Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Asphalt Mixture Performance Characterization Using Small-Scale Cylindrical Specimens

http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r26.pdf

BRIAN K. DIEFENDERFER, Ph.D., P.E.
Senior Research Scientist

BENJAMIN F. BOWERS, Ph.D.
Research Scientist

STACEY D. DIEFENDERFER, Ph.D., P.E.
Senior Research Scientist

Final Report VCTIR 15-R26

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454

www.VTRC.net

Standard Title Page—Report on State Project

Report No.: VCTIR 15-R26	Report Date: June 2015	No. Pages: 53	Type Report: Final	Project No.: RC00081
			Period Covered: October 2013–April 2015	Contract No.:

Title:
Asphalt Mixture Performance Characterization Using Small-Scale Cylindrical Specimens

Key Words:
Dynamic modulus, small scale, characterization, asphalt

Author(s):
Brian K. Diefenderfer, Ph.D., P.E., Benjamin F. Bowers, Ph.D., and Stacey D. Diefenderfer, Ph.D., P.E.

Performing Organization Name and Address:
Virginia Center for Transportation Innovation and Research
530 Edgemont Road
Charlottesville, VA 22903

Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Supplementary Notes:

Abstract:

The results of dynamic modulus testing have become one of the primarily used performance criteria to evaluate the laboratory properties of asphalt mixtures. This test is commonly conducted to characterize asphalt mixtures mechanistically using an asphalt mixture performance tester as developed in NCHRP Project 9-29. The typical test specimen geometry consists of a cylinder having a 100-mm diameter and a 150-mm height. This geometry is practical for laboratory-prepared specimens produced using a gyratory compactor. However, the specimen scale is problematic when the test specimen is prepared from field cores and the investigator wishes to isolate the testing to a single asphalt mixture material/layer. This is because most asphalt mixture layers, especially surface and intermediate layers, are placed having a thickness less than 150 mm.

This study investigated the use of small-scale cylindrical specimens as an alternative means to conduct dynamic modulus testing of asphalt mixtures. To validate the small-scale approach, the dynamic modulus from small-scale specimens was compared to the dynamic modulus from full-size specimens (100 × 150 mm) using asphalt mixtures having a nominal maximum aggregate size (NMAS) of 9.5, 12.5, 19.0, and 25.0 mm. Small-scale cylindrical specimens having a diameter and height of 38 × 135 mm, 50 × 135 mm, 38 × 110 mm, and 50 × 110 mm were studied.

Based on the findings of the study, for 9.5- and 12.5-mm NMAS mixtures, any of the four small-scale geometry dimensions appears to be a suitable alternative to the full-size specimen when the full-size specimen cannot be produced. For 19.0- and 25.0-mm NMAS mixtures, the two small-scale geometries having a diameter of 50 mm appear to be suitable alternatives to the full-size specimen when the full-size specimen cannot be produced.

FINAL REPORT

ASPHALT MIXTURE PERFORMANCE CHARACTERIZATION USING SMALL-SCALE CYLINDRICAL SPECIMENS

Brian K. Diefenderfer, Ph.D., P.E.
Senior Research Scientist

Benjamin F. Bowers, Ph.D.
Research Scientist

Stacey D. Diefenderfer, Ph.D., P.E.
Senior Research Scientist

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

June 2015
VCTIR 15-R26

DISCLAIMER

ABSTRACT

The results of dynamic modulus testing have become one of the primarily used performance criteria to evaluate the laboratory properties of asphalt mixtures. This test is commonly conducted to characterize asphalt mixtures mechanistically using an asphalt mixture performance tester as developed in NCHRP Project 9-29. The typical test specimen geometry consists of a cylinder having a 100-mm diameter and a 150-mm height. This geometry is practical for laboratory-prepared specimens produced using a gyratory compactor. However, the specimen scale is problematic when the test specimen is prepared from field cores and the investigator wishes to isolate the testing to a single asphalt mixture material/layer. This is because most asphalt mixture layers, especially surface and intermediate layers, are placed having a thickness less than 150 mm.

This study investigated the use of small-scale cylindrical specimens as an alternative means to conduct dynamic modulus testing of asphalt mixtures. To validate the small-scale approach, the dynamic modulus from small-scale specimens was compared to the dynamic modulus from full-size specimens (100 × 150 mm) using asphalt mixtures having a nominal maximum aggregate size (NMAS) of 9.5, 12.5, 19.0, and 25.0 mm. Small-scale cylindrical specimens having a diameter and height of 38 × 135 mm, 50 × 135 mm, 38 × 110 mm, and 50 × 110 mm were studied.

Based on the findings of the study, for 9.5- and 12.5-mm NMAS mixtures, any of the four small-scale geometry dimensions appears to be a suitable alternative to the full-size specimen when the full-size specimen cannot be produced. For 19.0- and 25.0-mm NMAS mixtures, the two small-scale geometries having a diameter of 50 mm appear to be suitable alternatives to the full-size specimen when the full-size specimen cannot be produced.

FINAL REPORT

ASPHALT MIXTURE PERFORMANCE CHARACTERIZATION USING SMALL-SCALE CYLINDRICAL SPECIMENS

Brian K. Diefenderfer, Ph.D., P.E.
Senior Research Scientist

Benjamin F. Bowers, Ph.D.
Research Scientist

Stacey D. Diefenderfer, Ph.D., P.E.
Senior Research Scientist

INTRODUCTION

In the report for National Cooperative Highway Research Program (NCHRP) Project 9-19, Witczak et al. (2002) recommended dynamic modulus testing as one of the tests to characterize mechanistically the performance of asphalt mixtures. The test can be readily performed using an asphalt mixture performance tester (AMPT) as developed in NCHRP Project 9-29 (Bonaquist, 2008) and in accordance with the American Association of State Highway and Transportation Officials (AASHTO) TP 79, *Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)* (AASHTO, 2013). The test is conducted by subjecting a cylindrical specimen to an axial compressive sinusoidal load over a range of temperatures and loading frequencies. The dimensions of the cylindrical test specimen are 150 mm in height and 100 mm in diameter. This test specimen geometry is practical for laboratory-prepared specimens produced using a gyratory compactor. However, the specimen scale is problematic when the test specimen is produced from field cores and the investigator wishes to isolate the testing to a single asphalt mixture material/layer. This is because most asphalt mixture layers, especially surface and intermediate layers, are placed having a thickness less than 150 mm.

The difficulty in producing full-size test specimens from field cores is the primary reason several studies have investigated alternative test specimen geometries. The most prevalent alternative test specimen geometries include indirect tensile (IDT) and a reduced scale (or *small-scale*) version of the cylindrical geometry specified in AASHTO TP 79 (AASHTO, 2013). This report describes the efforts undertaken by the Virginia Department of Transportation (VDOT) to develop procedures to conduct dynamic modulus tests on small-scale cylindrical specimens tested axially. Dynamic modulus tests were conducted on 16 plant-produced asphalt mixtures using four small-scale specimen geometries and the specified full-scale specimen geometry. The mixtures used in the study encompassed four nominal maximum aggregate sizes (NMASs), three performance grade (PG) binder types, and various levels of reclaimed asphalt pavement (RAP), and they included both dense-graded asphalt and stone matrix asphalt (SMA) mixtures. The small-scale specimen geometries included two specimen diameters (38 and 50 mm) and two specimen heights (110 and 130 mm). Test results from specimens of each small-scale geometry were compared to the results from specimens of full-size geometry.

PURPOSE AND SCOPE

This purpose of this study was to investigate the use of small-scale specimens as an alternative means to conduct dynamic modulus testing of asphalt mixture materials. The specific objectives of the study were to (1) investigate the feasibility of conducting dynamic modulus tests using the AMPT on small-scale specimens produced from asphalt mixtures; (2) determine an optimum small-scale specimen geometry from the four options tested; and (3) compare the results of dynamic modulus testing using small-scale specimens versus full-size specimens.

The scope of the study included a literature review and the laboratory evaluation of 16 asphalt mixtures. All testing was conducted in the asphalt laboratory of the Virginia Center for Transportation Innovation and Research (VCTIR) on specimens fabricated at VCTIR from asphalt mixtures produced by contractors in Virginia.

METHODS

Literature Review

A literature review was conducted by searching various transportation-related databases such as: Transport Research International Documentation (TRID) bibliographic database, the catalog of Transportation Libraries (TLCat), the Catalog of Worldwide Libraries (WorldCat), and the Transportation Research Board Research in Progress (RiP) and Research Needs Statements (RNS) databases.

Laboratory Evaluation

The laboratory evaluation consisted of dynamic modulus testing that was conducted on small-scale and full-size specimens produced from 16 asphalt mixtures. The mixtures were plant produced; test specimens were fabricated in the laboratory using a gyratory compactor in accordance with AASHTO PP 60, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)* (AASHTO, 2013). Dynamic modulus testing was conducted in accordance with AASHTO TP 79 (AASHTO, 2013) with slight modifications; a reduced set of temperatures was used. The dynamic modulus describes the stress-strain relationship for a linear viscoelastic material. The test is conducted by subjecting a cylindrical specimen to an axial compressive sinusoidal load over a range of temperatures and loading frequencies. Testing was conducted at temperatures of 4.4, 21.1, 37.8, and 54.4 °C. At each temperature, testing was conducted at loading frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz.

As shown in Table 1, 16 asphalt mixtures were used to fabricate small-scale and full-size specimens for dynamic modulus testing. The Lab Mix ID is given as xx-yyyy, where *xx* are the last two digits of the calendar year in which the mixture was sampled and *yyyy* is the consecutive number of the mixture as recorded in the laboratory (starting with 1000). These mixtures represent typical mixtures used in Virginia. The NMAS ranged from 9.5 to 25 mm. The binder performance grades included PG 64-22, PG 70-22, and PG 76-22. The mixtures included 15 dense-graded mixtures and 1 SMA mixture. For the first 5 mixtures tested (12-1028, 13-1070, 13-1088, 12-1041, and 12-1052), testing was first completed on 135-mm-height specimens, which were then trimmed down to 110 mm in height. The testing at the 135-mm height was conducted at temperatures of 4.4, 21.1, and 37.8 °C. Since there was a concern that the specimens could be damaged during testing at higher temperatures, the 54.4 °C temperature was not used. After the specimens for these 5 mixtures were tested as 135-mm-height specimens, the ends of the specimens were equally trimmed to produce 110-mm-height specimens. The testing was then repeated with the addition of the 54.4 °C test temperature. For the remainder of the study, unique 135- and 110-mm-height specimens were tested, and testing was conducted at all four temperatures for each diameter/ height combination.

Table 1. Asphalt Mixtures Tested

Nominal Maximum Aggregate Size, mm	Lab Mix ID	Binder Performance Grade
9.5	12-1028[a]	70-22
	13-1070[a,b]	64-22
	13-1088[a]	64-22
	13-1107[c]	64-22
	13-1119	64-22
	13-1121	64-22
	13-1125	64-22
12.5	12-1041[a]	76-22
	12-1052[a]	70-22
	13-1118	64-22
19.0	13-1104	64-22
	13-1106	64-22
	13-1128	64-22
	14-1006	70-22
25.0	13-1108[c]	64-22
	13-1120	64-22

[a] Testing was not conducted at 54.4 °C for 135-mm-height specimens (110-mm-height specimens were trimmed from 135-mm-height specimens).
[b] Stone matrix asphalt mixture.
[c] Testing was not conducted at 54.4 °C for any specimens.

Custom Hardware Fabrication

Prior to testing, some test fixture components had to be custom-machined to accommodate the reduced specimen size. Specifically, custom arms for the linear variable displacement transducer (LVDT) stud gluing jig and testing platens for the AMPT were manufactured from aluminum; photographs of each are shown in Figures 1 and 2, respectively. A unique set of gluing jig arms was manufactured for the small-scale specimens because of their decreased diameter. The upper portion of each gluing jig arm had to be extended so that the arm could apply pressure to the LVDT stud as it was being glued to the specimen. For the 38- and 50-mm-diameter specimens, the upper portions of the arms were extended by approximately 32 and 25 mm, respectively. All other dimensions for the custom arms were the same as for the stock gluing arms. Custom testing platens for the AMPT were also machined to facilitate centering the specimen during testing. A unique set of platens was fabricated to match the diameter of the small-scale specimens. Removable spacer blocks, used as the lower support for the small-scale specimens, were also manufactured for the different specimen heights. Testing was conducted using standard LVDT gauges and studs; the LVDT stud spacing was 70 mm.

Figure 1. Photograph of LVDT Stud Gluing Jig Showing Custom Arms

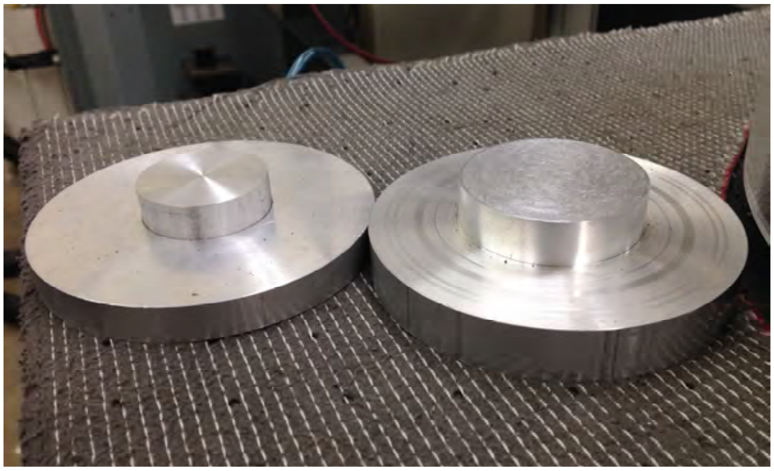

Figure 2. Photograph of AMPT Testing Platens With Removable Spacer Blocks for 38- and 50-mm-Diameter Small-Scale Specimens

Specimen Preparation

The small-scale specimens were prepared in the laboratory as follows. From each mixture type, 8 to 10 150-mm-diameter by 200-mm-height samples were prepared in a gyratory compactor. Three were used to fabricate full-size (100-mm diameter, 150-mm height) specimens that were used as the control; the remainder were used to produce the small-scale specimens. The full-size specimens were fabricated in accordance with AASHTO PP 60 (AASHTO, 2013). The small-scale specimens were fabricated by coring perpendicular to the long axis of a gyratory specimen using a sample holder as shown in Figure 3; generally, three small-scale specimens were cored from each gyratory sample. In some cases, the height of the gyratory sample was less than 200 mm, and from these samples, only two small-scale specimens were produced. The small-scale specimens were fabricated such that, at a minimum, the top and bottom approximately 1 in of the gyratory sample was avoided. This decision was made in an effort to maintain a uniform air void content between specimens (in accordance with the findings of Chen et al., 2013). Figures 4 and 5 show photographs of the gyratory sample after the small-scale specimens were cored and specimens prepared for testing, respectively. The small-scale specimens were then trimmed to length by use of a conventional wet saw to produce three samples each at 38-mm and 50-mm diameter by 110-mm height and three each at 38-mm and 50-mm diameter by 135-mm height.

Figure 3. Core Drill Sample Holder Used to Extract Small-Scale Cylindrical Specimens From Gyratory Sample

Figure 4. Gyratory Samples After Small-Scale Cylindrical Specimens Were Cored

Figure 5. Examples of 38 mm (*right*) and 50 mm (*left*) in Diameter Small-Scale Cylindrical Specimens Prepared for Testing

The specimens were all prepared from plant-produced mixtures. The gyratory samples were compacted either while still hot from original mixing or later by reheating in the laboratory. The intent was to produce gyratory samples that were compacted such that a full-size (100-mm diameter by 150-mm height) specimen would be produced at 7% to 8% air voids. However, some mixtures were produced with specimens having an air void content as high as 12%. Some specimen replicate groups were beyond the ±0.5% of the average air void specified in AASHTO PP 60 (AASHTO, 2013). Figure 6 shows the cumulative distribution of the air void content of the bulk specimens from all specimens with respect to specimen geometry. The legend in Figure 6 shows the specimen diameter and height for five sets of specimens having different geometries. As can be seen in Figure 6, the 50th percentile bulk air void content ranges from approximately 6.5% to 7.0% and the overall air void content ranges from 2% to 12%.

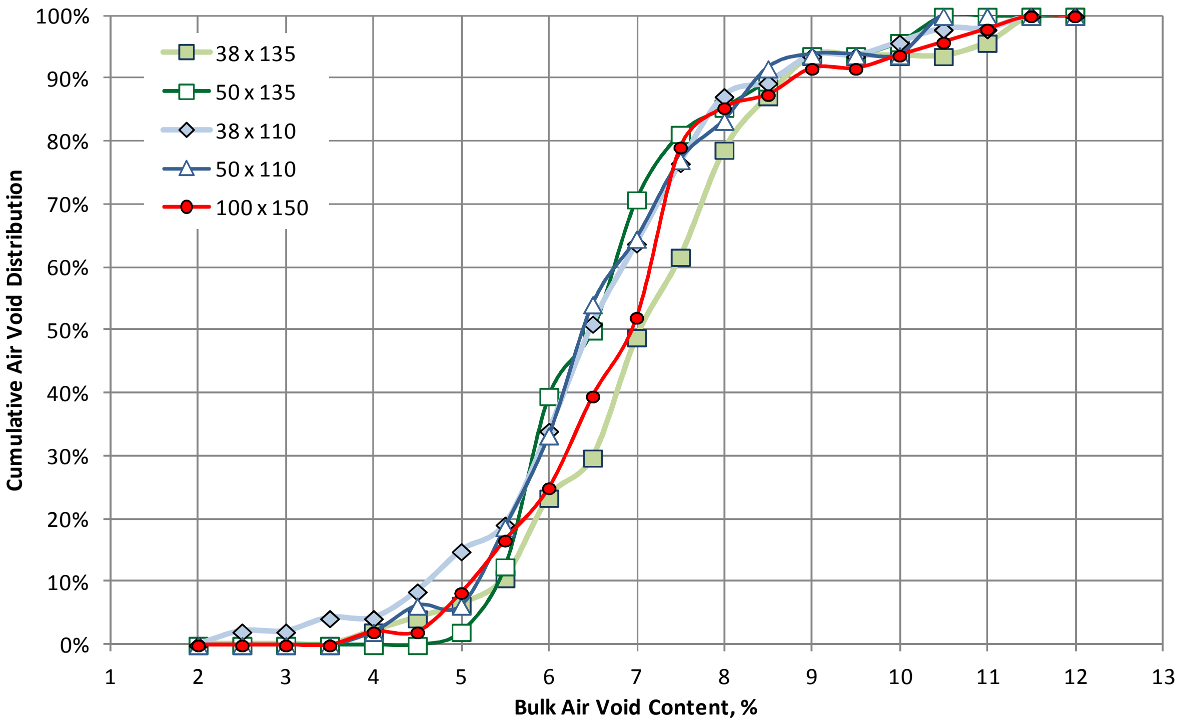

Figure 6. Bulk Air Void Content of Small-Scale and Full-Size Specimens Shown As Cumulative Percentage

Dynamic Modulus Testing

Small-scale dynamic modulus testing was conducted on cylindrical specimens having heights of 110 and 135 mm and diameters of 38 and 50 mm. The test results from these small-scale specimens were compared to the results from full-size specimens. All testing was conducted on an AMPT generally in accordance with AASHTO TP 79 (AASHTO, 2013). Deviations from the specification included using test specimens with higher-than-recommended air void contents and higher-than-recommended specimen-to-specimen variability. Data from these specimens were not removed from the data set in order to cover as wide a range of conditions as possible.

Originally, the researchers sought to replicate the work of Li and Gibson (2013) by testing specimens having a height of 110 and 140 mm. Although Li and Gibson (2013) used only one specimen diameter (38 mm), a second diameter (50 mm) was added to the current study to see if the larger diameter might correlate better with the full-size specimen geometry for larger NMAS mixtures. It was found that a small-scale specimen height of greater than 135 mm could not be achieved for a 50-mm-diameter specimen. When a small-scale specimen is cored horizontally from the parent 150-mm-diameter gyratory specimen, the two ends are rounded. The two ends must be trimmed so that they are flat and parallel. During this study, it was found that the maximum height that could be obtained was approximately 135 mm for the 50-mm-diameter specimens and slightly more than 140 mm for the 38-mm-diameter specimens. To keep all the 38- and 50-mm-diameter specimens the same height, the 135 mm height was chosen as the maximum height for all small-scale specimens rather than the 140-mm height used by Li and Gibson (2013). Figure 7 shows a photograph of a 38-mm-diameter by 110-mm-height specimen with LVDT gauges attached in the AMPT.

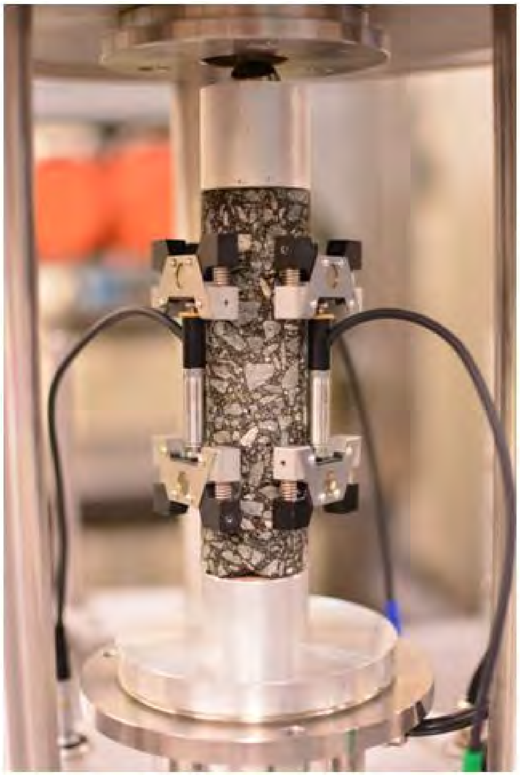

Figure 7. Close-up of 38-mm-Diameter Specimen Within AMPT Test Frame

RESULTS AND DISCUSSION

Literature Review

Conducting dynamic modulus tests on field-placed asphalt mixture materials in accordance with the AASHTO TP 79 (AASHTO, 2013) test procedure is problematic since the specification calls for a cylindrical test specimen having a 100-mm diameter and a 150-mm height. As most asphalt mixture layers are placed in the field at less than 150 mm, the fabrication of a 150-mm-height test specimen requires either the test specimen to be created from a single core containing multiple layers/materials or multiple cores wherein the desired layer is stacked until a sufficient height is achieved or an alternate test geometry to be employed. Pellinen et al. (2006) referenced a study in which they attempted to stack cores in different ways but could not achieve a scenario where strain measurements over the joints were not needed. The most prevalent alternative test specimen geometries include IDT and a reduced scale (or *small-scale*) version of the cylindrical geometry specified in AASHTO TP 79.

Kim et al. (2004) conducted a study on the development and analysis of dynamic modulus testing on asphalt mixture materials using the IDT specimen geometry. The study developed a methodology to conduct dynamic modulus testing using disk-shaped specimens having a 150-mm diameter and a thickness as thin as 38 mm. IDT testing was conducted by applying a compressive sinusoidal load to a specimen diametrically to produce a tensile response within the specimen. Kim et al. (2004) presented the results from 12 mixtures used in North Carolina. A gyratory compactor was used to prepare full-size cylindrical specimens that were tested axially, in accordance with AASHTO TP 79, and IDT specimens. Full-size cylindrical specimens were created from 150-mm-diameter samples having a height of 178 mm. IDT specimens were prepared from 150-mm-diameter samples compacted to a height of 60 mm. The parallel faces were trimmed so that a final IDT specimen height of 38 mm was produced. The specimens were produced such that the air void content was 4% ± 0.5%. Mixtures tested contained NMASs ranging from 9.5 to 25 mm with asphalt binder grades of PG 64-22 and PG 70-22. The percent asphalt ranged from 4.2% to 5.4% for base and intermediate mixtures to 5.0% to 6.4% for surface mixtures. Three replicates for each mixture type were tested.

Kim et al. (2004) analyzed the data by visually examining dynamic modulus master curves from full-size cylindrical and IDT specimens. The visual analysis showed good agreement between the two specimen geometries. Next, a statistical analysis was conducted using a *t*-test (with unequal variances) for each mixture at six reduced frequencies (0.0001, 0.03, 2, 1, 400, and 24,000 Hz) to represent the entire master curve. The null hypothesis was that the dynamic modulus using the IDT geometry was the same as the dynamic modulus using the full-size cylindrical geometry. A *p*-value was compared to a critical value of 0.05 ($p > 0.05$ = no statistical difference). The statistical testing showed that of all tests conducted (12 mixtures × 5 reduced frequencies), 90% were found to have no statistical difference between the two test specimen geometries. The authors noted that the agreement between the two geometries decreased as the NMAS increased (see Table 2). The authors attributed these differences to the shorter gauge length used for the IDT geometry (50.8 mm) as compared to the maximum particle size. The authors also noted that for some replicates using the IDT geometry, the displacements between the two parallel surfaces were significantly different and suggested that a larger gauge length may be needed for large aggregate particle mixtures.

In addition, Kim et al. (2004) computed a percentage difference between the moduli from the two geometries; 288 combinations (8 frequencies × 3 temperatures [-10, 10, and 35 °C] × 12 mixtures) were studied. The authors found that about 70% of the tests had a difference less than 10%, as shown in Table 2.

A majority of the high percentage differences were found at the 35° C test temperature. The authors considered that the differences might be attributable to orientation of compaction among other effects. The authors also compared the phase angles by plotting the vertical and horizontal phase angle from the IDT geometry along with the phase angle from the full-size cylindrical specimen geometry. In most cases, the phase angle from the full-size cylindrical specimens was between the vertical and horizontal phase angles from the IDT specimens.

Table 2. Summary of Percent Difference in Dynamic Moduli From Full-Size Cylindrical and IDT Specimens

	Nominal Maximum Aggregate Size, mm				
	9.5	**12.5**	**19.0**	**25.0**	**All**
p-value					
Greater than 0.05	95%	80%	95%	75%	90%
% Difference					
Less than 5%	48%	46%	28%	25%	39%
Between 5% and 10%	21%	33%	42%	19%	31%
Between 10% and 20%	21%	21%	26%	19%	22%
Greater than 20%	10%	0%	4%	38%	8%

Data were taken from Kim et al. (2004).

Kutay et al. (2009) examined full-size cylindrical specimens for dynamic modulus testing and both full-size and small-scale cylindrical specimens for unixial tension-compression fatigue testing using the simplified viscoelastic continuum damage (S-VECD). The authors used small-scale cylindrical specimens with two different geometries: 71.4 × 150 mm and 38.1 × 100 mm. The mixtures were created using the same gradation but contained different additives such as crumb rubber, terpolymer, styrene-butadiene-styrene (SBS) polymer–modified binder, air-blown asphalt binder, and fiber reinforcement as well as a control. Small-scale specimens were cut horizontally out of a gyratory sample in groups of three, and the full-size specimens were created using the traditional vertical coring method. Samples were also cut horizontally from a field slab from an accelerated loading facility. When the authors examined the damage characteristic curves defined by the S-VECD theory using a uniaxial tension-compression test, they found no difference between the results from full-size and small-scale test specimens.

Pellinen et al. (2006) examined another approach to the testing of road cores. The authors objected to using the IDT resilient modulus test because it is considered a non-homogenous test, meaning that its response is shape-dependent and assumptions about elastic and viscoelastic behavior must be made. A method was proposed that used rectangular specimens cut from cores sized 80 × 75 × 130 mm. Results from the rectangular specimens were compared to results from full-size cylindrical samples. Rectangular samples were used because they could be easily fabricated from existing road cores for forensic and/or post-construction analysis and comparison. This also allowed the authors to investigate the anisotropy within the gyratory sample by cutting the rectangular sample both vertically and horizontally within the sample. In addition, the authors investigated the impact of using a sulfur compound to hold a specimen together in the case that the core was too thin to create a single specimen and the effect of capping the specimen to create smooth loading surfaces. The use of a composite specimen was investigated by cutting the 80 × 75 × 130 mm sample into two 37.5 × 75 × 130 mm samples and binding them together using the sulfur compound as a bonding agent.

The rectangular specimens described in Pellinen et al. (2006) were found to be slightly stiffer than their cylindrical gyratory counterparts. An analysis of variance (ANOVA) comparing the laterally loaded, vertically loaded, and composite rectangular specimens found no significant differences at $\alpha = 0.05$. The same result was found when the rectangular specimens and the traditionally made gyratory specimens were compared. The authors also noted the discrepancy between a lack of significant differences from statistical analysis and the observed differences in stiffness values between sample types. They cited the small sample size and high degree of variability in the dynamic modulus test, referencing a coefficient of variability as high as 47% between samples, as being the cause of the acceptance of the null hypothesis despite the general trends. Based on this finding, the authors stated that a 10% to 15% modulus increase can be considered acceptable when different specimen geometries are examined. The authors concluded that more testing was needed to validate these results, but that the initial findings indicated that using rectangular specimens is a feasible way to test pavement cores.

Witczak et al. (2000) conducted a study to determine the minimum test specimen dimensions for uniaxial testing that would provide accurate material characterization independent of NMAS and specimen size. The authors tested cylindrical specimens with diameters of 70, 100, and 150 mm and height-to-diameter (H/D) ratios of 1.0, 1.5, 2.0, and 3.0

using the dynamic modulus and repeated load permanent deformation (RLPD) tests. These tests were conducted on mixtures with an NMAS of 12.5 mm and 19 mm and an air void content tolerance of ±0.5% and mixtures with an NMAS of 37.5 mm and an air void content tolerance of ±1.0%. Duplicate specimens were tested for each mixture type, diameter, and H/D ratio, totaling 216 specimens. The authors then analyzed the data using a two-way ANOVA considering specimen diameter and aspect ratio. When the H/D ratio required a specimen taller than the standard 150-mm height for the dynamic modulus test, multiple specimens were stacked and an adhesive was used at the joint. However, during the RLPD test, because of the sensitivity to the lateral restraint caused by the glue in the stacked specimens, a thin layer of asphalt binder was used along the joint instead.

The dynamic modulus testing by Witczak et al. (2000) was conducted at a high stiffness condition (4 °C, 16 Hz, 145 psi nominal stress) and a low stiffness condition (40 °C, 0.1 Hz, 5 psi nominal stress). The strains were measured using two LVDTs 180 degrees apart with a gauge length equal to the specimen diameter. The ANOVA of the data showed that there was no significant difference between the means for all samples; however, upon further study, the authors decided that the ANOVA could not detect the difference between means because of the variability of the data, particularly for samples with an H/D ratio below 1.5. Thus, the authors concluded that dynamic modulus tests should be conducted on samples with a minimum H/D ratio of 1.5. When examining the phase angle, the authors determined that the specimen diameter did have a significant effect but ultimately concluded that more research was needed to study this effect. The RLPD tests were conducted to 6,000 cycles at 40 °C and a stress level of 20 psi for the same suite of specimen dimensions. It was recommended that for RLPD tests, a minimum specimen diameter of 100 mm and a minimum H/D ratio of 1.5 should be required to characterize the material. In addition, the authors stated that the within-specimen variability was higher than the between-specimen variability and that additional instrumentation could improve the reliability of the E* and RLPD tests.

Li and Gibson (2013) compared the results of dynamic modulus testing using small-scale cylindrical specimens having a 38-mm diameter and both a 110- and 140-mm height with the dynamic modulus from full-size specimens. All sets of specimens were tested using axial compression loading in accordance with ASSHTO TP 79 (AASHTO, 2013). Small-scale cylindrical specimens were prepared by coring vertically or horizontally through 150-mm-diameter field cores or gyratory-prepared samples. Testing was conducted at temperatures of 4.4, 21.1, 37.8, and 54.4 °C at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz on three replicates per mixture. Ten mixtures were tested having an NMAS that ranged from 4.75 to 19.0 mm. The binder PG ranged from PG 58-34 to PG 82-22. The study showed that, in general, the dynamic modulus of the small-scale specimens was less than that of the full-size specimens. The authors found that the difference between the dynamic modulus of the 110-mm-height small-scale and full-size specimens to be generally less than 20%. The difference between the dynamic modulus of the 140-mm-height small-scale and full-size specimens was generally found to be greater than 20%.

Laboratory Evaluation

Figure 8 shows an example of the dynamic modulus testing results for a single asphalt mixture; the results are included for both 38- and 50-mm-diameter specimens having a height of 110 mm. The figure shows the dynamic modulus values at the four test temperatures. For each temperature, there are six data points corresponding to the six test frequencies. Each data point represents the average dynamic modulus of three replicates. The data are plotted with respect to a dividing line representing the line of equality. Surrounding the line of equality are two sets of dashed lines representing ±10% and ±20% difference from the line of equality. As can be seen in Figure 8, the data at 4.4, 21.1, and 37.8 °C for both specimen diameters for this particular mixture lie nearly on the line of equality. Based on Figure 8, it can be said that there is little difference between the dynamic modulus from full-size or small-scale specimens for this mixture at either specimen diameter at the three lowest test temperatures. The data from the 54.4 °C test temperature show that the small-scale specimens are up to approximately 10% to 20% stiffer (at certain frequencies) than the full-size specimens at the 50- and 38-mm diameters, respectively.

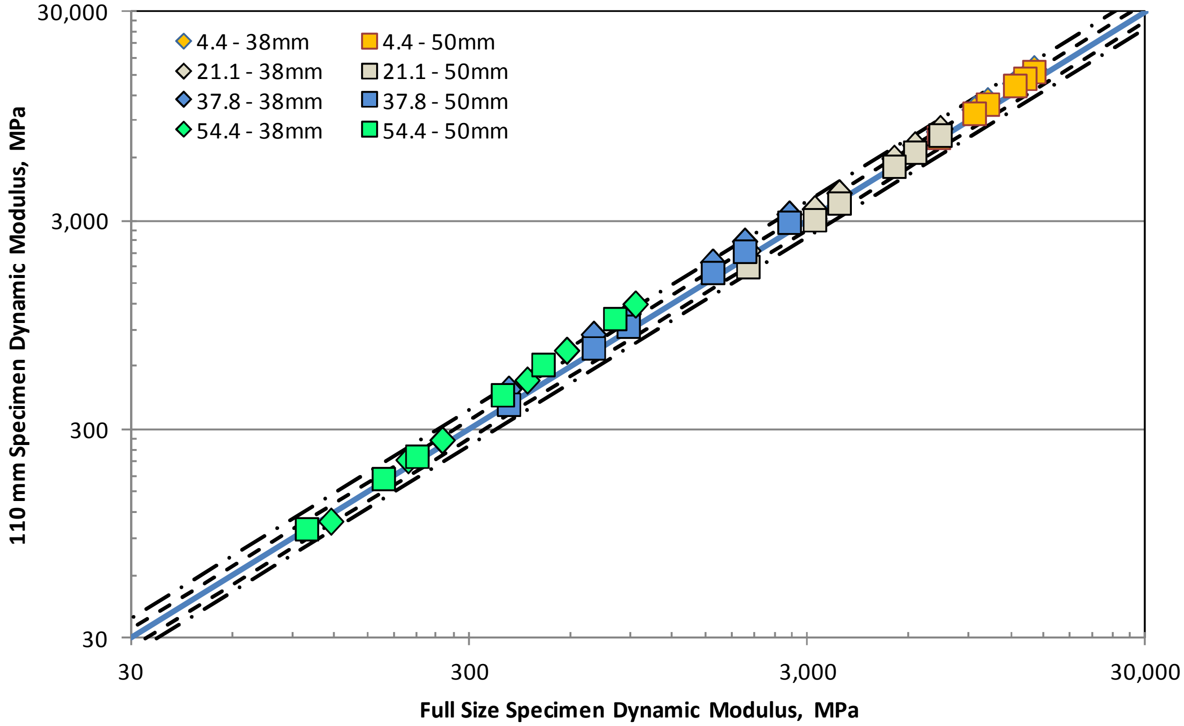

Figure 8. Example Showing Dynamic Modulus of 110 mm in Height Small-Scale Specimen Versus Full-Size Specimen

Assessing Agreement

The main difficulty in assessing the agreement between specimen geometries using the results of dynamic modulus testing is that the agreement should ideally be compared at each temperature and frequency combination. This is because the potential difference in dynamic modulus between the different temperatures and frequencies is greater than that between mixtures or even specimen geometries. From the studies described in the literature review, agreement between different specimen geometries was assessed by either conducting statistical analysis; quantifying the percent difference at a chosen temperature and frequency combination (e.g., 21.1 °C and 10 Hz); or comparing all the temperature/frequency combinations graphically by visual inspection with respect to the line of equality. While attempting to assess agreement, it is important also to consider the inherent between-specimen variability.

Figure 9 shows the average between-specimen coefficient of variation (COV) for dynamic modulus with respect to specimen geometry. The results shown in Figure 9 are the average COVs across all frequencies and mixture types and are calculated from the COVs of the three replicates. As can be seen in Figure 9, the 54.4 °C test temperature has the highest average between-specimen COV and that the COV decreases with decreasing test temperature. The COV for the three replicates at the 4.4, 21.1, and 37.8 °C test temperatures ranged from approximately 1% to 38%. The COV for the three replicates at the 54.4 °C test temperature ranged from approximately 4% to 51%. Because of the significantly higher COV at the 54.4 °C test temperature, the data from this temperature were not used in further analysis of the specimen geometries.

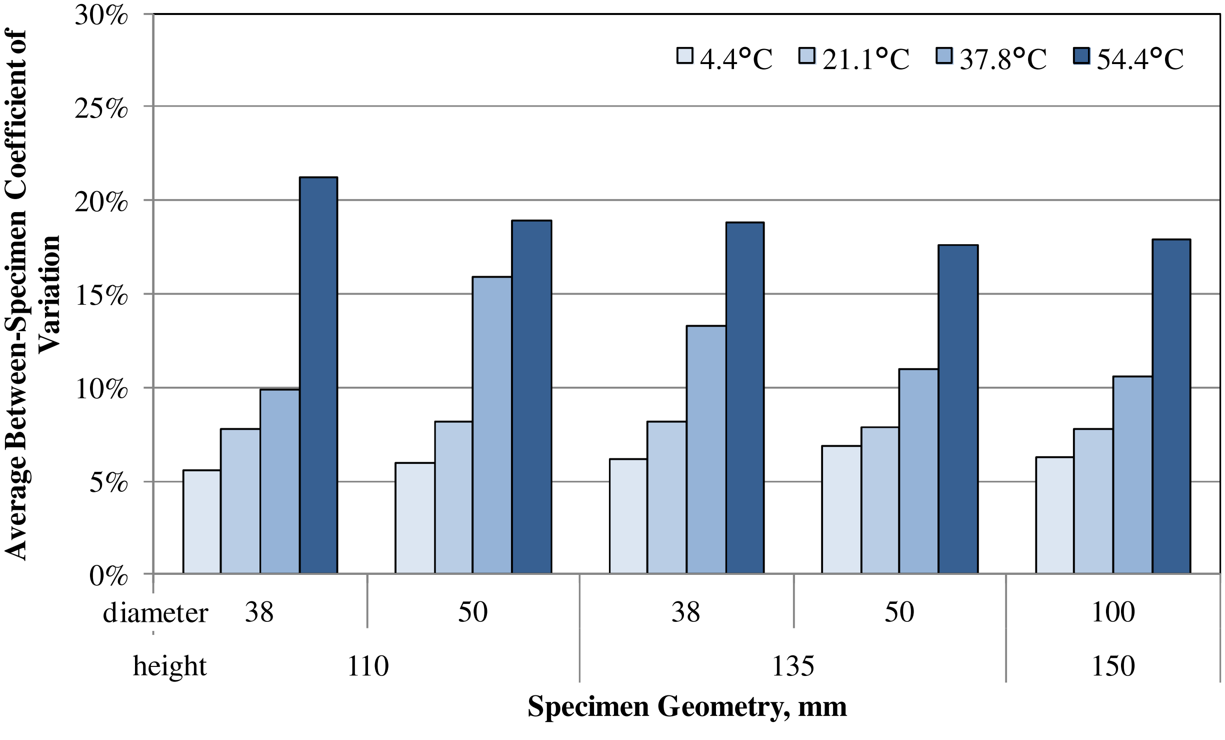

Figure 9. Average Between-Specimen Coefficient of Variation for Dynamic Modulus With Respect to Specimen Geometry

Results From Specimens 135 mm in Height

Figures 10 and 11 show the results of dynamic modulus tests for 135-mm-height small-scale specimens at 38- and 50-mm diameters, respectively, versus the results from full-size specimens.

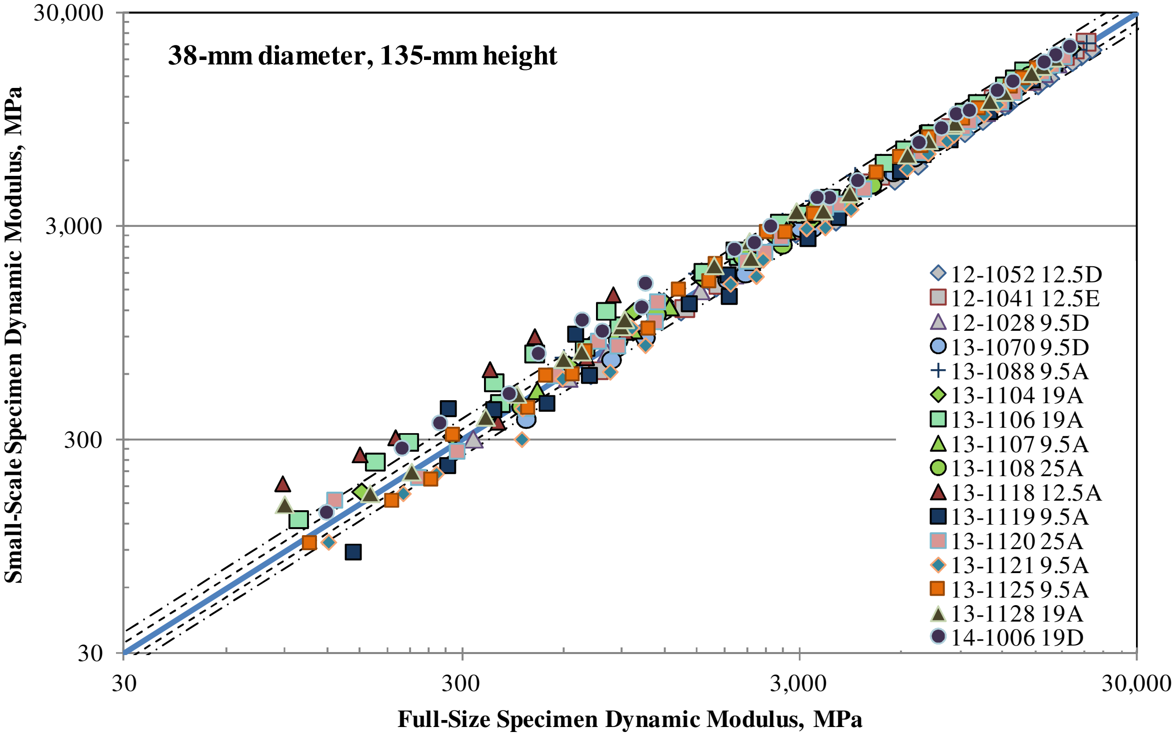

Figure 10. Results Showing Dynamic Modulus of Small-Scale Specimen 38 mm in Diameter by 135 mm in Height Versus Full-Size Specimen

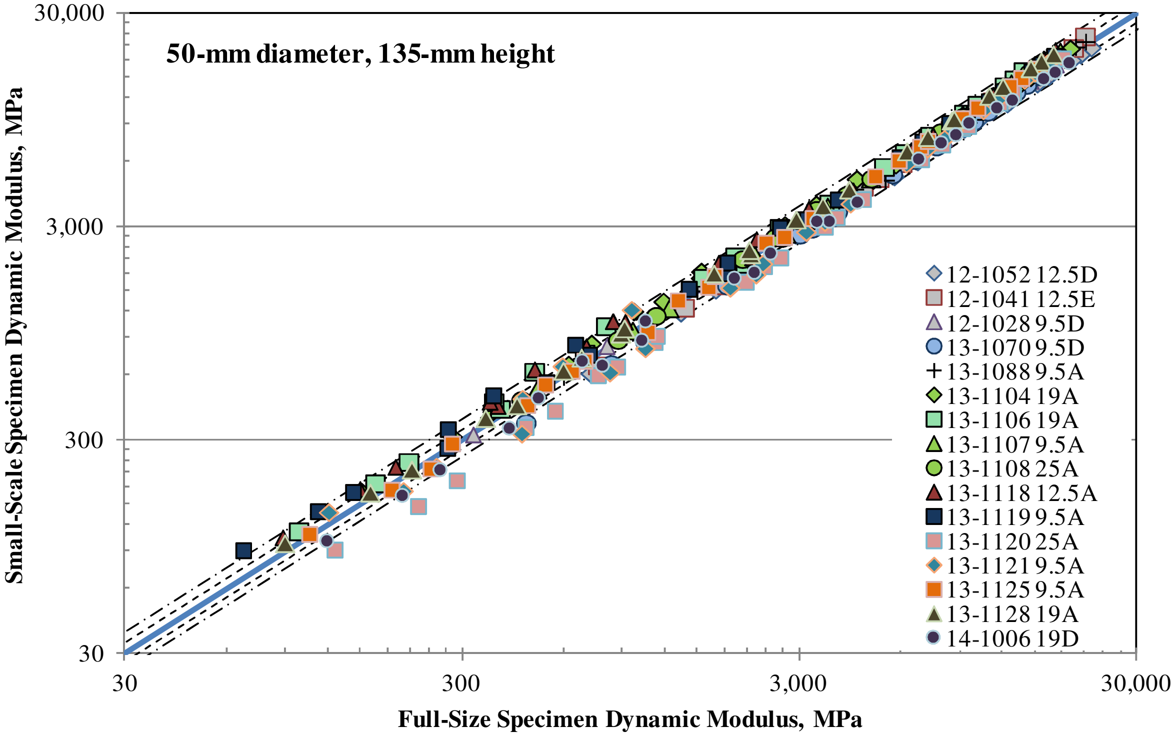

Figure 11. Results Showing Dynamic Modulus of 50-mm-Diameter by 135-mm-Height Small-Scale Specimens Versus Full-Size Specimens

In the two figures, each mixture is identified in the legend as xx-xxxx yy.yz, where *xx-xxxx* is the Lab Mix ID as defined previously; *yy.y* is the NMAS in millimeters; and *z* represents the binder PG where A = PG 64-22, D = PG 70-22, and E = PG 76-22. As can be seen from each figure, the agreement of dynamic modulus between small-scale and full-size specimens generally decreases with decreasing stiffness. By visual inspection, the agreement of dynamic modulus between small-scale and full-size specimens generally improves with increasing small-scale specimen diameter when the 38-mm-diameter small-scale specimen results (Figure 10) are compared to the 50-mm-diameter small-scale specimen results (Figure 11).

Results From Specimens 110 mm in Height

Figures 12 and 13 show the results of dynamic modulus tests for 110-mm-height small-scale specimens at 38- and 50-mm diameters, respectively, versus full-size specimens. As can be seen in each figure, the agreement of dynamic modulus between small-scale and full-size specimens generally decreases with decreasing stiffness as was found for the 135-mm-height small-scale specimens. By visual inspection, it is less clear if the agreement of dynamic modulus between small-scale and full-size specimens increases with increasing small-scale specimen diameter when moving from the 38-mm-diameter small-scale specimen results (Figure 12) to the 50-mm-diameter small-scale specimen results (Figure 13).

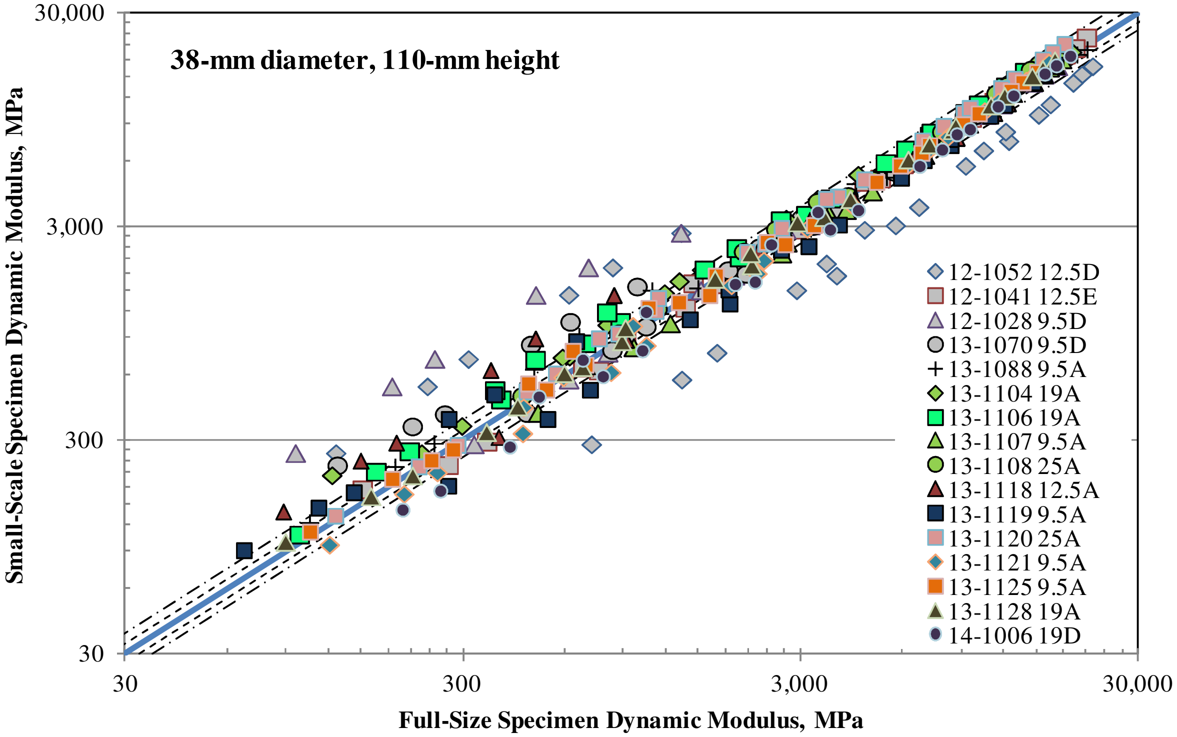

Figure 12. Results Showing Dynamic Modulus of 38 mm in Diameter by 110 mm in Height Small-Scale Specimen Versus Full-Size Specimen

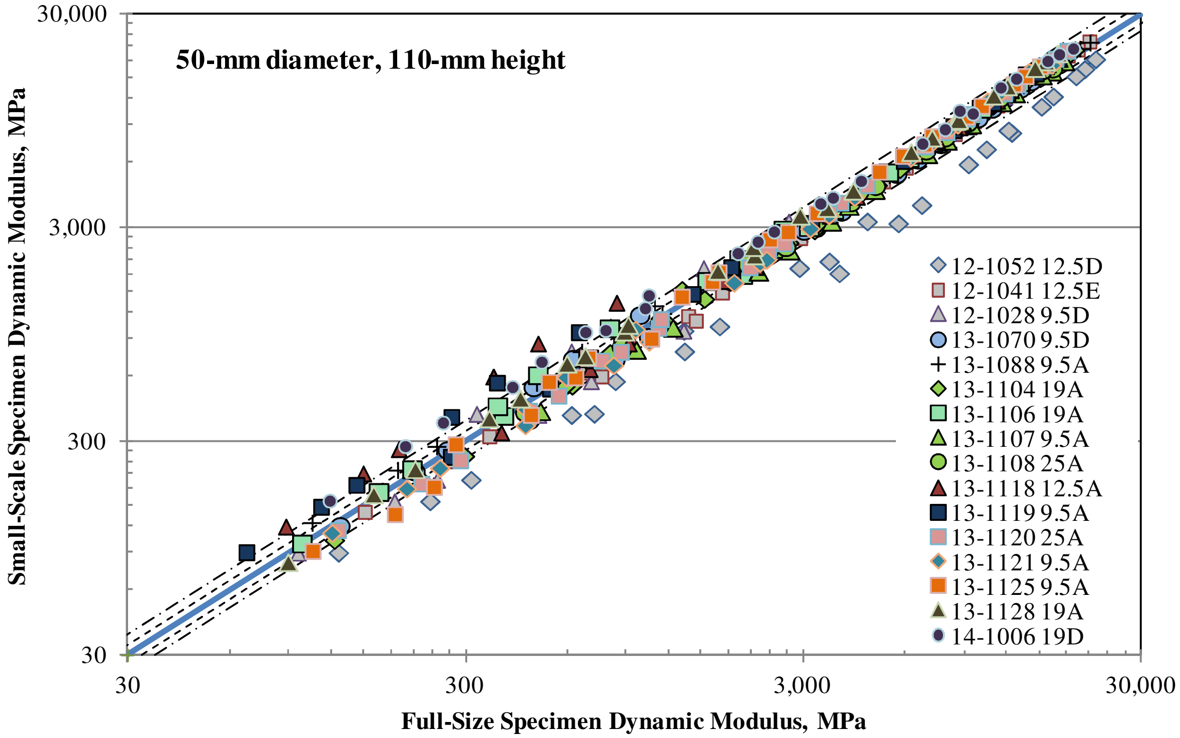

Figure 13. Results Showing Dynamic Modulus of 50 mm in Diameter by 110 mm in Height Small-Scale Specimens Versus Full-Size Specimens

Figures 12 and 13 show the influence of repeated testing on small-scale specimens. The first five mixtures tested (12-1028, 13-1070, 13-1088, 12-1041, and 12-1052) were first tested as 135-mm-height specimens at 4.4, 21.1, and 37.8 °C. Following this, they were trimmed down to 110-mm-height specimens by removing approximately 12.5 mm from each end of the specimen using a wet saw. The specimens having a new height of 110 mm were then retested at 4.4, 21.1, 37.8, and 54.4 °C. As can be seen in Figures 12 and 13, the results from the five mixtures (12-1028, 12-1041, 12-1052, 13-1070, and 13-1088) that were retested are less comparable to their full-size companions than the results from those mixtures that were not retested. This is likely due to the small-scale specimens being damaged during testing at the 135-mm height or during the trimming procedure. After reviewing the data from the five retested mixtures, the researchers decided to use unique specimens for each height for the remainder of the study.

Small-Scale Geometry Evaluation

An evaluation of the small-scale specimen geometry was completed by reviewing the dynamic modulus results on a sample-by-sample and mixture-by-mixture level, and ultimately conclusions and recommendations were drawn from the trends set by the average dynamic modulus values with respect to NMAS for the 16 tested mixtures. These efforts were carried out through all four NMASs based on the initial assumption that certain NMASs might require different small-scale sample sizes. For example, one might hypothesize that a larger NMAS (e.g., 25.0 mm) may require a larger specimen to characterize the mixture more accurately than that of a smaller NMAS mixture (e.g., 9.5 mm) simply based on the proportion of cross-sectional area that a single aggregate particle may occupy.

The approach for the small-scale specimen geometry evaluation compared the ratio of the small-scale specimen dynamic modulus to the full-size specimen dynamic modulus (henceforth referred to as *SS/FS ratio*) for each mixture. The SS/FS ratio was calculated as the average dynamic modulus from the three small-scale specimen replicates divided by the average dynamic modulus from the three full-size specimen replicates. The SS/FS ratio was calculated for each temperature and at each frequency. The SS/FS ratio values for all mixtures are provided in Appendix A. The dynamic modulus testing results showed that test data obtained at 54.4 °C had a much higher specimen-to-specimen variation and the SS/FS ratio was often found to be greater than ±20%. For these reasons, the specimen geometry evaluation was carried out only on data obtained at 4.4, 21.1, and 37.8 °C.

Figures 14 through 17 show the average SS/FS ratio of all of the mixtures for each of the respective small-scale geometries at a test frequency of 10 Hz. The data for the other frequencies followed a similar trend with the exception of the 12.5-mm NMAS at the 0.1 Hz frequency (as can be seen in Appendix B). From these figures, a SS/FS ratio of 1.0 indicates that the average dynamic modulus from small-scale and full-size specimens is the same. An SS/FS ratio of 1.1 or 0.9 indicates that the average dynamic modulus from the small-scale specimens is 10% stiffer or less stiff than the full-size specimens, respectively.

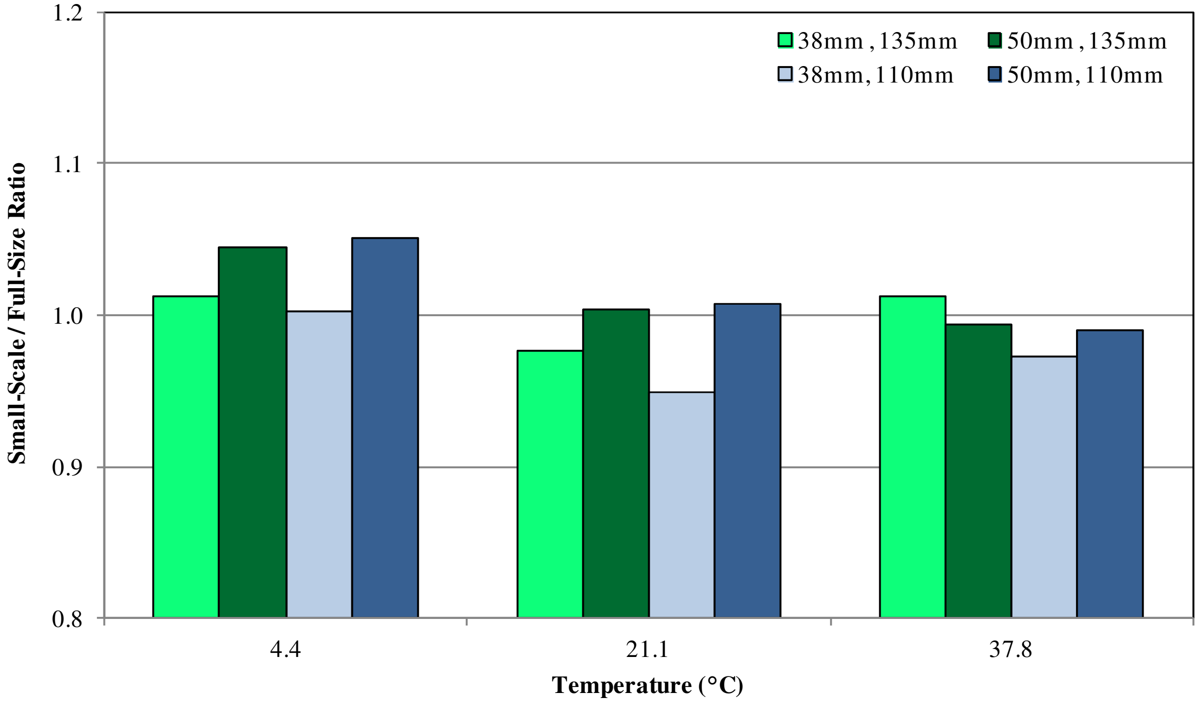

Figure 14. Small-Scale / Full-Size Dynamic Modulus Ratio at 10 Hz and Three Temperatures for 9.5-mm NMAS Mixtures

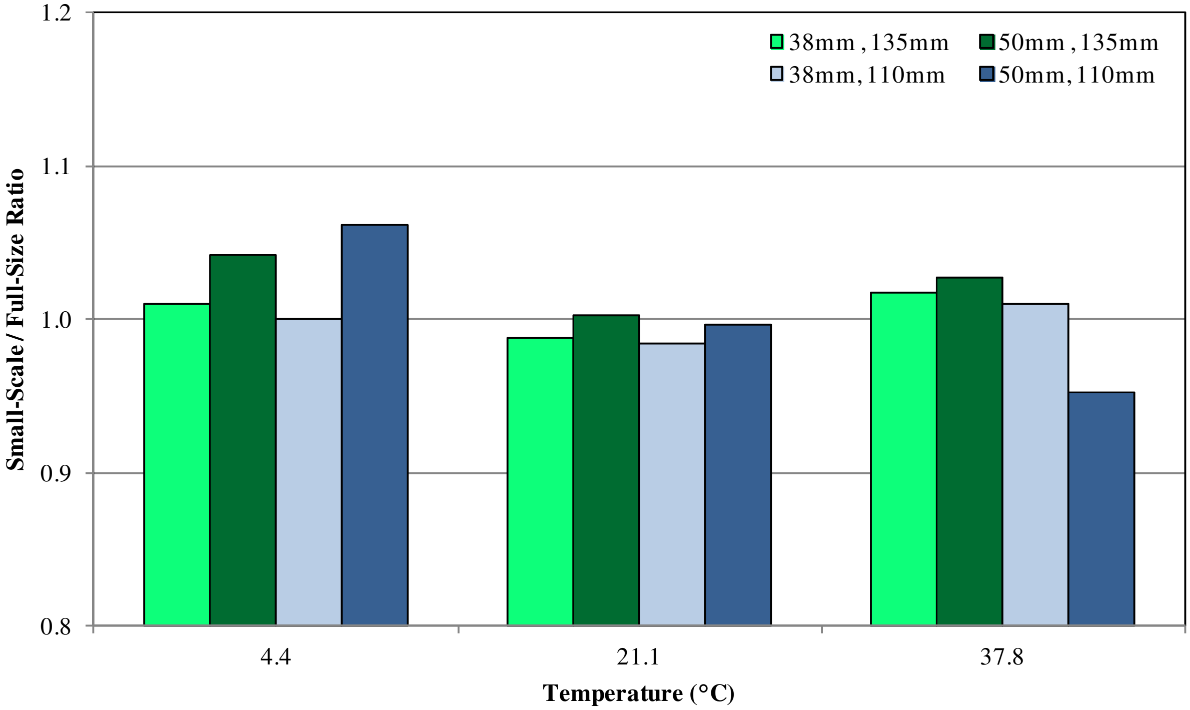

Figure 15. Small-Scale / Full-Size Dynamic Modulus Ratio at 10 Hz and Three Temperatures for 12.5-mm NMAS Mixtures

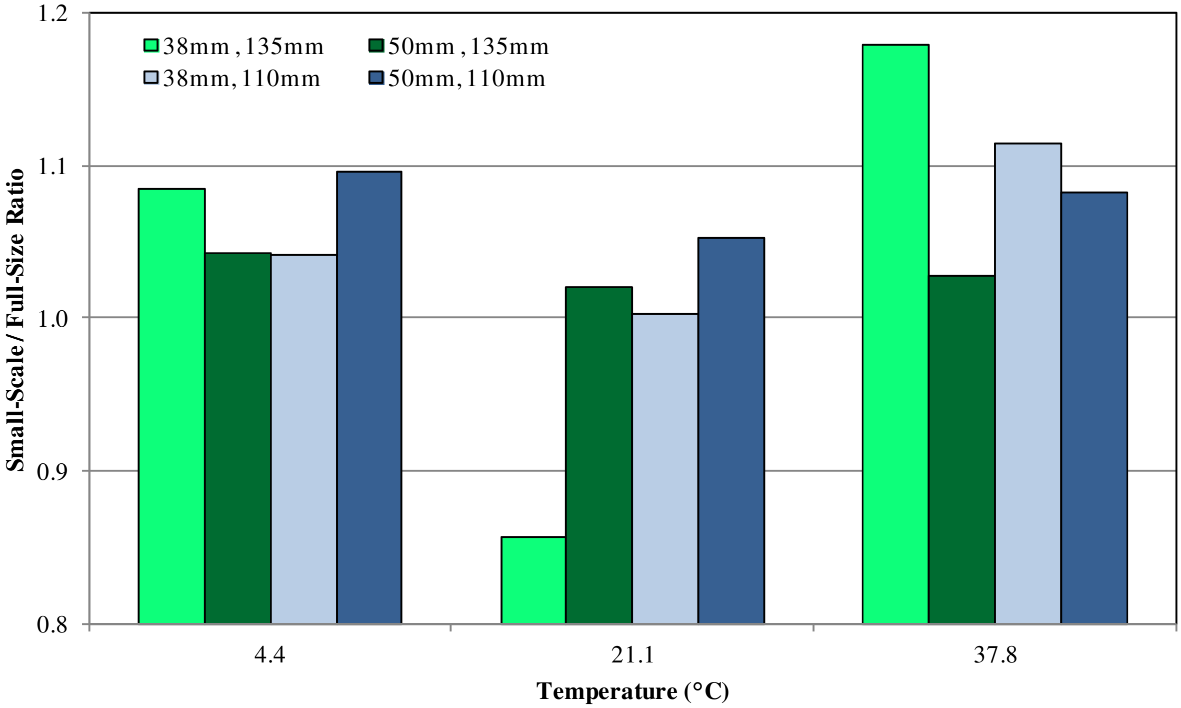

Figure 16. Small-Scale / Full-Size Dynamic Modulus Ratio at 10 Hz and Three Temperatures for 19.0-mm NMAS Mixtures

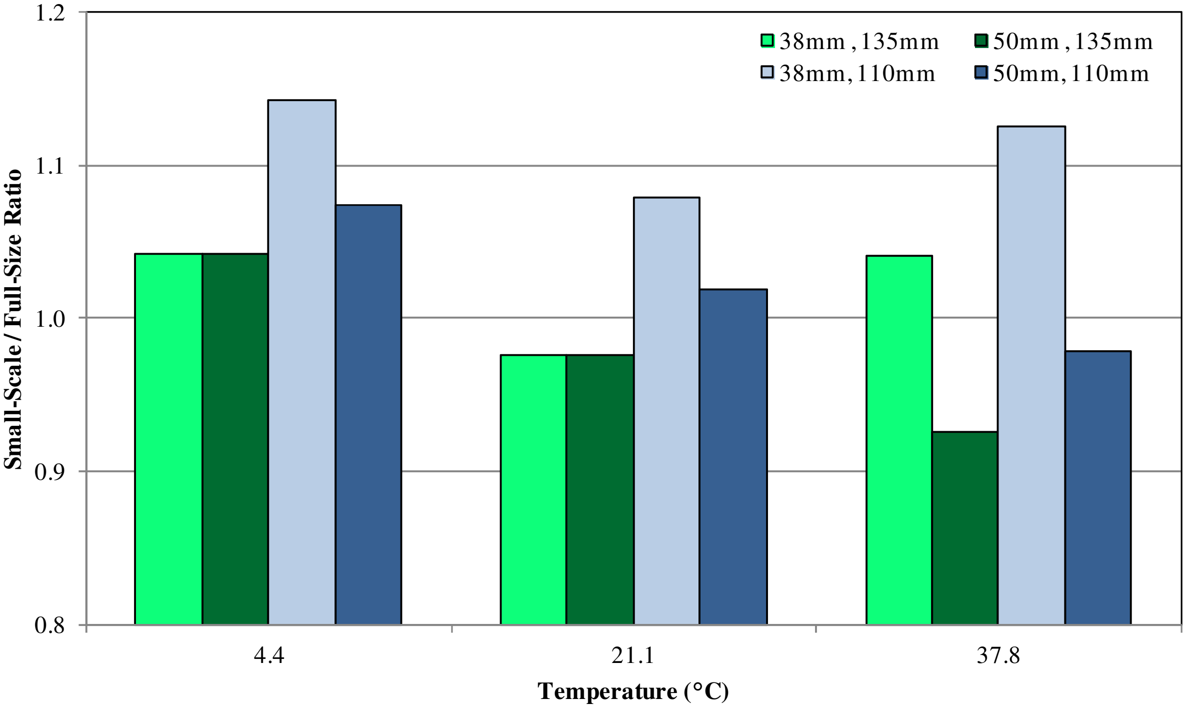

Figure 17. Small-Scale / Full-Size Dynamic Modulus Ratio at 10 Hz and Three Temperatures for 25.0-mm NMAS Mixtures

The SS/FS ratio for all small-scale specimen geometries from the 9.5- and 12.5-mm NMAS mixtures was found to lie within the range from 0.95 to 1.06 (i.e., about a 6% difference). Thus, there does not appear to be a significant difference between the specimen geometries for these NMASs. The SS/FS ratio for all small-scale geometries from 19.0-mm NMAS mixtures was found to lie within the range from 0.86 to 1.18. For these mixtures, the 38 × 135 mm specimen geometry had the greatest departure from a ratio of 1.0. If this geometry is ignored, the SS/FS ratio for 19.0-mm NMAS mixtures ranged from 1.0 to 1.11. The SS/FS ratio for all small-scale geometries from 25.0-mm NMAS mixtures was found to lie within the range from 0.93 to 1.14. For these mixtures, the 38 × 110 mm specimen geometry had the greatest departure from a ratio of 1.0. If this geometry is ignored, the SS/FS ratio for 25.0-mm NMAS mixtures ranged from 0.93 to 1.07.

From the results, the difference in SS/FS ratio between the four small-scale specimen geometries evaluated for 9.5- and 12.5-mm NMAS mixtures does not appear to be significant. However, for 19.0- and 25.0-mm NMAS mixtures, the 38-mm diameter was found to have the largest departure from an SS/FS ratio of 1.0; the effect of height appears to be mixed. This finding supports the initial hypothesis that measuring the dynamic modulus from a small-scale specimen having a larger diameter is beneficial for the larger NMAS mixtures.

SUMMARY OF FINDINGS

- Compared to the number of studies conducted on assessing asphalt mixture properties, there have been comparatively few studies on assessing alternative specimen geometries for dynamic modulus testing.

- According to Pellinen et al. (2006), a 10% to 15% modulus difference is acceptable between different geometries.

- There was no consistent method used to evaluate the difference in modulus between the various alternative geometry studies.

- The between-specimen variability was found to be highest for the dynamic modulus data obtained at the 54.4 °C test temperature.

- The departure from an SS/FS ratio of 1.0 was found to be similar for all small-scale specimen geometries for 9.5- and 12.5-mm NMAS mixtures.

- The largest departure from an SS/FS ratio of 1.0 was found for small-scale specimens having a diameter of 38 mm for 19.0- and 25.0-mm NMAS mixtures.

- There did not appear to be a clear trend with respect to departure from an SS/FS ratio of 1.0 and small-scale specimen height for 19.0- and 25.0-mm NMAS mixtures.

CONCLUSIONS

- *The use of small-scale cylindrical specimens is a feasible way to characterize asphalt mixtures using dynamic modulus when full-size cylindrical specimens cannot be fabricated.*

- *For 9.5- and 12.0-mm NMAS mixtures, any of the four small-scale geometries is a suitable alternative to full-size specimens.*

- *For 19.0- and 25.0-mm NMAS mixtures, 50-mm-diameter small-scale specimens are suitable alternatives to full-size specimens.*

RECOMMENDATIONS

1. *VCTIR and VDOT's Materials Division should use small-scale cylindrical specimens to characterize asphalt mixture performance using dynamic modulus testing when full-size specimens cannot be fabricated.*

2. *VCTIR should continue to study the applicability of using small-scale cylindrical specimens for dynamic modulus testing with additional mixture types (including permeable drainage layers and in-place recycled materials).*

3. *VCTIR should investigate the relationships between laboratory-prepared specimens and small-scale specimens obtained from pavement cores.*

BENEFITS AND IMPLEMENTATION

The direct cost savings to VDOT of measuring the dynamic modulus using small-scale specimens in lieu of full-size specimens is difficult to estimate. The primary benefit of using this test methodology is the ability to conduct forensic analysis of existing pavement structures since in situ layers are rarely placed sufficiently thick to allow fabrication of full-size specimens. An additional benefit is that the small-scale specimen geometry could be used for local calibration of materials properties for in situ pavement materials with AASHTOWare Pavement ME Design.

The recommendations provided in this report will be implemented through training provided to VDOT's Materials Division by VCTIR personnel. VDOT's Assistant State Materials Engineer, in coordination with VCTIR, will facilitate the implementation efforts, which are anticipated to take effect by the end of the first quarter of calendar year 2016. In addition, the 2015 version of AASHTO TP 79, *Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT),* will include a note allowing the use of small-scale cylindrical specimens for dynamic modulus testing.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of Sara Link, University of Virginia; Charles Schwartz and Sadaf Khosravifar, University of Maryland; Mostafa Elseifi, Louisiana State University; Troy Deeds, Donnie Dodds, Benjamin Earl, Ken Elliton, and Kim Snead, VCTIR; Trenton Clark, Virginia Asphalt Association; and the personnel at S. L. Williamson, Superior Paving, Lee Hy Paving, Independence Construction Materials, Colony Construction, and Virginia Paving. The authors acknowledge Ed Deasy and Linda Evans, VCTIR, for their assistance with the editorial process. Rob Crandol, VDOT Materials Division; David Lee, VDOT Salem District; and Harikrishnan Nair, VCTIR, served as the Technical Review Panel for this study.

REFERENCES

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 33rd Edition and AASHTO Provisional Standards*. Washington, DC, 2013.

Bonaquist, R. *Refining the Simple Performance Tester for Use in Routine Practice*. NCHRP Report 614. Transportation Research Board of the National Academies, Washington, DC, 2008.

Chen, J., Huang, B., and Shu, X. Air-Void Distribution Analysis of Asphalt Mixture Using Discrete Element Method. *Journal of Materials in Civil Engineering*, Vol. 25, No. 10, 2013, pp. 1375-1385.

Kim, Y.R., Seo, Y., King, M., and Momen, M. Dynamic Modulus Testing of Asphalt Concrete in Indirect Tension Mode. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1891. Transportation Research Board of the National Academies, Washington, DC, 2004, pp. 163-173.

Kutay, M.E., Gibson, N., Youtcheff, J., and Dongre, R. Use of Small Samples to Predict Fatigue Lives of Field Cores; Newly Developed Formulation Based on Viscoelastic Continuum Damage Theory. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2127. Transportation Research Board of the National Academies, Washington, DC, 2009, pp. 90-97.

Li, X., and Gibson, N. Using Small Scale Specimens for AMPT Dynamic Modulus and Fatigue Tests. *Journal of the Association of Asphalt Paving Technologists*, Vol. 82, 2013, pp. 579-615.

Pellinen, T.K., Xiao, S, and Raval, S.Y. Dynamic Modulus Testing of Thin Pavement Cores. *Journal of ASTM International,* Vol. 3, No. 4, 2006, pp. 144-157.

Witczak, M.W., Bonaquist, R., Von Quintus, H., and Kaloush, K. Specimen Geometry and Aggregate Size Effects in Uniaxial Compression and Constant Height Shear Tests. *Journal of the Association of Asphalt Paving Technologists,* Vol. 69, 2000, pp. 733-793.

Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus, H. *Simple Performance Test for Superpave Mix Design.* NCHRP Report 465. Washington, DC, 2002.

APPENDIX A

SMALL-SCALE / FULL-SIZE DYNAMIC MODULUS RATIO SHOWN FOR 9.5-, 12.5-, 19.0-, AND 25.0-mm NMAS WITH RESPECT TO TEST FREQUENCY

Vertical bars with dashed borders signify data from specimens that were tested at 135-mm height prior to testing at 110-mm height.

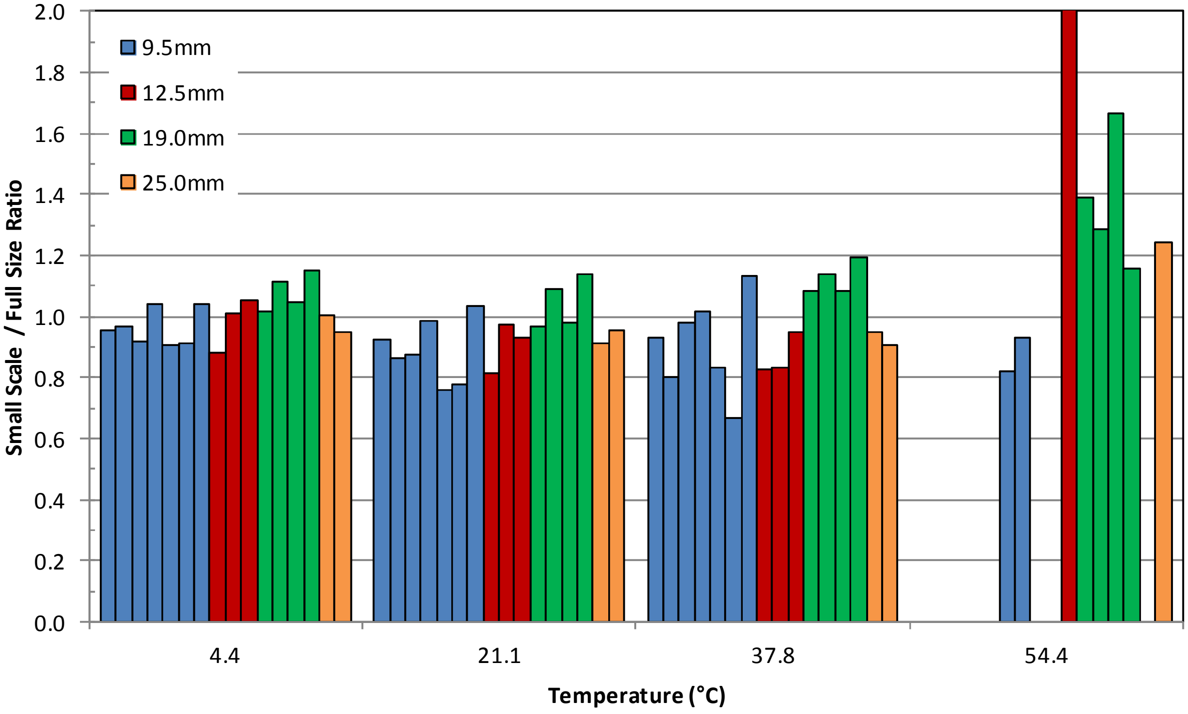

Figure A1. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 135 mm Specimens, 0.1 Hz

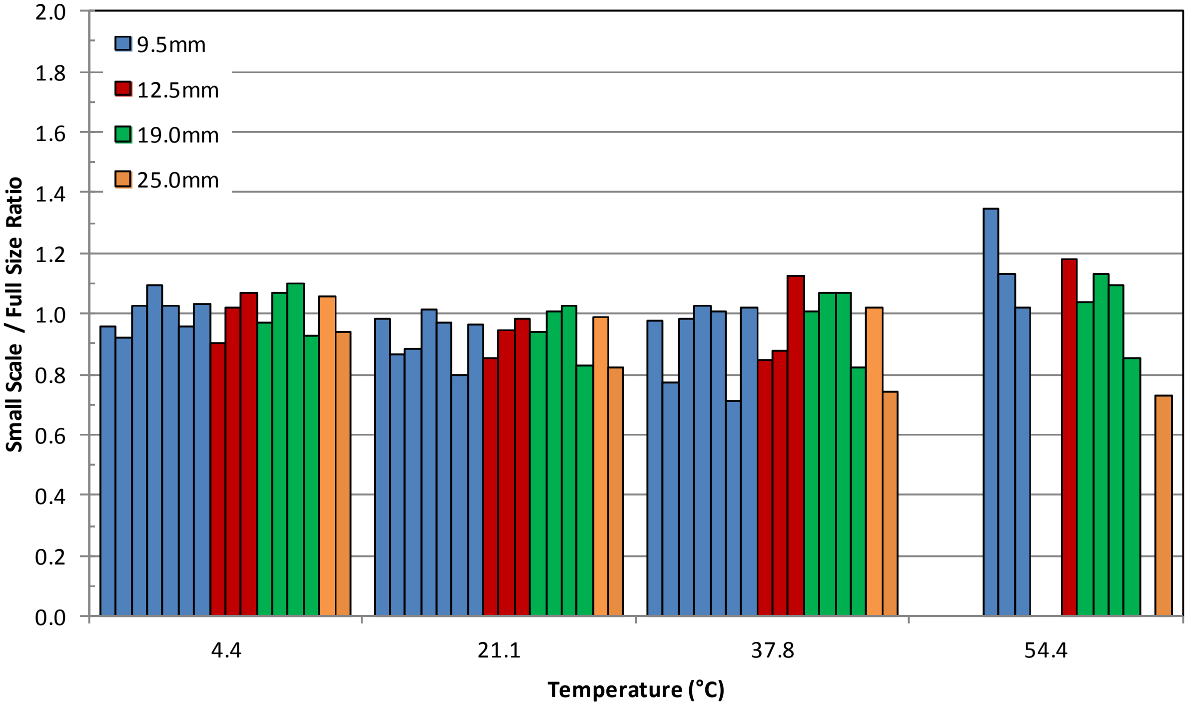

Figure A2. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 135 mm Specimens, 0.1 Hz

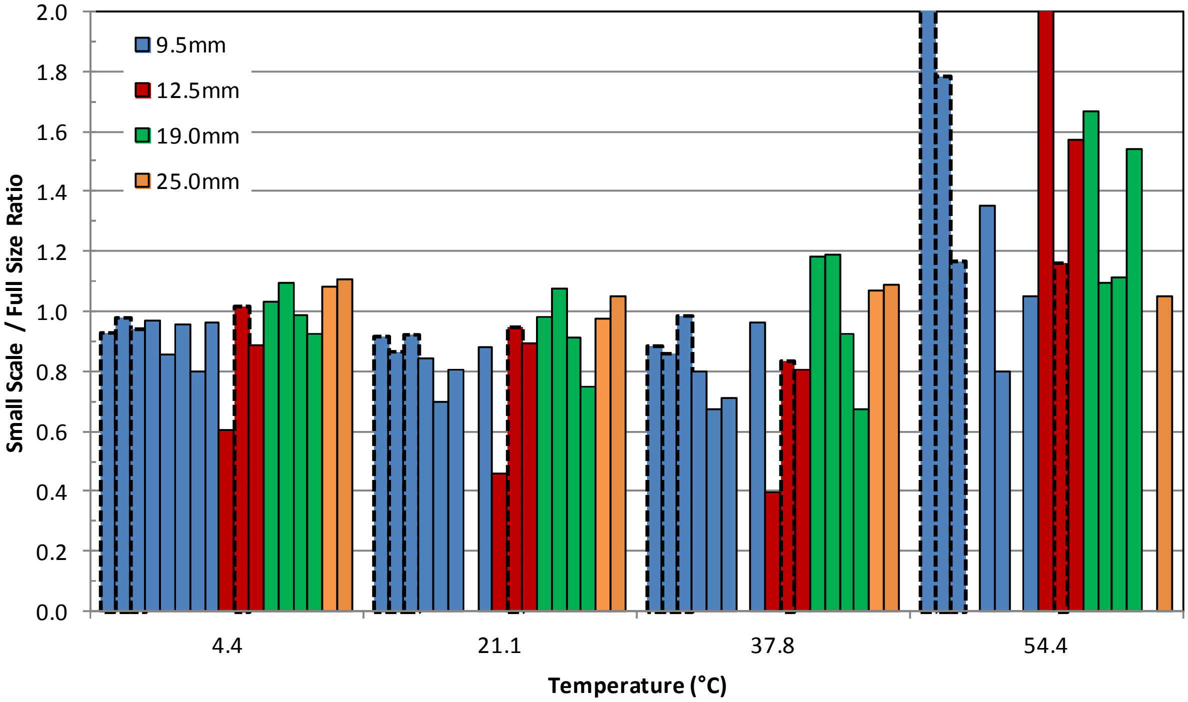

Figure A3. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 110 mm Specimens, 0.1 Hz

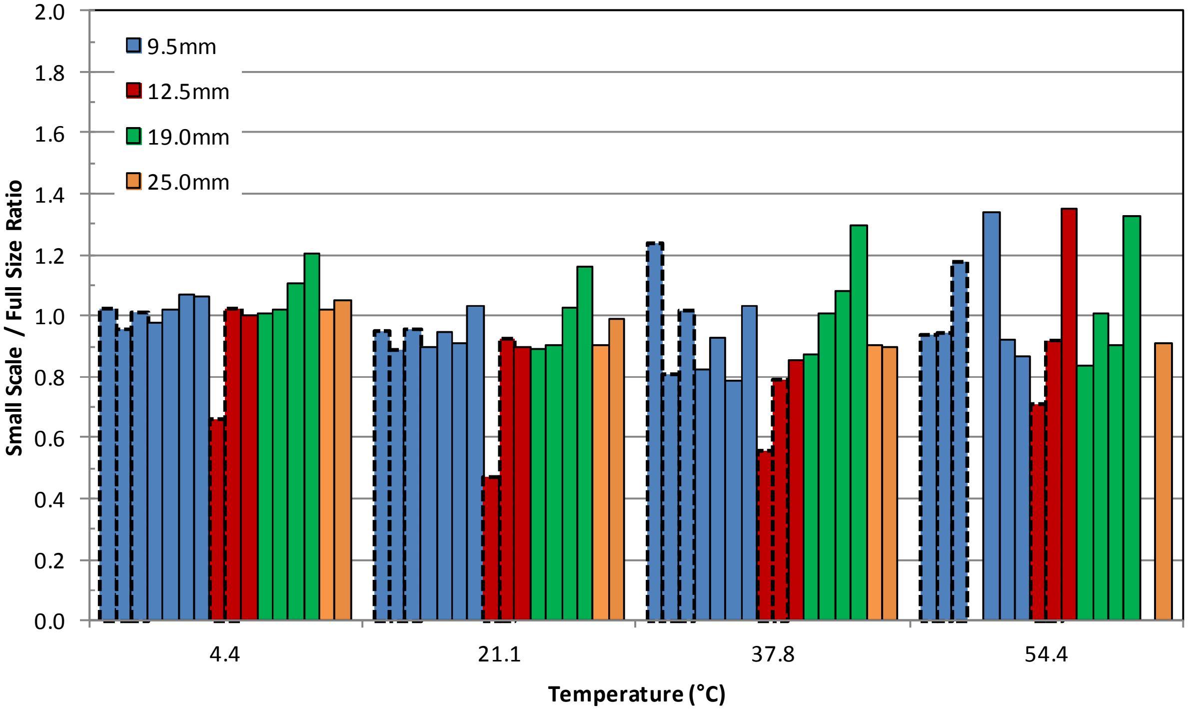

Figure A4. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 110 mm Specimens, 0.1 Hz

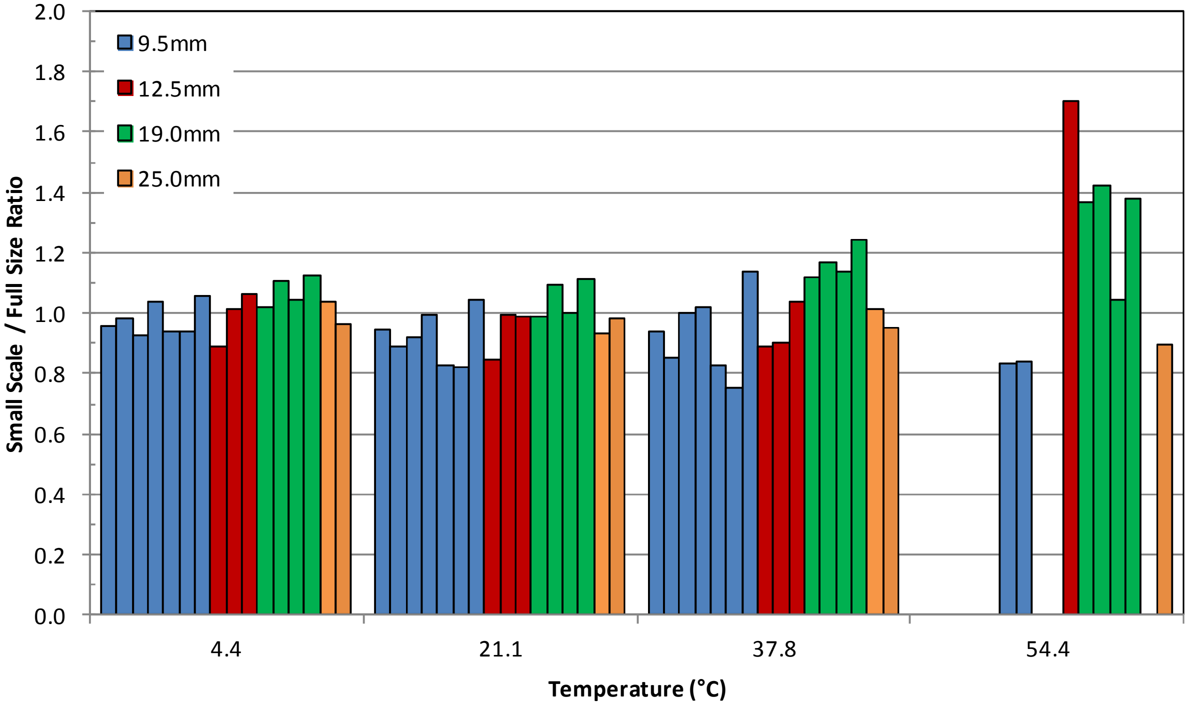

Figure A5. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 135 mm Specimens, 0.5 Hz

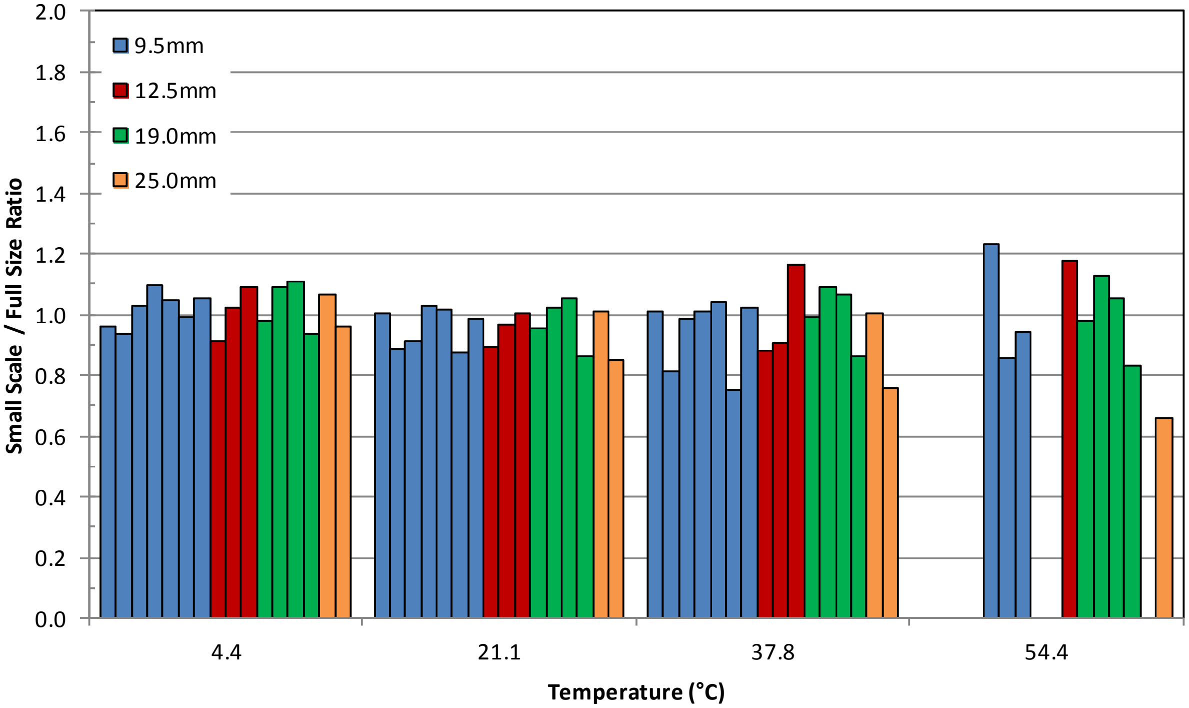

Figure A6. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 135 mm Specimens, 0.5 Hz

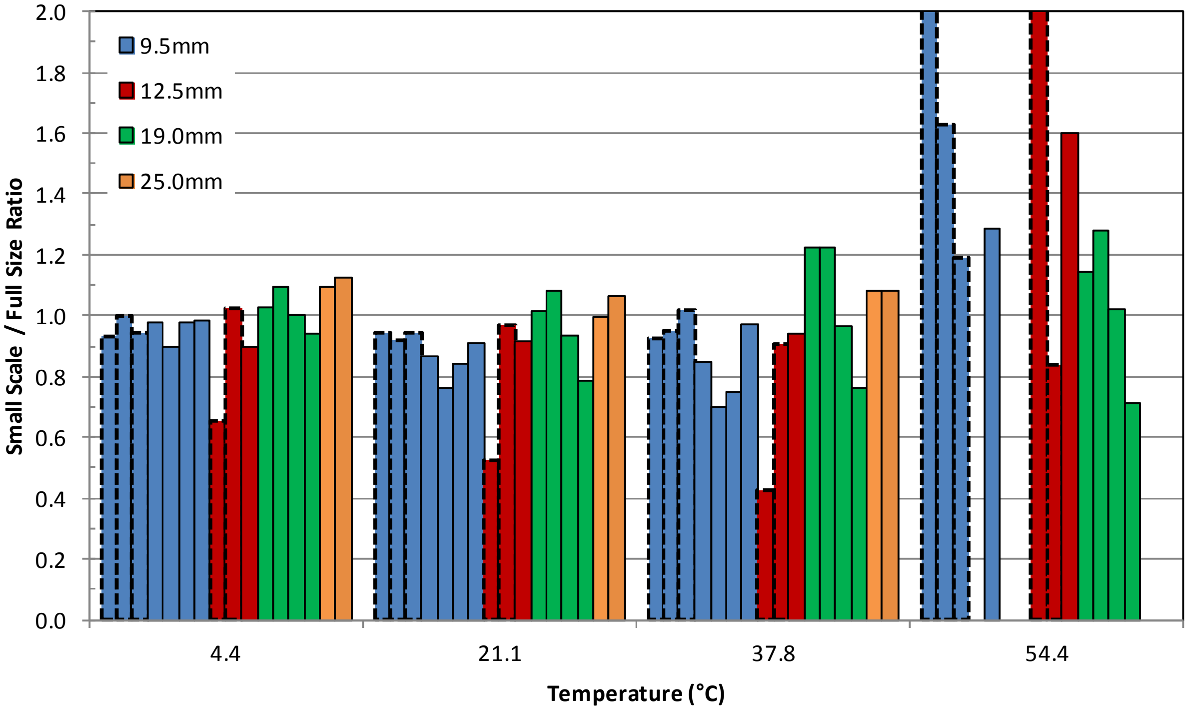

Figure A7. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 110 mm Specimens, 0.5 Hz

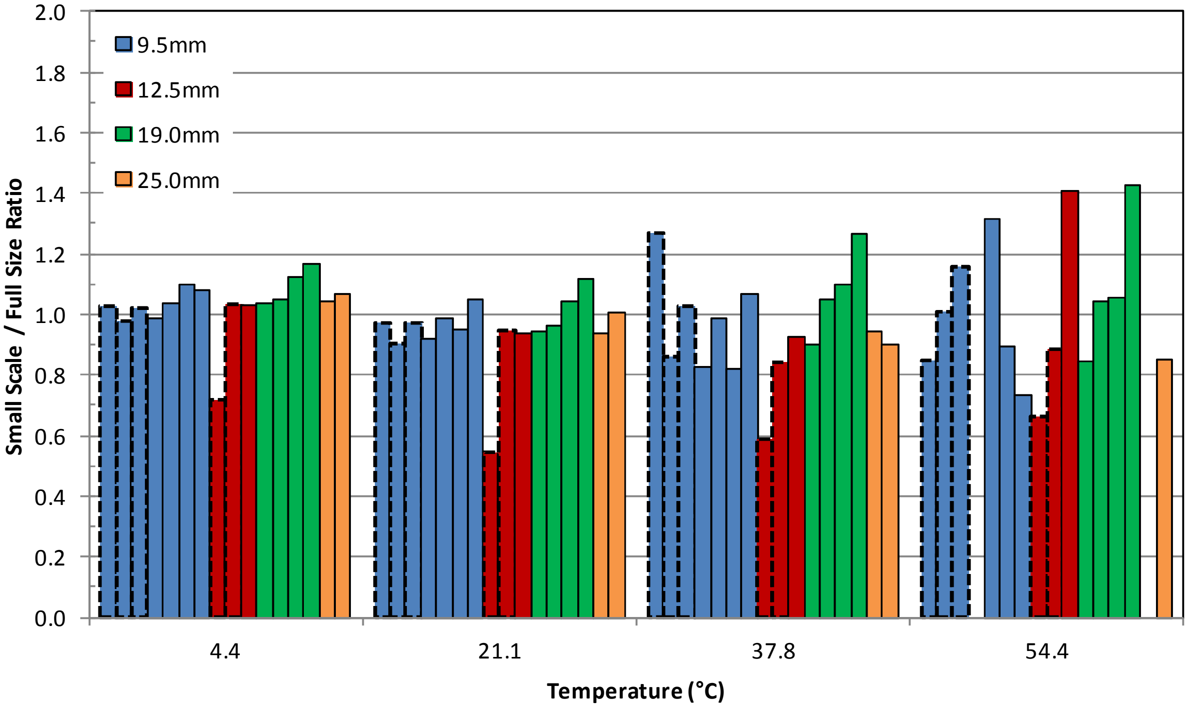

Figure A8. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 110 mm Specimens, 0.5 Hz

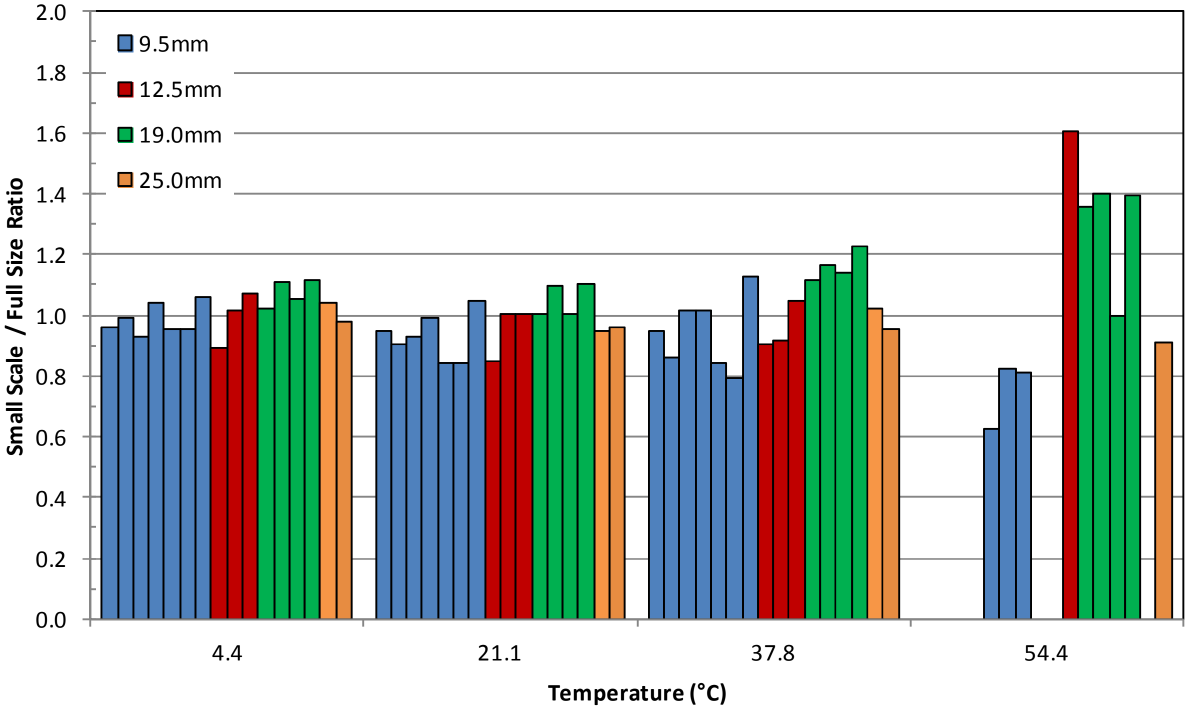

Figure A9. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 135 mm Specimens, 1 Hz

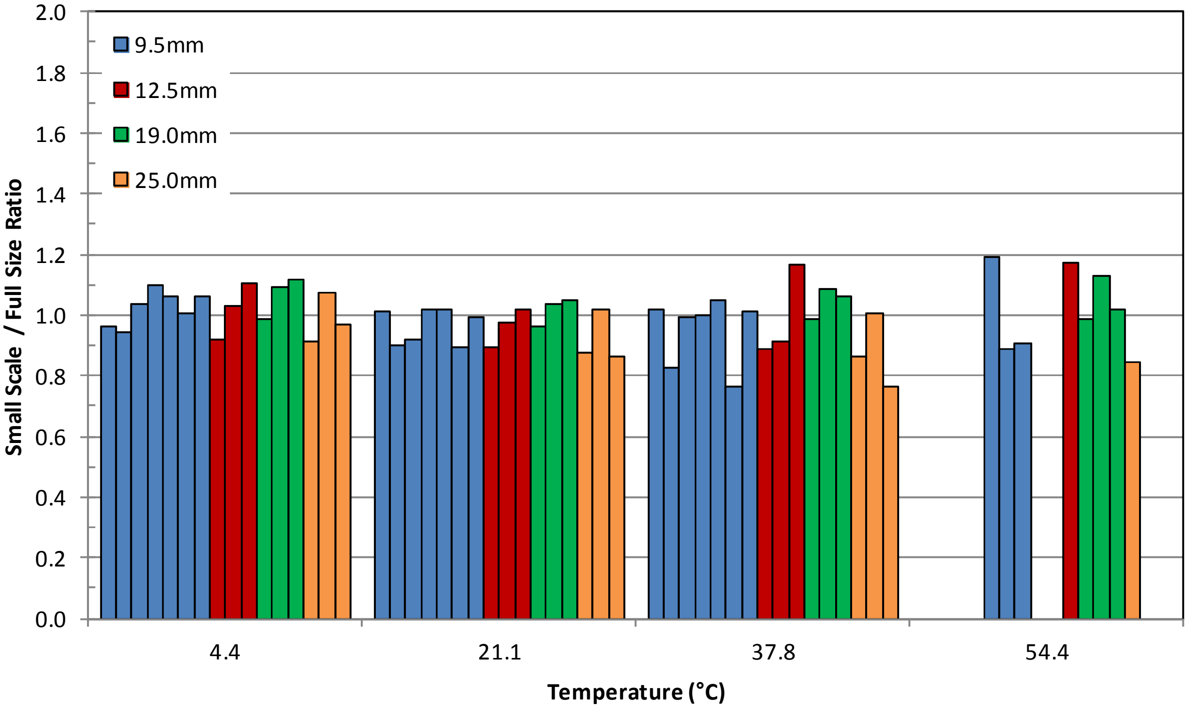

Figure A10. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 135 mm Specimens, 1 Hz

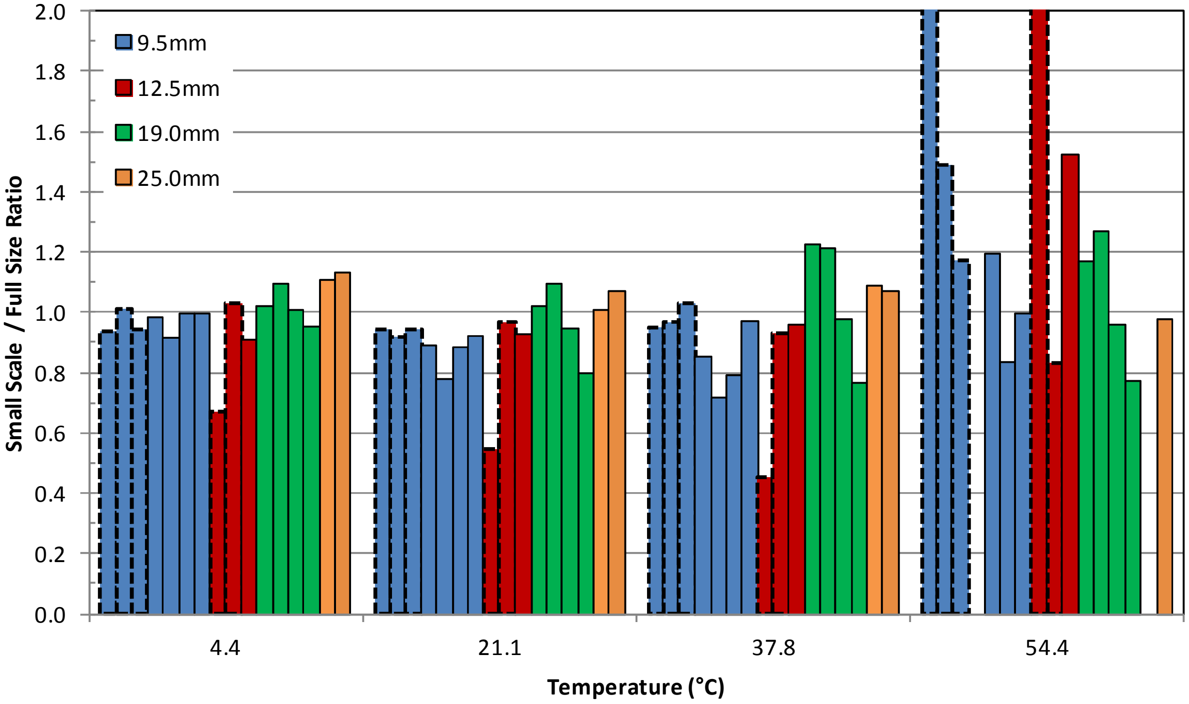

Figure A11. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 110 mm Specimens, 1 Hz

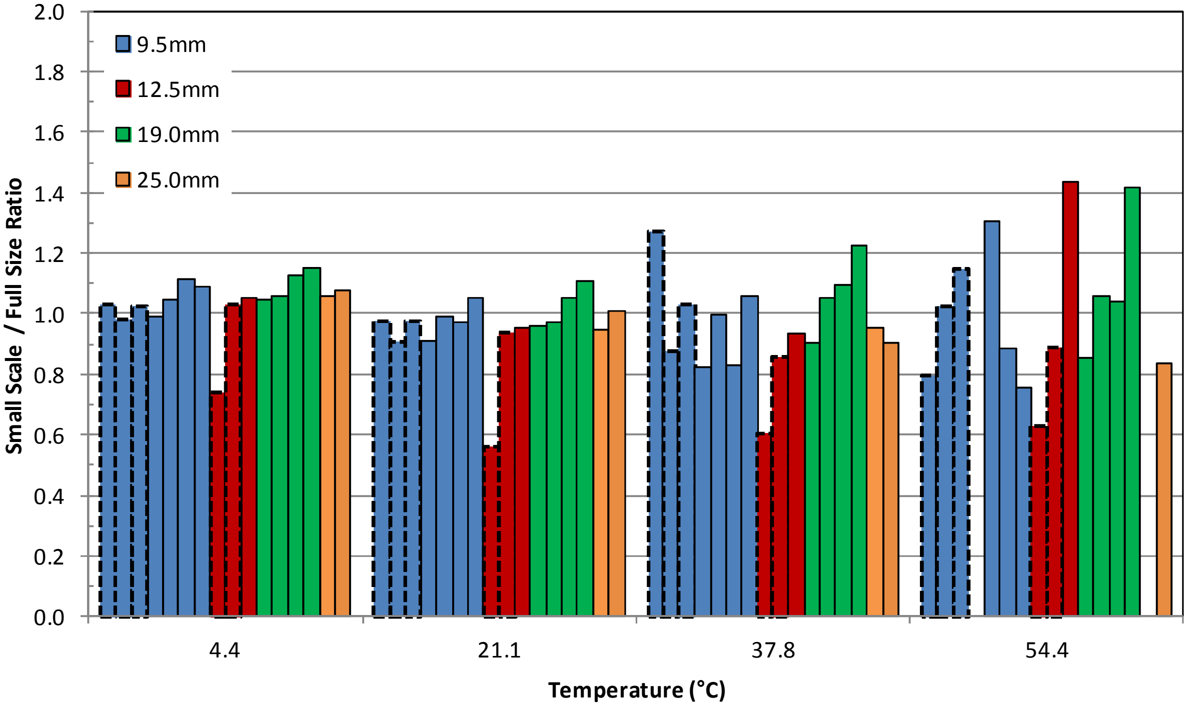

Figure A12. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 110 mm Specimens, 1 Hz

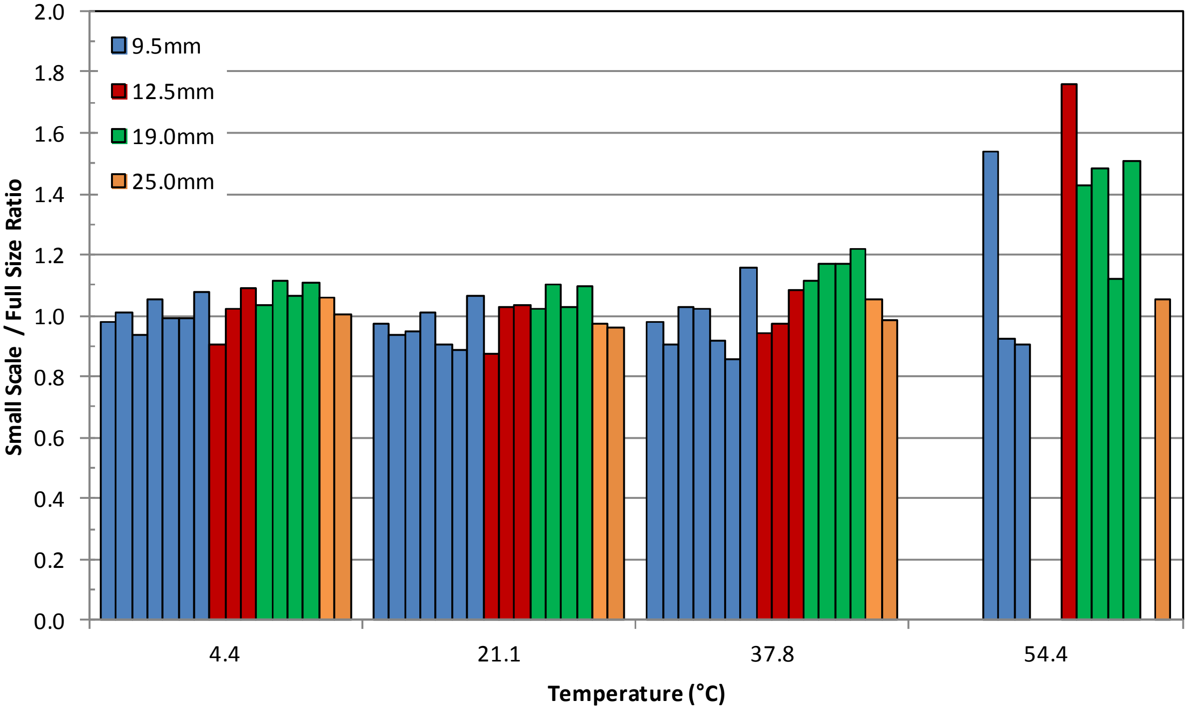

Figure A13. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 135 mm Specimens, 5 Hz

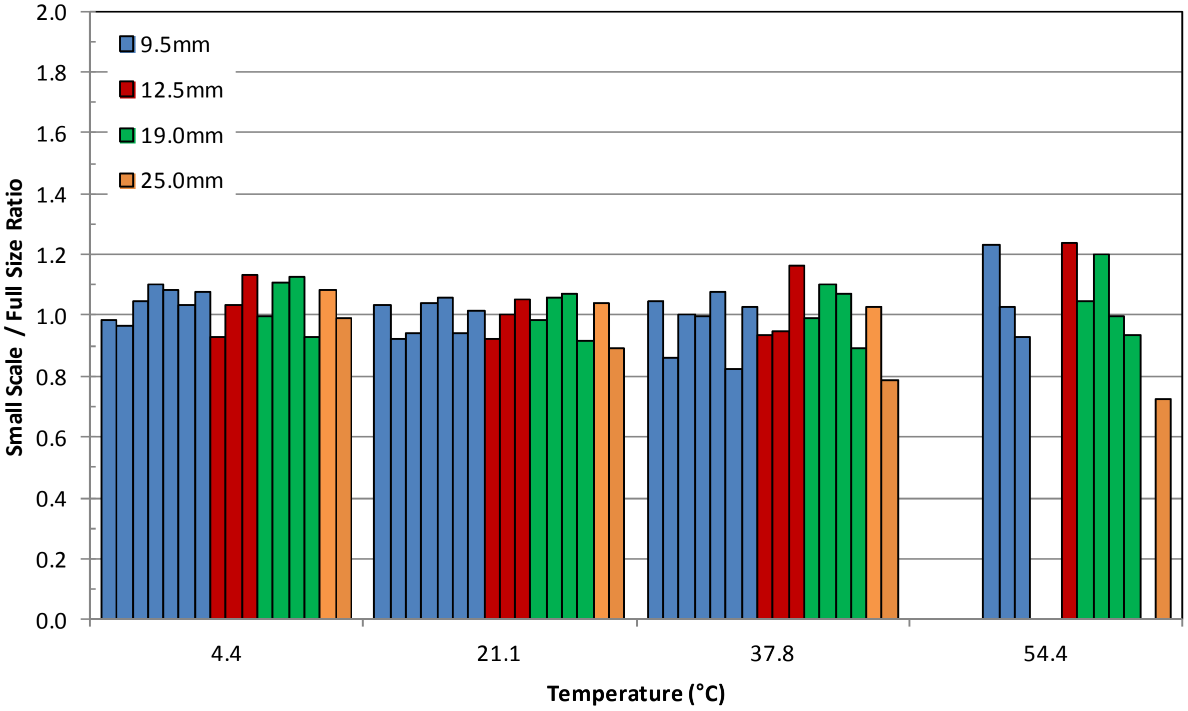

Figure A14. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 135 mm Specimens, 5 Hz

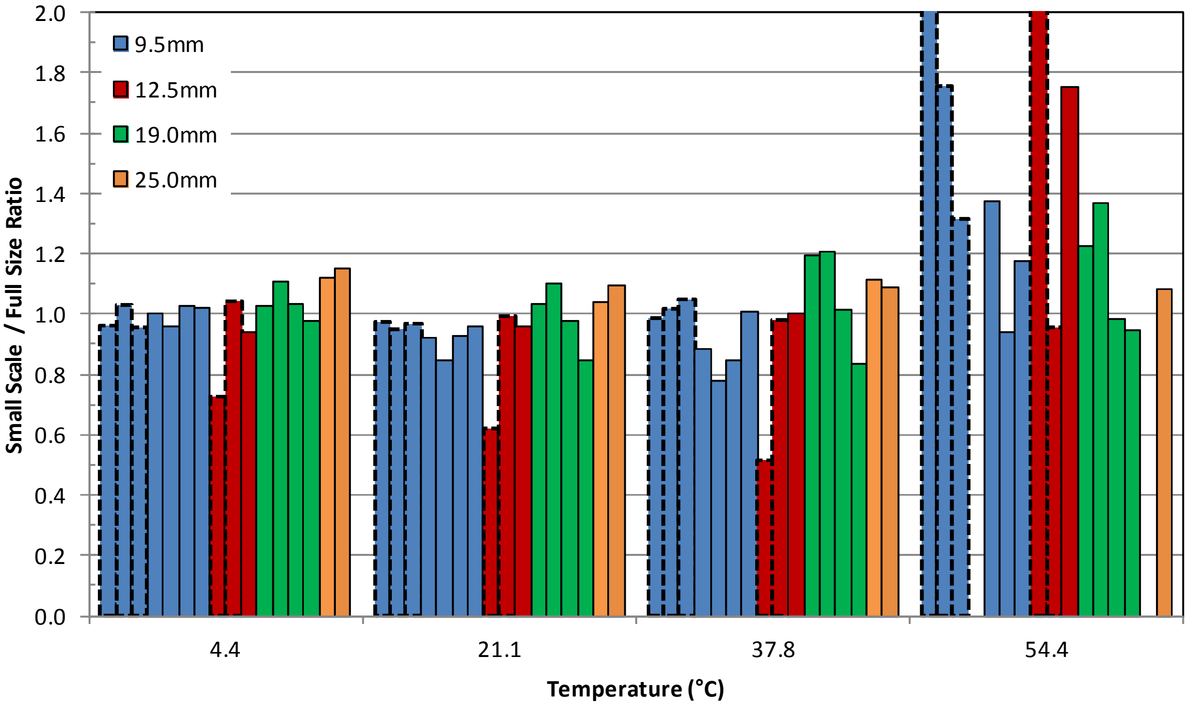

Figure A15. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 110 mm Specimens, 5 Hz

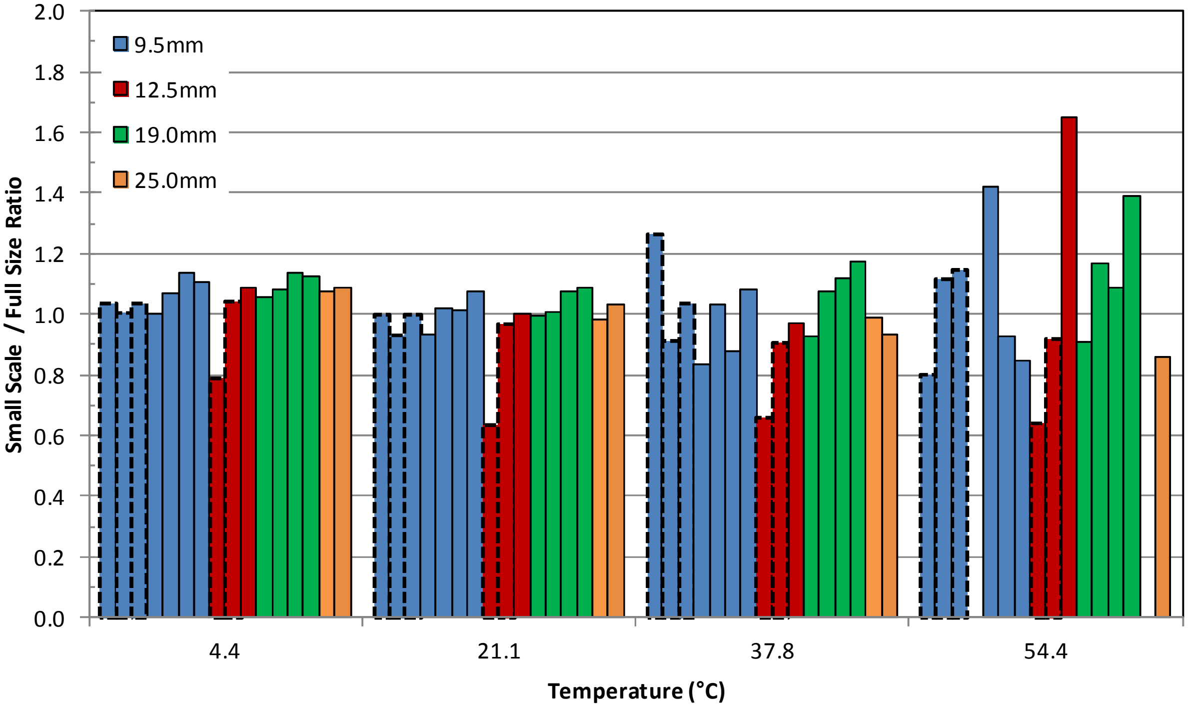

Figure A16. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 110 mm Specimens, 5 Hz

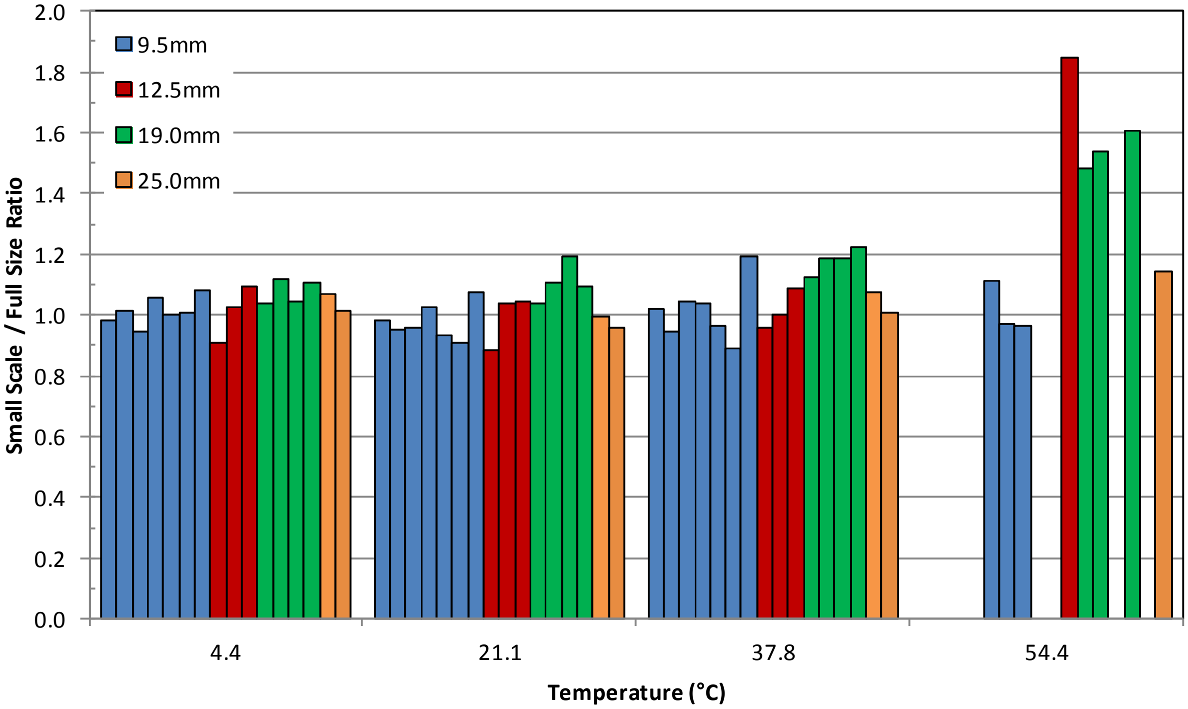

Figure A17. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 135 mm Specimens, 10 Hz

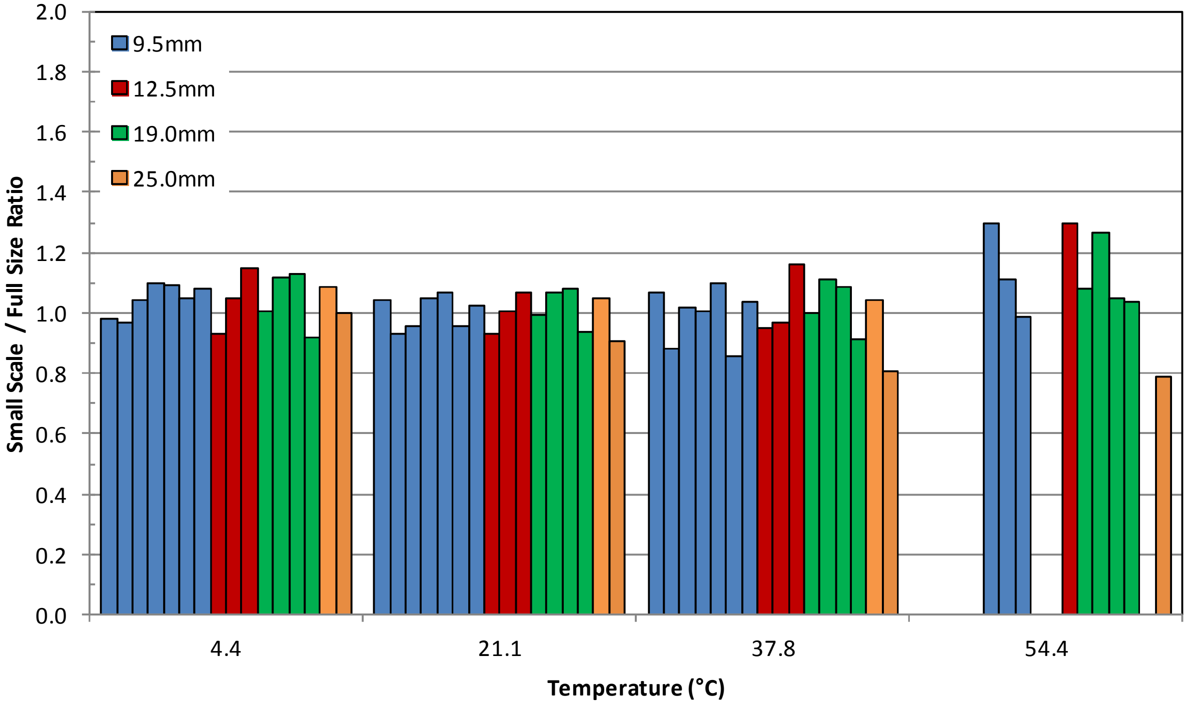

Figure A18. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 135 mm Specimens, 10 Hz

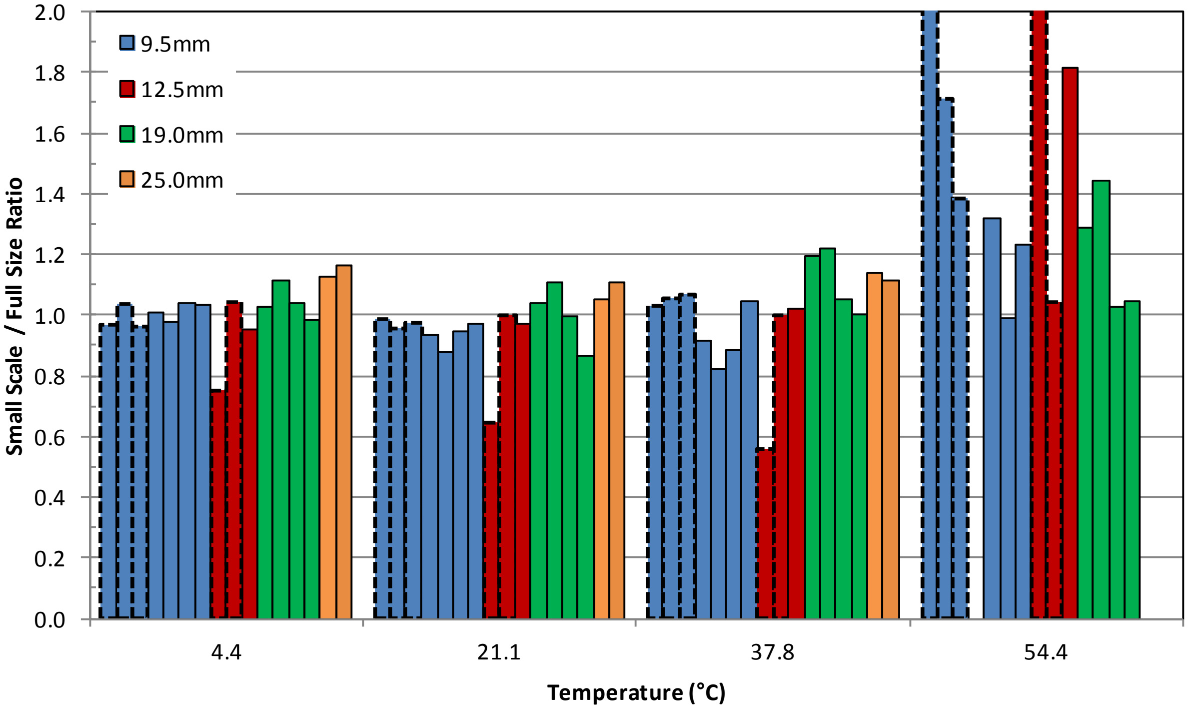

Figure A19. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 110 mm Specimens, 10 Hz

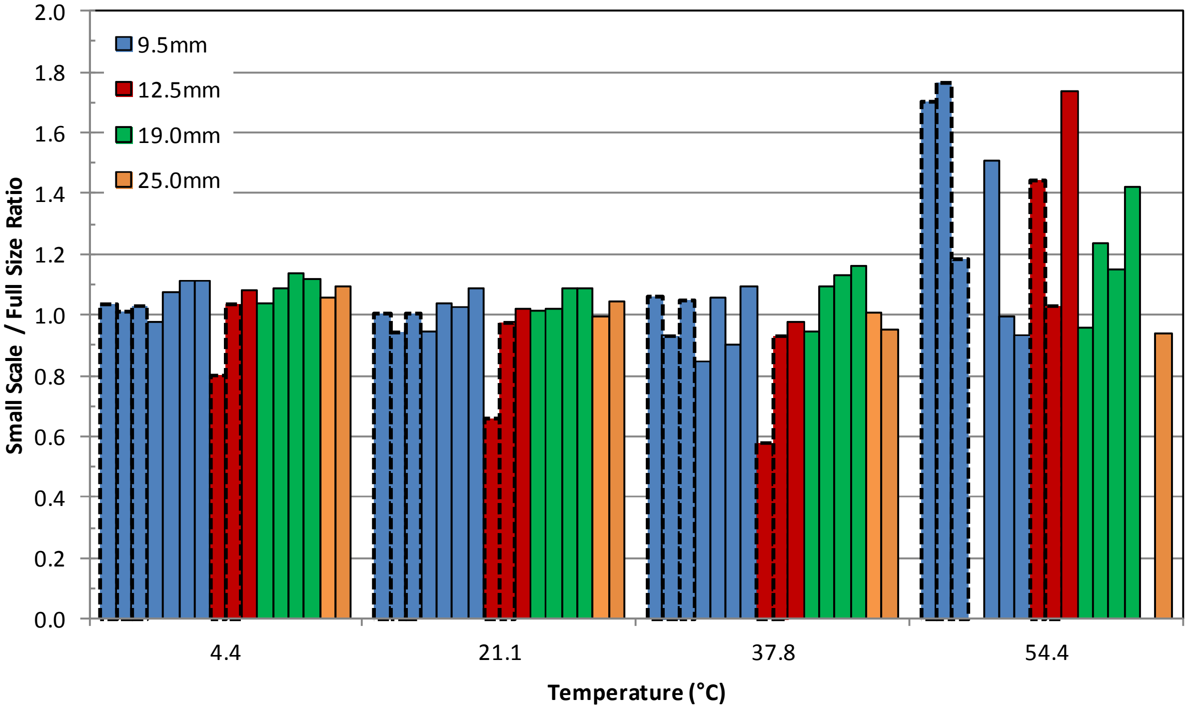

Figure A20. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 110 mm Specimens, 10 Hz

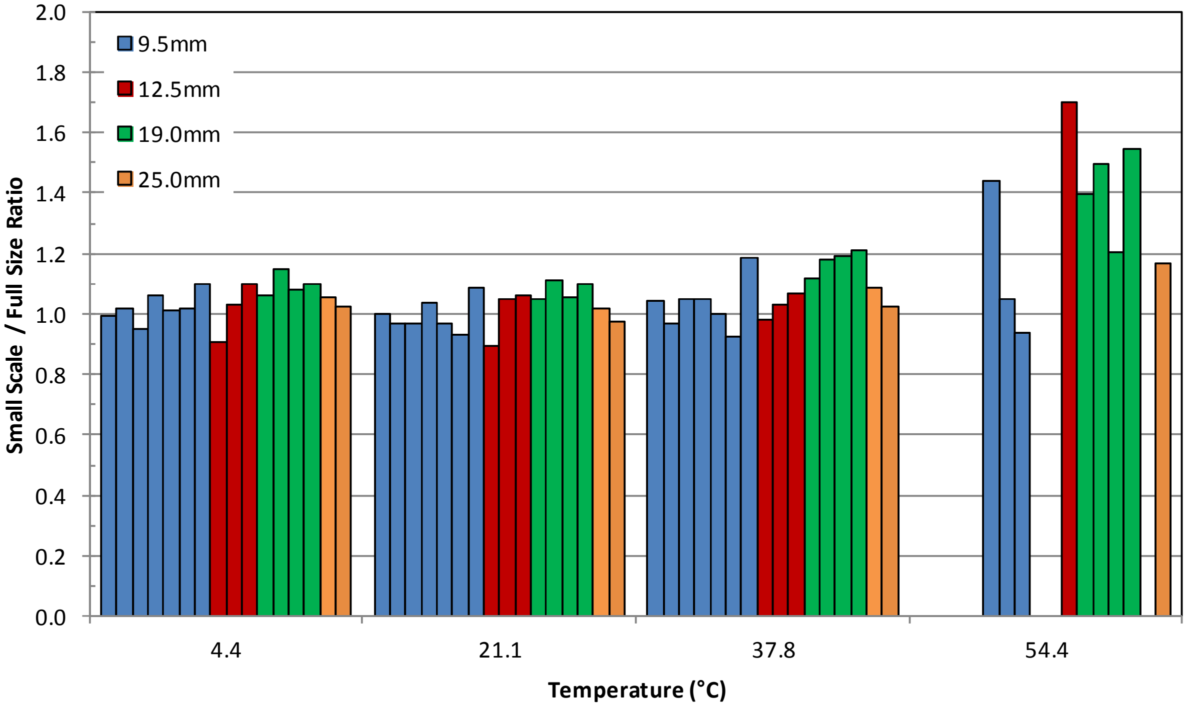

Figure A21. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 135 mm Specimens, 25 Hz

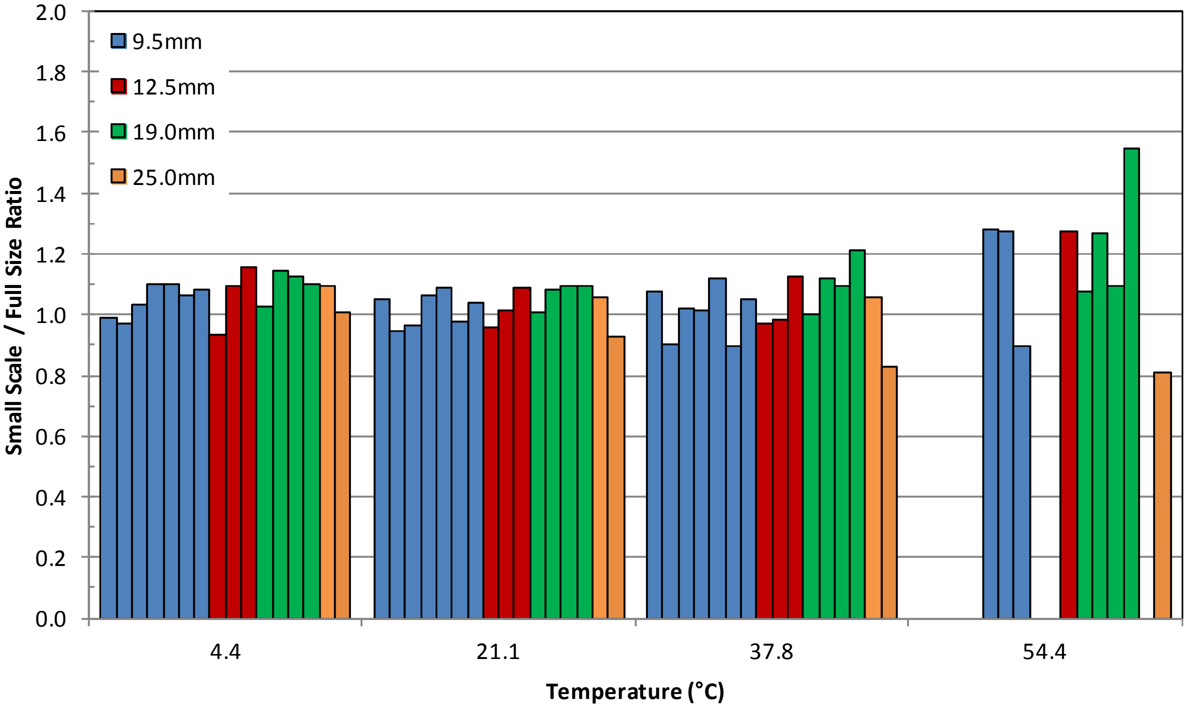

Figure A22. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 135 mm Specimens, 25 Hz

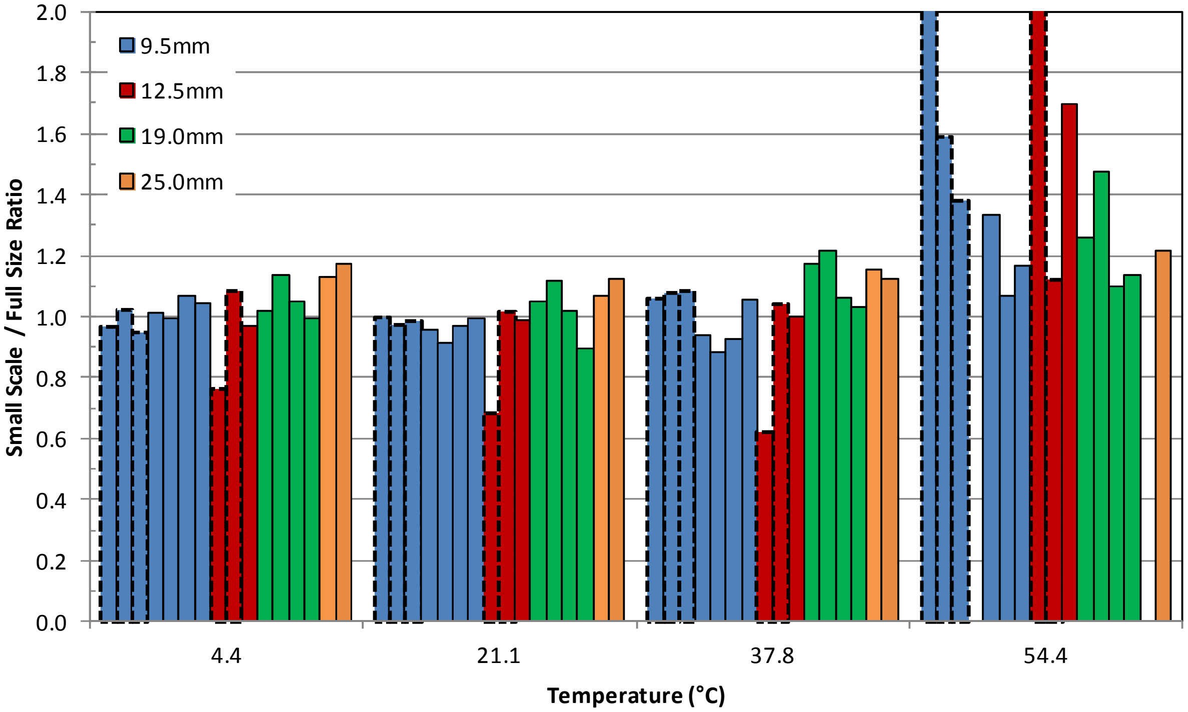

Figure A23. Small-Scale / Full-Size Dynamic Modulus Ratio for 38 × 110 mm Specimens, 25 Hz

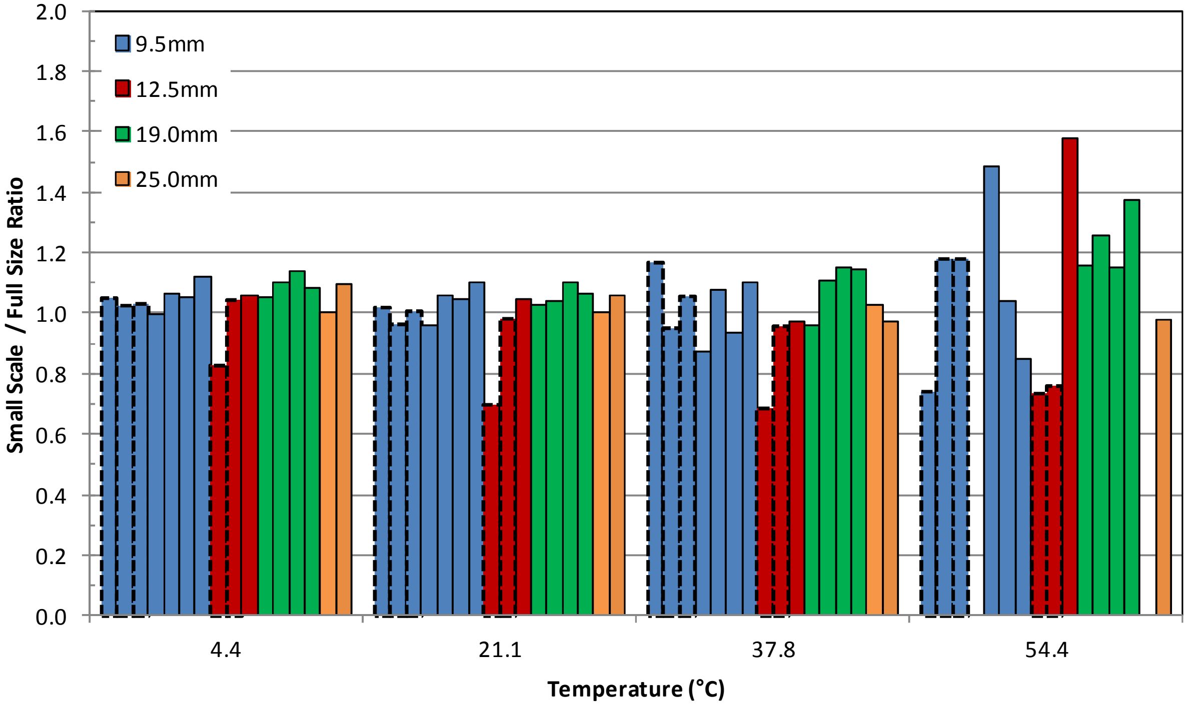

Figure A24. Small-Scale / Full-Size Dynamic Modulus Ratio for 50 × 110 mm Specimens, 25 Hz

APPENDIX B

AVERAGE SMALL-SCALE / FULL-SIZE DYNAMIC MODULUS RATIO SHOWN FOR 9.5-, 12.5-, 19.0-, AND 25.0-mm NMAS WITH RESPECT TO TEST FREQUENCY

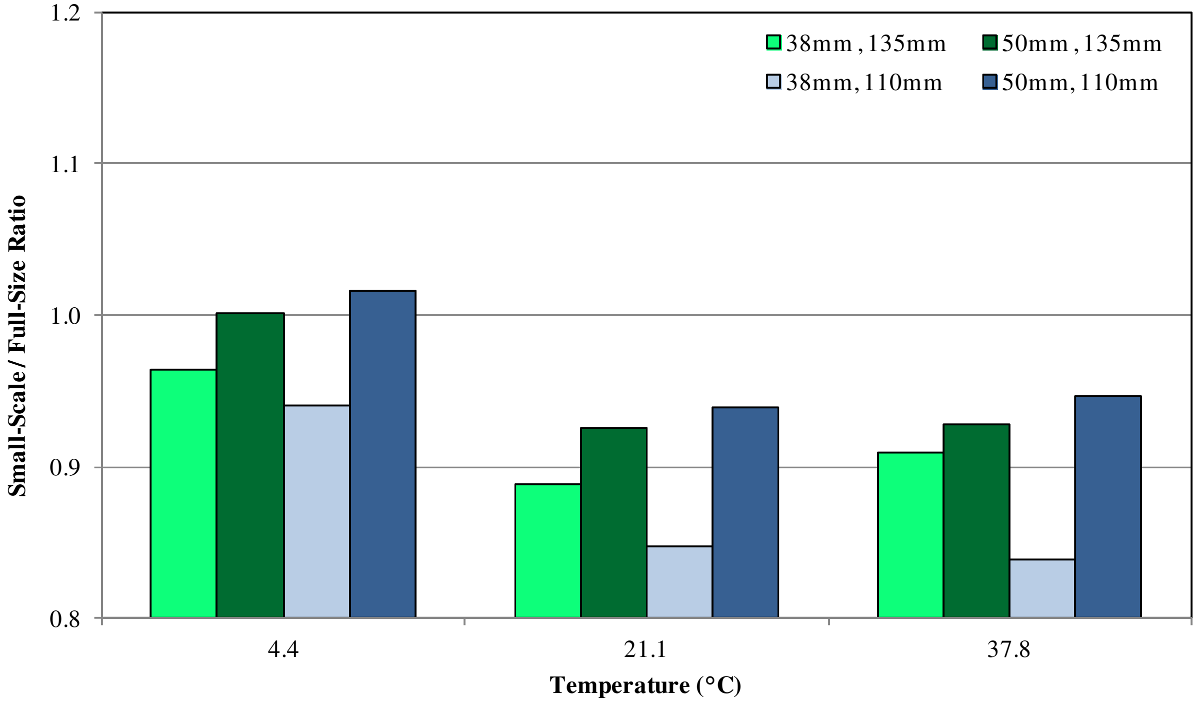

Figure B1. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 9.5-mm NMAS, 0.1 Hz

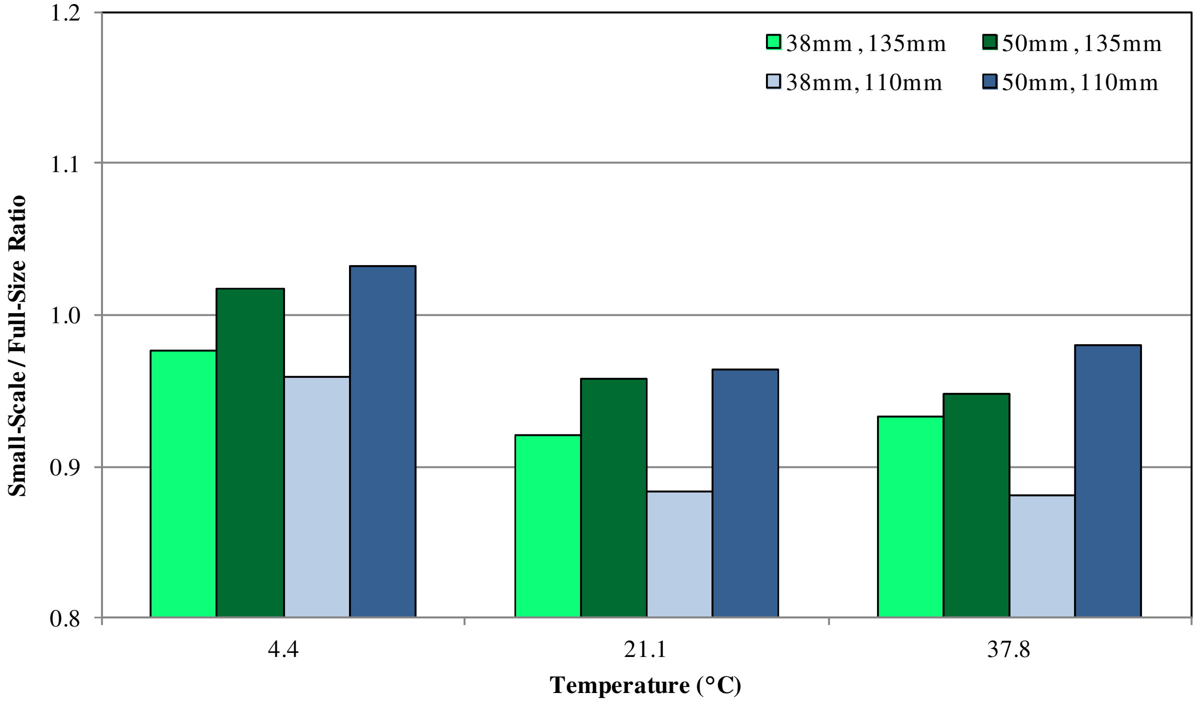

Figure B2. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 9.5-mm NMAS, 0.5 Hz

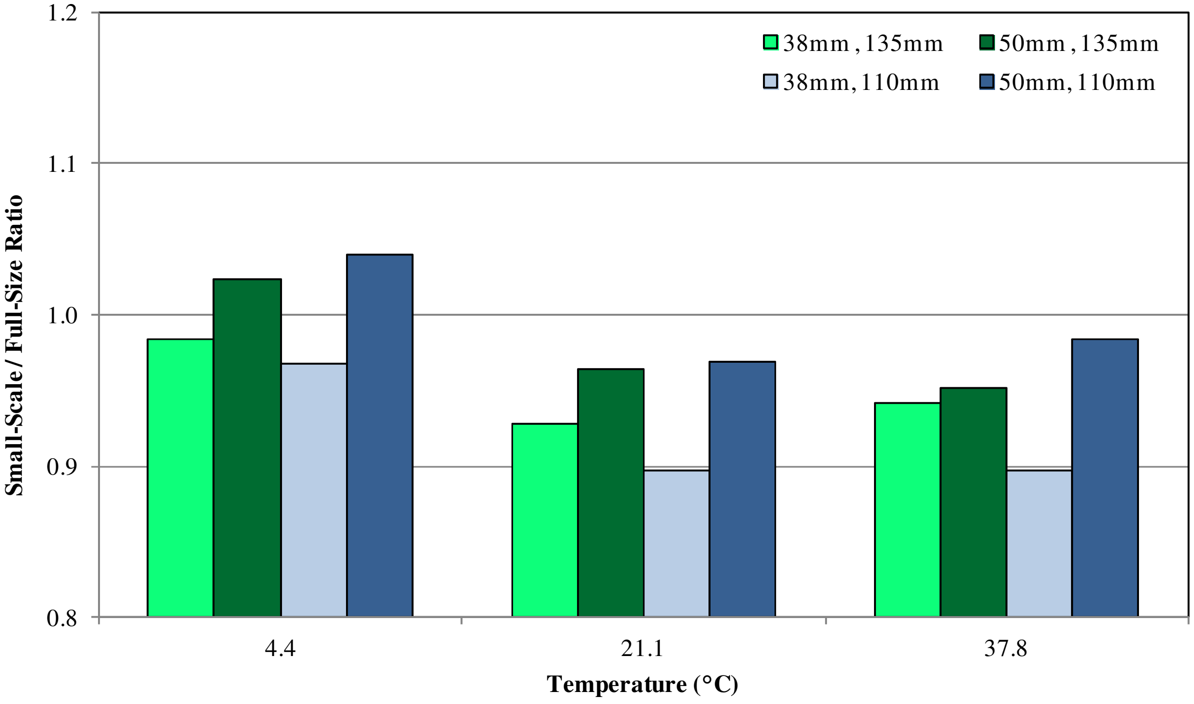

Figure B3. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 9.5-mm NMAS, 1 Hz

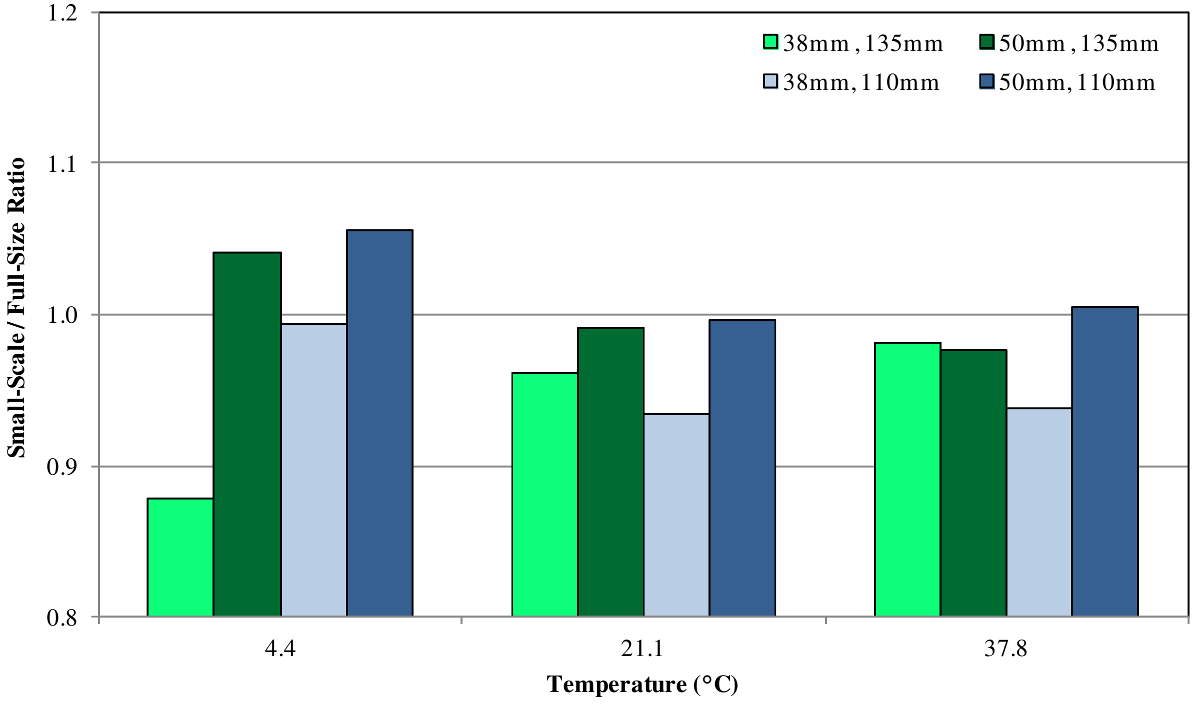

Figure B4. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 9.5-mm NMAS, 5 Hz

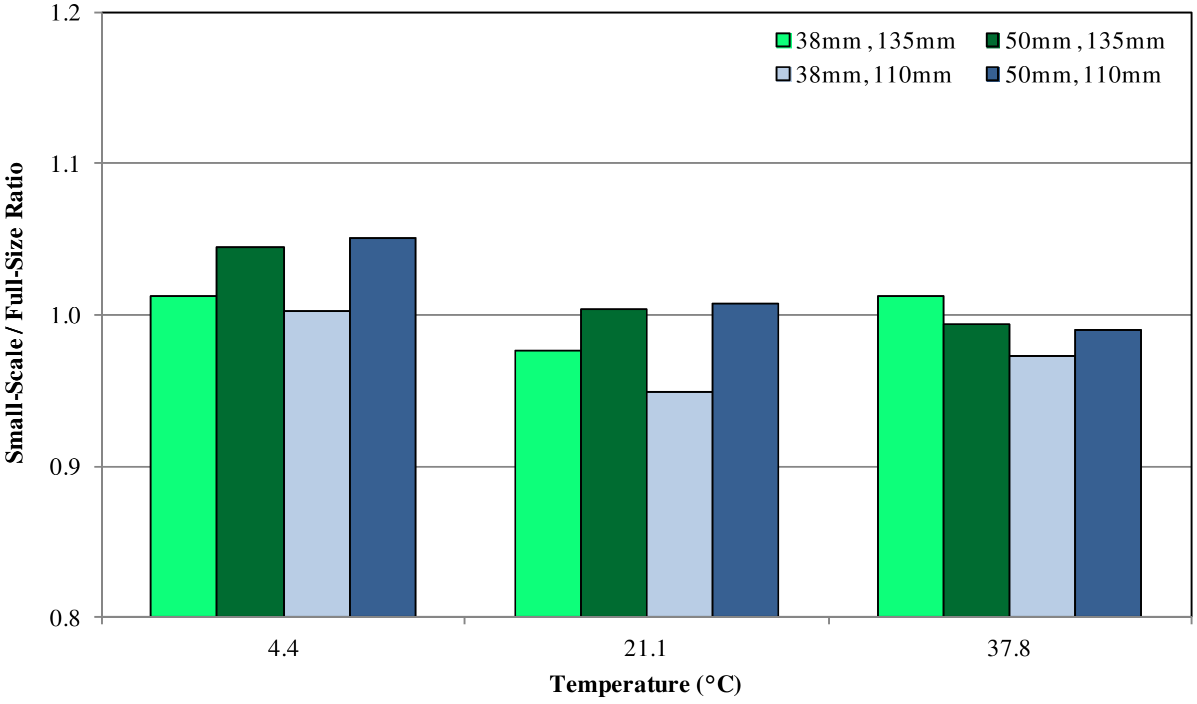

Figure B5. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 9.5-mm NMAS, 10 Hz

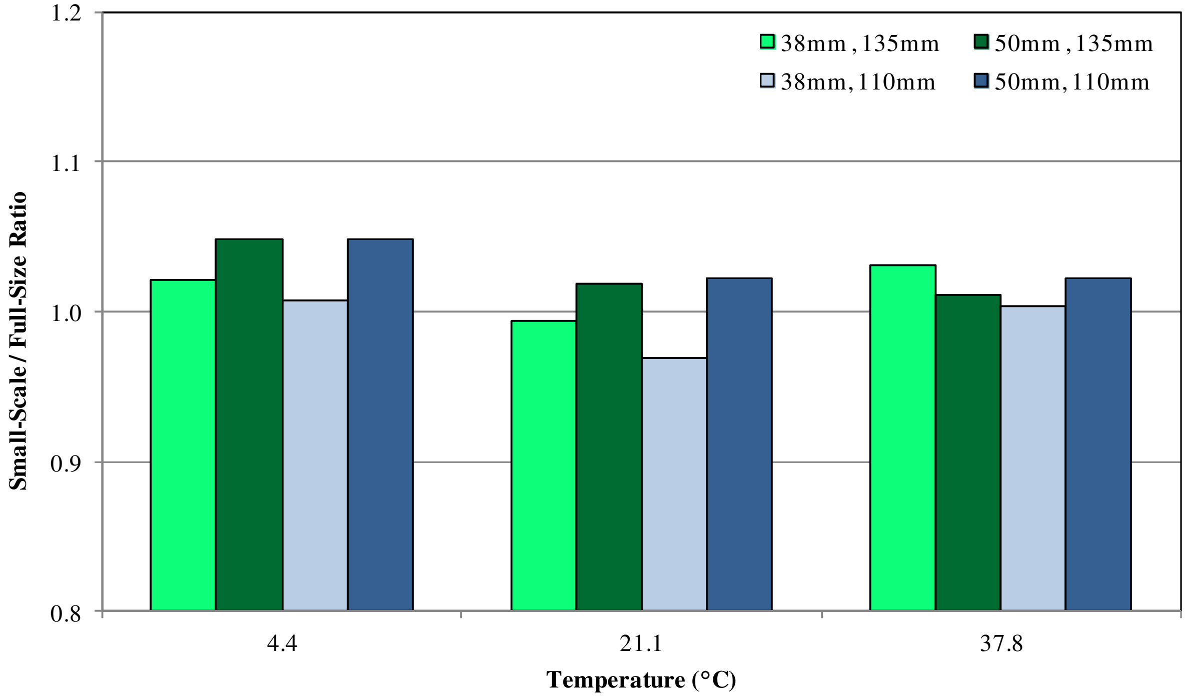

Figure B6. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 9.5-mm NMAS, 25 Hz

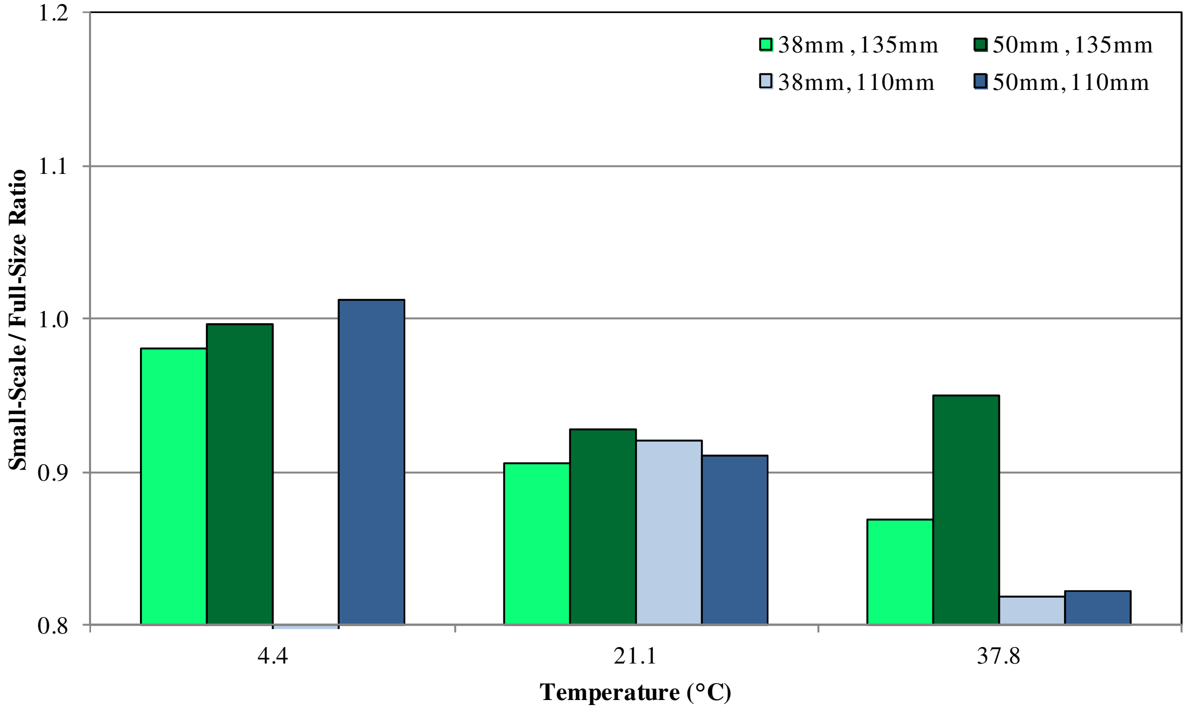

Figure B7. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 12.5-mm NMAS, 0.1 Hz

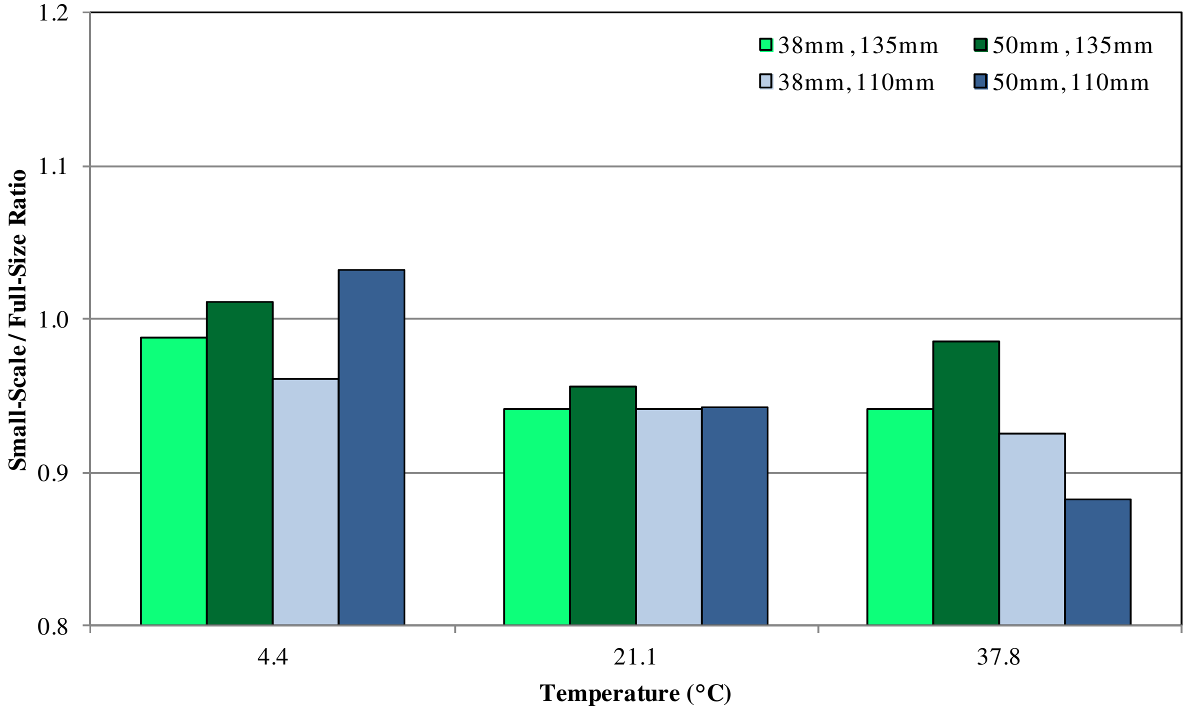

Figure B8. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 12.5-mm NMAS, 0.5 Hz

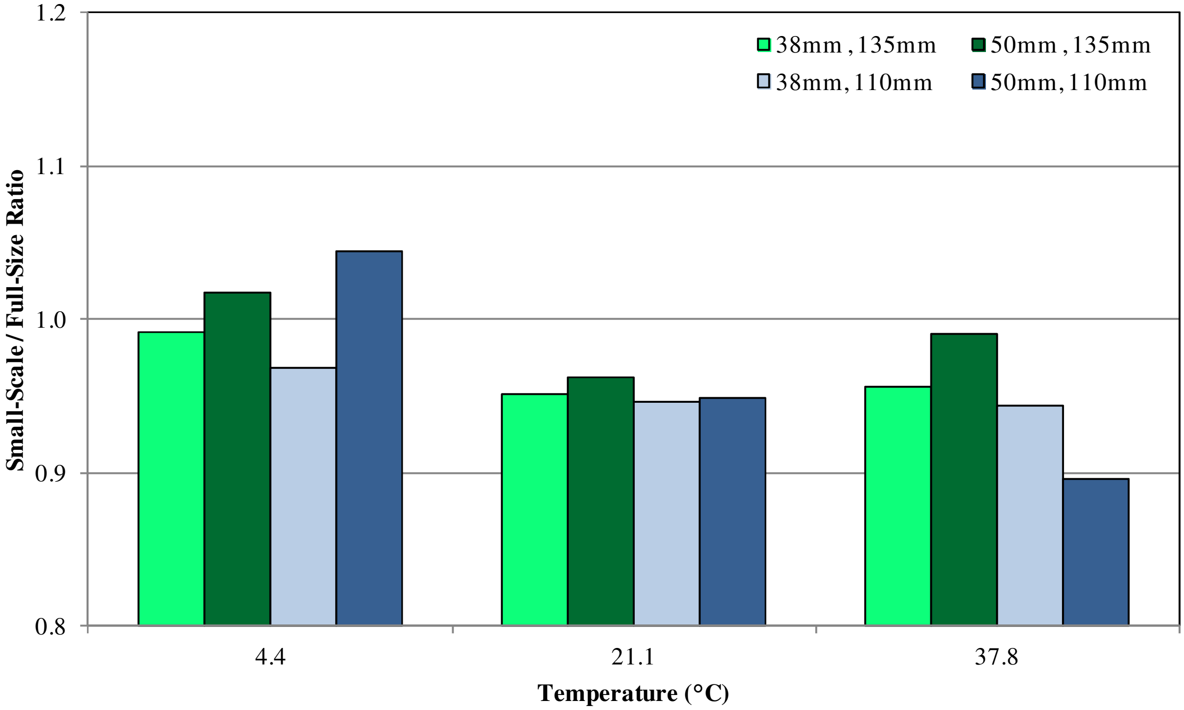

Figure B9. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 12.5-mm NMAS, 1 Hz

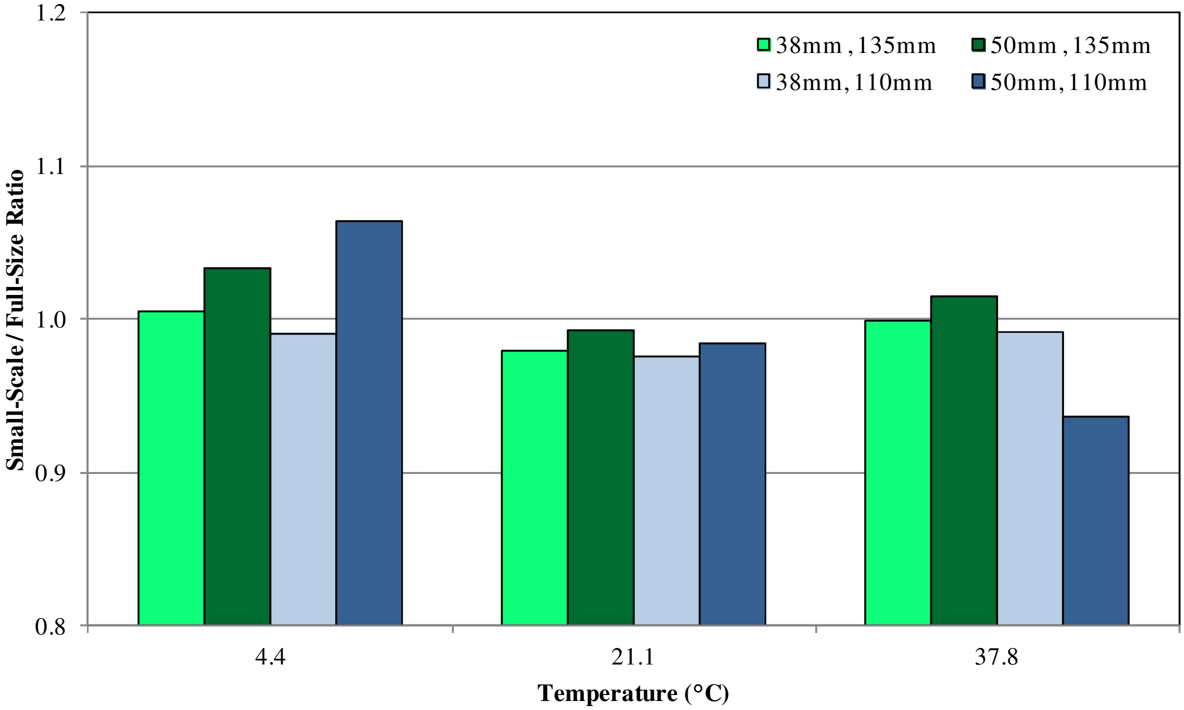

Figure B10. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 12.5-mm NMAS, 5 Hz

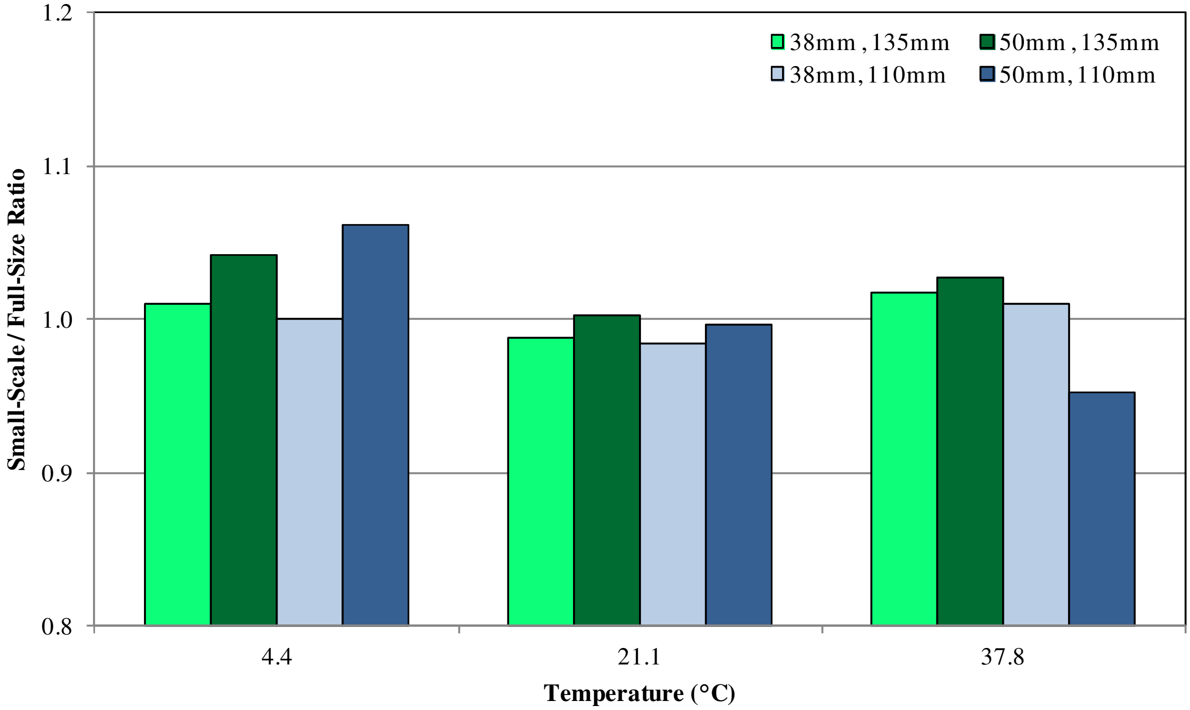

Figure B11. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 12.5-mm NMAS, 10 Hz

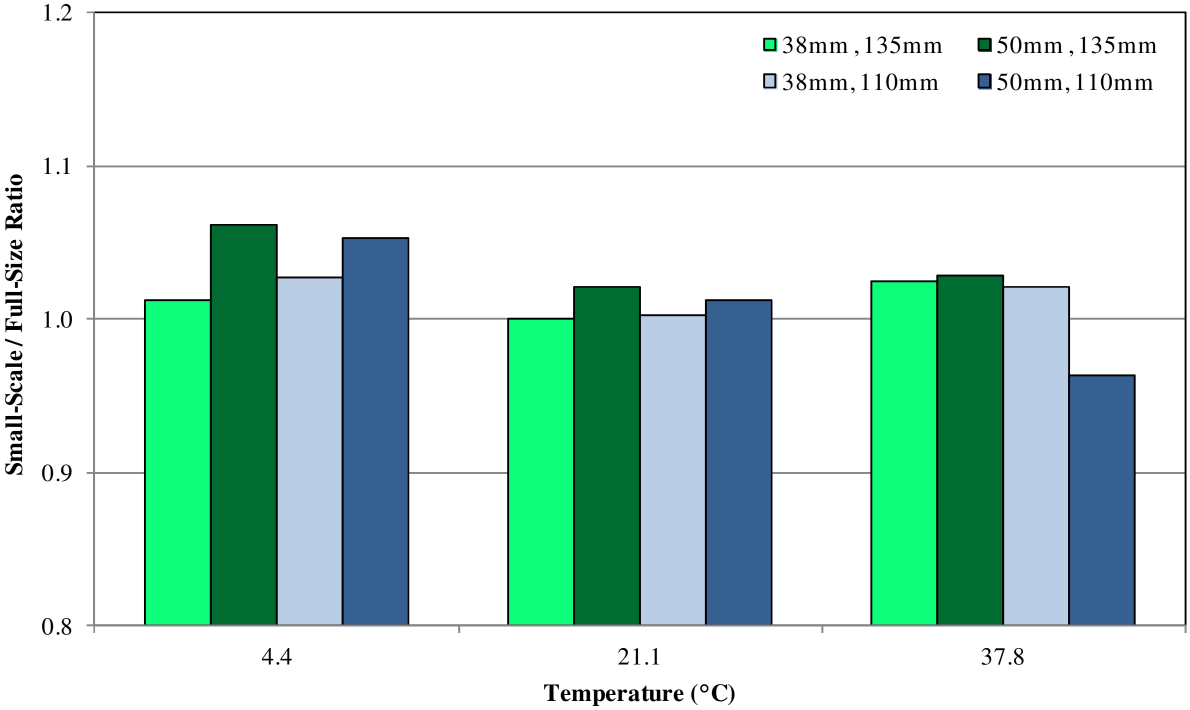

Figure B12. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 12.5-mm NMAS, 25 Hz

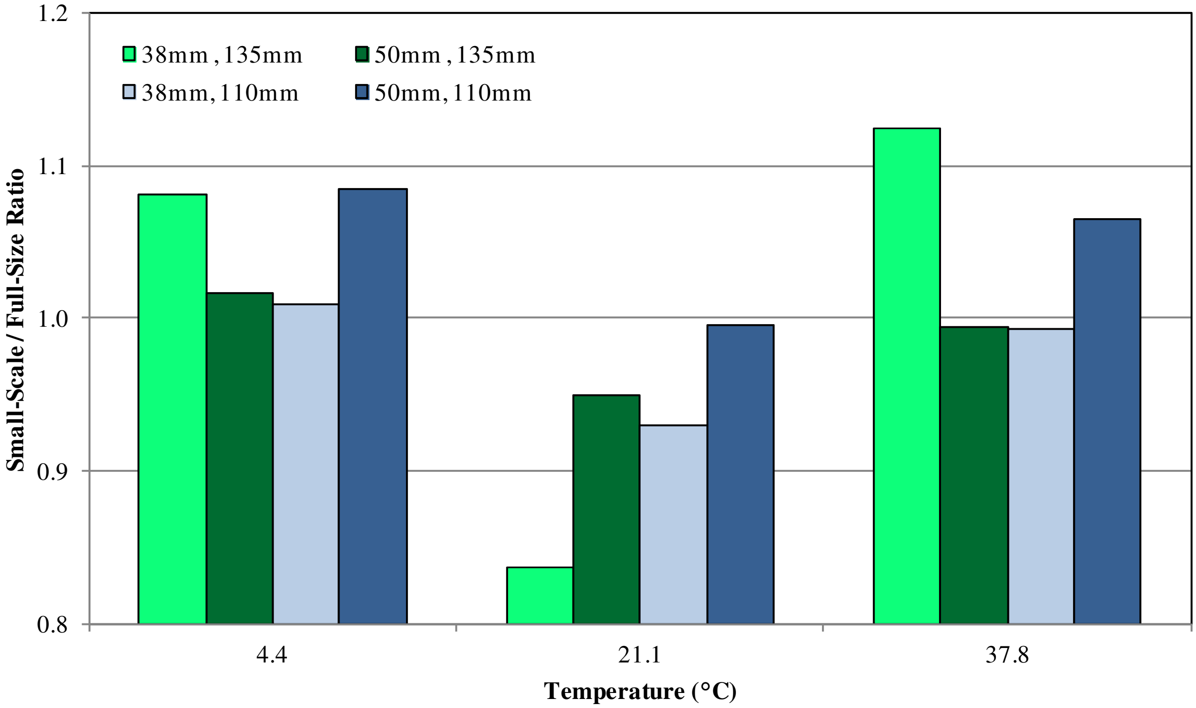

Figure B13. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 19.0-mm NMAS, 0.1 Hz

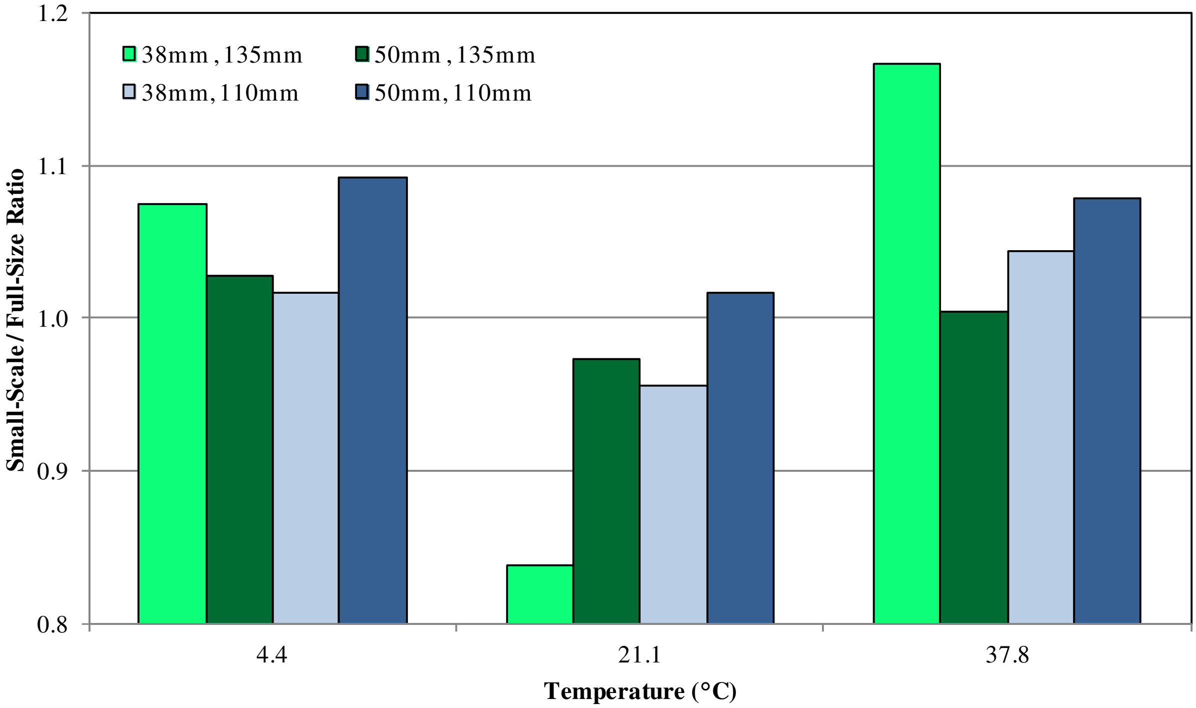

Figure B14. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 19.0-mm NMAS, 0.5 Hz

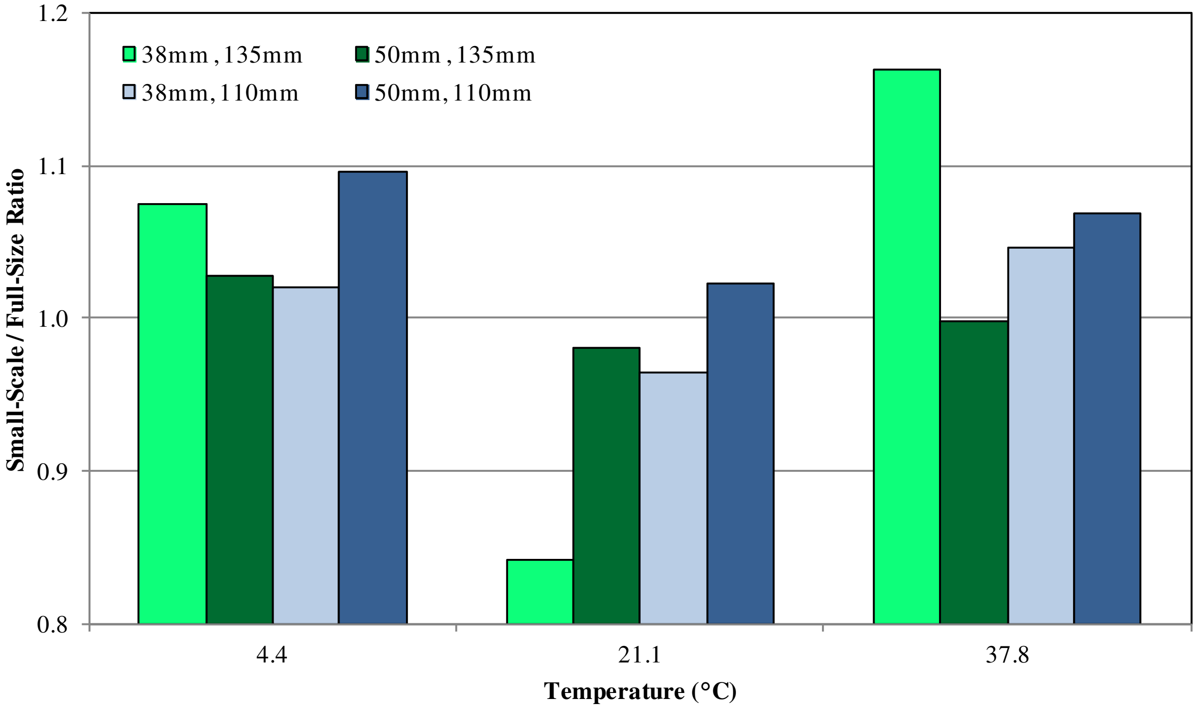

Figure B15. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 19.0-mm NMAS, 1 Hz

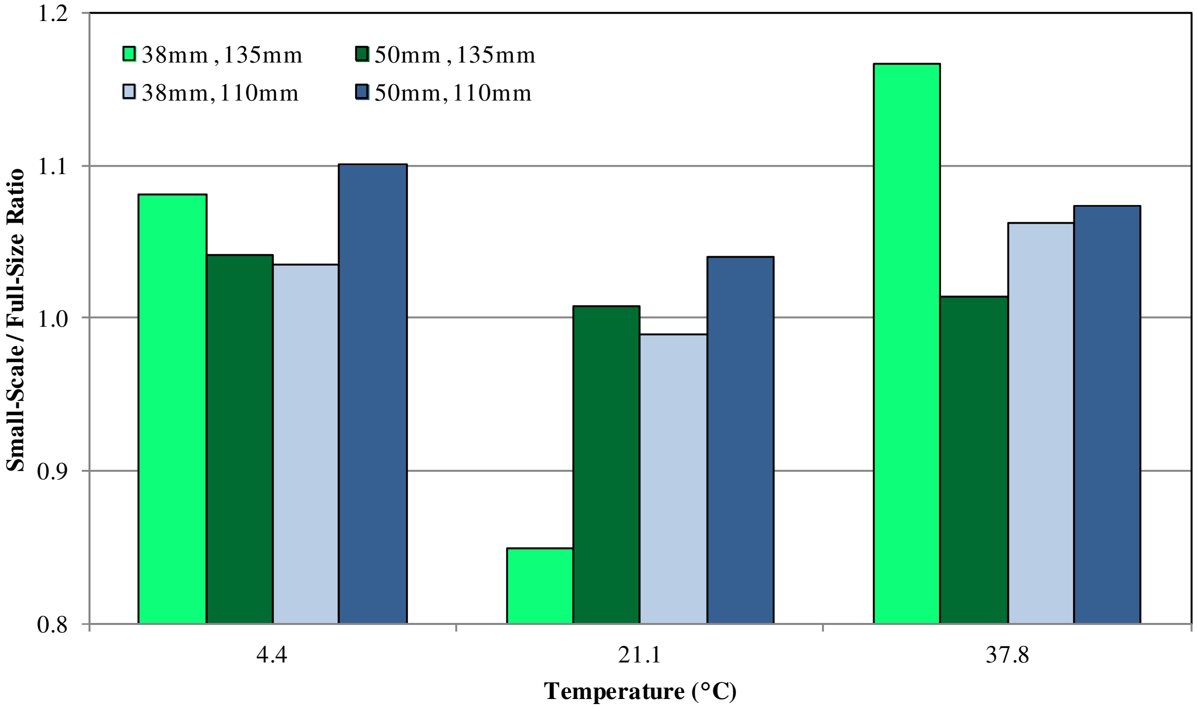

Figure B16. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 19.0-mm NMAS, 5 Hz

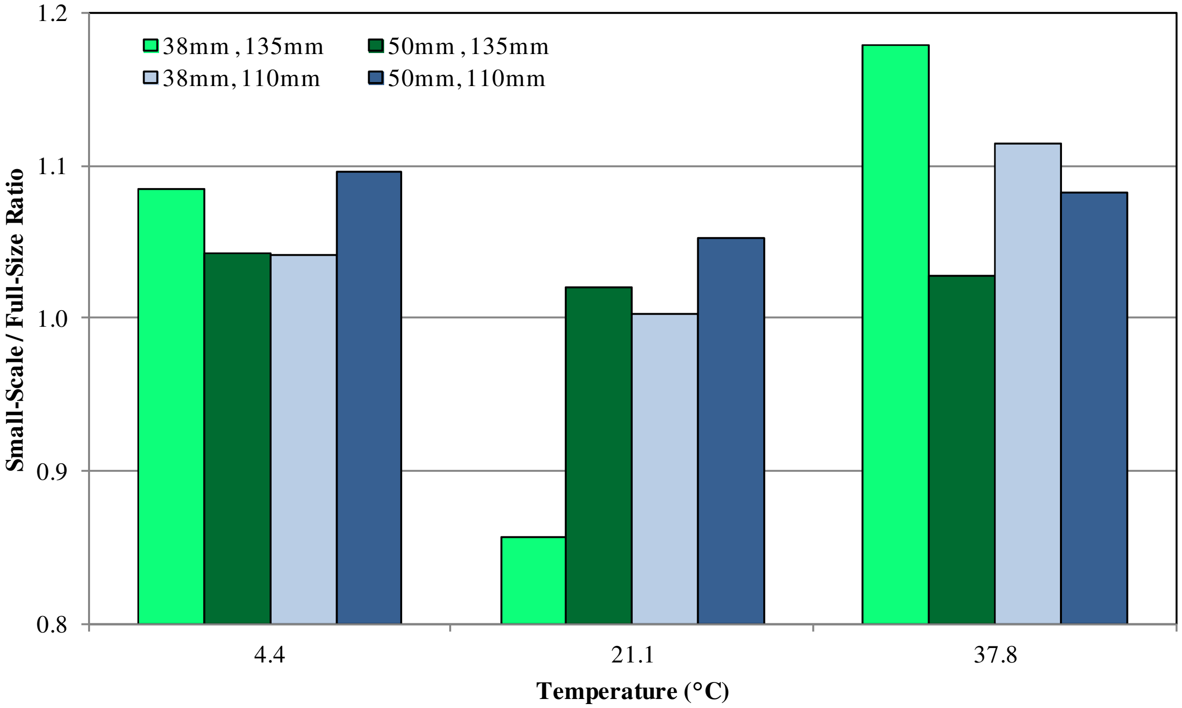

Figure B17. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 19.0-mm NMAS, 10 Hz

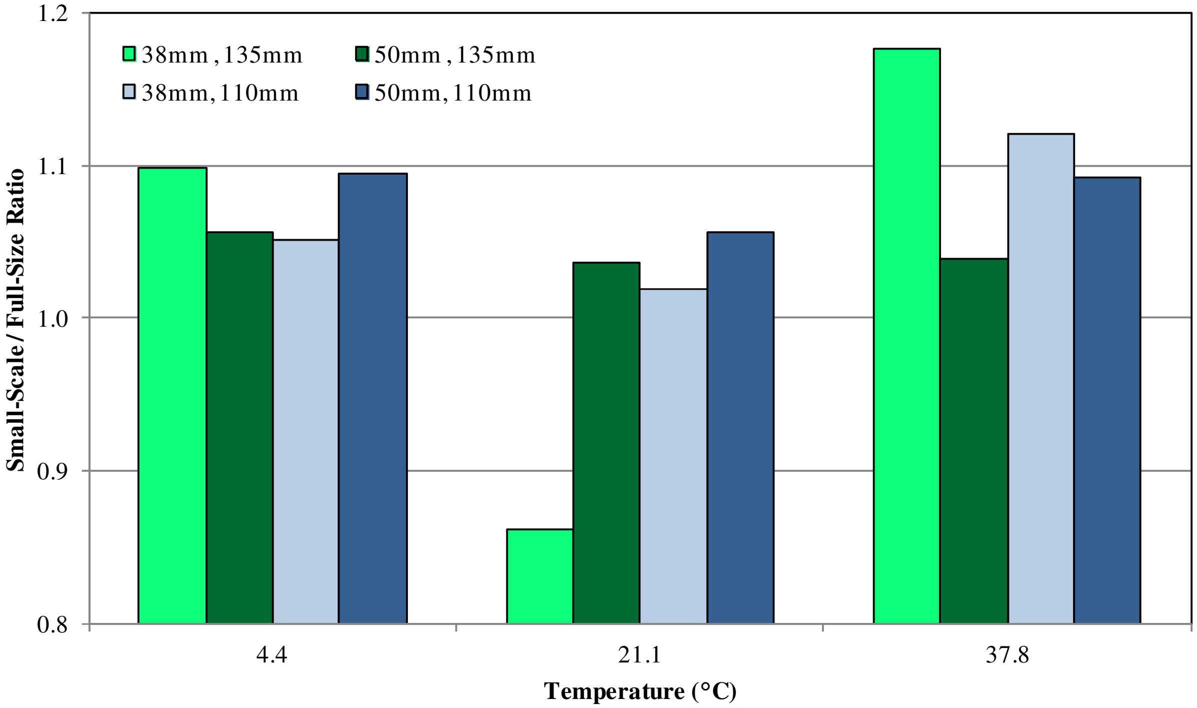

Figure B18. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 19.0-mm NMAS, 25 Hz

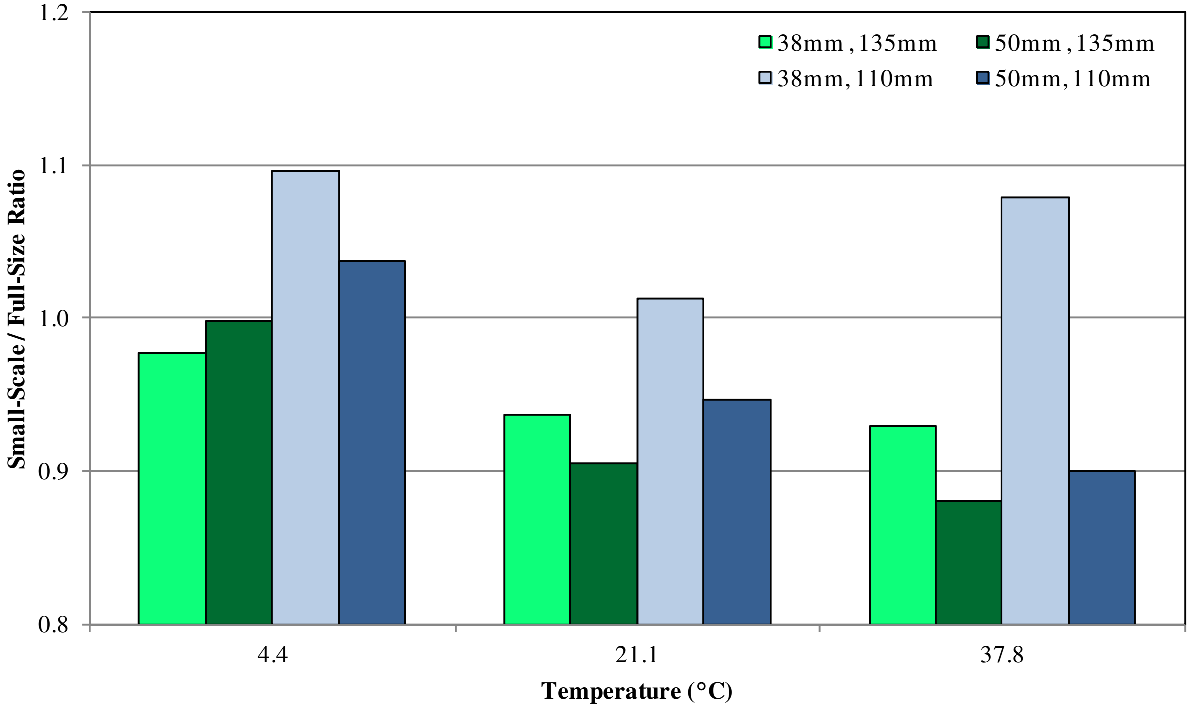

Figure B19. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 25.0-mm NMAS, 0.1 Hz

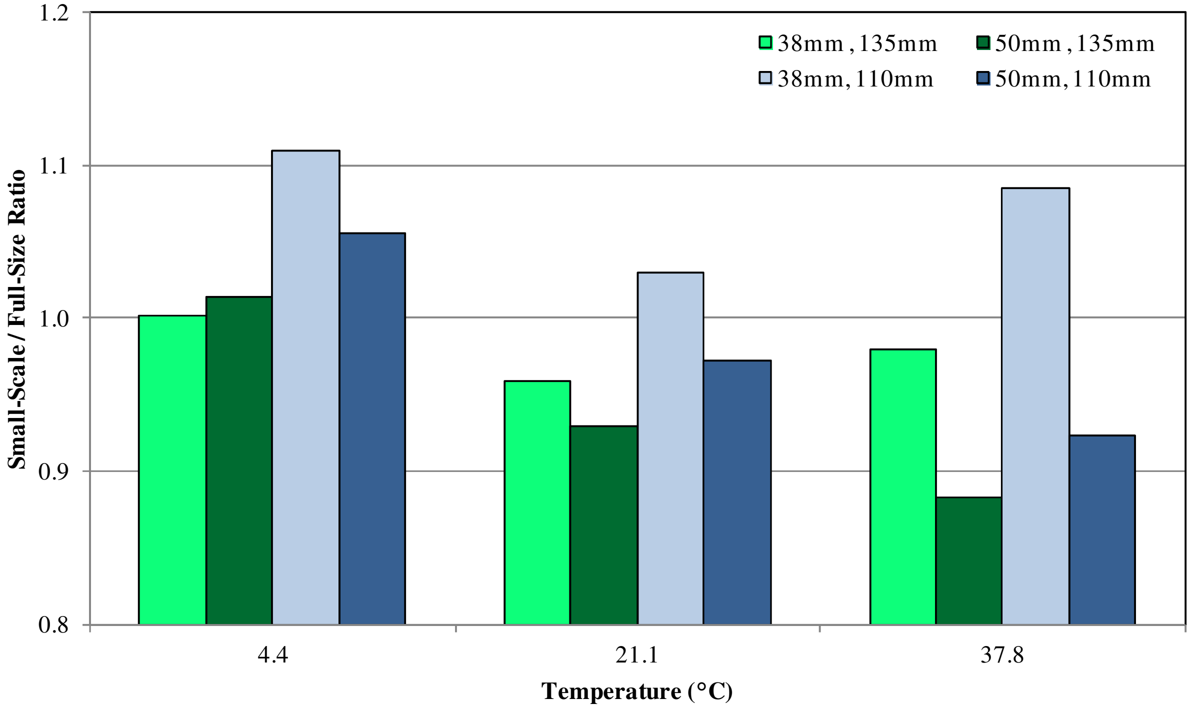

Figure B20. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 25.0-mm NMAS, 0.5 Hz

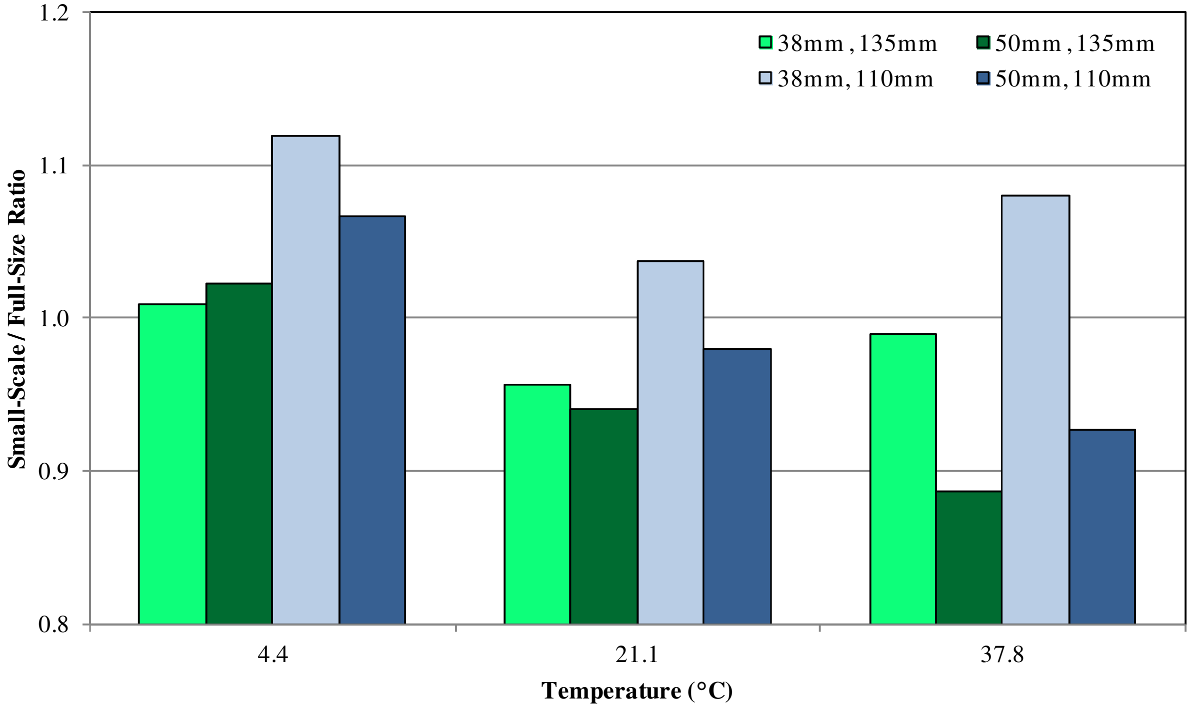

Figure B21. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 25.0-mm NMAS, 1 Hz

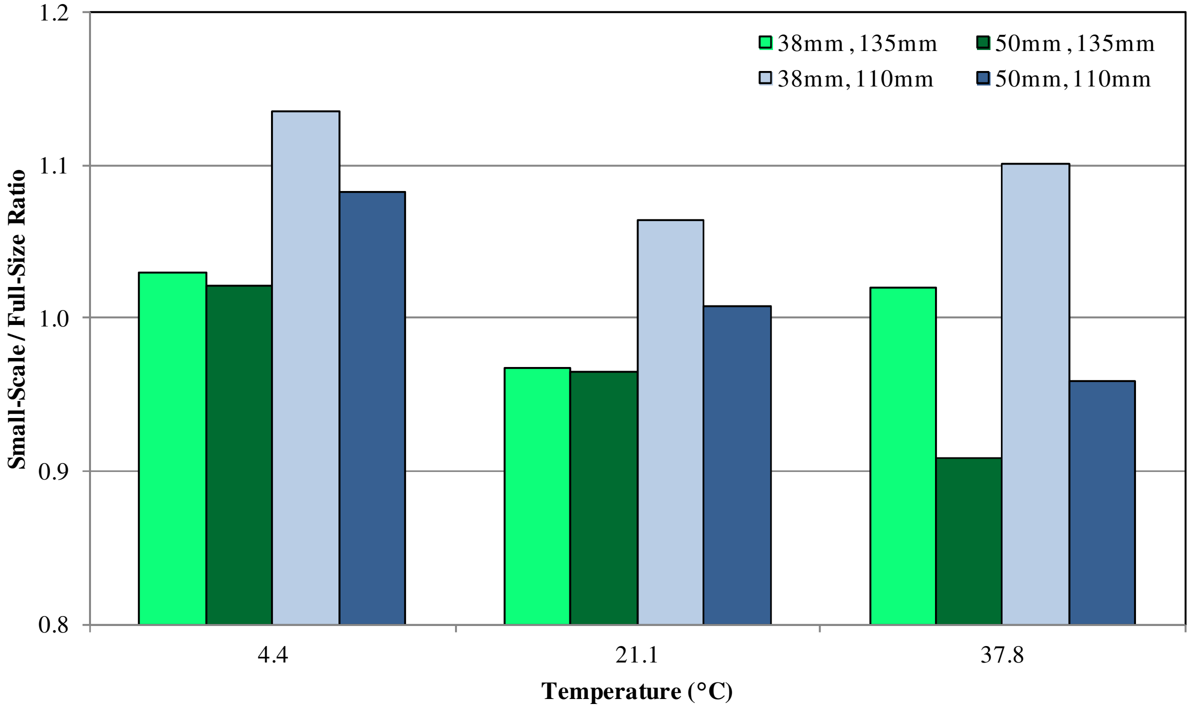

Figure B22. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 25.0-mm NMAS, 5 Hz

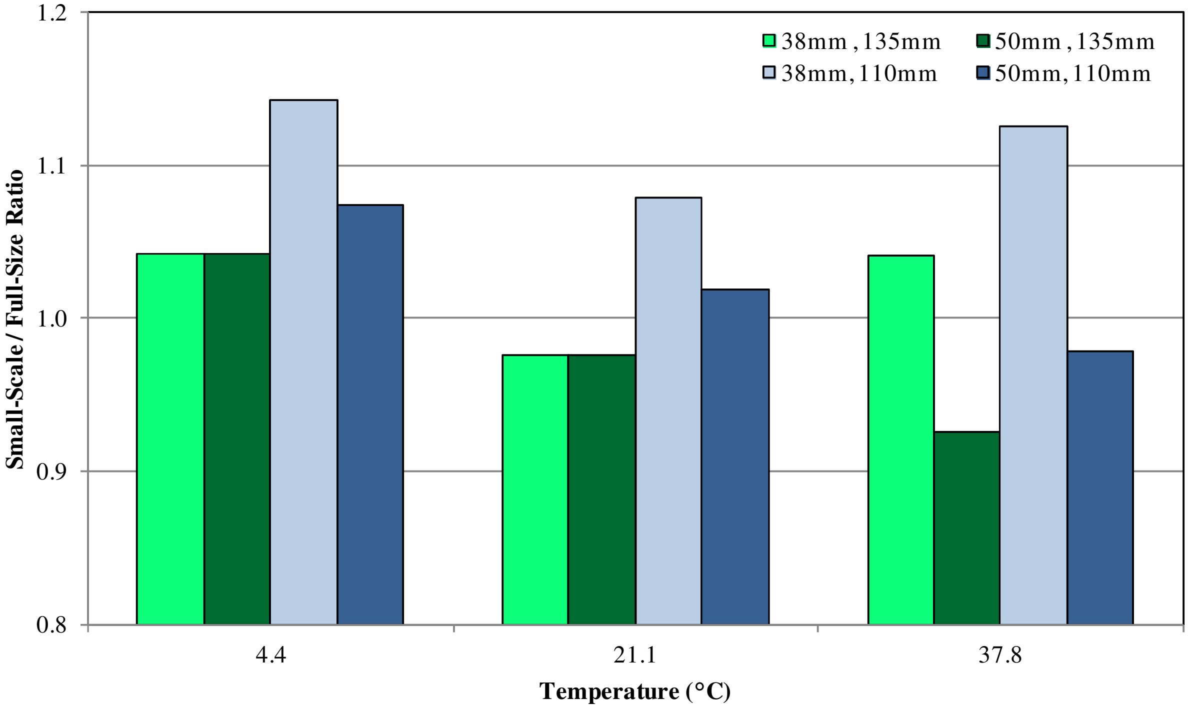

Figure B23. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 25.0-mm NMAS, 10 Hz

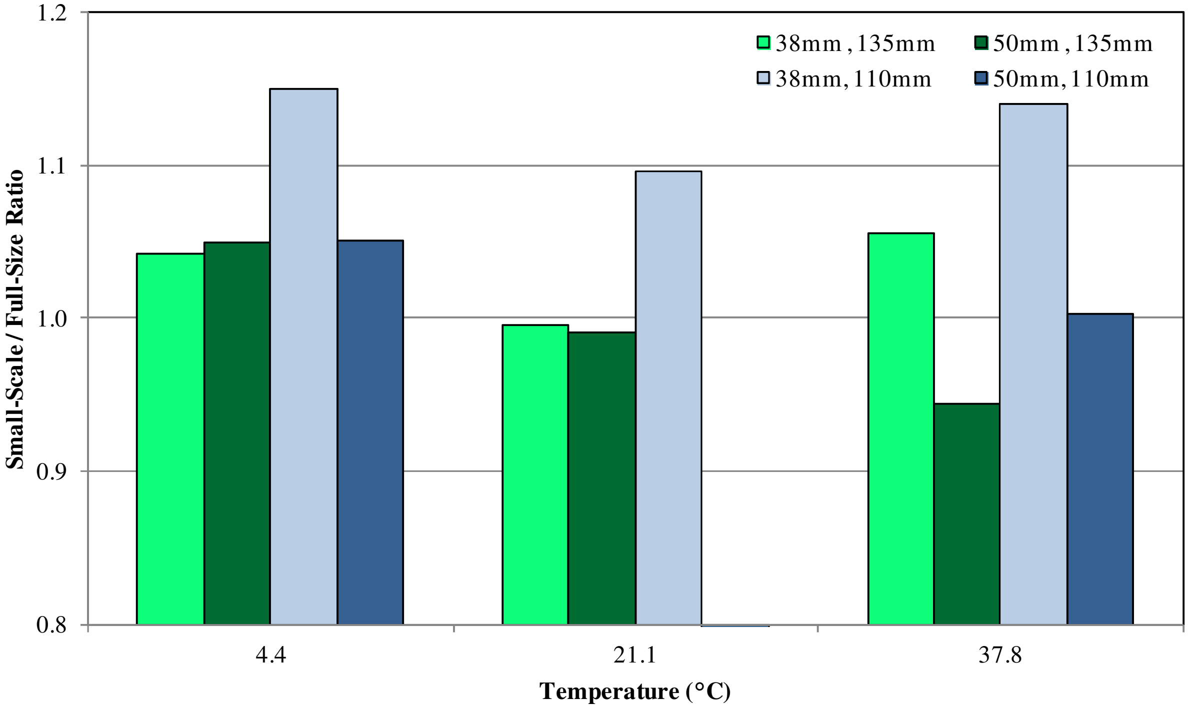

Figure B24. Average Small-Scale / Full-Size Dynamic Modulus Ratio for 25.0-mm NMAS, 25 Hz