Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 8(5):337-345

Evaluation of Multiple Stress Creep and Recovery (MSCR) Data for Arizona

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Abstract: In the recently released AASHTO M332 asphalt binder specification, the Multiple Stress Creep and Recovery (MSCR) test replaces the current modulus and phase angle based method used for high temperature characterization. In anticipation of possible future adoption of this standard, the Arizona Department of Transportation (ADOT) has cataloged Multiple Stress Creep and Recovery (MSCR) test results on more than 375 different asphalt binder samples dating back to 2008. In this paper, this database is reviewed to evaluate potential implications of the adoption of a revised grading procedure based on the outcomes from the MSCR test. The database is graded in both the current and the M332 system to compare temporal changes in asphalt binder under both systems. The standard is then evaluated for its ability to detect polymer modified asphalt binder supplied in Arizona, and for the interaction between grade and temperature. It is found that under the M332 system the number of required grades for the state of Arizona would increase from the current number of eight to a total of fourteen. Future work includes the reduction of the total number of grades through engineering judgment and knowledge of asphalt binder selection based on local Arizona conditions. Under this review, Arizona asphalt binder suppliers may not necessarily have to add additional storage capacity to their facilities to accommodate a transition to the M332 standard.

DOI: 10.6135/ijprt.org.tw/2015.8(4).337

***Key words**: Asphalt binder; Implementation; MSCR; Rutting; Rheology.*

Introduction

Since the original Superpave asphalt binder specification was released, limitations in the high temperature parameter, $|G^*|/\sin\delta$, have been noted [1-5]. In this parameter, $|G^*|$ represents the dynamic shear modulus and δ is the linear viscoelastic phase angle determined via repeated oscillatory loading at 10 rad/s. Testing is performed at multiple temperatures for specification purposes. These limitations have been particularly obvious with respect to polymer modified asphalts and their ability to properly show their benefits. To address this limitation and in an attempt to consolidate disparate, so-called PG plus tests, researchers developed the Multiple Stress Creep Recovery (MSCR) test method [1-2, 6]. The test method essentially stems from the theory that experiments related to performance, instead of tests that relate to the presence of modifiers, are more valuable at grading asphalt binder. It is further postulated that in order to relate to asphalt mixture rutting performance one must consider the nonlinear viscoelastic characteristics of the asphalt binder. Other parameters such as ease of testing, compatibility with existing equipment, and lack of bias to modification type were also considered in developing the test.

Separate from the test and parameter, a second issue that arises in the original Superpave specification is the issue of climate and traffic considerations in the grade. The current Superpave specification, AASHTO M320 [7], is purely climate based and would suggest that the same asphalt binder should be used in a given location regardless of whether it was to be used as part of an interstate highway or a relatively low volume collector street. Recognizing this shortcoming, many states, including Arizona, have created a system of grade bumping wherein the specified grade is one level greater than the climate based grade, e.g., for an interstate a PG 70-22 asphalt binder is specified in a climate where the maximum 7-day consecutive pavement temperature (98% reliability) is 64°C and the minimum pavement temperature (98% reliability) is greater than -22°C. The recently released AASHTO M332 specification [8] seemingly solves this issue by adding a designation in the grade to account for traffic. In this new system grade bumping would be eliminated in lieu of specifying asphalt binder to match the traffic and climate. There has been a large amount of national interest in this standard as evidenced by a regularly updated Asphalt Institute survey [9],which indicates that 20 states have implemented or will soon implement (at least partially) the MSCR test in specification. An additional 16 states are listed as considering implementation or as undergoing testing/evaluation.

This proposed system has raised some questions with respect to what impacts it might have on not only the materials specified, but also on the engineering properties of materials that are actually delivered to an agency. The Arizona Department of Transportation (ADOT) is one such agency, and it has been engaged in a multi-year study of material characterization to investigate the impacts from a transition to an M332 based specification. These evaluation efforts are currently hindered by the fact that much of the validation work of the MSCR test and M332 standard did not include some of the key types used in Arizona [6, 10-11]. Specifically, the development efforts did not consider a large proportion of non-modified PG

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Note: Submitted April 21, 2014; Revised January 19, 2015; Accepted January 20, 2015.

76-16 asphalt binders, which ADOT regularly uses. Major questions that arise include:

- What is the apparent consistency of currently delivered materials according to MSCR based grading?
- What is the correlation between asphalt binder grades being delivered under the grade bumping system and what would be specified in the M332 system?
- How many asphalt binder grades would suppliers need to deliver under a M332 based system as compared to the existing specification?

The objective of this study is to evaluate the ADOT MSCR test database to identify the impacts of a change to MSCR based asphalt binder grading for the state of Arizona and answer some of the aforementioned questions.

Methods and Materials

Test Method

The MSCR test method is detailed in AASHTO T350 [12]. It essentially involves the application of 10 cycles of creep and recovery shear loading (1 second loading and 9 seconds of rest) at both 0.1 kPa and 3.2 kPa. A series of 10 pre-test cycles are also applied prior to the measurement cycles. The test is performed under isothermal conditions in a shear rheometer with samples 25 mm in diameter and 1 mm thick. For each loading cycle the initial strain, maximum strain at the end of the creep loading, and strain at the end of the recovery portion are recorded. These values are used to calculate two key parameters, the non-recovered creep compliance at 0.1 and 3.2 kPa ($J_{nr0.1}$ and $J_{nr3.2}$ respectively) and the percentage of maximum strain that recovers after 3.2 kPa loading ($R_{3.2}$). The specific equations used to calculate these parameters are detailed in the standard.

AASHTO M332 Specification

The AASHTO M332 specification designates a traffic and climate specific grade, and should be contrasted with the more widespread AASHTO M320 system, which specifies an asphalt binder only through its temperature grade. Like the M320 system, M332 system sets parametric limits for unaged $|G^*|/\sin\delta$, pressure aging vessel (PAV) $|G^*|\sin(\delta)$, creep stiffness, and (if used) direct tension failure strain. The M332 system follows the same rules and procedures for unaged and PAV aged asphalt binder; however, the part of the specification related to short term aging is based on a traffic level dependent $J_{nr3.2}$ limits instead of a single limit on $|G^*|/\sin\delta$. There are four different Equivalent Single Axle Load (ESAL) based traffic levels included in the specification; (S)tandard (less than 10 million ESALs), (H)eavy (between 10 and 30 million ESALs), (V)ery Heavy (greater than 30 million ESALs), and (E)xtreme (greater than 30 million ESALs plus standing traffic). Upper limits on the $J_{nr3.2}$ value decrease with each successive traffic level; 4.5 kPa^{-1}for the ‘S’ level, 2 kPa^{-1} for the ‘H’ level, 1 kPa^{-1} for the ‘V’ level, and 0.5 kPa^{-1} for the ‘E’ level. There also exists an increase in the maximum allowable $|G^*|\sin(\delta)$ parameter from 5000 to 6000 kPa for all non-‘S’ level asphalt binders.

Materials

The database used in this study includes 375 individual asphalt binder samples, and has been divided into three separate groups (A, B, and C), which are summarized in total in Table 1. Note that not all producers deliver the same grades and also that in many cases multiple samples of the same asphalt binder grade from the same supplier are available, which permits evaluation of temporal changes in the grade or parameters.

Group A is the primary database and includes results from 339 individual asphalt binder samples tested between 2008 and 2014. ADOT performed the standard tests required for AASHTO M320 tests and also the MSCR test for each of these samples. The two sets of tests (AASHTO M320 and the MSCR test) were done at the exact same time in the same lab, by the same technician, and with the same equipment. Since the testing was part of regular quality assurance operations, ADOT knew beforehand what the performance grade was supposed to be and carried out the AASHTO M320 testing to confirm that the standard was met. Thus, for a given grade (PG 70-22 for example) only single high, intermediate, and low temperatures were selected (70℃, 28℃, and -12℃ respectively). The samples in group A represented data from five different distributors (labeled as I-M in this paper) and 10 different grades. The PG 76-22TR+ and PG 70-22TR+ asphalt binders contain digested crumb rubber and SBS polymer modification. These asphalt binders are provided from only a single supplier in Arizona and so the supplier information is intentionally left out of this paper to retain anonymity.

The effect of temperature changes on the grading results could not be evaluated with the Group A materials and so two additional groups, Groups B and C, were included in the testing program. In Group B, additional MSCR tests at 6℃ below (Group B-1) or 6℃ and 12℃ below the standard temperature (Group B-2) were tested. It is also noted that a large portion of the Group B materials were polymer modified, although the exact type and content is unknown. In Group C additional intermediate temperature DSR testing was completed at three and six degrees below the standard temperatures. These temperatures were 31 and 28℃ for the PG 76-16 asphalt binder, 25 and 22℃ for the PG 70-22 asphalt binder, and 31 and 28℃ for the PG 70-10 asphalt binder. Groups B and C were considerably smaller than Group A.

Results

Classification of Asphalt Binders by AASHTO M332 Standard

The asphalt binder samples from Group A were graded according to the AASHTO M332 system based on the $J_{nr3.2}$ values at the AASHTO M320 high temperature grade. These results were then tracked over time to observe any temporal changes in the grade. At the same time, the $|G^*|/\sin\delta$ parameter from short term aged asphalt binder was tracked and compared with the $J_{nr3.2}$ so that the apparent variability could be compared. It should be kept in mind the analysis is performed on asphalt binders produced to the M320 standard and therefore it is only an estimate of what might be expected under the M332 system. Fig. 1 provides a summary of the results that were

Table 1. Summary of Data Used in this Study.

Group	Grade	Supplier					Total
		I	J	K	L	M	
A	PG 76-22TR+[a]						10
	PG 70-22TR+[a]						13
	PG 76-16	13	23	27	--	--	63
	PG 70-22	2	4	1	--	1	8
	PG 70-10	5	2	20	33	1	61
	PG 64-28	10	6	--	--	--	16
	PG 64-22	5	10	10	28	1	54
	PG 64-16	17	10	10	15	--	52
	PG 58-28	1	--	--	1	1	3
	PG 58-22	4	17	9	28	1	59
B-1[b]	PG 76-22TR+						4
	PG 76-16						1
	PG 70-22TR+						4
B-2[b]	PG 76-28						4
	PG 76-22						2
	PG 70-34						1
	PG 70-28						2
	PG 70-22TR+						8
	PG 70-22						7
	PG 64-34						1
	PG 64-28						2
C[b]	PG 76-16	1	--	1	--	1	3
	PG 70-22	2	--	1	--	1	4
	PG 70-10	--	--	1	--	--	1

[a] Binder represents a proprietary product only sold by a single supplier thus the anonymous identify of the supplier is withheld

[b] Group B and C suppliers are not reported

obtained for PG 76-16 and PG 58-22.

It is evident from this figure that over time the properties of the supplied material change. The degree of consistency is vendor and grade interdependent, and if the information was available, could likely be traced back to the business decisions made with respect to sources of raw supply, approaches to blending multiple grades to achieve targets, and overall quantity of materials supplied. Later in this paper a comparison of these changes with respect to those of the AASHTO M332 $|G^*|/\sin\delta$ parameter will be shown. Fig. 1(a) is representative of the data from most grades with most asphalt binders grading in the 'Standard' range, but in Fig. 1(b) it is observed that many of the PG 58-22 asphalt binder grade outside the 'Standard' traffic range. One primary reason for these occurrences is that ADOT accepts asphalt binder that meet grade requirements even if it would meet more stringent requirements. Thus, it is likely that much of the PG 58-22 asphalt binder that ADOT purchases could also be sold as a PG 64-22.

Based on these results the rates of failing ($J_{nr3.2} > 4.5$), 'S', 'H', 'V', and 'E' classifications were identified. This analysis was possible on Group A materials since it was being performed at the same temperature grade used in the M320 system. The assembled

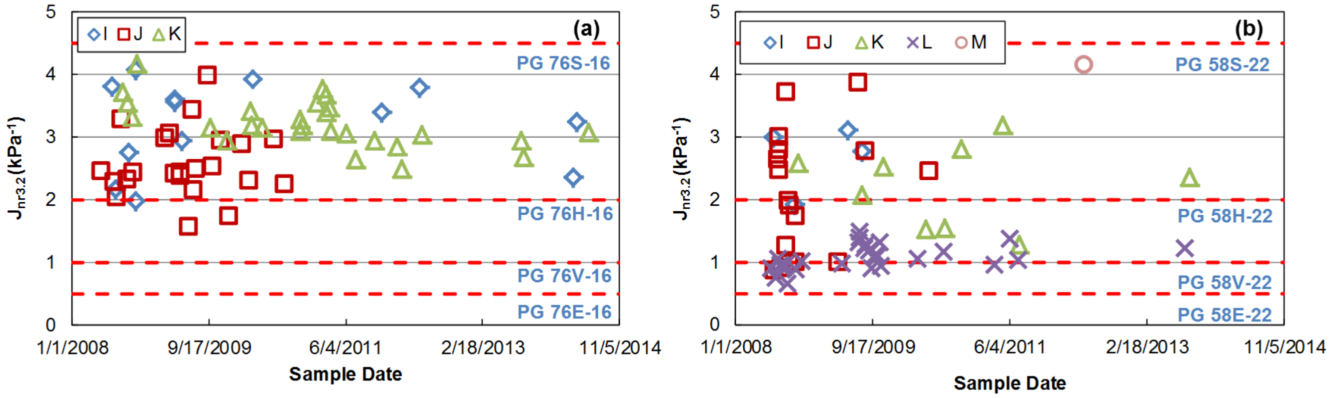


Fig. 1. (a) Asphalt Binder PG 76-16 and (b) PG 58-22 Grouped by Supplier.

data are shown in Table 2 where it is seen that in general the non-TR+ (e.g., non-modified asphalt binders) evaluate as ‘Standard’. The obvious exception to this rule is the PG 58-22 asphalt binder, and the likely reason for this has been discussed above. The modified asphalt binders generally grade at H, V, and E traffic levels.

Temporal Consistency Assessed by M332 and M320

In addition to compiling the shadow grade for each of the asphalt binders; the average, standard deviation, and coefficient of variation (CV) of the $J_{nr3.2}$ and $|G^*|/\sin\delta$ parameters were calculated via Eqs. (1) through (3) respectively. In these equations the variable x represents either the $J_{nr3.2}$ or the $|G^*|/\sin\delta$ parameter, the subscript k represents a particular supplier and climate grade, and N is the total number of samples in the supplier-grade combination.

$$\bar{x}_k = \frac{\sum_{n=1}^{N_k} (x_k)_n}{N_k} \tag{1}$$

$$SD_k(x) = \sqrt{\frac{\sum_{n=1}^{N} \left[(x_k)_n - (\bar{x}_k)_n \right]^2}{N-1}} \tag{2}$$

$$CV_k(x) = \frac{SD_k(x)}{\bar{x}_k} \tag{3}$$

Comparative analysis of these two parameters was performed to examine the apparent variability of the asphalt binder. The values are shown in Table 2 for all asphalt binders and suppliers having ten

Table 2. MSCR and M320 Parameter Analysis (Results at Same High Temperature Grade as in AASHTO M320).

Grade	Supplier	N[a]	% by Traffic Grade					$J_{nr3.2}$ (kPa^{-1})		$\|G^*\|/\sin\delta$ (kPa)	
			Fail	S	H	V	E	Avg.	CV	Avg.	CV
PG 76-22TR+[b]		10	0.00	10.00	50.00	30.00	20.00	1.23	0.50	3.50	0.32
PG 76-16	I	13	0.00	92.31	7.69	0.00	0.00	3.21	0.22	3.18	0.24
	J	23	0.00	91.30	8.70	0.00	0.00	2.58	0.21	3.67	0.19
	K	27	0.00	100.00	0.00	0.00	0.00	3.22	0.12	2.94	0.09
PG 70-22TR+[b]		13	0.00	7.69	30.77	38.46	23.08	0.87	0.25	2.98	0.28
PG 70-22	I	2	0.00	50.00	0.00	0.00	50.00	1.27	--	4.12	--
	J	4	0.00	100.00	0.00	0.00	0.00	2.55	--	3.58	--
	K	1	0.00	100.00	0.00	0.00	0.00	3.55	--	2.59	--
	M	1	0.00	100.00	0.00	0.00	0.00	4.18	--	2.31	--
PG 70-10	I	5	0.00	100.00	0.00	0.00	0.00	3.39	--	3.03	--
	J	2	0.00	100.00	0.00	0.00	0.00	2.70	--	3.47	--
	K	20	5.00	95.00	0.00	0.00	0.00	3.25	0.21	3.25	0.23
	L	33	0.00	96.97	3.03	0.00	0.00	2.86	0.24	3.57	0.31
	M	1	0.00	100.00	0.00	0.00	0.00	3.65	--	2.69	--
PG 64-28	I	10	0.00	100.00	0.00	0.00	0.00	2.76	0.14	3.38	0.11
	J	6	0.00	66.67	33.33	0.00	0.00	2.07	--	4.25	--
PG 64-22	I	5	0.00	100.00	0.00	0.00	0.00	2.55	--	3.80	--
	J	10	0.00	100.00	0.00	0.00	0.00	2.74	0.11	3.56	0.09
	K	10	0.00	100.00	0.00	0.00	0.00	2.58	0.08	3.67	0.08
	L	28	0.00	96.43	3.57	0.00	0.00	2.77	0.19	3.48	0.17
	M	1	0.00	100.00	0.00	0.00	0.00	3.91	--	4.91	--
PG 64-16	I	17	0.00	70.59	29.41	0.00	0.00	2.51	0.23	3.96	0.22
	J	10	0.00	90.00	10.00	0.00	0.00	2.49	0.15	3.98	0.15
	K	10	0.00	100.00	0.00	0.00	0.00	3.14	0.15	3.22	0.14
	L	15	0.00	100.00	0.00	0.00	0.00	2.72	0.18	3.52	0.15
PG 58-28	I	1	0.00	0.00	100.00	0.00	0.00	2.70	--	3.58	--
	L	1	0.00	0.00	100.00	0.00	0.00	2.67	--	3.56	--
	M	1	0.00	0.00	100.00	0.00	0.00	3.28	--	3.28	--
PG 58-22	I	4	0.00	75.00	25.00	0.00	0.00	2.71	--	3.50	--
	J	17	0.00	47.06	29.41	23.53	0.00	2.08	0.47	5.56	0.46
	K	9	0.00	66.67	33.33	0.00	0.00	2.22	--	4.58	--
	L	28	0.00	0.00	60.71	39.29	7.14	1.08	0.20	8.05	0.15
	M	1	0.00	100.00	0.00	0.00	0.00	4.15	--	2.39	--

[a] Number of samples

[b] TR+ = digested crumb rubber and SBS polymer modification

or more samples. It is noted that this consistency metric does not reflect the variation of the experiment (e.g., an assessment of AASHTO T350), rather it is an indication of how consistent the materials appear to be over time looking through the lenses of two different standards. In this respect the asphalt binders would appear to be slightly more consistent in the M320 system than they are in the M332 system. When the most extreme point is eliminated this covariance is found to be on average 11% less for the $|G^*|/\sin\delta$ parameter than it is for $J_{nr3.2}$. If the PG 76-22TR+ is not included then this average difference decreases to approximately 8%. It is not immediately evident whether the results from PG 76-22TR+ are representative of what would be expected from other modified systems. The only other such system in this database (PG 70-22TR+) does not show a large difference in consistency. This result may be due to an overall limited number of samples in the case of PG 76-22TR+ (only 10 samples were available).

In interpreting this result it should be kept in mind that the data had been gathered over many years. A variety of changes in the asphalt binders over time may play a factor in this consistency. It should also be kept in mind that the data itself was gathered on asphalt binders that were produced under the AASHTO M320 system. Thus, either directly or indirectly, suppliers control their processes to maximize the consistency in $|G^*|/\sin\delta$. The data then suggests that the processes used to control variation in the existing system could be used to control the variation as assessed in the AASHTO M332 system. It also suggests that if day-to-day or month over month consistency is important, then the $J_{nr3.2}$ variable might be more sensitive to real changes in the material.

Detecting Polymer Modification

The process of detecting polymer modification in asphalt binders is accomplished by evaluating the percent recovery, $R_{3.2}$, along with the $J_{nr3.2}$. Modified asphalt binders tend to recover a higher percentage of the imposed strain than non-modified asphalt binders due to the presence of the elastomeric polymer. Recall that $R_{3.2}$ depends on both the amount of recovered strains and the magnitude of the strain resulting from the imposed loading. While the elastic recovery of the modifier would be expected to be similar across all base asphalt binder types (assuming asphalt binder/modifier compatibility), the viscoelastoplastic response of the base asphalt binder could differ, and thus the $R_{3.2}$ required to detect modifiers would change depending on the overall stiffness of the asphalt binder.

The proposed relationship for detecting polymer modification is shown in Eq. (4) and in Fig. 2 along with some select non-modified Group A asphalt binders, PG 76-22TR+ and PG 70-22TR+ from Group A, and the modified asphalt binders in Group B. The $J_{nr3.2}$ and $R_{3.2}$ shown in this graph are those taken at the stated binder's regular high temperature grade (e.g., 76°C for the PG 76-16 and 58°C for the PG 58-22 materials). While the basic form of the function, decreasing exponential, can be surmised from the arguments above a theoretical derivation for the arguments in the function does not exist. Instead researchers developed this function from empirical evaluation of systematically altered polymer modified asphalt binders, but without peer reviewed publication of the findings [13], J. D'Angelo, personal communication March 26,

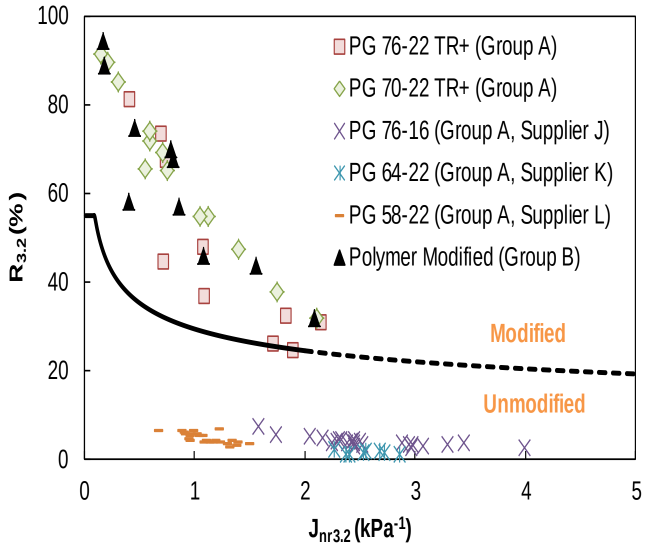


Fig. 2. Presence of Modifiers.

2015). The form shown in Eq. (4) is the same one given in AASHTO T350 protocol [12]. It can be seen that the comparison of R to $J_{nr3.2}$ is effective at detecting the presence of modifiers. It is not clear in the current study if this criterion can be effectively used to assess the relative amounts of modification present; however, it is clear that the function does delineate between asphalt binders with and without polymeric modification when they are tested at the current M320 grade temperature. It is important to note that TR+ modified asphalt binders supplied to ADOT are required to have at least 2% styrene-butadiene-styrene (SBS) polymer and a minimum 8% digested crumb rubber. In addition to these requirements, TR+ asphalt binders are required to meet AASHTO M320 and specific requirements for solubility (ASTM D2042), softening point (AASHTO T53), phase angle (AASHTO T315), and elastic recovery (AASHTO T301). It is anticipated that a transition to M332 would result in future data points that lie just above the function line on the R to $J_{nr3.2}$ plot presented in M332.

$$R = \begin{cases} 29.37\left(J_{nr3.2}\right)^{-0.263} & J_{nr3.2} \geq 0.1 \\ 55 & J_{nr3.2} < 0.1 \end{cases} \tag{4}$$

Multi-Temperature Grade Determination

The typical effect of temperature changes on the $J_{nr3.2}$ parameter are shown in Fig. 3. In this figure, the $J_{nr3.2}$ values are plotted as a function of temperature for two example cases, a PG 76S-16 and a PG 70S-22. As expected, the $J_{nr3.2}$ decreases as the temperature decreases. In this particular example the effect of a single standard high temperature drop is equivalent to a single level increase in the traffic grade, which means that these asphalt binders are not only a PG 76S-16 and PG 70S-22, but they are also a PG 70H-16 and PG 64V-16 and PG 64H-22 respectively.

To consolidate all of the results for Group B, the data have been normalized by dividing the $J_{nr3.2}$ values at each temperature increment by the $J_{nr3.2}$ at the highest test temperature. The results are plotted as this ratio versus the change in temperature in Fig. 4(a). The change in temperature is simply the difference between the

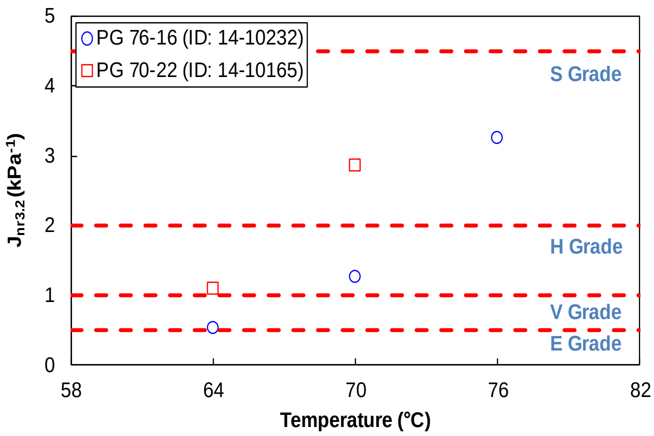


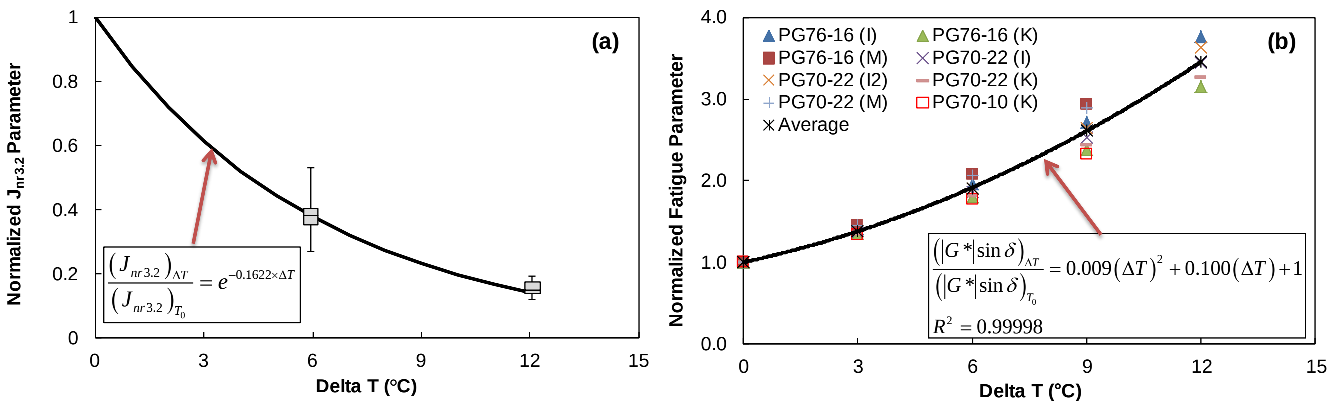
Fig. 3. Typical Effect of Temperature Change on $J_{nr3.2}$.

standard high temperature grade and the test temperature of the data point (either 6 or 12° less than the standard temperature). The data is shown with the boxed area bracketing the 25th and 75th quartiles and the vertical lines showing the 90th percentile of the data. The figure also shows a fitted exponential function for the data, which will be used in the subsequent section to predict the multi-temperature grades for Group A materials. As seen in this graph there is some scatter, particularly at the six degree increment; however, as can also be seen in this data the number of points with the exceptionally high values is limited and that the fitting error within the inter-quartile range is approximately ±8%.

In both the M320 and M332 grading systems the actual grade depends on another parameter, $|G^*|\sin\delta$ at a temperature between the high and low temperature grade. This parameter and temperature comprise the portion of the grade meant to ensure that the asphalt binder is sufficient to control fatigue cracking. The parameter and temperature are relevant to the assessment of multiple temperature grades because a change in the high temperature grade by 6°C is also associated with a change in the intermediate temperature grade by 3°C. Group C has been used to evaluate how a 3 or 6°C change in the intermediate temperature grade affects the $|G^*|\sin\delta$ parameter. The data from this group have been compiled using a normalization method like that used to evaluate the effect of a temperature change on the J_{nr}, and the results are shown in Fig. 4(b). In this figure the x-axis represents the difference between the standard intermediate grade test temperature and the temperature of the plotted test. Since intermediate temperatures increment by 3° the tests were performed at each 3° interval lower than the standard temperature grade. The fitted function was found to yield an overall average error of less than 2% for the experimental results and a maximum error of approximately 13%.

The equations shown in Fig. 4(a) and (b) have been applied to the materials in Group A to develop a more complete picture of what a change to the M332 based system would mean in Arizona, and the results are shown in Table 3. In these equations, ΔT represents the change in temperature, the variables with subscript ΔT are the value of the parameter ($J_{nr3.2}$ or $|G^*|\sin\delta$) at the given change in temperature, and variables with the subscript T_0 represent the value of that parameter at the standard temperature grade. Note that not all of these drops produce relevant high temperature grades for Arizona. For example, a 12°C high temperature grade drop on an asphalt binder with a climate grade of PG 64X-22 results in a climate graded PG 52X-22, and there are no climatic regions in Arizona that would require such an asphalt binder. The relevant climate grades for the state include PG 76X-16, PG 70X-10, PG 64X-22, PG 64X-28, PG 58X-22, and PG 58X-28. The temperature grade drop combinations that match these relevant grades are highlighted in gray in Table 3. Note that when the high temperature is decremented by 6 or 12°C that the intermediate temperature is also decreased by 3 or 6°C, e.g., the intermediate test temperature for PG 64X-22 is 25°C and the intermediate test temperature for PG 52X-22 is 19°C. The percentages in Table 3 are the result of appropriate adjustments to both the $J_{nr3.2}$ and the $|G^*|\sin\delta$ parameter. To interpret the importance of this information examine the rows for the PG 76X-16 grade and supplier I in Tables 2 and 3. Based on the data in Table 2 it is found that currently the PG 76-16 that this supplier provides could grade as a PG 76S-16 (92.31% of the time), a PG 76H-16 (7.69%), and would never fail to meet one of the traffic grades at 76°C. The results in Table 3 show that the same material and supplier at a high temperature grade of 70°C would carry traffic grades of H (76.92% of the time) and V (23.08%). At 64°C it would carry grades of V (30.77%), E (46.15%), or fail to meet the requirements (23.08%). In this case, and in all other failure cases, the inability to meet specification occurs because the parameter at the intermediate temperature exceeds the threshold of 5000 or 6000 kPa.

A summary of the compiled data across all suppliers and grades



$$\frac{(J_{nr3.2})_{\Delta T}}{(J_{nr3.2})_{T_0}} = e^{-0.1622\times\Delta T}$$

$$\frac{(|G^*|\sin\delta)_{\Delta T}}{(|G^*|\sin\delta)_{T_0}} = 0.009(\Delta T)^2 + 0.100(\Delta T) + 1$$

$$R^2 = 0.99998$$

Fig. 4. Effect of Temperature Change on Binder Parameters; (a) $J_{nr3.2}$ and (b) Fatigue Parameter.

Table 3. Estimated Effect of a 6 and 12°C Reduction in the High Temperature Grade on the Traffic Grade of Group A Materials.

Grade	Supplier	N	% by Traffic Grade (6°C Change)					% by Traffic Grade (12°C Change)				
			Fail	S	H	V	E	Fail	S	H	V	E
PG 76-22TR+		10	0.00	0.00	0.00	40.00	60.00	10.00	0.00	0.00	0.00	90.00
PG 76-16	I	13	0.00	0.00	76.92	23.08	0.00	23.08	0.00	0.00	30.77	46.15
	J	23	0.00	0.00	34.78	65.22	0.00	0.00	0.00	0.00	4.35	95.65
	K	27	0.00	0.00	92.59	7.41	0.00	3.70	0.00	0.00	22.22	74.07
PG 70-22TR+		13	0.00	0.00	0.00	23.08	76.92	0.00	0.00	0.00	0.00	100.00
PG 70-22	I	2	0.00	0.00	0.00	50.00	50.00	0.00	0.00	0.00	0.00	100.00
	J	4	25.00	0.00	25.00	50.00	0.00	50.00	0.00	0.00	0.00	50.00
	K	1	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
	M	1	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
PG 70-10	I	5	40.00	0.00	60.00	0.00	0.00	80.00	0.00	0.00	20.00	0.00
	J	2	0.00	0.00	50.00	50.00	0.00	0.00	0.00	0.00	0.00	100.00
	K	20	15.00	0.00	70.00	15.00	0.00	65.00	0.00	0.00	20.00	15.00
	L	33	3.03	0.00	57.58	36.36	3.03	18.18	0.00	0.00	15.15	66.67
	M	1	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
PG 64-28	I	10	0.00	0.00	50.00	50.00	0.00	0.00	0.00	0.00	0.00	100.00
	J	6	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	100.00
PG 64-22	I	5	0.00	0.00	20.00	80.00	0.00	20.00	0.00	0.00	0.00	80.00
	J	10	20.00	0.00	50.00	30.00	0.00	70.00	0.00	0.00	0.00	30.00
	K	10	0.00	0.00	40.00	60.00	0.00	80.00	0.00	0.00	0.00	20.00
	L	28	0.00	0.00	53.57	46.43	0.00	7.14	0.00	0.00	7.14	85.71
	M	1	0.00	0.00	100.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00
PG 64-16	I	17	11.76	0.00	35.29	58.82	0.00	11.76	0.00	0.00	0.00	88.24
	J	10	0.00	0.00	30.00	70.00	0.00	0.00	0.00	0.00	0.00	100.00
	K	10	10.00	0.00	70.00	20.00	0.00	70.00	0.00	0.00	10.00	20.00
	L	15	0.00	0.00	46.67	53.33	0.00	0.00	0.00	0.00	13.33	86.67
PG 58-28	I	1	0.00	0.00	100.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00
	L	1	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
	M	1	0.00	0.00	100.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00
PG 58-22	I	4	0.00	0.00	75.00	25.00	0.00	0.00	0.00	0.00	0.00	100.00
	J	17	17.65	0.00	29.41	35.29	17.65	29.41	0.00	0.00	5.88	64.71
	K	9	0.00	0.00	22.22	66.67	11.11	55.56	0.00	0.00	0.00	44.44
	L	28	10.71	0.00	0.00	14.29	82.14	71.43	0.00	0.00	0.00	35.71
	M	1	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00

Shaded cells represent practical resultant Arizona grades given a 6°C and 12°C reduction in high grade test temperature.

Table 1. Summary of Overall Grading Patterns for Group A Asphalt Binder Including Predicted Change in Traffic Grade with Temperature Reduction.

	Number of Asphalt Binder Samples	%S	%H	%V	%E	%Fail
All Asphalt Binder Grades						
Original Traffic Grade	339	73.9	14.1	6.7	2.1	3.2
Traffic Grade at 6°C Temperature Drop	339	0.0	44.6	37.2	13.2	5.0
Traffic Grade at 12°C Temperature Drop	339	0.0	0.0	9.1	64.5	26.4
Only Asphalt Binder Grades Likely to be Used						
Original Traffic Grade[a]	256	76.2	14.1	5.9	0.0	3.9
Traffic Grade at 6°C Temperature Drop[b]	91	0	37.4	47.3	12.1	3.3
Traffic Grade at 12°C Temperature Drop[c]	31	0	0	6.5	83.9	9.7

[a] PG 76-16, PG 70-10, PG 64-22, PG 58-22, PG 58-28

[b] PG 70-22TR+, PG 70-22, PG 64-28, PG 64-22

[c] PG 76-22TR+, PG 70-22TR+, PG 70-22

for Arizona is shown in Table 4. Examining the data as a whole it is found that in most cases a single temperature drop results in a one or two level increase in the traffic grade. Commensurate with this change is an increased likelihood of the asphalt binder failing to meet the intermediate temperature grade requirements (5% likelihood). This likelihood increases substantially (to 26.4%) with a drop of two temperature levels; however, as noted previously a two temperature level drop in some grades would not be likely used in Arizona. So while the overall average values in Table 4 suggest that there would be a 26.4% chance that this asphalt binder would fail to meet the required $|G^*|\sin\delta$ value at the intermediate temperature, there is a 100% chance that the asphalt binder would never be specified in the first place. Based on an examination of only the Arizona conditions it is found that the average failure rate of the asphalt binders is substantially reduced to only 9.7% in the case of a 12° reduction in the high temperature grade.

The data in these tables suggest that as a basic rule of thumb an Arizona asphalt binder with a given high temperature grade in the AASHTO M320 system will have a traffic rating of Standard in the M332 system. Furthermore, every one temperature increment decrease will most likely result in an increase in traffic grade to the next level (Standard to Heavy, Heavy to Very Heavy, etc.). There are notable exceptions (for example the PG 64S-22 is equally likely to become a PG 64H-22 or a PG 64V-22) so care must be exercised in using this rule of thumb.

Asphalt Binder Grading in Arizona Under AASHTO M332

Examining the effect of a specification change on the grade assigned to a given asphalt binder is one major component of an assessment of the AASHTO M332 protocol. The second major component is an evaluation of the grades that would be specified in the State under strict adherence to the protocol requirements. Arizona consists of primarily two macroclimate regions. In the south the state can be generally classified as dry desert or semi-desert with an average air temperature of 22℃ and summertime high temperatures regularly exceeding 45℃. The northern part of the state consists of largely grassland, woodland, and forest zones with an average annual temperature of 15℃ and regular snowfalls during the winter. Interspersed within these macro regions are various microclimate zones as well as a transition zone from between the northern and southern areas.

To meet these diverse needs ADOT currently uses eight different grades under the AASHTO M320 grading system; PG 76-16, PG 70-22, PG 70-10, PG 64-28, PG 64-22, PG 64-16, PG 58-28, and PG 58-22. Of these eight grades, three of them, PG 76-16, PG 70-10, and PG 64-22 are estimated to constitute almost 90% of the asphalt binder used on ADOT facilities. The distribution of grades are shown by roadway in Fig. 5(a), which shows that in general asphalt binders with smaller high and low temperature grades are located in the northern areas of the state and those with larger high and low temperature grades are located in the central to southern portions of the state. Strict adherence to climate based grades is difficult to observe in this map since ADOT follows the process of grade bumping the high temperature grade for facilities with high traffic volume (e.g., interstates). These grades were largely established using the climate software, LTPPBind Version 2.1, and engineering judgment to reduce the number of grades further. Based on this software and experience, the expected grades that would be required according to strict adherence with the AASHTO M332 grading system are summarized in Fig. 5(b).

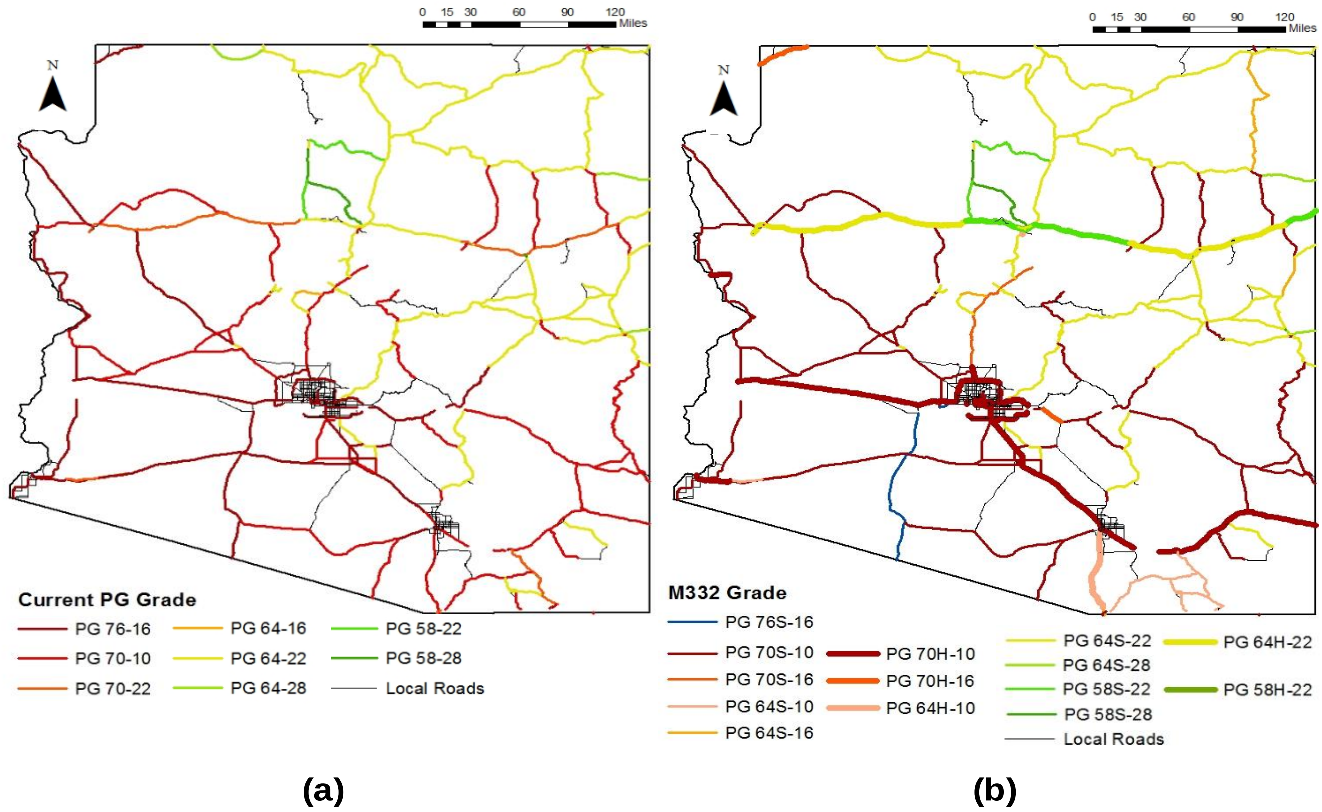


Fig. 5. Distribution of Asphalt Binder Grades Across Arizona; (a) ADOT Current Specifications and (b) Strict Adherence to AASHTO M332 Specification.

From Fig. 5 the climatic zones in Arizona are much more clearly differentiated since the M332 grading system separates climate and traffic during the specification process. It is also observed from this figure that according to AASHTO M332, Arizona would require 14 different asphalt binder grades. Based on the analysis shown previously it is likely that some of these would actually come from the same supply. For example PG 70H-16 may be exactly the same as PG 76S-16. Similar grade equivalences occur in other cases as well such that the total number of asphalt binders required from strict adherence to M332 would likely be 11. Additional engineering adjustment could be applied to consolidate the limited number of required PG 64X-XX to a single grade, likely PG 64X-22, which would further reduce the number to 7, which is more in line with the number currently supplied in Arizona under the existing specification.

Conclusions

In this study a database of Arizona asphalt binders currently produced to meet the AASHTO M320 binder grading system were evaluated under an alternative grading system, AASHTO M332. This alternative system replaces the low strain level oscillatory loading test that is used in M320 to assess the rheological properties of short term aged asphalt binder with a multiple stress level repeated creep and recovery test at load levels that exceed the linear viscoelastic limit. The conclusions from this study were that in general the binders currently used in Arizona meet the standard traffic requirements of the M332 system at the high temperature specified in M320. There exists some scatter and a slightly less consistency with the $J_{nr3.2}$ parameter than currently exists under the M320 parameter. This result is reasonable since the binders were produced to the M320 standard. It may suggest that a change to the M332 system could prompt suppliers to slightly reformulate the binders to better meet the standard requirements. The resulting spatial distribution of specified asphalt binders was also examined and it was found that strict adherence to the M332 system would result in an increase in required grades from 8 to 13, but that through engineering judgment this number could be reduced to 7 or possibly fewer grades. Thus, asphalt binder suppliers would not necessarily have to add additional storage capacity to their facilities to accommodate a transition to the M332 standard.

Acknowledgements

This study was funded by the Arizona Pavement/Materials conference. Authors wish to acknowledge the ADOT Asphalt Binder Lab and Dan Anderson (Lab Supervisor) for testing efforts and work to create and maintain the database used in this research work.

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