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Obtaining asphalt binder rheological properties from BBR strength test—the effect of loading rate

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Abstract Selecting asphalt binders that have good cracking resistance at low temperatures is the first step in designing asphalt mixtures for durable asphalt pavements in cold regions. To evaluate low-temperature cracking resistance of binders, rheological properties (creep stiffness and m-value), and fracture properties (failure stress and strain) are required. Recently, a new strength test was developed to measure the fracture properties of binders using a modified BBR (Bending Beam Rheometer), called BBR-Pro. In this paper, we investigate the idea of using the BBR strength test to also obtain rheological properties. We performed strength tests at different loading rates and verified the assumption of linear viscoelasticity (LVE) condition of binders at these loading rates. We used analytical and numerical methods to obtain creep compliance from strength test experimental data and compared the results to experimental creep compliance data. We have found that both methods predict creep compliance and creep stiffness values similar to the experimental results, whereas the numerical method is more accurate than the analytical method for obtaining the m-value. We also found that the BBR strength test performed using the original loading rate is too short to accurately predict rheological properties for 240 s. We show that by reducing the loading rate we achieve good estimation of creep compliance.

Keywords BBR strength test · Rheological properties · Linear viscoelasticity · Loading rate

1 Introduction

Low-temperature cracking is the main distress in asphalt pavements located in cold temperature regions. A major contribution to improving the characterization of low-temperature properties of binders was the development of the Performance Grade (PG) system during the Strategic Highway Research Program (SHRP) in the early 1990s (Anderson and Kennedy

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1993). In the PG system the low-temperature properties of asphalt binder are evaluated by two tests, the Bending Beam Rheometer (BBR) (AASHTO T313-12) and the Direct Tension Tester (DTT) (AASHTO T314-12). The BBR is used to obtain rheological properties from a creep test performed on a beam using the three-point bending configuration. The creep stiffness (the inverse of creep compliance) and m-value (slope of creep stiffness with respect to time on a double logarithmic scale) were selected as performance criteria. The DTT is used to obtain the fracture properties of the binders using a uniaxial tension test performed on a dog-bone-shaped sample at a constant strain rate of 3%/min. The strain rate was chosen based on practical considerations (Dongré 1994).

Due to the high cost of DTT and the complex sample preparation process, many agencies do not use DTT when determining the PG of the binder. However, based on previous studies, binders with similar creep properties do not have similar fracture properties (Marasteanu et al. 2017).

An alternative strength test, using the BBR configuration, was recently developed with the aim of providing a simpler and more cost-effective way of obtaining both fracture and rheological properties (Marasteanu et al. 2012). This new test is based on a modified BBR device, BBR Pro, which is capable of loading the test specimens at different loading rates until failure occurs. By taking into account the size effect and the cooling medium effect it was demonstrated that the results of DTT and BBR are consistent (Marasteanu et al. 2012; Falchetto et al. 2012).

One advantage of the BBR strength test is that the constant stress rate can be controlled very accurately, unlike the DTT, in which the constant strain rate assumption is not valid, especially at the beginning of the test (Marasteanu and Anderson 2000). That means that linear viscoelastic (LVE)-based models can be conveniently applied to BBR strength test experimental data to obtain rheological properties.

Recent studies have shown that BBR creep compliance can be successfully used to predict the entire stress-strain curve in BBR strength test until the point of failure by the LVE theory (Marasteanu et al. 2017; Matias De Oliveira et al. 2019). This indicates that the LVE theory is applicable to both BBR creep and BBR strength tests, which implies that we should also be able to obtain rheological properties, such as creep stiffness and the m-value, from the BBR strength test. That means that both rheological and strength properties of asphalt binders can be evaluated by performing a single BBR strength test.

In addition, the stress history of BBR strength test is easier to control, whereas the instantaneous loading at the beginning of BBR creep test may cause oscillations of the stress that can affect the accurate calculation of creep compliance, especially in the beginning phase.

In this paper, we investigate the idea of using the BBR strength test to obtain rheological properties. We performed BBR creep and BBR strength tests on the same asphalt binders. We developed two methods (analytical and numerical), based on LVE, to perform the interconversion between the strength data and creep data. We checked the LVE assumption for the BBR strength data obtained at different loading rates. We compared the rheological properties obtained from interconversion of the BBR strength test data to the experimentally obtained rheological properties. Based on the results, we propose a procedure to obtain both the rheological and strength properties of asphalt binder from a single BBR strength test.

2 Test methods and materials

In the previous work, in which creep experimental data were used to predict strength test stress-strain curves, a creep test (AASHTO T313-12) was performed first, followed by a

Table 1 Asphalt binders tested

Cells	Performance Grade (PG)	Loading rate
Cell 20	PG 52S-34	Fast (40 N in 60 s) Medium (40 N in 240 s) Slow (40 N in 480 s)
Cell 21	PG 58H-34	Fast (40 N in 60 s) Medium (40 N in 240 s) Slow (40 N in 480 s)
Cell 22	PG 58H-34	Fast (40 N in 60 s) Medium (40 N in 240 s) Slow (40 N in 480 s)
Cell 23	PG 64E-34 (highly modified)	Fast (40 N in 60 s) Medium (40 N in 240 s) Slow (40 N in 480 s)

strength test. The loading rate of the strength test was chosen to limit the duration of the test to no more than one minute (Marasteanu et al. 2017). This was done for practical reasons, similar to the determination of the strain rate for DTT (Dongré 1994). Since test results showed that the failure stress does not exceed 12 MPa, using beam theory, it was calculated that a loading rate of 40 N/60 s would ensure failure within one minute. This loading rate is referred to in this paper as "fast" loading rate.

Since the fast loading rate limits the duration of the BBR strength test to one minute or less, which is considerably less than the 240 s of the BBR creep test, two other slower loading rates called "medium" (40 N/240 s) and "slow" (60 N/480 s) are also investigated.

Similar to the previous work (Marasteanu et al. 2017; Matias De Oliveira et al. 2019), both BBR creep and strength tests were performed on the same specimen. First, a creep test was performed for 240 s, followed by 240 s of recovery. Then a strength test at a constant loading rate was performed, and failure of the asphalt binder beam occurred.

The procedure described above was used to test four asphalt binders used in MnROAD Cells 20, 21, 22, and 23, which were constructed in the summer of 2016. Table 1 details the binders used. The four binders have the same PG lower limit of −34. The binder used in Cell 23 was highly modified. The binders in Cell 21 and 22 were the same; however, the binder in Cell 22 contained an antistrip agent. For each binder, three replicates were tested. The BBR strength test was performed using three different loading rates, as described in Table 1.

3 LVE theory of three-point bending beam

In Euler–Bernoulli beam theory the middle span deflection of a three-point bending beam can be expressed as

$$\delta(t) = \frac{P(t)L^3}{48EI}, \tag{1}$$

where δ is the deflection at the middle span, P is the magnitude of the concentrated force, E is the Young modulus, I is the second moment of the section, and L is the length of the span.

According to the elastic–viscoelastic correspondence principle, the elastic solution can be transferred to the viscoelastic solution in the Laplace domain by replacing E with $s\overline{Y}(s)$ or $1/s\overline{J}(s)$, where $\overline{Y}(s)$ and $\overline{J}(s)$ are the Laplace transformations of relaxation modulus and creep compliance, respectively.

Thus, by the correspondence of $E \to 1/s\overline{J}(s)$, the viscoelastic solution in the Laplace domain can be derived as

$$\overline{\delta}(s) = \frac{\overline{P}(s)L^3}{48I} s\overline{J}(s). \tag{2}$$

The viscoelastic solution in the time domain can be derived by conducting an inverse Laplace transformation to Eq. (2). The result can be expressed by the equation

$$\delta(t) = \frac{L^3}{48I} J(t) * \dot{P}(t), \tag{3}$$

where the operator * means the convolution: $f(t) * g(t) = \int_0^t f(\tau) g(t-\tau) d\tau$.

3.1 LVE solution of BBR creep test

In BBR creep test the instantaneous applied constant loading can be express as

$$P(t) = P_0 H(t), \tag{4}$$

where $H(t)$ is the Heaviside step function, whose value is zero for negative arguments and one for positive arguments, and is discontinuous at point zero.

Substituting Eq. (4) into Eq. (3) and applying the property of the convolution of the Heaviside step function $f(t) * \dot{H}(t) = f(t)$, the viscoelastic solution can be obtained:

$$\delta_c(t) = \frac{P_0 L^3}{48I} J(t), \tag{5}$$

where δ_c represents the deflection of middle span in the BBR creep test.

By rearranging Eq. (5) the creep compliance can be expressed as a function of creep test data:

$$J(t) = \frac{48I}{P_0 L^3} \delta_c(t). \tag{6}$$

3.2 LVE solution of BBR strength test

In the BBR strength test the load is a proportional function of time, which can be expressed by

$$P(t) = \alpha t, \tag{7}$$

where α (N/s) is the loading rate.

Substituting Eq. (7) into Eq. (3) and applying the property of convolution $f(t) * 1 = \int_0^t f(\tau) d\tau$, the viscoelastic solution of BBR strength test can be obtained as

$$\delta_s(t) = \frac{\alpha L^3}{48I} \int_0^t J(\tau) d\tau, \tag{8}$$

where δ_s represents the deflection of middle span in the BBR strength test.

Therefore, taking the derivative of Eq. (8) and with some rearrangements, the creep compliance can be obtained from strength test data by using the following differential form:

$$J(t) = \frac{48I}{\alpha L^3} \frac{d\delta_s(t)}{dt}. \tag{9}$$

4 Checking LVE conditions for BBR strength test

By using Eqs. (5)–(9) creep compliance in BBR creep test can be converted to a stress-strain relation in the BBR strength test, and vice versa. However, this requires LVE to be applicable to both BBR creep and BBR strength test. Since BBR creep test has been shown to be in the linear viscoelastic regime (Marasteanu and Anderson 2000), it is only necessary to show that BBR strength test is performed within the linear viscoelastic regime.

LVE conditions are checked by converting creep experimental data to strength data and comparing it to strength experimental data obtained at different loading rates.

4.1 Interconversion of BBR creep and strength data

We use both analytical and numerical methods to perform interconversions.

4.1.1 Analytical method

In the analytical method, we use the Burgers model to perform the interconversion between BBR creep and strength test. This model has been successfully used by many authors to characterize the rheological behavior of asphalt binders.

First, the Burgers model, as expressed in the following equation, is used to describe the creep behavior:

$$J(t) = \frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2}\left(1 - e^{-\frac{tE_2}{\eta_2}}\right). \tag{10}$$

Substituting Eq. (10) into Eq. (5), we obtain:

$$\delta_c(t) = \frac{P_0 L^3}{48I}\left(\frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2}\left(1 - e^{-\frac{tE_2}{\eta_2}}\right)\right). \tag{11}$$

Similarly, substituting Eq. (10) into Eq. (8) and integrating, we can obtain the solution

$$\delta_s(t) = \frac{\alpha L^3}{48I}\left(\frac{t}{E_1} + \frac{t^2}{2\eta_1} + \frac{1}{E_2}\left(t - \frac{\eta_2}{E_2}(1 - e^{-\frac{tE_2}{\eta_2}})\right)\right). \tag{12}$$

Therefore, by Eqs. (11) and (12), the BBR creep test and strength test results are connected through Burgers model parameters E_1, η_1, E_2, and η_2.

4.1.2 Numerical method

The second method is a numerical method, which does not need any rheological model. By comparing Eqs. (5) and (8) we obtain the following relationship between creep and strength:

$$\delta_s(t) = \frac{P_0}{\alpha}\int_0^t \frac{\delta_c(\tau)}{P_0} d\tau, \tag{13a}$$

and vice versa,

$$\delta_c(t) = \frac{P_0}{\alpha}\frac{d\delta_s(t)}{dt}. \tag{13b}$$

The numerical solutions are obtained by performing numerical differentiation and integration directly and do not require a rheological model.

Although numerical methods do not need a rheological model, using unstable numerical methods with noisy experimental data can propagate the noise and lead to unacceptable results. Thus stable numerical integration and differentiation methods must be adopted.

Numerical integration is typically stable. Since the experimental data are dense enough, a simple numerical integration method, such as the one-degree Newton–Cotes formula, also referred to as the trapezoidal method, can be used. The formula of the trapezoidal method is shown in the equation

$$\int_a^b f(x)\,dx = \frac{1}{2}\sum_{n=1}^{N}(x_{n+1}-x_n)\left[f(x_n)+f(x_{n+1})\right], \tag{14}$$

where $a = x_1 < x_2 < \cdots < x_N < x_{N+1} = b$.

Compared to numerical integration, numerical differentiation is less stable and very sensitive to input noise. First, a simple numerical differentiation method, the central difference method, was used, and the results had unacceptable noise levels. Therefore a more complex numerical method, capable of smoothing the noise in the original data, was used, which is called the smooth noise-robust differentiation method (Holoborodko 2008). The expression is shown in the equation

$$f'\left(x^*\right) = \frac{1}{h}\sum_{k=1}^{M} c_k \cdot \left[f\left(x^*+kh\right) - f\left(x^*-kh\right)\right], \tag{15}$$

where

$$c_k = \frac{1}{2^{2m+1}}\left[\binom{2m}{m-k+1} - \binom{2m}{m-k-1}\right], \qquad m = \frac{N-3}{2}, \qquad M = \frac{N-1}{2}.$$

4.2 Comparison of converted and experimental strength test data

In the analytical method, the Burgers model (Eq. (11)) is fitted to creep test experimental data by using nonlinear regression. The regressed Burgers model parameters are listed in Table 2. Then we use Burgers model parameters and Eq. (12) to predict the stress-strain relation in the BBR strength test. Note that under ideal testing conditions, the set of model parameters should be the same for "fast", "medium", and "slow" sets of testing, since the creep test is performed identically in all three cases. However, due to small variations in conditioning time and in sample preparation, the values are slightly different. This is observed in particular for the "fast" set of testing, in which a conditioning time of 1.5 h, instead of 1 h, was used, which resulted in an increase in creep stiffness due to physical hardening effects (Basu et al. 2003). Comprehensive evaluations of physical hardening effects have been performed by Struik (1978) for amorphous polymers and Bahia (1991) for asphalt binders. Also, due to less repeatable specimen preparation, observed for highly polymer modified binders, higher differences are observed for Cell 23.

In the numerical method, the trapezoidal method (Eq. (14)) is used to compute the integration of Eq. (13a).

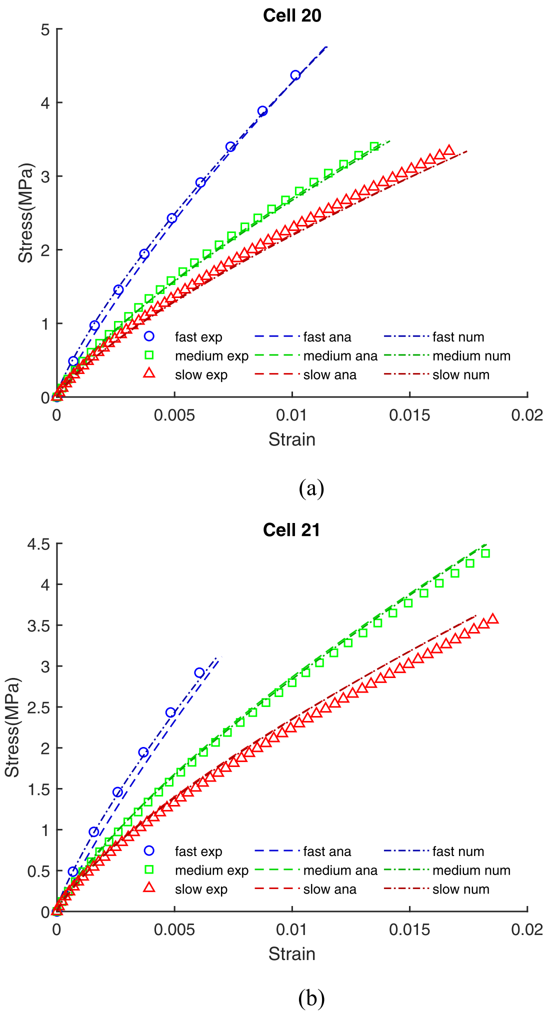


Fig. 1 Comparison of predicted and experimental BBR strength data (exp, ana, and num represent experimental data, analytical method, and numerical method, respectively)

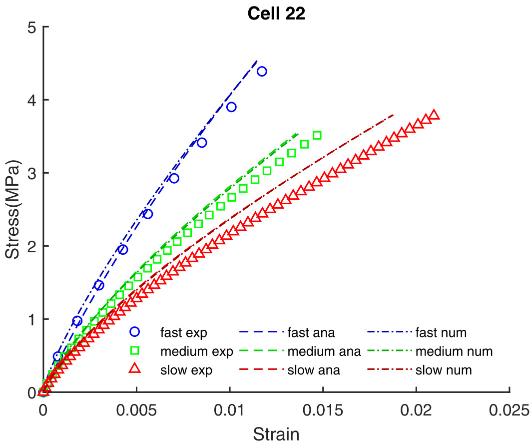
Plots of the converted and experimental strength data are shown in Fig. 1 for both analytical and numerical methods. As shown, both analytical and numerical methods predict very well BBR strength experimental data for all binders and all loading rates. Therefore the LVE assumption of BBR strength test is verified.

5 Rheological properties from BBR strength test

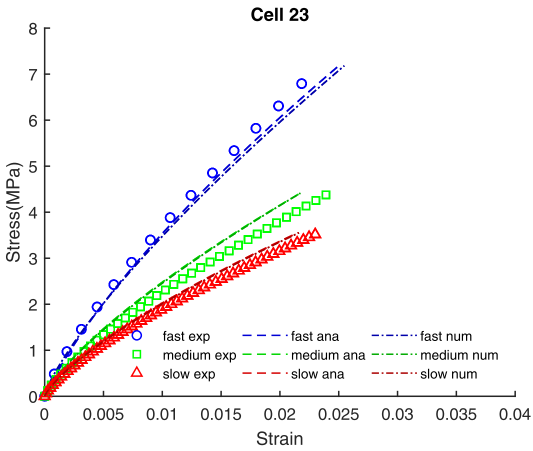
Knowing that BBR strength test is performed under linear viscoelastic conditions, the inverse problem of obtaining creep compliance from BBR strength experimental data is investigated next.

In the analytical method, the Burgers model parameters obtained from fitting Eq. (12) to the strength experimental data are input into Eq. (10) to obtain the creep compliance. Burgers model parameters are listed in Table 3. For the same reasons detailed for Table 2,

Fig. 1 (*Continued*)



(c)



(d)

discrepancies in the model parameters values are observed between the "fast", "medium", and "slow" sets of testing, respectively.

The predicted creep compliance curves are shown in Fig. 2. As shown, for all binders and loading rates, the creep compliance predicted by the analytical method greatly deviated from the experimental data, although in the beginning of the test the match was reasonable. To investigate this issue, the Burgers model parameters listed in Table 2 and the parameters listed in Table 3 were compared, and the relative differences were computed and listed in Table 4.

As shown in Table 4, the relative difference is significant (as high as 3666.7% for the η_1 of cell 23 at medium loading rate). Given that both sets of the parameters match or predict well the strength test data, we can conclude that the Burgers model parameters, especially η_1, are not sensitive to the strength test data. This means that significant changes in η_1 will not affect the stress-strain curve in the strength test; however, the same change will cause great variations in the value of creep compliance, especially in the long term. In addition, the BBR strength test (that lasts for 30 s, 60 s, and 150 s for fast, medium, and slow loading

Table 2 Burgers model parameters regressed from BBR creep test

Cell	Loading rate of the following strength test	Burgers model parameters			
		E_1 (MPa)	η_1 (MPa s)	E_2 (MPa)	η_2 (MPa s)
Cell20	fast	582	76792	442	19492
	medium	463	65022	368	17400
	slow	429	67731	344	18076
Cell21	fast	550	80030	494	21253
	medium	496	76165	378	18957
	slow	486	74117	365	18254
Cell22	fast	540	71194	415	19337
	medium	484	72653	374	18739
	slow	483	75506	372	18814
Cell23	fast	531	35415	523	9787
	medium	514	32279	504	9464
	slow	480	40658	372	10470

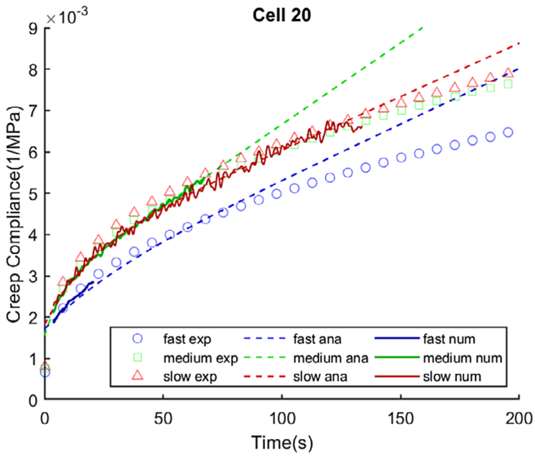
Table 3 Burgers model parameters regressed from BBR strength test

Cell	Loading rate	Burgers model parameters			
		E_1 (MPa)	η_1 (MPa s)	E_2 (MPa)	η_2 (MPa s)
Cell20	fast	616	93440	381	16801
	medium	522	68265	340	13979
	slow	462	65627	355	19354
Cell21	fast	710	51630	360	12338
	medium	499	49338	469	19294
	slow	508	68520	343	13181
Cell22	fast	588	43227	337	12940
	medium	489	40473	438	16807
	slow	443	2457352	145	14810
Cell23	fast	563	39357	549	10090
	medium	441	1215871	163	8467
	slow	395	810041	135	10815

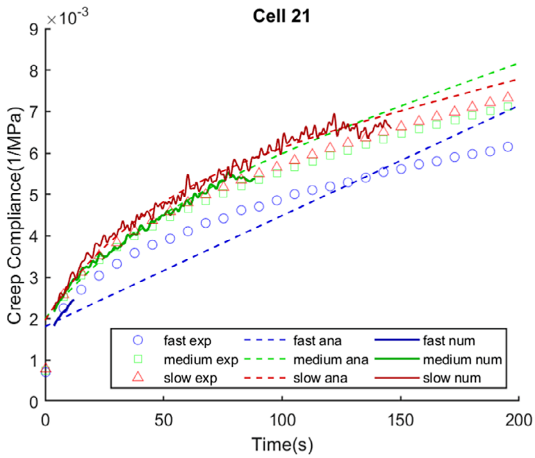
rate, respectively) is shorter than BBR creep test (duration of 240 s). For times longer than the duration of the BBR strength test, the analytical method cannot provide an accurate description of the viscoealstic behavior.

In the numerical method, to get relative smooth differential results, the filter length N in Eq. (15) must be chosen large enough. In this paper, N is chosen as 31, which means that the differentiation of a certain point is evaluated by the value of 31 points around the point calculated. As seen in Fig. 2, the noise of numerical method is controlled within a reasonable range. If N is chosen too small, then the fluctuations will become unacceptable. Note that the

Fig. 2 Creep compliance obtained from BBR strength test data (exp, ana, and num represent experimental data, analytical method, and numerical method, respectively)



(a)



(b)

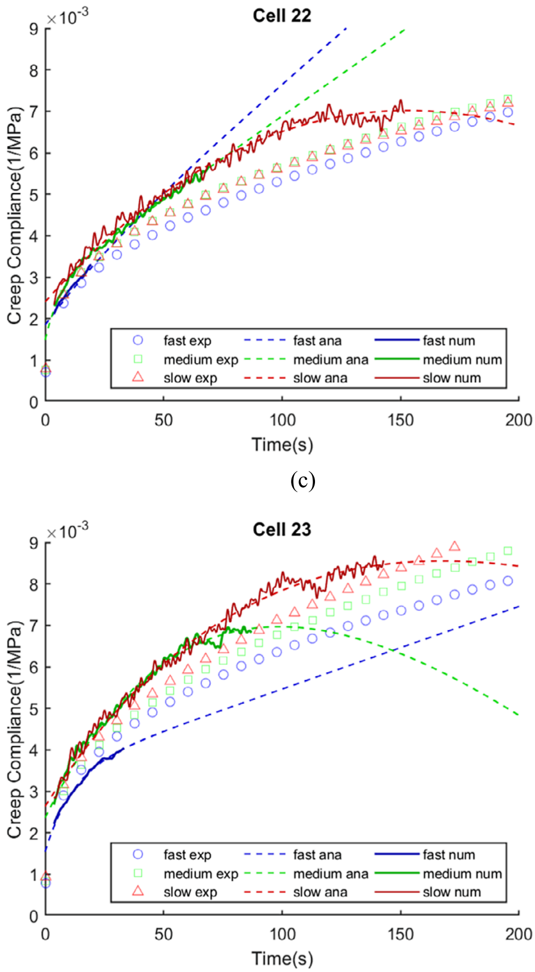
fluctuations do not appear in numerical integration results of Fig. 1, as numerical integration is a more stable operation than differentiation.

As shown in Fig. 2, the prediction of creep compliance using the numerical method covers the exact duration of the experimental strength test used due to the bounds of the integration in Eqs. (13a), (13b). The test duration is about 30 s, 60 s, and 150 s for fast, medium, and slow loading rates, respectively. It is obvious that the duration of the fast loading rate strength test is too short. A lower loading rate is required to accurately estimate creep stiffness and m-value at 60 s, as use in the current performance grade (PG) specification.

It is observed that numerical method estimations match well the creep experimental data over the duration of the strength test. Therefore, using a slower loading rate in the strength test can provide enough information to correctly estimate the current specification parameters.

Comparing the numerical and analytical method results shown in Fig. 2, we can conclude that within the duration of the strength test, the predictions of creep compliance from both

Fig. 2 (*Continued*)



(c)

(d)

analytical and numerical methods are in exact agreement with each other and match well the experimental data. For times longer than the duration of the strength test, analytical method predictions begin to deviate significantly from the experimental results.

The predicted and experimental creep stiffnesses and m-values at 60 s, which are used in the current specifications, are shown in Tables 5 and 6. For the fast loading rate tests, the results are not available for the numerical method since the duration was shorter than 60 s. The relative differences between the different methods and the experimental data, also shown in Tables 5 and 6, are expressed as a percent of their means.

According to AASHTO T313-12, the maximum acceptable differences between different samples of the same material are 17.8% and 6.8% for creep stiffness and m-value, respectively. Excluding the predictions from the "fast" strength tests, all other creep stiffness predictions satisfy this requirement. For m-value, numerical method predictions match the experimental data better than the analytical method predictions. The numerical method results, except for the medium loading rate of Cell 20, satisfy the required 6.8% difference,

Table 4 Relative difference of Burgers model parameters obtained from creep and strength test data

Cell	Loading rate	Relative difference between creep and strength test			
		E_1	η_1	E_2	η_2
Cell20	fast	5.8%	21.7%	−13.8%	−13.8%
	medium	12.7%	4.9%	−7.6%	−19.6%
	slow	7.7%	−3.1%	3.3%	7.0%
Cell21	fast	28.9%	−35.5%	−27.0%	−41.9%
	medium	0.6%	−35.2%	24.0%	1.7%
	slow	4.5%	−7.5%	−6.1%	−27.7%
Cell22	fast	8.8%	−39.3%	−18.7%	−33.0%
	medium	1.0%	−44.3%	17.3%	−10.3%
	slow	−8.1%	3154.5%	−61.1%	−21.2%
Cell23	fast	6.0%	11.1%	5.0%	3.0%
	medium	−14.2%	3666.7%	−67.5%	−10.5%
	slow	−17.6%	1892.3%	−63.5%	3.3%

Table 5 Comparison of creep stiffnesses obtained from creep test and predicted using analytical and numerical methods

Cell	Loading rate	Creep stiffness at 60 s (MPa)				
		Creep test	Analytical method	Difference between creep test & analytical method (%)	Numerical method	Difference between creep test & numerical method (%)
Cell20	fast	239	237	−0.65	–	–
	medium	197	198	0.39	194	−1.73
	slow	190	202	6.03	200	5.31
Cell21	fast	244	205	−15.64	–	–
	medium	215	206	−4.20	205	−4.46
	slow	208	194	−6.82	186	−10.55
Cell22	fast	226	184	−18.63	–	–
	medium	210	188	−10.59	187	−10.98
	slow	210	187	−10.86	179	−14.66
Cell23	fast	185	198	6.87	–	–
	medium	176	153	−12.62	149	−15.24
	slow	169	154	−9.19	150	−11.58

while for the analytical method, only three out of the eight samples satisfy that requirement. Therefore the numerical method is better than the analytical method in predicting m-value.

Table 6 Comparison of m-values obtained from creep test and predicted from analytical and numerical methods

Cell	Loading rate	m-value at 60 s (MPa s^{-1})				
		Creep test	Analytical method	Difference between creep test & analytical method (%)	Numerical method	Difference between creep test & numerical method (%)
Cell20	fast	0.345	0.344	−0.26	–	–
	medium	0.333	0.354	6.32	0.369	10.26
	slow	0.327	0.365	11.50	0.350	6.79
Cell21	fast	0.321	0.415	29.47	–	–
	medium	0.336	0.393	16.69	0.346	2.90
	slow	0.337	0.343	1.76	0.320	−5.13
Cell22	fast	0.352	0.429	21.61	–	–
	medium	0.337	0.416	23.54	0.360	6.69
	slow	0.331	0.356	7.52	0.311	−6.35
Cell23	fast	0.326	0.396	21.53	–	–
	medium	0.347	0.278	−19.82	0.328	−5.67
	slow	0.357	0.338	−5.19	0.335	−6.38

6 Conclusions

In this paper, we verified the LVE assumption of the BBR strength test at different loading rates. Then we used the BBR strength test results to obtain the creep compliance, the creep stiffness, and the m-value using both analytical and numerical methods. We have found that:

(1) Creep compliance can be calculated from BBR strength test data. The predicted creep compliance is only accurate for a loading time not exceeding the duration of the strength test. For times longer than the duration of the strength test, analytical method predictions begin to deviate significantly from the experimental results, whereas numerical method predictions are limited to the duration of the strength test.
(2) The "fast" loading rate strength test is too short and cannot be used to accurately estimate specification rheological properties obtained at 60 s loading time.
(3) Using the "medium" or "slow" loading rate, the creep stiffness and m-value can be obtained accurately from BBR strength test data. For creep stiffness, there is no significant difference between the analytical and numerical methods. For m-value, the numerical method is more accurate than the analytical method.

Based on these results, we can conclude that the BBR strength test can be used to obtain the rheological properties of asphalt binders when a slower loading rate is used. Using this procedure, we can obtain both rheological and strength properties from a single BBR strength test, which significantly simplifies the evaluation process of low temperature cracking resistance.

The loading pattern in the BBR strength test is much easier to control, compared to the instantaneous loading in the BBR creep test. This avoids the dynamic effect caused by the instantaneous loading at the beginning of BBR creep test, which increases the accuracy of the creep compliance results, especially at shorter loading times.

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