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Assessment of Dynamic Modulus Testing of Airfield Asphalt Mixes Using Small-Scale Test Specimens

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16. Abstract

Dynamic modulus is a fundamental property of viscoelastic materials and is typically used as an indicator of mix performance and input for the structural design of flexible pavements. Dynamic modulus can be measured in the laboratory using the Asphalt Mixture Performance Tester (AMPT) using the standard-size test specimen geometry (100-mm diameter by 150-mm length). However, determining dynamic modulus from specimens representing field conditions (field cores) is challenging because the lift thickness of pavement layers is usually less than 150 mm. Therefore, this study compared dynamic modulus test results measured from three airfield asphalt mixes using the standard-size and two small-scale test specimen geometries. The comparative study used several approaches, including evaluating dynamic modulus magnitudes, master curves, statistical variability, and modeled pavement responses from pavement analysis software. Overall, dynamic modulus values from small-scale test specimens show uniformity and good agreement compared to the standard geometry and present less than a 10% difference. Therefore, it is recommended to implement small geometries in dynamic modulus testing to determine performance properties in the laboratory. However, results from small-scale test specimens conducted at high temperatures may need a careful review before implementation since they show more variability and less consistency than the standard-size test specimen's results.

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LIST OF ACRONYMS

AMPT	Asphalt mixture performance tester
AASHTO	Association of State Highway Officials
E*	Dynamic modulus
FAA	Federal Aviation Administration
NCHRP	National Cooperative Highway Research Program
NAPTF	National Airport Pavement Test Facility
NMAS	Nominal maximum aggregate size
PG	Performance grade
PRR	Pavement response ratio
TSR	Tensile strength ratio
VMA	Voids in mineral aggregate
VFA	Voids filled with asphalt

EXECUTIVE SUMMARY

The Asphalt Mixture Performance Tester (AMPT) is a computer-controlled hydraulic testing device that was developed under the National Cooperative Highway Research Program (NCHRP) Project 9-29 to standardize asphalt mix performance testing. The FAA Airport Technology Research and Development branch performs laboratory testing of airfield asphalt mixes to evaluate test procedures that could be more representative of aircraft loading conditions. One of the asphalt mix properties typically assessed in the AMPT is the dynamic modulus, a fundamental property of viscoelastic materials and important in the performance analysis of flexible pavements. Dynamic modulus testing of asphalt mixes is readily available using the standard-size test specimen geometry (100-mm diameter by 150-mm length), but determining dynamic modulus from specimens representing field conditions (field cores) is challenging because the lift thickness of pavement layers is usually less than 150 mm. Therefore, this study compared dynamic modulus test results measured from three airfield asphalt mixes using the standard-size and two small-scale test specimen geometries. This comparative study used several approaches, including evaluating dynamic modulus magnitudes, master curves, statistical variability, and modeled pavement responses from pavement analysis software.

Overall, dynamic modulus values from small-scale test specimens show uniformity and good agreement and present less than a 10% difference compared to the standard geometry. Therefore, it is recommended to implement small geometries to determine dynamic modulus properties in the laboratory, particularly when testing field cores.

In general, the implementation of small-scale test geometries can enable the following benefits:

1. Evaluation of dynamic modulus of field compacted materials with pavement layers and lifts with less than 150-mm thickness.

2. Utilization of less material in the laboratory because more small-scale geometry test specimens are obtained from a single laboratory compacted gyratory pill compared to the standard-size geometry test specimen.

INTRODUCTION

BACKGROUND

As pavement materials become more complex by using recycled materials and additives, ongoing industry initiatives are developing new testing methods to characterize mix performance properly. In these efforts, the Asphalt Mixture Performance Tester (AMPT) was designed under the National Cooperative Highway Research Program (NCHRP) Project 9-29 to standardize asphalt mix performance testing enabling the practical characterization of asphalt mixes (Bonaquist, 2008; Witczak et al., 2002). The AMPT is the preferable device over other load frames because of its versatility and simplicity. The FAA Airport Technology Research and Development branch has recently acquired an AMPT (see Figure 1) to perform laboratory testing of airfield asphalt mixes and to evaluate test procedures and conditions that could be more representative of aircraft loading conditions.

Asphalt mix performance evaluation has always presented challenges due to the asphalt's viscoelastic behavior. Different material properties are used as indicators of performance and behavior. For example, the dynamic modulus (E*) is a fundamental property of viscoelastic materials and describes the relationship between stress and strain under different loading conditions. The dynamic modulus represents the stiffness of asphalt mixes and is typically used to indicate the performance characteristics of the asphalt mix. The phase angle is another fundamental property of asphalt materials and reflects the phase lag between stress and strain during laboratory sinusoidal loading, as shown in Figure 1. Phase angles are often used as an indication of the relaxation capacity of the mix and depict the relationship between the elastic and viscous responses of the mix. The relationship between stress and strain in asphalt mix is obtained during laboratory testing as a function of loading frequency and temperature.

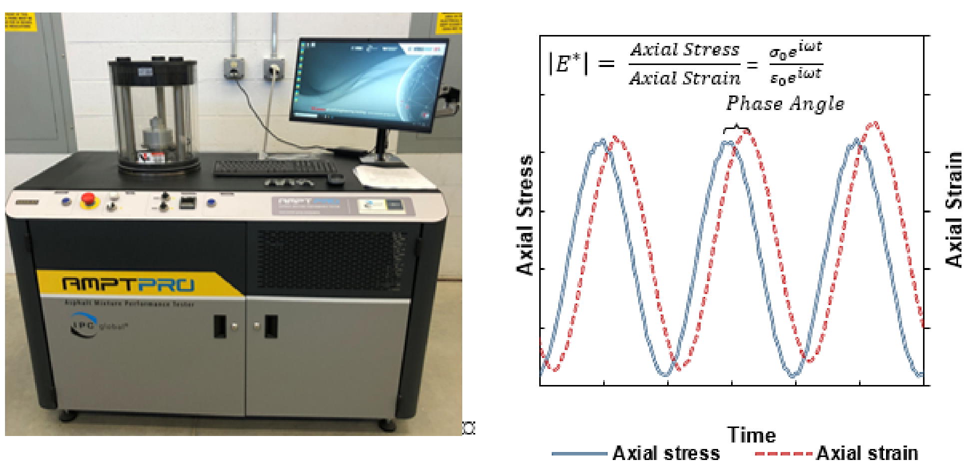


Figure 1. NextGen Pavement Materials Laboratory AMPT and Sinusoidal Load Wave during Dynamic Modulus Testing

Determining dynamic modulus and phase angle is readily available using American Association of State Highway and Transportation Officials (AASHTO) TP 79 (AASHTO, 2015). The tests are conducted on cylindrical specimens 100 mm in diameter and 150 mm in length, typically prepared in the laboratory using reheated sampled loose mix.

However, conducting dynamic modulus tests using specimens representing field conditions (field cores) has been challenging mainly because the lift thickness of pavement layers is usually less than 150 mm. Recently, researchers have evaluated alternative geometries for dynamic modulus testing of highway asphalt mixes in the AMPT using different test specimen geometries (Bowers et al., 2015; Lee et al., 2017; Kutay et al., 2009, Kuchiishi et al., 2023). For example, cylindrical test specimens with diameters and lengths smaller than the standard geometry have been documented. In addition, small-scale test specimens have been fabricated from field cores by coring small cylinders horizontally within the pavement layer lift boundaries. Moreover, prismatic specimens with dimensions as small as 12.5-mm thickness x 25-mm width x 110-mm length have been evaluated for the thinnest asphalt layers and lifts in pavements.

SCOPE

This technical note documents a study conducted at the NextGen Pavement Materials Laboratory located at the National Airport Pavement Test Facility (NAPTF) to investigate the feasibility of using small geometries in dynamic modulus testing for three-airfield pavement mixes. Evaluations from dynamic modulus and phase angle data from an array of testing frequencies and temperatures and using different test specimen geometries were performed in the laboratory using the AMPT. The analysis compared dynamic modulus magnitudes, master curves, and statistical variability. In addition, the comparative analysis used modeled pavement responses implementing the 3D-Move pavement analysis software from the evaluated test specimen geometries. The study presented in this technical note is limited to three airfield asphalt mixes and three test specimen geometries.

MATERIALS AND APPROACH

Laboratory testing was conducted on three P-401 plant-produced surface asphalt mixes evaluated at the FAA NextGen Pavement Materials Laboratory. The P-401 mixes contained asphalt binder performance grades (PGs): PG 64-22 and PG 76-22. Two mixes have a nominal maximum aggregate sizes (NMASs) of 19.0 mm, and one a NMAS of 12.5 mm. Table 1 summarizes the volumetric properties and other important mix characteristics, including NMAS, asphalt binder content, tensile strength ratio (TSR), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). It should be noted that both P-401 mixes A and B presented the same characteristics and differed only in the asphalt binder PG.

Table 1. Mix Characteristics of CC9 P-401

Mix	P-401A	P-401B	P-401C
PG	76-22	64-22	64-22
Number of Gyrations	75		75
Asphalt Binder Content, %	5.0		6.2
Air Voids @ Optimum AC, %	3.5		3.5
VMA, %	15.7		15.5
VFA, %	77.7		77.4
NMAS, mm	19.0		12.5
TSR, %	95.3	93.8	93.7
APA Rut depth at 8,000 passes, mm	2.667	6.786	6.950

<u>SPECIMEN PREPARATION</u>

Test specimens were prepared from plant-produced mixes reheated in the oven until reaching the corresponding compaction temperature. Then, cylinders were compacted using a Superpave Gyratory Compactor following the AASHTO PP60 standard procedure (AASHTO, 2016). In this study, the provisional standards AASHTO PP 99 (AASHTO, 2021) was followed for the preparation of small-scale test specimens. This study evaluated geometries of three different test specimens, the standard geometry with 100 diameter x 150 mm length, and two small geometries, 50 mm x 110 mm and 38 mm x 110 mm, as shown in Figure 2. All specimens (standard-size and small-scale) were fabricated by coring parallel to the long axis of the gyratory-compacted cylinder. Therefore, one standard-size specimen and either three 50-mm or four 38-mm test specimens were fabricated from a single gyratory-compacted cylinder. The bulk-specific density of the specimens was determined to calculate their air voids content. Multiple gyratory-compacted cylinders were prepared to produce dynamic modulus test specimens for each mix and geometry with the same target air voids content for proper comparison.

Figure 2. NextGen Laboratory AMPT and Dynamic Modulus Test Specimens

DYNAMIC MODULUS TEST

The dynamic modulus tests were conducted in the AMPT machine per AASHTO TP 79 (AASHTO, 2015) for standard-size specimens and according to AASHTO TP 132 (AASHTO, 2019) for small-scale specimens. Three temperatures, 39 °F (4 °C), 68 °F (20 °C), and 104 °F (40 °C), were used for all test specimen geometries. Three loading frequencies (10 Hz, 1 Hz, and 0.1 Hz) were selected for all temperatures. During small-scale test specimen testing, the strain within the linear elastic region required 50 to 75 peak-to-peak microstrains instead of 85 to 115, as required by AASHTO TP 79 for standard-size specimens. The dynamic modulus of each mix was assessed using at least three specimens. Therefore, a minimum of 9 different specimens and 81 different combinations of testing frequencies and temperatures were evaluated as part of this study for each mix. During laboratory testing, each specimen's dynamic modulus and phase angle values were obtained by first testing at the lowest temperature and highest frequency. Next, all test frequencies were evaluated in descending order before moving to the next warmer temperature. Figure 3 summarizes the laboratory test plan used in this study.

The dynamic modulus and phase angle data were used to develop master curves for graphical analysis and interpretation of test data. Dynamic modulus master curves resemble a sigmoidal (S-shaped) function. Master curves at a reference temperature of 68 °F (20 °C) in the log-log reference plane were generated by shifting data according to the time-temperature superposition principle as shown in Figure 4. The amount of horizontal shifting of dynamic modulus values to the reference temperature master curve describes the temperature dependency of the asphalt mix. In equation 1, the $|E^*|$ is dynamic modulus (ksi); ω_r is reduced frequency (Hz); δ is the minimum value of modulus (ksi); $\delta+\alpha$ is the maximum value of modulus (ksi); and δ, β, γ, and α are fitting parameters describing the shape of the sigmoidal function. The reduced frequency was computed using the Arrhenius function and William-Landel-Ferry equation provided in Equation 2. Where ω_r is the reduced frequency at the reference temperature (Hz), ω is loading frequency at the test temperature (Hz), T_r is reference temperature (°F). T is test temperature (°F), and ΔE_a is activation energy treated as a fitting parameter. In the master curve development, the fitting and shifting parameters are found through optimization by minimizing the sum of square errors between the logarithm of the measured and predicted dynamic modulus values.

$$\text{Log}|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma \log \omega_r}} \quad (1)$$

$$\log \omega_r = \log \omega + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (2)$$

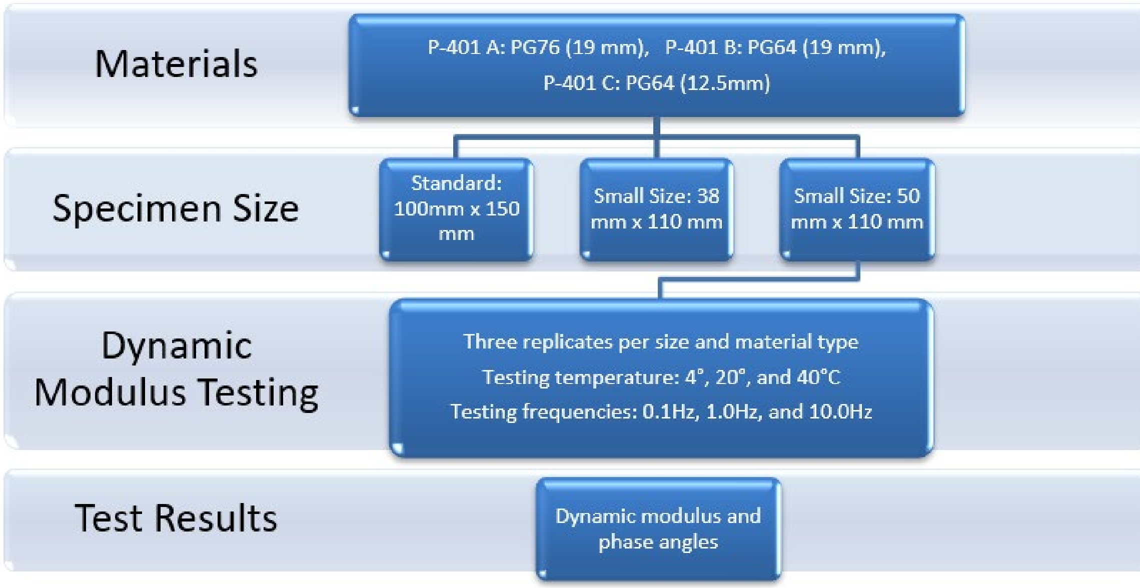


Figure 3. Test Plan

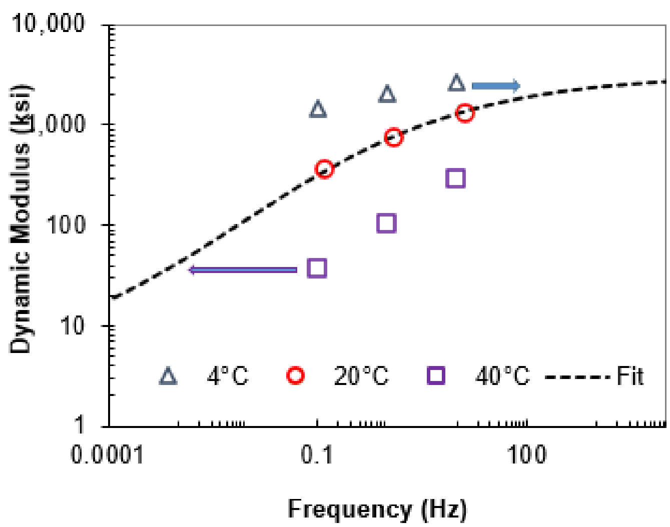
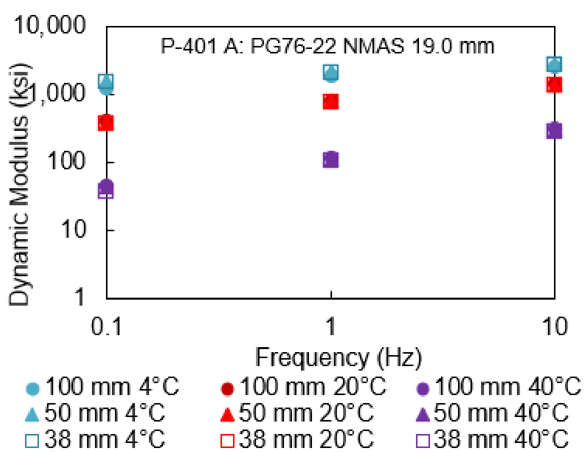


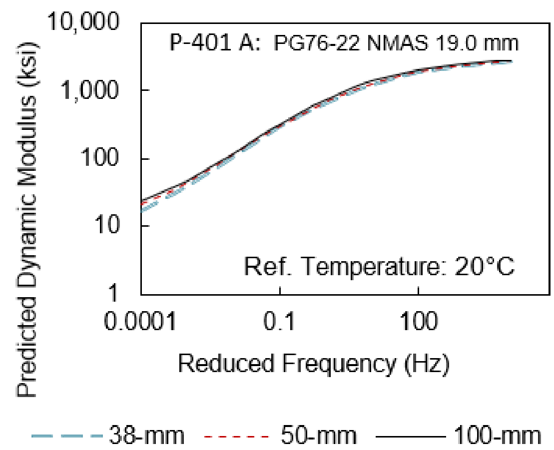
Figure 4. Dynamic Modulus Values Shifted to a 20°C Reference Temperature

TEST RESULTS AND DISCUSSION

Figure 5(a–f) shows dynamic modulus results for the mixes evaluated in this study. Figure 5 (a, c, e) depicts AMPT-measured data with minimum variability between test results from the three different geometries. In Figure 5(a, c, e), each data point represents the average dynamic modulus of three replicates. Similar observations are presented in master curves in Figure 5 (b, d, f) when the time-temperature superposition principle was applied, and dynamic modulus values were shifted to the reference temperature (20 °C) to generate master curves. Master curves show agreement along the entire frequency range except at low-frequency values, where some differences among the master curves are observed. It should be noted that dynamic modulus at low-frequency values is equivalent to high-temperature test conditions. Under high-temperature and low-frequency test conditions, the asphalt mix shows the lowest stiffness and higher specimen-to-specimen variability during testing. It is noted that differences in dynamic modulus values and master curves are not significant among the three test specimen sizes. This is particularly true in Figure 5(f) (NMAS 12.5 mm), where the master curves are almost perfectly collinear among the entire frequency range including high temperature.



(a)



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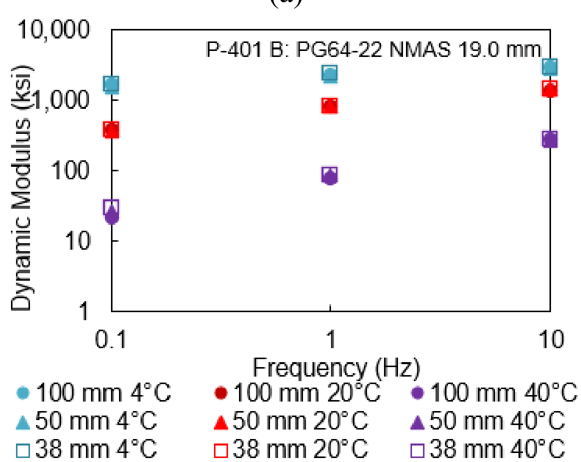

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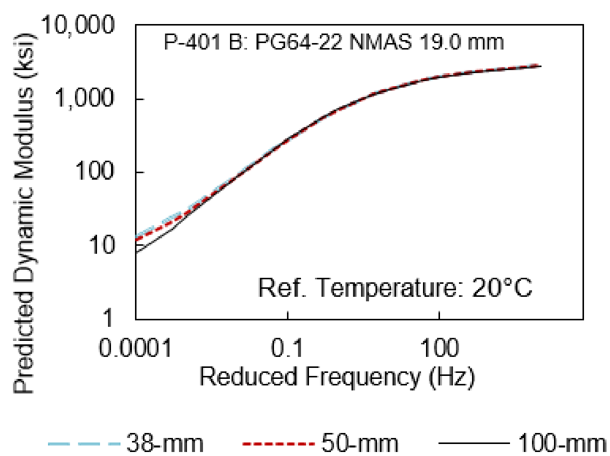

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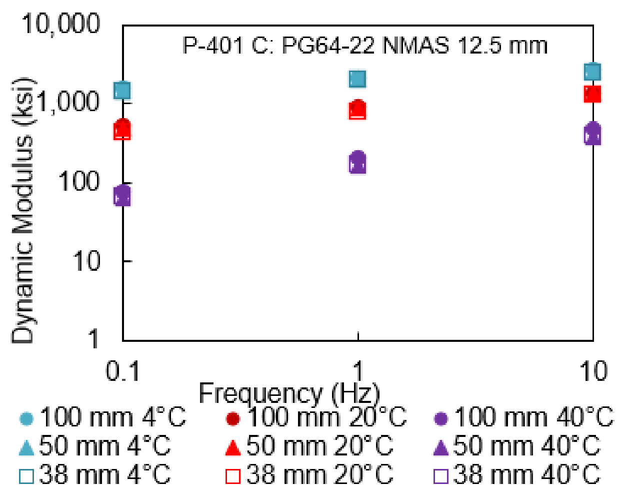

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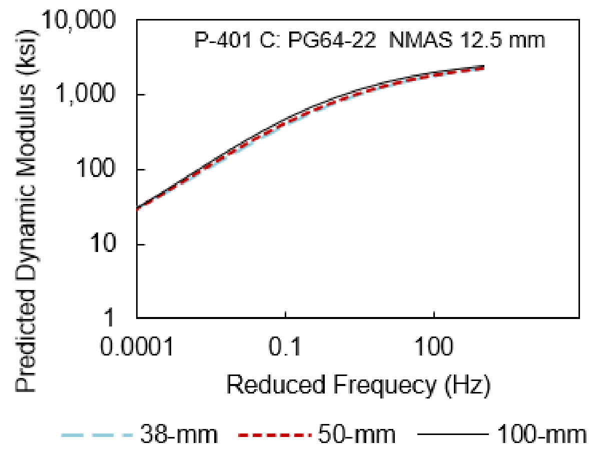
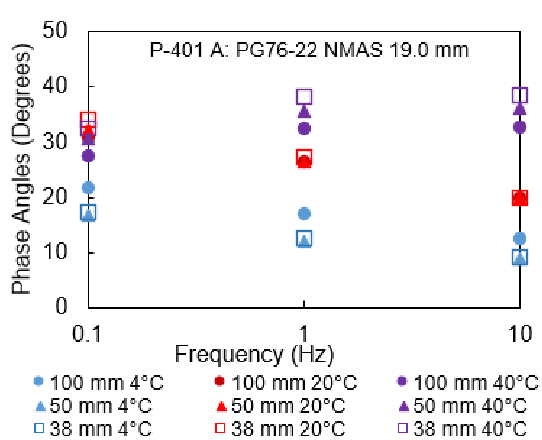


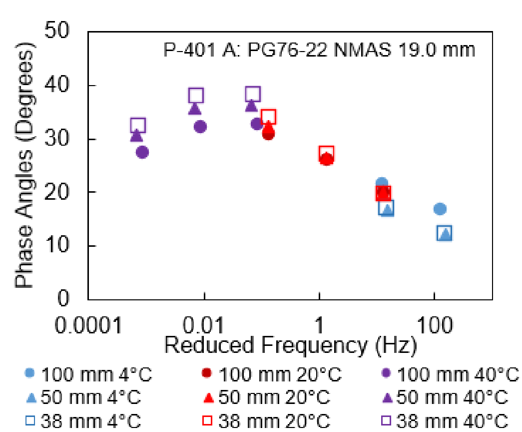
(f)

Figure 5. Dynamic Modulus (E*) Measured Test Results and Master Curves for (a) Measured E* PG76-22 NMAS 19.0 mm, (b) E* Master Curve PG76-22 NMAS 19.0 mm, (c) Measured E* PG64-22 NMAS 19.0 mm, (d) E* Master Curve PG64-22 NMAS 19.00 mm, (e) Measured E* PG64-22 NMAS 12.5 mm, and (f) E* Master Curve PG64-22 NMAS 12.5 mm

Figure 6(a–f) shows measured and shifted phase angle results for the three mixes. The shifted phase angles developed from the dynamic modulus master curves are shown in Figure 6(b, d, f). Figure 6(a) presents some variability in phase angle values among the test geometries in the 76-22 mix. For example, the standard PG76-22 100-mm diameter geometry shows the lowest values at high temperature (40 °C) and highest values at low temperature (4 °C). The distinction is also observed in Figure 6(b) among the shifted values, especially at low frequency (high-temperature values). The discrepancy in phase angle values among the different test geometries may be attributed to inherent variability in lab measurements obtained at high temperatures. Conversely, better agreement among all test geometries is observed in the test results from the PG64-22 mixes, as shown in Figure 6(e, f).



(a)



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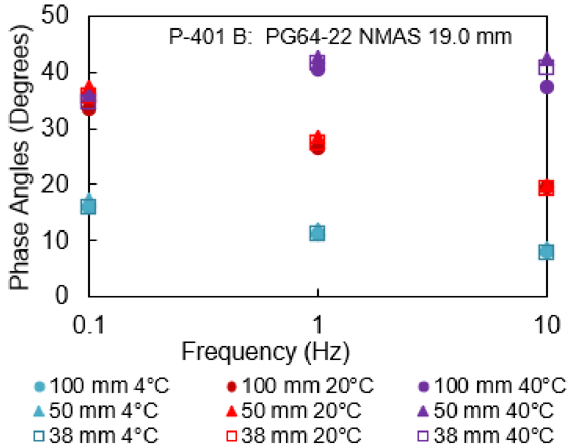

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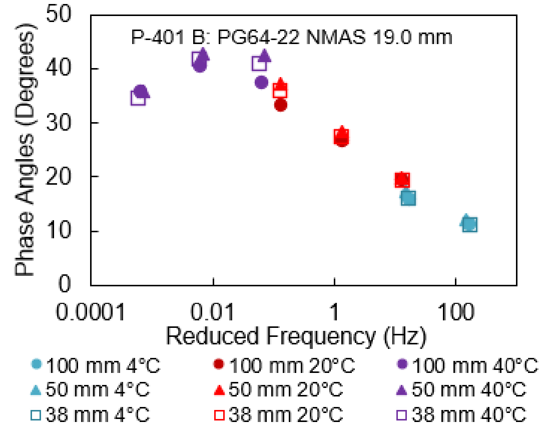

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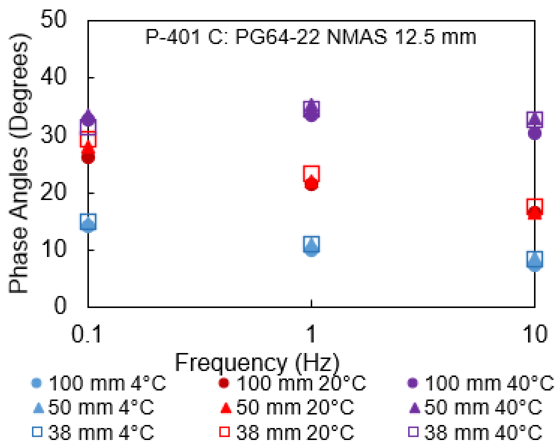

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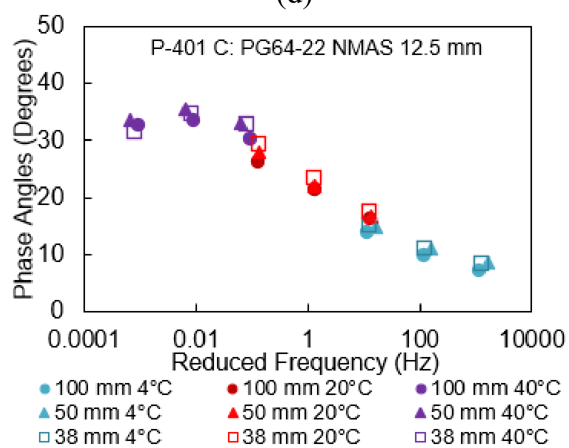
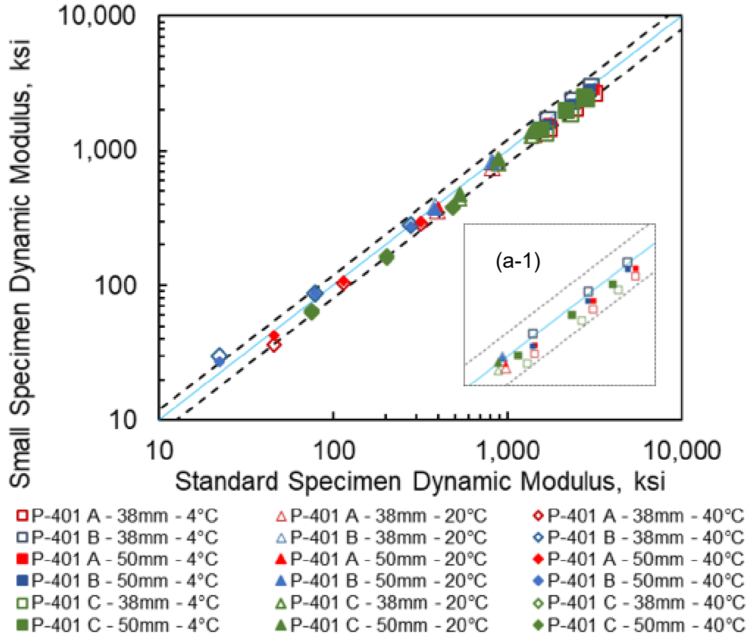


(f)

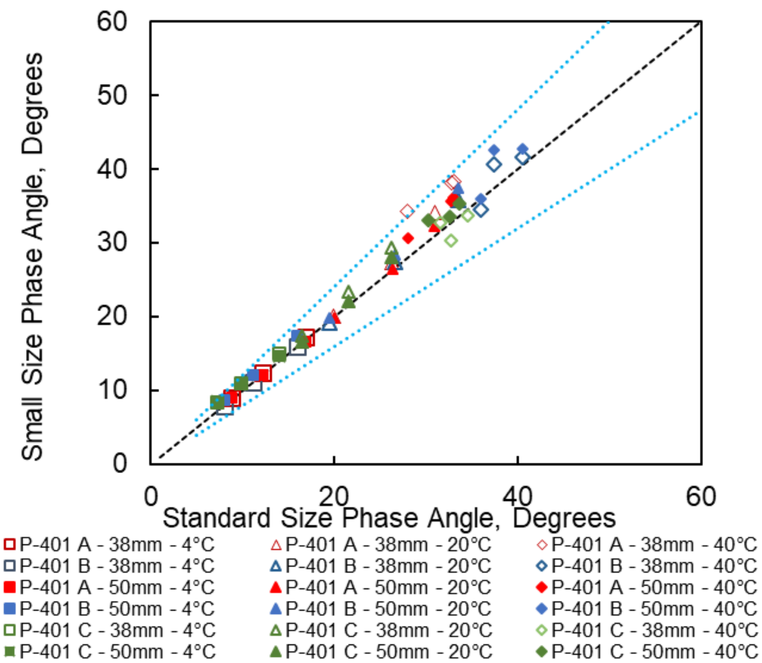
Figure 6. Phase Angles Test Results: (a) Measured Phase Angles PG76-22 NMAS 19.0 mm, (b) Shifted Phase Angles PG76-22 NMAS 19.0 mm, (c) Measured Phase Angles PG64-22 NMAS 19.0 mm, (d) Shifted Phase Angles PG64-22 NMAS 19.0 mm, (e) Measured Phase Angles PG64-22 NMAS 12.5 mm, and (f) Shifted Phase Angles PG64-22 NMAS 12.5 mm

A different way to illustrate test results is presented in Figure 7. Here, dynamic modulus and phase angle values of the standard-size specimen are plotted against the corresponding results of small geometries. Three lines are also observed in each figure. The equality line and the ±10% difference from the equality line are depicted in the scatterplots. Figure 7(a) shows test specimen's results from mixes with NMAS of 19.0 mm in blue and red. Results from test specimens fabricated using the mix with a NMAS of 12.5 mm are presented in green. Excellent agreement was observed between the standard-size and small-scale dynamic modulus test results, with almost all pairs surrounding the equality line and well within the 10% difference. Only in a few instances, at high frequencies, some differences are observed in the inset (a-1). Here some variability is observed in dynamic modulus values at high frequency (low temperature). Figure 7(b) shows agreement between phase angle values showing almost all data points around the equality line and the 90%

difference interval along the entire data set. Again, some variability in phase angle values from different test specimen sizes is observed at high temperatures.



(a)



(b)

Figure 7. Average Standard-Size Test Results vs Small-Scale Geometry Test Results for (a) Dynamic Modulus and (b) Phase Angles

STATISTICAL ANALYSIS

Statistical analysis was conducted to identify significant differences in mean property values between standard geometry and small-scale geometry test specimens using two-tailed t-tests. The study considered the size of the test specimens as the treatment with null hypothesis H_0: difference in dynamic modulus and phase angle values equal to zero. The analysis assumed an α-value of 0.05 (confidence level 95%). The test specimens were prepared from the same mix type, but only three specimens were evaluated per pair. Therefore, unequal sample variance was selected for the analysis. Table 2 indicates statistical significance when the p-value is ≤ than the α-value of 0.05. As shown in Table 2, most cases (85%) show no statistical significance, thus rejecting the null hypothesis and suggesting no difference between property values. Statistical significance was determined only in some instances highlighted in green, which correspond to extreme temperatures. This observation is probably due to the more significant variability observed among test replicates at high and low temperatures. Observations from Table 2 are similar to those made by other researchers when they found good agreement between small-scale and full-size dynamic modulus values and some variability in test results from extreme temperature testing (Bowers et al., 2015; Lee et al., 2017).

Table 2. P-Values of Statistically Significant Difference Analysis Between the Standard-Size and Small-Scale Specimen Dynamic Modulus Test Results

Dynamic Modulus							
Mix	Test Frequency	38-mm			50-mm		
		4 °C	20 °C	40 °C	4 °C	20 °C	40 °C
PG76-22 – 19.0	10Hz	0.01	0.07	0.25	0.03	0.05	0.43
	1Hz	0.01	0.07	0.46	0.06	0.14	0.69
	0.1Hz	0.02	0.12	0.13	0.05	0.34	0.56
PG64-22 – 19.0	10Hz	0.90	0.71	0.98	0.53	0.85	0.96
	1Hz	0.84	0.82	0.50	0.53	0.94	0.71
	0.1Hz	0.77	0.93	0.23	0.47	0.71	0.42
PG64-22 – 12.5	10Hz	0.19	0.30	0.04	0.22	0.97	0.03
	1Hz	0.16	0.20	0.08	0.20	0.38	0.06
	0.1Hz	0.18	0.14	0.17	0.24	0.32	0.11
Phase Angle							
Mix	Test Frequency	38-mm			50-mm		
		4 °C	20 °C	40 °C	4 °C	20 °C	40 °C
PG76-22 – 19.0	10Hz	0.39	0.56	0.00	0.48	0.75	0.08
	1Hz	0.53	0.91	0.00	0.52	0.82	0.00
	0.1Hz	0.48	0.82	0.07	0.57	0.03	0.02
PG64-22 – 19.0	10Hz	0.31	0.55	0.43	0.01	0.71	0.04
	1Hz	0.62	0.15	0.54	0.03	0.46	0.65
	0.1Hz	0.95	0.12	0.50	0.02	0.13	0.77
PG64-22 – 12.5	10Hz	0.05	0.23	0.08	0.02	0.86	0.07
	1Hz	0.17	0.22	0.33	0.02	0.67	0.17
	0.1Hz	0.29	0.17	0.34	0.11	0.35	0.69

MECHANISTIC ANALYSIS

Determining dynamic modulus is particularly important in evaluating flexible pavement performance as dynamic modulus is one of the primary input parameters in the structural design of flexible pavements under mechanistic and mechanistic-empirical pavement analysis methodologies. The 3-D Move software (Siddharthan et al., 2002) (see Figure 8) is a pavement analysis tool that uses the continuum-based finite layer approach to evaluate a pavement layered system's response to a moving surface load. The 3-D Move version 2.1 was used to calculate pavement responses under typical airfield conditions in a flexible pavement section using dynamic modulus values from the evaluated mixes and test specimen sizes. The pavement system was characterized by a combination of viscoelastic (dynamic modulus) and elastic horizontal layers for the asphalt and unbound layers, respectively. The maximum vertical compressive strain (ε_r) and the maximum tensile strain (ε_t) at the middle and bottom of the asphalt layer, pavement responses typically associated with rutting and bottom-up fatigue cracking damage, were used in this investigation, respectively. The determination of ε_r and ε_t enabled the evaluation of the effect of small-scale test specimens in dynamic modulus testing through the assessment of pavement response ratios (PRRs), calculated using Equation 3. If the PRR is higher than 1.0, it suggests that using the small-scale test specimens overpredicts pavement responses associated with pavement damage. Conversely, pavement response ratios lower than 1.0 indicate under prediction pavement responses from small-scale test specimens relative to the standard-size specimen.

$$PRR = \frac{\varepsilon_{Small}}{\varepsilon_{Standard}} \quad (3)$$

where ε_{Small} is either ε_r or ε_t as obtained from 3D-Move using dynamic modulus values from small-scale test specimens, and $\varepsilon_{Standard}$ is ε_r or ε_t as obtained from 3D-Move using dynamic modulus values from standard-size test specimens.

Figure 8 shows that PRRs are consistently within 5%–7% of the unity, denoted by red-dashed horizontal line, indicating excellent agreement of ε_r and ε_t from both small specimen geometries. However, some PRRs of pavement responses at 40 °C of the 19.0 mm mixes are about 10% away from the unity for both 19-mm mixes. This finding can indicate that pavement responses from pavement analysis using data from small-scale test specimens might show more variability and less consistency at high testing temperatures than responses from standard-size test specimens. The high variability in dynamic modulus test results can be explained by the fact that at high temperatures, the aggregate gradation plays a significant role in the dynamic modulus response. Therefore, more variability is expected as the aggregate structure and stone contact could differ slightly from specimen to specimen and from different test specimen sizes. According to Figure 8, there is more variation in the 19.0-mm mixes than in the 12.5-mm mix, indicating that the NMAS could affect the accuracy and uniformity of test results in smaller test samples. Given this variability in materials composition and actual laboratory testing repeatability, 90% agreement still offers comparable response values. Accordingly, results from small-scale test specimens conducted at high temperatures might need a thorough review before implementation, as noted by the other researchers (Bowers et al., 2015; Lee et al., 2017; Kutay et al., 2009).

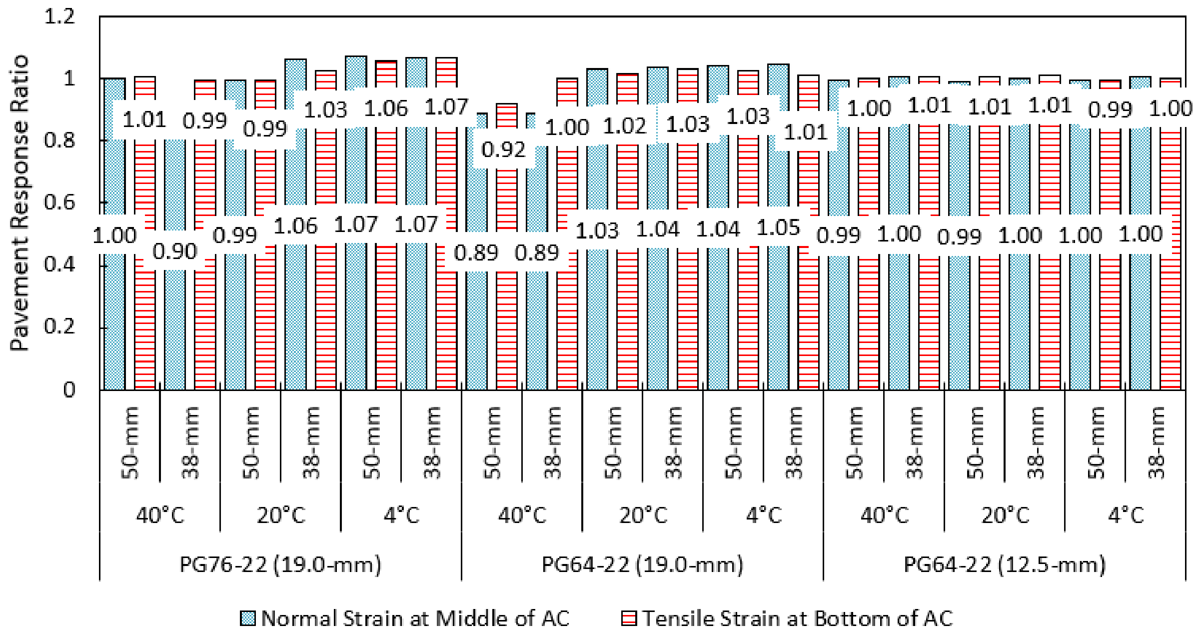


Figure 8. Pavement Response Ratios

SUMMARY AND RECOMMENDATIONS

This study used different approaches to compare the consistency of dynamic modulus and phase angle results measured from two small-scale test specimen geometries compared to the standard geometry using airfield asphalt mixes. From the analysis of results, dynamic modulus values show uniformity and good agreement among the different geometries. Therefore, it is recommended to implement small geometries in dynamic modulus testing. However, special attention is needed when using small-scale specimens in high-temperature testing, as higher variabilities and lower consistencies were observed in test results and statistical and mechanistic analysis.

Overall, no significant difference in results was observed between the 38-mm and 50-mm small-scale test geometries. However, more mixes with different NMAS need to be examined to validate findings from this study, as it is expected that larger NMAS and the specimen diameter/NMAS ratio can affect the quality and consistency of results from small-scale test specimens, especially the 38-mm diameter ones, as indicated in similar investigations. Another aspect that could influence dynamic modulus test results in small-scale test specimens is the coring direction. This study did not evaluate small-scale specimens cored perpendicular to the long gyratory-compacted cylinders axis. Therefore, additional testing, evaluating, and comparing this effect could be warranted.

In general, the implementation of small-scale test specimens can enable the following benefits:

1. Evaluation of dynamic modulus of pavement layers and lifts with less than 150-mm thickness.

2. Utilization of less material in the laboratory as more small-scale test specimens can be obtained from a single laboratory compacted gyratory pill compared to the standard-size test specimen.

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