic shear rheometer (ER-DSR). These researchers developed a relation between the ER-DSR and ER measured in the ductility bath (ER-DB). A constant shear strain is applied for two minutes and relaxed for thirty minutes. The ER at the end of the relaxation time is calculated by Eq.(1).

$$ER - DSR = \frac{\text{Recovered strain at the end of the relaxation time}}{\text{Strain at the end of loading time}} \times 100 \quad (1)$$

On the other hand, new test methods such as AASHTO TP 101 “Standard method of test for estimating damage tolerance of asphalt binders using the linear amplitude sweep” has been developed by some professionals [13]. The AASHTO TP 101 method is often called as the Linear Amplitude Sweep (LAS) test method. The LAS test method is used to predict the fatigue life of the asphalt binders [14–16]. The undamaged rheological properties and damage characteristics of the binder are being measured through LAS test. From the frequency sweep test, a parameter α is determined, which represents the undamaged property of the binder. Subsequently, an amplitude sweep test is run in a strain-controlled mode using oscillatory shear, and peak shear strain and shear stress are measured. The fatigue life is then calculated using Eq.(2) [17].

$$N_f = A (\gamma_{max})^B \quad (2)$$

where, N_f = Fatigue performance parameter, γ_{max} = The maximum expected binder strain for a given pavement structure, and A and B = Coefficients that depend on material characteristics.

Table 1
MSCR grading based on J_{nr} value.

MSCR grade description	Traffic volume	J_{nr} (kPa ⁻¹) criteria	MSCR grading
S: Standard	<3 million ESALs	$J_{nr} \leq 4.5$ and ≥ 2.0	PG 64S-22
H: Heavy	>3 million ESALs	$J_{nr} \leq 2.0$ and ≥ 1.0	PG 64H-22
V: Very Heavy	>10 million ESALs	$J_{nr} \leq 1.0$ and ≥ 0.5	PG 64V-22
E: Extreme	>30 million ESALs	$J_{nr} \leq 0.5$	PG 64E-22

Johnson et al. [14] used a Viscoelastic Continuum Damage (VECD) model for analyzing the LAS test results. The main benefit of the VECD is that the test results of asphalt binder at specific conditions can be used for predicting the binder's fatigue performance at other conditions.

In the meantime, AASHTO TP 123 “Measuring asphalt binder yield energy and elastic recovery using the dynamic shear rheometer” has also been developed [18]. This test was a combination of the binder yield energy test (BYET) and DSR-based elastic recovery (DSR-ER) tests [19]. Binder yield energy is the area under the curve until the sample yields, which represents the toughness of an asphalt binder and the shear strain at the maximum shear stress at peak stress. In this test method, a monotonic constant shear load is applied to the asphalt binder at an intermediate temperature. It is claimed that AASHTO TP 123 can promisingly predict low-temperature fatigue and thermal cracking [20].

2. Objectives

The main objectives of this study are to: (1) recommend an effective test method to evaluate modified asphalt binders as replacements of the ER test; (2) classify modified asphalt binders based on the proposed test method; and (3) analyze fatigue properties of PG Plus binders and recommend a suitable DSR-based test method.

3. Materials and methodology

In this study, ARDOT and TXDOT certified SBS-modified PG 70-22 and PG 76-22 binders were collected from ten sources (binder suppliers). Nomenclature was developed for the study to identify the samples, as shown in Table 2. It can be noted that non-modified PG 64-22 binders (e.g., S1B1 and S2B1) were also collected and tested in the laboratory, but corresponding test results are not presented or discussed in this manuscript.

Table 2
Nomenclature of binders.

Source	Performance Grade	Binder Identification
Source 1	PG 70-22	S1B3
Source 1	PG 76-22	S1B4
Source 2	PG 70-22	S2B3
Source 2	PG 76-22	S2B4
Source 3	PG 70-22	S3B3
Source 3	PG 76-22	S3B4
Source 4	PG 70-22	S4B3
Source 4	PG 76-22	S4B4
Source 5	PG 70-22	S5B3
Source 5	PG 76-22	S5B4
Source 6	PG 70-22	S6B3
Source 6	PG 76-22	S6B4
Source 7	PG 70-22	S7B3
Source 7	PG 76-22	S7B4
Source 8	PG 70-22	S8B3
Source 8	PG 76-22	S8B4
Source 9	PG 70-22	S9B3
Source 9	PG 76-22	S9B4
Source 10	PG 70-22	S10B3
Source 10	PG 76-22	S10B4

3.1. Superpave tests

Routine Superpave tests such as rotational viscosity (RV) (AASHTO T 316), dynamic shear rheometry (DSR) (AASHTO T 315), rotational thin-film oven (RTFO) aging (AASHTO T 240), and pressure-aging vessel (PAV) aging (AASHTO R 28) were included in the test plan. The typical DSR test measures the complex shear modulus (G^*) and phase angle (δ) of the asphalt binder. A modular compact rheometer (MCR 302) was used to conduct AASHTO T 315 along with other DSR-based tests, as summarized later on.

3.2. Multiple Stress Creep Recovery (MSCR)

The MSCR test was conducted according to AASHTO T 350 using MSCR 320, Rheoplus32 V3.62 software to capture and analyze test data. As per AASHTO T 350, RTFO-aged asphalt binder samples (25 mm in diameter and 1 mm in thickness) were tested for 10 cycles at different stress levels (i.e., 0.1 kPa, 3.2 kPa, and 10 kPa); each cycle consists of a constant creep stress for 1-second duration followed by a 9 seconds recovery of zero stress (rest period). The performance indicators of the MSCR test are %R and J_{nr} . All samples were tested in accordance with AASHTO T350 as a representative climate temperature of 64°C.

3.3. Elastic Recovery via Dynamic Shear Rheometer (ER-DSR)

The ER-DSR test was conducted according to AASHTO TP 123-16. Unaged and short term aged samples (8 mm in diameter and 2 mm in thickness) were tested for the percent ER. A constant strain rate of 0.023 s^{-1} was used to achieve 277.78% strain at 25°C. Then the zero-shear stress was maintained to recover the sample for 30 minutes.

Table 3

Viscosities and failing temperature from dsr test results of modified asphalt binders.

Binder Name	Viscosity (Pa.s) at Different Temperatures				Minimum Temperature Corresponding to ($G^*/\sin\delta$) ≥ 1 kPa (Unaged) or 2.2 kPa (RTFO) ($^{\circ}\text{C}$)	True PG Grade
	135 $^{\circ}\text{C}$	150 $^{\circ}\text{C}$	165 $^{\circ}\text{C}$	180 $^{\circ}\text{C}$		
S1B3	1.27	0.60	0.31	0.18	77.4	PG 77-XX
S1B4	1.93	0.87	0.45	0.26	82.6	PG 82-XX
S2B3	1.27	0.55	0.28	0.16	78.2	PG 78-XX
S2B4	1.77	0.76	0.35	0.19	83.1	PG 82-XX
S3B3	1.34	0.58	0.33	0.18	76.1	PG 76-XX
S3B4	1.56	0.65	0.32	0.18	82.2	PG 82-XX
S4B3	1.35	0.64	0.35	0.20	78.3	PG 78-XX
S4B4	2.96	1.26	0.68	0.38	83.5	PG 82-XX
S5B3	0.87	0.42	0.24	0.14	72.7	PG 72-XX
S5B4	1.35	0.66	0.35	0.21	77.6	PG 77-XX
S6B3	0.99	0.49	0.26	0.15	73.4	PG 73-XX
S6B4	1.52	0.75	0.42	0.25	79.6	PG 79-XX
S7B3	2.72	1.09	0.55	0.30	75.9	PG 75-XX
S7B4	3.05	1.32	0.68	0.39	84.1	PG 82-XX
S8B3	1.33	0.63	0.35	0.21	73.8	PG 73-XX
S8B4	2.18	0.90	0.50	0.24	80.8	PG 80-XX
S9B3	1.42	0.70	0.38	0.23	75.2	PG 75-XX
S9B4	1.60	0.80	0.46	0.28	77.8	PG 77-XX
S10B3	1.11	0.51	0.28	0.15	74.6	PG 74-XX
S10B4	2.68	1.06	0.53	0.30	83.1	PG 82-XX

3.4. Linear Amplitude Sweep (LAS)

The LAS test was conducted in accordance with AASHTO TP101, on PAV aged specimens 8 mm diameter by 2 mm thick. This test consists of two steps; first, a frequency sweep test was performed to define the undamaged material response followed by application of a linear oscillatory strain sweep with strain amplitudes ranging from 0.1% to 30%. The frequency sweep test was performed by maintaining binder's intermediate temperatures (temperature where $G^*\sin\delta = 5000$ kPa) to resist fatigue damage and a constant 0.1% oscillatory shear loading over a range of frequencies from 0.2-30 Hz. The amplitude sweep test was conducted at the same temperature and a constant frequency of 10 Hz. Strain amplitude was increased from 0.1% to 30%.

3.5. Binder Yield Energy Test (BYET)

The BYET test was conducted according to AASHTO TP 123 to predict binder fatigue performance. This test is performed in a DSR on an 8 mm thick sample using 8 mm parallel plate geometry. Shear load was applied to the sample at a rate of $2.30\% \text{ s}^{-1}$ until a 4140% strain is reached. Two parameters, yield energy and shear strain at maximum shear stress were measured.

4. Results and discussions

4.1. Superpave test results

In this study, DSR and RV tests were conducted to evaluate properties at high service temperatures and viscosity of the modified binders, respectively. Viscosity values satisfied Superpave acceptance criterion for pumping. The true PG (high) temperatures of the modified binders were determined from the

DSR tests of unaged and RTFO aged samples. A summary of the test results is shown in Table 3.

4.2. Correlation of MSCR percent recovery (%R) and non-recoverable creep compliance (J_{nr}) with ER value

The ER values of modified binders were obtained from respective suppliers. The MSCR %R values at 3.2 kPa were used for analysis. Fig. 1(a) shows the relationship between the MSCR %R parameter and the ER value. A higher MSCR %R was observed for a higher ER of asphalt binders. Fig. 1(a) also shows that the coefficient of determination (R^2) is fairly good between these two parameters. It can be concluded that 70% ER value correlates well with the 30% MSCR %R value for PG 70-22 binder whereas, 80% ER value correlates well with the 50% MSCR %R value for PG 76-22 binder. Another MSCR parameter, J_{nr} , has a good correlation ($R^2=0.80$) with the % ER value shown in Fig. 1(b). A lower J_{nr} value indicates a higher % ER of the modified asphalt binder. It can be seen that a 70% ER value correlates well with the 0.5 (kPa^{-1}) MSCR J_{nr} value for PG 70-22 binder, whereas, 80% ER value correlates well with the 0.1 (kPa^{-1}) MSCR J_{nr} value for PG 76-22 binder.

4.3. Correlation between ER-DSR and ER

Correlation between the ER-DSR and traditional ER is shown in Fig. 2. A better correlation was found between the ER-DSR and ER of RTFO-aged asphalt binders ($R^2=0.85$) compared to the correlation between the ER-DSR and ER values for unaged asphalt binders ($R^2=0.67$). Variation of the ER-DSR test results was possibly due to the mode of loading, strain rate, sample geometry, temperature control, and operator sensitivity. From Fig. 2(b), it can be said that a 70% ER value correlates well with the 40% ER-DSR

value for PG 70-22 binders, as seen from the left side of the linear trend line. On the other hand, an 80% ER value correlates well with the 50% ER-DSR value for PG 76-22 binders as the datapoints cluster on the right side of the line graph.

Thus, the ER-DSR is found to be the best effective and simplest test method to replace the ER using a ductility bath (AASHTO T 301). The MSCR was also found to be a viable and effective alternative to AASHTO T 301. Table 4 shows the recommended ER-DSR values of the testing parameter against the ER values using a ductility bath.

4.4. Quadrant plot

A quadrant plot helps to disclose whether the binders could be categorized as “User Risk,” “Supplier Risk,” “Both at Risk,” or “None at Risk.” Quadrant plots are drawn using the %R at 3.2 kPa and ER value for both PG 70-22 and PG 76-22 binders. The ARDOT recommends that the minimum elastic recovery values for PG 70-22 and PG 76-22 are 40% and 50%, respectively. According to the Asphalt Institute, the minimum %R value for PG 70-22 and PG 76-22 binders will be 25% and 35%, respectively. All PG 70-22 binders fall in the first quadrant except one sample, which falls in the fourth quadrant (supplier risk) shown in Fig. 3(a). However, it meets the ER criteria but fails to meet the MSCR %R criteria. Besides, all PG 76-22 binders fall in the first quadrant except for two samples, which fall in the fourth quadrant (Supplier Risk) shown in Fig. 3(b).

Another set of quadrant plots is drawn where %R is replaced by ER-DSR, as shown in Fig. 4. The minimum recommended ER-DSR values for PG 70-22 and PG 76-22 are 40% and 50%, respectively. From Fig. 4, it is seen that all binders fall in the first quadrant and satisfy the ER-DSR and ER criteria. Therefore, there is no user or supplier at risk.

Fig 1. (a) Correlation between %R at 3.2 kPa and ER (%) and (b) Correlation between J_{nr} at 3.2 kPa and ER (%).

Fig 2. (a) Correlation between ER-DSR (%) for unaged binder and ER (%) (b) Correlation between ER-DSR (%) for RTFO-aged binder and ER.

Table 4

Recommended value of testing parameter against the value of ER (AASHTO T 301).

Performance grade	AHTD's minimum % ER (AASHTO T 301) (Unaged)	Recommended minimum % ER-DSR value (Unaged)	Recommended minimum % ER-DSR value (RTFO-aged sample)	Recommended maximum J_{nr} value (kPa^{-1})	Minimum %R according to AI	Recommended minimum %R (RTFO-aged)
PG 70-22	40	40	40	0.5	25	30
PG 76-22	50	50	50	0.1	35	50

Fig. 3. (a) Quadrant plot for PG 70-22 and (b) Quadrant plot for PG 76-22.

Fig. 4. (a) Quadrant plot using ER-DSR for PG 70-22 and (b) Quadrant plot using ER-DSR for PG 76-22.

4.5. Proposed grading of the binder using ER-DSR

A grading system is proposed to classify modified binders based on ER-DSR test results. Binders are graded in four categories similar to MSCR, where S means Standard, H means Heavy, V means Very heavy, and E means Extreme. The recommended ER-DSR grading system is shown in Table 5.

4.6. Linear Amplitude Sweep (LAS) test

LAS test temperature was determined from the DSR test results of PAV-aged samples. The LAS test temperature corresponded to the $G^*\sin\delta$ value of 5000 kPa of the PAV-aged binder. Fatigue lives of eight of the 20 tested binders were calculated for strain levels of 2.5% and 5%. Two LAS parameters, “A” and “B” have been calculated and are shown in Fig. 5(a) and Fig. 5(b). The “A” parameter is higher for the S1B4 binder compared to the other binders, which mean that it has higher fatigue resistance. The absolute value of the LAS parameter “B” is also higher for the S1B4 binder.

The number of cycles (N_f) at 2.5% strain is shown in Fig. 5(c). Also, SBS and PPA modified S1B4 binder showed better fatigue resistance compared to the other binders. The VECD model was developed for the S1B4 binder as shown in Fig. 5(d). A well-established trend is the material integrity decreased with the

increasing of damage intensity is observed in the VECD model. In this model, “C” vs. damage intensity was plotted, where “C” was calculated using Eq. (3).

$$C(t) = \frac{G^*(t)}{G^*_{initial}} \quad (3)$$

4.7. Binder Yield Energy Test (BYET)

Yield energies of the tested binders are shown in Fig. 6. Higher yield energy values are the indicator of better fatigue resistance. Binder with a higher grade (PG 76-22) showed higher yield energy value compared to the lower grade (PG 70-22). Similar findings were reported by another group of researchers, and they reported a good correlation with the crack length after 100,000 wheel passes [19]. In the current study, monotonic constant shear loading was applied. The VECD concepts can be used to model the damage growth of the modified binder.

Table 5

ER-DSR grading based on ER-DSR (%) value.

ER-DSR Grade Description	ER-DSR (%) Criteria	ER-DSR Grading
S: Standard	$20\% \leq \text{ER-DSR} \leq 30\%$	ER-DSR 25:S
H: Heavy	$30\% < \text{ER-DSR} \leq 45\%$	ER-DSR 25:H
V: Very Heavy	$45\% < \text{ER-DSR} \leq 60\%$	ER-DSR 25:V
E: Extreme	$60\% > \text{ER-DSR}$	ER-DSR 25:E

Fig. 5. (a) LAS parameter “A”, (b) LAS parameter “B”, (c) number of cycles to failure at 2.5% strain, and (d) VECD model for S1B4 binder.

Fig. 6. BYET value for the RTFO-aged modified asphalt binders.

5. Conclusions

This study explored some recently developed PG Plus tests (MSCR %R and ER-DSR) as an alternative to the conventional ER test for conditions prevailing in Arkansas. The LAS and BYET tests were also evaluated to find the binder's fatigue resistance. Based on the test results and without penalizing suppliers and producers, specific MSCR and ER-DSR guidelines are proposed to ARDOT as follows:

1. The ER-DSR test is the best alternative to the ER test (AASHTO T 301). A very good correlation ($R^2 = 0.85$) was found between ER-DSR and ER values. The recommended

ER-DSR values of 40% and 50% for RTFO-aged PG 70-22 and PG 76-22 binders have been recommended respectively.

2. Also, a good correlation ($R^2 = 0.60$ for MSCR %R vs. ER and $R^2 = 0.80$ for J_{nr} vs. ER) between ER and MSCR test parameters were also obtained. The recommended MSCR %R values are 25% and 35% for PG 70-22 and PG 76-22 binders, and J_{nr} values are 0.50 kPa^{-1} and 0.10 kPa^{-1} for PG 70-22 and PG 76-22 binders, respectively. In the case an agency is not equipped with conducting ER-DSR, the MSCR test can be adopted.
3. The LAS model parameters, “A” and “B,” along with the number of cycles to failure (N_f) at 2.5% strains for the tested binders have been determined. The developed VECD curve can be used to determine the amount of damage accumulation against known material integrity.
4. The BYET test results suggest that the yield energy of the binder can adequately predict the fatigue resistance of asphalt binders.

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Conflicts of interest

Include appropriate disclosures.

Authors' contributions

M M Tariq Morshed contributed to the literature review, conducted all laboratory tests, and analyzed test results under the supervision of Dr. Zahid Hossain, who is the Principal Investigator of this project. Dr. Chen reviewed the project plan and provided technical support to the research team. Dr. Baumgardner provided test samples and technical support as an industry partner for this project. While the first author prepared the initial draft, all other authors reviewed the manuscript.

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