VTRC
Virginia Transportation Research Council

We Bring Innovation to Transportation

# Investigation of Binder Aging and Mixture Performance in Service: Reclaimed Asphalt Pavement Mixtures

http://www.virginiadot.org/vtrc/main/online_reports/pdf/18-r26.pdf

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

**HARIKRISHNAN NAIR, Ph.D., P.E.**
**Senior Research Scientist**

**BENJAMIN F. BOWERS, Ph.D., P.E.**
**Research Scientist**

Final Report VTRC 18-R26

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

**Standard Title Page - Report on Federally Funded Project**

| 1. Report No.:<br>FHWA/VTRC 18-R26 | 2. Government Accession No.: | 3. Recipient's Catalog No.: |
|---|---|---|
| 4. Title and Subtitle:<br>Investigation of Binder Aging and Mixture Performance in Service: Reclaimed Asphalt Pavement Mixtures | | 5. Report Date:<br>June 2018<br>6. Performing Organization Code: |
| 7. Author(s):<br>Stacey D. Diefenderfer, Ph.D., P.E., Harikrishnan Nair, Ph.D., P.E., and Benjamin F. Bowers, Ph.D., P.E. | | 8. Performing Organization Report No.:<br>VTRC 18-R26 |
| 9. Performing Organization and Address:<br>Virginia Transportation Research Council<br>530 Edgemont Road<br>Charlottesville, VA 22903 | | 10. Work Unit No. (TRAIS):<br>11. Contract or Grant No.:<br>101902 |
| 12. Sponsoring Agencies' Name and Address:<br>Virginia Department of Transportation<br>1401 E. Broad Street<br>Richmond, VA 23219<br>Federal Highway Administration<br>400 North 8th Street, Room 750<br>Richmond, VA 23219-4825 | | 13. Type of Report and Period Covered:<br>Final<br>14. Sponsoring Agency Code: |
| 15. Supplementary Notes: | | |

16. Abstract:


In 2007, the Virginia Department of Transportation piloted a specification allowing up to 30% reclaimed asphalt pavement (RAP) in certain dense-graded asphalt surface mixtures while changing virgin binder grade requirements. The change affected only mixtures requiring an end binder grade of either PG 64-22 or PG 70-22. For mixtures specifying PG 64-22 binder, the virgin binder grade at RAP contents of 30% or less was no longer required to change. For mixtures specifying PG 70-22 binder, the virgin binder grade at RAP contents of 21% to 30% was no longer required to change from PG 64-22 to PG 64-28. Prior to this, both types of surface mixtures were allowed to contain only up to 20% RAP before binder grade adjustments were required. An initial laboratory study of mixtures produced under the pilot specification indicated that there were no significant differences for fatigue, rutting, and susceptibility to moisture between the higher content (21% to 30%) RAP mixtures and comparison mixtures (20% RAP or less).

The current study evaluated the in-service performance of these mixtures after approximately 7 years and encompassed field visits and a laboratory investigation of a sample of 23 in-service pavements used in the initial laboratory evaluation. Cores were collected from each site and used to evaluate the binder and mixture properties. These data were compared to data from the original construction, when available, to assess the changes in the mixtures over time. Historical performance and maintenance data were also collected and evaluated to investigate the long-term performance characteristics of the sites.

Laboratory testing, including dynamic modulus determination, repeated load permanent deformation analysis, and extracted binder grading and analysis, consistently showed no trends in the results with regard to RAP content. Overlay test results were influenced by more than just RAP (air-void content, etc.), and therefore no trend directly related to RAP content was shown. No trends in field performance could be determined because of the underlying structural conditions. Individual locations were found to show better or worse pavement performance, but this was attributed primarily to structural differences in the pavements and preexisting conditions. Surface deterioration observed in numerous test sections included fatigue cracking, longitudinal cracking, transverse cracking, raveling, and potholes. Binder analysis indicated that depth within a layer (in this case, top half versus bottom half) significantly affects binder properties, with stiffness decreasing with depth. However, increasing RAP contents appeared to mitigate the differences between the top half and bottom half of layers, possibly because of the preexisting aged composition of the RAP and its influence on the virgin binder properties.


| 17 Key Words: | 18. Distribution Statement: |
|---|---|
| RAP, pavement performance, mixture performance, dynamic modulus, repeated load permanent deformation test, overlay test, performance grade, aging, GPC | No restrictions. This document is available to the public through NTIS, Springfield, VA 22161. |

| 19. Security Classif. (of this report): | 20. Security Classif. (of this page): | 21. No. of Pages: | 22. Price: |
|---|---|---|---|
| Unclassified | Unclassified | 152 | |

**FINAL REPORT**

# INVESTIGATION OF BINDER AGING AND MIXTURE PERFORMANCE IN SERVICE: RECLAIMED ASPHALT PAVEMENT MIXTURES

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

**Harikrishnan Nair, Ph.D., P.E.**
**Senior Research Scientist**

**Benjamin F. Bowers, Ph.D., P.E.**
**Research Scientist**

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

June 2018
VTRC 18-R26

## DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

## ABSTRACT

In 2007, the Virginia Department of Transportation piloted a specification allowing up to 30% reclaimed asphalt pavement (RAP) in certain dense-graded asphalt surface mixtures while changing virgin binder grade requirements. The change affected only mixtures requiring an end binder grade of either PG 64-22 or PG 70-22. For mixtures specifying PG 64-22 binder, the virgin binder grade at RAP contents of 30% or less was no longer required to change. For mixtures specifying PG 70-22 binder, the virgin binder grade at RAP contents of 21% to 30% was no longer required to change from PG 64-22 to PG 64-28. Prior to this, both types of surface mixtures were allowed to contain only up to 20% RAP before binder grade adjustments were required. An initial laboratory study of mixtures produced under the pilot specification indicated that there were no significant differences for fatigue, rutting, and susceptibility to moisture between the higher content (21% to 30%) RAP mixtures and comparison mixtures (20% RAP or less).

The current study evaluated the in-service performance of these mixtures after approximately 7 years and encompassed field visits and a laboratory investigation of a sample of 23 in-service pavements used in the initial laboratory evaluation. Cores were collected from each site and used to evaluate the binder and mixture properties. These data were compared to data from the original construction, when available, to assess the changes in the mixtures over time. Historical performance and maintenance data were also collected and evaluated to investigate the long-term performance characteristics of the sites.

Laboratory testing, including dynamic modulus determination, repeated load permanent deformation analysis, and extracted binder grading and analysis, consistently showed no trends in the results with regard to RAP content. Overlay test results were influenced by more than just RAP (air-void content, etc.), and therefore no trend directly related to RAP content was shown. No trends in field performance could be determined because of the underlying structural conditions. Individual locations were found to show better or worse pavement performance, but this was attributed primarily to structural differences in the pavements and preexisting conditions. Surface deterioration observed in numerous test sections included fatigue cracking, longitudinal cracking, transverse cracking, raveling, and potholes. Binder analysis indicated that depth within a layer (in this case, top half versus bottom half) significantly affects binder properties, with stiffness decreasing with depth. However, increasing RAP contents appeared to mitigate the differences between the top half and bottom half of layers, possibly because of the preexisting aged composition of the RAP and its influence on the virgin binder properties.

**FINAL REPORT**

# INVESTIGATION OF BINDER AGING AND MIXTURE PERFORMANCE IN SERVICE: RECLAIMED ASPHALT PAVEMENT MIXTURES

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

**Harikrishnan Nair, Ph.D., P.E.**
**Senior Research Scientist**

**Benjamin F. Bowers, Ph.D., P.E.**
**Research Scientist**

## INTRODUCTION

As of 2013, approximately 85% of Virginia's interstates and 97% of Virginia's primary routes consisted of an asphalt surface (Virginia Department of Transportation [VDOT], 2013). This equates to approximately 8,700 directional miles (approximately 25,720 lane-miles) of asphalt-surfaced pavement for interstate and primary routes that require ongoing maintenance. VDOT awarded 483 contracts in calendar year 2013 that included approximately 6.1 million tons of various asphalt mixtures with a materials value of approximately $515 million. This represents a significant investment in asphalt paving.

Since 2007, VDOT has allowed the production and placement of dense-graded asphalt mixtures having up to 30% reclaimed asphalt pavement (RAP) with no change in binder grade. This allowance affected only mixtures requiring an end binder grade of either PG 64-22 or PG 70-22. For mixtures specifying PG 64-22 binder, the virgin binder grade at RAP contents of 30% or less was no longer required to change. For mixtures specifying PG 70-22 binder, the virgin binder grade at RAP contents of 21% to 30% was no longer required to change from PG 64-22 to PG 64-28. Prior to this, both types of surface mixtures were allowed to contain only up to 20% RAP before binder grade adjustments were required. An initial study of these mixtures with a higher RAP content (Maupin et al., 2008) indicated that in the laboratory, there were no significant differences between the higher RAP content (21% to 30%) mixtures and the comparison mixtures (20% RAP or less) with regard to fatigue, rutting, and susceptibility to moisture. In addition, there were no construction problems attributed to the use of the mixtures with the higher RAP content. During the study, binder was recovered from mixtures sampled during construction and graded to determine the effect of adding higher percentages of RAP, and it was found that in nearly all cases, the increased RAP content resulted in a combined binder grade that increased one high temperature grade over that of the virgin binder grade. Since the 2008 work, the use of these mixtures with a higher RAP content has continued to increase, and more recently, interest in incorporating even higher percentages of RAP into mixtures has increased.

Unfortunately, there is still not a great understanding of the impact of mixing aged binder from the RAP with virgin binder. In practice, the presence or absence of RAP and its impact on the long-term binder properties is generally ignored, with the exception of the assumption that the RAP will stiffen the mixture and may be used to "bump" the binder grade during production. Work conducted by Apeagyei et al. (2011) on plant mixtures indicated that some mixtures for which RAP contents greater than 20% were used in order to stiffen the mixture from the base binder grade of PG 64-22 to PG 70-22 may not be stiffening from the RAP. In addition, there are no detailed field studies indicating how the presence of RAP affects binder grade and performance over the service life of the mixture. In fact, few studies have been performed to assess changes in virgin binder properties over the service life of the mixture or to relate such changes to the actual mixture performance (Al-Azri et al., 2006; Al-Khateeb et al., 2005; Glover et al., 2008; Woo et al., 2008).

The increasing use of RAP in mixtures and this lack of documented performance indicate a need to examine mixtures produced with various RAP contents to assess their long-term performance and the benefits of allowing varying percentages of RAP.

## PURPOSE AND SCOPE

The purpose of the study was to address a number of questions about the long-term properties of asphalt binders and their impact on pavement performance. The influence of RAP on binder grade was a primary consideration. The study addressed the question of how RAP content influences binder grade and mixture performance by looking at the following:

- Is there any difference in the performance of asphalt mixtures containing varying percentages of RAP after 7 to 8 years of service life?
- What is the effect of 7 to 8 years of service on the binder grade of the mixtures and how is this affected by varying percentages of RAP?
- Does depth within the surface layer affect the aging of the binder?

The study scope encompassed field visits and a laboratory investigation of a sample of in-service pavements constructed with varying binders and RAP contents. These pavements included the trial sections evaluated during construction in 2007 by Maupin et al. (2008) and the comparison sites from that study. Site visits were conducted and visual assessments were performed at 23 locations. Cores were collected from each site and used to evaluate the mixture properties, including the binder characteristics. These data were compared to data from the original construction when available to assess the changes in the mixtures over time. Historical performance and maintenance data were also collected and evaluated to investigate the long-term performance characteristics of the sites.

# METHODS

## Literature Review

A literature review was conducted by searching various databases related to transportation engineering such as Transport Research International Documentation (TRID), 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.

## Site Evaluation

### Locations

Twenty-three sites were evaluated in this study. These included 12 sites paved with mixtures having RAP contents of 21% to 30% (shown in Table 1) that were considered "higher RAP" mixtures and 11 sites paved with mixtures containing RAP contents of 20% or less that were considered the comparison group (shown in Table 2). Figure 1 shows the geographical spread of the site locations.

The designation of 21% RAP contents not being included in the comparison group of projects, despite the minimal change in RAP content, was based on the specification used at the time of construction that determined that RAP contents exceeding 20% were considered "high RAP."

**Table 1. Sites Evaluated With Mixtures Containing RAP Contents of 21% to 30%**

| Site | Route | County | Year | NMAS | Binder | % RAP | Contractor |
|---|---|---|---|---|---|---|---|
| A | SR 6 | Goochland | 2007 | 12.5 mm | PG 64-22 | 25 | Branscome Richmond |
| B | SR 6 | Goochland | 2007 | 19.0 mm | PG 64-22 | 30 | Branscome Richmond |
| C | CR 703 | Dinwiddie | 2007 | 12.5 mm | PG 64-22 | 25 | B.P. Short & Son Paving Co., Inc. |
| D | SR 40 | Dinwiddie | 2007 | 12.5 mm | PG 64-22 | 25 | B.P. Short & Son Paving Co., Inc. |
| F | SR 24 | Appomattox | 2007 | 9.5 mm | PG 64-22 | 25 | Marvin V. Templeton and Sons |
| J | CR 611 | Surry | 2007 | 12.5 mm | PG 64-22 | 25 | B.P. Short & Son Paving Co., Inc. |
| O | US 29 | Pittsylvania | 2007 | 12.5 mm | PG 64-22 | 21 | W-L Construction and Paving |
| P | CR 988 | Pittsylvania | 2007 | 12.5 mm | PG 64-22 | 21 | W-L Construction and Paving |
| R | US 221 | Floyd | 2007 | 12.5 mm | PG 64-22 | 30 | Adams Construction Co. |
| S | US 58 | Carroll | 2007 | 12.5 mm | PG 64-22 | 30 | Adams Construction Co. |
| U | US 29 | Nelson | 2007 | 12.5 mm | PG 64-22 | 25 | Marvin V. Templeton & Sons |
| X | I-664 | Chesapeake | 2007 | 12.5 mm | PG 64-22 | 30 | Branscome, Inc. |

NMAS = nominal maximum aggregate size; RAP = reclaimed asphalt pavement; SR = State Route; CR = County Route; US = US Route; I = interstate; PG = performance grade.

**Table 2. Comparison Sites With Mixtures Containing RAP Contents of 20% or Less**

| Site | Route | County | Year | NMAS | Binder | % RAP | Contractor |
|---|---|---|---|---|---|---|---|
| E | I-64 | Louisa | 2006 | 9.5 mm | PG 70-22 | 0 | Mega Construction |
| H, I | SR 211 | Rappahannock | 2006 | 9.5 mm | PG 64-22 | 20 | Superior Paving Corp. |
| K, L | US 220 | Highland | 2006 | 12.5 mm | PG 64-22 | 10 | B&S Contracting, Inc. |
| M, N | SR 143 | York | 2006 | 9.5 mm | PG 64-22 | 20 | Branscome, Inc. |
| Q | US 11 | Montgomery | 2006 | 9.5 mm | PG 70-22 | 15 | Adams Construction Co. |
| T | SR 671 | South Hampton | 2006 | 9.5 mm | PG 64-22 | 10 | Rose Brothers Paving Company, Inc. |
| V | I-64 | Louisa | 2007 | 9.5 mm | PG 70-22 | 0 | S.L. Williamson Company, Inc. |
| W | US 301 | Caroline | 2007 | 12.5 mm | PG 70-22 | 20 | Branscome Richmond |

NMAS = nominal maximum aggregate size; RAP = reclaimed asphalt pavement; SR = State Route; CR = County Route; US = US Route; I = interstate; PG = performance grade.


**Figure 1. Site Locations**

Mix designs were compiled and are presented in Appendix A. A brief summary of the designs is provided in Table 3. Mixtures A and B contained a single production surface mixture sampled at two locations along the same site. Mixture B (IM) is the intermediate layer located in section B. Mixtures C/D, O/P, and R/S were each sampled from two unique sites, although the mix designs were the same. Mixtures H/I, K/L, and M/N were produced as both hot mix asphalt (HMA) and warm mix asphalt (WMA); both types of mixtures were evaluated. Mixtures H and K were produced as WMA using Sasobit as an additive; Mixture M was produced as a WMA using the Evotherm DAT additive system.

**Table 3. Mix Design Summary**

| Section | Mix Design | NMAS | Binder | Design AC | RAP Content |
|---|---|---|---|---|---|
| A | 4047-739 | 12.5 mm | PG 64-22 | 5.6% | 25% |
| B | 4047-739 | 12.5 mm | PG 64-22 | 5.6% | 25% |
| B (IM) | 4047-738 | 19.0 mm | PG 64-22 | 5.0% | 30% |
| C, D | 4015-722 | 12.5 mm | PG 64-22 | 5.5% | 25% |
| E | 4047-200608 | 9.5 mm | PG 70-22 | 5.6% | 0% |
| F | 3014-2007-15 | 9.5 mm | PG 64-22 | 5.5% | 25% |
| H, I | 7008-200615 | 9.5 mm | PG 64-22 | 5.5% | 20% |
| J | 4015-07-19 | 12.5 mm | PG 64-22 | 5.8% | 25% |
| K, L | 8012-612 | 12.5 mm | PG 64-22 | 5.2% | 10% |
| M, N | 5011-06-10 | 9.5 mm | PG 64-22 | 5.7% | 20% |
| O, P | 3007-2007-18 | 12.5 mm | PG 64-22 | 5.9% | 21% |
| Q | 2025-200531 | 9.5 mm | PG 70-22 | 5.7% | 15% |
| R, S | 2065-2007-4 | 12.5 mm | PG 64-22 | 5.5% | 30% |
| T | 5024-200605 | 9.5 mm | PG 64-22 | 5.5% | 10% |
| U | 3005-2007-06 | 12.5 mm | PG 64-22 | 5.7% | 25% |
| V | 7017-2007-10 | 9.5 mm | PG 70-22 | 5.7% | 0% |
| W | 4051-720 | 12.5 mm | PG 70-22 | 5.4% | 20% |
| X | 5029-2007-04 | 12.5 mm | PG 64-22 | 5.4% | 30% |

NMAS = nominal maximum aggregate size; AC = asphalt content; RAP = reclaimed asphalt pavement.

## Coring

Ten cores 6 in (150 mm) in diameter were taken from each pavement site for evaluation. Core locations were randomized along the length and width of the pavement site.

## Visual Survey

A visual survey was conducted at each pavement section in accordance with the guidelines for distress identification by Miller and Bellinger (2003) in order to provide specific measurements of distresses. Condition indices were not calculated from the visual distress surveys conducted. The survey distances varied depending on the length of the pavement section and the traffic control setup, vehicle traffic volumes, and roadway geometry for safety purposes. The minimum survey distance was 1,000 ft, and the maximum was 3,500 ft. Most surveys were conducted on sections of 1,000 or 1,500 ft.

## Pavement Management System (PMS) Data

Distress data for comparison and RAP sites were extracted from VDOT's Pavement Management System (PMS). VDOT's Maintenance Division acquires and maintains the results of an annual condition survey of all interstates, all primaries, and approximately 20% of secondary pavements. For the survey, detailed distress data for each 0.1 mile of right-lane or principal-direction pavement surface are collected and summarized. Condition is reported on a scale from 0 to 100, heavily distressed to new or like new, respectively. The overall section rating, the Critical Condition Index, is the lower of two ratings that summarize the load related and non-load related distresses for a pavement. In addition to other possibilities, a Critical Condition Index of 60 will typically trigger a maintenance action for the existing surface.

## Laboratory Materials Evaluation

### Core Air Voids

Air-void contents were determined in accordance with AASHTO T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (American Association of State Highway and Transportation Officials [AASHTO], 2014).

### Permeability

Permeability testing on cores collected from each site was performed in accordance with Virginia Test Method (VTM) 120, Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter (VDOT, 2014).

### Dynamic Modulus

Dynamic modulus tests were performed with an Asphalt Mixture Performance Tester generally in accordance with AASHTO T 342, Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures (AASHTO, 2014). Tests were performed on specimens 38 mm in diameter by 110 mm tall cored horizontally from field cores, as described in Bowers, et al., 2015a. Three testing temperatures (4.4°C, 21.1°C, and 37.8°C) and six testing frequencies from 0.1 to 25 Hz were used. Tests were conducted starting from the coldest to the warmest temperatures. In addition, at each test temperature, the tests were performed starting from the highest to the lowest frequency. Load levels were selected in such a way that at each temperature-frequency combination, the applied strain was in the range of 75 to 125 macrostrain. All tests were conducted in the uniaxial mode without confinement. Stress versus strain values were captured continuously and used to calculate dynamic modulus. The results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

### Repeated Load Permanent Deformation

The repeated load permanent deformation (RLPD) test (also known as the flow number test) is used to evaluate the rutting resistance of asphalt mixtures. An Asphalt Mixture Performance Tester with a 15 kN loading capacity was used to conduct the tests. Tests were performed on specimens 38 mm in diameter by 110 mm tall cored horizontally from field cores. All RLPD testing was conducted on specimens previously tested for dynamic modulus. Tests were conducted at 54°C based on LTPPBind software that represents the 50% reliability maximum high pavement temperature at locations in central Virginia. A repeated haversine axial compressive load pulse of 0.1 s every 1.0 s was applied to the specimens. The tests were performed in the confined mode using a confining stress of 10 psi (68.9 kPa) and a deviator stress of 70 psi (483 kPa). The tests were continued for 10,000 cycles or a permanent strain of 10%, whichever came first. During the test, permanent strain ($\varepsilon p$) versus the number of loading cycles was recorded automatically, and the results were used to estimate the flow number. The flow number was determined numerically as the cycle number at which the strain rate is at a minimum based on the Francken model.

In addition to calculations of the flow number, the slope and intercepts of the secondary portion of the cycle versus permanent strain curve was estimated in log-log space by the application of a power-law function (Eq. 1):

$$\varepsilon_p = aN^b \quad \text{[Eq. 1]}$$

where

$\varepsilon_p$ = permanent strain
a = intercept in log-log space
N = cycle number
b = slope in log-log space.

The slope of this line is indicative of the plastic strain rate of the mixture. A higher slope relative to other mixtures indicates a mixture that is likely more susceptible to rutting. The intercept of the line is indicative of the plastic strain at cycle N = 1 (Khosravifar et al., 2015; Von Quintus et al., 2012).

**Texas Overlay Test**

The Texas overlay test was performed to assess the susceptibility of each mixture to cracking. Testing was performed on field cores 150 mm in diameter and of varying thicknesses using a universal testing machine with a loading capacity of 25 to 100 kN generally in accordance with TX-248-F, Test Procedure for Overlay Test (Texas Department of Transportation, 2009). Testing was performed at a temperature of 25 ± 0.5°C. Loading was applied for a total of 1,200 cycles or until a reduction of 93% or more of the maximum load was reached.

**Binder Extraction and Recovery**

Extraction of binder from cores was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder From Hot Mix Asphalt (HMA), Method A (AASHTO, 2014) using n-propyl bromide as the solvent. Binder was recovered from the solvent in accordance with the Rotavap recovery procedure specified in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder From Asphalt Mixtures (AASHTO, 2014).

**Binder Testing**

Binder grading was performed in accordance with AASHTO M 320, Performance-Graded Asphalt Binder (AASHTO, 2014). In addition, shear modulus mastercurves were generated for the recovered binders. Nine test temperatures from 5 to 85°C and 10 test frequencies from 0.01 to 25 Hz were used to generate data for mastercurve construction. Mastercurves were constructed using least squares optimization of the Christensen-Anderson model (Christensen and Anderson, 1992) (Eqs. 2 and 3):

$$G^*(\omega) = G_g \cdot \left(1 + \frac{\omega_C^{\frac{\log 2}{R}}}{\omega}\right)^{-\left(\frac{R}{\log 2}\right)} \quad \text{[Eq. 2]}$$

$$\delta(\omega) = \frac{90}{\left[1+\left(\frac{\omega}{\omega_C}\right)^{\frac{\log 2}{R}}\right]} \quad \text{[Eq. 3]}$$

where

$G^*(\omega)$ = complex shear modulus, kPa
$\delta(\omega)$ = phase angle, rad
$G_g$ = glassy modulus, kPa
$\omega_C$ = crossover frequency
$\omega$ = reduced frequency
R = rheological index.

Temperature shift factors were fitted to the Williams-Landel-Ferry (WLF) equation (Eq. 4):

$$\log a_T = \frac{-C_1 (T-T_R)}{(C_2+T-T_R)} \quad \text{[Eq. 4]}$$

where

$a_T$ = shift function
$C_1$ and $C_2$ = empirical constants
T = test temperature, °C
$T_R$ = reference temperature, °C.

**Gel Permeation Chromatography**

Gel permeation chromatography (GPC) was performed to analyze the molecular weight distribution of the asphalt binder after the recovery process. Testing was performed using an EcoSEC GPC by Tosoh Biosciences, which had a guard column, one TSKgel SuperHZ2500 column with a mean pore size of 30 Å, two TSKgel SuperHZ3000 columns with a mean pore size of 75 Å, and one TSKgel SuperHZ4000 column with a mean pore size of 200 Å in series. Columns were calibrated using polystyrene standards. The elution solvent was tetrahydrofuran stabilized with butylated hydroxytoluene.

Analysis of the data consisted of calculating the percentage of large molecules present within the molecular weight distribution of the binder. This process involves taking the area of the first 5/13 s of the chromatogram and dividing it by the total area beneath the chromatogram. This ratio, converted to a percentage, relates to the stiffness of the binder and its oxidative properties (Bowers et al., 2014; Bowers et al., 2015b; Doh et al., 2008; Kim et al., 2006, Lee et al., 2006; Zhao et al., 2014). A higher percentage of large molecular sizes (LMS) equates to a stiffer binder.

## RESULTS AND DISCUSSION

### Literature Review

RAP is commonly used in varying percentages in asphalt mixtures because of its economic and environmental benefits. In the past, RAP was successfully used under the Marshall mix design method (Decker, 1997; Kandhal, 1997); however, during the initial adoption of the Superpave mix design method, the use of RAP initially decreased because the design method was based on virgin mixtures. Over time, the use of RAP in Superpave mixtures grew as additional guidance on its incorporation was developed (McDaniel and Anderson, 2001; McDaniel and Shah, 2003; National Cooperative Highway Research Program, 2001; West et al., 2013), although there are often still concerns expressed about potential impacts on performance.

A 2007 survey of state agencies showed that average allowable RAP contents in asphalt mixtures ranged from 10% to 20%, with the average amount actually used being 12%. Uncertainty with regard to the long-term performance of asphalt pavements containing RAP materials was the primary reason reported for this limited use (Copeland, 2011). A more recent survey of the states indicated that not only has the tonnage of RAP used increased but the average RAP content of asphalt mixtures has also increased to approximately 17% (Hansen and Newcomb, 2011). However, with increased RAP use, concerns have increased about the potential impact of RAP contents on mixture performance and service life.

Although numerous field sections have been placed around the United States to evaluate Superpave mixtures with RAP contents greater than 20% to 25%, very little has been published on the topic of their long-term field performance. In addition, the number of studies evaluating even pre-Superpave mixtures containing RAP is limited. In 2009, the National Center for Asphalt Technology (NCAT) (West et al., 2011) examined the Specific Pavement Studies 5 (SPS5) information in the database of the Long-Term Pavement Performance program (LTPP). SPS5 consisted of 50 mm and 125 mm overlays constructed from virgin and 30% RAP mixtures. The NCAT study found that the 30% RAP overlays performed as well as the virgin overlays in terms of the international roughness index, rutting, block cracking, and raveling. NCAT has also evaluated HMA with a higher RAP content on the pavement test track in several studies (West et al., 2012; Willis et al., 2012). In 2006, four surface mixtures containing 45% RAP with various asphalt binders (PG 52-28, PG 67-22, PG 76-22, and PG 76-22 with Sasobit) were constructed over a perpetual asphalt pavement foundation to assess surface performance. After 20 million equivalent single-axle loads, less texture change and cracking were measured in the sections produced with softer virgin asphalt grades. In 2009, a structural pavement study was conducted on the test track to compare a control virgin HMA test section to HMA and WMA sections containing 50% RAP. The RAP and virgin structural sections were designed and constructed to have equivalent binder contents, and all other properties were held within normal production tolerances. The structural sections containing 50% RAP withstood 10 million equivalent single-axle loads of trafficking, and their performance was equivalent to that of the control with regard to both cracking and rutting.

Anderson and Daniel (2013) examined case studies of roadway sections from across the United States constructed from 1977 to 1999 that contained 20% to 72% RAP. The analysis

used approximately 10 years of in-service pavement condition data to evaluate the performance of the sections versus that of the virgin control sections. Although there were differences in performance, namely, the RAP sections were less crack resistant, of lower ride quality, and more rut resistant than the control sections, these differences were in many cases not statistically significant. None of the distress factors was severe enough to be detrimental to the expected life spans of the RAP sections, which were typically less than 5% different than that of the virgin sections.

## Site Evaluation

### Visual Survey

Visual survey data were compiled and evaluated for all sites. Table 4 presents a summary of the cracking and raveling data for sites with mixtures having ≤20% RAP and sites with mixtures having 21% to 30% RAP. Distresses were classified as low, medium, or high, and quantitative measures are presented for each classification. In addition, the number of sites exhibiting each distress severity and the percentage of sites exhibiting each distress severity are shown.

Statistical analysis was performed using two-sample, two-tailed unequal variance *t*-tests with a level of significance of $\alpha = 0.05$ to assess the differences in quantified distresses between the sites with mixtures having ≤20% RAP and those with mixtures having 21% to 30% RAP, as shown in Table 5. Tests were performed by comparing the pools of data for each severity. In addition, data for all severities for each distress were compared. The results indicated that all sites performed similarly based on the visual assessment.

In addition, statistical analysis using two-tailed paired *t*-tests was performed to compare total percentages of lane area or length observed for each distress level across all sites; the results are shown in Table 6. The results again indicated no significant difference between sites with mixtures having ≤20% RAP and sites with mixtures having >20% RAP.

The visual survey and coring results showed several distress types in both categories of sections. Examples of these distresses follow. It should be noted that terminology differs between cracking as determined in the visual survey and as described here. The visual survey does not distinguish the origin of cracking, such as top-down or bottom-up, particularly as this distinction requires some knowledge of the structural condition of the pavement or some level of forensic investigation, such as coring to determine the crack origin. Cracking is described here in terms of origin where applicable to enable further an understanding of the mechanisms involved and to distinguish between cracking that may be due to material properties and that which is structurally related and thus not a direct measure of material properties or performance. For example, top-down cracking is dependent on surface layer material properties, as it originates at the surface. However, bottom-up cracking originates in the lower pavement layers because of insufficient structural capacity for the applied loading and propagates upward; these cracks are indicative of the surface material's strength being exceeded but are driven by structural incapacity, and it is improper to attribute this directly to a lack of performance of the surface material.

**Table 4. Summary of Visual Survey Cracking and Raveling Data**

| ≤20% RAP | | | | 21% to 30% RAP | | | |
|---|---|---|---|---|---|---|---|
| Site | Low Severity | Medium Severity | High Severity | Site | Low Severity | Medium Severity | High Severity |
| **Fatigue Cracking, ft²** | | | | | | | |
| E | 1,240 | 600 | 5,800 | A | 3,608 | 1,650 | 249 |
| H | 0 | 433 | 0 | B | 18,040 | 4,530 | 500 |
| I | 0 | 998 | 0 | C | 2,017 | 0 | 0 |
| K | 0 | 119 | 0 | D | 1,736 | 0 | 0 |
| L | 0 | 8 | 0 | F | 0 | 0 | 0 |
| M | 0 | 0 | 0 | J | 112 | 0 | 0 |
| N | 0 | 0 | 0 | O | 0 | 0 | 0 |
| Q | 0 | 988.2 | 0 | P | 0 | 9.2 | 0 |
| T | 0 | 502.2 | 0 | R | 0 | 319 | 0 |
| V | 0 | 0 | 0 | S | 0 | 101.1 | 0 |
| W | 0 | 20.9 | 0 | U | 0 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Total | 1,240 | 3,669.3 | 5,800 | Total | 25,513 | 6,609.3 | 749 |
| No. Sites | 1 | 8 | 1 | No. Sites | 5 | 5 | 2 |
| % Sites | 9% | 73% | 9% | % Sites | 42% | 42% | 17% |
| **Longitudinal Cracking, Wheelpath, ft** | | | | | | | |
| E | 0 | 0 | 0 | A | 0 | 0 | 0 |
| H | 0 | 962 | 0 | B | 40 | 0 | 0 |
| I | 0 | 3,000 | 0 | C | 22 | 0 | 0 |
| K | 184 | 0 | 0 | D | 49 | 0 | 0 |
| L | 67 | 72 | 0 | F | 0 | 0 | 0 |
| M | 0 | 0 | 0 | J | 39 | 232 | 0 |
| N | 0 | 0 | 0 | O | 1816 | 197.2 | 0 |
| Q | 0 | 3.4 | 0 | P | 122.6 | 52.7 | 0 |
| T | 136.3 | 211.7 | 0 | R | 0 | 1208 | 0 |
| V | 0 | 0 | 0 | S | 25.2 | 8034 | 0 |
| W | 0 | 450.2 | 0 | U | 6.2 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Total | 387.3 | 4,699.3 | 0 | Total | 2,120 | 9,723.9 | 0 |
| No. Sites | 2 | 5 | 0 | No. Sites | 6 | 3 | 0 |
| % Sites | 18% | 45% | 0% | % Sites | 50% | 25% | 0% |
| **Longitudinal Cracking, Non-wheelpath, ft** | | | | | | | |
| E | 0 | 0 | 44 | A | 0 | 1,000 | 1,000 |
| H | 0 | 1,000 | 0 | B | 130 | 110 | 250 |
| I | 0 | 25 | 0 | C | 16 | 0 | 0 |
| K | 0 | 1,686 | 0 | D | 0 | 0 | 0 |
| L | 0 | 1,112 | 0 | F | 0 | 406 | 0 |
| M | 0 | 1,231.9 | 0 | J | 184 | 92 | 0 |
| N | 0 | 1,000 | 0 | O | 0 | 0 | 0 |
| Q | 0 | 0 | 0 | P | 0 | 0 | 0 |
| T | 0 | 343.3 | 0 | R | 0 | 39 | 0 |
| V | 0 | 0 | 0 | S | 115.7 | 480.8 | 0 |
| W | 0 | 202.3 | 0 | U | 0 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Total | 0 | 6,600.5 | 44 | Total | 445.7 | 2,127.8 | 1,250 |
| No. Sites | 0 | 4 | 1 | No. Sites | 4 | 6 | 2 |
| % Sites | 0% | 36% | 9% | % Sites | 33% | 50% | 17% |
| **Transverse Cracking, Unsealed, ft** | | | | | | | |
| E | 0 | 33 | 0 | A | 0 | 0 | 0 |
| H | 0 | 21 | 0 | B | 0 | 0 | 0 |
| I | 0 | 0 | 0 | C | 9.5 | 0 | 0 |
| K | 27 | 19 | 0 | D | 0 | 0 | 0 |
| L | 0 | 17 | 0 | F | 0 | 161 | 0 |
| M | 0 | 0 | 0 | J | 0 | 0 | 0 |
| N | 168 | 204 | 228 | O | 0 | 0 | 0 |
| Q | 0 | 12 | 0 | P | 0 | 148 | 50 |
| T | 5 | 7 | 0 | R | 0 | 20 | 0 |
| V | 147 | 36 | 0 | S | 12 | 34 | 0 |
| W | 0 | 6 | 0 | U | 31 | 24 | 0 |
| | | | | X | 0 | 0 | 0 |
| Total | 347 | 355 | 228 | Total | 52.5 | 387 | 50 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| No. Sites | 4 | 9 | 1 | No. Sites | 3 | 5 | 1 |
| % Sites | 36% | 82% | 9% | % Sites | 25% | 42% | 8% |
| **Raveling, ft$^2$** | | | | | | | |
| E | 0 | 0 | 0 | A | 0 | 0 | 0 |
| H | 0 | 0 | 0 | B | 720 | 860 | 0 |
| I | 0 | 0 | 0 | C | 0 | 0 | 0 |
| K | 0 | 0 | 0 | D | 66 | 0 | 0 |
| L | 0 | 0 | 0 | F | 0 | 0 | 0 |
| M | 0 | 172.4 | 0 | J | 0 | 0 | 0 |
| N | 0 | 0 | 0 | O | 0 | 0 | 0 |
| Q | 0 | 5 | 0 | P | 0 | 0 | 0 |
| T | 0 | 0 | 0 | R | 0 | 117 | 0 |
| V | 0 | 0 | 0 | S | 0 | 0 | 0 |
| W | 0 | 230 | 0 | U | 0 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Total | 0 | 407.4 | 0 | Total | 786 | 977 | 0 |
| No. Sites | 0 | 2 | 0 | No. Sites | 2 | 2 | 0 |
| % Sites | 0% | 18% | 0% | % Sites | 17% | 17% | 0% |

No sealed longitudinal cracking, bleeding, or reflection cracking was observed.

**Table 5. *p*-Value Results From Two-Sample, Two-Tailed *t*-Tests Performed on Pooled Visual Survey Data**

| Distress | Low Severity | Medium Severity | High Severity | All Severities |
|---|---|---|---|---|
| Fatigue | 0.2034 | 0.6003 | 0.4000 | 0.2900 |
| Longitudinal, Wheelpath | 0.3673 | 0.6016 | - | 0.4823 |
| Longitudinal, Non-wheelpath | 0.0770 | 0.0587 | 0.2588 | 0.2860 |
| Transverse, Unsealed | 0.1857 | 0.9993 | 0.4503 | 0.2431 |
| Raveling | 0.2964 | 0.5669 | - | 0.2577 |

*p*-values less than or equal to 0.05 indicate significant differences between datasets for sites with mixtures having RAP contents ≤ 20% and those with mixtures having RAP contents of 21% to 30%. - = no test performed as all data points were zero.

**Table 6. *p*-Value Results From Paired, Two-Tailed *t*-Tests Performed on Paired Percentage by Severity Level**

| Distress | Severity | Percentage RAP | | *p*-value |
|---|---|---|---|---|
| | | ≤20% RAP[a] | 21%-30% RAP[b] | |
| Fatigue Cracking[c] | Low | 0.9% | 12.1% | 0.6193 |
| | Medium | 2.7% | 3.1% | |
| | High | 4.2% | 0.4% | |
| Longitudinal Cracking, Wheelpath[d] | Low | 3.4% | 12.0% | 0.2090 |
| | Medium | 40.6% | 55.2% | |
| | High | 0.0% | 0.0% | |
| Longitudinal Cracking, Non-wheelpath[d] | Low | 0.0% | 2.5% | 0.5462 |
| | Medium | 57.4% | 12.1% | |
| | High | 0.4% | 7.1% | |
| Transverse Cracking, Unsealed[d] | Low | 3.0% | 0.3% | 0.0792 |
| | Medium | 3.1% | 2.2% | |
| | High | 2.0% | 0.3% | |
| Raveling[c] | Low | 0.0% | 4.5% | 0.2366 |
| | Medium | 3.5% | 5.6% | |
| | High | 0.0% | 0.0% | |

*p*-values less than or equal to 0.05 indicate significant differences between comparison and RAP datasets; RAP = reclaimed asphalt pavement.
[a] For sites with ≤20% RAP, the number of sites evaluated was 11, the total length evaluated was 11,500 ft, and the total lane area evaluated was 138,000 ft$^2$.
[b] For sites with 21%-30% RAP, the number of sites evaluated was 12, the total length evaluated was 17,600 ft, and the total lane area evaluated was 211,200 ft$^2$.
[c] Percentage = quantity/total lane area evaluated.
[d] Percentage = quantity/total length evaluated.

The purpose of discussing the general conditions observed in the sections is to note that all sections are undergoing various types of deterioration. Most of the deterioration observed was not directly influenced by the surface material properties; in fact, most appeared to be related to structural deficiencies within the underlying layers. Distresses such as fatigue cracking, delamination, and moisture damage in underlying layers will eventually result in cracking that is apparent on the surface of a pavement. However, this should not be attributed to poor performance of the surface material.

High severity fatigue cracking was observed at several locations in Section A (25% RAP), located along SR 6 in Goochland County, as shown in Figure 2. In addition, several new asphalt patches were observed. A detailed forensic evaluation was not performed to evaluate cracking causes although it appeared that since most of the cracks were located along the wheelpath, pavement structural issues were a contributing factor. The presence of moisture in the fatigued areas supports the inference of structural issues.

Top-down cracking was observed in a number of sections, as validated by cores. Top-down cracking was included in the visual survey under the longitudinal wheelpath cracking category. Sites H and I (20% RAP) located along US 211 in Rappahannock County were found to have top-down cracking, as shown in Figure 3. Site R (30% RAP) located on US 221 in Floyd County exhibited cracking in the right wheelpath within the surface layer. Sites O (21% RAP) and U (25% RAP) located along US 29 in Nelson and Pittsylvania counties, respectively, were found to be in generally excellent condition, although cracking was observed. Full-depth cores indicated that most of the cracks were within the surface layer originating from the top.

**Figure 2. Cracking and Patches on Section A, SR 6 in Goochland County**

**Figure 3. Cores From Sites H and I (SR 211 in Rappahannock County) Showed That Cracking Was Initiating From the Top Down**

Raveling was also observed among the sites. A core from Site C (25% RAP), located along CR 703 in Dinwiddie County, displayed mixture raveling, as shown in Figure 4, although this was not seen in the visual survey. Medium severity raveling, as shown in Figure 5, was observed in Site Q (15% RAP) located along US 11 in Montgomery County. Visual survey data indicated that Sites B and D exhibited low severity raveling and Sites B, M, R, and W displayed medium severity raveling.

**Figure 4. Mixture Raveling in a Core From Site C, CR 703 in Dinwiddie County**

**Figure 5. Raveling Observed in Site Q, US 11 in Montgomery County**

Delamination was also found in a number of sites during coring. In addition to raveling, Site Q (15% RAP) located on US 11 in Montgomery County was found to have debonded layers when cored, as shown in Figure 6. Cores from section R (30% RAP), located on US 221 in Floyd County, were also debonded, as shown in Figure 7. Construction records reported that shoving and cracking were "prevalent" throughout the mat and the longitudinal edges appeared to move "inches per roller pass." Although Site S (30% RAP), located on US 58 in Carroll County, was in reasonably good condition based on the visual survey, full-depth cores revealed debonded layers, as shown in Figure 8.

**Figure 6. Cores Indicated Debonding and Stripping in Site Q (US 11 in Montgomery County)**

**Figure 7. Delaminated Pavement Layers Found in Site R (US 221 in Floyd County)**


**Figure 8. Debonding Shown in a Core From Site S (US 58 in Carroll County)**

Moisture damage was also observed in cores. Cores from Site F (25% RAP), located on SR 24 in Appomattox County, showed evidence of moisture damage and several full-depth cracks, as shown in Figure 9. Site Q (15% RAP) located on US 11 in Montgomery County was found to have moisture damage in addition to the debonding previously mentioned, as shown in Figure 6. Fines pumping through cracks on the surface were seen in Site T (10% RAP) located on SR 671 in South Hampton County; cores indicated moisture damage, as shown in Figure 10.


**Figure 9. Full depth Crack Seen in Site F, SR 24 in Appomattox County**

**Figure 10. Pumping of Fines and Moisture Damage in a Core From Site T (SR 671 in South Hampton County)**

## Pavement Management System Data

Distress data were extracted from VDOTs Pavement Management System (PMS) for both sites with mixtures having ≤20% RAP and those having 21% to 30% RAP; the data are summarized in Tables 7 and 8. For some sites, exact mile points were not available, and hence PMS data are not shown. Complete details are provided in Appendix B. All sites showed low rut depths of less than 0.16 in with the exception of Site A/B, which had a rut depth of 0.23 in. Most of the pavements were in acceptable ride condition. Very low truck traffic was found for all sites except I-664. With the exception of secondary pavements, most sites had automated distress data available beginning in 2007. Some of the predominant failure mechanisms observed in comparison sites were stripping of underlying layers, debonding, longitudinal cracking, and joint failures, which are not directly attributable to the surface mixture performance.

**Table 7. 2014 PMS Distress Data for Sites With Mixtures Having RAP Contents of 20% or Less**

| Site | Route | County | % RAP | CCI | IRI, in/mile | Rut Depth, in | Traffic, AADTT |
|---|---|---|---|---|---|---|---|
| E | I-64 | Louisa | 0 | - | - | - | - |
| H, I | SR 211 | Rappahannock | 20 | 27 | 60 | 0.11 | 54 |
| K, L | US 220 | Highland | 10 | 40 | 78 | 0.09 | 17 |
| M, N | SR 143 | York | 20 | 46 | 106 | 0.08 | 82 |
| Q | US 11 | Montgomery | 15 | 78 | 90 | 0.13 | 81 |
| T | SR 671 | South Hampton | 10 | - | - | - | - |
| V | I-64 | Louisa | 0 | - | - | - | - |
| W | US 301 | Caroline | 20 | - | - | - | - |

PMS = VDOT's Pavement Management System; RAP = reclaimed asphalt pavement; CCI = Critical Condition Index; IRI = International Roughness Index; AADTT = average annual daily truck traffic; - = data not available.

**Table 8. 2014 PMS Distress Data for Sites With Mixtures Having RAP Contents of 21% to 30%**

| Site | Route | County | % RAP | CCI | IRI, in/mile | Rut Depth, in | Traffic, AADTT |
|---|---|---|---|---|---|---|---|
| A, B | SR 6 | Goochland | 25 | 75 | 109 | 0.23 | 121 |
| C[a] | CR 703 | Dinwiddie | 25 | 95 | 128 | 0.15 | 48 |
| D | SR 40 | Dinwiddie | 25 | 82 | 90 | 0.12 | 67 |
| F | SR 24 | Appomattox | 25 | 95 | 75 | 0.09 | 189 |
| J | CR 611 | Surry | 25 | - | - | - | - |
| O | US 29 | Pittsylvania | 21 | 86 | 75 | 0.15 | 889 |
| P | CR 988 | Pittsylvania | 21 | - | - | - | - |
| R | US 221 | Floyd | 30 | 61 | 114 | 0.11 | 60 |
| S | US 58 | Carroll | 30 | 66 | 113 | 0.14 | 57 |
| U | US 29 | Nelson | 25 | 93 | 73 | 0.16 | 806 |
| X | I-664 | Chesapeake | 30 | 89 | 81 | 0.16 | 2163 |

PMS = VDOT's Pavement Management System; RAP = reclaimed asphalt pavement; CCI = Critical Condition Index; IRI = International Roughness Index; AADTT = average annual daily truck traffic; - = data not available.

[a] Only 2010 data were available.

## Laboratory Materials Evaluation

### Core Air Voids

Air voids were measured for all undamaged cores. The results are shown in Tables 9 and 10. Individual measurements were variable, as typically expected. Average air-void contents for each section ranged from 4.6% to 8.9%.

**Table 9. Air-void Content and Permeability Test Results for Cores From Sections With Mixtures Having RAP Contents of 20% or Less**

| Site | % RAP | Property | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E | 0 | VTM, % | 11.9 | 10.5 | 8.1 | 6.4 | 6.2 | 8.1 | 6.3 | 5.7 | 6.2 | 6.8 | 7.6 |
| | | Permeability x $10^{-5}$ cm/sec | 117.4 | 66.9 | 17.3 | 0.7 | 0.5 | 18.6 | 0.7 | 0.0 | 0.3 | 1.9 | 22.4 |
| H | 20 | VTM, % | 6.8 | 7.4 | 6.5 | - | 3.6 | 5.6 | 6.8 | 7.0 | 3.6 | 4.9 | 5.8 |
| | | Permeability x $10^{-5}$ cm/sec | 3.1 | 3.9 | 0.9 | NA | 0.0 | 0.5 | 1.4 | 3.0 | 0.0 | 0.1 | 1.4 |
| I | 20 | VTM, % | 6.4 | 5.3 | 6.0 | 5.7 | 5.8 | 6.0 | 5.8 | 5.8 | 7.0 | 7.6 | 6.1 |
| | | Permeability x $10^{-5}$ cm/sec | 55.3 | 0.2 | 4.2 | 0.6 | 2.7 | 3.4 | 2.2 | 1.4 | 1.3 | 0.9 | 7.2 |
| K | 10 | VTM, % | 6.5 | 4.7 | 4.1 | 6.8 | 4.0 | 5.6 | 8.8 | 8.2 | 6.2 | 5.3 | 6.0 |
| | | Permeability x $10^{-5}$ cm/sec | 0.0 | 0.0 | 0.0 | 22.9 | 0.0 | 0.0 | 3.6 | 4.1 | 0.2 | 1.0 | 3.2 |
| L | 10 | VTM, % | 7.5 | 4.6 | 5.0 | 7.3 | 6.3 | 4.6 | 7.9 | 6.6 | 6.5 | 6.0 | 6.2 |
| | | Permeability x $10^{-5}$ cm/sec | 48.9 | 0.0 | 0.0 | 33.4 | 20.3 | 0.5 | 49.0 | 20.7 | 547.8 | 0.3 | 72.1 |
| M | 20 | VTM, % | 5.5 | - | 7.7 | 5.7 | 6.3 | 10.0 | 7.6 | 7.9 | 7.7 | 8.4 | 7.4 |
| | | Permeability x $10^{-5}$ cm/sec | 0.0 | NA | 1.5 | 0.0 | 0.0 | 6.2 | 1.3 | 2.4 | 1.4 | 3.3 | 1.8 |
| N | 20 | VTM, % | 7.4 | 10.6 | - | 8.4 | 9.5 | 10.1 | 8.9 | 7.6 | 7.9 | 8.1 | 8.7 |
| | | Permeability x $10^{-5}$ cm/sec | 68.6 | 499.7 | NA | 98.3 | 194.9 | 462.2 | 143.1 | 72.1 | 86.2 | 135.0 | 195.6 |
| Q | 15 | VTM, % | 6.1 | 8.2 | - | 9.9 | 9.0 | 11.4 | 8.6 | 7.1 | 8.4 | 9.5 | 8.7 |
| | | Permeability x $10^{-5}$ cm/sec | 8.9 | 48.1 | NA | 292.2 | 157.5 | 606.2 | 84.7 | 14.4 | 59.5 | 182.8 | 161.6 |
| T | 10 | VTM, % | 6.1 | 5.6 | 7.2 | 6.4 | 7.7 | 5.8 | 7.1 | 6.5 | 6.3 | 3.8 | 6.3 |
| | | Permeability x $10^{-5}$ cm/sec | 4.5 | 4.2 | 9.5 | 5.8 | 10.2 | 5.1 | 7.8 | 4.9 | 5.7 | 0.0 | 5.8 |
| V | 0 | VTM, % | 8.1 | 9.6 | - | 8.8 | 8.6 | 8.3 | 10.0 | 7.6 | 7.0 | 6.9 | 8.3 |
| | | Permeability x $10^{-5}$ cm/sec | 17.1 | 85.2 | NA | 29.2 | 10.2 | 30.4 | 93.6 | 13.0 | 5.9 | 11.6 | 32.9 |
| W | 20 | VTM, % | 10.0 | 8.6 | 9.6 | 12.8 | 7.5 | 6.0 | 5.7 | 3.2 | 3.9 | 4.3 | 7.2 |
| | | Permeability x $10^{-5}$ cm/sec | NA | 0.8 | 2.3 | 370.8 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 41.7 |

RAP = reclaimed asphalt pavement; VTM = voids in total mix; NA = testing not performed; - = core was broken or damaged.

**Table 10. Air-void Content and Permeability Test Results for Cores From Sections With Mixtures Having RAP Contents of 21%-30%**

| Site | % RAP | Property | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A[a] | 25 | VTM, % | 4.4 | 7.3 | 4.8 | 6.5 | 6.4 | 5.2 | 6.8 | 5.7 | 6.2 | 6.7 | 6.0 |
| | | Permeability x $10^{-5}$ cm/sec | 0.0 | 8.7 | 0.8 | 8.6 | 3.8 | 0.6 | 22.7 | 9.7 | 0.5 | 0.5 | 5.6 |
| B[b] | 25 | VTM, % | 7.9 | 8.9 | 6.8 | 5.5 | 8.4 | 9.6 | 10.6 | 11.1 | 8.6 | 12.0 | 8.9 |
| | | Permeability x $10^{-5}$ cm/sec | NA | 14.9 | 0.0 | 0.0 | 13.8 | 17.8 | 29.7 | 80.3 | 22.3 | 93.1 | 30.2 |
| B (IM) | 30 | VTM, % | 6.9 | 6.3 | 5.4 | 4.5 | 6.9 | 8.9 | 7.5 | 8.2 | 6.9 | 6.8 | 6.8 |
| | | Permeability x $10^{-5}$ cm/sec | NA | 0.0 | 0.0 | 0.0 | 4.1 | 17.9 | 8.5 | 13.1 | 5.6 | 3.6 | 5.9 |
| C | 25 | VTM, % | 6.0 | 10.6 | 2.1 | 2.7 | 3.6 | 3.9 | 2.9 | 4.0 | 4.3 | 5.7 | 4.6 |
| | | Permeability x $10^{-5}$ cm/sec | 0.0 | 9.0 | 12.4 | 20.3 | 28.8 | 9.4 | 97.5 | 6.0 | 23.4 | 137.7 | 34.5 |
| D | 25 | VTM, % | 8.0 | 7.5 | 8.3 | 6.7 | 8.2 | 7.7 | 10.3 | 8.4 | 7.3 | 11.5 | 8.4 |
| | | Permeability x $10^{-5}$ cm/sec | 3.0 | 0.0 | 4.3 | 0.0 | 5.0 | 0.0 | 23.5 | 4.3 | 0.0 | 57.4 | 9.8 |
| F | 25 | VTM, % | 6.8 | 4.1 | 8.4 | - | 4.8 | 3.7 | 4.5 | 4.0 | 4.5 | 4.6 | 5.0 |
| | | Permeability x $10^{-5}$ cm/sec | 0.3 | 0.0 | 0.7 | NA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| J | 25 | VTM, % | 6.4 | 7.3 | 10.5 | 7.8 | 10.3 | 8.6 | 8.2 | 8.5 | 8.9 | 8.3 | 8.5 |
| | | Permeability x $10^{-5}$ cm/sec | 1.0 | 0.0 | 48.2 | 24.6 | NA | 24.8 | 15.4 | 65.7 | 55.3 | 0.0 | 26.1 |
| O | 21 | VTM, % | 7.8 | 6.0 | 6.0 | 6.5 | 8.7 | 7.8 | 7.1 | - | 7.9 | 6.2 | 7.1 |
| | | Permeability x $10^{-5}$ cm/sec | 4.39 | 0 | 0 | 0 | 9.76 | 4.59 | 2.86 | NA | 5.39 | 0 | 3.0 |
| P | 21 | VTM, % | 7.3 | - | 7.1 | 6.5 | 9.8 | 7.7 | 6.1 | 7.7 | 6.2 | 6.8 | 7.3 |
| | | Permeability x $10^{-5}$ cm/sec | 2.3 | NA | 1.9 | 0.6 | 32.9 | 5.7 | 0.0 | 4.7 | 0.0 | 1.0 | 5.4 |
| R | 30 | VTM, % | 8.0 | - | 9.1 | 7.0 | 8.3 | 9.4 | 10.3 | 9.3 | 8.4 | 8.6 | 8.7 |
| | | Permeability x $10^{-5}$ cm/sec | 12.0 | NA | 44.0 | 10.8 | 15.1 | 77.9 | 143.3 | 57.6 | 18.5 | 19.0 | 44.2 |
| S | 30 | VTM, % | 6.6 | - | 10.7 | 6.3 | 9.1 | 8.4 | 9.2 | 9.4 | 7.5 | 9.0 | 8.5 |
| | | Permeability x $10^{-5}$ cm/sec | 0.0 | NA | 384.2 | 0.0 | 182.5 | 44.5 | 205.9 | 210.9 | 12.1 | 167.7 | 134.2 |
| U | 25 | VTM, % | 8.1 | 7.1 | 7.8 | 5.6 | 6.1 | 5.3 | 7.8 | 5.1 | 5.3 | 6.8 | 6.5 |
| | | Permeability x $10^{-5}$ cm/sec | 2.3 | 3.1 | 0.3 | 0.0 | 0.0 | 0.0 | 1.6 | 0.0 | 0.0 | 0.0 | 0.7 |
| X | 30 | VTM, % | 6.4 | 6.0 | 5.1 | 6.0 | 5.5 | 4.6 | 5.5 | 4.9 | 4.5 | 4.8 | 5.3 |
| | | Permeability x $10^{-5}$ cm/sec | NA | 1.6 | 0.8 | 3.1 | 5.1 | 0.4 | 1.6 | 0.9 | 0.0 | 0.0 | 1.5 |

RAP = reclaimed asphalt pavement; VTM = voids in total mix; IM = intermediate mix; NA = testing not performed; - = core was broken or damaged.

[a] All mixtures are surface mixtures unless noted.

[b] Sections A and B were composed of a single contiguous surface mixture.

## Permeability

Permeability was measured for all undamaged cores. A summary of permeability results is presented in Tables 9 and 10. Section 211.03 of VDOT's *Road and Bridge Specifications* (VDOT, 2007) requires a maximum design permeability of 150 x $10^{-5}$ cm/sec at 7.5% air voids for mixtures. All mixtures except that from Site N met this criterion despite the variability in air-void contents, indicating that permeability should not be a concern.

## Dynamic Modulus

Dynamic modulus test results are presented in Appendix C. Because of insufficient core thickness, dynamic modulus testing was not performed on specimens from Sites A, F, H, I, and Q. Tables 11 and 12 show summaries of the test results for evaluated mixtures having RAP contents of 20% or less and those having RAP contents of 21% to 30%, respectively.

To identify any trends in modulus associated with RAP content, the dynamic modulus values at all temperatures and three frequencies, 0.1 Hz, 1.0 Hz, and 10 Hz, were graphed for all mixtures. The selected frequencies were chosen because they would provide results that spanned the range of frequencies tested. Figures 11 through 13 show the results; all mixtures were ordered by increasing RAP content and virgin binder grade. The results indicated that neither RAP content nor virgin binder grade appears to have meaningful or trending influences on the measured modulus.

This visual assessment was further investigated using *t*-tests to evaluate significant differences between individual mixture test results at each temperature and frequency combination. The two-tailed *t*-test was employed assuming unequal variance for analysis. The results indicated that there were differences at a level of significance of $\alpha = 0.05$ between datasets for individual mixtures; however, there were no consistent trends in the significant differences that indicated any dependence on mixture properties. Table 13 presents an example of the analysis results for all mixtures at a temperature of 21.1°C (70°F) and test frequencies of 1 Hz and 5 Hz. Complete results are shown in Appendix D.

Statistical comparisons of the modulus values were performed to determine if there were significant differences between mixtures with RAP contents less than or equal to 20% and those with RAP contents of 21% to 30%. No significant differences were found using the two-tailed *t*-test assuming unequal variance at a level of significance of $\alpha = 0.05$ for any combination of temperature and frequency.

**Table 11. Dynamic Modulus Test Results for Mixtures Having RAP Contents 20% or Less**

| Temp., °C | Frequency, Hz | E | V | K | L | T | M | N | W |
|---|---|---|---|---|---|---|---|---|---|
| | | 9.5 mm | 9.5 mm | 12.5 mm | 12.5 mm | 9.5 mm | 9.5 mm | 9.5 mm | 12.5 mm |
| | | PG 70-22 | PG 70-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 70-22 |
| | | 0% RAP | 0% RAP | 10% RAP | 10% RAP | 10% RAP | 20% RAP | 20% RAP | 20% RAP |
| 37.8 | 0.1 | 166,387 | 94,328 | 101,231 | 123,587 | 60,836 | 62,042 | 50,098 | 64,493 |
| | 0.5 | 309,027 | 179,460 | 194,829 | 220,022 | 122,107 | 116,771 | 96,425 | 127,188 |
| | 1 | 391,408 | 232,640 | 252,544 | 275,427 | 160,919 | 150,345 | 125,487 | 169,539 |
| | 5 | 645,611 | 413,261 | 443,960 | 451,889 | 296,457 | 263,362 | 223,469 | 320,292 |
| | 10 | 777,886 | 514,981 | 550,418 | 544,230 | 374,995 | 326,264 | 279,060 | 412,149 |
| | 25 | 968,175 | 666,690 | 705,898 | 661,662 | 492,113 | 418,586 | 360,503 | 550,418 |
| 21.1 | 0.1 | 773,341 | 521,942 | 574,688 | 573,527 | 368,178 | 327,129 | 280,976 | 375,309 |
| | 0.5 | 1,100,933 | 802,929 | 863,845 | 813,758 | 584,429 | 495,879 | 426,642 | 630,576 |
| | 1 | 1,255,205 | 940,521 | 1,005,256 | 922,440 | 693,715 | 578,519 | 497,931 | 762,657 |
| | 5 | 1,644,582 | 1,317,861 | 1,383,611 | 1,208,744 | 1,010,115 | 797,995 | 690,127 | 1,150,149 |
| | 10 | 1,817,661 | 1,491,568 | 1,559,107 | 1,332,606 | 1,164,145 | 899,824 | 778,626 | 1,334,540 |
| | 25 | 2,041,309 | 1,723,676 | 1,781,111 | 1,491,471 | 1,377,351 | 1,036,410 | 896,966 | 1,590,097 |
| 4.4 | 0.1 | 2,163,769 | 1,787,010 | 1,865,523 | 1,541,944 | 1,457,774 | 1,047,058 | 943,554 | 1,568,583 |
| | 0.5 | 2,509,829 | 2,173,100 | 2,237,255 | 1,793,246 | 1,813,479 | 1,266,577 | 1,131,342 | 2,009,159 |
| | 1 | 2,657,574 | 2,337,524 | 2,398,150 | 1,894,096 | 1,973,455 | 1,364,092 | 1,212,165 | 2,200,367 |
| | 5 | 2,988,067 | 2,702,633 | 2,763,548 | 2,125,721 | 2,348,088 | 1,583,556 | 1,404,301 | 2,643,215 |
| | 10 | 3,120,389 | 2,850,378 | 2,913,421 | 2,214,339 | 2,508,500 | 1,675,124 | 1,485,113 | 2,827,268 |
| | 25 | 3,280,124 | 3,035,204 | 3,100,036 | 2,316,736 | 2,710,682 | 1,788,460 | 1,583,953 | 3,053,914 |

RAP = reclaimed asphalt pavement; temp. = temperature.

**Table 12. Dynamic Modulus Test Results for Mixtures Having RAP Contents From 21%-30%**

| Temp., °C | Frequency, Hz | O | P | B | C | D | J | U | R | S | X |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 9.5 mm | 9.5 mm | 12.5 mm | 12.5 mm | 12.5 mm | 9.5 mm | 9.5 mm | 9.5 mm | 9.5 mm | 12.5 mm |
| | | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 | PG 64-22 |
| | | 21% RAP | 21% RAP | 25% RAP | 25% RAP | 25% RAP | 25% RAP | 25% RAP | 30% RAP | 30% RAP | 30% RAP |
| 37.8 | 0.1 | 103,243 | 98,331 | 41,940 | 93,675 | 71,924 | 75,555 | 39,871 | 128,706 | 99,133 | 150,172 |
| | 0.5 | 193,770 | 188,481 | 84,678 | 171,352 | 141,426 | 150,462 | 77,300 | 241,343 | 193,384 | 270,350 |
| | 1 | 249,271 | 242,020 | 116,209 | 216,503 | 187,195 | 197,831 | 103,755 | 304,918 | 251,350 | 341,274 |
| | 5 | 432,792 | 414,179 | 236,702 | 362,111 | 343,063 | 352,006 | 200,200 | 500,912 | 440,915 | 564,245 |
| | 10 | 534,947 | 507,632 | 315,844 | 440,915 | 433,808 | 436,322 | 260,826 | 602,922 | 544,907 | 683,224 |
| | 25 | 681,242 | 644,112 | 430,810 | 549,499 | 564,390 | 558,830 | 348,622 | 747,089 | 695,794 | 849,631 |
| 21.1 | 0.1 | 536,301 | 533,352 | 267,014 | 439,077 | 417,564 | 431,294 | 246,467 | 647,110 | 556,365 | 684,868 |
| | 0.5 | 802,155 | 782,140 | 476,255 | 645,805 | 658,810 | 652,766 | 415,678 | 909,435 | 829,326 | 981,567 |
| | 1 | 930,175 | 902,618 | 589,046 | 746,509 | 777,015 | 760,868 | 504,683 | 1,030,976 | 958,361 | 1,121,770 |
| | 5 | 1,275,123 | 1,221,991 | 921,134 | 1,023,821 | 1,107,846 | 1,056,600 | 766,524 | 1,338,408 | 1,291,802 | 1,488,764 |
| | 10 | 1,433,069 | 1,369,059 | 1,082,416 | 1,151,551 | 1,262,311 | 1,194,627 | 893,771 | 1,475,614 | 1,441,095 | 1,653,188 |
| | 25 | 1,644,099 | 1,566,987 | 1,306,113 | 1,326,998 | 1,471,021 | 1,379,550 | 1,069,750 | 1,568,293 | 1,638,684 | 1,868,327 |
| 4.4 | 0.1 | 1,720,486 | 1,697,715 | 1,281,408 | 1,403,627 | 1,521,736 | 1,446,364 | 1,068,203 | 1,779,371 | 1,743,861 | 1,949,887 |
| | 0.5 | 2,056,731 | 2,012,930 | 1,666,193 | 1,696,216 | 1,875,144 | 1,747,753 | 1,372,975 | 2,049,866 | 2,051,848 | 2,291,886 |
| | 1 | 2,202,978 | 2,149,314 | 1,838,788 | 1,824,671 | 2,026,612 | 1,880,269 | 1,509,214 | 2,164,059 | 2,179,699 | 2,436,730 |
| | 5 | 2,534,002 | 2,457,374 | 2,241,074 | 2,125,963 | 2,373,204 | 2,190,601 | 1,833,808 | 2,424,499 | 2,469,339 | 2,761,856 |
| | 10 | 2,670,434 | 2,586,409 | 2,407,481 | 2,254,708 | 2,517,226 | 2,320,507 | 1,971,546 | 2,532,890 | 2,588,923 | 2,893,212 |
| | 25 | 2,836,406 | 2,745,467 | 2,276,947 | 2,431,750 | 2,692,722 | 2,481,015 | 2,143,851 | 2,670,289 | 2,735,411 | 3,076,588 |

RAP = reclaimed asphalt pavement; temp. = temperature.

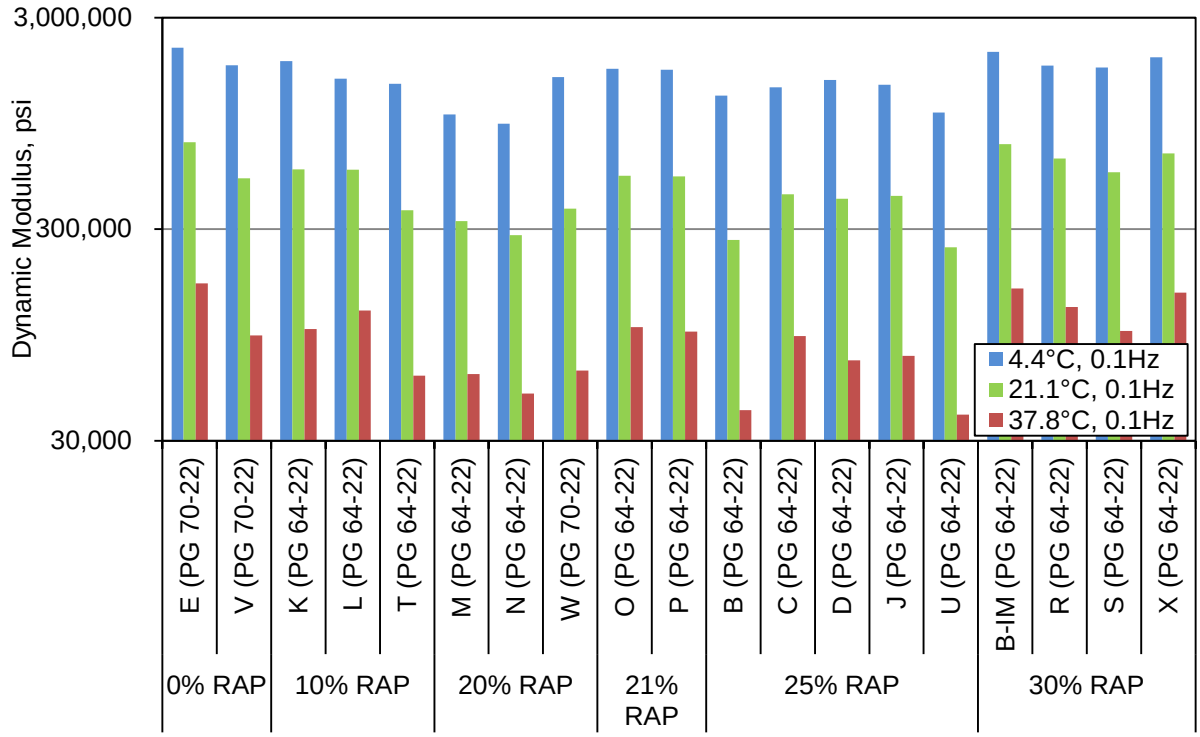


**Figure 11. Dynamic Modulus Values at All Test Temperatures and 0.1 Hz Frequency for All Tested Cores. RAP = reclaimed asphalt pavement.**

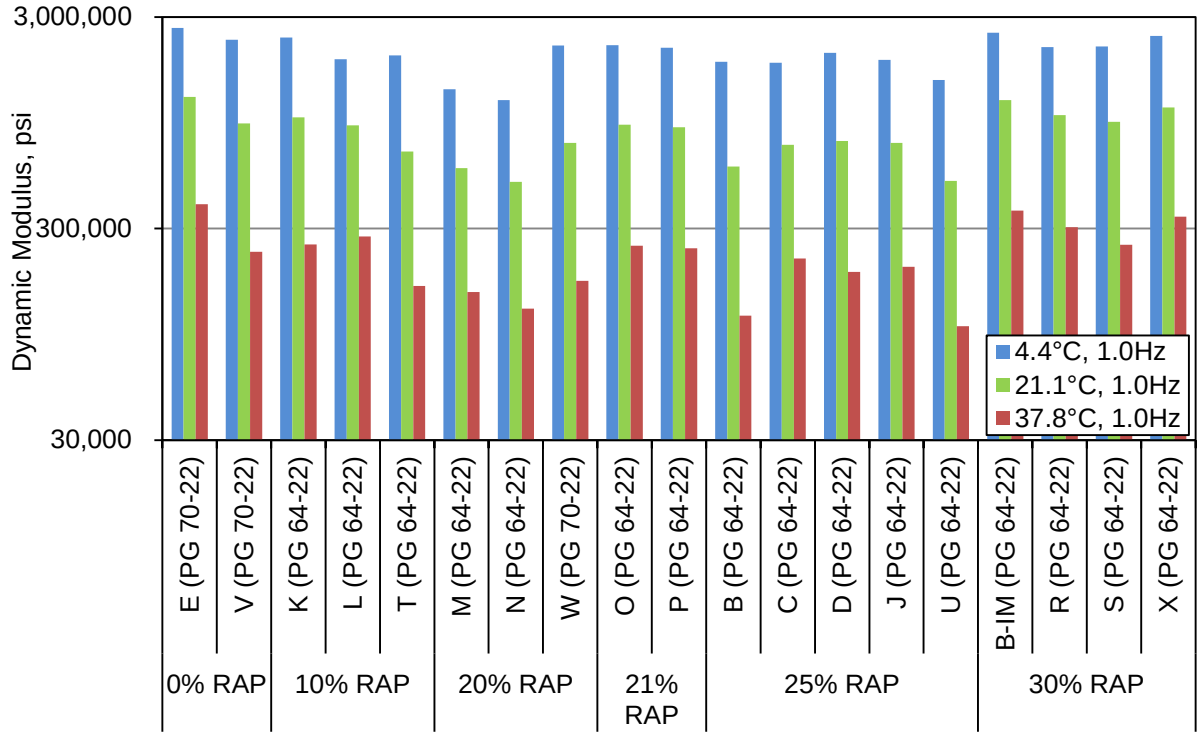


**Figure 12. Dynamic Modulus Values at All Test Temperatures and 1.0 Hz Frequency for All Tested Cores. RAP = reclaimed asphalt pavement.**

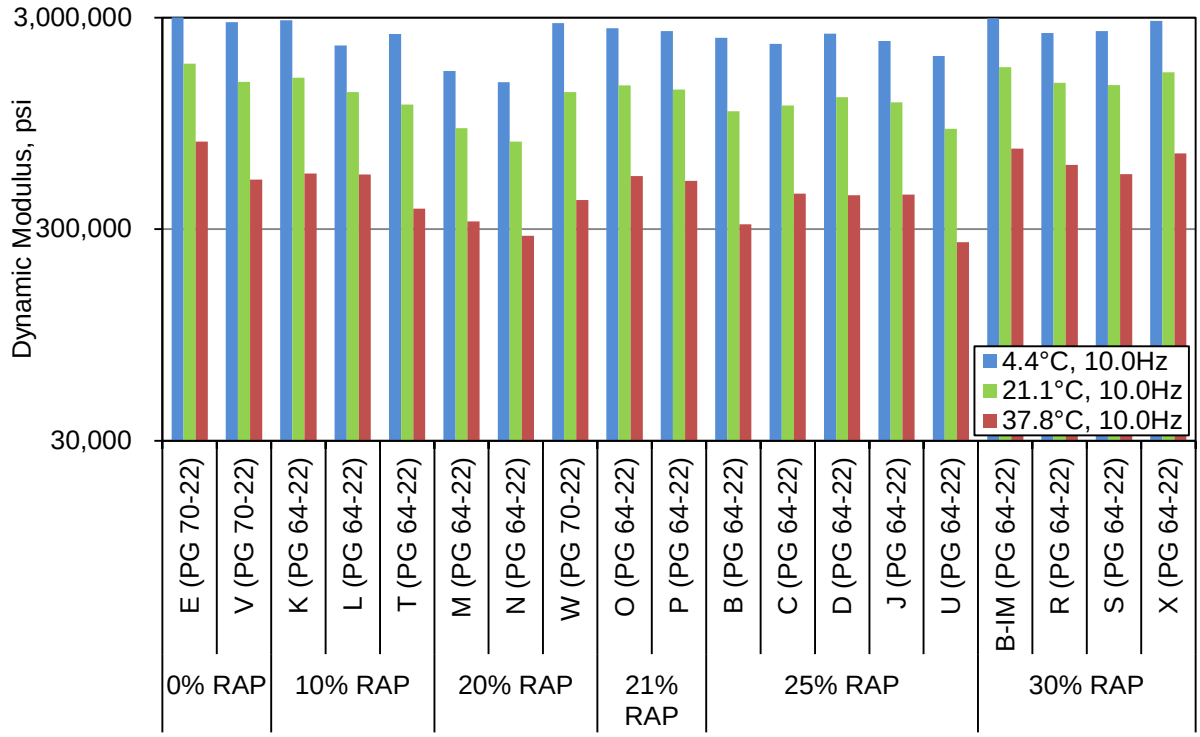


**Figure 13. Dynamic Modulus Values at All Test Temperatures and 10.0 Hz Frequency for All Tested Cores. RAP = reclaimed asphalt pavement.**

**Table 13. *t*-test Comparisons of Mixtures at 21.1ºC (70ºF) and 1 Hz (lower left half of table) and 5 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | **0.0331** | 0.3005 | **0.0259** | **0.0241** | **0.0238** | **0.0103** | **0.0081** | **0.0314** | **0.0379** | 0.7502 | 0.0791 | **0.0087** | **0.0100** | **0.0088** | **0.0035** | 0.0734 | **0.0424** | 0.4695 |
| V (0%) | **0.0325** | | 0.7562 | 0.8089 | 0.1668 | 0.3797 | **0.0417** | 0.1069 | 0.9007 | 0.7171 | 0.0976 | 0.3719 | 0.1194 | **0.0210** | **0.0045** | **0.0030** | 0.1336 | 0.7024 | 0.3342 |
| K (10%) | 0.3315 | 0.7800 | | 0.6989 | 0.2249 | 0.5284 | 0.2858 | 0.3114 | 0.7273 | 0.6454 | 0.3849 | 0.3558 | 0.3349 | 0.3073 | 0.1089 | 0.1417 | 0.9007 | 0.8203 | 0.6416 |
| L (10%) | **0.0179** | 0.3215 | 0.4937 | | 0.1521 | 0.5420 | 0.0883 | 0.1571 | 0.9362 | 0.8618 | 0.0791 | 0.4140 | 0.1822 | 0.0960 | **0.0187** | **0.0134** | 0.2083 | 0.6248 | 0.3007 |
| T (10%) | **0.0396** | 0.1854 | 0.2097 | 0.2676 | | 0.2427 | 0.6443 | 0.5803 | 0.1421 | 0.1891 | **0.0290** | 0.7997 | 0.5082 | 0.5622 | 0.2607 | 0.4061 | 0.1132 | 0.1658 | 0.0846 |
| M (20%) | **0.0212** | 0.2654 | 0.4607 | 0.9084 | 0.2976 | | 0.2258 | 0.3245 | 0.5188 | 0.7491 | 0.0578 | 0.5608 | 0.3785 | 0.2556 | 0.0903 | 0.0508 | 0.1386 | 0.3076 | 0.2130 |
| N (20%) | **0.0066** | **0.0476** | 0.2265 | 0.1729 | 0.8611 | 0.1931 | | 0.8455 | 0.1022 | 0.2106 | **0.0310** | 0.9976 | 0.7135 | 0.7909 | 0.0864 | 0.0700 | **0.0172** | **0.0415** | 0.1132 |
| W (20%) | **0.0123** | 0.1760 | 0.3781 | 0.6473 | 0.4006 | 0.6970 | 0.3266 | | 0.1596 | 0.2810 | **0.0246** | 0.9361 | 0.8888 | 0.9830 | 0.0634 | 0.1127 | **0.0419** | 0.0909 | 0.1138 |
| O (21%) | **0.0251** | 0.6420 | 0.6589 | 0.5860 | 0.1778 | 0.4810 | 0.0766 | 0.3322 | | 0.8165 | 0.0862 | 0.3990 | 0.1846 | 0.1144 | **0.0236** | **0.0194** | 0.2792 | 0.7294 | 0.3191 |
| P (21%) | **0.0272** | 0.4240 | 0.5286 | 0.9216 | 0.2521 | 0.8326 | 0.1848 | 0.6027 | 0.6846 | | 0.0792 | 0.4740 | 0.3220 | 0.2416 | **0.0441** | 0.0515 | 0.2777 | 0.5954 | 0.2765 |
| B (25%) | 0.5749 | **0.0459** | 0.4400 | **0.0278** | **0.0510** | **0.0301** | **0.0080** | **0.0183** | **0.0409** | **0.0425** | | 0.0924 | **0.0271** | **0.0332** | **0.0185** | **0.0138** | 0.1992 | 0.1147 | 0.6320 |
| C (25%) | 0.0813 | 0.2890 | 0.2835 | 0.4745 | 0.9568 | 0.4986 | 0.9641 | 0.6154 | 0.3494 | 0.4511 | 0.1015 | | 0.8795 | 0.9410 | 0.2906 | 0.4541 | 0.2332 | 0.3382 | 0.1692 |
| D (25%) | **0.0079** | 0.1016 | 0.3106 | 0.4290 | 0.5335 | 0.4522 | 0.4913 | 0.7334 | 0.2000 | 0.4094 | **0.0113** | 0.7329 | | 0.8446 | 0.0542 | 0.0888 | **0.0441** | 0.0993 | 0.1237 |
| J (25%) | **0.0051** | **0.0109** | 0.2485 | 0.2034 | 0.7401 | 0.2179 | 0.7678 | 0.3989 | 0.0811 | 0.2179 | **0.0056** | 0.8897 | 0.6092 | | **0.0148** | **0.0340** | 0.0052 | 0.0125 | 0.1219 |
| U (25%) | **0.0043** | **0.0004** | 0.0931 | **0.0272** | 0.2500 | 0.0676 | 0.0773 | **0.0382** | **0.0152** | **0.0352** | **0.0042** | 0.3384 | **0.0413** | **0.0104** | | 0.1712 | **0.0030** | **0.0020** | **0.0500** |
| B-IM (30%) | **0.0027** | **0.0024** | 0.1472 | **0.0545** | 0.5503 | 0.0747 | 0.2101 | **0.0956** | **0.0235** | **0.0689** | **0.0028** | 0.6709 | **0.1270** | **0.0936** | 0.0508 | | **0.0013** | **0.0029** | 0.0565 |
| R (30%) | 0.0413 | 0.6614 | 0.8465 | 0.2555 | 0.1798 | 0.2300 | 0.0519 | 0.1460 | 0.4967 | 0.3451 | 0.0590 | 0.2657 | 0.0870 | 0.0091 | 0.0001 | **0.0024** | | 0.1735 | 0.5962 |
| S (30%) | 0.0242 | 0.6432 | 0.7002 | 0.4370 | 0.1956 | 0.3420 | 0.0483 | 0.2318 | 0.8569 | 0.5517 | 0.0339 | 0.3227 | 0.1305 | 0.0171 | 0.0012 | **0.0033** | 0.3976 | | 0.3739 |
| X (30%) | 0.4275 | 0.3783 | 0.7030 | 0.2019 | 0.0817 | 0.1874 | 0.0853 | 0.1432 | 0.2992 | 0.2243 | 0.6191 | 0.1502 | 0.1127 | 0.0949 | 0.0392 | 0.0556 | 0.4280 | 0.3239 | |

Shaded bold cells indicate significant differences in modulus values between sites at a level of significance of $\alpha = 0.05$.

## Repeated Load Permanent Deformation

RLPD tests were performed on eight mixtures using small-scale specimens. The number of mixtures was limited by the availability of cores of suitable thickness with which to prepare test specimens. A common method for analyzing RLPD data is to evaluate the flow number ($F_N$), which occurs between the linear secondary and the tertiary phase of cycles, versus the accumulated strain.

Figure 14 shows averaged test results for each of the eight mixtures tested. None of the specimens tested ever reached tertiary flow; thus the $F_N$ could not be recorded. This is likely due to the fact that the specimens were tested in a confined setting, which would reduce the tendency for the mixture to flow after 10,000 cycles. In addition, there were no instances of rutting observed in the field sites, indicating that the mixtures are not rut susceptible and supporting the lack of tertiary flow. An alternative method for evaluating these mixtures is to regress a power-law function onto the specimen's secondary portion. This allows for a slope and an intercept to be estimated, which can be in turn be used as a rutting indicator for mixture comparisons.

Figure 15 shows the average secondary portion slope and intercept of the replicates for each mixture tested. Mixtures are grouped in accordance with their RAP content. The secondary portion was defined as the linear portion after the primary stage was completed, visually established as 1,000 cycles, to the completion of the test, as no tertiary flow occurred.

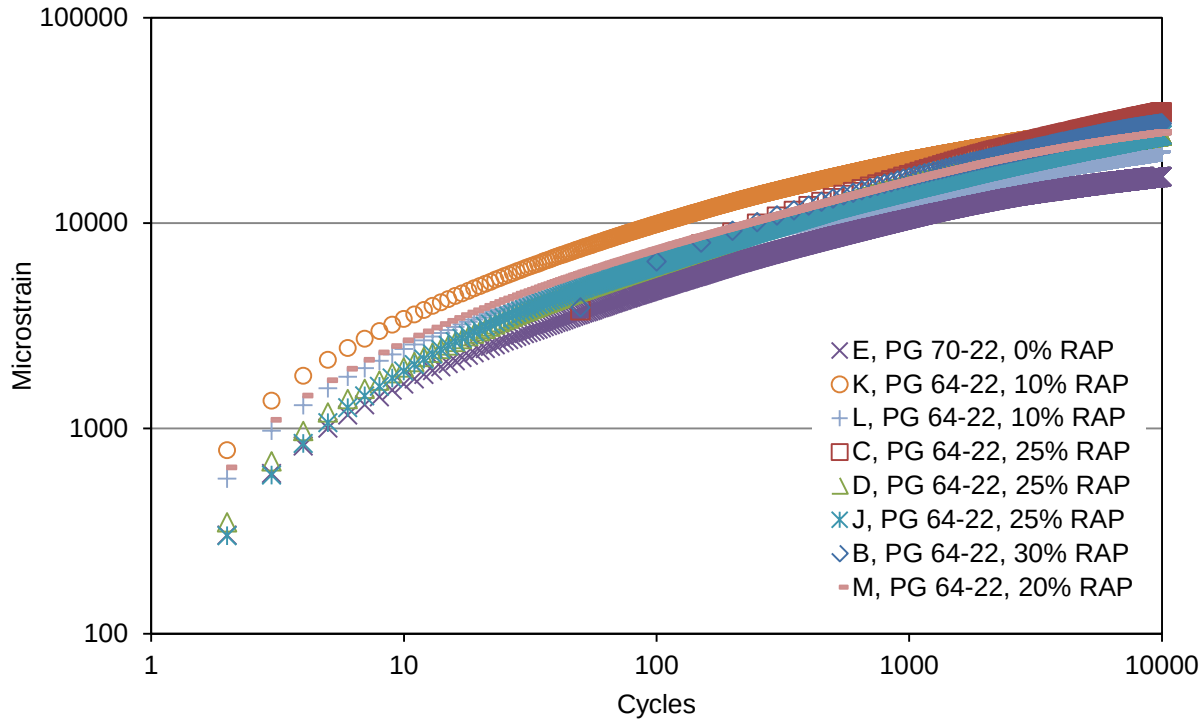


**Figure 14. Average RLPD Data for Each Mixture Tested. RLPD = repeated load permanent deformation; RAP = reclaimed asphalt pavement.**

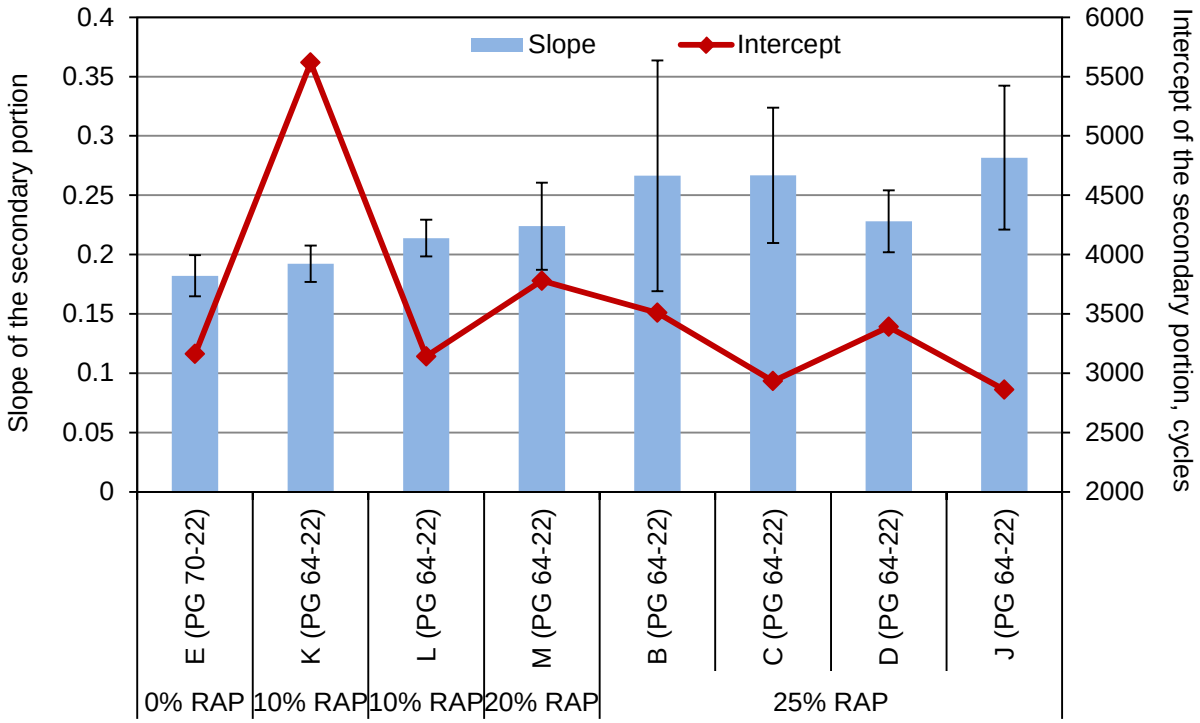


**Figure 15. Average Slope and Intercept of Each Mixture, Grouped by RAP Content. Error bars indicate 1 standard deviation.**

The trend represented in Figure 15 is that the average slope generally increases as RAP contents are increased. This would be indicative of a higher potential for plastic deformation or rutting. One might expect that the intercept would be lower for these mixtures if the secondary slope is indeed higher versus the lower-RAP mixtures; however, this also does not seem to be the case. Compared to the field performance of the mixtures, which does not indicate any tendencies toward excessive rutting, the trends are interesting.

There are a few potential reasons for the contradiction in performance with the test result indication that the higher RAP samples may be more susceptible to rutting. The specifications under which these mixtures were designed and produced allowed mixtures specified to incorporate PG 70-22 binder, but which containing 21% or more RAP, to use a PG 64-22 virgin asphalt base binder in lieu of the required PG 70-22 binder as long as the resultant combined binder met the requirements for a PG 70-22 binder. In addition, it was assumed that all of the RAP binder was available to contribute to the total asphalt content of the mixture. However, it has been found that these assumptions do not always result in a mixture with a performance comparable to that of mixtures designed with 20% RAP or less and PG 70-22 virgin binder. Apeagyei et al. (2011) reported an increase in rutting $F_N$ because of a PG grade reduction of the virgin binder. They noted that increasing RAP contents resulted in a notable reduction in the effective binder content of the mixture. A lower effective binder content could yield a less rut-resistant asphalt mixture because of a lack of binder to glue the aggregates together.

In addition, a lack of complete blending between the virgin and RAP binders can affect rutting resistance. This could explain why the recovered binder grades for the higher RAP mixtures were of equal or greater stiffness than those of the lower-RAP mixtures. The recovery

process forces blending to occur, resulting in a well-blended composite material that does not necessarily exist under actual production and service conditions. Theoretically, in practice the softer binder could be forming a mid-grade composite through blending with the RAP (e.g., a grade between the recovered grade and the initial virgin binder grade) but not completely blending with the RAP binder. If this is the case, there could be pockets of softer composite binder and pockets of stiff binder and/or RAP binder, leading to a decrease in rut resistance.

An alternate reason for the contradictions in test results to conventionally expected performance is that there could be error introduced into the RLPD test results when used with the small-scale test geometry. Although the use of the small-scale geometry has been validated for dynamic modulus testing (Bowers et al., 2015a; Li and Gibson, 2013), there is no literature reporting the use of small-scale specimens for RLPD testing. There is a possibility that the RLPD strain parameters used in the test, although appropriate for larger specimen sizes, may be inducing damage in the mixture past the threshold of desired behavior.

**Texas Overlay Test**

The Texas overlay test was conducted on 13 of the mixtures. Replicate tests were performed on each mixture, and the number of replicates ranged from four to six. The target coefficient of variation (COV) between cores was less than 30%, which was found to be difficult to achieve in many cases, most likely because of specimen variability. There are many approaches to reducing the data in an effort to narrow the COV and exclude outliers. One approach is to remove the samples with the highest and lowest number of cycles to failure, assuming at least five replicates are available. An alternative approach is to remove the data points that appear to be outliers by a test of reasonableness. This second approach was used in this study. Figure 16 shows the data prior to the removal of believed outlier specimens, and Figure 17 shows the data after outliers were removed. On the primary (left) y-axis is the number of cycles to failure, as represented by the blue bars with error bars representing ±1 standard deviation, and the secondary (right) y-axis represents the COV as represented by the line.

It is worth noting that the COV was reduced after the removal of outlier data; however, Mixtures P and X still maintained COV values higher than the 30% recommended by the test method. For both mixtures, this was partially attributed to the low number of cycles to failure. There was no evidence of a conclusive trend between RAP content and cracking susceptibility as measured by the overlay test.

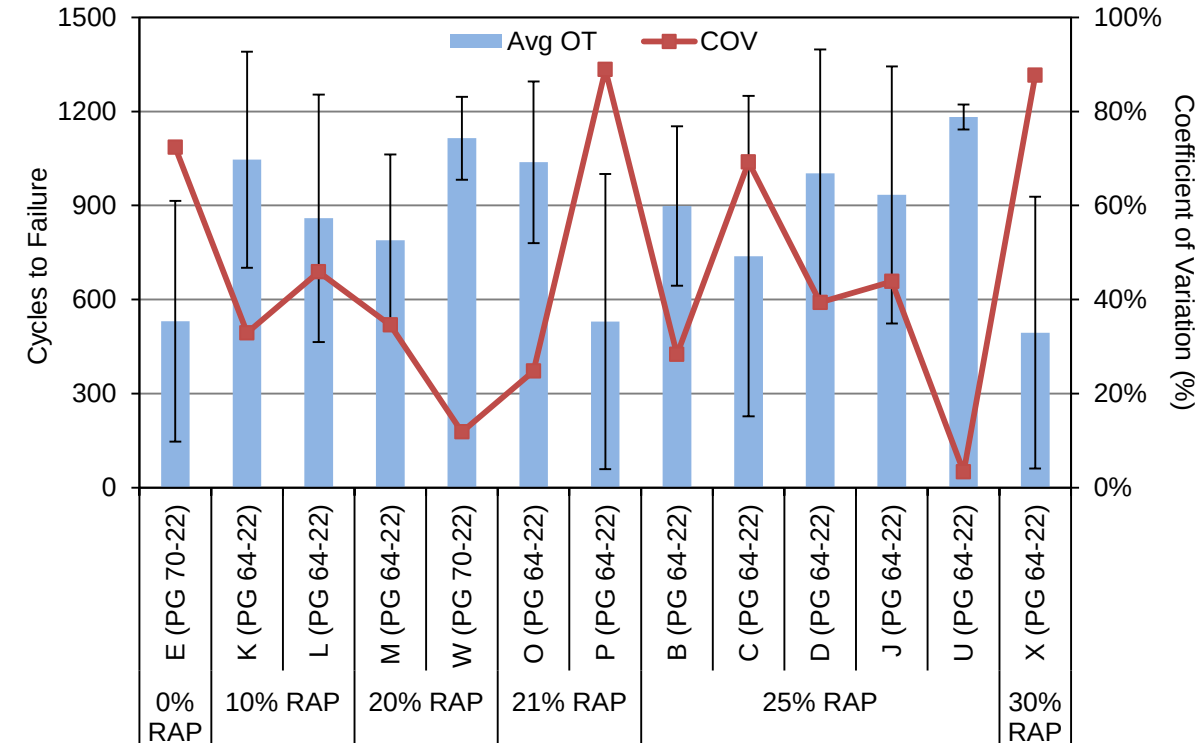


**Figure 16. Overlay Test Results Prior to Removal of Outlier Data. Error bars indicate 1 standard deviation. OT = overlay test; COV = coefficient of variation; RAP = reclaimed asphalt pavement.**

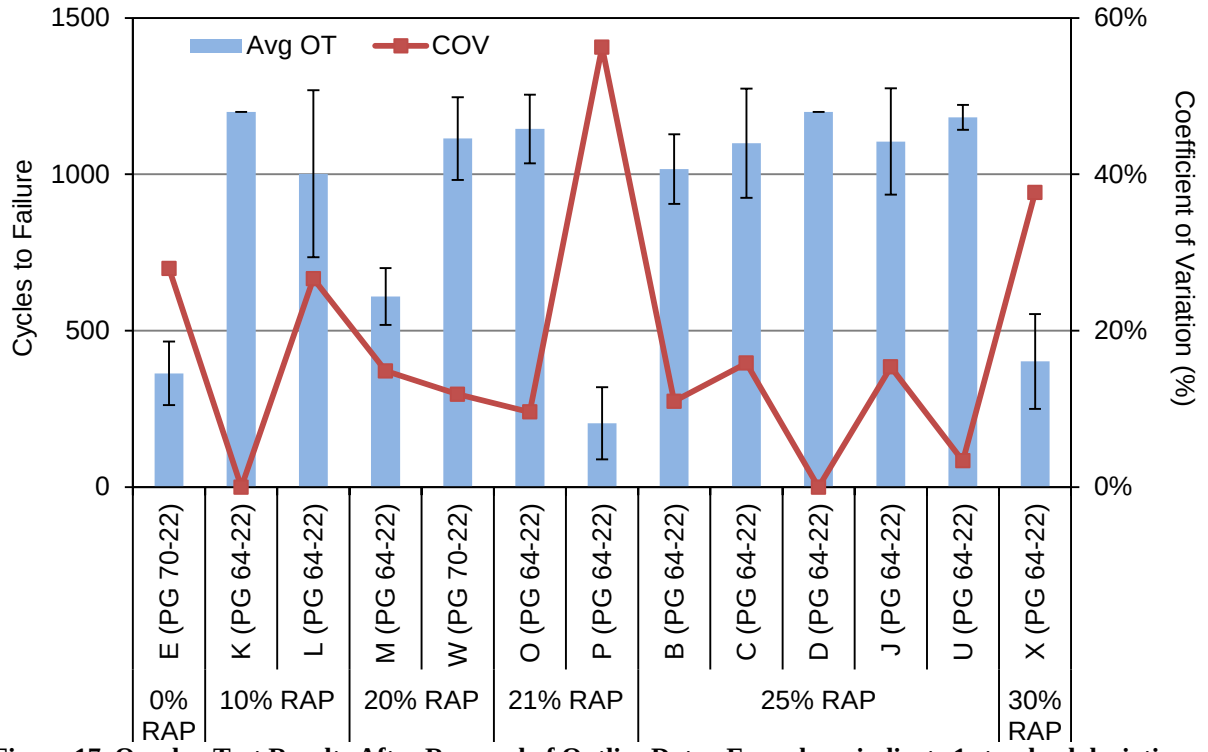


**Figure 17. Overlay Test Results After Removal of Outlier Data. Error bars indicate 1 standard deviation. OT = overlay test; COV = coefficient of variation; RAP = reclaimed asphalt pavement.**

## Binder Testing

*Performance Grading*

A summary of the detailed results of binder grading is shown in Appendix F. Table 14 summarizes the performance grade for binder from each site. Of interest, most of the binders graded as a PG 82-XX binder, with the exception of two full surface and two bottom-half specimens that graded as a PG 76-XX binder and one top-half specimen that graded as a PG 88-XX binder. The top-half specimen from Site B did not meet the PG criteria as specified in AASHTO M 320, as the failure temperatures exceeded the limits of the specification.

**Table 14. Summary of Performance Grading Results for Extracted and Recovered Binders**

| Site | Location Within Layer[a] | % RAP | Performance Grade | Failure Temperature, °C | | | |
|---|---|---|---|---|---|---|---|
| | | | | High | Intermediate | Stiffness | M-value |
| A | Bottom | 25 | 82-16 | 78.47 | 26.5 | -22.6 | -21.7 |
| A | Top | 25 | 82-16 | 82.81 | 29.67 | -20.5 | -18.5 |
| B | Bottom | 25 | 82-10 | 89.42 | 34.62 | -16.2 | -14.7 |
| B | Top | 25 | NA[b] | 103.9 | 40.43 | -14.4 | -4.9 |
| B | Intermediate[c] | 30 | 76-16 | 79.68 | 27.12 | -22.0 | -21.6 |
| C | Full | 25 | 82-10 | 87.21 | 30.9 | -19.8 | -15.6 |
| D | Full | 25 | 82-16 | 84.55 | 29.74 | -21.0 | -19.3 |
| E | Full | 0 | 82-10 | 89.29 | 35.2 | -16.0 | -14.6 |
| F | Full | 25 | 82-16 | 80.35 | 27.1 | -22.9 | -18.6 |
| F | Full | 25 | 82-10 | 84.77 | 27.76 | -22.2 | -15.2 |
| H | Bottom | 20 | 76-16 | 81.15 | 28.46 | -22.1 | -18.5 |
| H | Top | 20 | 82-16 | 83.52 | 29.22 | -21.3 | -17.2 |
| I | Bottom | 20 | 82-16 | 86.38 | 31.57 | -19.6 | -16.5 |
| I | Top | 20 | 88-10 | 88.71 | 33.06 | -18.5 | -14.3 |
| J | Full | 25 | 82-10 | 84.27 | 31.7 | -20.8 | -15.6 |
| K | Full | 10 | 76-16 | 82.89 | 31.6 | -20.7 | -16.6 |
| L | Full | 10 | 82-10 | 84.84 | 33.26 | -18.7 | -12.0 |
| M | Full | 20 | 82-16 | 83.03 | 28.37 | -24.0 | -18.7 |
| N | Bottom | 20 | 82-16 | 88.79 | 31.84 | -19.0 | -16.0 |
| N | Top | 20 | 82-16 | 88.94 | 29.26 | -22.4 | -17.7 |
| O | Full | 21 | 82-10 | 89.00 | 36.6 | -17.8 | -10.7 |
| P | Full | 21 | 82-10 | 84.29 | 32.58 | -20.3 | -13.0 |
| Q | Bottom | 15 | 76-10 | 84.76 | 29.15 | -24.9 | -15.6 |
| Q | Top | 15 | 82-10 | 92.33 | 34.64 | -23.0 | -11.8 |
| R | Bottom | 30 | 82-10 | 83.88 | 31.85 | -21.4 | -14.0 |
| R | Top | 30 | 82-10 | 85.65 | 32.06 | -21.2 | -13.2 |
| S | Bottom | 30 | 82-16 | 84.27 | 29.08 | -20.5 | -16.5 |
| S | Top | 30 | 82-10 | 88.33 | 34.52 | -19.4 | -12.0 |
| U | Full | 25 | 76-16 | 77.79 | 27.33 | -23.2 | -18.5 |
| V | Bottom | 0 | 82-16 | 84.26 | 30.31 | -19.3 | -18.8 |
| V | Top | 0 | 82-10 | 92.06 | 36.42 | -15.9 | -13.2 |
| W | Full | 20 | 82-16 | 82.72 | 30.73 | -20.9 | -17.6 |
| X | Full | 30 | 82-16 | 86.25 | 30.81 | -19.8 | -17.1 |

Note: Sections A and B contain a contiguous surface mixture.

[a] All cores are surface layer cores unless otherwise noted. Selected cores were split into a top half and a bottom half for evaluation.

[b] Did not meet requirements for standard performance grade in accordance with AASHTO M 320.

[c] Intermediate = core taken from intermediate layer.

Table 15 shows the comparison of failure temperatures for binder extracted from the top half and the bottom half of cores. The results indicated that in nearly every case, the binder recovered from the top half of the core was stiffer than that obtained from the bottom half. This was expected, as the surface of the cores undergoes ultraviolet exposure; in addition, the rate of diffusion of oxygen would be expected to be higher at the upper portion of the core, leading to increased aging, as compared to the lower portion (Glover et al., 2014). In addition, the difference in failure temperature between the top half and bottom half of cores generally decreased with increasing RAP content, with the exception of Core B. Figure 18 shows that the trends are generally the same for all failure temperatures. The influence of factors such as core air-void contents was not evaluated, as multiple cores were combined to acquire sufficient recovered binder for grading.

Table 16 presents the results of binder grading performed during this study on recovered binder from cores at 6 to 7 years of service as compared to the binder grading performed on virgin binders, RAP stockpile samples, and loose mixtures sampled during construction in 2006 and 2007. Table 16 indicates that all mixtures, regardless of RAP content, gained one to two high-temperature performance grades over the in-service period evaluated. Low-temperature grades were similarly affected, with only one site (Site W) found to retain the as-constructed low-temperature grade in-service. The results for Sites Q and R, wherein cores were split into a top half and a bottom half for evaluation, indicated that the increase in grade temperature was influenced by proximity to the surface of the pavement. Figure 19 shows the indication that the mixtures containing less RAP aged over the 6-year period to a greater extent than those containing higher RAP contents; Sites V and Q (top half) had the highest true grade results and the lowest RAP contents, whereas the sites with mixtures having 25% to 30% RAP resulted in lower differences in failure temperatures.

**Table 15. Comparison of Failure Temperatures for Binder Extracted From the Top Half and Bottom Half of Cores**

| Failure Temperatures | Half | Site | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **V** | **Q** | **H** | **I** | **N** | **A** | **B** | **F** | **R** | **S** |
| | | **0% RAP** | **15% RAP** | **20% RAP** | **20% RAP** | **20% RAP** | **25% RAP** | **25% RAP** | **25% RAP** | **30% RAP** | **30% RAP** |
| RTFO failure temperature, ºC | Top | 92.1 | 92.3 | 83.5 | 88.7 | 88.9 | 82.8 | 103.9 | 84.8 | 85.7 | 88.3 |
| | Bottom | 84.3 | 84.8 | 81.2 | 86.4 | 86.8 | 78.5 | 89.4 | 80.4 | 83.9 | 84.3 |
| Difference | | 7.8 | 7.6 | 2.4 | 2.3 | 2.1 | 4.3 | 14.5 | 4.4 | 1.8 | 4.1 |
| PAV failure temperature, ºC | Top | 36.4 | 34.6 | 29.2 | 33.1 | 29.3 | 29.7 | 40.4 | 27.8 | 32.1 | 34.5 |
| | Bottom | 30.3 | 29.2 | 28.5 | 31.6 | 31.8 | 26.5 | 34.6 | 27.1 | 31.9 | 29.1 |
| Difference | | 6.1 | 5.5 | 0.8 | 1.5 | -2.6 | 3.2 | 5.8 | 0.7 | 0.2 | 5.4 |
| Stiffness failure temperature, ºC | Top | -15.9 | -23.0 | -21.3 | -18.5 | -22.4 | -20.5 | -14.4 | -22.2 | -21.2 | -19.4 |
| | Bottom | -19.3 | -24.9 | -22.1 | -19.6 | -19.0 | -22.6 | -16.2 | -22.9 | -21.4 | -20.5 |
| Difference | | 3.5 | 1.9 | 0.8 | 1.0 | -3.5 | 2.1 | 1.8 | 0.7 | 0.2 | 1.1 |
| M-value failure temperature, ºC | Top | -13.2 | -11.8 | -17.2 | -14.3 | -17.7 | -18.5 | -4.9 | -15.2 | -13.2 | -12.0 |
| | Bottom | -18.8 | -15.6 | -18.5 | -16.5 | -16.0 | -21.7 | -14.7 | -18.6 | -14.0 | -16.5 |
| Difference (Top – Bottom) | | 5.6 | 3.8 | 1.3 | 2.2 | -1.7 | 3.2 | 9.8 | 3.4 | 0.9 | 4.5 |

RAP = reclaimed asphalt pavement; RTFO = rolling thin film oven; PAV = pressure aging vessel.

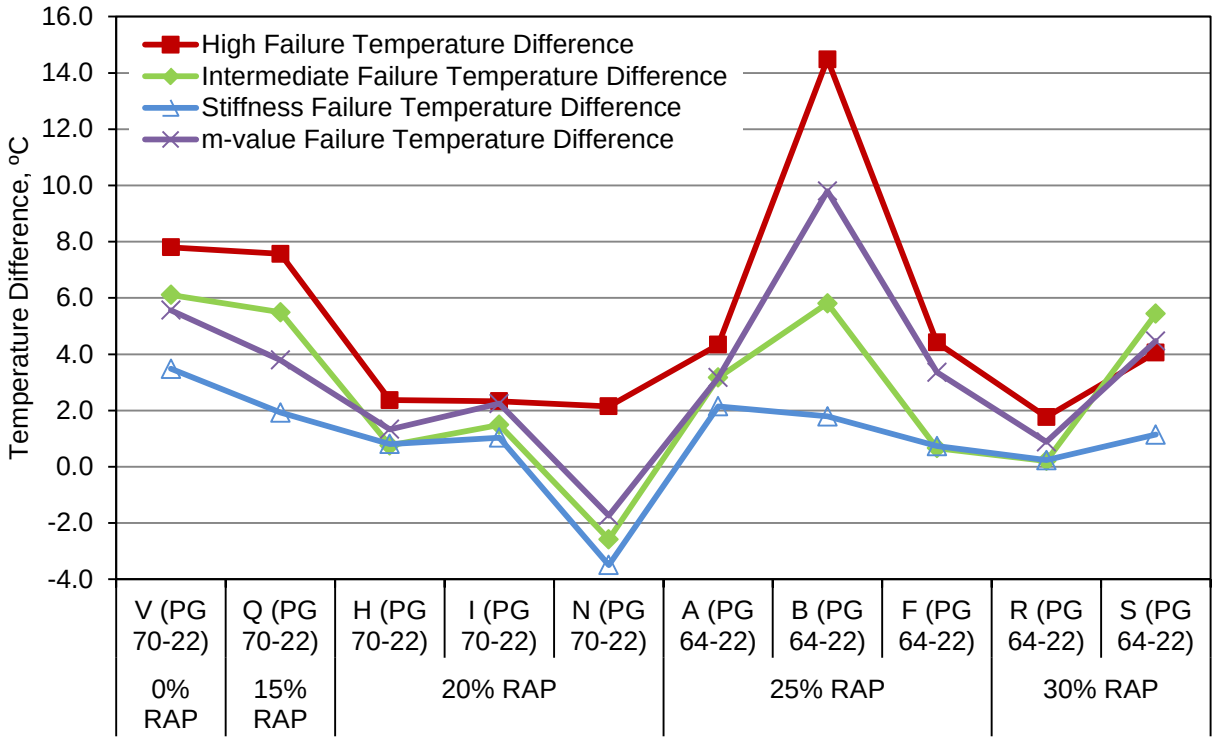


**Figure 18. Difference in Failure Temperatures for Binder Extracted From Top Half and Bottom Half of Cores. Difference is expressed as top half failure temperature – bottom half failure temperature. RAP = reclaimed asphalt pavement.**

The observed trends of increased aging, as measured by changes in failure temperatures, in mixtures having lower percentages of RAP may support the hypothesis that since RAP has already undergone significant aging (assuming the RAP source is from milled pavement and not from plant waste), it will not continue to stiffen and further age extensively.

Increased scrutiny of the role that aging plays in mixture performance, especially as related to binder aging, has led to the development of additional parameters proposed to be indicative of cracking potential. One of these parameters, $\Delta T_{cr}$, was suggested by Anderson et al. (2011) as an index to predict the thermal cracking potential of binders. $\Delta T_{cr}$ is the difference in critical temperature determined using the bending beam rheometer (BBR) stiffness and that determined using the BBR m-value. As binders age, the difference between the critical temperatures is known to increase, as the aging process affects the stiffness and relaxation properties differently. Minimum thresholds for $\Delta T_{cr}$ of -2.5 and -5.0 representing the cracking warning and cracking limit, respectively, have been suggested (Anderson et al., 2011; Rowe, 2011). The cracking warning is intended to indicate an accelerated risk of cracking wherein preventative action should be taken. The cracking limit indicates that the materials need immediate remediation to prevent cracking. $\Delta T_{cr}$ has been further investigated and was found to be related to more universal cracking. Reinke et al. (2016) evaluated $\Delta T_{cr}$ relative to performance data for two sets of pavement sites and found only moderate correlation to thermal cracking ($R^2$ = 0.62 and $R^2$ = 0.46, respectively, for each site) but a much greater correlation to fatigue or total cracking ($R^2$ = 0.95 and $R^2$ = 0.97, respectively, for each site).

**Table 16. Comparison of Performance Grading Results From Samples Collected at Construction and After 6 Years in Service**

| Site | RAP | Virgin Binder (At Construction) | | Abson Recovery (At Construction) | | | | Rotavap Recovery (6-7 Years In-Service) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | RAP Stockpile | | Loose Mix | | Cores | |
| | | Performance Grade | True Grade | Performance Grade | True Grade | Performance Grade | True Grade | Performance Grade | True Grade |
| V | 0% | PG 70-22 | PG 72-23 | NA | NA | PG 70-22 | PG 73-25 | PG 82-10 | PG 92-13 |
| Q[a] | 15% | PG 70-22 | PG 71-24 | PG 82-22 | PG 85-27 | PG 70-22 | PG 73-23 | Top: PG 82-10 | PG 92-11 |
| | | PG 70-22 | PG 71-23 | PG 82-22 | PG 85-27 | PG 76-22 | PG 76-22 | Bottom: PG 82-10 | PG 84-15 |
| W | 20% | PG 70-22 | PG 72-24 | PG 82-16 | PG 94-16 | PG 76-16 | PG 79-16 | PG 82-16 | PG 82-17 |
| O[a] | 21% | PG 64-22 | PG 65-24 | PG 82-10 | PG 95-14 | PG 76-16 | PG 77-21 | PG 82-10 | PG 89-10 |
| | | PG 64-22 | PG 66-24 | PG 82-10 | PG 95-14 | PG 70-22 | PG 72-22 | | |
| | | PG 64-22 | PG 66-25 | PG 82-10 | PG 95-14 | PG 70-22 | PG 74-22 | | |
| D | 25% | PG 64-22 | PG 67-24 | PG 82-10 | PG 88-13 | PG 76-22 | PG 76-22 | PG 82-16 | PG 84-19 |
| F | 25% | PG 64-22 | PG 66-24 | PG 82-16 | PG 90-18 | PG 70-22 | PG 71-22 | PG 82-10 | PG 84-15 |
| J | 25% | PG 64-22 | PG 67-24 | PG 82-10 | PG 96-13 | PG 70-22 | PG 71-23 | PG 82-10 | PG 84-15 |
| U[a] | 25% | PG 64-22 | PG 65-24 | PG 82-16 | PG 94-17 | PG 70-22 | PG 73-23 | PG 76-16 | PG 77-18 |
| | | PG 64-22 | PG 64-24 | PG 82-16 | PG 94-17 | PG 64-22 | PG 69-25 | | |
| | | PG 64-22 | PG 65-24 | PG 82-16 | PG 94-17 | PG 70-22 | PG 74-22 | | |
| R | 30% | PG 64-22 | PG 64-24 | PG 82-28 | PG 83-18 | PG 76-16 | PG 76-20 | Top: PG 82-10 | PG 85-13 |
| | | | | | | | | Bottom: PG 82-10 | PG 83-14 |
| X | 30% | PG 64-22 | PG 67-26 | PG 82-16 | PG 93-17 | PG 76-22 | PG 76-25 | PG 82-16 | PG 86-17 |

RAP = reclaimed asphalt pavement.

[a] Several samples were collected over multiple days of construction.

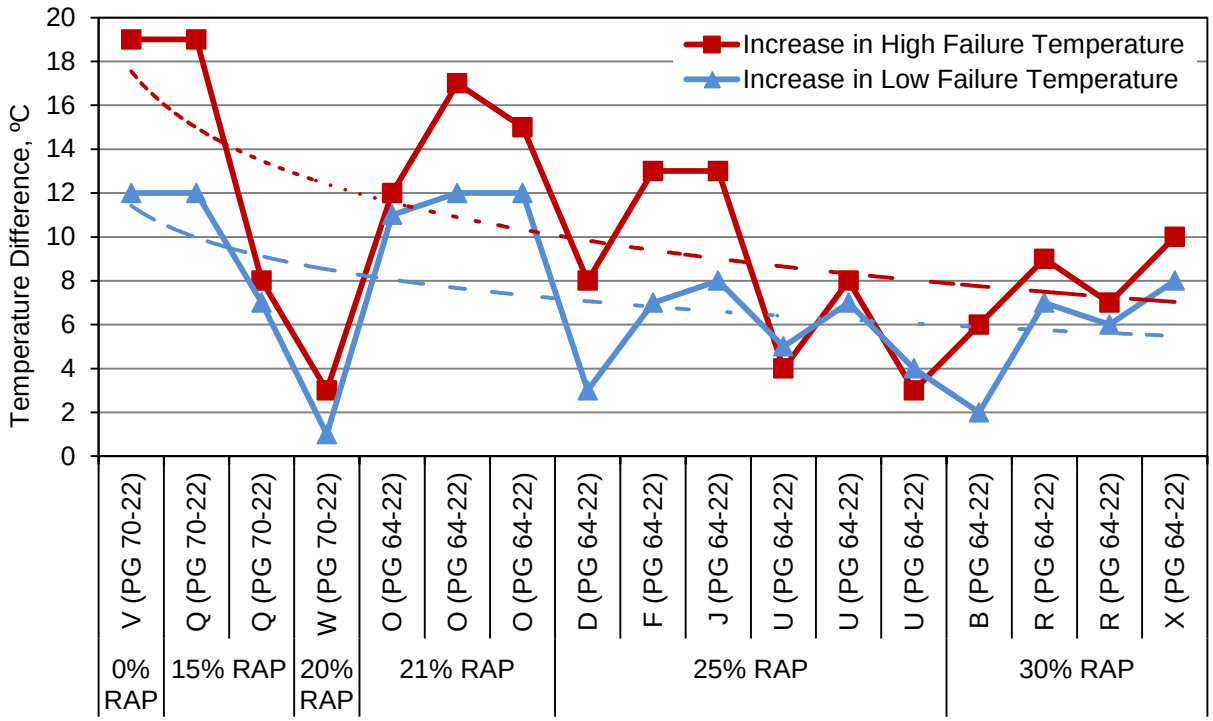


**Figure 19. Increase in High and Low Failure Temperatures With RAP Content. RAP = reclaimed asphalt pavement.**

$\Delta T_{cr}$ was determined for each of the recovered binders, and the results are presented in Tables 17 through 19. Table 17 shows the results for binders recovered from the entire core, and Tables 18 and 19 present the results for binder recovered from cores that were split into the top and bottom layers prior to recovery. An examination of the results provided several interesting observations. Table 17 indicates that values of $\Delta T_{cr}$ exceeding the cracking warning and cracking limit were found across the range of RAP contents. Only three mixtures, having 0% RAP, 25% RAP, and 30% RAP (an intermediate mixture), had values that stayed below the cracking warning value after their time in service. The values for mixtures having 10% RAP, 21% RAP, and 25% RAP were all found to exceed the cracking limit value.

Tables 18 and 19 indicate that values of $\Delta T_{cr}$ were reduced as the binder was located farther from the surface, supporting the role that aging plays in changing binder properties. As indicated in Table 18, only one binder did not exceed the cracking warning and five exceeded the cracking limit. Table 19 indicates that even at the increased depth from the surface, only three binders did not exceed the cracking warning and two exceeded the cracking limit. The variation of difference in $\Delta T_{cr}$ between the top half and bottom half of cores was also striking, ranging from approximately 0.5 to 8.0ºC, demonstrating that aging is a unique process for every binder.

The relationships among $\Delta T_{cr}$, RAP content, continuous low temperature grade, and the stiffness and m-value failure temperatures were further examined using correlation analysis. This analysis indicated a minimal correlation between $\Delta T_{cr}$ and RAP content with a coefficient of -0.1554. Critical cracking temperature was found only moderately correlated with the continuous low temperature grade and with the m-value failure temperature, having correlation coefficients of 0.6988 and 0.7007, respectively. There was no correlation with the stiffness

failure temperature, indicated by a correlation coefficient of 0.1604. The outcomes of this analysis suggest that although there are concerns about the cracking potential of the binders, these concerns are independent of the RAP content of the mixture.

**Table 17. Critical Cracking Temperature for Binders Recovered From Cores**

| Section | RAP Content | Continuous Grade | Stiffness Failure Temperature, °C | M-value Failure Temperature, °C | $\Delta T_{cr}$ |
|---|---|---|---|---|---|
| E | 0% | 89-14 | -16.0 | -14.6 | -1.4 |
| K | 10% | 82-16 | -20.7 | -16.6 | *-4.1* |
| L | 10% | 84-12 | -18.7 | -12.0 | **-6.7** |
| M | 20% | 83-18 | -24.0 | -18.7 | **-5.2** |
| W | 20% | 82-17 | -20.9 | -17.6 | *-3.3* |
| O | 21% | 89-10 | -17.8 | -10.7 | **-7.1** |
| P | 21% | 84-13 | -20.3 | -13.0 | **-7.2** |
| C | 25% | 87-15 | -19.8 | -15.6 | *-4.2* |
| D | 25% | 84-19 | -21.0 | -19.3 | -1.7 |
| J | 25% | 84-15 | -20.8 | -15.6 | **-5.2** |
| U | 25% | 77-18 | -23.2 | -18.5 | *-4.7* |
| B-IM | 30% | 79-21 | -22.0 | -21.6 | -0.4 |
| X | 30% | 86-17 | -19.8 | -17.1 | *-2.8* |

Values of $\Delta T_{cr}$ exceeding the cracking warning value of -2.5 are italicized, and values exceeding the cracking limit of -5.0 are in bold type. RAP = reclaimed asphalt pavement; IM = intermediate mix.

**Table 18. Critical Cracking Temperature for Binders Recovered From Top Half of Cores**

| Section | RAP Content | Continuous Grade | Stiffness Failure Temperature, °C | M-value Failure Temperature, °C | $\Delta T_{cr}$ |
|---|---|---|---|---|---|
| V | 0% | 92-13 | -15.9 | -13.2 | *-2.7* |
| Q | 15% | 92-11 | -23.0 | -11.8 | **-11.2** |
| H | 20% | 83-17 | -21.3 | -17.2 | *-4.1* |
| I | 20% | 88-14 | -18.5 | -14.3 | *-4.3* |
| N | 20% | 88-17 | -22.4 | -17.7 | *-4.7* |
| A | 25% | 82-18 | -20.5 | -18.5 | -2.0 |
| B | 25% | 103-4 | -14.4 | -4.9 | **-9.5** |
| F | 25% | 84-15 | -22.2 | -15.2 | **-7.0** |
| R | 30% | 85-13 | -21.2 | -13.2 | **-8.0** |
| S | 30% | 88-12 | -19.4 | -12.0 | **-7.4** |

Values of $\Delta T_{cr}$ exceeding the cracking warning value of -2.5 are italicized, and values exceeding the cracking limit of -5.0 are in bold type. RAP = reclaimed asphalt pavement.

**Table 19. Critical Cracking Temperature for Binders Recovered From Bottom Half of Cores**

| Section | RAP Content | Continuous Grade | Stiffness Failure Temperature, ºC | M-value Failure Temperature, ºC | $\Delta T_{cr}$ |
|---|---|---|---|---|---|
| V | 0% | 84-18 | -19.3 | -18.8 | -0.6 |
| Q | 15% | 84-15 | -24.9 | -15.6 | **-9.4** |
| H | 20% | 81-18 | -22.1 | -18.5 | *-3.6* |
| I | 20% | 86-16 | -19.6 | -16.5 | *-3.0* |
| N | 20% | 88-16 | -19.0 | -16.0 | *-3.0* |
| A | 25% | 78-21 | -22.6 | -21.7 | -1.0 |
| B | 25% | 89-14 | -16.2 | -14.7 | -1.5 |
| F | 25% | 80-18 | -22.9 | -18.6 | *-4.3* |
| R | 30% | 83-14 | -21.4 | -14.0 | **-7.4** |
| S | 30% | 84-16 | -20.5 | -16.5 | *-4.1* |

Values of $\Delta T_{cr}$ exceeding the cracking warning value of -2.5 are italicized, and values exceeding the cracking limit of -5.0 are in bold type. RAP = reclaimed asphalt pavement.

*Shear Modulus Mastercurves*

Binder testing was also performed on extracted and recovered binders to collect shear modulus and phase angle data; summaries of the data collected are presented in Appendix G. Figure 20 shows an example of a shifted mastercurve.

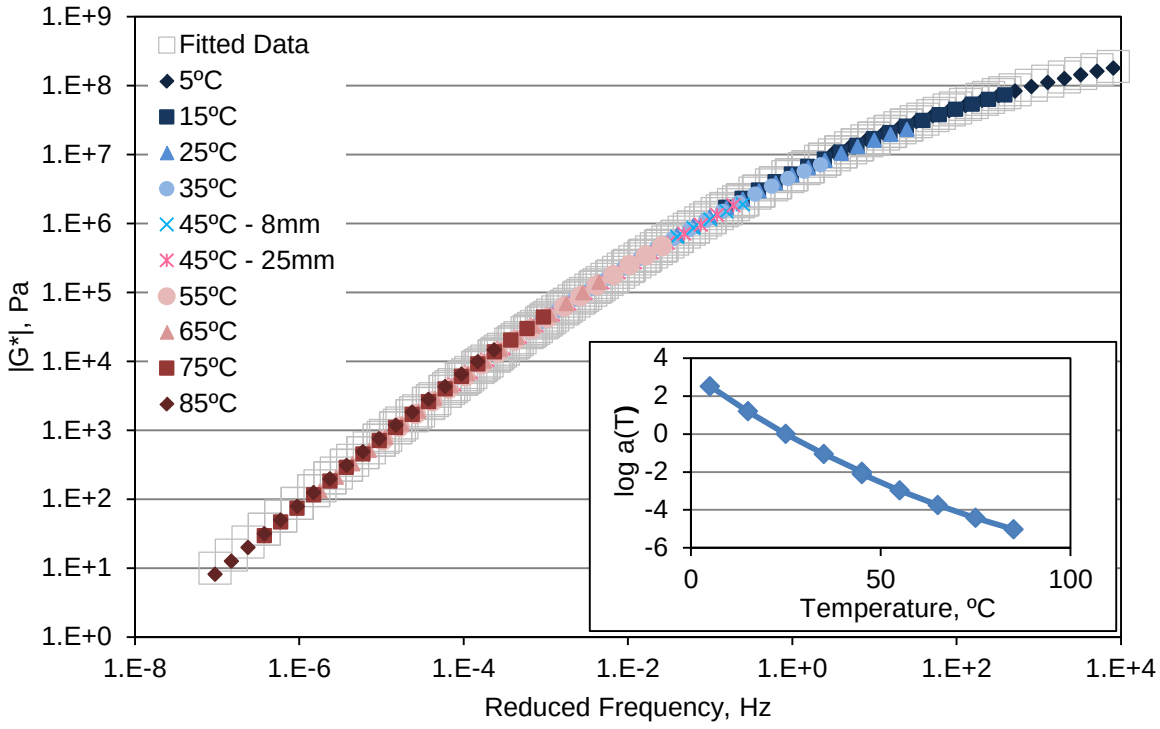


**Figure 20. Example of Shifted Mastercurve Showing Measured and Fitted Data and Shift Factors**

Analysis of the differences in measured modulus values between the top half and bottom half of cores was performed by plotting the log (G*) for the top half versus the bottom half measured modulus values at each temperature frequency combination, as shown in Figure 21. Fitting trendlines to the data indicated that the difference in the modulus between the top half and bottom half of the cores was consistent irrespective of RAP content.

Evaluation of the modulus and phase angle data was performed in Black Space, wherein the complex modulus is plotted versus the phase angle to compare changes in each. It is claimed that the use of Black Space diagrams can offer clear illustrations of aging impacts (see Rowe discussion in Anderson et al., 2011). Figure 22 shows the Black Space plots for extracted binder from mixtures with varying RAP contents at temperatures from 5 to 45°C at a test frequency of 0.09959 rad/sec (0.01585 Hz) using an 8 mm plate size. Similar plots can be generated for all frequencies tested. Generally the figure shows the increase in stiffness and decrease in phase angle exhibited by the binders with decreasing test temperature. The patterning of response is generally similar at each temperature and can be seen in the callout for results at 25°C. As shown, neither the phase angle nor stiffness follows any trends with RAP content; this is likely influenced by the various base binders used in the mixtures and the varying stiffness of each RAP source. Considering that the shown data are at intermediate binder temperatures, wherein dynamic shear rheometer data are typically related to fatigue (the intermediate temperature G*sin delta measurement), these results are supportive of the visual survey and PMS indications that the 21% to 30% RAP mixtures are generally not any more likely to undergo premature fatigue cracking than the mixtures containing lesser amounts of RAP.

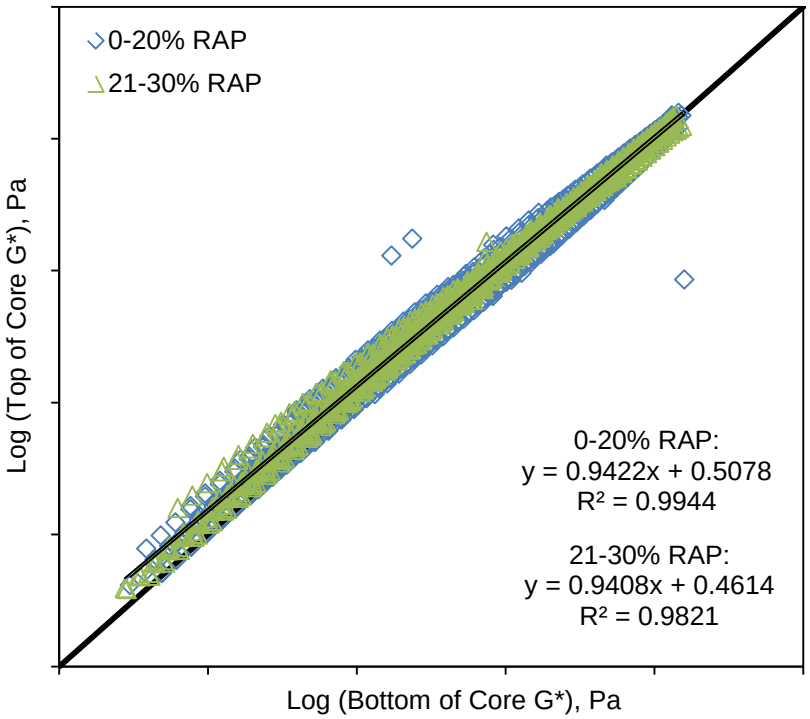


**Figure 21. Plot of Log (G*) for Top of Cores Versus Bottom of Cores**

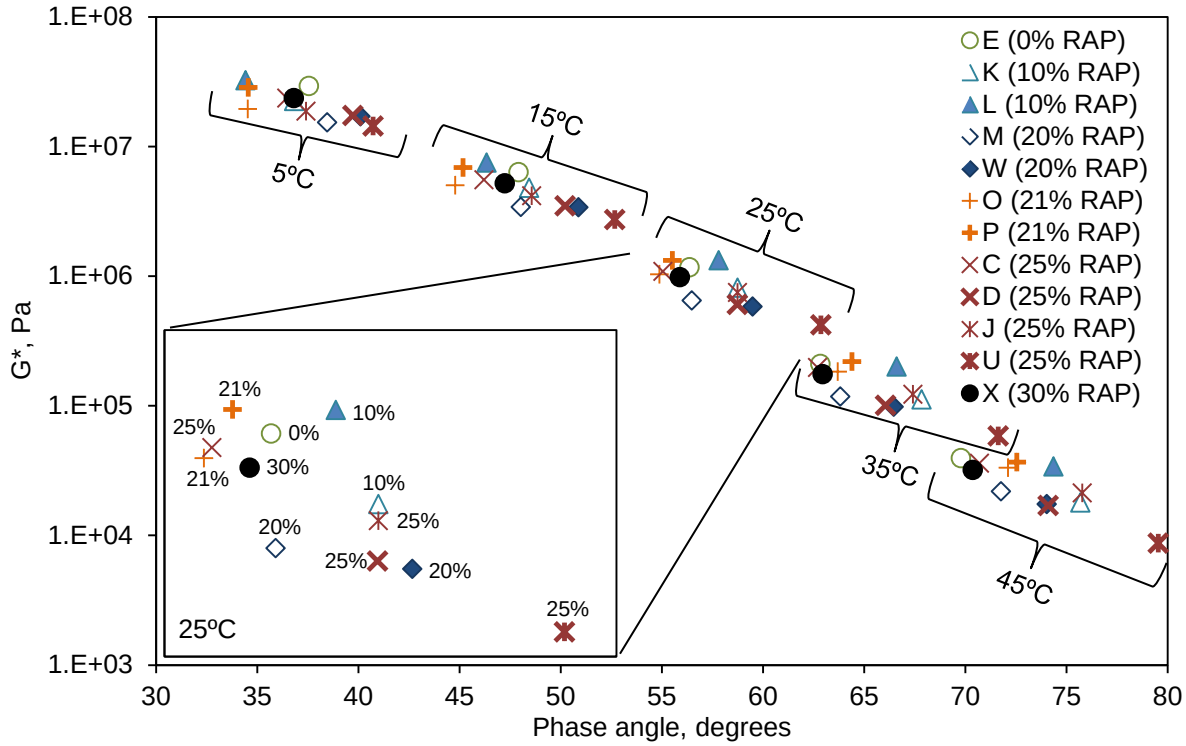


**Figure 22. Black Space Plot. Plot is of extracted binders from sections with mixtures having various RAP contents at a frequency of 0.09959 rad/sec and temperatures of 5°C, 15°C, 25°C, 35°C, and 45°C. The callout shows enlarged distribution of response at 25°C for clarity.**

Figure 23 shows the Black Space plots for extracted binder from mixtures with varying RAP contents at temperatures from 45 to 85°C at a test frequency of 0.09959 rad/sec (0.01585 Hz) using a 25 mm plate size. Clearly it can be seen that the responses overlap more at the higher temperatures, especially at 65°C and above. By investigation of the callout in Figure 21, which shows the details of the 65°C data, it is still evident that neither the binder stiffness nor phase angle responses follow any trend with RAP content.

## GPC

In an effort to investigate further the trend shown in Table 13 as it related to the stiffness levels of the top and bottom of the cores, GPC was employed to investigate the percentage of LMS in the mixture. Small samples of the binder (25 mg) were collected after recovery and after aging in the pressure aging vessel (PAV) and dissolved in tetrahydrofuran, the elution solvent for the GPC. These samples were then injected into the GPC in triplicate, and the LMS was calculated from the resultant molecular weight distribution. The percentage of LMS and failure temperatures are shown in Figure 24 for the recovered samples and in Figure 25 for the PAV-aged samples.

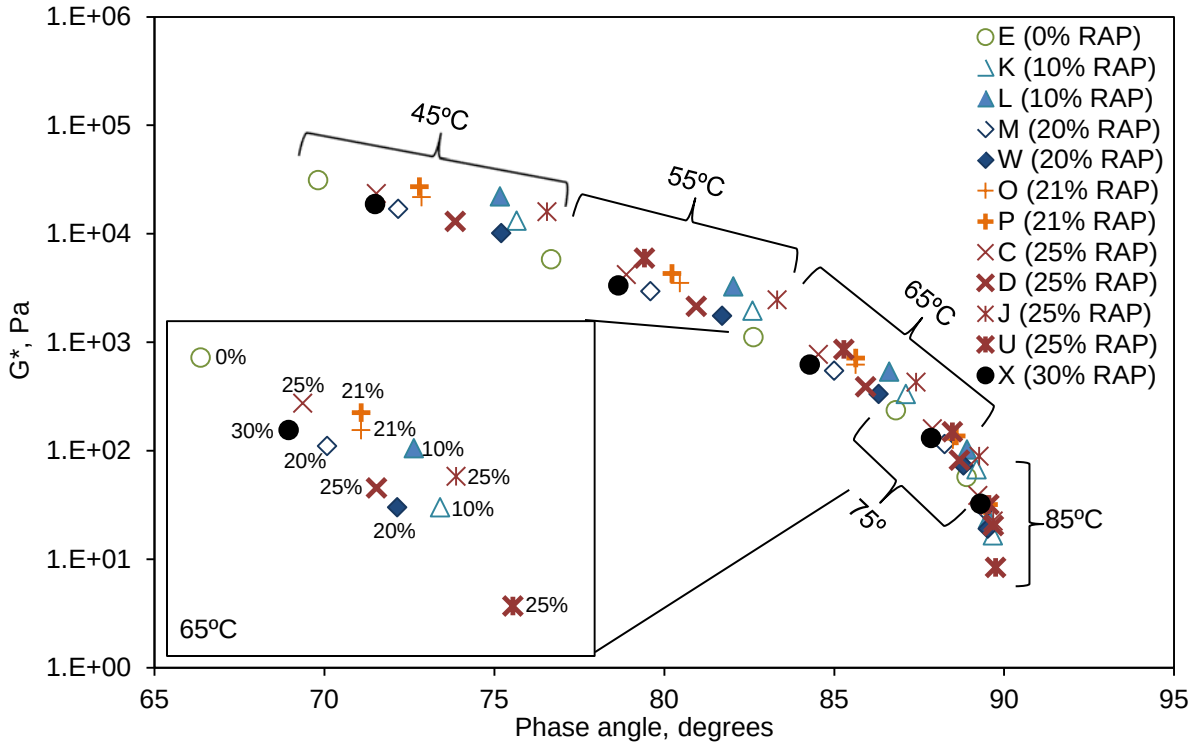


**Figure 23. Black Space Plot. Plot is of extracted binders from sections with mixtures having various RAP contents at a frequency of 0.09959 rad/sec and temperatures of 45°C, 55°C, 65°C, 75°C, and 85°C. The callout shows enlarged distribution of response at 65°C.**

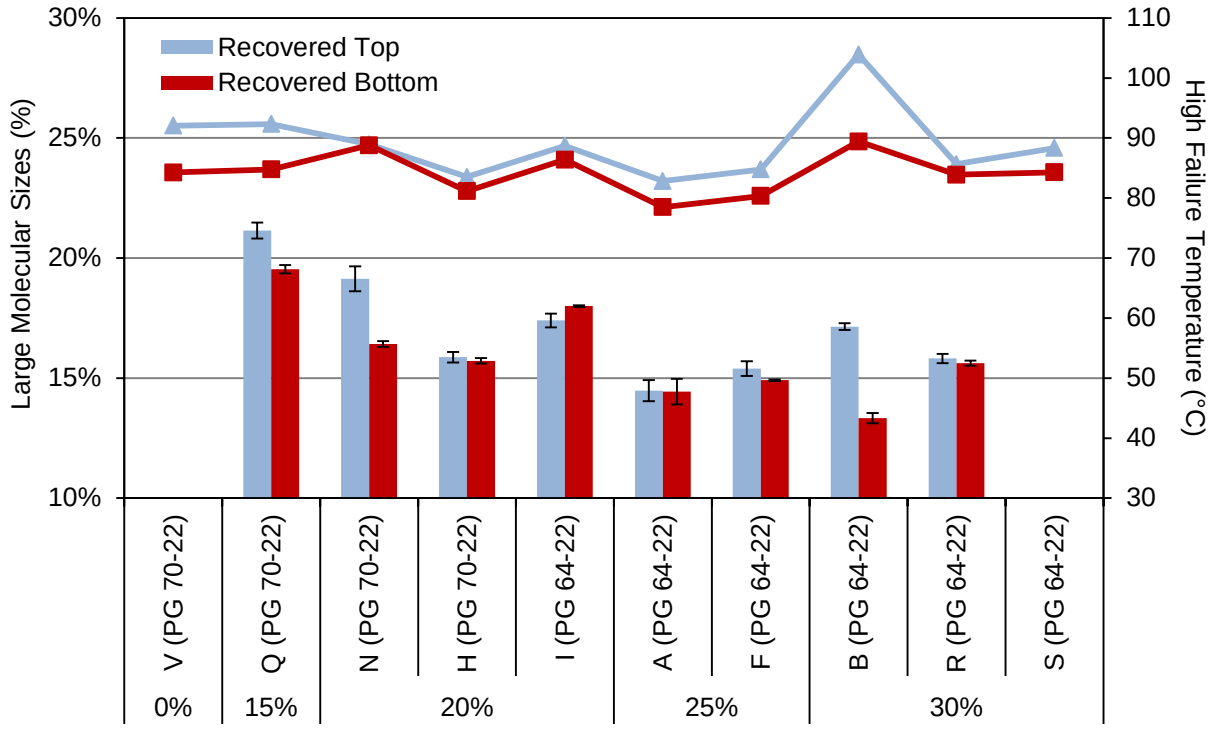


**Figure 24. LMS and Failure Temperature for Recovered Binders. Bars indicate LMS values, and lines indicate failure temperature. Error bars indicate 1 standard deviation. Recovered LMS values were not available for Samples V and S. LMS = large molecular sizes.**

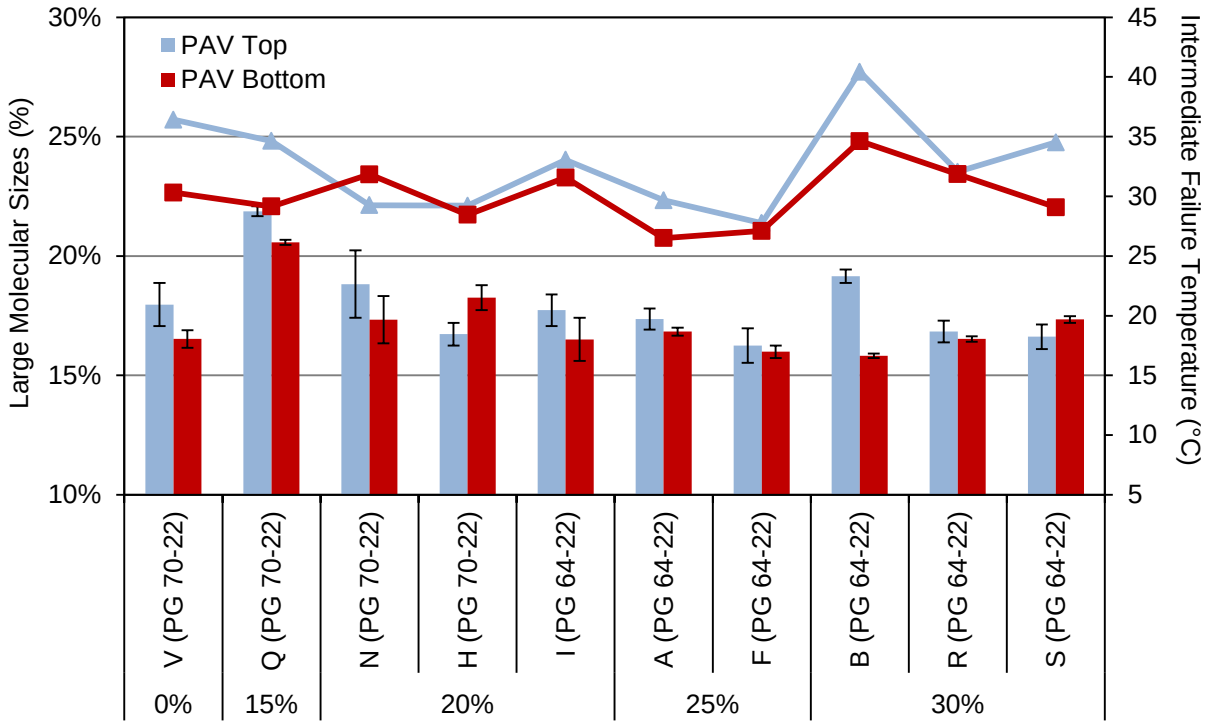


**Figure 25. LMS and Failure Temperature for Recovered Binders After PAV Aging. Bars indicate LMS values, and lines indicate failure temperature. Error bars indicate 1 standard deviation. LMS = large molecular sizes.**

The molecular weight distributions were generally in agreement with the trends found for failure temperatures of the binders. However, there are cases, such as that of rolling thin film oven (RTFO) Binder I and PAV Binders H and S, for which the molecular weight distributions actually show the bottom half of the core to be more highly oxidized. The failure temperature was not in agreement in these cases, showing that the top half was actually stiffer than the bottom half. However, in the case of PAV Binder N, the failure temperature grade showed that the bottom half of the core was stiffer than the top half. Overall, it was found that the top half of cores was stiffer and/or more highly oxidized than their respective bottom half.

## Supplementary Analysis

Because of concerns expressed regarding the use of sites with WMA and the inclusion of RAP sites with 21% RAP, which would not be acceptable under specifications adopted since 2007, selected additional analyses were performed to assess if these sites were significantly affecting overall results. For this assessment, WMA Sites H, K, and M and RAP Sites O and P were eliminated from the dataset. The analyses included consideration of the visual survey results; dynamic modulus, RLPD, and Texas overlay test results; and binder grading information. All information and analyses are presented in Appendix G.

## SU MMARY OF FINDINGS

### Literature Review

- The survey of the literature indicated that few studies have been performed on long-term performance of RAP-containing mixtures.

- Case studies of pre-Superpave mixtures indicated that RAP mixtures generally performed as well as virgin mixtures.

- Test track studies of mixtures containing 45% RAP found that softer virgin binder grades may improve the performance of these mixtures.

- Test track studies of HMA and WMA mixtures containing 50% RAP found performance equivalent to that of a control virgin mixture.

### Condition Data

- Visual survey data of the sites indicated that there were no significant differences ($\alpha = 0.05$) between the percentage of sites with mixtures having RAP contents ≤20% and the percentage of sites with mixtures having RAP contents of 21% to 30% exhibiting each distress.

- Visual survey data and coring showed a number of distresses in both sets of sections: top-down and bottom-up fatigue cracking, longitudinal and transverse cracking, raveling, delamination of layers, and moisture damage in underlying layers. It should be noted that some of these distresses are not influenced by the surface mixture; rather, they are indicative of the structural condition of the underlying pavement.

- Distress data extracted from PMS indicated that most of the pavements were in acceptable ride condition and had low rut depths of less than 0.16 in. Only Sites A and B had a higher rut depth of 0.23 in.

### Laboratory Analysis of Field Cores

- Air-void contents and permeability of cores were comparable between both sets of sections overall. Only one section (Section N, with a mixture having 20% RAP) did not meet design permeability requirements.

- Dynamic modulus test results indicated that neither RAP content nor virgin binder grade appeared to have discernable or trending influences on the measured modulus.

- RLPD test results on eight mixtures indicated that none of the mixtures reached tertiary flow in confined testing. Visual investigation of the slope and intercept of the secondary portion of the strain accumulation indicated a correlation between RAP content and increasing slope,

which may indicate some susceptibility to rutting related to virgin binder grade, blending and effective binder content, or test error.

- The results of the Texas overlay test showed no conclusive trends indicating that increased RAP contents positively or negatively affected mixtures.

## Analysis of Extracted Binder

- Extracted binder from the top half and bottom half of cores indicated that in nearly every case, the binder extracted from the top half of the core was stiffer than that from the bottom half.

- The differences in failure temperature of binder extracted from the top half and bottom half of cores decreased with increasing RAP content.

- Comparison of binder grades determined from mixture collected during construction and from cores at 6 years of service indicated that all mixtures, regardless of RAP content, gained one to two high-temperature performance grades over the 6-year in-service period evaluated. Low-temperature grades were similarly affected, with only one section found to retain the as-constructed low-temperature grade in service.

- RAP content appeared to have an influence on the rate of aging of virgin binder–RAP blends. The difference in binder failure temperature before and after 6 to 7 years of service increased with decreasing RAP content.

- Data plots indicated that the mixtures containing less RAP aged over the 6-year period to a greater extent than those containing higher RAP contents; Sections V and Q (top half) containing 0% and 15% RAP, respectively, had the highest true grade results and the lowest RAP contents, whereas the sections with mixtures containing 25% to 30% RAP resulted in lower true grades. This may support the hypothesis that since RAP has already undergone significant aging (assuming the RAP source is from milled pavement and not from plant waste), it may not continue to stiffen and age further as extensively when reclaimed.

- Examination of the critical cracking temperatures suggested that although there are concerns about the cracking potential of the binders, these concerns are independent of the mixture RAP contents.

- Construction and comparison of binder shear modulus mastercurves indicated that the difference in the modulus between the top half and bottom half of cores was consistent irrespective of RAP content.

- Black Space analysis indicated that neither the phase angle nor the shear stiffness of the extracted binders followed any trend with respect to RAP content. This result was likely influenced by the various base binders used in the mixtures and the varying stiffness of each RAP source.

- Molecular weight distributions determined by GPC and binder failure temperatures were generally in agreement that the top half of cores was stiffer and more oxidized than the bottom half of cores.

## CONCLUSIONS

- *Laboratory testing, including dynamic modulus determination, RLPD analysis, and extracted binder grading and analysis consistently showed no trends in results with RAP content. These results should not be extrapolated to RAP contents above the 30% maximum evaluated in this study.*

- *Overlay test results were influenced by more than just RAP (air-void content, etc.), and therefore no trend directly related to RAP content was shown.*

- *No trends in field performance could be determined because of the underlying structural conditions. Individual locations were found to show better or worse pavement performance, but this was attributed primarily to structural differences in the pavements and preexisting conditions. Surface deterioration observed in numerous test sections included fatigue cracking, longitudinal cracking, transverse cracking, raveling, and potholes.*

- *Binder analysis indicated that depth within a layer (in this case, top half versus bottom half) significantly affects binder properties, with stiffness decreasing with depth. However, increasing RAP contents appeared to mitigate the differences between the top half and bottom half of layers, possibly because of the preexisting aged composition of the RAP and its influence on the virgin binder properties.*

## RECOMMENDATIONS

1. *VDOT's Material Division should not make any changes to the allowance of RAP contents of up to 30% as currently specified.*

2. *VDOT's Materials Division and the Virginia Transportation Research Council (VTRC) should continue to evaluate the use of RAP contents to assess the potential for performance and economic benefits.* This effort should include evaluating potential ways to make these mixtures more durable and longer lasting; this may include investigating current and emerging technologies such as softer binder grades or rejuvenating agents. This work should be performed using plant-produced material placed to evaluate actual production, construction, and in-service performance. Accelerated performance testing of these mixtures would be appropriate.

3. *VDOT's Materials Division and VTRC should further investigate the causes and solutions to the structural issues observed in this study such as layer debonding and moisture damage.* Although this study did not target these deficiencies, they were widely observed and indicate a need for attention.

## BENEFITS AND IMPLEMENTATION

### Benefits

The benefit of implementing Recommendation 1 is that the use of RAP will continue as currently permitted in the specifications. No changes to practice are necessary.

The benefit of implementing Recommendation 2 is that it will provide VDOT with the most current feasible options for improving mixture durability. Techniques and technologies are continually evolving to improve mixture durability while using RAP for economic and environmental benefits; without continued attention to this emerging area, VDOT may miss opportunities to improve mixture durability and realize cost savings.

The benefit of implementing Recommendation 3 is that if structural issues can be addressed or mitigated through optimized maintenance treatments and rehabilitation efforts, lifetime cost savings can be achieved.

### Implementation

*With regard to Recommendation 1,* VDOT's Materials Division will make no changes to VDOT's specifications regarding the use of RAP contents up to 30% based on the outcomes of this study.

*With regard to Recommendation 2,* VTRC, with the assistance of the Materials Division, will continue to evaluate the use of RAP contents to assess the potential for performance and economic benefits. This will be accomplished through a combination of current work to evaluate the feasibility of RAP contents greater than 30% and a currently proposed project to assess the use of rejuvenators. As appropriate, when additional opportunities are identified to assess new advancements in the use of RAP, additional work will be proposed through VTRC's Asphalt Research Advisory Committee.

*With regard to Recommendation 3,* the Materials Division has been addressing tack issues that affect delamination with the support of VTRC.

## ACKNOWLEDGMENTS

The authors thank Troy Deeds and Donnie Dodds, of VTRC, and Samuel Deloach, Ben Earl, Ken Elliton, Shane Moomaw, and Kim Snead, formerly of VTRC, for their outstanding efforts in sample collection and testing. In addition, the assistance of Andrew Wallis, formerly of the University of Virginia, in compiling visual survey data is acknowledged. Appreciation is also extended to Linda Evans of VTRC for her editorial assistance. The authors are also appreciative of the project's technical review panel for their expertise and guidance: Bill Bailey, Rob Crandol, Raja Shekharan, Bryan Smith, Alex Teklu, Chaz Weaver, and Mike Wells of VDOT; Brian Diefenderfer of VTRC; and Trenton Clark of the Virginia Asphalt Association.

## REFERENCES


Al-Azri, N.A., S.H. Jung, K.M. Lunsford, A. Ferry, J.A. Bullin, R.R. Davison, and C.J. Glover. Binder Oxidative Aging in Texas Pavements: Hardening Rates, Hardening Susceptibilities, and Impact of Pavement Depth. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1962, 2006, pp. 12-20.

Al-Khateeb, G., X. Qi, A. Shenoy, K. Stuart, and T. Mitchell. Assessment of Aging at FHWA's Pavement Testing Facility. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1940, 2005, pp. 146-155.

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, 2014.

Anderson, E.D., and J.S. Daniel. Long-Term Performance of Pavement With High Recycled Asphalt Content: Case Studies. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2371, 2013, pp. 1-12.

Anderson, R.M., G.N. King, D.I. Hanson, and P.B. Blankenship. Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking. *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, 2011, pp. 615-663.

Apeagyei, A.K., B.K. Diefenderfer, and S.D. Diefenderfer. Rutting Resistance of Asphalt Concrete Mixtures That Contain Recycled Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2208, 2011, pp. 9-16.

Bowers, B.F., Diefenderfer, B.K., and Diefenderfer, S.D. Evaluation of Dynamic Modulus in Asphalt Paving Mixtures Utilizing Small-Scale Specimen Geometries. *Journal of the Association of Asphalt Paving Technologists*, Vol. 84, 2015a, pp. 497-526.

Bowers, B.F., B. Huang, X. Shu, and B.C. Miller. Investigation of Reclaimed Asphalt Pavement Blending Efficiency Through GPC and FTIR. *Construction and Building Material,* Vol. 50, No. 15, 2014, pp. 517-523.

Bowers, B.F., J. Moore, B. Huang, and X. Shu. Blending Efficiency of Reclaimed Asphalt Pavement: An Approach Utilizing Rheological Properties and Molecular Weight Distributions. *FUEL,* Vol. 135, 2015b, pp. 63-68.

Christensen, D.W., Jr., and Anderson, D.A. Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements. *Journal of the Association of Asphalt Paving Technologists*, Vol. 61, 1992, pp. 67-117.

Copeland, A. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*. FHWA-HRT-11-021. Federal Highway Administration, Washington, DC, 2011.

Decker, D. Hot-Mix Recycling: State of the Practice. *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, 1997, pp. 704-722.

Doh, Y.S., S.N. Amirkhanian, and K.W. Kim. Analysis of Unbalanced Binder Oxidation Level in Recycled Asphalt Mixture Using GPC. *Construction and Building Materials*, Vol. 22, No.6, 2008, pp. 1253-1260.

Glover C.J., A.E. Martin, A. Chowdhury, R. Han, N. Prapaitrakul, X. Jin, and J. Lawrence. *Evaluation of Binder Aging and Its Influence in Aging of Hot Mix Asphalt Concrete: Literature Review and Experimental Design*. FHWA/TX-08/0-6009-1. Texas Department of Transportation, Austin, 2008.

Glover, C.J., R. Han, X. Jin, N. Prapaitrakul, Y. Cui, A. Rose, J.J. Lawrence, M. Padigala, E. Arambula, E.S. Park, and A. Epps Martin. *Evaluation of Binder Aging and Its Influence in Aging of Hot Mix Asphalt Concrete: Technical Report*. FHWA/TX-14/0-6009-2. Texas Department of Transportation, Austin, 2014.

Hansen, K.E., and D.E. Newcomb. *Asphalt Pavement Mix Production Survey on Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, and Warm-Mix Asphalt Usage: 2009-2010*. Information Series 138. National Asphalt Pavement Association, Lanham, MD, 2011.

Kandhal, P. Recycling of Asphalt Pavements: An Overview. *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, 1997, pp. 686-703.

Khosravifar, S., I. Haider, Z. Afsharikia, and C.W. Schwartz. Application of Time-Temperature Superposition to Develop Master Curves of Cumulative Plastic Strain in Repeated Load Permanent Deformation Tests. *International Journal of Pavement Engineering*, Vol. 16, No. 3, 2015, pp. 214-223.

Kim, K.W., K. Kim, Y.S. Dog, and S.N. Amirkhanian. Estimation of RAP's Binder Viscosity Using GPC Without Binder Recovery. *Journal of Materials in Civil Engineering*, Vol. 18, No. 4, 2006, pp. 1253-1260.

Lee, S.J., S.N. Amirkhanian, and K. Shatanawi. Effects of Reaction Time on Physical and Chemical Properties of Rubber-modified Binders. *International Rubber Conference 2006, Compendium of Papers CD-ROM*, Lyon, France, May 16-18, 2006.

Li, X., and N. Gibson. 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.

Maupin, G.W., Jr., S.D. Diefenderfer, and J.S. Gillespie. *Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia*. VTRC 08-R22. Virginia Transportation Research Council, Charlottesville, 2008.

McDaniel, R., and R.M. Anderson. *NCHRP Report 452: Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual.* Transportation Research Board, Washington, DC, 2001.

McDaniel, R.S., and A. Shah. Use of Reclaimed Asphalt Pavement Under Superpave Specifications. *Journal of the Association of Asphalt Paving Technologists*, Vol. 72, 2003, pp. 226-252.

Miller, J.S., and W.Y. Bellinger. *Distress Identification Manual for the Long Term Pavement Performance Program (Fourth Revised Edition).* FHWA-RD-03-031. Federal Highway Administration, Washington, DC, 2003.

National Cooperative Highway Research Program. *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines.* NCHRP Research Results Digest No. 253. Transportation Research Board, Washington, DC, 2001.

Reinke, G., Hanz, A., Anderson, R.M., Ryan, M., Engber, S., and Herlitzka, D. *Impact of Re-refined Engine Oil Bottoms on Binder Properties and Mix Performance on Two Pavements in Minnesota.* 6th Eurasphalt & Eurobitume Congress, Prague, Czech Republic, 2016.

Rowe, G.M. Prepared Discussion for Paper by Anderson et al.: Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking. *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, 2011, pp. 649-662.

Texas Department of Transportation. *Test Procedure for Overlay Test Tex-248-F. Effective Dates: January 2009–October 2013.* 2009. http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/archives/248-80109.pdf. Accessed August 2, 2015.

Virginia Department of Transportation. *Road and Bridge Specifications.* Richmond, 2007.

Virginia Department of Transportation. Separate-Cover Contract Documents: Special Provision Copied Notes, Special Provisions, and Supplemental Specifications for Plant Mix Schedules—Statewide. 2013 Paving Season. Volume 2 (F) 2013 PM-10-22-12 Rev. 09-07-12. Richmond, 2012.

Virginia Department of Transportation. Mileage Tables—The State Highway Systems. 2013. http://www.virginiadot.org/VDOT/Projects/asset_upload_file789_5535.pdf. Accessed December 8, 2014.

Virginia Department of Transportation. Virginia Test Methods. 2014. http://www.virginiadot.org/business/resources/Materials/bu-mat-VTMs.pdf. Accessed May 19, 2015.

Von Quintus, H.L., J. Mallela, R. Bonaquist, C.W. Schwartz, and R.L. Carvalho. *NCHRP Report 719: Calibration of Rutting Models for Structural and Mix Design*. Transportation Research Board, Washington, DC, 2012.

West, R., J. Michael, R. Turochy, and S. Maghsoodloo. Use of Data From Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2208, 2011, pp. 82-89.

West, R., D. Timms, J.R. Willis, B. Powell, N. Tran, D. Watson, M. Sakhaeifar, R. Brown, M. Robbins, A. Vargas-Nordcbeck, F. Villacorta, X. Guo, and J. Nelson. *Phase IV NCAT Pavement Test Track Findings*. NCAT Report 12-10. National Center for Asphalt Technology, Auburn, 2012.

West, R.C., J.R. Willis, and M. Marasteanu. *NCHRP Report 752: Improved Mix Design, Evaluation, and Materials Management Practices for Hot-Mix Asphalt with High Reclaimed Asphalt Pavement Content*. Transportation Research Board, Washington, DC, 2013.

Willis, J.R., P. Turner, G. Julian, A. Taylor, N. Tran, and F. Padula. *Effects of Changing Virgin Binder Grade and Content on RAP Mixture Properties*. NCAT Report 12-03. National Center for Asphalt Technology, Auburn, 2012.

Woo, W.J., A. Chowdhury, and C.J. Glover. Field Aging of Unmodified Asphalt Binder in Three Texas Long-Term Performance Pavements. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2051, 2008, pp. 15-22.

Zhao, S., B.F. Bowers, B. Huang, and X. Shu. Characterizing Rheological Properties of Binder and Blending Efficiency of Asphalt Paving Mixtures Containing RAS Through GPC. *Journal of Materials in Civil Engineering,* Vol. 26, No. 5, 2014, pp. 941-946.

# APPENDIX A

# MIX DESIGNS

**Table A1. Job Mix 4047-739 Used in Sections A and B**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4047-739 |
| Mix Type | | SM-12.5D |
| Asphalt Content | | 5.60% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 19.0 mm (3/4 in) | | 100.0% |
| 12.5 mm (1/2 in) | | 96.0% |
| 9.5 mm (3/8 in) | | 89.0% |
| 2.36 mm (No. 8) | | 46.0% |
| 0.075 mm (No. 200) | | 6.5% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 29 | Granite | 60% |
| Recycled 1/2 in | Recycled | 25% |
| Sand | Sand | 15% |

**Table A2. Job Mix 4047-738 Used in Section B**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4047-739 |
| Mix Type | | IM-19.0D |
| Asphalt Content | | 5.00% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 25.0 mm (1 in) | | 100.0% |
| 19.0 mm (3/4 in) | | 96.0% |
| 12.5 mm (1/2 in) | | 77.0% |
| 2.36 mm (No. 8) | | 34.0% |
| 0.075 mm (No. 200) | | 5.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 68 | Granite | 50% |
| Recycled 1/2 in | Recycled | 30% |
| Sand | Sand | 20% |

**Table A3. Job Mix 4015-722 Used in Sections C and D**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4015-722 |
| Mix Type | | SM-12.5D |
| Asphalt Content | | 5.50% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 19.0 mm (3/4 in) | | 100.0% |
| 12.5 mm (1/2 in) | | 96.0% |
| 9.5 mm (3/8 in) | | 89.0% |
| 2.36 mm (No. 8) | | 41.0% |
| 0.075 mm (No. 200) | | 5.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Granite | 42% |
| Recycled 1/2 in | Recycled | 25% |
| No. 10 Screenings | Screenings | 15% |
| Sand | Sand | 10% |
| No. 10 Screenings | Screenings | 8% |

**Table A4. Job Mix 4047-608 Used in Section E**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4047-608 |
| Mix Type | | SM-9.5D |
| Asphalt Content | | 5.60% |
| Asphalt Type | | PG 70-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 94.0% |
| 4.75 mm (No. 4) | | 69.0% |
| 2.36 mm (No. 8) | | 51.0% |
| 0.075 mm (No. 200) | | 5.5% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| Top Size 1/2 in (No. 28) | Granite | 70% |
| Sand | Sand | 20% |
| Recycled 1/2 in | Recycled | 10% |

**Table A5. Job Mix 3007-2007-15 Used in Section F**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 3014-2007-15 |
| Mix Type | | SM-9.5D |
| Asphalt Content | | 5.50% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.9% |
| VMA | | 15.7% |
| VFA | | 75.2% |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | 2.598 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 94.0% |
| 4.75 mm (No. 4) | | 58.0% |
| 2.36 mm (No. 8) | | 44.0% |
| 0.075 mm (No. 200) | | 4.8% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Greenstone | 43% |
| Recycled 1/2 in | Recycled | 25% |
| Sand | Sand | 22% |
| Sand | Greenstone | 10% |

**Table A6. Job Mix 7008-200615 Used in Sections H and I**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 7008-200615 |
| Mix Type | | SM-9.5A |
| Asphalt Content | | 5.50% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 92.0% |
| 4.75 mm (No. 4) | | 60.0% |
| 2.36 mm (No. 8) | | 43.0% |
| 0.075 mm (No. 200) | | 5.7% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Silstone | 43% |
| Sand | Sand | 16% |
| No. 10 Screenings | Granite | 15% |
| No. 10 Screenings | Silstone | 14% |
| Recycled 1/2 in | Recycled | 12% |

**Table A7. Job Mix 4015-719 Used in Section J**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4015-719 |
| Mix Type | | SM-9.5A |
| Asphalt Content | | 5.87% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 96.0% |
| 4.75 mm (No. 4) | | 63.0% |
| 2.36 mm (No. 8) | | 44.0% |
| 0.075 mm (No. 200) | | 5.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Granite | 35% |
| No. 10 Screenings | Screenings | 25% |
| Recycled 1/2 in | Recycled | 25% |
| Sand | Sand | 10% |

**Table A8. Job Mix 48012-612 Used in Sections K and L**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Batch Plant |
| Job Mix ID | | 4015-722 |
| Mix Type | | SM-12.5A |
| Asphalt Content | | 5.20% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.3% |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 19.0 mm (3/4 in) | | 100.0% |
| 12.5 mm (1/2 in) | | 96.0% |
| 9.5 mm (3/8 in) | | 86.0% |
| 2.36 mm (No. 8) | | 34.0% |
| 0.075 mm (No. 200) | | 6.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 78 | Granite | 35% |
| No. 8 | Granite | 23% |
| No. 10 Screenings | Limestone | 17% |
| Sand | Sandstone | 14% |
| Recycled 1/2 in | Recycled | 10% |
| 0 | Hydrated Lime | 1% |

**Table A9. Job Mix 5011-200610 Used in Sections M and N**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4015-719 |
| Mix Type | | SM-9.5A |
| Asphalt Content | | 5.87% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.6% |
| VMA | | 16.2% |
| VFA | | 77.8% |
| FA Ratio | | 0.90 |
| $P_{be}$ | | 5.5% |
| $G_{mm}$ | | 2.475 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 93.0% |
| 4.75 mm (No. 4) | | 61.0% |
| 2.36 mm (No. 8) | | 44.0% |
| 0.075 mm (No. 200) | | 5.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| Top Size 1/2 in (No. 28) | Granite | 29% |
| No. 8 | Granite | 26% |
| Sand | Sand | 25% |
| Recycled 1/2 in | Recycled | 20% |

**Table A10. Job Mix 3007-2007-18 Used in Sections O and P**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 3005-2007-06 |
| Mix Type | | SM-9.5D |
| Asphalt Content | | 5.90% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.8% |
| VMA | | 15.8% |
| VFA | | 74.6% |
| FA Ratio | | 1.10 |
| $P_{be}$ | | 5.3% |
| $G_{mm}$ | | 2.436 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 94.0% |
| 4.75 mm (No. 4) | | 63.0% |
| 2.36 mm (No. 8) | | 46.0% |
| 0.075 mm (No. 200) | | 5.8% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Granite | 40% |
| No. 10 Screenings | Granite | 27% |
| Recycled 1/2 in | Recycled | 21% |
| Sand | Sand | 12% |

**Table A11. Job Mix 2025-200531 Used in Section Q**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 2025-200531 |
| Mix Type | | SM-9.5D |
| Asphalt Content | | 5.87% |
| Asphalt Type | | PG 70-22 |
| **Volumetric Data** | | |
| VTM | | 3.5% |
| VMA | | 15.3% |
| VFA | | 80.0% |
| FA Ratio | | 1.08 |
| $P_{be}$ | | 5.5% |
| $G_{mm}$ | | 2.466 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 90.0% |
| 4.75 mm (No. 4) | | 57.0% |
| 2.36 mm (No. 8) | | 38.0% |
| 0.075 mm (No. 200) | | 6.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Quartzite | 45% |
| No. 10 Screenings | Quartzite | 25% |
| Recycled 1/2 in | Recycled | 15% |
| Sand | Sand | 15% |

**Table A12. Job Mix 2065-2007-04 Used in Sections R and S**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 2065-2007-04 |
| Mix Type | | SM-9.5D |
| Asphalt Content | | 5.50% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.4% |
| VMA | | 16.0% |
| VFA | | 78.9% |
| FA Ratio | | 1.12 |
| $P_{be}$ | | 5.4% |
| $G_{mm}$ | | 2.488 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 94.0% |
| 4.75 mm (No. 4) | | 58.0% |
| 2.36 mm (No. 8) | | 42.0% |
| 0.075 mm (No. 200) | | 6.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Quartzite | 40% |
| Recycled 1/2 in | Recycled | 30% |
| Sand | Sand | 17% |
| No. 10 Screenings | Quartzite | 13% |

**Table A13. Job Mix 5024-200605 Used in Section T**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 5024-200605 |
| Mix Type | | SM-9.5A |
| Asphalt Content | | 5.50% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.9% |
| VMA | | 16.0% |
| VFA | | 75.4% |
| FA Ratio | | 1.10 |
| $P_{be}$ | | 5.3% |
| $G_{mm}$ | | 2.463 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 96.0% |
| 4.75 mm (No. 4) | | 67.0% |
| 2.36 mm (No. 8) | | 48.0% |
| 0.075 mm (No. 200) | | 6.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 78 | Granite | 42% |
| No. 10 Screenings | Granite | 29% |
| Sand | Sand | 19% |
| Recycled 1/2 in | Recycled | 10% |

**Table A14. Job Mix 3005-2007-06 Used in Section U**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 3005-2007-06 |
| Mix Type | | SM-12.5D |
| Asphalt Content | | 5.70% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 4.0% |
| VMA | | 16.1% |
| VFA | | 75.0% |
| FA Ratio | | 1.00 |
| $P_{be}$ | | 5.1% |
| $G_{mm}$ | | 2.558 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 19.0 mm (3/4 in) | | 100.0% |
| 12.5 mm (1/2 in) | | 96.0% |
| 9.5 mm (3/8 in) | | 86.0% |
| 2.36 mm (No. 8) | | 44.0% |
| 0.075 mm (No. 200) | | 5.1% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| Sand | Aplite | 30% |
| No. 78 | Aplite | 30% |
| Recycled 1/2 in | Recycled | 25% |
| No. 8 | Aplite | 15% |

**Table A15. Job Mix 7017-200710 Used in Section V**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 7017-200710 |
| Mix Type | | SM-9.5D |
| Asphalt Content | | 5.70% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | - |
| VMA | | - |
| VFA | | - |
| FA Ratio | | - |
| $P_{be}$ | | - |
| $G_{mm}$ | | - |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 12.5 mm (1/2 in) | | 100.0% |
| 9.5 mm (3/8 in) | | 97.0% |
| 4.75 mm (No. 4) | | 62.0% |
| 2.36 mm (No. 8) | | 44.0% |
| 0.075 mm (No. 200) | | 5.0% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 8 | Greenstone | 48% |
| Manufactured Sand | Manufactured Sand | 25% |
| Sand | Sand | 15% |
| No. 10 Screenings | Greenstone | 12% |

**Table A16. Job Mix 4051-720 Used in Section W**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 4051-720 |
| Mix Type | | SM-12.5D |
| Asphalt Content | | 5.70% |
| Asphalt Type | | PG 70-22 |
| **Volumetric Data** | | |
| VTM | | 4.0% |
| VMA | | 16.1% |
| VFA | | 75.0% |
| FA Ratio | | 1.00 |
| $P_{be}$ | | 5.1% |
| $G_{mm}$ | | 2.558 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 19.0 mm (3/4 in) | | 100.0% |
| 12.5 mm (1/2 in) | | 96.0% |
| 9.5 mm (3/8 in) | | 83.0% |
| 2.36 mm (No. 8) | | 40.0% |
| 0.075 mm (No. 200) | | 5.5% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 78 | Granite | 41% |
| No. 10 Screenings | Screenings | 24% |
| Recycled 1/2 in | Recycled | 20% |
| Sand | Natural Sand | 15% |

**Table A17. Job Mix 5029-2007-04 Used in Section X**

| **Mix Information** | | |
|---|---|---|
| Plant Type | | Drum Mix Plant |
| Job Mix ID | | 5029-2007-04 |
| Mix Type | | SM-12.5D |
| Asphalt Content | | 5.40% |
| Asphalt Type | | PG 64-22 |
| **Volumetric Data** | | |
| VTM | | 3.8% |
| VMA | | 16.2% |
| VFA | | 76.3% |
| FA Ratio | | 1.00 |
| $P_{be}$ | | 5.3% |
| $G_{mm}$ | | 2.460 |
| **Sieve Data** | | |
| **Sieve** | | **Percent Passing** |
| 19.0 mm (3/4 in) | | 100.0% |
| 12.5 mm (1/2 in) | | 97.0% |
| 9.5 mm (3/8 in) | | 86.0% |
| 2.36 mm (No. 8) | | 45.0% |
| 0.075 mm (No. 200) | | 5.4% |
| **Aggregate Information** | | |
| **Size** | **Type** | **Percent** |
| No. 78 | Granite | 36% |
| Recycled 1 in | Recycled | 30% |
| Sand | Sand | 22% |
| No. 10 Screenings | Granite | 9% |
| No. 8 | Granite | 3% |

# APPENDIX B

# PAVEMENT MANAGEMENT SYSTEM DISTRESS DATA

**Table B1. PMS Distress Data for Sections A and B, SR 6, Goochland County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 97 | 95 | 87 | 82 | 82 | 72 | 75 |
| LDR | 100 | 96 | 89 | 82 | 82 | 72 | 75 |
| NDR | 97 | 97 | 94 | 90 | 97 | 80 | 91 |
| IRI | 92 | 93 | 95 | 96 | 102 | 108 | 109 |
| Rut Depth | 0.05 | 0.07 | 0.1 | 0.12 | 0.16 | 0.21 | 0.23 |
| Number of Trucks | 164 | 164 | 164 | 119 | 120 | 121 | 121 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B2. PMS Distress Data for Section C, CR 703, Dinwiddie County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | | | 95 | | | | |
| LDR | | | 95 | | | | |
| NDR | | | 100 | | | | |
| IRI | | | 128 | | | | |
| Rut Depth | | | 0.15 | | | | |
| Number of Trucks | | | 48 | | | | |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B3. PMS Distress Data for Section D, SR 40, Dinwiddie County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | - | 99 | 96 | 99 | 98 | 95 | 82 |
| LDR | - | 99 | 97 | 99 | 98 | 95 | 83 |
| NDR | - | 100 | 99 | 100 | 100 | 98 | 87 |
| IRI | - | 86 | 89 | 89 | 89 | 91 | 90 |
| Rut Depth | - | 0.06 | 0.12 | 0.1 | 0.12 | 0.13 | 0.12 |
| Number of Trucks | - | 78 | 74 | 62 | 72 | 67 | 67 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B4. PMS Distress Data for Section F, SR 24, Appomattox County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 99 | 96 | 90 | 98 | 95 | 97 | 94 |
| LDR | 100 | 97 | 92 | 99 | 96 | 98 | 95 |
| NDR | 99 | 99 | 96 | 99 | 97 | 98 | 97 |
| IRI | 70 | 72 | 74 | 75 | 75 | 96 | 84 |
| Rut Depth | 0.09 | 0.11 | 0.09 | 0.09 | 0.09 | 0.1 | 0.12 |
| Number of Trucks | 184 | 184 | 187 | 190 | 189 | 160 | 160 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B5. PMS Distress Data for Section H, SR 211, Rappahannock County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 85 | 83 | 92 | 76 | 77 | 54 | 52 |
| LDR | 85 | 83 | 100 | 76 | 80 | 54 | 54 |
| NDR | 98 | 94 | 92 | 95 | 85 | 75 | 65 |
| IRI | 77 | 78 | 76 | 78 | 82 | 81 | 90 |
| Rut Depth | 0.08 | 0.06 | 0.08 | 0.07 | 0.09 | 0.07 | 0.09 |
| Number of Trucks | 79 | 79 | 81 | 58 | 54 | - | - |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B6. PMS Distress Data for Section I, SR 211, Rappahannock County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 95 | 71 | 84 | 71 | 56 | 51 | 27 |
| LDR | 95 | 71 | 92 | 71 | 56 | 51 | 27 |
| NDR | 100 | 94 | 84 | 94 | 80 | 71 | 68 |
| IRI | 56 | 60 | 58 | 57 | 59 | 60 | 60 |
| Rut Depth | 0.08 | 0.08 | 0.08 | 0.09 | 0.1 | 0.1 | 0.11 |
| Number of Trucks | 79 | 79 | 81 | 58 | 54 | - | |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B7. PMS Distress Data for Sections K and L, US 220, Highland County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 99 | 100 | 87 | 75 | 43 | 50 | 40 |
| LDR | 100 | 100 | 89 | 75 | 43 | 50 | 40 |
| NDR | 99 | 100 | 87 | 84 | 62 | 69 | 62 |
| IRI | 70 | 77 | 68 | 76 | 79 | 79 | 78 |
| Rut Depth | 0.07 | 0.06 | 0.1 | 0.1 | 0.09 | 0.11 | 0.09 |
| Number of Trucks | 30 | 30 | 31 | 31 | 16 | 17 | 17 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B8. PMS Distress Data for Section N, SR 143, York County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 90 | 96 | 84 | 80 | 77 | 40 | 46 |
| LDR | 99 | 99 | 97 | 96 | 95 | 95 | 96 |
| NDR | 90 | 96 | 84 | 80 | 77 | 40 | 46 |
| IRI | 94 | 89 | 89 | 97 | 97 | 101 | 106 |
| Rut Depth | 0.05 | 0.05 | 0.07 | 0.07 | 0.07 | 0.09 | 0.08 |
| Number of Trucks | 149 | 149 | 75 | 82 | 82 | 82 | 82 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B9. PMS Distress Data for Section O, US 29, Pittsylvania County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 100 | 92 | 96 | 98 | 94 | 92 | 86 |
| LDR | 100 | 99 | 97 | 99 | 98 | 95 | 87 |
| NDR | 100 | 93 | 98 | 99 | 95 | 95 | 91 |
| IRI | 71 | 80 | 75 | 74 | 74 | 96 | 75 |
| Rut Depth | 0.04 | 0.09 | 0.11 | 0.11 | 0.11 | 0.14 | 0.15 |
| Number of Trucks | 962 | 966 | 922 | 859 | 869 | 889 | 889 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B10. PMS Distress Data for Section Q, US 11, Montgomery County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 100 | 99 | 87 | 91 | 78 | 89 | 78 |
| LDR | 100 | 99 | 91 | 91 | 79 | 90 | 79 |
| NDR | 100 | 100 | 91 | 99 | 93 | 95 | 93 |
| IRI | 82 | 83 | 84 | 88 | 86 | 88 | 90 |
| Rut Depth | 0.07 | 0.09 | 0.14 | 0.12 | 0.11 | 0.12 | 0.13 |
| Number of Trucks | 89 | 89 | 89 | 85 | 82 | 81 | 81 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B11. PMS Distress Data for Section R, US 221, Floyd County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 100 | 98 | 87 | 89 | 67 | 69 | 61 |
| LDR | 100 | 98 | 87 | 90 | 71 | 70 | 62 |
| NDR | 100 | 99 | 96 | 96 | 79 | 84 | 82 |
| IRI | 87 | 92 | 98 | 96 | 100 | 101 | 114 |
| Rut Depth | 0.07 | 0.07 | 0.11 | 0.09 | 0.13 | 0.11 | 0.11 |
| Number of Trucks | 107 | 105 | 114 | 114 | 112 | 100 | 60 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B12. PMS Distress Data for Section S, US 58, Carroll County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 100 | 97 | 85 | 89 | 81 | 78 | 66 |
| LDR | 100 | 99 | 86 | 90 | 84 | 79 | 66 |
| NDR | 100 | 97 | 95 | 96 | 88 | 90 | 86 |
| IRI | 94 | 99 | 105 | 99 | 103 | 100 | 113 |
| Rut Depth | 0.06 | 0.09 | 0.14 | 0.11 | 0.1 | 0.12 | 0.14 |
| Number of Trucks | 108 | 108 | 125 | 119 | 96 | 95 | 57 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B13. PMS Distress Data for Section U, US 29, Nelson County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 93 | 88 | 95 | 99 | 98 | 93 | 93 |
| LDR | 96 | 88 | 95 | 99 | 98 | 93 | 94 |
| NDR | 93 | 94 | 98 | 100 | 99 | 99 | 96 |
| IRI | 71 | 71 | 69 | 70 | 93 | 92 | 73 |
| Rut Depth | 0.1 | 0.17 | 0.14 | 0.1 | 0.11 | 0.14 | 0.16 |
| Number of Trucks | 826 | 826 | 351 | 914 | 831 | 806 | 806 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

**Table B14. PMS Distress Data for Section X, I 664, Chesapeake County**

| Parameter | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
| CCI | 92 | 91 | 91 | 87 | 90 | 90 | 89 |
| LDR | 94 | 91 | 91 | 89 | 93 | 92 | 90 |
| NDR | 96 | 98 | 97 | 92 | 93 | 96 | 93 |
| IRI | 82 | 86 | 76 | 79 | 78 | 86 | 81 |
| Rut Depth | 0.16 | 0.18 | 0.15 | 0.15 | 0.17 | 0.17 | 0.16 |
| Number of Trucks | 2385 | 2461 | 2514 | 1909 | 2253 | 2197 | 2163 |

CCI = Critical Condition Index; LDR = load related distress rating; NDR = non-load related distress rating; IRI = International Roughness Index.

# APPENDIX C

# DYNAMIC MODULUS TEST RESULTS

**Table C1. Section B Dynamic Modulus Data**

| Section | B | | Mix Type | SM-12.5D | | RAP Content | 25% |
|---|---|---|---|---|---|---|---|
| Specimen | | B3 | | B4 | | B5 | |
| Air Voids | | 6.6% | | 4.5% | | 8.2% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, ° | Dynamic Modulus, MPa | Phase Angle, ° | Dynamic Modulus, MPa | Phase Angle, ° |
| 4.4ºC | 25 | 22028 | 12.84 | 29110 | 36.72 | 18717 | 3.97 |
| | 10 | 20595 | 6.49 | 22711 | 6.96 | 18158 | 4.33 |
| | 5 | 19561 | 6.89 | 21610 | 7.44 | 17642 | 4.60 |
| | 1 | 17093 | 8.17 | 18866 | 8.92 | 16317 | 5.47 |
| | 0.5 | 16026 | 8.82 | 17643 | 9.67 | 15726 | 5.89 |
| | 0.1 | 13591 | 10.59 | 14814 | 11.83 | 14273 | 7.11 |
| 21.1ºC | 25 | 12887 | 13.19 | 13862 | 14.37 | 13810 | 7.96 |
| | 10 | 11327 | 14.69 | 12105 | 16.06 | 12694 | 9.12 |
| | 5 | 10150 | 16.05 | 10762 | 17.53 | 11811 | 10.17 |
| | 1 | 7549 | 19.80 | 7825 | 21.48 | 9717 | 12.91 |
| | 0.5 | 6555 | 21.40 | 6723 | 23.03 | 8817 | 14.29 |
| | 0.1 | 4463 | 25.79 | 4441 | 27.19 | 6757 | 18.00 |
| 37.8ºC | 25 | 5591 | 24.82 | 5735 | 25.95 | 7132 | 18.58 |
| | 10 | 4416 | 26.81 | 4463 | 28.06 | 6016 | 20.76 |
| | 5 | 3618 | 28.40 | 3593 | 29.51 | 5177 | 22.63 |
| | 1 | 2116 | 31.69 | 2015 | 32.40 | 3421 | 27.24 |
| | 0.5 | 1645 | 32.32 | 1535 | 32.72 | 2803 | 28.77 |
| | 0.1 | 859.7 | 33.44 | 774.7 | 33.12 | 1615 | 32.36 |

**Table C2. Section C Dynamic Modulus Data**

| **Section** | **C** | | **Mix Type** | **SM-12.5D** | | **RAP Content** | **25%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **C1** | | **C9** | | **C10** | |
| **Air Voids** | | **6.7%** | | **4.3%** | | **5.3%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 13222 | 8.86 | 18195 | 6.54 | 18882 | 6.17 |
| | 10 | 12014 | 9.62 | 16822 | 7.03 | 17801 | 6.64 |
| | 5 | 11083 | 10.26 | 15958 | 7.56 | 16933 | 7.09 |
| | 1 | 8968 | 11.83 | 13916 | 9.02 | 14858 | 8.37 |
| | 0.5 | 8097 | 12.52 | 13039 | 9.73 | 13949 | 9.03 |
| | 0.1 | 6220 | 14.08 | 10969 | 11.80 | 11844 | 10.91 |
| 21.1ºC | 25 | 5969 | 15.21 | 10374 | 13.72 | 11105 | 12.99 |
| | 10 | 4953 | 15.29 | 9075 | 15.22 | 9791 | 14.3 |
| | 5 | 4241 | 15.71 | 8127 | 16.52 | 8809 | 15.57 |
| | 1 | 2832 | 15.75 | 5990 | 20.01 | 6619 | 18.92 |
| | 0.5 | 2383 | 16.18 | 5185 | 21.52 | 5790 | 20.30 |
| | 0.1 | 1522 | 17.81 | 3522 | 25.38 | 4038 | 24.18 |
| 37.8ºC | 25 | 2147 | 20.30 | 4376 | 25.69 | 4843 | 24.23 |
| | 10 | 1741 | 22.09 | 3479 | 27.31 | 3900 | 25.96 |
| | 5 | 1415 | 23.54 | 2846 | 28.67 | 3229 | 27.31 |
| | 1 | 841.2 | 26.77 | 1681 | 31.41 | 1956 | 30.41 |
| | 0.5 | 675.3 | 28.53 | 1320 | 31.91 | 1549 | 31.06 |
| | 0.1 | 388.4 | 32.32 | 714.9 | 32.87 | 834.3 | 32.38 |

**Table C3. Section D Dynamic Modulus Data**

| **Section** | **D** | | **Mix Type** | **SM-12.5D** | | **RAP Content** | **25%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **D4** | | **D6** | | **D9** | |
| **Air Voids** | | **6.2%** | | **7.2%** | | **7.2%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 20084 | 6.72 | 17614 | 7.62 | 17999 | 6.43 |
| | 10 | 18812 | 7.27 | 16366 | 8.51 | 16889 | 7.15 |
| | 5 | 17792 | 7.82 | 15353 | 9.30 | 15943 | 7.77 |
| | 1 | 15346 | 9.41 | 12929 | 11.55 | 13644 | 9.50 |
| | 0.5 | 14279 | 10.20 | 11863 | 12.68 | 12644 | 10.41 |
| | 0.1 | 11805 | 12.53 | 9380 | 15.83 | 10291 | 12.96 |
| 21.1ºC | 25 | 11294 | 14.75 | 9234 | 17.51 | 9899 | 14.10 |
| | 10 | 9771 | 16.52 | 7782 | 19.52 | 8557 | 16.58 |
| | 5 | 8633 | 18.05 | 6756 | 21.19 | 7526 | 18.33 |
| | 1 | 6183 | 22.25 | 4581 | 25.49 | 5308 | 22.86 |
| | 0.5 | 5291 | 23.96 | 3826 | 26.94 | 4510 | 24.62 |
| | 0.1 | 3426 | 28.65 | 2339 | 30.58 | 2872 | 29.47 |
| 37.8ºC | 25 | 4417 | 28.05 | 3273 | 30.52 | 3984 | 28.82 |
| | 10 | 3412 | 29.84 | 2472 | 31.52 | 3089 | 30.74 |
| | 5 | 2724 | 31.16 | 1923 | 32.38 | 2449 | 32.15 |
| | 1 | 1492 | 33.65 | 1028 | 33.09 | 1352 | 34.05 |
| | 0.5 | 1123 | 33.87 | 773.3 | 32.85 | 1029 | 33.96 |
| | 0.1 | 552.6 | 34.02 | 396.9 | 31.75 | 538.2 | 33.06 |

**Table C4. Section E Dynamic Modulus Data**

| Section | E | | Mix Type | SM-9.5D | | RAP Content | 0% |
|---|---|---|---|---|---|---|---|
| Specimen | | E5 | | E7 | | E9 | |
| Air Voids | | 5.9% | | 5.9% | | 6.0% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 22985 | 5.43 | 23230 | 5.02 | 21632 | 5.79 |
| | 10 | 21907 | 5.93 | 22172 | 5.46 | 20464 | 6.27 |
| | 5 | 20980 | 6.36 | 21303 | 5.87 | 19523 | 6.79 |
| | 1 | 18669 | 7.62 | 19105 | 7.04 | 17196 | 8.23 |
| | 0.5 | 17630 | 8.26 | 18113 | 7.63 | 16171 | 8.92 |
| | 0.1 | 15166 | 10.03 | 15771 | 9.25 | 13819 | 10.93 |
| 21.1ºC | 25 | 14216 | 11.57 | 14867 | 11.02 | 13140 | 12.47 |
| | 10 | 12689 | 13.48 | 13337 | 12.29 | 11571 | 14.04 |
| | 5 | 11496 | 14.81 | 12141 | 13.39 | 10380 | 15.40 |
| | 1 | 8800 | 18.39 | 9444 | 16.45 | 7719 | 19.27 |
| | 0.5 | 7715 | 19.99 | 8360 | 17.87 | 6697 | 20.98 |
| | 0.1 | 5436 | 24.17 | 6011 | 21.74 | 4549 | 25.44 |
| 37.8ºC | 25 | 6776 | 22.37 | 7229 | 21.36 | 6021 | 24.56 |
| | 10 | 5460 | 24.93 | 5871 | 23.52 | 4759 | 26.92 |
| | 5 | 4534 | 26.76 | 4927 | 25.19 | 3893 | 28.65 |
| | 1 | 2764 | 30.68 | 3079 | 29.16 | 2253 | 32.37 |
| | 0.5 | 2188 | 31.40 | 2466 | 30.29 | 1738 | 33.21 |
| | 0.1 | 1183 | 33.11 | 1362 | 32.90 | 896.6 | 34.31 |

**Table C5. Section J Dynamic Modulus Data**

| Section | J | | Mix Type SM-9.5D | | | RAP Content | 25% |
|---|---|---|---|---|---|---|---|
| Specimen | | J1 | | J2 | | J4 | |
| Air Voids | | 6.3% | | 7.2% | | 7.3% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, ° | Dynamic Modulus, MPa | Phase Angle, ° | Dynamic Modulus, MPa | Phase Angle, ° |
| 4.4ºC | 25 | 15991 | 7.81 | 17252 | 7.13 | 18075 | 6.90 |
| | 10 | 14960 | 8.56 | 16126 | 7.67 | 16912 | 7.32 |
| | 5 | 14103 | 9.09 | 15199 | 8.17 | 16009 | 7.82 |
| | 1 | 12035 | 10.59 | 13010 | 9.56 | 13847 | 9.32 |
| | 0.5 | 11154 | 11.33 | 12089 | 10.28 | 12908 | 10.08 |
| | 0.1 | 9157 | 13.43 | 9937 | 12.31 | 10823 | 12.21 |
| 21.1ºC | 25 | 8796 | 15.54 | 9548 | 14.23 | 10191 | 14.66 |
| | 10 | 7657 | 17.04 | 8215 | 15.71 | 8838 | 16.35 |
| | 5 | 6787 | 18.31 | 7231 | 17.11 | 7837 | 17.74 |
| | 1 | 4875 | 21.84 | 5168 | 20.77 | 5695 | 21.61 |
| | 0.5 | 4176 | 23.24 | 4419 | 22.39 | 4907 | 23.11 |
| | 0.1 | 2743 | 26.99 | 2885 | 26.69 | 3293 | 27.25 |
| 37.8ºC | 25 | 3618 | 27.47 | 3812 | 27.42 | 4129 | 26.89 |
| | 10 | 2835 | 29.11 | 2956 | 29.18 | 3234 | 28.63 |
| | 5 | 2286 | 30.36 | 2374 | 30.60 | 2621 | 30.00 |
| | 1 | 1288 | 32.94 | 1309 | 33.29 | 1495 | 32.91 |
| | 0.5 | 984.7 | 33.24 | 982.5 | 33.70 | 1145 | 33.47 |
| | 0.1 | 511.7 | 33.61 | 475.3 | 34.26 | 575.8 | 34.43 |

**Table C6. Section L Dynamic Modulus Data**

| Section | L | | Mix Type | SM-9.5A | | RAP Content | 10% |
|---|---|---|---|---|---|---|---|
| Specimen | | L1 | | L4 | | L7 | |
| Air Voids | | 6.9% | | 7.2% | | 7.4% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 19651 | 5.51 | 15184 | 5.36 | 13085 | 6.77 |
| | 10 | 18628 | 5.91 | 14533 | 6.45 | 12641 | 7.85 |
| | 5 | 17799 | 6.35 | 13958 | 6.95 | 12212 | 8.67 |
| | 1 | 15755 | 7.53 | 12393 | 8.47 | 11030 | 11.89 |
| | 0.5 | 14830 | 8.18 | 11737 | 9.26 | 10525 | 13.38 |
| | 0.1 | 12639 | 10.00 | 10050 | 11.47 | 9205 | 16.24 |
| 21.1ºC | 25 | 11899 | 11.86 | 9546 | 13.57 | 9405 | 10.22 |
| | 10 | 10519 | 13.20 | 8533 | 14.84 | 8512 | 11.53 |
| | 5 | 9480 | 14.42 | 7712 | 16.14 | 7810 | 12.67 |
| | 1 | 7152 | 17.76 | 5763 | 19.68 | 6165 | 15.67 |
| | 0.5 | 6262 | 19.27 | 5039 | 21.18 | 5531 | 17.17 |
| | 0.1 | 4358 | 23.39 | 3428 | 25.14 | 4077 | 21.17 |
| 37.8ºC | 25 | 5198 | 23.76 | 4195 | 25.89 | 4293 | 27.41 |
| | 10 | 4168 | 25.87 | 3356 | 27.57 | 3733 | 26.80 |
| | 5 | 3437 | 27.38 | 2746 | 28.89 | 3164 | 27.29 |
| | 1 | 2046 | 30.13 | 1610 | 31.25 | 2041 | 30.73 |
| | 0.5 | 1610 | 30.65 | 1265 | 31.71 | 1676 | 31.48 |
| | 0.1 | 870.1 | 31.27 | 693.2 | 31.59 | 993 | 33.65 |

**Table C7. Section M Dynamic Modulus Data**

| Section | M | | Mix Type | SM-9.5A (WMA) | | RAP Content | 20% |
|---|---|---|---|---|---|---|---|
| Specimen Air Voids | | M3 7.7% | | M7 6.6% | | M9 7.5% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 16134 | 7.13 | 18189 | 7.14 | 18789 | 6.81 |
| | 10 | 15152 | 7.61 | 17039 | 7.91 | 17595 | 7.3 |
| | 5 | 14356 | 8.13 | 16074 | 8.46 | 16666 | 7.77 |
| | 1 | 12362 | 9.52 | 13774 | 10.06 | 14426 | 9.07 |
| | 0.5 | 11519 | 10.23 | 12750 | 10.9 | 13433 | 9.71 |
| | 0.1 | 9571 | 12.37 | 10444 | 13.38 | 11198 | 11.74 |
| 21.1ºC | 25 | 9231 | 14.26 | 10206 | 14.84 | 11212 | 13.62 |
| | 10 | 8068 | 15.66 | 8818 | 16.53 | 9775 | 15.3 |
| | 5 | 7189 | 16.95 | 7803 | 17.99 | 8684 | 16.74 |
| | 1 | 5301 | 20.38 | 5598 | 21.9 | 6350 | 20.63 |
| | 0.5 | 4577 | 21.86 | 4778 | 23.57 | 5461 | 22.26 |
| | 0.1 | 3098 | 25.84 | 3113 | 27.9 | 3637 | 26.79 |
| 37.8ºC | 25 | 3840 | 26.06 | 4045 | 28.11 | 4595 | 26.8 |
| | 10 | 3043 | 27.67 | 3150 | 29.85 | 3582 | 28.77 |
| | 5 | 2489 | 29.01 | 2535 | 31.17 | 2897 | 30.25 |
| | 1 | 1473 | 31.63 | 1435 | 33.73 | 1660 | 33.46 |
| | 0.5 | 1162 | 32.25 | 1109 | 34.12 | 1291 | 34.11 |
| | 0.1 | 632.8 | 33.31 | 581.9 | 34.45 | 685.1 | 35.15 |

**Table C8. Section N Dynamic Modulus Data**

| Section | N | | Mix Type | SM-9.5A | | RAP Content | 20% |
|---|---|---|---|---|---|---|---|
| Specimen | | N6 | | N7 | | N10 | |
| Air Voids | | 10.1% | | 8.7% | | 8.4% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, ° | Dynamic Modulus, MPa | Phase Angle, ° | Dynamic Modulus, MPa | Phase Angle, ° |
| 4.4ºC | 25 | 16699 | 6.27 | 16060 | 7.37 | 16060 | 7.37 |
| | 10 | 15702 | 6.90 | 15012 | 8.03 | 15012 | 8.03 |
| | 5 | 14882 | 7.52 | 14160 | 8.57 | 14160 | 8.57 |
| | 1 | 12901 | 9.14 | 12165 | 10.14 | 12165 | 10.14 |
| | 0.5 | 12058 | 9.96 | 11335 | 10.89 | 11335 | 10.89 |
| | 0.1 | 10072 | 12.26 | 9434 | 13.03 | 9434 | 13.03 |
| 21.1ºC | 25 | 9695 | 14.44 | 8849 | 15.02 | 8849 | 28.24 |
| | 10 | 8427 | 16.15 | 7669 | 16.72 | 7669 | 30.04 |
| | 5 | 7480 | 17.67 | 6785 | 18.23 | 6785 | 31.49 |
| | 1 | 5398 | 21.84 | 4888 | 22.26 | 4888 | 34.01 |
| | 0.5 | 4621 | 23.54 | 4189 | 23.90 | 4189 | 34.31 |
| | 0.1 | 3023 | 27.96 | 2771 | 28.09 | 2771 | 34.21 |
| 37.8ºC | 25 | 3922 | 28.07 | 3518 | 28.24 | 3518 | 28.24 |
| | 10 | 3028 | 30.08 | 2725 | 30.04 | 2725 | 30.04 |
| | 5 | 2422 | 31.64 | 2179 | 31.49 | 2179 | 31.49 |
| | 1 | 1346 | 34.41 | 1224 | 34.01 | 1224 | 34.01 |
| | 0.5 | 1028 | 34.77 | 939 | 34.31 | 939 | 34.31 |
| | 0.1 | 521.7 | 35.00 | 483.2 | 34.21 | 483.2 | 34.21 |

**Table C9. Section O Dynamic Modulus Data**

| **Section** | **O** | | **Mix Type** | **SM-9.5D** | | **RAP Content** | **21%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **2** | | **0** | | **0** | |
| **Air Voids** | | **5.8%** | | **5.6%** | | **6.3%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 19782 | 5.64 | 20082 | 6.19 | 18805 | 5.99 |
| | 10 | 18703 | 6.16 | 18944 | 6.74 | 17589 | 7.28 |
| | 5 | 17807 | 6.63 | 18033 | 7.27 | 16574 | 7.84 |
| | 1 | 15606 | 7.95 | 15826 | 8.79 | 14135 | 9.36 |
| | 0.5 | 14609 | 8.63 | 14844 | 9.56 | 13089 | 10.09 |
| | 0.1 | 12287 | 10.52 | 12582 | 11.7 | 10718 | 12.05 |
| 21.1ºC | 25 | 11706 | 13.10 | 11975 | 13.54 | 10326 | 15.09 |
| | 10 | 10236 | 14.58 | 10554 | 15.15 | 8852 | 16.66 |
| | 5 | 9147 | 15.96 | 9457 | 16.53 | 7771 | 18.07 |
| | 1 | 6731 | 19.61 | 7020 | 20.12 | 5489 | 21.68 |
| | 0.5 | 5822 | 21.16 | 6099 | 21.51 | 4671 | 23.12 |
| | 0.1 | 3920 | 25.22 | 4150 | 25.20 | 3023 | 26.94 |
| 37.8ºC | 25 | 4874 | 25.22 | 5290 | 25.77 | 3927 | 27.48 |
| | 10 | 3836 | 27.23 | 4199 | 27.38 | 3030 | 29.44 |
| | 5 | 3116 | 28.78 | 3426 | 28.68 | 2410 | 30.79 |
| | 1 | 1804 | 31.83 | 2017 | 31.35 | 1335 | 33.56 |
| | 0.5 | 1408 | 32.39 | 1580 | 31.78 | 1020 | 34.03 |
| | 0.1 | 757.5 | 33.32 | 850.9 | 32.68 | 527.1 | 35.18 |

**Table C10. Section P Dynamic Modulus Data**

| **Section** | **P** | | **Mix Type** | **SM-9.5D** | | **RAP Content** | **21%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **P1** | | **P6** | | **P8** | |
| **Air Voids** | | **7.3%** | | **7.2%** | | **7.6%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 17325 | 6.65 | 19703 | 6.44 | 19760 | 5.98 |
| | 10 | 16256 | 7.52 | 18574 | 6.92 | 18668 | 6.40 |
| | 5 | 15358 | 8.13 | 17683 | 7.31 | 17788 | 6.76 |
| | 1 | 13179 | 9.78 | 15553 | 8.40 | 15725 | 7.80 |
| | 0.5 | 12210 | 10.66 | 14620 | 8.97 | 14806 | 8.38 |
| | 0.1 | 9984 | 13.10 | 12439 | 10.72 | 12693 | 9.94 |
| 21.1ºC | 25 | 9451 | 15.40 | 11384 | 13.18 | 11577 | 12.73 |
| | 10 | 8110 | 17.14 | 9992 | 14.63 | 10216 | 14.03 |
| | 5 | 7124 | 18.56 | 8949 | 15.92 | 9203 | 15.17 |
| | 1 | 5029 | 22.23 | 6680 | 19.52 | 6961 | 18.53 |
| | 0.5 | 4273 | 23.58 | 5816 | 21.09 | 6089 | 19.91 |
| | 0.1 | 2753 | 26.99 | 3995 | 25.27 | 4284 | 23.90 |
| 37.8ºC | 25 | 3619 | 28.46 | 4806 | 25.45 | 4898 | 24.63 |
| | 10 | 2793 | 29.79 | 3812 | 27.33 | 3895 | 26.51 |
| | 5 | 2222 | 30.88 | 3134 | 28.75 | 3211 | 27.95 |
| | 1 | 1237 | 32.65 | 1852 | 32.00 | 1917 | 31.15 |
| | 0.5 | 945.6 | 32.80 | 1445 | 32.70 | 1508 | 31.84 |
| | 0.1 | 491.5 | 32.44 | 747.4 | 34.19 | 795 | 33.26 |

**Table C11. Section R Dynamic Modulus Data**

| **Section** | **R** | | **Mix Type** | **SM-9.5D** | | **RAP Content** | **30%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **R4** | | **R6** | | **R9** | |
| **Air Voids** | | **7.0%** | | **9.3%** | | **8.3%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 19388 | 5.81 | 18250 | 5.50 | 17595 | 5.68 |
| | 10 | 18319 | 6.22 | 17380 | 5.74 | 16692 | 5.96 |
| | 5 | 17493 | 6.60 | 16685 | 6.02 | 15971 | 6.31 |
| | 1 | 15511 | 7.70 | 15024 | 6.78 | 14227 | 7.36 |
| | 0.5 | 14650 | 8.28 | 14292 | 7.22 | 13458 | 7.93 |
| | 0.1 | 12575 | 10.13 | 12557 | 8.56 | 11673 | 9.54 |
| 21.1ºC | 25 | 11509 | 12.67 | 10899 | 6.93 | 10031 | 10.06 |
| | 10 | 10154 | 14.03 | 10494 | 11.67 | 9874 | 13.04 |
| | 5 | 9139 | 15.34 | 9595 | 12.68 | 8950 | 14.27 |
| | 1 | 6873 | 19.10 | 7579 | 15.60 | 6873 | 17.59 |
| | 0.5 | 5987 | 20.78 | 6756 | 17.03 | 6068 | 19.09 |
| | 0.1 | 4114 | 25.38 | 4945 | 21.05 | 4326 | 23.15 |
| 37.8ºC | 25 | 4931 | 25.47 | 5544 | 21.46 | 4978 | 23.12 |
| | 10 | 3893 | 27.58 | 4545 | 23.66 | 4033 | 25.10 |
| | 5 | 3186 | 29.21 | 3831 | 25.38 | 3344 | 26.78 |
| | 1 | 1859 | 32.80 | 2428 | 29.50 | 2020 | 30.64 |
| | 0.5 | 1440 | 33.59 | 1962 | 30.69 | 1590 | 31.63 |
| | 0.1 | 732.9 | 35.01 | 1098 | 33.42 | 831.3 | 33.77 |

**Table C12. Section S Dynamic Modulus Data**

| **Section** | **S** | | **Mix Type** | **SM-9.5D** | | **RAP Content** | **30%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **S4** | | **S6** | | **S9** | |
| **Air Voids** | | **5.9%** | | **8.2%** | | **7.7%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 20122 | 6.04 | 17598 | 5.81 | - | - |
| | 10 | 19023 | 6.52 | 16677 | 6.24 | - | - |
| | 5 | 18144 | 6.91 | 15907 | 6.67 | - | - |
| | 1 | 16013 | 8.10 | 14044 | 7.91 | - | - |
| | 0.5 | 15071 | 8.75 | 13223 | 8.57 | - | - |
| | 0.1 | 12789 | 10.69 | 11258 | 10.45 | - | - |
| 21.1ºC | 25 | 11938 | 13.17 | 10574 | 12.73 | 11383 | 12.56 |
| | 10 | 10448 | 14.71 | 9337 | 14.20 | 10023 | 14.02 |
| | 5 | 9336 | 16.12 | 8395 | 15.57 | 8989 | 15.42 |
| | 1 | 6889 | 20.18 | 6260 | 19.26 | 6674 | 19.23 |
| | 0.5 | 5955 | 21.95 | 5429 | 20.90 | 5770 | 20.89 |
| | 0.1 | 3965 | 26.87 | 3669 | 25.22 | 3874 | 25.22 |
| 37.8ºC | 25 | 4916 | 26.79 | 4583 | 25.58 | 4893 | 25.47 |
| | 10 | 3820 | 29.02 | 3615 | 27.52 | 3836 | 27.58 |
| | 5 | 3071 | 30.70 | 2946 | 29.08 | 3103 | 29.14 |
| | 1 | 1710 | 33.98 | 1711 | 32.25 | 1778 | 32.01 |
| | 0.5 | 1295 | 34.55 | 1330 | 32.84 | 1375 | 32.55 |
| | 0.1 | 635.3 | 34.92 | 692.8 | 33.74 | 722.4 | 33.07 |

**Table C13. Section T Dynamic Modulus Data**

| Section | T | | Mix Type | SM-9.5A | | RAP Content | 10% |
|---|---|---|---|---|---|---|---|
| Specimen | | T3 | | T4 | | - | |
| Air Voids | | 6.9% | | 5.8% | | - | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 17498 | 8.14 | 19881 | 7.51 | - | - |
| | 10 | 16124 | 8.86 | 18467 | 8.18 | - | - |
| | 5 | 15038 | 9.54 | 17341 | 8.83 | - | - |
| | 1 | 12512 | 11.35 | 14701 | 10.59 | - | - |
| | 0.5 | 11441 | 12.27 | 13566 | 11.51 | - | - |
| | 0.1 | 9023 | 14.94 | 11079 | 14.00 | - | - |
| 21.1ºC | 25 | 8618 | 17.95 | 10375 | 16.45 | - | - |
| | 10 | 7227 | 19.83 | 8826 | 18.35 | - | - |
| | 5 | 6234 | 21.36 | 7695 | 19.94 | - | - |
| | 1 | 4212 | 25.43 | 5354 | 24.20 | - | - |
| | 0.5 | 3517 | 26.91 | 4542 | 25.77 | - | - |
| | 0.1 | 2172 | 30.66 | 2905 | 29.96 | - | - |
| 37.8ºC | 25 | 2922 | 32.41 | 3864 | 30.18 | - | - |
| | 10 | 2218 | 33.26 | 2953 | 31.67 | - | - |
| | 5 | 1738 | 34.08 | 2350 | 32.76 | - | - |
| | 1 | 932 | 35.37 | 1287 | 34.87 | - | - |
| | 0.5 | 703.3 | 35.23 | 980.5 | 34.89 | - | - |
| | 0.1 | 349.1 | 35.25 | 489.8 | 34.64 | - | - |

**Table C14. Section U Dynamic Modulus Data**

| Section | U | | Mix Type | SM-9.5D | | RAP Content | 25% |
|---|---|---|---|---|---|---|---|
| Specimen | | U1 | | U3 | | U7 | |
| Air Voids | | 6.1% | | 6.0% | | 7.2% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 15667 | 7.24 | 15276 | 8.44 | 13401 | 8.43 |
| | 10 | 14399 | 8.86 | 14074 | 9.27 | 12307 | 9.02 |
| | 5 | 13387 | 9.85 | 13118 | 9.99 | 11426 | 9.58 |
| | 1 | 10975 | 12.30 | 10863 | 12.09 | 9379 | 10.97 |
| | 0.5 | 9953 | 13.61 | 9895 | 13.10 | 8551 | 11.60 |
| | 0.1 | 7658 | 16.93 | 7738 | 16.04 | 6699 | 13.03 |
| 21.1ºC | 25 | 7647 | 19.82 | 7660 | 18.58 | 6820 | 15.82 |
| | 10 | 6357 | 22.05 | 6372 | 20.62 | 5758 | 17.18 |
| | 5 | 5422 | 23.83 | 5450 | 22.4 | 4983 | 18.36 |
| | 1 | 3504 | 28.47 | 3553 | 26.79 | 3382 | 20.86 |
| | 0.5 | 2862 | 29.89 | 2899 | 28.38 | 2837 | 22.04 |
| | 0.1 | 1640 | 33.37 | 1680 | 32.03 | 1778 | 24.46 |
| 37.8ºC | 25 | 2449 | 34.93 | 2267 | 33.12 | 2495 | 27.64 |
| | 10 | 1809 | 35.29 | 1667 | 34.46 | 1919 | 28.92 |
| | 5 | 1358 | 35.68 | 1270 | 35.47 | 1513 | 29.84 |
| | 1 | 672.8 | 35.08 | 637.9 | 35.59 | 835.4 | 31.56 |
| | 0.5 | 492.8 | 34.04 | 464.3 | 34.79 | 641.8 | 31.87 |
| | 0.1 | 250.7 | 31.46 | 231 | 32.33 | 343.0 | 32.70 |

**Table C15. Section V Dynamic Modulus Data**

| **Section** | **V** | | **Mix Type** | **SM-9.5D** | | **RAP Content** | **0%** |
|---|---|---|---|---|---|---|---|
| **Specimen** | | **V1** | | **V8** | | **V9** | |
| **Air Voids** | | **7.9%** | | **7.3%** | | **6.7%** | |
| **Temperature** | **Frequency, Hz** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** | **Dynamic Modulus, MPa** | **Phase Angle, º** |
| 4.4ºC | 25 | 21056 | 5.92 | 20836 | 5.70 | 20889 | 7.20 |
| | 10 | 19794 | 6.42 | 19641 | 6.21 | 19523 | 7.96 |
| | 5 | 18808 | 6.89 | 18669 | 6.73 | 18425 | 8.62 |
| | 1 | 16350 | 8.24 | 16262 | 8.15 | 15738 | 10.46 |
| | 0.5 | 15237 | 8.94 | 15170 | 8.87 | 14542 | 11.36 |
| | 0.1 | 12583 | 10.92 | 12585 | 10.80 | 11795 | 13.87 |
| 21.1ºC | 25 | 12143 | 12.94 | 11992 | 13.59 | 11518 | 15.29 |
| | 10 | 10568 | 14.41 | 10415 | 15.24 | 9869 | 17.21 |
| | 5 | 9376 | 15.64 | 9251 | 16.62 | 8632 | 18.68 |
| | 1 | 6756 | 18.83 | 6680 | 20.22 | 6018 | 22.53 |
| | 0.5 | 5793 | 20.18 | 5728 | 21.86 | 5087 | 24.08 |
| | 0.1 | 3811 | 23.62 | 3762 | 25.96 | 3223 | 27.93 |
| 37.8ºC | 25 | 4761 | 24.20 | 4702 | 26.34 | 4327 | 28.82 |
| | 10 | 3705 | 26.09 | 3641 | 28.40 | 3306 | 30.46 |
| | 5 | 2994 | 27.53 | 2924 | 30.00 | 2630 | 31.64 |
| | 1 | 1712 | 30.37 | 1646 | 33.10 | 1454 | 33.84 |
| | 0.5 | 1332 | 31.02 | 1266 | 33.78 | 1114 | 33.95 |
| | 0.1 | 706.5 | 32.45 | 659.2 | 34.87 | 585.4 | 33.84 |

**Table C16. Section W Dynamic Modulus Data**

| Section | W | | Mix Type | SM-12.5D | | RAP Content | 25% |
|---|---|---|---|---|---|---|---|
| Specimen | | W5 | | W6 | | W7 | |
| Air Voids | | 5.4% | | 3.8% | | 3.8% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 19768 | 7.11 | 20842 | 8.84 | 22558 | 7.46 |
| | 10 | 18407 | 7.69 | 19079 | 9.92 | 20994 | 8.32 |
| | 5 | 17298 | 8.26 | 17659 | 10.85 | 19716 | 9.06 |
| | 1 | 14597 | 9.82 | 14334 | 13.50 | 16582 | 11.34 |
| | 0.5 | 13406 | 10.57 | 12922 | 14.80 | 15230 | 12.47 |
| | 0.1 | 10646 | 12.62 | 9737 | 18.39 | 12062 | 15.62 |
| 21.1ºC | 25 | 10384 | 12.39 | 10210 | 19.9 | 12296 | 16.93 |
| | 10 | 8800 | 13.83 | 8377 | 22.25 | 10427 | 19.16 |
| | 5 | 7649 | 14.96 | 7090 | 24.12 | 9051 | 21.00 |
| | 1 | 5180 | 17.58 | 4474 | 28.94 | 6121 | 25.8 |
| | 0.5 | 4339 | 18.87 | 3615 | 30.44 | 5089 | 27.54 |
| | 0.1 | 2682 | 22.46 | 2025 | 33.77 | 3056 | 31.8 |
| 37.8ºC | 25 | 3864 | 24.15 | 3166 | 35.12 | 4355 | 32.32 |
| | 10 | 2964 | 26.28 | 2294 | 35.83 | 3267 | 33.90 |
| | 5 | 2349 | 28.02 | 1738 | 36.17 | 2538 | 34.83 |
| | 1 | 1324 | 31.26 | 870.8 | 35.77 | 1312 | 36.06 |
| | 0.5 | 1027 | 32.13 | 639.4 | 34.81 | 964.4 | 35.64 |
| | 0.1 | 554.4 | 34.15 | 315.5 | 32.67 | 464.1 | 34.11 |

**Table C17. Section X Dynamic Modulus Data**

| Section | X | | Mix Type | SM-12.5D | | RAP Content | 25% |
|---|---|---|---|---|---|---|---|
| Specimen | | X2 | | X5 | | X7 | |
| Air Voids | | 5.2% | | 5.4% | | 5.1% | |
| Temperature | Frequency, Hz | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º | Dynamic Modulus, MPa | Phase Angle, º |
| 4.4ºC | 25 | 21052 | 6.26 | 22666 | 4.78 | 19919 | 3.15 |
| | 10 | 19815 | 6.79 | 21727 | 5.08 | 18302 | 7.33 |
| | 5 | 18821 | 7.31 | 20943 | 5.46 | 17363 | 7.93 |
| | 1 | 16419 | 8.84 | 18938 | 6.53 | 15045 | 9.67 |
| | 0.5 | 15363 | 9.56 | 18014 | 7.05 | 14029 | 10.55 |
| | 0.1 | 12867 | 11.62 | 15788 | 8.51 | 11677 | 12.95 |
| 21.1ºC | 25 | 12181 | 13.63 | 14945 | 10.41 | 11519 | 15.03 |
| | 10 | 10683 | 15.22 | 13477 | 11.53 | 10035 | 16.75 |
| | 5 | 9551 | 16.49 | 12330 | 12.55 | 8913 | 18.17 |
| | 1 | 7063 | 19.92 | 9687 | 15.30 | 6453 | 21.97 |
| | 0.5 | 6129 | 21.26 | 8606 | 16.56 | 5568 | 23.38 |
| | 0.1 | 4182 | 24.94 | 6291 | 19.85 | 3693 | 27.12 |
| 37.8ºC | 25 | 5497 | 26.05 | 7209 | 20.42 | 4868 | 27.37 |
| | 10 | 4418 | 27.61 | 5898 | 22.2 | 3816 | 28.97 |
| | 5 | 3623 | 29.00 | 4963 | 23.65 | 3085 | 30.19 |
| | 1 | 2157 | 32.09 | 3154 | 27.01 | 1748 | 32.56 |
| | 0.5 | 1702 | 32.56 | 2541 | 28.10 | 1349 | 32.79 |
| | 0.1 | 936.6 | 33.39 | 1465 | 30.63 | 704.6 | 32.95 |

# APPENDIX D

# DYNAMIC MODULUS STATISTICAL ANALYSIS

**Table D1. *t*-test Comparisons of Mixtures at 4.4°C (40°F) and 0.1 Hz (lower left half of table) and 0.5 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | **0.0440** | 0.4320 | **0.0438** | 0.0811 | **0.0090** | **0.0040** | **0.0207** | **0.0177** | **0.0336** | 0.3709 | 0.0793 | **0.0098** | **0.0026** | **0.0006** | **0.0058** | **0.0153** | 0.1139 | 0.3357 |
| V (0%) | **0.0300** | | 0.8388 | 0.1744 | 0.2463 | **0.0500** | **0.0228** | 0.2445 | 0.2805 | 0.3163 | 0.1175 | 0.2108 | 0.0910 | **0.0165** | **0.0020** | **0.0003** | 0.1243 | 0.5279 | 0.5588 |
| K (10%) | 0.3898 | 0.8012 | | 0.2630 | 0.2768 | 0.3455 | 0.1864 | 0.5049 | 0.5867 | 0.5162 | 0.6472 | 0.2300 | 0.3214 | 0.2138 | 0.0817 | 0.1740 | 0.5701 | 0.5926 | 0.8761 |
| L (10%) | **0.0336** | 0.2397 | 0.3719 | | 0.9386 | 0.6325 | 0.6601 | 0.3812 | 0.2923 | 0.3867 | 0.0671 | 0.7802 | 0.7248 | 0.8366 | 0.1409 | 0.5661 | 0.2997 | 0.3412 | 0.1193 |
| T (10%) | 0.0742 | 0.2546 | 0.2843 | 0.7201 | | 0.6788 | 0.5840 | 0.4062 | 0.3277 | 0.4077 | 0.1067 | 0.7273 | 0.7725 | 0.7486 | 0.1724 | 0.5118 | 0.3498 | 0.3654 | 0.1340 |
| M (20%) | **0.0097** | 0.0838 | 0.3910 | 0.8761 | 0.5887 | | 0.1074 | 0.4077 | 0.1923 | 0.4569 | **0.0174** | 0.5246 | 0.8510 | 0.1871 | **0.0080** | 0.0771 | 0.1332 | 0.4465 | 0.1386 |
| N (20%) | **0.0050** | **0.0177** | 0.2374 | 0.4905 | 0.8222 | 0.1665 | | 0.0776 | **0.0328** | 0.1082 | **0.0068** | 0.9994 | 0.2270 | 0.6095 | **0.0322** | 0.6718 | **0.0230** | 0.1961 | 0.0626 |
| W (20%) | **0.0105** | 0.1438 | 0.3934 | 0.8900 | 0.6016 | 0.9943 | 0.2595 | | 0.7328 | 0.9822 | **0.0485** | 0.3606 | 0.4079 | 0.1129 | **0.0096** | 0.0696 | 0.7452 | 0.8222 | 0.2415 |
| O (21%) | **0.0201** | 0.5261 | 0.6541 | 0.3718 | 0.2890 | 0.2291 | 0.0527 | 0.3060 | | 0.7801 | **0.0483** | 0.3034 | 0.2406 | **0.0468** | **0.0031** | **0.0291** | 0.9463 | 0.9783 | 0.3034 |
| P (21%) | **0.0438** | 0.5560 | 0.6171 | 0.4711 | 0.3277 | 0.4257 | 0.1425 | 0.4650 | 0.8883 | | 0.0720 | 0.3598 | 0.4369 | 0.1499 | **0.0177** | 0.0972 | 0.7992 | 0.8460 | 0.2592 |
| B (25%) | 0.3748 | **0.0148** | 0.5451 | 0.0610 | 0.1233 | **0.0116** | **0.0032** | **0.0206** | **0.0341** | 0.0843 | | 0.1083 | **0.0200** | **0.0052** | **0.0010** | **0.0090** | **0.0385** | 0.1802 | 0.6489 |
| C (25%) | 0.0834 | 0.2681 | 0.2825 | 0.6682 | 0.8659 | 0.5831 | 0.9698 | 0.5929 | 0.3381 | 0.3765 | 0.1160 | | 0.5786 | 0.8659 | 0.3447 | 0.9200 | 0.3108 | 0.3212 | 0.1424 |
| D (25%) | **0.0092** | 0.1092 | 0.3356 | 0.9174 | 0.7583 | 0.7104 | 0.4187 | 0.7580 | 0.2108 | 0.3404 | **0.0188** | 0.6986 | | 0.3773 | **0.0206** | 0.1738 | 0.2289 | 0.3989 | 0.1187 |
| J (25%) | **0.0031** | **0.0219** | 0.2604 | 0.6059 | 0.9531 | 0.2600 | 0.7294 | 0.3732 | 0.0680 | 0.1741 | **0.0028** | 0.8840 | 0.5805 | | **0.0197** | 0.3867 | **0.0333** | 0.2140 | 0.0682 |
| U (25%) | **0.0011** | **0.0004** | 0.0952 | 0.0754 | 0.2065 | **0.0120** | **0.0174** | **0.0208** | **0.0054** | **0.0254** | **0.0001** | 0.3156 | **0.0308** | **0.0146** | | **0.0335** | **0.0017** | 0.0746 | **0.0211** |
| B-IM (30%) | **0.0028** | **0.0008** | 0.1624 | 0.2191 | 0.4379 | **0.0475** | 0.1409 | 0.0835 | 0.0196 | 0.0680 | **0.0004** | 0.6789 | 0.1307 | 0.1277 | 0.0294 | | **0.0068** | 0.2014 | 0.0631 |
| R (30%) | **0.0266** | 0.9010 | 0.7830 | 0.2499 | 0.2566 | **0.0840** | 0.0162 | 0.1524 | 0.5770 | 0.5898 | 0.0142 | 0.2748 | 0.1137 | 0.0220 | 0.0004 | **0.0011** | | 0.9908 | 0.2880 |
| S (30%) | **0.0880** | 0.7660 | 0.7110 | 0.3583 | 0.2734 | 0.3345 | 0.1693 | 0.3396 | 0.8813 | 0.8015 | 0.1669 | 0.3168 | 0.2544 | 0.1649 | 0.0644 | 0.1162 | 0.8060 | | 0.3490 |
| X (30%) | 0.3585 | **0.4566** | 0.8099 | 0.1555 | 0.1262 | **0.1570** | **0.0863** | 0.1526 | 0.3302 | 0.3163 | 0.5932 | 0.1604 | 0.1217 | 0.0897 | 0.0308 | 0.0570 | 0.4393 | 0.3978 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D2. *t*-test Comparisons of Mixtures at 4.4ºC (40ºF) and 1.0 Hz (lower left half of table) and 5.0 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0641 | 0.4878 | 0.0572 | 0.1133 | 0.0076 | 0.0027 | 0.0689 | 0.0126 | 0.0238 | 0.4918 | 0.0709 | 0.0118 | 0.0021 | 0.0007 | 0.0094 | 0.0060 | 0.1422 | 0.2754 |
| V (0%) | 0.0506 | | 0.8384 | 0.1369 | 0.2777 | 0.0537 | 0.0384 | 0.6424 | 0.1170 | 0.1643 | 0.4866 | 0.1586 | 0.0874 | 0.0202 | 0.0086 | 0.0000 | 0.0416 | 0.3849 | 0.7330 |
| K (10%) | 0.4490 | 0.8463 | | 0.1478 | 0.2752 | 0.2754 | 0.1246 | 0.7041 | 0.4774 | 0.3708 | 0.8123 | 0.1612 | 0.2738 | 0.1522 | 0.0591 | 0.1848 | 0.3252 | 0.4120 | 0.9959 |
| L (10%) | 0.0487 | 0.1591 | 0.2205 | | 0.5015 | 0.4087 | 0.9429 | 0.1504 | 0.2253 | 0.3037 | 0.0772 | 0.9995 | 0.4199 | 0.8172 | 0.3491 | 0.6776 | 0.3378 | 0.3203 | 0.1002 |
| T (10%) | 0.0898 | 0.2536 | 0.2759 | 0.7788 | | 0.9018 | 0.3701 | 0.2855 | 0.4534 | 0.6450 | 0.1379 | 0.5272 | 0.9117 | 0.5109 | 0.1440 | 0.6370 | 0.7291 | 0.6545 | 0.1825 |
| M (20%) | 0.0088 | 0.0465 | 0.3271 | 0.5391 | 0.7315 | | 0.0619 | 0.1215 | 0.1353 | 0.5558 | 0.0982 | 0.4448 | 0.9933 | 0.1415 | 0.0151 | 0.1704 | 0.5602 | 0.6622 | 0.1153 |
| N (20%) | 0.0036 | 0.0267 | 0.1652 | 0.7480 | 0.4992 | 0.0876 | | 0.0258 | 0.0151 | 0.0783 | 0.0380 | 0.9471 | 0.1176 | 0.4425 | 0.0800 | 0.2165 | 0.0319 | 0.2442 | 0.0384 |
| W (20%) | 0.0279 | 0.3129 | 0.5564 | 0.2732 | 0.3613 | 0.2733 | 0.0502 | | 0.4497 | 0.3065 | 0.3793 | 0.1775 | 0.1516 | 0.0328 | 0.0051 | 0.0642 | 0.1759 | 0.4713 | 0.5617 |
| O (21%) | 0.0164 | 0.2160 | 0.5563 | 0.2655 | 0.3591 | 0.1802 | 0.0261 | 0.9848 | | 0.6014 | 0.1953 | 0.2571 | 0.2811 | 0.0312 | 0.0042 | 0.0416 | 0.2980 | 0.7618 | 0.2681 |
| P (21%) | 0.0299 | 0.2519 | 0.4727 | 0.3535 | 0.4649 | 0.4848 | 0.0951 | 0.7623 | 0.7275 | | 0.1375 | 0.3382 | 0.6200 | 0.1383 | 0.0146 | 0.1992 | 0.8182 | 0.9575 | 0.1885 |
| B (25%) | 0.4015 | 0.2204 | 0.6959 | 0.0697 | 0.1055 | 0.0346 | 0.0127 | 0.0953 | 0.0797 | 0.0801 | | 0.0942 | 0.0871 | 0.0409 | 0.0121 | 0.0674 | 0.1143 | 0.2152 | 0.7349 |
| C (25%) | 0.0767 | 0.1913 | 0.2076 | 0.8462 | 0.6636 | 0.4945 | 0.9818 | 0.2908 | 0.2872 | 0.3510 | 0.1024 | | 0.4548 | 0.8326 | 0.3844 | 0.7040 | 0.3737 | 0.3480 | 0.1210 |
| D (25%) | 0.0102 | 0.0873 | 0.3091 | 0.6032 | 0.8073 | 0.8832 | 0.1783 | 0.3007 | 0.2501 | 0.4819 | 0.0296 | 0.5362 | | 0.2477 | 0.0188 | 0.3404 | 0.7052 | 0.6723 | 0.1107 |
| J (25%) | 0.0024 | 0.0172 | 0.1941 | 0.9539 | 0.6652 | 0.1639 | 0.5489 | 0.0720 | 0.0406 | 0.1422 | 0.0110 | 0.8564 | 0.3246 | | 0.0413 | 0.5949 | 0.0877 | 0.3011 | 0.0432 |
| U (25%) | 0.0005 | 0.0038 | 0.0749 | 0.1909 | 0.1625 | 0.0092 | 0.0436 | 0.0072 | 0.0029 | 0.0155 | 0.0025 | 0.3563 | 0.0189 | 0.0252 | | 0.0416 | 0.0075 | 0.1005 | 0.0107 |
| B-IM (30%) | 0.0080 | 0.0003 | 0.1784 | 0.8118 | 0.5512 | 0.1076 | 0.7630 | 0.0682 | 0.0360 | 0.1179 | 0.0219 | 0.9624 | 0.2098 | 0.6435 | 0.0410 | | 0.0962 | 0.3919 | 0.0733 |
| R (30%) | 0.0115 | 0.0659 | 0.4859 | 0.3149 | 0.4295 | 0.2007 | 0.0250 | 0.7752 | 0.7029 | 0.9179 | 0.0607 | 0.3278 | 0.3255 | 0.0437 | 0.0029 | 0.0184 | | 0.8313 | 0.1417 |
| S (30%) | 0.1221 | 0.4638 | 0.5346 | 0.3341 | 0.4370 | 0.5126 | 0.2084 | 0.9171 | 0.9019 | 0.8834 | 0.1841 | 0.3272 | 0.4754 | 0.2375 | 0.0798 | 0.2480 | 0.9320 | | 0.2933 |
| X (30%) | 0.3201 | 0.6112 | 0.9113 | 0.1103 | 0.1452 | 0.1333 | 0.0541 | 0.3035 | 0.2949 | 0.2380 | 0.6748 | 0.1352 | 0.1166 | 0.0600 | 0.0174 | 0.0670 | 0.2358 | 0.3272 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D3. *t*-Test Comparisons of Mixtures at 4.4°c (40°F) and 10.0 Hz (lower left half of table) and 25.0 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0743 | 0.5462 | 0.0674 | 0.1467 | 0.0061 | 0.0019 | 0.1914 | 0.0096 | 0.0245 | 0.8484 | 0.0724 | 0.0161 | 0.0025 | 0.0013 | 0.0791 | 0.0044 | 0.1694 | 0.2227 |
| V (0%) | 0.0696 | | 0.8171 | 0.1246 | 0.3107 | 0.0664 | 0.0370 | 0.8886 | 0.0669 | 0.1295 | 0.5222 | 0.1446 | 0.0903 | 0.0231 | 0.0121 | 0.1373 | 0.0388 | 0.3483 | 0.7550 |
| K (10%) | 0.5085 | 0.8284 | | 0.1052 | 0.2864 | 0.2292 | 0.0942 | 0.8771 | 0.3974 | 0.2884 | 0.6221 | 0.1349 | 0.2358 | 0.1161 | 0.0450 | 0.1124 | 0.2174 | 0.3205 | 0.9371 |
| L (10%) | 0.0612 | 0.1309 | 0.1257 | | 0.3192 | 0.3228 | 0.8543 | 0.1042 | 0.2018 | 0.2638 | 0.1268 | 0.7783 | 0.3132 | 0.6246 | 0.6103 | 0.9294 | 0.3346 | 0.3007 | 0.0983 |
| T (10%) | 0.1262 | 0.2925 | 0.2791 | 0.4095 | | 0.8947 | 0.2876 | 0.2465 | 0.5972 | 0.8834 | 0.2721 | 0.4361 | 0.9389 | 0.3879 | 0.1258 | 0.3170 | 0.8575 | 0.9307 | 0.2267 |
| M (20%) | 0.0073 | 0.0580 | 0.2552 | 0.3657 | 0.9884 | | 0.0409 | 0.0748 | 0.1176 | 0.6491 | 0.2575 | 0.4367 | 0.9327 | 0.1410 | 0.0224 | 0.3266 | 0.9056 | 0.8189 | 0.0633 |
| N (20%) | 0.0024 | 0.0412 | 0.1105 | 0.9645 | 0.3305 | 0.0514 | | 0.0191 | 0.0085 | 0.0730 | 0.1517 | 0.8497 | 0.0910 | 0.3710 | 0.1397 | 0.7845 | 0.0465 | 0.2853 | 0.0167 |
| W (20%) | 0.1068 | 0.8565 | 0.7797 | 0.1246 | 0.2654 | 0.0951 | 0.0216 | | 0.1985 | 0.1360 | 0.5470 | 0.1229 | 0.0900 | 0.0204 | 0.0046 | 0.1191 | 0.0620 | 0.2909 | 0.8974 |
| O (21%) | 0.0114 | 0.0922 | 0.4442 | 0.2127 | 0.5078 | 0.1172 | 0.0117 | 0.3051 | | 0.5339 | 0.3476 | 0.2554 | 0.3335 | 0.0349 | 0.0084 | 0.2145 | 0.1593 | 0.6791 | 0.1618 |
| P (21%) | 0.0230 | 0.1461 | 0.3337 | 0.2837 | 0.7417 | 0.5900 | 0.0741 | 0.2076 | 0.5620 | | 0.2891 | 0.3552 | 0.7597 | 0.1493 | 0.0182 | 0.2720 | 0.6216 | 0.9676 | 0.1137 |
| B (25%) | 0.5282 | 0.5906 | 0.8650 | 0.0822 | 0.1725 | 0.1322 | 0.0523 | 0.5580 | 0.2511 | 0.1741 | | 0.1572 | 0.2605 | 0.1773 | 0.1025 | 0.1212 | 0.2508 | 0.2872 | 0.5730 |
| C (25%) | 0.0690 | 0.1482 | 0.1448 | 0.9172 | 0.4733 | 0.4269 | 0.9264 | 0.1451 | 0.2469 | 0.3333 | 0.0960 | | 0.4288 | 0.8707 | 0.3867 | 0.7238 | 0.4575 | 0.4086 | 0.1147 |
| D (25%) | 0.0131 | 0.0892 | 0.2586 | 0.3639 | 0.9697 | 0.9648 | 0.1020 | 0.1175 | 0.2998 | 0.6827 | 0.1253 | 0.4266 | | 0.2135 | 0.0222 | 0.3170 | 0.8769 | 0.8627 | 0.0751 |
| J (25%) | 0.0021 | 0.0216 | 0.1361 | 0.7255 | 0.4539 | 0.1361 | 0.4057 | 0.0256 | 0.0304 | 0.1394 | 0.0593 | 0.8281 | 0.2253 | | 0.0672 | 0.5882 | 0.1801 | 0.3730 | 0.0171 |
| U (25%) | 0.0008 | 0.0105 | 0.0527 | 0.4502 | 0.1364 | 0.0185 | 0.1012 | 0.0047 | 0.0056 | 0.0154 | 0.0193 | 0.3931 | 0.0196 | 0.0504 | | 0.7201 | 0.0166 | 0.1322 | 0.0039 |
| B-IM (30%) | 0.0076 | 0.0004 | 0.1857 | 0.5300 | 0.6582 | 0.1817 | 0.1287 | 0.0600 | 0.0369 | 0.2560 | 0.0960 | 0.6159 | 0.4168 | 0.4027 | 0.0379 | | 0.3370 | 0.2991 | 0.1131 |
| R (30%) | 0.0049 | 0.0402 | 0.2723 | 0.3395 | 0.9113 | 0.8065 | 0.0367 | 0.1031 | 0.2076 | 0.7129 | 0.1367 | 0.3971 | 0.9093 | 0.1204 | 0.0107 | 0.2012 | | 0.7860 | 0.0509 |
| S (30%) | 0.1517 | 0.3663 | 0.3685 | 0.3106 | 0.7698 | 0.7290 | 0.2606 | 0.3692 | 0.7171 | 0.9914 | 0.2361 | 0.3605 | 0.7589 | 0.3297 | 0.1118 | 0.4776 | 0.8008 | | 0.2681 |
| X (30%) | 0.2561 | 0.7941 | 0.9492 | 0.0999 | 0.2073 | 0.1089 | 0.0333 | 0.7371 | 0.2584 | 0.1738 | 0.7606 | 0.1168 | 0.1100 | 0.0371 | 0.0088 | 0.0744 | 0.1128 | 0.2883 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D4. *t*-test Comparisons of Mixtures at 21.1°C (70°F) and 0.1 Hz (lower left half of table) and 0.5 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0344 | 0.2887 | 0.0341 | 0.0217 | 0.0251 | 0.0128 | 0.0076 | 0.0347 | 0.0431 | 0.8108 | 0.0781 | 0.0094 | 0.0126 | 0.0103 | 0.0039 | 0.0942 | 0.0499 | 0.4908 |
| V (0%) | 0.0388 | | 0.7508 | 0.8692 | 0.1655 | 0.4215 | 0.0419 | 0.0891 | 0.9920 | 0.8310 | 0.1181 | 0.4113 | 0.1285 | 0.0293 | 0.0068 | 0.0033 | 0.0919 | 0.5458 | 0.3166 |
| K (10%) | 0.2637 | 0.7256 | | 0.7962 | 0.2326 | 0.5466 | 0.3067 | 0.2935 | 0.7547 | 0.6893 | 0.3668 | 0.3879 | 0.3436 | 0.3303 | 0.1139 | 0.1381 | 0.8113 | 0.8550 | 0.6127 |
| L (10%) | 0.0627 | 0.3537 | 0.9938 | | 0.1288 | 0.3988 | 0.0639 | 0.0871 | 0.8942 | 0.7633 | 0.1219 | 0.3879 | 0.1275 | 0.0684 | 0.0162 | 0.0078 | 0.2096 | 0.8013 | 0.3430 |
| T (10%) | 0.0171 | 0.1592 | 0.2500 | 0.0848 | | 0.2370 | 0.5968 | 0.6744 | 0.1360 | 0.1777 | 0.0332 | 0.7431 | 0.5119 | 0.5195 | 0.2638 | 0.3555 | 0.0945 | 0.1634 | 0.0862 |
| M (20%) | 0.0304 | 0.5590 | 0.5840 | 0.2328 | 0.2175 | | 0.2415 | 0.2534 | 0.5128 | 0.7075 | 0.0765 | 0.5981 | 0.3676 | 0.2774 | 0.0950 | 0.0439 | 0.1102 | 0.2981 | 0.2144 |
| N (20%) | 0.0223 | 0.0536 | 0.3544 | 0.0471 | 0.5000 | 0.2871 | | 0.9125 | 0.1116 | 0.2182 | 0.0465 | 0.9683 | 0.7926 | 0.7766 | 0.0869 | 0.0481 | 0.0121 | 0.0379 | 0.1208 |
| W (20%) | 0.0083 | 0.0573 | 0.2593 | 0.0290 | 0.9259 | 0.1471 | 0.4230 | | 0.1246 | 0.2190 | 0.0332 | 0.9327 | 0.7619 | 0.7696 | 0.0732 | 0.1146 | 0.0264 | 0.0706 | 0.1058 |
| O (21%) | 0.0427 | 0.8164 | 0.8025 | 0.5928 | 0.1199 | 0.5098 | 0.1351 | 0.0732 | | 0.8569 | 0.1118 | 0.4206 | 0.1797 | 0.1276 | 0.0257 | 0.0179 | 0.2323 | 0.7183 | 0.3206 |
| P (21%) | 0.0599 | 0.8876 | 0.7956 | 0.6436 | 0.1527 | 0.6148 | 0.2347 | 0.1348 | 0.9739 | | 0.1032 | 0.4867 | 0.2998 | 0.2512 | 0.0465 | 0.0468 | 0.2581 | 0.6281 | 0.2895 |
| B (25%) | 0.9066 | 0.1631 | 0.3466 | 0.2359 | 0.0582 | 0.1283 | 0.0906 | 0.0605 | 0.1758 | 0.1765 | | 0.0929 | 0.0397 | 0.0492 | 0.0251 | 0.0202 | 0.2681 | 0.1467 | 0.6418 |
| C (25%) | 0.0753 | 0.5376 | 0.4721 | 0.3524 | 0.6093 | 0.7032 | 0.8816 | 0.6359 | 0.4879 | 0.5176 | 0.1135 | | 0.9425 | 0.9681 | 0.2697 | 0.3821 | 0.2214 | 0.3509 | 0.1756 |
| D (25%) | 0.0118 | 0.1362 | 0.3500 | 0.0626 | 0.5434 | 0.3139 | 0.9614 | 0.5398 | 0.1540 | 0.2402 | 0.0770 | 0.8708 | | 0.9356 | 0.0580 | 0.0772 | 0.0347 | 0.0953 | 0.1251 |
| J (25%) | 0.0200 | 0.0681 | 0.3832 | 0.0493 | 0.4292 | 0.3358 | 0.7364 | 0.3406 | 0.1578 | 0.2697 | 0.0938 | 0.9512 | 0.8066 | | 0.0163 | 0.0256 | 0.0058 | 0.0126 | 0.1295 |
| U (25%) | 0.0128 | 0.0075 | 0.1262 | 0.0131 | 0.2587 | 0.0921 | 0.0460 | 0.0958 | 0.0269 | 0.0510 | 0.0441 | 0.2254 | 0.0617 | 0.0124 | | 0.2577 | 0.0049 | 0.0026 | 0.0527 |
| B-IM (30%) | 0.0059 | 0.0033 | 0.1342 | 0.0046 | 0.2646 | 0.0370 | 0.0225 | 0.1192 | 0.0157 | 0.0432 | 0.0404 | 0.2588 | 0.0596 | 0.0138 | 0.5625 | | 0.0012 | 0.0033 | 0.0555 |
| R (30%) | 0.1691 | 0.0550 | 0.6372 | 0.2444 | 0.0523 | 0.0697 | 0.0136 | 0.0095 | 0.1533 | 0.2354 | 0.4317 | 0.1951 | 0.0185 | 0.0109 | 0.0068 | 0.0015 | | 0.1412 | 0.6520 |
| S (30%) | 0.0667 | 0.3407 | 0.9006 | 0.7159 | 0.1591 | 0.3078 | 0.0267 | 0.0445 | 0.7303 | 0.7695 | 0.2121 | 0.4025 | 0.0834 | 0.0185 | 0.0003 | 0.0043 | 0.1166 | | 0.3776 |
| X (30%) | 0.5472 | 0.2922 | 0.5603 | 0.4426 | 0.0982 | 0.2288 | 0.1462 | 0.1018 | 0.3309 | 0.3355 | 0.6760 | 0.2005 | 0.1341 | 0.1547 | 0.0627 | 0.0608 | 0.7804 | 0.3820 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D5. *t*-test Comparisons of Mixtures at 21.1ºC (70ºF) and 1.0 Hz (lower left half of table) and 5.0 Hz (upper right half of table).**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0325 | 0.3315 | 0.0179 | 0.0396 | 0.0212 | 0.0066 | 0.0123 | 0.0251 | 0.0272 | 0.5749 | 0.0813 | 0.0079 | 0.0051 | 0.0043 | 0.0027 | 0.0413 | 0.0242 | 0.4275 |
| V (0%) | 0.0331 | | 0.7800 | 0.3215 | 0.1854 | 0.2654 | 0.0476 | 0.1760 | 0.6420 | 0.4240 | 0.0459 | 0.2890 | 0.1016 | 0.0109 | 0.0004 | 0.0024 | 0.6614 | 0.6432 | 0.3783 |
| K (10%) | 0.3005 | 0.7562 | | 0.4937 | 0.2097 | 0.4607 | 0.2265 | 0.3781 | 0.6589 | 0.5286 | 0.4400 | 0.2835 | 0.3106 | 0.2485 | 0.0931 | 0.1472 | 0.8465 | 0.7002 | 0.7030 |
| L (10%) | 0.0259 | 0.8089 | 0.6989 | | 0.2676 | 0.9084 | 0.1729 | 0.6473 | 0.5860 | 0.9216 | 0.0278 | 0.4745 | 0.4290 | 0.2034 | 0.0272 | 0.0545 | 0.2555 | 0.4370 | 0.2019 |
| T (10%) | 0.0241 | 0.1668 | 0.2249 | 0.1521 | | 0.2976 | 0.8611 | 0.4006 | 0.1778 | 0.2521 | 0.0510 | 0.9568 | 0.5335 | 0.7401 | 0.2500 | 0.5503 | 0.1798 | 0.1956 | 0.0817 |
| M (20%) | 0.0238 | 0.3797 | 0.5284 | 0.5420 | 0.2427 | | 0.1931 | 0.6970 | 0.4810 | 0.8326 | 0.0301 | 0.4986 | 0.4522 | 0.2179 | 0.0676 | 0.0747 | 0.2300 | 0.3420 | 0.1874 |
| N (20%) | 0.0103 | 0.0417 | 0.2858 | 0.0883 | 0.6443 | 0.2258 | | 0.3266 | 0.0766 | 0.1848 | 0.0080 | 0.9641 | 0.4913 | 0.7678 | 0.0773 | 0.2101 | 0.0519 | 0.0483 | 0.0853 |
| W (20%) | 0.0081 | 0.1069 | 0.3114 | 0.1571 | 0.5803 | 0.3245 | 0.8455 | | 0.3322 | 0.6027 | 0.0183 | 0.6154 | 0.7334 | 0.3989 | 0.0382 | 0.0956 | 0.1460 | 0.2318 | 0.1432 |
| O (21%) | 0.0314 | 0.9007 | 0.7273 | 0.9362 | 0.1421 | 0.5188 | 0.1022 | 0.1596 | | 0.6846 | 0.0409 | 0.3494 | 0.2000 | 0.0811 | 0.0152 | 0.0235 | 0.4967 | 0.8569 | 0.2992 |
| P (21%) | 0.0379 | 0.7171 | 0.6454 | 0.8618 | 0.1891 | 0.7491 | 0.2106 | 0.2810 | 0.8165 | | 0.0425 | 0.4511 | 0.4094 | 0.2179 | 0.0352 | 0.0689 | 0.3451 | 0.5517 | 0.2243 |
| B (25%) | 0.7502 | 0.0976 | 0.3849 | 0.0791 | 0.0290 | 0.0578 | 0.0310 | 0.0246 | 0.0862 | 0.0792 | | 0.1015 | 0.0113 | 0.0056 | 0.0042 | 0.0028 | 0.0590 | 0.0339 | 0.6191 |
| C (25%) | 0.0791 | 0.3719 | 0.3558 | 0.4140 | 0.7997 | 0.5608 | 0.9976 | 0.9361 | 0.3990 | 0.4740 | 0.0924 | | 0.7329 | 0.8897 | 0.3384 | 0.6709 | 0.2657 | 0.3227 | 0.1502 |
| D (25%) | 0.0087 | 0.1194 | 0.3349 | 0.1822 | 0.5082 | 0.3785 | 0.7135 | 0.8888 | 0.1846 | 0.3220 | 0.0271 | 0.8795 | | 0.6092 | 0.0413 | 0.1270 | 0.0870 | 0.1305 | 0.1127 |
| J (25%) | 0.0100 | 0.0210 | 0.3073 | 0.0960 | 0.5622 | 0.2556 | 0.7909 | 0.9830 | 0.1144 | 0.2416 | 0.0332 | 0.9410 | 0.8446 | | 0.0104 | 0.0936 | 0.0091 | 0.0171 | 0.0949 |
| U (25%) | 0.0088 | 0.0045 | 0.1089 | 0.0187 | 0.2607 | 0.0903 | 0.0864 | 0.0634 | 0.0236 | 0.0441 | 0.0185 | 0.2906 | 0.0542 | 0.0148 | | 0.0508 | 0.0001 | 0.0012 | 0.0392 |
| B-IM (30%) | 0.0035 | 0.0030 | 0.1417 | 0.0134 | 0.4061 | 0.0508 | 0.0700 | 0.1127 | 0.0194 | 0.0515 | 0.0138 | 0.4541 | 0.0888 | 0.0340 | 0.1712 | | 0.0024 | 0.0033 | 0.0556 |
| R (30%) | 0.0734 | 0.1336 | 0.9007 | 0.2083 | 0.1132 | 0.1386 | 0.0172 | 0.0419 | 0.2792 | 0.2777 | 0.1992 | 0.2332 | 0.0441 | 0.0052 | 0.0030 | 0.0013 | | 0.3976 | 0.4280 |
| S (30%) | 0.0424 | 0.7024 | 0.8203 | 0.6248 | 0.1658 | 0.3076 | 0.0415 | 0.0909 | 0.7294 | 0.5954 | 0.1147 | 0.3382 | 0.0993 | 0.0125 | 0.0020 | 0.0029 | 0.1735 | | 0.3239 |
| X (30%) | 0.4695 | 0.3342 | 0.6416 | 0.3007 | 0.0846 | 0.2130 | 0.1132 | 0.1138 | 0.3191 | 0.2765 | 0.6320 | 0.1692 | 0.1237 | 0.1219 | 0.0500 | 0.0565 | 0.5962 | 0.3739 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D6. *t*-test Comparisons of Mixtures at 21.1ºC (70ºF) and 10.0 Hz (lower left half of table) and 25.0 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0362 | 0.3457 | 0.0231 | 0.0627 | 0.0232 | 0.0058 | 0.0233 | 0.0188 | 0.0209 | 0.4130 | 0.0805 | 0.0083 | 0.0025 | 0.0011 | 0.0028 | 0.0084 | 0.0139 | 0.3838 |
| V (0%) | 0.0343 | | 0.8126 | 0.1811 | 0.2117 | 0.2261 | 0.0620 | 0.3003 | 0.3999 | 0.2486 | 0.0179 | 0.2291 | 0.0920 | 0.0149 | 0.0004 | 0.0016 | 0.1144 | 0.2778 | 0.4431 |
| K (10%) | 0.3495 | 0.7818 | | 0.3148 | 0.2030 | 0.3996 | 0.1689 | 0.4764 | 0.5930 | 0.4310 | 0.4879 | 0.2231 | 0.2798 | 0.1925 | 0.0737 | 0.1503 | 0.4240 | 0.5756 | 0.7566 |
| L (10%) | 0.0186 | 0.2364 | 0.4083 | | 0.5653 | 0.6856 | 0.3533 | 0.5534 | 0.3435 | 0.6485 | 0.0428 | 0.5733 | 0.8963 | 0.4572 | 0.0569 | 0.2506 | 0.6029 | 0.3441 | 0.1260 |
| T (10%) | 0.0487 | 0.1977 | 0.2057 | 0.3667 | | 0.3793 | 0.8463 | 0.3081 | 0.2343 | 0.3521 | 0.1047 | 0.8621 | 0.6079 | 0.9894 | 0.2257 | 0.6755 | 0.3467 | 0.2515 | 0.0921 |
| M (20%) | 0.0226 | 0.2506 | 0.4309 | 0.9031 | 0.3304 | | 0.1641 | 0.7810 | 0.4529 | 0.9176 | 0.0508 | 0.4381 | 0.5253 | 0.1908 | 0.0447 | 0.1256 | 0.8874 | 0.4467 | 0.1675 |
| N (20%) | 0.0060 | 0.0528 | 0.2017 | 0.2364 | 0.9836 | 0.1841 | | 0.1229 | 0.0545 | 0.1525 | 0.0130 | 0.9471 | 0.3243 | 0.7133 | 0.0711 | 0.6526 | 0.0929 | 0.0511 | 0.0615 |
| W (20%) | 0.0158 | 0.2191 | 0.4098 | 0.9890 | 0.3577 | 0.9114 | 0.2143 | | 0.6824 | 0.8753 | 0.0440 | 0.3816 | 0.4150 | 0.1518 | 0.0206 | 0.0838 | 0.8606 | 0.6933 | 0.2103 |
| O (21%) | 0.0225 | 0.5324 | 0.6225 | 0.4614 | 0.2007 | 0.4738 | 0.0657 | 0.4525 | | 0.5678 | 0.0300 | 0.3047 | 0.2090 | 0.0517 | 0.0059 | 0.0268 | 0.4782 | 0.9569 | 0.2800 |
| P (21%) | 0.0239 | 0.3334 | 0.4793 | 0.8030 | 0.2920 | 0.8730 | 0.1710 | 0.8076 | 0.6317 | | 0.0397 | 0.4193 | 0.5082 | 0.1930 | 0.0242 | 0.1031 | 0.9917 | 0.5711 | 0.1836 |
| B (25%) | 0.4954 | 0.0286 | 0.4742 | 0.0301 | 0.0756 | 0.0366 | 0.0072 | 0.0251 | 0.0333 | 0.0390 | | 0.1073 | 0.0158 | 0.0018 | 0.0001 | 0.0005 | 0.0088 | 0.0132 | 0.6113 |
| C (25%) | 0.0802 | 0.2589 | 0.2524 | 0.5083 | 0.9628 | 0.4688 | 0.9502 | 0.5021 | 0.3271 | 0.4355 | 0.1043 | | 0.6095 | 0.8449 | 0.3842 | 0.9371 | 0.4104 | 0.3109 | 0.1347 |
| D (25%) | 0.0081 | 0.0985 | 0.2969 | 0.6124 | 0.5624 | 0.4885 | 0.4137 | 0.5903 | 0.2063 | 0.4527 | 0.0120 | 0.6734 | | 0.4424 | 0.0291 | 0.1933 | 0.4231 | 0.1973 | 0.1033 |
| J (25%) | 0.0038 | 0.0111 | 0.2246 | 0.2935 | 0.8400 | 0.2122 | 0.7408 | 0.2658 | 0.0676 | 0.2078 | 0.0021 | 0.8639 | 0.5339 | | 0.0156 | 0.3635 | 0.0918 | 0.0341 | 0.0699 |
| U (25%) | 0.0027 | 0.0002 | 0.0860 | 0.0359 | 0.2417 | 0.0599 | 0.0719 | 0.0301 | 0.0109 | 0.0305 | 0.0010 | 0.3595 | 0.0365 | 0.0111 | | 0.0137 | 0.0043 | 0.0020 | 0.0278 |
| B-IM (30%) | 0.0027 | 0.0021 | 0.1494 | 0.1063 | 0.6073 | 0.0968 | 0.3383 | 0.0910 | 0.0250 | 0.0807 | 0.0011 | 0.7838 | 0.1530 | 0.1621 | 0.0266 | | 0.0311 | 0.0119 | 0.0581 |
| R (30%) | 0.0334 | 0.7128 | 0.7332 | 0.2739 | 0.2131 | 0.2916 | 0.0672 | 0.2562 | 0.6394 | 0.3872 | 0.0268 | 0.2757 | 0.1158 | 0.0148 | 0.0001 | 0.0029 | | 0.4527 | 0.1775 |
| S (30%) | 0.0187 | 0.4268 | 0.6377 | 0.3890 | 0.2168 | 0.3875 | 0.0484 | 0.3732 | 0.9334 | 0.5529 | 0.0158 | 0.3154 | 0.1559 | 0.0226 | 0.0014 | 0.0049 | 0.5642 | | 0.2674 |
| X (30%) | 0.4079 | 0.4026 | 0.7394 | 0.1645 | 0.0846 | 0.1784 | 0.0745 | 0.1643 | 0.2902 | 0.2048 | 0.6145 | 0.1417 | 0.1082 | 0.0841 | 0.0344 | 0.0561 | 0.3659 | 0.2986 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D7. *t*-test Comparisons of Mixtures at 37.8ºC (100ºF) and 0.1 Hz (lower left half of table) and 0.5 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0423 | 0.1329 | 0.0821 | 0.0149 | 0.0351 | 0.0283 | 0.0125 | 0.0449 | 0.0414 | 0.7851 | 0.0502 | 0.0175 | 0.0294 | 0.0128 | 0.0088 | 0.1570 | 0.0624 | 0.5602 |
| V (0%) | 0.0589 | | 0.7854 | 0.1463 | 0.1682 | 0.7697 | 0.0480 | 0.0757 | 0.6231 | 0.7678 | 0.2005 | 0.8530 | 0.1134 | 0.0781 | 0.0013 | 0.0069 | 0.0950 | 0.2725 | 0.2154 |
| K (10%) | 0.1276 | 0.8222 | | 0.6685 | 0.2767 | 0.7175 | 0.3986 | 0.3004 | 0.9858 | 0.9159 | 0.2870 | 0.7252 | 0.3918 | 0.4616 | 0.1352 | 0.1453 | 0.4557 | 0.9792 | 0.3470 |
| L (10%) | 0.1532 | 0.1331 | 0.5075 | | 0.0494 | 0.1361 | 0.0417 | 0.0218 | 0.4383 | 0.3820 | 0.3615 | 0.3349 | 0.0320 | 0.0478 | 0.0079 | 0.0054 | 0.5061 | 0.2847 | 0.4357 |
| T (10%) | 0.0203 | 0.1358 | 0.2693 | 0.0315 | | 0.1831 | 0.4857 | 0.8635 | 0.1086 | 0.1362 | 0.0935 | 0.3389 | 0.5192 | 0.3728 | 0.2352 | 0.2677 | 0.0319 | 0.1667 | 0.0888 |
| M (20%) | 0.0505 | 0.8132 | 0.7648 | 0.1216 | 0.1448 | | 0.2119 | 0.1218 | 0.5259 | 0.6549 | 0.1847 | 0.9516 | 0.2069 | 0.2832 | 0.0336 | 0.0224 | 0.0840 | 0.3703 | 0.1961 |
| N (20%) | 0.0391 | 0.0375 | 0.4004 | 0.0510 | 0.4392 | 0.2080 | | 0.4776 | 0.1605 | 0.2133 | 0.1286 | 0.5298 | 0.9463 | 0.4976 | 0.0083 | 0.0381 | 0.0401 | 0.0370 | 0.1283 |
| W (20%) | 0.0194 | 0.0790 | 0.3030 | 0.0235 | 0.8174 | 0.1177 | 0.4984 | | 0.0947 | 0.1302 | 0.1002 | 0.3725 | 0.5715 | 0.3163 | 0.0859 | 0.1321 | 0.0180 | 0.0581 | 0.0955 |
| O (21%) | 0.0654 | 0.5981 | 0.9510 | 0.3410 | 0.0915 | 0.5275 | 0.1571 | 0.0943 | | 0.8880 | 0.2414 | 0.6483 | 0.1523 | 0.2064 | 0.0299 | 0.0260 | 0.2222 | 0.9887 | 0.2739 |
| P (21%) | 0.0535 | 0.8045 | 0.9292 | 0.2466 | 0.1156 | 0.7080 | 0.2000 | 0.1234 | 0.8139 | | 0.2230 | 0.7302 | 0.2074 | 0.2757 | 0.0400 | 0.0370 | 0.1988 | 0.8674 | 0.2504 |
| B (25%) | 0.8445 | 0.2453 | 0.3086 | 0.4839 | 0.1234 | 0.2316 | 0.1611 | 0.1316 | 0.2978 | 0.2652 | | 0.1794 | 0.1207 | 0.1400 | 0.0666 | 0.0667 | 0.5104 | 0.2444 | 0.8207 |
| C (25%) | 0.0577 | 0.9766 | 0.8312 | 0.2751 | 0.2352 | 0.9374 | 0.3946 | 0.2728 | 0.7106 | 0.8547 | 0.2410 | | 0.5238 | 0.6399 | 0.1259 | 0.1380 | 0.2037 | 0.6206 | 0.2015 |
| D (25%) | 0.0291 | 0.0710 | 0.3890 | 0.0346 | 0.4685 | 0.1646 | 0.9112 | 0.5847 | 0.1403 | 0.1850 | 0.1549 | 0.3814 | | 0.6329 | 0.0327 | 0.0509 | 0.0266 | 0.0693 | 0.1187 |
| J (25%) | 0.0386 | 0.0495 | 0.4392 | 0.0506 | 0.3635 | 0.2232 | 0.6353 | 0.3950 | 0.1780 | 0.2325 | 0.1685 | 0.4491 | 0.6917 | | 0.0028 | 0.0230 | 0.0441 | 0.0189 | 0.1414 |
| U (25%) | 0.0182 | 0.0016 | 0.1446 | 0.0127 | 0.2470 | 0.0320 | 0.0116 | 0.1191 | 0.0334 | 0.0379 | 0.0917 | 0.1002 | 0.0264 | 0.0060 | | 0.6733 | 0.0111 | 0.0015 | 0.0607 |
| B-IM (30%) | 0.0138 | 0.0088 | 0.1481 | 0.0086 | 0.2724 | 0.0234 | 0.0513 | 0.1601 | 0.0284 | 0.0335 | 0.0912 | 0.1002 | 0.0515 | 0.0346 | 0.8409 | | 0.0072 | 0.0121 | 0.0599 |
| R (30%) | 0.2128 | 0.1523 | 0.4374 | 0.8133 | 0.0370 | 0.1352 | 0.0677 | 0.0345 | 0.2948 | 0.2213 | 0.5519 | 0.2360 | 0.0519 | 0.0695 | 0.0221 | 0.0166 | | 0.1641 | 0.6433 |
| S (30%) | 0.0711 | 0.4928 | 0.9449 | 0.1852 | 0.1325 | 0.5014 | 0.0110 | 0.0616 | 0.7998 | 0.9594 | 0.2726 | 0.8060 | 0.0440 | 0.0145 | 0.0010 | 0.0095 | 0.1977 | | 0.2719 |
| X (30%) | 0.6968 | 0.2271 | 0.3130 | 0.5106 | 0.1016 | 0.2121 | 0.1404 | 0.1090 | 0.2867 | 0.2493 | 0.8981 | 0.2263 | 0.1328 | 0.1473 | 0.0743 | 0.0724 | 0.5970 | 0.2574 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D8. *t*-test Comparisons of Mixtures at 37.8ºC (100ºF) and 1.0 Hz (lower left half of table) and 5.0 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0228 | 0.1471 | 0.0268 | 0.0157 | 0.0167 | 0.0112 | 0.0050 | 0.0261 | 0.0220 | 0.6290 | 0.0508 | 0.0065 | 0.0142 | 0.0070 | 0.0028 | 0.0594 | 0.0398 | 0.4403 |
| V (0%) | 0.0350 | | 0.7724 | 0.3273 | 0.1995 | 0.6016 | 0.0582 | 0.1006 | 0.7074 | 0.9864 | 0.1289 | 0.5909 | 0.1643 | 0.0486 | 0.0009 | 0.0091 | 0.0690 | 0.2236 | 0.1996 |
| K (10%) | 0.1342 | 0.7744 | | 0.9410 | 0.2532 | 0.6475 | 0.3539 | 0.3119 | 0.9200 | 0.7918 | 0.2667 | 0.5400 | 0.3924 | 0.4241 | 0.1164 | 0.1447 | 0.6061 | 0.9767 | 0.3833 |
| L (10%) | 0.0588 | 0.1679 | 0.7482 | | 0.1074 | 0.2411 | 0.0415 | 0.0464 | 0.7367 | 0.5336 | 0.1835 | 0.3824 | 0.0738 | 0.0562 | 0.0074 | 0.0058 | 0.2930 | 0.7461 | 0.2985 |
| T (10%) | 0.0131 | 0.1772 | 0.2686 | 0.0624 | | 0.2278 | 0.5521 | 0.7109 | 0.1285 | 0.1720 | 0.0431 | 0.5271 | 0.4871 | 0.4163 | 0.2616 | 0.3828 | 0.0699 | 0.1825 | 0.0661 |
| M (20%) | 0.0278 | 0.7201 | 0.6919 | 0.1515 | 0.1952 | | 0.2148 | 0.1913 | 0.5016 | 0.7287 | 0.1032 | 0.7366 | 0.3228 | 0.3223 | 0.0545 | 0.0304 | 0.0752 | 0.3097 | 0.1622 |
| N (20%) | 0.0225 | 0.0487 | 0.3868 | 0.0380 | 0.4964 | 0.2133 | | 0.7572 | 0.1407 | 0.2180 | 0.0667 | 0.7591 | 0.8232 | 0.4967 | 0.0334 | 0.0586 | 0.0155 | 0.0696 | 0.0985 |
| W (20%) | 0.0094 | 0.0810 | 0.3013 | 0.0246 | 0.8186 | 0.1361 | 0.5309 | | 0.1178 | 0.1851 | 0.0491 | 0.6678 | 0.6655 | 0.4711 | 0.0654 | 0.1369 | 0.0173 | 0.0698 | 0.0779 |
| O (21%) | 0.0369 | 0.6375 | 0.9642 | 0.5111 | 0.1123 | 0.5140 | 0.1565 | 0.0991 | | 0.7838 | 0.1488 | 0.4931 | 0.1844 | 0.1977 | 0.0280 | 0.0260 | 0.2705 | 0.8703 | 0.2463 |
| P (21%) | 0.0340 | 0.8002 | 0.8867 | 0.4332 | 0.1417 | 0.6558 | 0.2138 | 0.1393 | 0.8740 | | 0.1209 | 0.6101 | 0.2877 | 0.3084 | 0.0379 | 0.0402 | 0.1980 | 0.6218 | 0.2007 |
| B (25%) | 0.7467 | 0.1780 | 0.2757 | 0.3040 | 0.0766 | 0.1595 | 0.1101 | 0.0846 | 0.2131 | 0.1936 | | 0.0987 | 0.0604 | 0.0782 | 0.0325 | 0.0300 | 0.3270 | 0.1721 | 0.7706 |
| C (25%) | 0.0486 | 0.7745 | 0.6669 | 0.3545 | 0.3908 | 0.8889 | 0.6008 | 0.4476 | 0.6008 | 0.6858 | 0.1492 | | 0.8422 | 0.9119 | 0.1786 | 0.2537 | 0.2188 | 0.4289 | 0.1506 |
| D (25%) | 0.0128 | 0.1367 | 0.3946 | 0.0381 | 0.4986 | 0.2457 | 0.9726 | 0.5808 | 0.1636 | 0.2270 | 0.1031 | 0.6206 | | 0.8264 | 0.0428 | 0.0744 | 0.0248 | 0.0974 | 0.0962 |
| J (25%) | 0.0244 | 0.0791 | 0.4606 | 0.0483 | 0.3686 | 0.3141 | 0.4478 | 0.3243 | 0.2140 | 0.2929 | 0.1229 | 0.7403 | 0.6646 | | 0.0016 | 0.0324 | 0.0183 | 0.0132 | 0.1157 |
| U (25%) | 0.0107 | 0.0011 | 0.1294 | 0.0070 | 0.2428 | 0.0386 | 0.0101 | 0.0773 | 0.0295 | 0.0396 | 0.0554 | 0.1422 | 0.0364 | 0.0020 | | 0.3120 | 0.0042 | 0.0001 | 0.0441 |
| B-IM (30%) | 0.0064 | 0.0074 | 0.1436 | 0.0047 | 0.2915 | 0.0236 | 0.0401 | 0.1293 | 0.0256 | 0.0372 | 0.0550 | 0.1655 | 0.0555 | 0.0234 | 0.5652 | | 0.0025 | 0.0131 | 0.0445 |
| R (30%) | 0.1207 | 0.0810 | 0.4869 | 0.4139 | 0.0359 | 0.0723 | 0.0300 | 0.0149 | 0.2206 | 0.1940 | 0.4637 | 0.2044 | 0.0220 | 0.0353 | 0.0083 | 0.0047 | | 0.1604 | 0.5238 |
| S (30%) | 0.0557 | 0.2326 | 0.9860 | 0.3694 | 0.1717 | 0.3389 | 0.0576 | 0.0603 | 0.9499 | 0.7950 | 0.2251 | 0.5482 | 0.0808 | 0.0212 | 0.0014 | 0.0134 | 0.1588 | | 0.2667 |
| X (30%) | 0.5221 | 0.2117 | 0.3577 | 0.3940 | 0.0829 | 0.1879 | 0.1220 | 0.0918 | 0.2681 | 0.2416 | 0.8029 | 0.1867 | 0.1146 | 0.1382 | 0.0565 | 0.0561 | 0.6216 | 0.2757 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha = 0.05$.

**Table D9. *T*-test Comparisons of Mixtures at 37.8ºC (100ºF) and 10.0 Hz (lower left half of table) and 25.0 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | K (10%) | L (10%) | T (10%) | M (20%) | N (20%) | W (20%) | O (21%) | P (21%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0173 | 0.1591 | 0.0115 | 0.0274 | 0.0136 | 0.0060 | 0.0043 | 0.0216 | 0.0153 | 0.4408 | 0.0574 | 0.0046 | 0.0074 | 0.0053 | 0.0016 | 0.0301 | 0.0253 | 0.3745 |
| V (0%) | 0.0199 | | 0.7845 | 0.9274 | 0.2161 | 0.4880 | 0.0738 | 0.1328 | 0.8319 | 0.7485 | 0.0777 | 0.4345 | 0.1572 | 0.0214 | 0.0008 | 0.0103 | 0.0898 | 0.3143 | 0.2098 |
| K (10%) | 0.1515 | 0.7706 | | 0.7652 | 0.2343 | 0.5978 | 0.3133 | 0.3420 | 0.8701 | 0.6868 | 0.2808 | 0.4187 | 0.3792 | 0.3598 | 0.1026 | 0.1499 | 0.7757 | 0.9431 | 0.4241 |
| L (10%) | 0.0191 | 0.5018 | 0.9598 | | 0.1811 | 0.6074 | 0.1130 | 0.1785 | 0.8066 | 0.8285 | 0.0629 | 0.4587 | 0.2201 | 0.1431 | 0.0175 | 0.0192 | 0.2055 | 0.5453 | 0.1970 |
| T (10%) | 0.0188 | 0.2037 | 0.2413 | 0.1271 | | 0.2603 | 0.6141 | 0.5603 | 0.1501 | 0.2143 | 0.0320 | 0.7077 | 0.4788 | 0.5005 | 0.2772 | 0.5297 | 0.1254 | 0.1914 | 0.0615 |
| M (20%) | 0.0145 | 0.5482 | 0.6218 | 0.3179 | 0.2375 | | 0.2318 | 0.3207 | 0.4962 | 0.8228 | 0.0501 | 0.5966 | 0.3960 | 0.3021 | 0.0751 | 0.0486 | 0.1319 | 0.3064 | 0.1494 |
| N (20%) | 0.0085 | 0.0623 | 0.3337 | 0.0523 | 0.5713 | 0.2191 | | 0.8635 | 0.1260 | 0.2218 | 0.0268 | 0.9427 | 0.6906 | 0.6474 | 0.0700 | 0.1048 | 0.0204 | 0.0650 | 0.0832 |
| W (20%) | 0.0046 | 0.1176 | 0.3218 | 0.0727 | 0.6339 | 0.2412 | 0.9218 | | 0.1661 | 0.2974 | 0.0211 | 0.9949 | 0.8507 | 0.8881 | 0.0513 | 0.1326 | 0.0385 | 0.0898 | 0.0796 |
| O (21%) | 0.0243 | 0.7370 | 0.9034 | 0.8866 | 0.1323 | 0.4873 | 0.1324 | 0.1350 | | 0.6799 | 0.0864 | 0.4007 | 0.2010 | 0.1610 | 0.0267 | 0.0298 | 0.3885 | 0.8299 | 0.2407 |
| P (21%) | 0.0181 | 0.9028 | 0.7405 | 0.5891 | 0.1851 | 0.7683 | 0.2169 | 0.2254 | 0.7229 | | 0.0576 | 0.5340 | 0.3606 | 0.2877 | 0.0354 | 0.0488 | 0.2218 | 0.4814 | 0.1724 |
| B (25%) | 0.5608 | 0.1079 | 0.2689 | 0.1334 | 0.0341 | 0.0797 | 0.0492 | 0.0363 | 0.1233 | 0.0912 | | 0.0855 | 0.0240 | 0.0338 | 0.0153 | 0.0105 | 0.1678 | 0.1040 | 0.7496 |
| C (25%) | 0.0531 | 0.5223 | 0.4857 | 0.3978 | 0.5918 | 0.6784 | 0.8300 | 0.8026 | 0.4482 | 0.5821 | 0.0882 | | 0.9170 | 0.9459 | 0.2372 | 0.4324 | 0.2396 | 0.3488 | 0.1317 |
| D (25%) | 0.0055 | 0.1686 | 0.3891 | 0.1051 | 0.4664 | 0.3635 | 0.7411 | 0.7268 | 0.1932 | 0.3238 | 0.0444 | 0.9502 | | 0.9235 | 0.0418 | 0.0976 | 0.0424 | 0.1016 | 0.0888 |
| J (25%) | 0.0110 | 0.0339 | 0.3930 | 0.0673 | 0.4449 | 0.3103 | 0.5582 | 0.6334 | 0.1792 | 0.2981 | 0.0589 | 0.9664 | 0.9579 | | 0.0038 | 0.0522 | 0.0076 | 0.0087 | 0.0973 |
| U (25%) | 0.0061 | 0.0008 | 0.1097 | 0.0091 | 0.2681 | 0.0622 | 0.0470 | 0.0604 | 0.0275 | 0.0361 | 0.0246 | 0.1997 | 0.0419 | 0.0021 | | 0.1468 | 0.0023 | 0.0001 | 0.0375 |
| B-IM (30%) | 0.0022 | 0.0100 | 0.1477 | 0.0080 | 0.4540 | 0.0371 | 0.0770 | 0.1440 | 0.0281 | 0.0435 | 0.0214 | 0.3214 | 0.0847 | 0.0411 | 0.2144 | | 0.0030 | 0.0096 | 0.0413 |
| R (30%) | 0.0440 | 0.0720 | 0.6732 | 0.2598 | 0.0894 | 0.0898 | 0.0145 | 0.0243 | 0.3196 | 0.2000 | 0.2606 | 0.2278 | 0.0308 | 0.0127 | 0.0032 | 0.0026 | | 0.2103 | 0.4210 |
| S (30%) | 0.0335 | 0.2388 | 0.9632 | 0.9863 | 0.1826 | 0.3000 | 0.0643 | 0.0784 | 0.8624 | 0.5459 | 0.1460 | 0.3913 | 0.1007 | 0.0097 | 0.0000 | 0.0117 | 0.1715 | | 0.2673 |
| X (30%) | 0.4186 | 0.1979 | 0.3934 | 0.2578 | 0.0616 | 0.1529 | 0.0902 | 0.0762 | 0.2409 | 0.1827 | 0.7701 | 0.1390 | 0.0919 | 0.1057 | 0.0406 | 0.0427 | 0.4704 | 0.2622 | |

Shaded bold cells indicate significant differences at a level of significance of $\alpha$=0.05.

# APPENDIX E

# BINDER GRADING RESULTS

**Table E1. Binder Test Results for Binder Extracted From Entire Core for Control Mixtures Containing 0%-20% RAP**

| **Section** | **E** | **K** | **L** | **M** | **W** |
|---|---|---|---|---|---|
| **Portion of Core** | **Entire** | **Entire** | **Entire** | **Entire** | **Entire** |
| **RAP Content** | **0%** | **10%** | **10%** | **20%** | **20%** |
| **Dynamic Shear, 10 rad/sec, specification: G*/sin delta >2.20 kPa** | | | | | |
| RTFO G*/sin δ, 76ºC | 10.28 | 4.603 | 6.735 | 4.973 | 4.795 |
| RTFO G*/sin δ, 82ºC | 5.014 | 2.169 | 3.113 | 2.462 | 2.367 |
| RTFO G*/sin δ, 88ºC | 2.529 | | 1.485 | 1.242 | 1.203 |
| RTFO G*/sin δ, 94ºC | 1.294 | | | | |
| RTFO G*/sin δ, 100ºC | | | | | |
| RTFO G*/sin δ, 106ºC | | | | | |
| RTFO G*, 76ºC | 9.992 | 4.557 | 6.651 | 4.888 | 4.729 |
| RTFO G*, 82ºC | 4.923 | 2.158 | 3.091 | 2.437 | 2.348 |
| RTFO G*, 88ºC | 2.501 | | 1.479 | 1.235 | 1.197 |
| RTFO G*, 94ºC | 1.286 | | | | |
| RTFO G*, 100ºC | | | | | |
| RTFO G*, 106ºC | | | | | |
| RTFO δ, 76ºC | 76.38 | 81.93 | 80.93 | 79.36 | 80.5 |
| RTFO δ, 82ºC | 79.10 | 84.14 | 83.20 | 81.85 | 82.77 |
| RTFO δ, 88ºC | 81.51 | | 85.07 | 83.98 | 84.74 |
| RTFO δ, 94ºC | 83.63 | | | | |
| RTFO δ, 100ºC | | | | | |
| RTFO δ, 106ºC | | | | | |
| *RTFO failure temp.* | *89.29* | *82.89* | *84.84* | *83.03* | *82.72* |
| **Dynamic Shear, 10 rad/sec, specification: G* sin delta <5000 kPa** | | | | | |
| PAV G* sin δ, 25.0ºC | | | | | |
| PAV G* sin δ, 28.0ºC | | | | 5195 | 6817 |
| PAV G* sin δ, 31.0ºC | | 5362 | 6453 | 3782 | 4851 |
| PAV G* sin δ, 34.0ºC | 5681 | 3783 | 4598 | 2735 | |
| PAV G* sin δ, 37.0ºC | 4128 | | | | |
| PAV G* sin δ, 40.0ºC | | | | | |
| PAV G*, 25.0ºC | | | | | |
| PAV G*, 28.0ºC | | | | 3.84E+6 | 1.00E+7 |
| PAV G*, 31.0ºC | | 7.70E+6 | 9.56E+6 | 5.54E+6 | 6.79E+6 |
| PAV G*, 34.0ºC | 8.04E+6 | 5.16E+6 | 6.44E+6 | 7.96E+6 | |
| PAV G*, 37.0ºC | 5.64E+6 | | | | |
| PAV G*, 40.0ºC | | | | | |
| PAV δ, 25.0ºC | | | | | |
| PAV δ, 28.0ºC | | | | 45.41 | 42.91 |
| PAV δ, 31.0ºC | | 47.10 | 42.48 | 43.10 | 45.61 |
| PAV δ, 34.0ºC | 44.99 | 44.12 | 45.57 | 40.74 | |
| PAV δ, 37.0ºC | 47.04 | | | | |
| PAV δ, 40.0ºC | | | | | |
| *PAV failure temp.* | *35.2* | *31.6* | *33.26* | *28.37* | *30.73* |
| **Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300** | | | | | |
| Stiffness, 0ºC | 133 | | 122 | | |
| M-value, 0ºC | 0.330 | | 0.312 | | |
| Stiffness, -6ºC | 300 | 189 | 227 | 124 | 166 |
| M-value, -6ºC | 0.291 | 0.305 | 0.276 | 0.320 | 0.310 |

| | | | | | |
|---|---|---|---|---|---|
| Stiffness, -12ºC | | 343 | | 241 | 343 |
| M-value, -12ºC | | 0.253 | | 0.276 | 0.272 |
| *Stiffness failure temp.* | *-16.0* | *-20.7* | *-18.7* | *-24.0* | *-20.9* |
| *M-value failure temp.* | *-14.6* | *-16.6* | *-12.0* | *-18.7* | *-17.6* |
| **Performance Grade** | **82-10** | **76-16** | **82-10** | **82-16** | **82-16** |

Shaded cells indicate the failure temperature.

**Table E2. Binder Test Results for Binder Extracted From Entire Core for Mixtures Containing 21%-30% RAP**

| **Section** | **O** | **P** | **C** | **D** | **J** | **U** | **B-IM** | **X** |
|---|---|---|---|---|---|---|---|---|
| **Portion of Core** | **Entire** | **Entire** | **Entire** | **Entire** | **Entire** | **Entire** | **Entire** | **Entire** |
| **RAP Content** | **21%** | **21%** | **25%** | **25%** | **25%** | **25%** | **30%** | **30%** |
| **Dynamic Shear, 10 rad/sec, specification: G*/sin delta >2.20 kPa** | | | | | | | | |
| RTFO G*/sin δ, 76ºC | 10.51 | | 8.309 | 6.210 | 6.052 | 2.751 | 3.433 | 7.321 |
| RTFO G*/sin δ, 82ºC | 5.000 | 2.891 | 4.032 | 2.959 | 2.859 | 1.298 | 1.662 | 3.582 |
| RTFO G*/sin δ, 88ºC | 2.454 | 1.412 | 2.015 | 1.459 | 1.407 | | | 1.803 |
| RTFO G*/sin δ, 94ºC | 1.226 | | | | | | | |
| RTFO G*/sin δ, 100ºC | | | | | | | | |
| RTFO G*/sin δ, 106ºC | | | | | | | | |
| RTFO G*, 76ºC | 10.30 | | 8.112 | 6.106 | 5.986 | 2.736 | 3.397 | 7.164 |
| RTFO G*, 82ºC | 4.944 | 2.870 | 3.974 | 2.930 | 2.843 | 1.295 | 1.652 | 3.534 |
| RTFO G*, 88ºC | 2.439 | 1.407 | 1.998 | 1.452 | 1.403 | | | 1.785 |
| RTFO G*, 94ºC | 1.222 | | | | | | | |
| RTFO G*, 100ºC | | | | | | | | |
| RTFO G*, 106ºC | | | | | | | | |
| RTFO δ, 76ºC | 78.64 | | 77.52 | 79.50 | 81.53 | 83.95 | 81.74 | 78.11 |
| RTFO δ, 82ºC | 81.35 | 83.06 | 80.27 | 82.00 | 83.84 | 85.79 | 83.87 | 80.69 |
| RTFO δ, 88ºC | 83.61 | 85.04 | 82.60 | 84.10 | 85.70 | | | 82.95 |
| RTFO δ, 94ºC | 85.37 | | | | | | | |
| RTFO δ, 100ºC | | | | | | | | |
| RTFO δ, 106ºC | | | | | | | | |
| *RTFO failure temp.* | *89.00* | *84.29* | *87.21* | *84.55* | *84.27* | *77.79* | *79.68* | *86.25* |
| **Dynamic Shear, 10 rad/sec, specification: G* sin delta <5000kPa** | | | | | | | | |
| PAV G* sin δ, 25.0ºC | | | | | | 6490 | 6399 | |
| PAV G* sin δ, 28.0ºC | | | | 6117 | | 4663 | 4538 | 6804 |
| PAV G* sin δ, 31.0ºC | | 5895 | 5525 | 4334 | 5361 | 3288 | 3163 | 4895 |
| PAV G* sin δ, 34.0ºC | 6369 | 4309 | 3964 | 3014 | 3976 | | 2167 | |
| PAV G* sin δ, 37.0ºC | 4819 | | | | | | | |
| PAV G* sin δ, 40.0ºC | | | | | | | | |
| PAV G*, 25.0ºC | | | | | | 9.95E+6 | 9.30E+6 | |
| PAV G*, 28.0ºC | | | | 8.90E+6 | | 6.75E+6 | 6.29E+6 | 1.03E+7 |
| PAV G*, 31.0ºC | | 9.21E+6 | 8.26E+6 | 6.02E+6 | 7.91E+6 | 4.52E+6 | 4.21E+6 | 7.05E+6 |
| PAV G*, 34.0ºC | 9.79E+6 | 6.36E+6 | 5.64E+6 | 4.01E+6 | 5.63E+6 | | 2.78E+6 | |
| PAV G*, 37.0ºC | 7.09E+6 | | | | | | | |
| PAV G*, 40.0ºC | | | | | | | | |
| PAV δ, 25.0ºC | | | | | | 40.71 | 43.46 | |
| PAV δ, 28.0ºC | | | | 43.41 | | 43.67 | 46.14 | 41.38 |
| PAV δ, 31.0ºC | | 39.80 | 41.96 | 46.10 | 42.65 | 46.65 | 48.76 | 44.02 |
| PAV δ, 34.0ºC | 40.60 | 42.63 | 44.64 | 48.78 | 44.92 | | 51.35 | |
| PAV δ, 37.0ºC | 42.80 | | | | | | | |
| PAV δ, 40.0ºC | | | | | | | | |
| *PAV failure temp.* | *36.6* | *32.58* | *30.9* | *29.74* | *31.7* | *27.33* | *27.12* | *30.81* |
| **Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300** | | | | | | | | |
| Stiffness, 0ºC | 132 | 99 | 86 | | 87 | | | |
| M-value, 0ºC | 0.305 | 0.337 | 0.342 | | 0.346 | | | |
| Stiffness, -6ºC | 248 | 189 | 185 | 162 | 173 | 130 | 132 | 187 |
| M-value, -6ºC | 0.260 | 0.264 | 0.297 | 0.328 | 0.297 | 0.319 | 0.346 | 0.308 |
| Stiffness, -12ºC | | | | 339 | | 261 | 298 | 392 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| M-value, -12ºC | | | | 0.277 | | 0.273 | 0.297 | 0.263 |
| *Stiffness failure temp.* | *-17.8* | *-20.3* | *-19.8* | *-21.0* | *-20.8* | *-23.2* | *-22.0* | *-19.8* |
| *M-value failure temp.* | *-10.7* | *-13.0* | *-15.6* | *-19.3* | *-15.6* | *-18.5* | *-21.6* | *-17.1* |
| **Performance Grade** | **82-10** | **82-10** | **82-10** | **82-16** | **82-10** | **76-16** | **76-16** | **82-16** |

Shaded cells indicate the failure temperature.

**Table E3. Binder Test Results for Binder Extracted From Top Half and Bottom Half of Cores for Mixtures Containing 21%-30% RAP**

| Section | V | V | Q | Q | H | H | I | I | N | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Portion of Core | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top |
| RAP Content | 0% | 0% | 15% | 15% | 20% | 20% | 20% | 20% | 20% | 20% |
| **Dynamic Shear, 10 rad/sec, specification: G*/sin delta >2.20 kPa** | | | | | | | | | | |
| RTFO G*/sin δ, 76ºC | 5.796 | 14.16 | 6.378 | 15.93 | 4.200 | 5.460 | 7.737 | 10.22 | 7.832 | 9.409 |
| RTFO G*/sin δ, 82ºC | 2.831 | 6.942 | 3.023 | 7.599 | 1.977 | 2.611 | 3.690 | 4.808 | 3.821 | 4.706 |
| RTFO G*/sin δ, 88ºC | 1.429 | 3.477 | 1.498 | 3.667 | | 1.292 | 1.820 | 2.348 | 1.917 | 2.413 |
| RTFO G*/sin δ, 94ºC | | 1.778 | | 1.817 | | | | 1.192 | | 1.269 |
| RTFO G*/sin δ, 100ºC | | | | | | | | | | |
| RTFO G*/sin δ, 106ºC | | | | | | | | | | |
| RTFO G*, 76ºC | 5.705 | 13.69 | 6.288 | 15.4 | 4.156 | 5.382 | 7.596 | 9.975 | 7.681 | 9.079 |
| RTFO G*, 82ºC | 2.805 | 6.789 | 3.000 | 7.447 | 1.966 | 2.590 | 3.650 | 4.740 | 2.776 | 4.596 |
| RTFO G*, 88ºC | 1.422 | 3.429 | 1.492 | 3.626 | | 1.286 | 1.809 | 2.330 | 1.904 | 2.378 |
| RTFO G*, 94ºC | | 1.764 | | 1.806 | | | | 1.187 | | 1.258 |
| RTFO G*, 100ºC | | | | | | | | | | |
| RTFO G*, 106ºC | | | | | | | | | | |
| RTFO δ, 76ºC | 79.84 | 75.20 | 80.37 | 75.23 | 81.64 | 80.31 | 79.03 | 77.55 | 78.73 | 74.77 |
| RTFO δ, 82ºC | 82.15 | 77.95 | 82.89 | 78.52 | 83.83 | 82.70 | 80.57 | 80.38 | 81.21 | 77.6 |
| RTFO δ, 88ºC | 84.18 | 80.47 | 84.90 | 81.37 | | 84.68 | 83.72 | 82.76 | 83.37 | 80.18 |
| RTFO δ, 94ºC | | 82.73 | | 83.62 | | | | 84.73 | | 82.47 |
| RTFO δ, 100ºC | | | | | | | | | | |
| RTFO δ, 106ºC | | | | | | | | | | |
| *RTFO failure temp.* | *84.26* | *92.06* | *84.76* | *92.33* | *81.15* | *83.52* | *86.38* | *88.71* | *88.79* | *88.94* |
| **Dynamic Shear, 10 rad/sec, specification: G* sin delta <5000 kPa** | | | | | | | | | | |
| PAV G* sin δ, 25.0ºC | | | | | | | | | | |
| PAV G* sin δ, 28.0ºC | 6558 | | 5596 | | 5267 | 5699 | | | | 5697 |
| PAV G* sin δ, 31.0ºC | 4607 | | 4175 | | 3754 | 4133 | 5337 | 6236 | 5470 | 4187 |
| PAV G* sin δ, 34.0ºC | | 6561 | 3069 | 5259 | | | 3781 | 4522 | 3969 | 3023 |
| PAV G* sin δ, 37.0ºC | | 4685 | | 4147 | | | | | | |
| PAV G* sin δ, 40.0ºC | | | | | | | | | | |
| PAV G*, 25.0ºC | | | | | | | | | | |
| PAV G*, 28.0ºC | 9.41E+6 | | 9.16E+6 | | 7.69E+6 | 8.67E+6 | | | | 8.89E+6 |
| PAV G*, 31.0ºC | 6.30E+6 | | 6.46E+6 | | 5.21E+6 | 5.96E+6 | 7.65E+0 | 9.41E+6 | 7.90E+6 | 6.23E+6 |
| PAV G*, 34.0ºC | | 9.56E+6 | 4.51E+6 | 8.63E+6 | | | 5.17E+0 | 6.48E+6 | 5.50E+6 | 4.30E+6 |
| PAV G*, 37.0ºC | | 6.52E+6 | | 6.65E+6 | | | | | | |
| PAV G*, 40.0ºC | | | | | | | | | | |
| PAV δ, 25.0ºC | | | | | | | | | | |
| PAV δ, 28.0ºC | 44.21 | | 37.65 | | 43.25 | 41.12 | | | | 39.85 |
| PAV δ, 31.0ºC | 46.96 | | 40.26 | | 46.09 | 43.9 | 44.27 | 41.5 | 43.85 | 42.26 |
| PAV δ, 34.0ºC | | 43.32 | 42.92 | 37.54 | | | 47.01 | 44.25 | 46.17 | 44.66 |
| PAV δ, 37.0ºC | | 45.96 | | 39.21 | | | | | | |
| PAV δ, 40.0ºC | | | | | | | | | | |
| *PAV failure temp.* | *30.31* | *36.42* | *29.15* | *34.64* | *28.46* | *29.22* | *31.57* | *33.06* | *31.84* | *29.26* |
| **Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300** | | | | | | | | | | |
| Stiffness, 0ºC | | 156 | 81 | 99 | | | | 102 | | |
| M-value, 0ºC | | 0.326 | 0.339 | 0.308 | | | | 0.342 | | |
| Stiffness, -6ºC | 193 | 305 | 137 | 165 | 158 | 178 | 220 | 218 | 215 | 158 |
| M-value, -6ºC | 0.322 | 0.277 | 0.297 | 0.281 | 0.319 | 0.308 | 0.305 | 0.283 | 0.3 | 0.313 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Stiffness, -12ºC | 427 | | | | 297 | 322 | 371 | | 423 | 287 |
| M-value, -12ºC | 0.274 | | | | 0.274 | 0.268 | 0.247 | | 0.256 | 0.268 |
| *Stiffness failure temp.* | *-19.3* | *-15.9* | *-24.9* | *-23.0* | *-22.1* | *-21.3* | *-19.6* | *-18.5* | *-19.0* | *-22.4* |
| *M-value failure temp.* | *-18.8* | *-13.2* | *-15.6* | *-11.8* | *-18.5* | *-17.2* | *-16.5* | *-14.3* | *-16.0* | *-17.7* |
| **Performance Grade** | **82-16** | **82-10** | **76-10** | **82-10** | **76-16** | **82-16** | **82-16** | **88-10** | **82-16** | **82-16** |

Shaded cells indicate the failure temperature.

**Table E4. Binder Test Results for Binder Extracted From Top Half and Bottom Half of Cores for Mixtures Containing 21% to 30% RAP**

| **Section** | **A** | **A** | **B** | **B** | **F** | **F** | **R** | **R** | **S** | **S** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Portion of Core** | **Bottom** | **Top** | **Bottom** | **Top** | **Bottom** | **Top** | **Bottom** | **Top** | **Bottom** | **Top** |
| **RAP Content** | **25%** | **25%** | **25%** | **25%** | **25%** | **25%** | **30%** | **30%** | **30%** | **30%** |
| **Dynamic Shear, 10 rad/sec, specification: G*/sin delta >2.20 kPa** | | | | | | | | | | |
| RTFO G*/sin δ, 76ºC | 2.966 | 5.480 | 10.45 | 43.34 | 3.819 | 6.786 | 5.815 | 7.343 | 6.071 | 10.22 |
| RTFO G*/sin δ, 82ºC | 1.436 | 2.648 | 50.62 | 22.49 | 1.784 | 3.088 | 2.730 | 2.414 | 2.842 | 4.706 |
| RTFO G*/sin δ, 88ºC | | 1.322 | 2.548 | 11.72 | | 1.469 | 1.339 | 1.655 | 1.411 | 2.256 |
| RTFO G*/sin δ, 94ºC | | | 1.324 | 6.198 | | | | | | 1.113 |
| RTFO G*/sin δ, 100ºC | | | | 3.322 | | | | | | |
| RTFO G*/sin δ, 106ºC | | | | 1.803 | | | | | | |
| RTFO G*, 76ºC | 2.945 | 5.407 | 101.7 | 39.26 | 3.787 | 6.687 | 5.748 | 7.234 | 5.991 | 10.03 |
| RTFO G*, 82ºC | 1.431 | 2.628 | 4.978 | 20.82 | 1.777 | 3.064 | 2.714 | 3.386 | 2.821 | 4.657 |
| RTFO G*, 88ºC | | 1.317 | 2.522 | 10.60 | | 1.463 | 1.335 | 1.648 | 1.406 | 2.244 |
| RTFO G*, 94ºC | | | 1.317 | 5.946 | | | | | | 1.110 |
| RTFO G*, 100ºC | | | | 3.229 | | | | | | |
| RTFO G*, 106ºC | | | | 1.769 | | | | | | |
| RTFO δ, 76ºC | | 80.66 | 76.80 | 64.96 | 82.57 | 80.24 | 81.27 | 80.10 | 80.66 | 79.08 |
| RTFO δ, 82ºC | 83.16 | 82.96 | 79.49 | 67.76 | 84.75 | 82.89 | 83.65 | 82.68 | 83.05 | 81.72 |
| RTFO δ, 88ºC | 85.08 | 84.89 | 81.86 | 70.72 | | 85.01 | 85.56 | 84.77 | 85.01 | 83.96 |
| RTFO δ, 94ºC | | | 83.92 | 73.59 | | | | | | 85.86 |
| RTFO δ, 100ºC | | | | 76.35 | | | | | | |
| RTFO δ, 106ºC | | | | 78.93 | | | | | | |
| *RTFO failure temp.* | *78.47* | *82.81* | *89.42* | *103.9* | *80.35* | *84.77* | *83.88* | *85.65* | *84.27* | *88.33* |
| **Dynamic Shear, 10 rad/sec, specification: G* sin delta <5000 kPa** | | | | | | | | | | |
| PAV G* sin δ, 25.0ºC | 5999 | | | | 6227 | | | | | |
| PAV G* sin δ, 28.0ºC | 4181 | 5950 | | | 4559 | 6017 | | | 5581 | |
| PAV G* sin δ, 31.0ºC | 2861 | 4355 | | | 3246 | 4385 | 5452 | 5558 | 4072 | |
| PAV G* sin δ, 34.0ºC | | | 5339 | 8786 | | | 4018 | 4120 | 2920 | 5267 |
| PAV G* sin δ, 37.0ºC | | | 3886 | 6901 | | | | | 2031 | 3903 |
| PAV G* sin δ, 40.0ºC | | | | 4721 | | | | | | |
| PAV G*, 25.0ºC | 8.55E+6 | | | | | | | | | |
| PAV G*, 28.0ºC | 5.68E+6 | 8.77E+6 | | | 9.83E+6 | 9.46E+6 | | | 8.60E+6 | |
| PAV G*, 31.0ºC | 3.72E+6 | 6.16E+6 | | | 6.73E+6 | 6.50E+6 | 8.35E+6 | 8.78E+6 | 5.95E+6 | |
| PAV G*, 34.0ºC | | | 7.59E+6 | 1.48E+7 | 4.55E+6 | | 5.83E+6 | 6.16E+6 | 4.06E+6 | 7.65E+6 |
| PAV G*, 37.0ºC | | | 5.33E+6 | 1.12E+7 | | | | | 2.70E+6 | 5.42E+6 |
| PAV G*, 40.0ºC | | | | 7.19E+6 | | | | | | |
| PAV δ, 25.0ºC | 44.56 | | | | 39.69 | | | | | |
| PAV δ, 28.0ºC | 47.41 | 42.73 | | | 42.60 | 39.50 | | | 40.45 | |
| PAV δ, 31.0ºC | 50.20 | 45.01 | | | 45.57 | 42.43 | 40.75 | 39.27 | 43.23 | |
| PAV δ, 34.0ºC | | | 44.74 | 36.51 | | | 43.75 | 41.98 | 45.97 | 43.49 |
| PAV δ, 37.0ºC | | | 46.85 | 38.19 | | | | | 48.82 | 45.82 |
| PAV δ, 40.0ºC | | | | 41.08 | | | | | | |
| *PAV failure temp.* | *26.50* | *29.67* | *34.62* | *40.43* | *27.10* | *27.76* | *31.85* | *32.06* | *29.08* | *34.52* |
| **Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300** | | | | | | | | | | |
| Stiffness, 0ºC | | | 142 | 193 | | 87 | 100 | 101 | | 135 |
| M-value, 0ºC | | | 0.338 | 0.276 | | 0.341 | 0.333 | 0.32 | | 0.314 |
| Stiffness, -6ºC | 142 | 174 | 293 | 352 | 140 | 160 | 178 | 181 | 179 | 225 |
| M-value, -6ºC | 0.350 | 0.317 | 0.289 | 0.248 | 0.319 | 0.294 | 0.284 | 0.282 | 0.304 | 0.272 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Stiffness, -12ºC | 279 | 360 | | | 271 | | | | 355 | |
| M-value, -12ºC | 0.297 | 0.276 | | | 0.275 | | | | 0.253 | |
| Stiffness failure temp. | -22.6 | -20.5 | -16.2 | -14.4 | -22.9 | -22.2 | -21.4 | -21.2 | -20.5 | -19.4 |
| M-value failure temp. | -21.7 | -18.5 | -14.7 | -4.9 | -18.6 | -15.2 | -14.0 | -13.2 | -16.5 | -12.0 |
| **Performance Grade** | **82-16** | **82-16** | **82-10** | **NA** | **82-16** | **82-10** | **82-10** | **82-10** | **82-16** | **82-10** |

Shaded cells indicate the failure temperature.

# APPENDIX F

# BINDER MASTERCURVE RESULTS

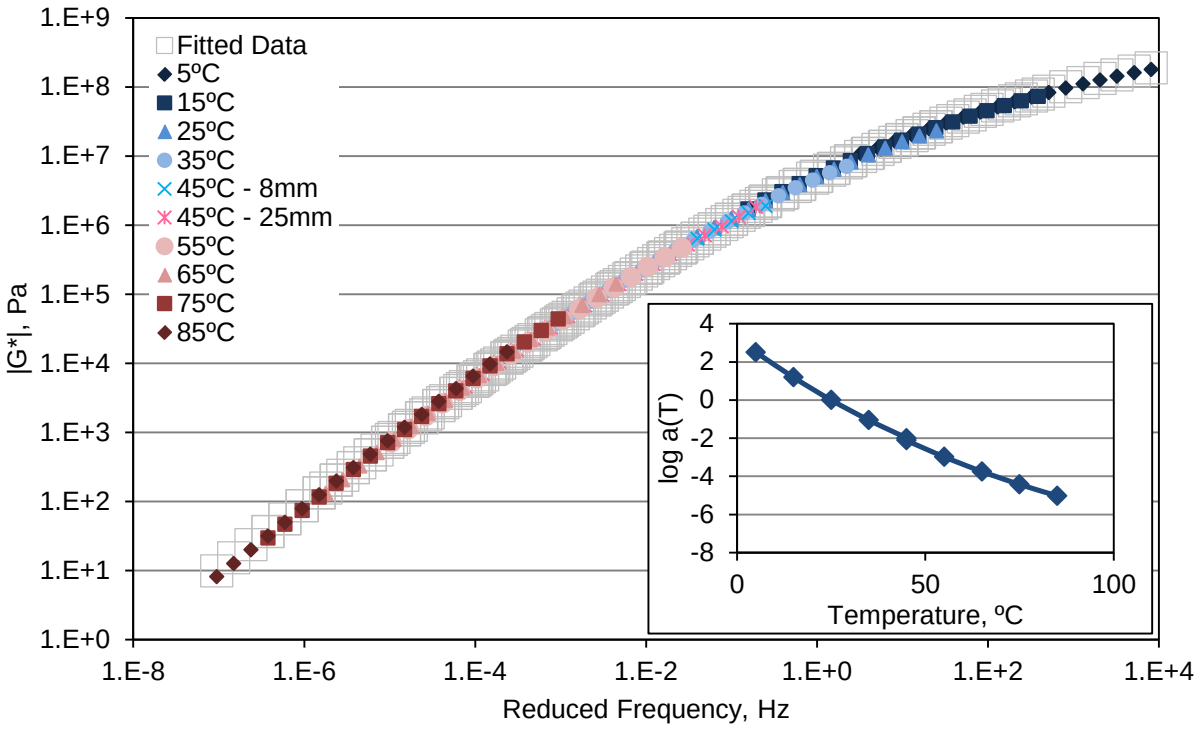


**Figure F1. Extracted Binder Mastercurve for Section A, Bottom Half of Cores**

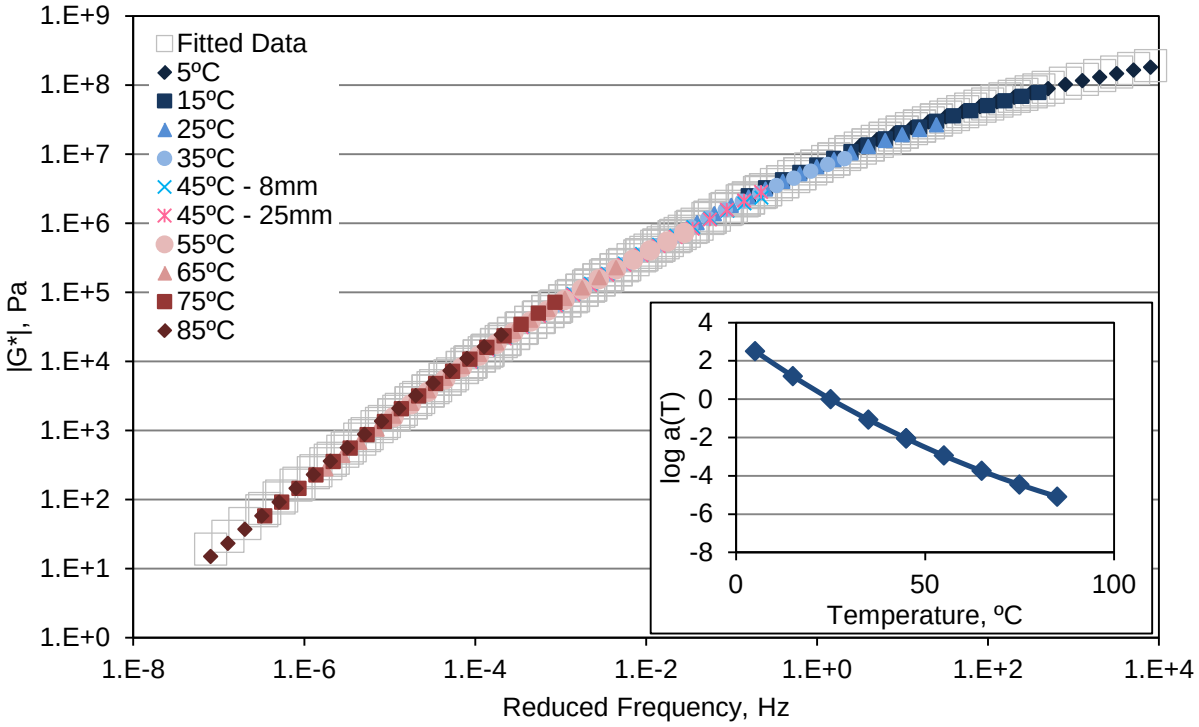


**Figure F2. Extracted Binder Mastercurve for Section A, Top Half of Cores**

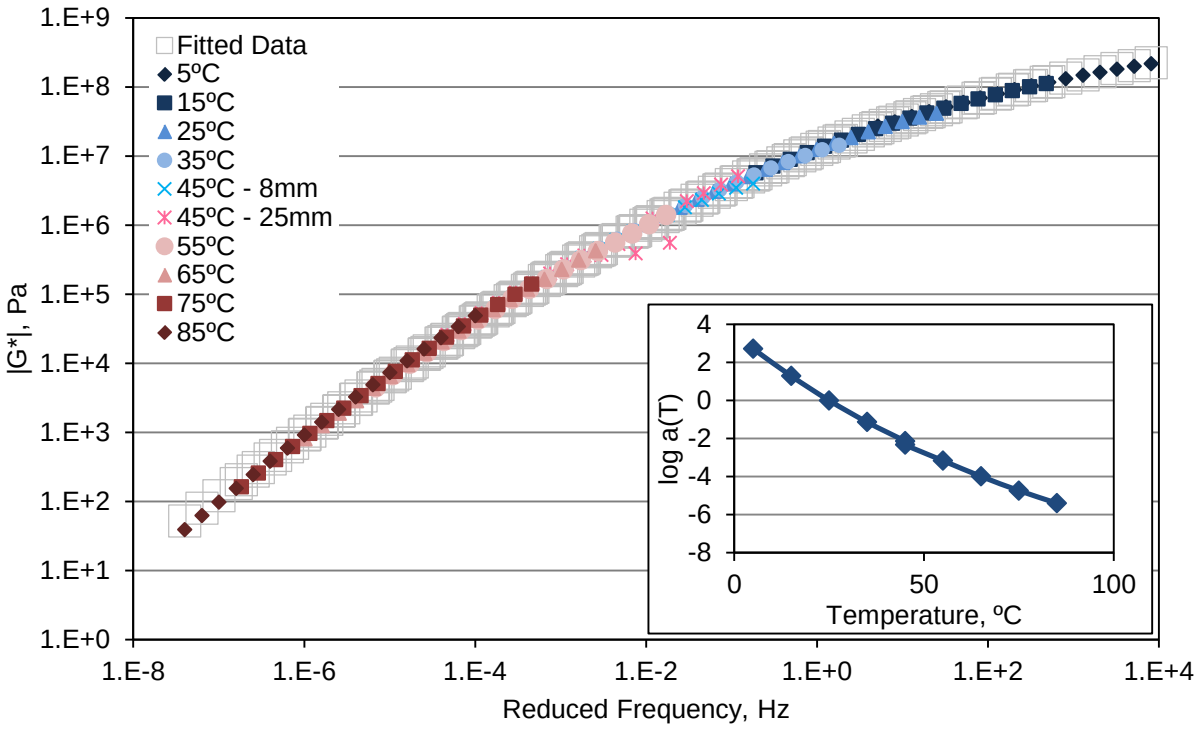


**Figure F3. Extracted Binder Mastercurve for Section B, Bottom Half of Cores**

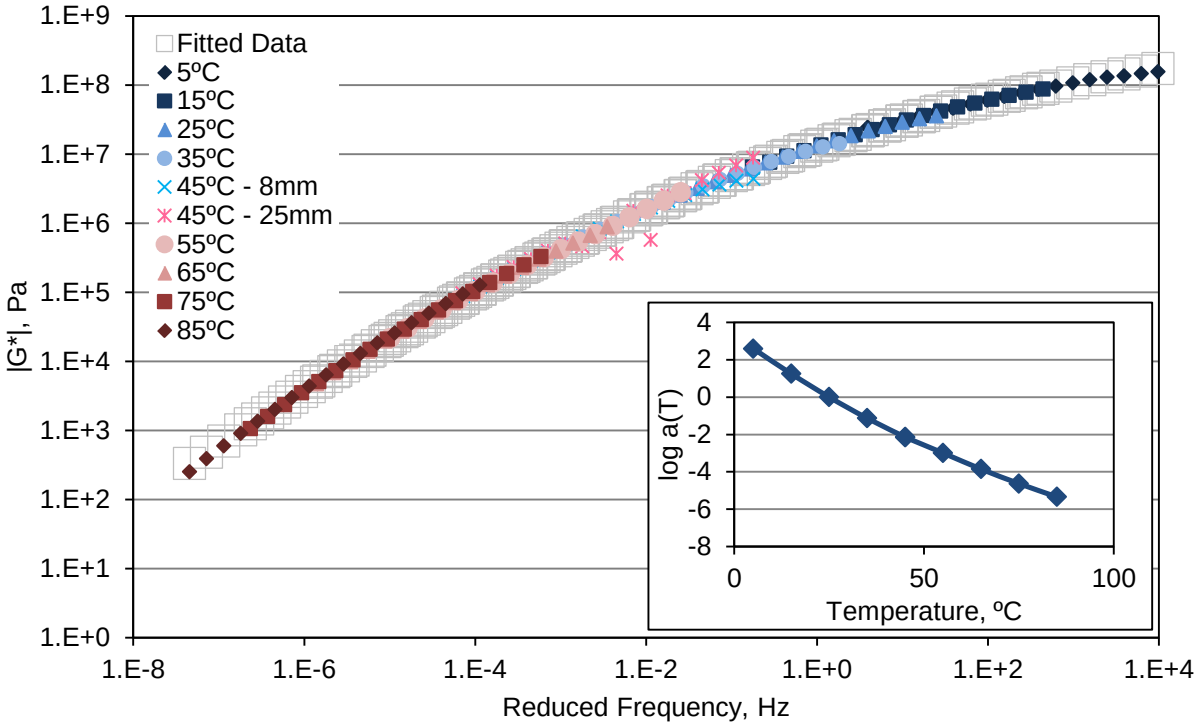


**Figure F4. Extracted Binder Mastercurve for Section B, Top Half of Cores**

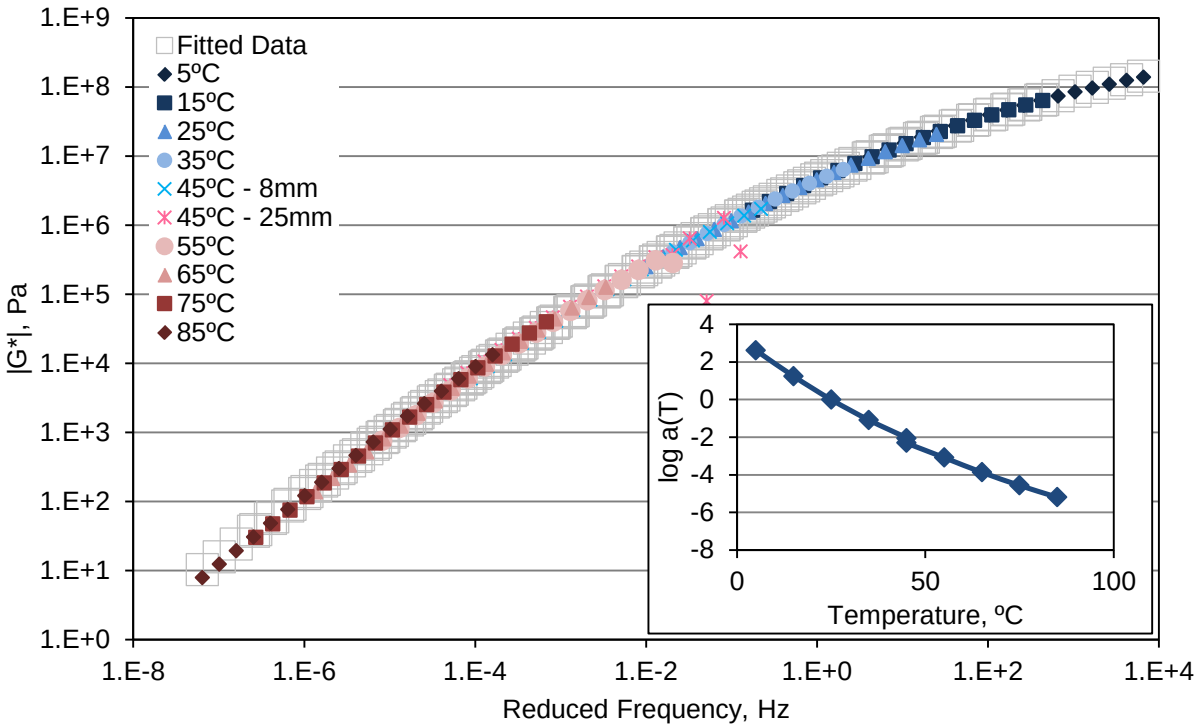


**Figure F5. Extracted Binder Mastercurve for Section B, Intermediate Layer, Entire Core**

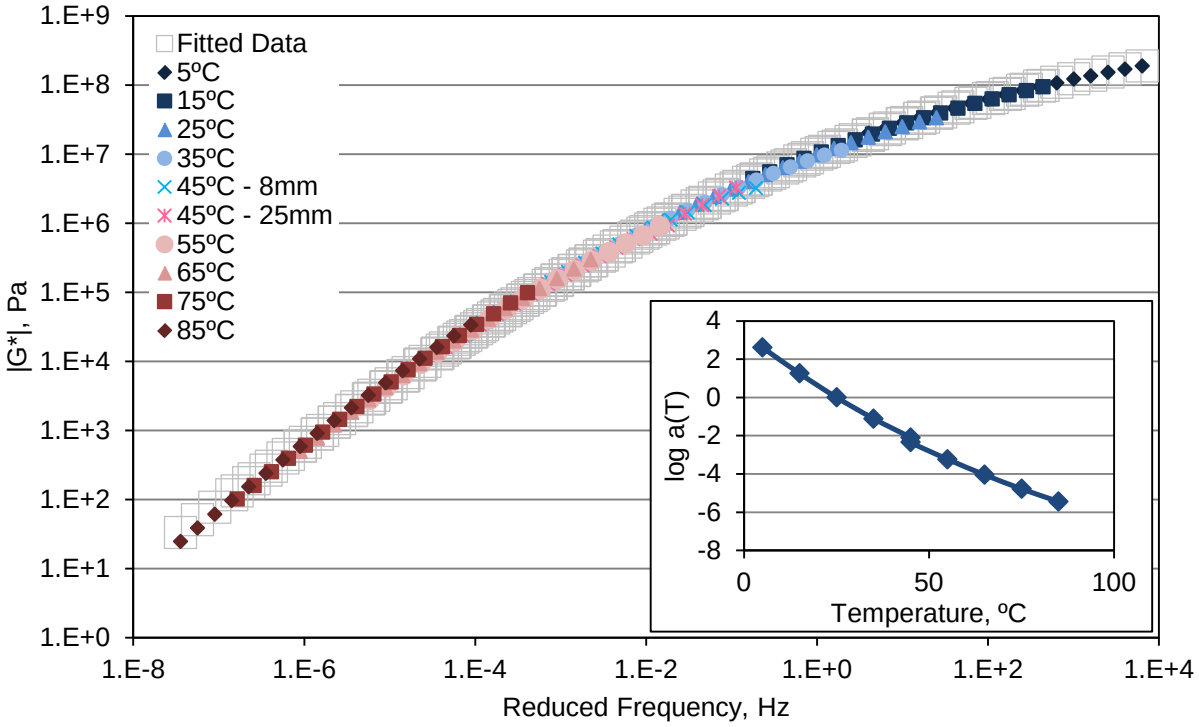


**Figure F6. Extracted Binder Mastercurve for Section C, Entire Core**

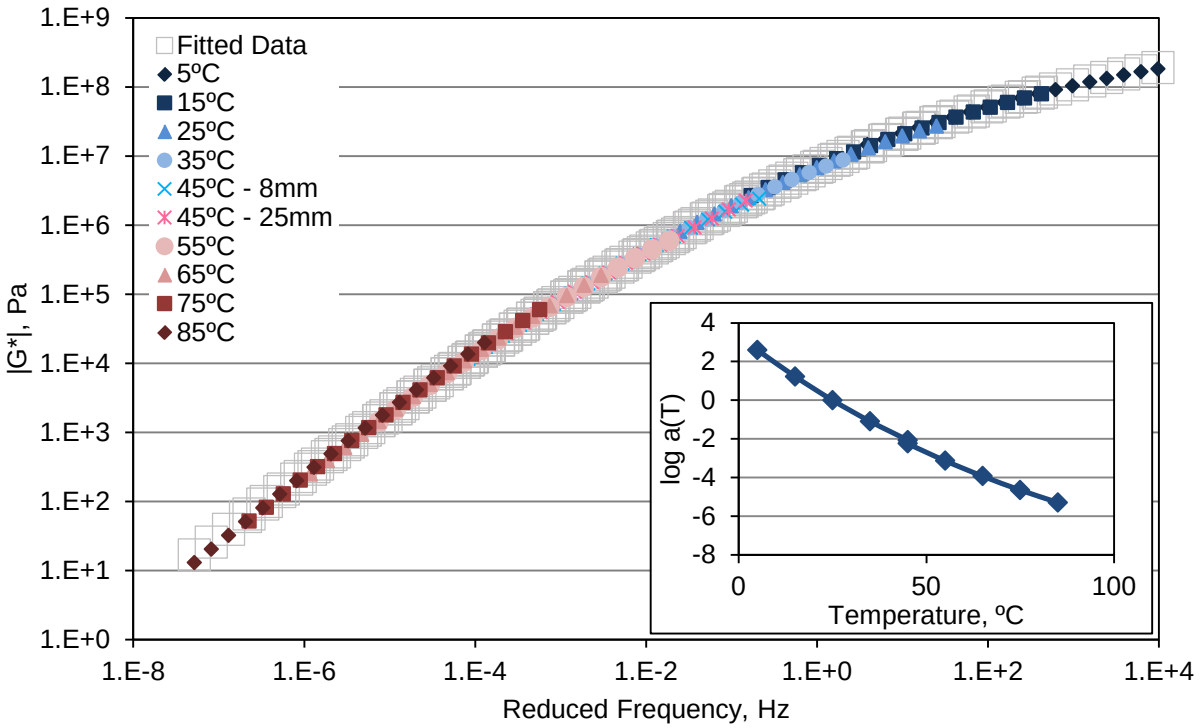


**Figure F7. Extracted Binder Mastercurve for Section D, Entire Core**

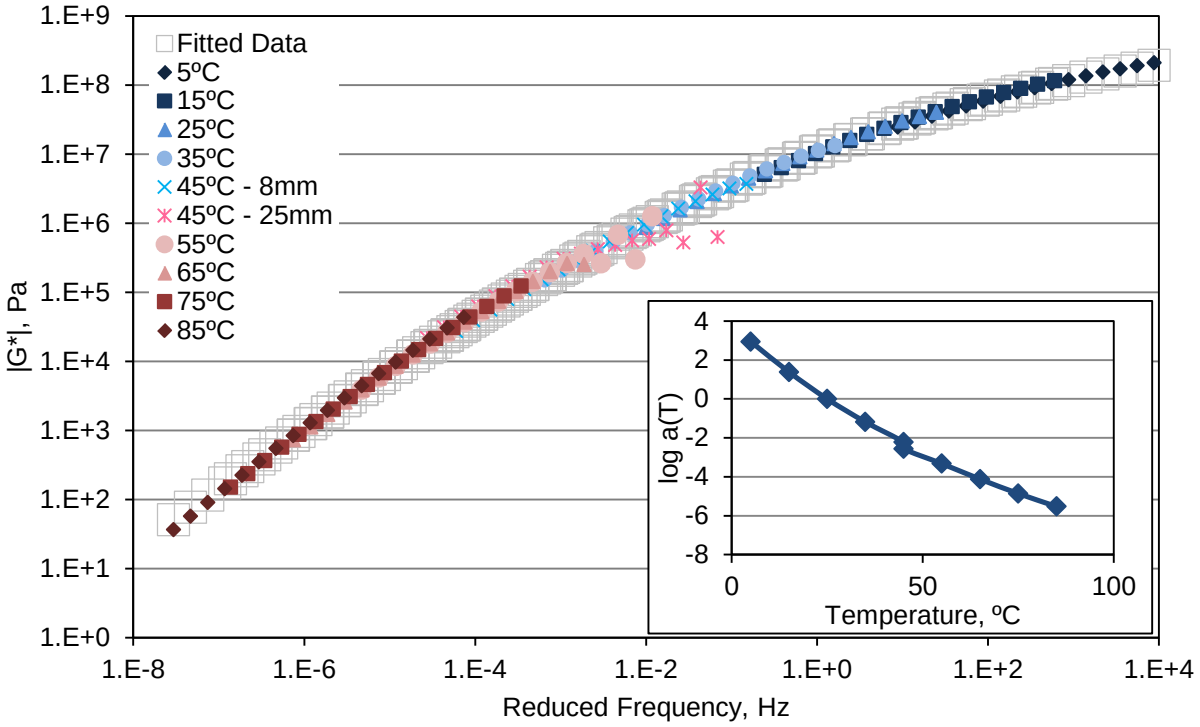


**Figure F8. Extracted binder Mastercurve for Section E, Entire Core**

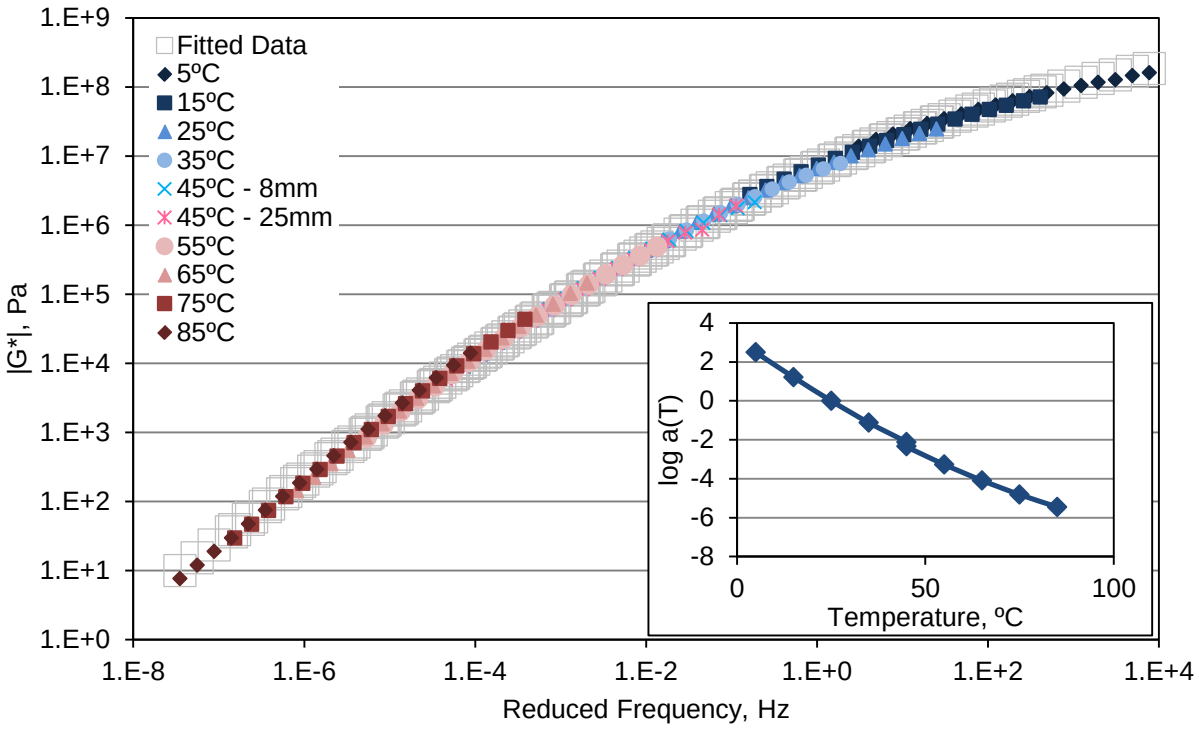


**Figure F9. Extracted Binder Mastercurve for Section F, Bottom Half of Cores**

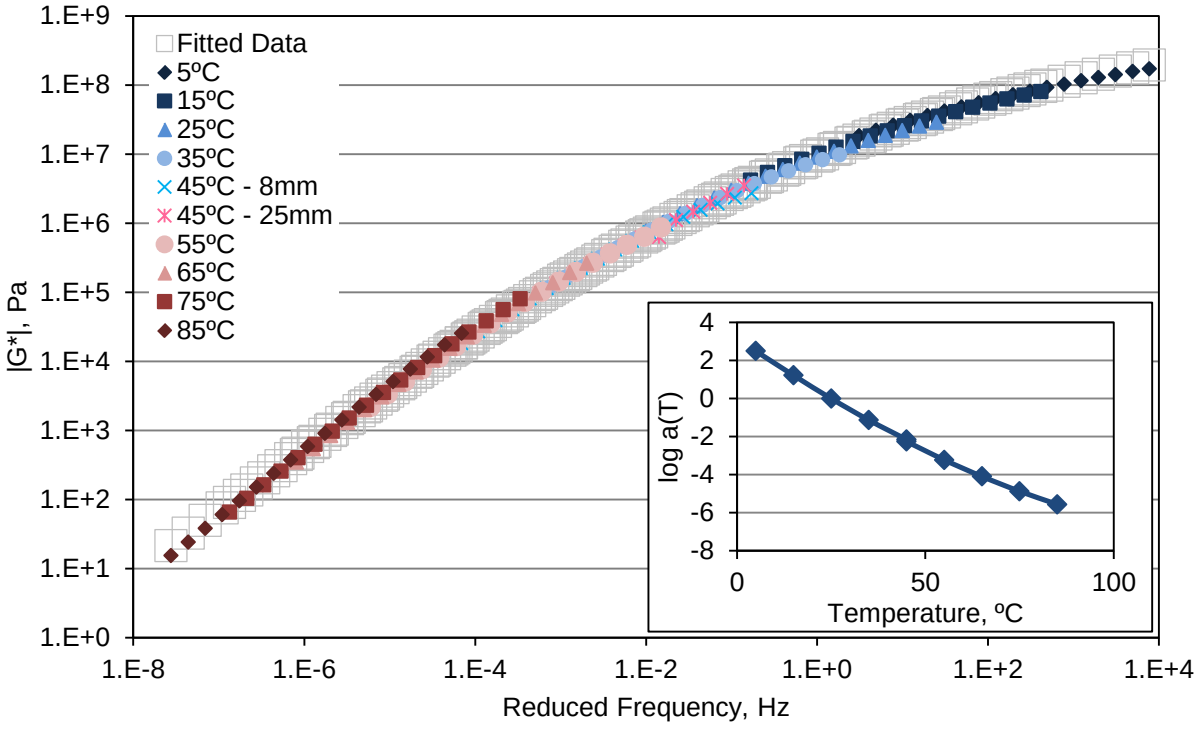


**Figure F10. Extracted Binder Mastercurve for Section F, Top Half of Cores**

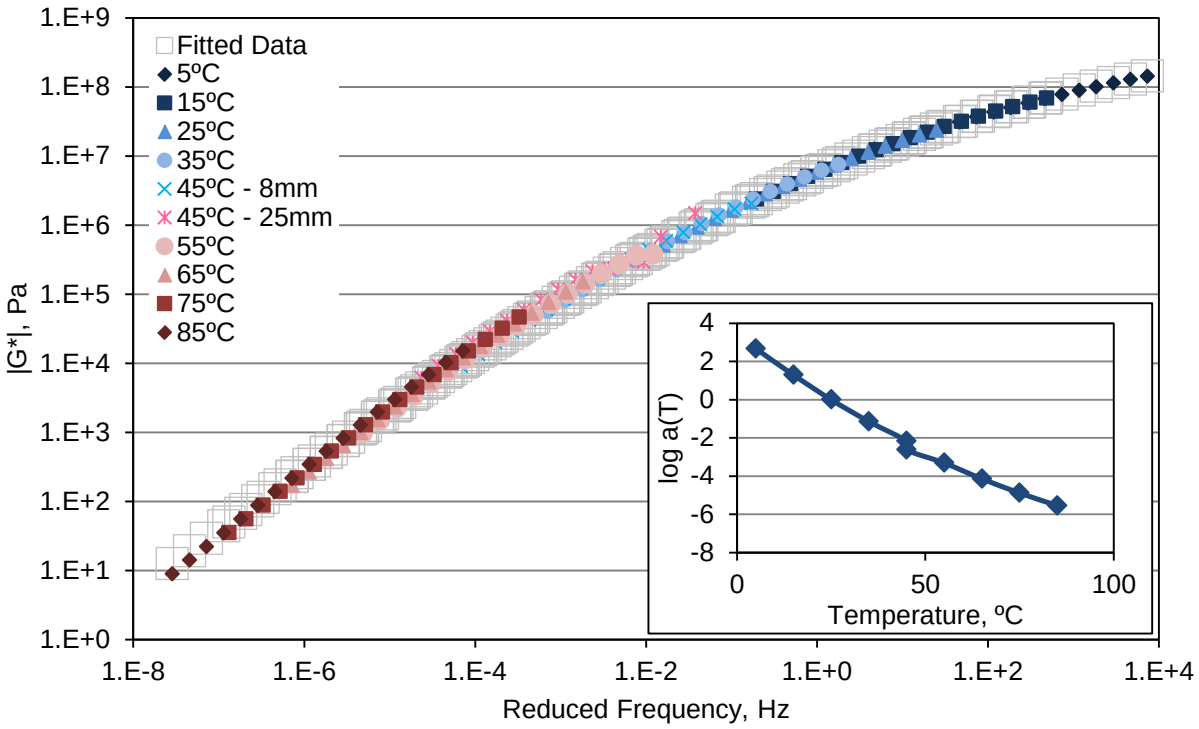


**Figure F11. Extracted Binder Mastercurve for Section H, Bottom Half of Cores**

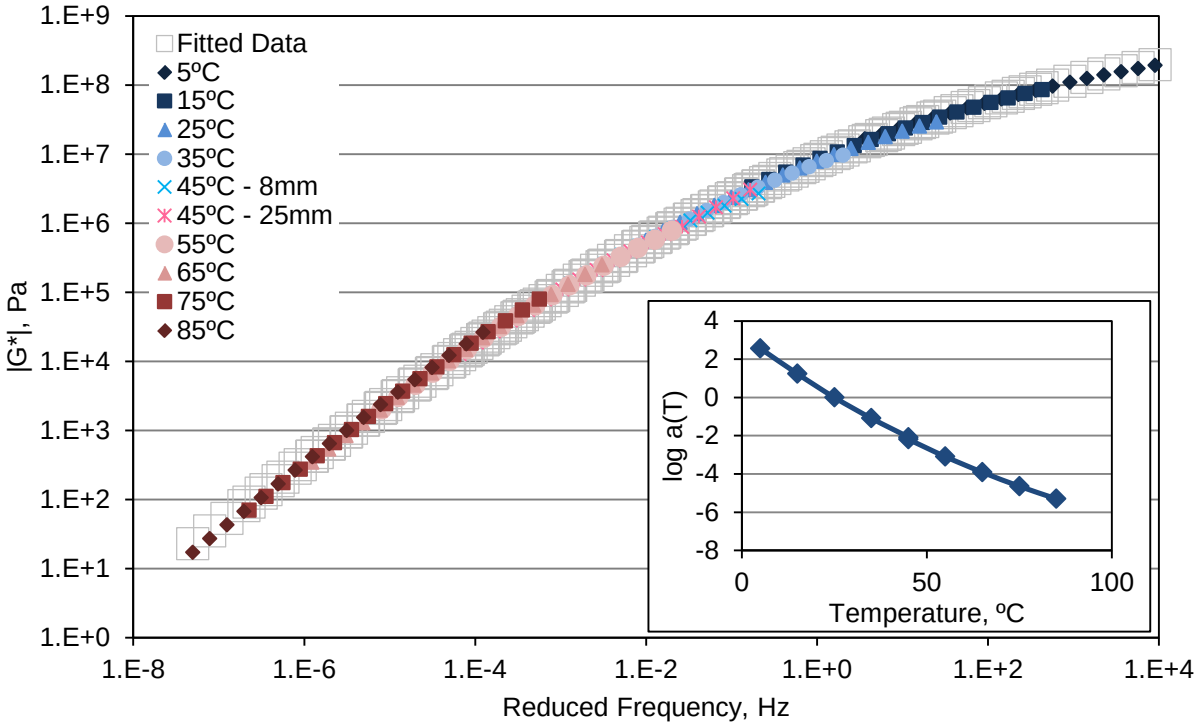


**Figure F12. Extracted Binder Mastercurve for Section H, Top Half of Cores**

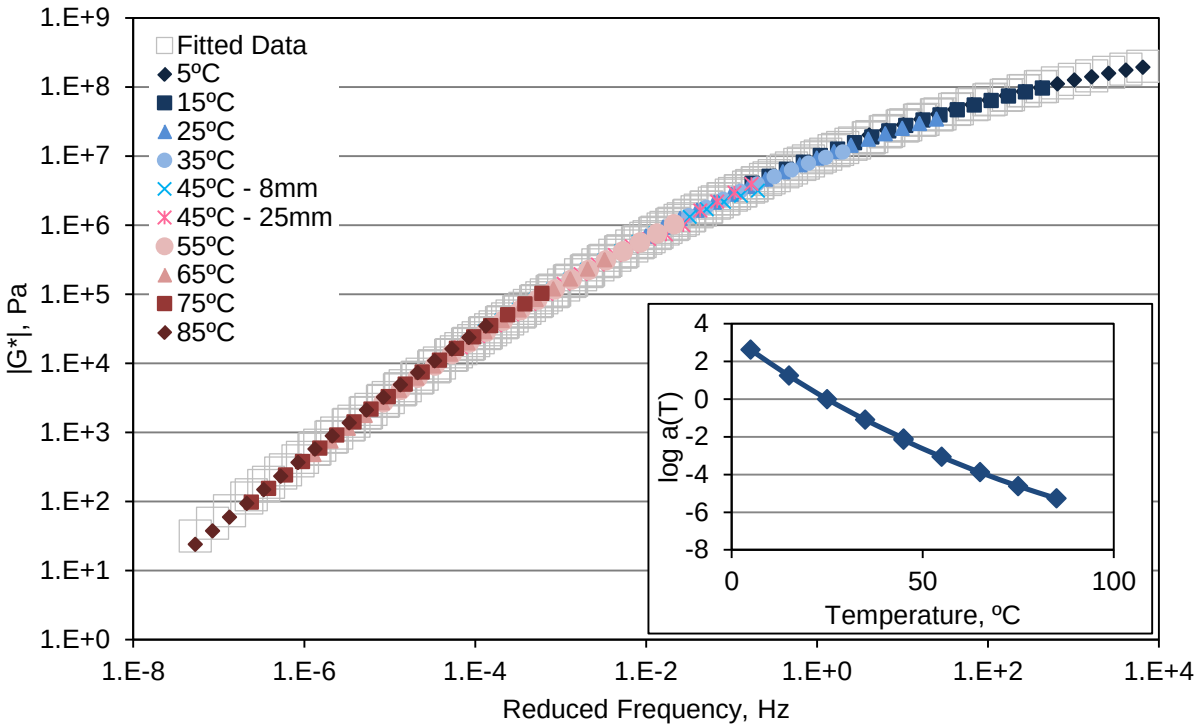


**Figure F13. Extracted Binder Mastercurve for Section I, Bottom Half of Cores**

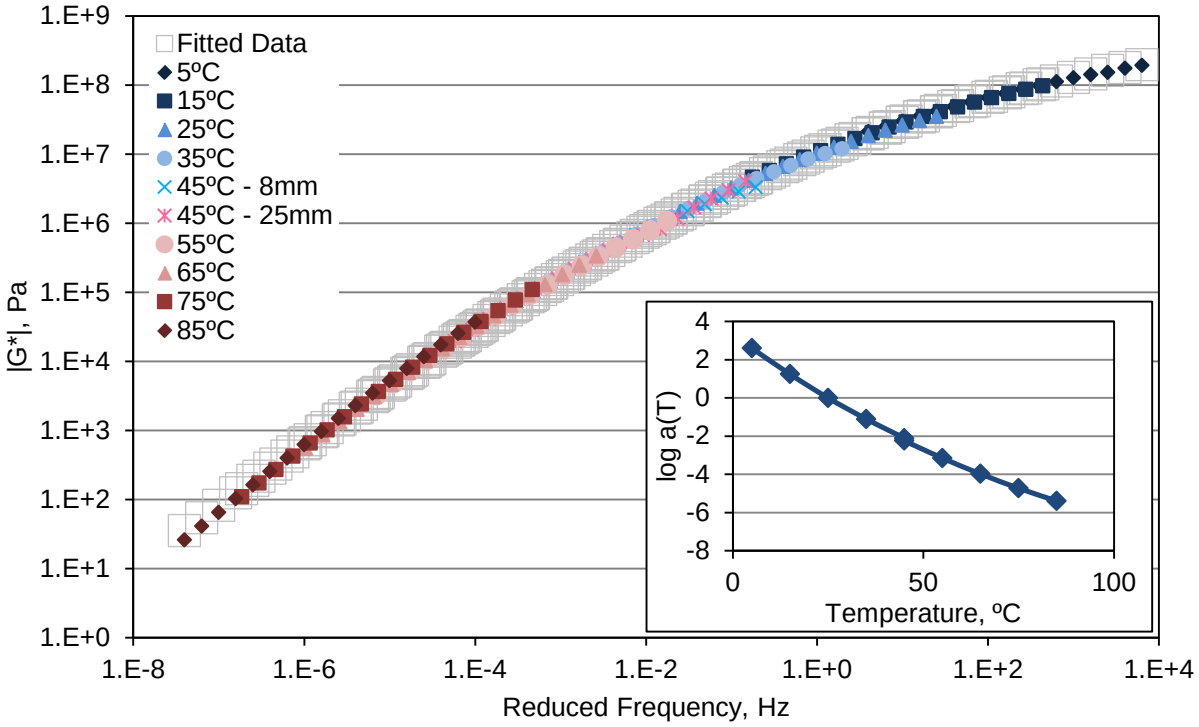


**Figure F14. Extracted Binder Mastercurve for Section I, Top Half of Cores**

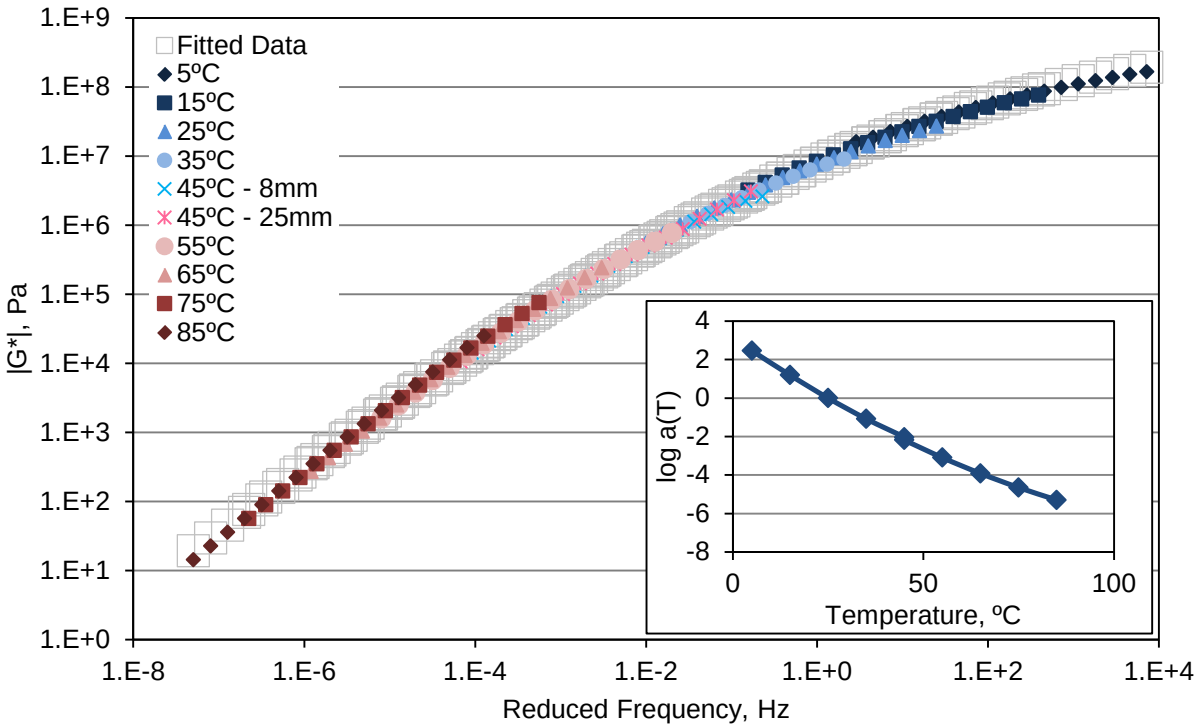


**Figure F15. Extracted Binder Mastercurve for Section J, Entire Core**

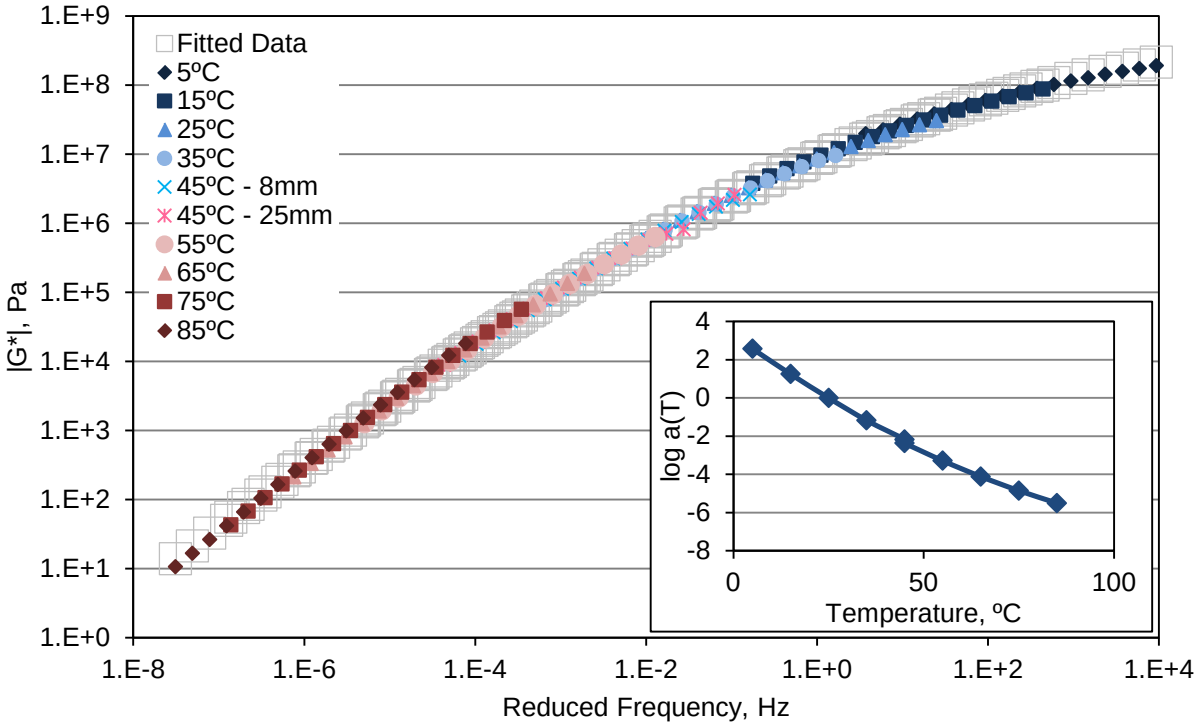


**Figure F16. Extracted Binder Mastercurve for Section K, Entire Core**

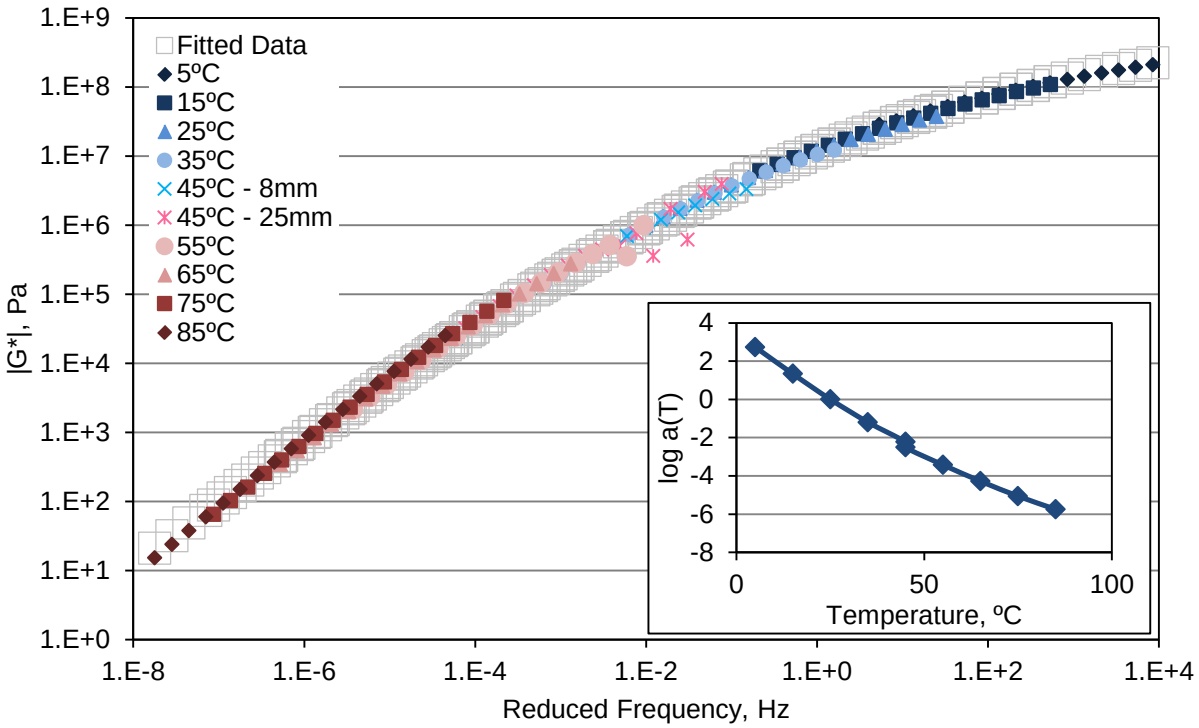


**Figure F17. Extracted Binder Mastercurve for Section L, Entire Core**

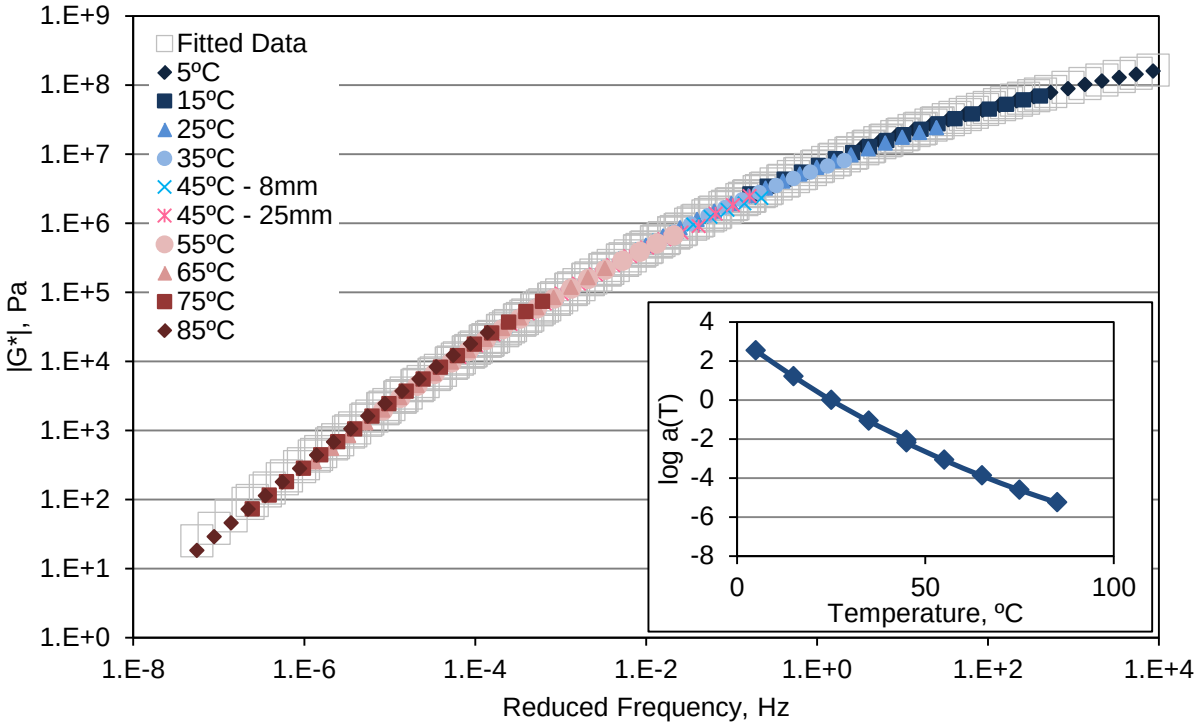


**Figure F18. Extracted Binder Mastercurve for Section M, Entire Core**

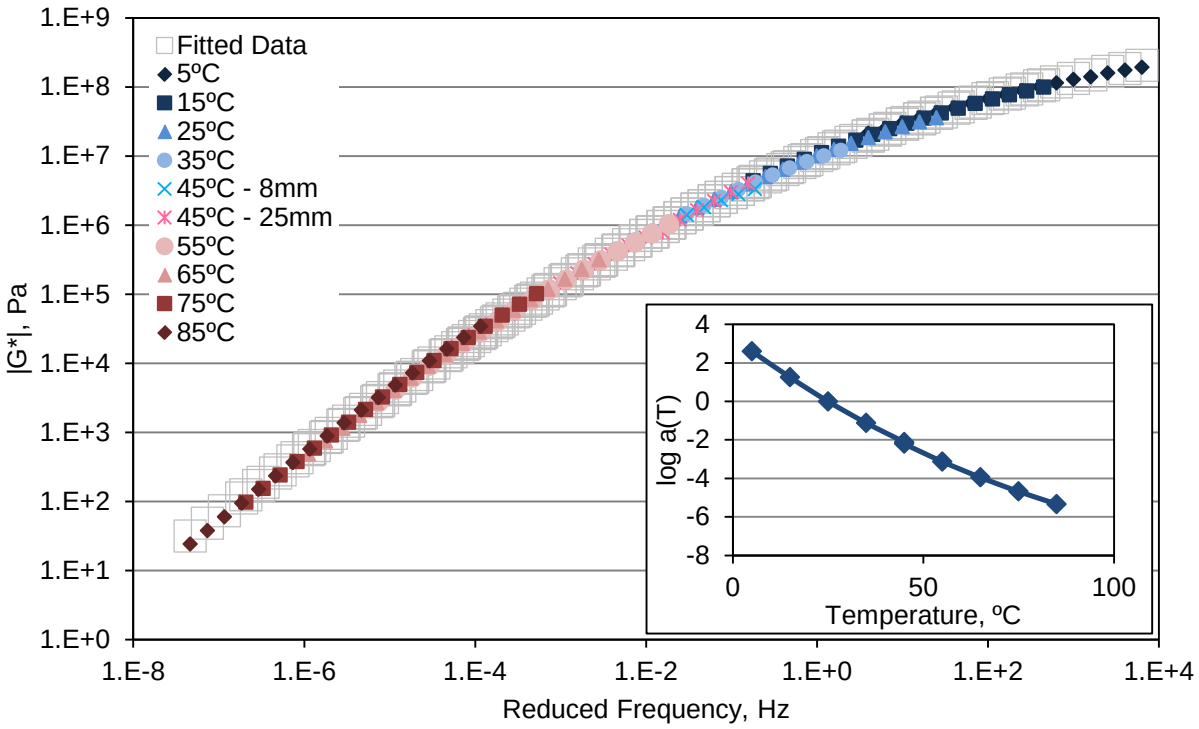


**Figure F19. Extracted Binder Mastercurve for Section N, Bottom Half of Cores**

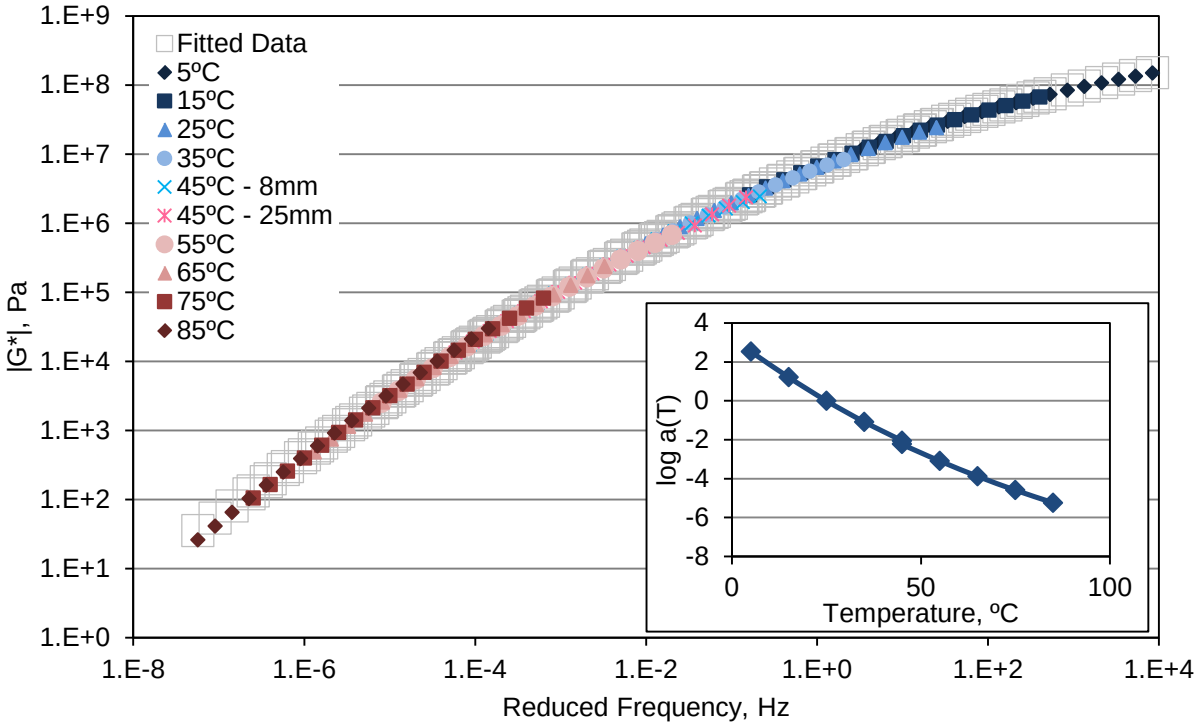


**Figure F20. Extracted Binder Mastercurve for Section N, Top Half of Cores**

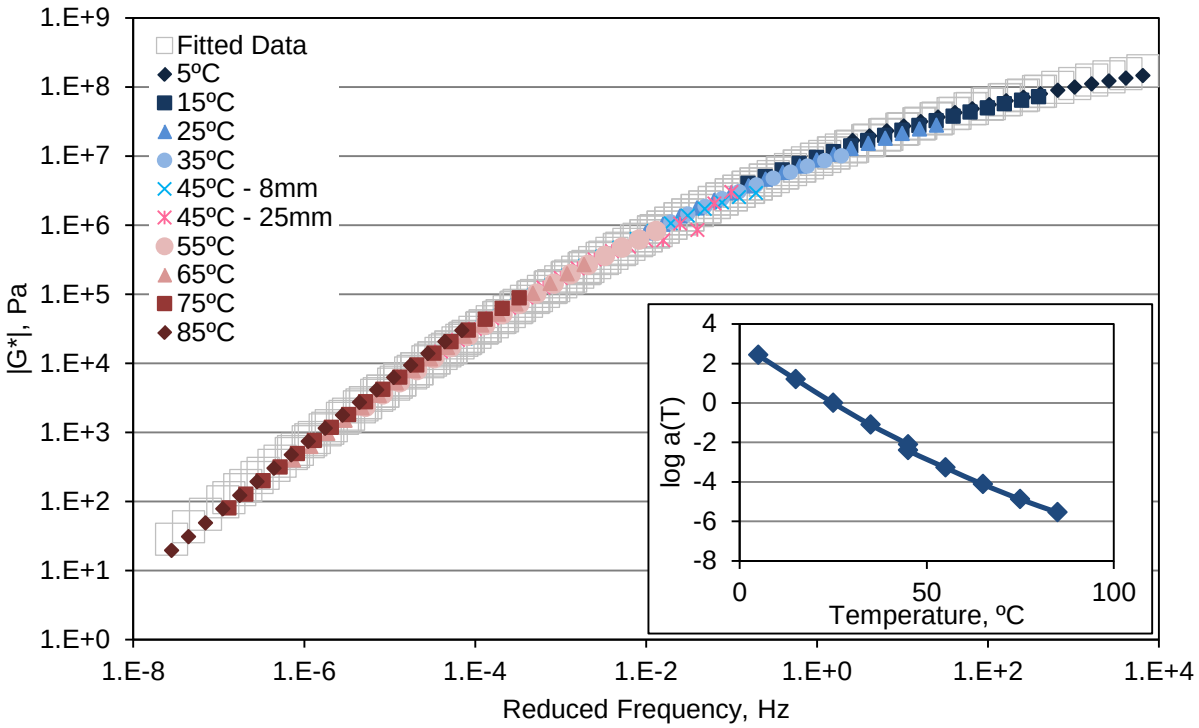


**Figure F21. Extracted Binder Mastercurve for Section O, Entire Core**

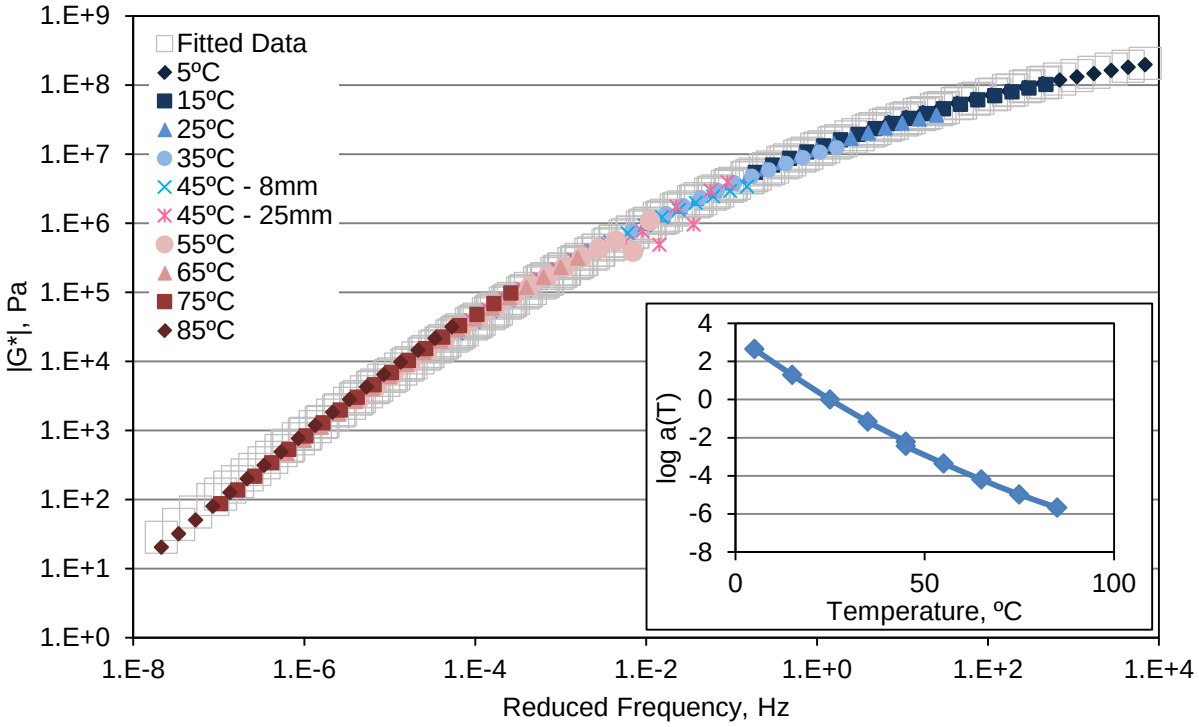


**Figure F22. Extracted Binder Mastercurve for Section P, Entire Core**

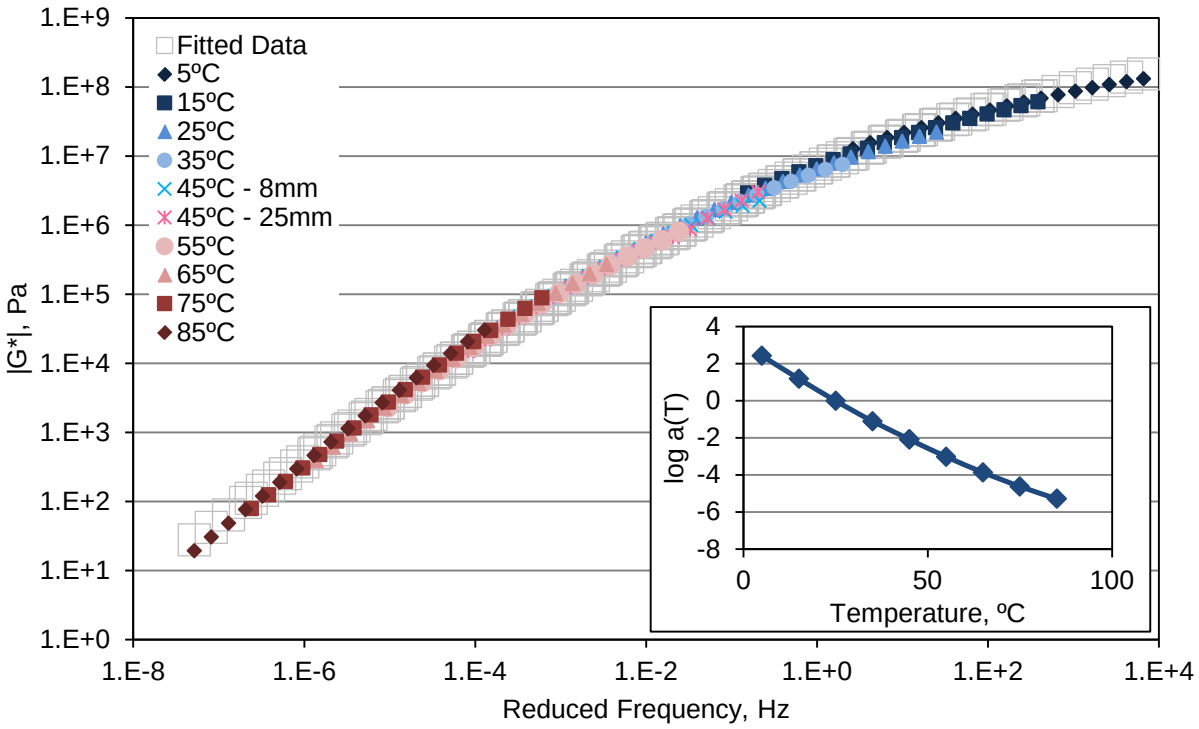


**Figure F23. Extracted Binder Mastercurve for Section Q, Bottom Half of Cores**

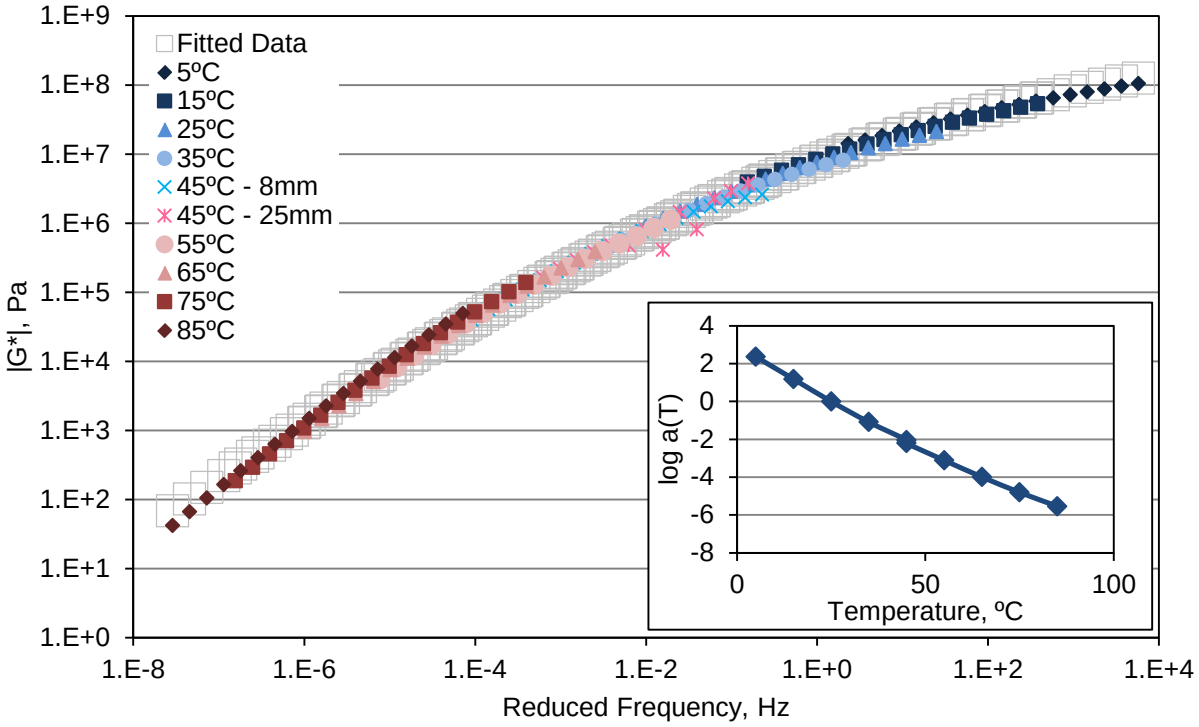


**Figure F24. Extracted Binder Mastercurve for Section Q, Top Half of Cores**

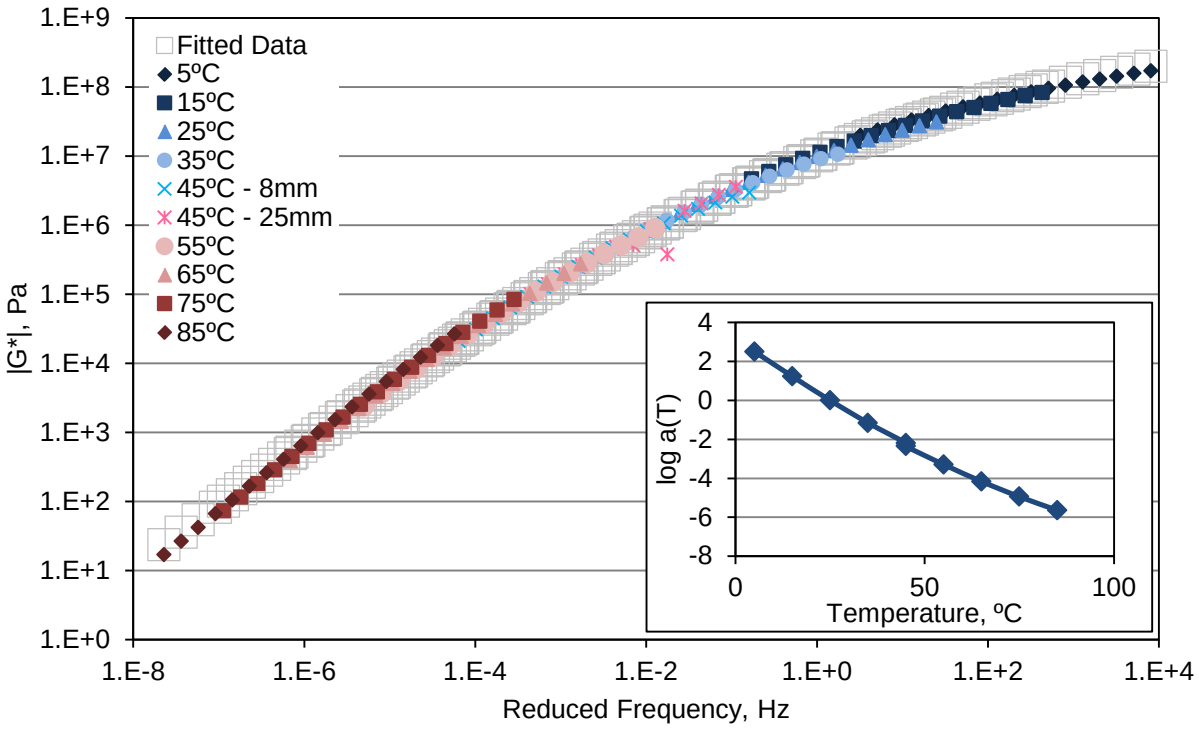


**Figure F25. Extracted Binder Mastercurve for Section R, Bottom Half of Cores**

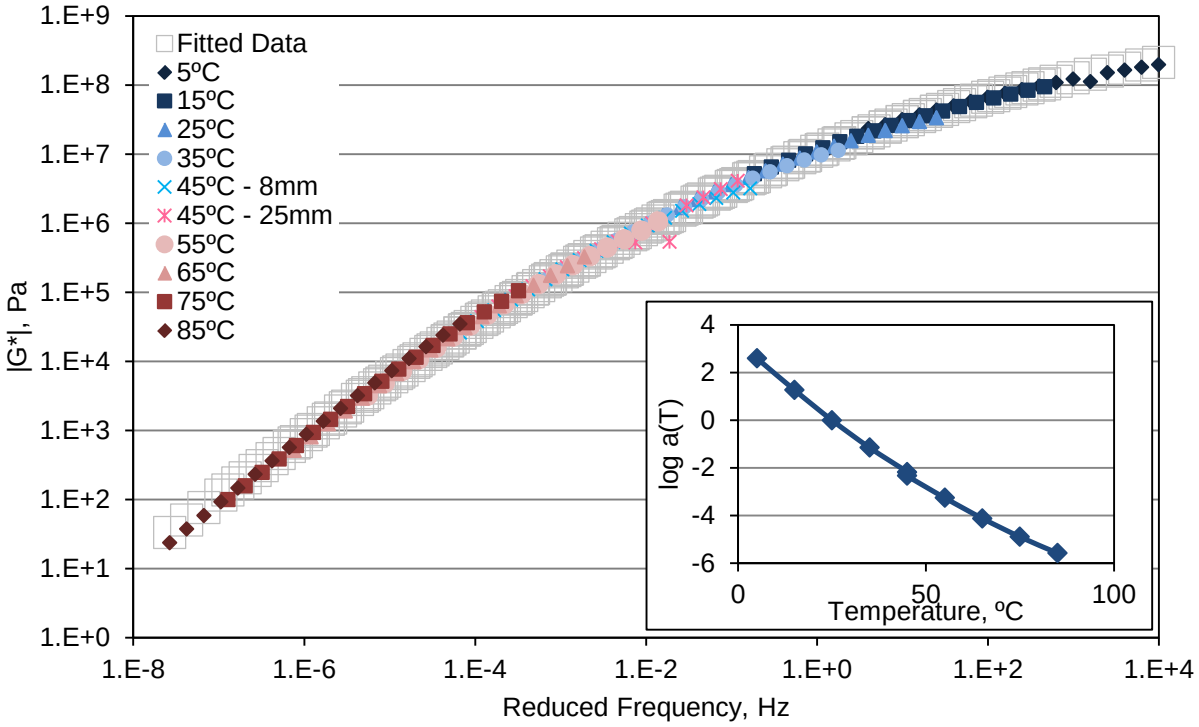


**Figure F26. Extracted Binder Mastercurve for Section R, Top Half of Cores**

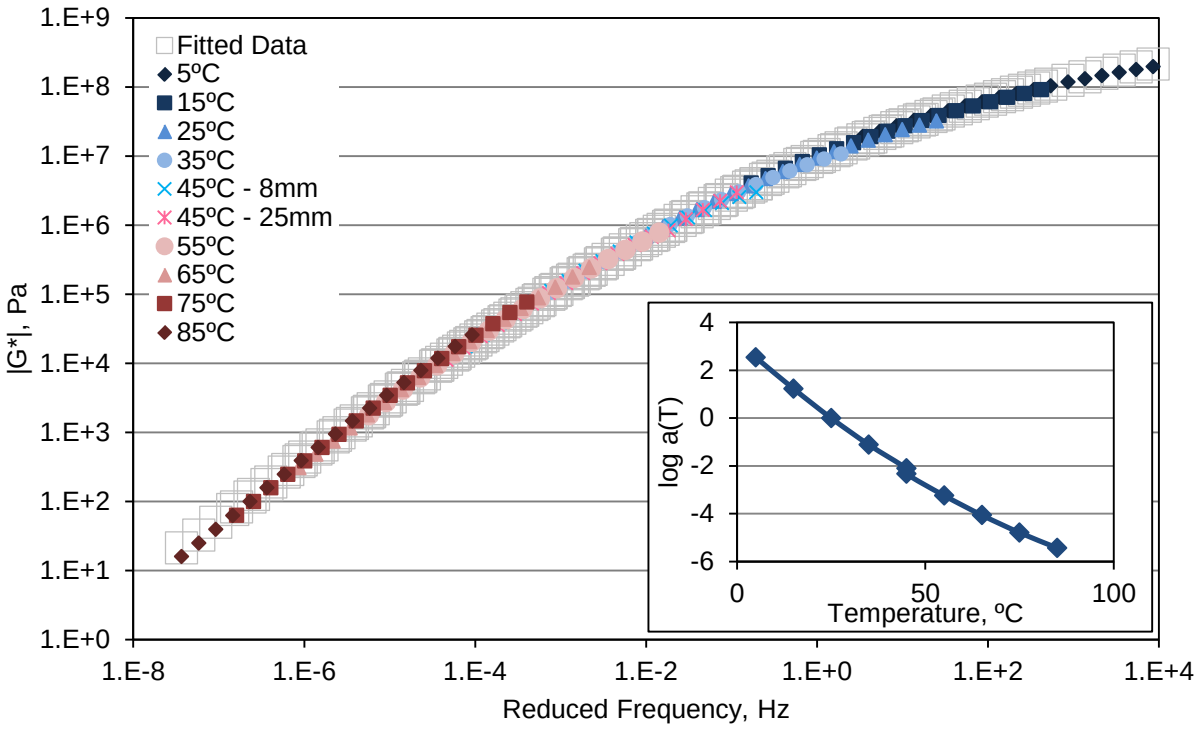


**Figure F27. Extracted Binder Mastercurve for Section S, Bottom Half of Cores**

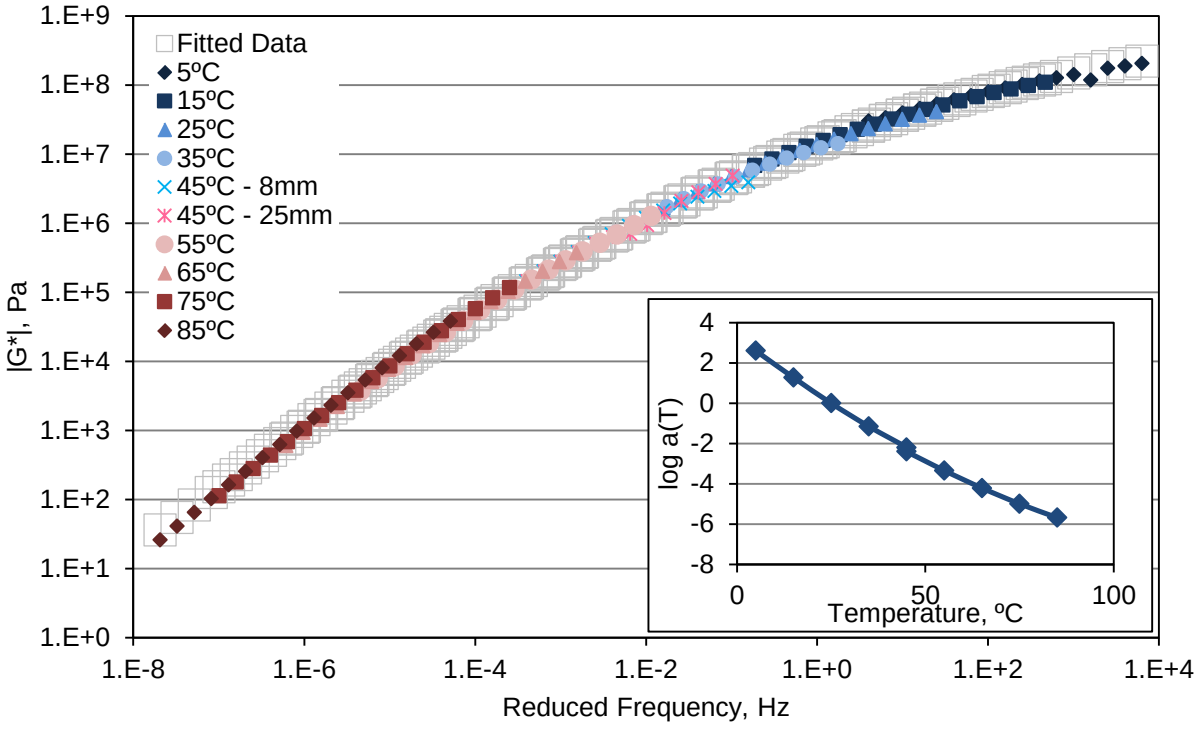


**Figure F28. Extracted Binder Mastercurve for Section S, Top Half of Cores**

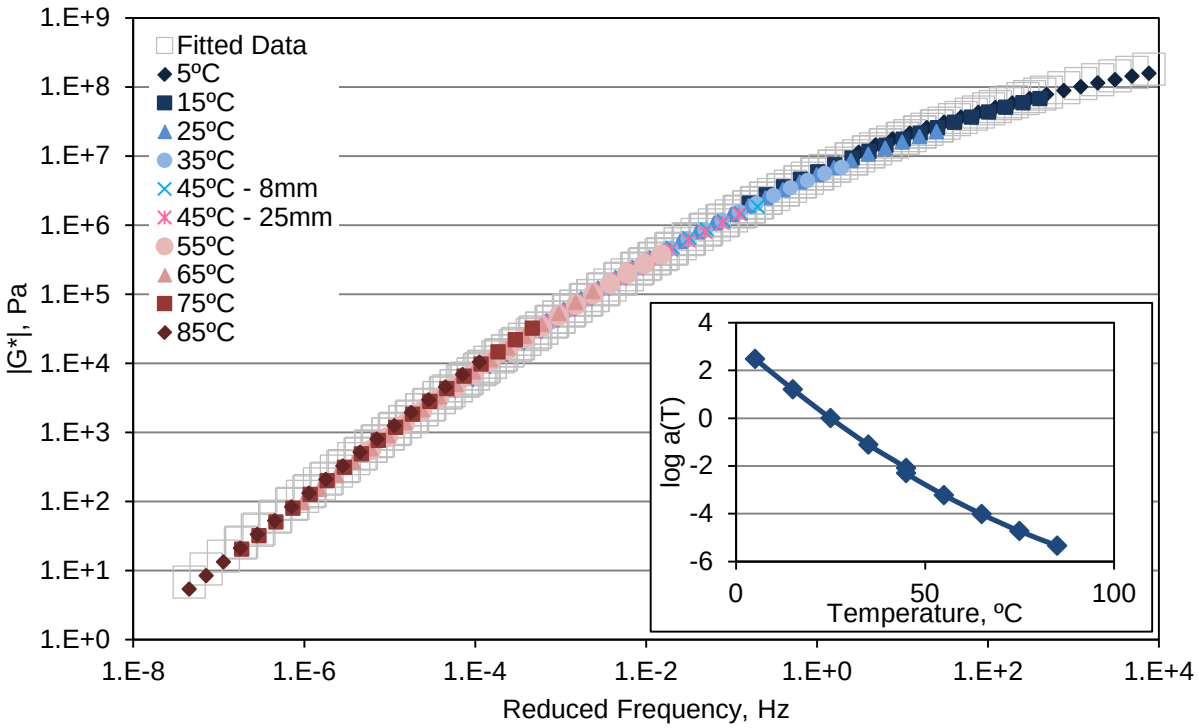


**Figure F29. Extracted Binder Mastercurve for Section U, Entire Core**

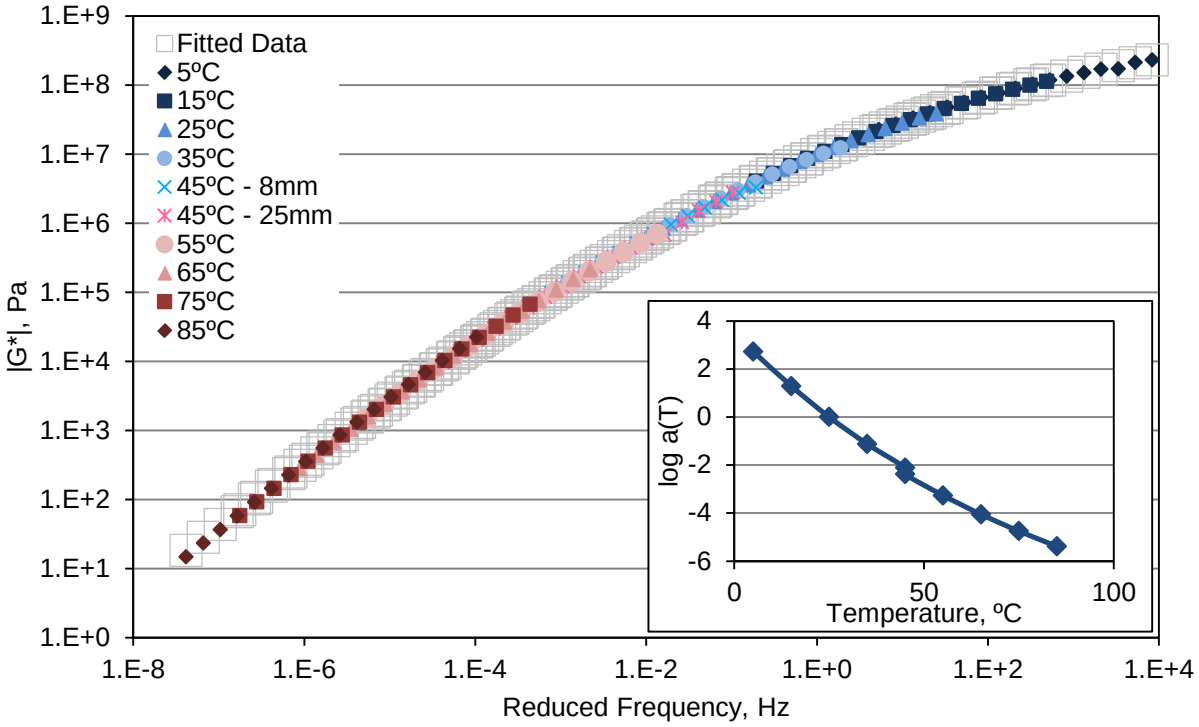


**Figure F30. Extracted Binder Mastercurve for Section V, Bottom Half of Cores**

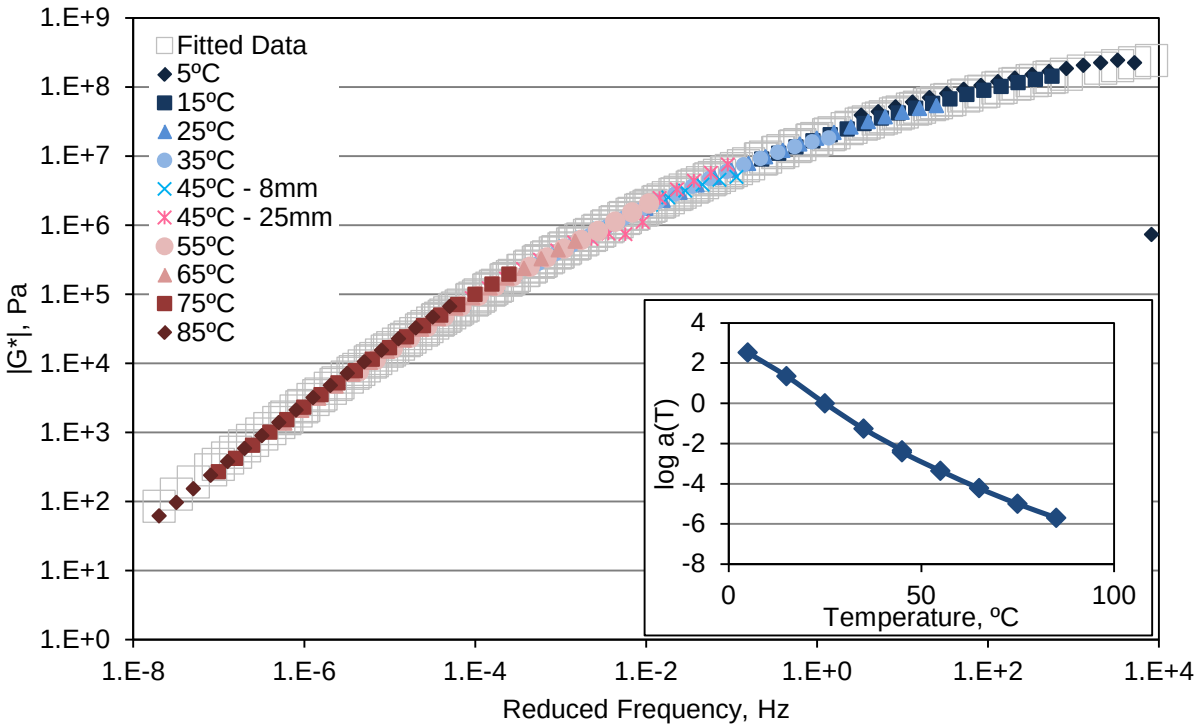


**Figure F31. Extracted Binder Mastercurve for Section V, Top Half of Cores**

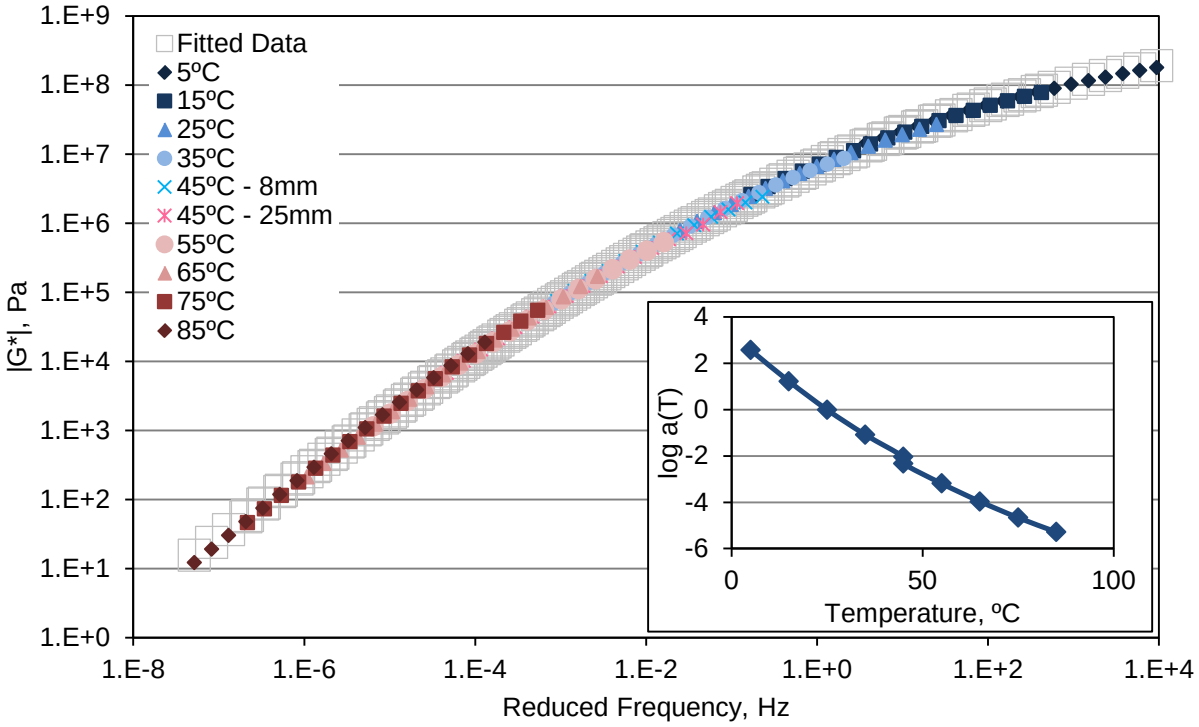


**Figure F32. Extracted Binder Mastercurve for Section W, Entire Core**

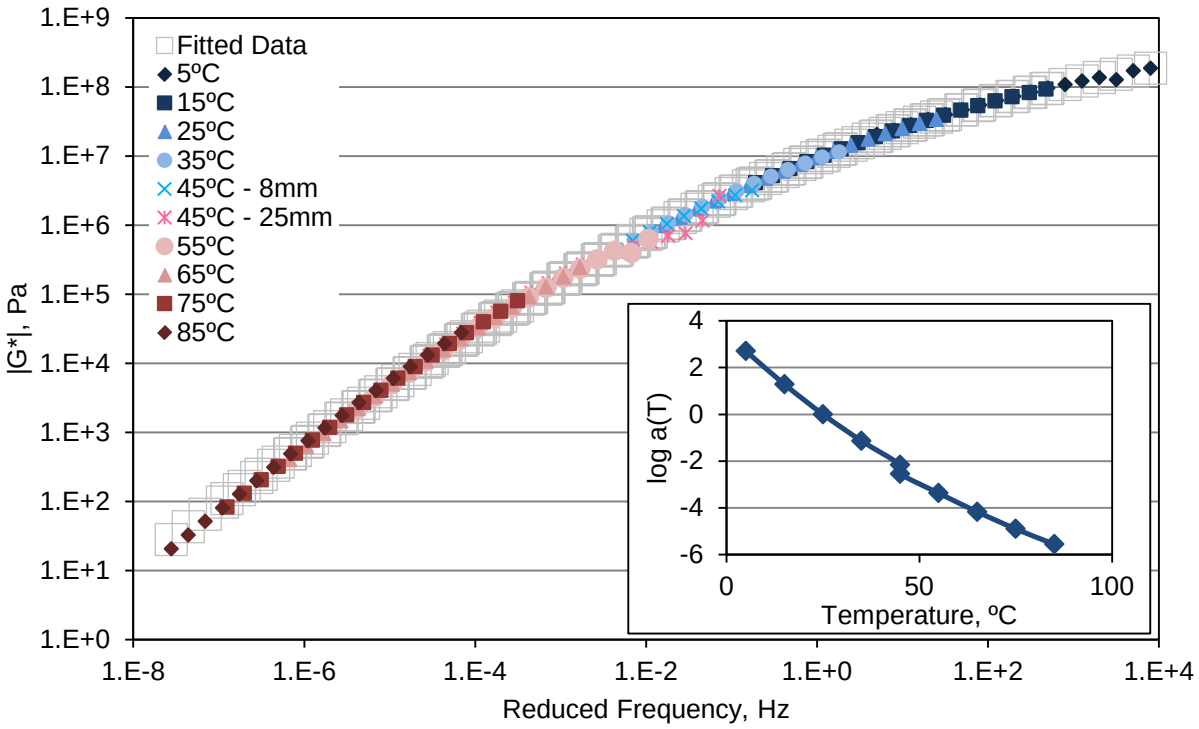


**Figure F33. Extracted Binder Mastercurve for Section X, Entire Core**

# APPENDIX G

# SUPPLEMENTARY ANALYSIS

Since the original work on RAP contents was performed in 2007 (Maupin et al., 2008) the specifications for RAP and binder grade contents for dense-graded mixtures have evolved. During the review of this work, it was requested that consideration be given to performing analyses with more recent specifications applied to the evaluated mixtures. These specifications changed the minimum RAP content for binder grade adjustments to dense-graded mixtures from >20% to >25%, as shown in Table G1, excerpted from VDOT specifications (VDOT, 2012).

Applying this specification to the evaluated sites in this study resulted in the deletion of two sites: O and P. These sites do not meet the requirement shown in Table G1 as they do not contain PG 70-22 binder in conjunction with the mixture RAP content of 21%. All remaining sites were considered under their original designation of comparison or RAP sites.

In addition, concerns were raised about the inclusion of three comparison sites paved with WMA. Experience and the data indicated that there were no significant differences between HMA and WMA; however, these three sites (K, H, and M) were also removed from the dataset evaluated in this appendix.

**Table G1. Recent Specifications for Binder Grade and Percentage of RAP**

TABLE II-14A
Recommended Performance Grade of Asphalt Cement

| Mix Type | Percentage of Reclaimed Asphalt Pavement (RAP) in Mix | | |
|---|---|---|---|
| | % RAP ≤ 25% | 25.0% < % RAP ≤ 30% | 25.0% < % RAP ≤ 35% |
| SM-4.75A, SM-9.0A, SM-9.5A, SM-12.5A | PG 64-22 | PG 64-22 | |
| SM-4.75D, SM-9.0D, SM-9.5D, SM-12.5D | PG 70-22 | PG 64-22 | |
| IM-19.0A | PG 64-22 | PG 64-22 | |
| IM-19.0D | PG 70-22 | PG 64-22 | |
| BM-25.0A | PG 64-22 | | PG 64-22 |
| BM-25.0D | PG 70-22 | | PG 64-22 |

Source: VDOT, 2012.

## Visual Survey Data

Visual survey data were compiled and analyzed for the 18 sections addressed in this Appendix. A summary of the data is shown in Table G2.

**Table G2. Summary of Visual Distress Surveys**

| **Fatigue Cracking, ft²** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Comparison Site | Low | Medium | High | RAP Site | Low | Medium | High |
| E | 1240 | 600 | 5800 | A | 3608 | 1650 | 249 |
| I | 0 | 998 | 0 | B | 18040 | 4530 | 500 |
| L | 0 | 8 | 0 | C | 2017 | 0 | 0 |
| N | 0 | 0 | 0 | D | 1736 | 0 | 0 |
| Q | 0 | 988.2 | 0 | F | 0 | 0 | 0 |
| T | 0 | 502.2 | 0 | J | 112 | 0 | 0 |
| V | 0 | 0 | 0 | R | 0 | 319 | 0 |
| W | 0 | 20.9 | 0 | S | 0 | 101.1 | 0 |
| | | | | U | 0 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Tot. Quantity | 1240 | 3117.3 | 5800 | Tot. Quantity | 25513 | 6600.1 | 749 |
| No. Sites w/ Distress | 1 | 6 | 1 | No. Sites w/ Distress | 5 | 4 | 2 |
| % Sites w/ Distress | 13% | 75% | 13% | % Sites w/ Distress | 50% | 40% | 20% |
| **Longitudinal Cracking, Wheelpath, ft** | | | | | | | |
| Comparison Site | Low | Medium | High | RAP Site | Low | Medium | High |
| E | 0 | 0 | 0 | A | 0 | 0 | 0 |
| I | 0 | 3000 | 0 | B | 40 | 0 | 0 |
| L | 67 | 72 | 0 | C | 22 | 0 | 0 |
| N | 0 | 0 | 0 | D | 49 | 0 | 0 |
| Q | 0 | 3.4 | 0 | F | 0 | 0 | 0 |
| T | 136.3 | 211.7 | 0 | J | 39 | 232 | 0 |
| V | 0 | 0 | 0 | R | 0 | 1208 | 0 |
| W | 0 | 450.2 | 0 | S | 25.2 | 8034 | 0 |
| | | | | U | 6.2 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Tot. Quantity | 203.3 | 3737.3 | 0 | Tot. Quantity | 181.4 | 9474 | 0 |
| No. Sites w/ Distress | 2 | 5 | 0 | No. Sites w/ Distress | 6 | 3 | 0 |
| % Sites w/ Distress | 25% | 63% | 0% | % Sites w/ Distress | 60% | 30% | 0% |
| **Longitudinal Cracking, Non-wheelpath, ft** | | | | | | | |
| Comparison Site | Low | Medium | High | RAP Site | Low | Medium | High |
| E | 0 | 0 | 44 | A | 0 | 1000 | 1000 |
| I | 0 | 25 | 0 | B | 130 | 110 | 250 |
| L | 0 | 1112 | 0 | C | 16 | 0 | 0 |
| N | 0 | 1000 | 0 | D | 0 | 0 | 0 |
| Q | 0 | 0 | 0 | F | 0 | 406 | 0 |
| T | 0 | 343.3 | 0 | J | 184 | 92 | 0 |
| V | 0 | 0 | 0 | R | 0 | 39 | 0 |
| W | 0 | 202.3 | 0 | S | 115.7 | 480.8 | 0 |
| | | | | U | 0 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Tot. Quantity | 0 | 2682.6 | 44 | Tot. Quantity | 445.7 | 2127.8 | 1250 |
| No. Sites w/ Distress | 0 | 4 | 1 | No. Sites w/ Distress | 4 | 6 | 2 |
| % Sites w/ Distress | 0% | 50% | 13% | % Sites w/ Distress | 40% | 60% | 20% |
| **Transverse Cracking, Unsealed, ft** | | | | | | | |
| Comparison Site | Low | Medium | High | RAP Site | Low | Medium | High |
| E | 0 | 33 | 0 | A | 0 | 0 | 0 |
| I | 0 | 0 | 0 | B | 0 | 0 | 0 |
| L | 0 | 17 | 0 | C | 9.5 | 0 | 0 |
| N | 168 | 204 | 228 | D | 0 | 0 | 0 |
| Q | 0 | 12 | 0 | F | 0 | 161 | 0 |
| T | 5 | 7 | 0 | J | 0 | 0 | 0 |
| V | 147 | 36 | 0 | R | 0 | 20 | 0 |
| W | 0 | 6 | 0 | S | 12 | 34 | 0 |
| | | | | U | 31 | 24 | 0 |
| | | | | X | 0 | 0 | 0 |
| Tot. Quantity | 320 | 315 | 228 | Tot. Quantity | 52.5 | 239 | 0 |
| No. Sites w/ Distress | 3 | 7 | 1 | No. Sites w/ Distress | 3 | 4 | 0 |
| % Sites w/ Distress | 18% | 64% | 9% | % Sites w/ Distress | 25% | 33% | 0% |

| **Raveling, ft$^2$** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Comparison Site | Low | Medium | High | RAP Site | Low | Medium | High |
| E | 0 | 0 | 0 | A | 0 | 0 | 0 |
| I | 0 | 0 | 0 | B | 720 | 860 | 0 |
| L | 0 | 0 | 0 | C | 0 | 0 | 0 |
| N | 0 | 0 | 0 | D | 66 | 0 | 0 |
| Q | 0 | 5 | 0 | F | 0 | 0 | 0 |
| T | 0 | 0 | 0 | J | 0 | 0 | 0 |
| V | 0 | 0 | 0 | R | 0 | 117 | 0 |
| W | 0 | 230 | 0 | S | 0 | 0 | 0 |
| | | | | U | 0 | 0 | 0 |
| | | | | X | 0 | 0 | 0 |
| Tot. Quantity | 0 | 235 | 0 | Tot. Quantity | 786 | 977 | 0 |
| No. Sites w/ Distress | 0 | 2 | 0 | No. Sites w/ Distress | 2 | 2 | 0 |
| % Sites w/ Distress | 0% | 18% | 0% | % Sites w/ Distress | 17% | 17% | 0% |

Statistical analyses were performed to assess the equivalency of the comparison and RAP datasets. Table G3 shows the results of *t*-tests performed to compare the comparison and RAP data for each distress at each severity. A two-sample, two-tailed *t*-test assuming unequal variance at a level of significance of $\alpha = 0.05$ was performed at each severity level for each distress. In addition, the same *t*-test was performed on the results for each distress using data for all severities. The results indicated that there were no significant differences in distresses between the comparison and RAP sites and are consistent with the results determined previously.

**Table G3. *p*-Value Results From Two-Sample, Two-Tailed *t*-Tests Performed on Visual Survey Data**

| **Distress** | **Low Severity** | **Medium Severity** | **High Severity** | **All Severities** |
|---|---|---|---|---|
| Fatigue Cracking | 0.2088 | 0.5887 | 0.4006 | 0.3193 |
| Longitudinal Cracking, Wheelpath | 0.7097 | 0.5934 | - | 0.5980 |
| Longitudinal Cracking, Non-wheelpath | 0.0761 | 0.5382 | 0.2647 | 0.8606 |
| Transverse Cracking, Unsealed | 0.2207 | 0.5988 | 0.3506 | 0.1003 |
| Raveling | 0.3006 | 0.4646 | - | 0.2057 |

*p*-values less than or equal to 0.05 indicate significant differences between comparison and RAP datasets. - = no test performed as all data points were zero.

## Dynamic Modulus

Dynamic modulus values were plotted for the subset of mixtures to investigate if there were apparent differences between the results for mixtures having 20% or less RAP and those having 25% and 30% RAP. Figures G1 through G3 do not show any trends with RAP content for modulus values at frequencies of 0.1 Hz, 1.0 Hz, and 10.0 Hz and all tested temperatures.

An example of two-sample, two-tailed *t*-test results comparing the modulus results for pairs of specimen sets tested at 70ºF and 1 Hz (lower left half of table) and 5 Hz (upper right half of table) are presented in Table G4 for the data subset. As previously found for the entire dataset, no trends in significant differences were shown between the subset of sites with mixtures having 20% or less RAP and those with mixtures having 25% to 30% RAP.

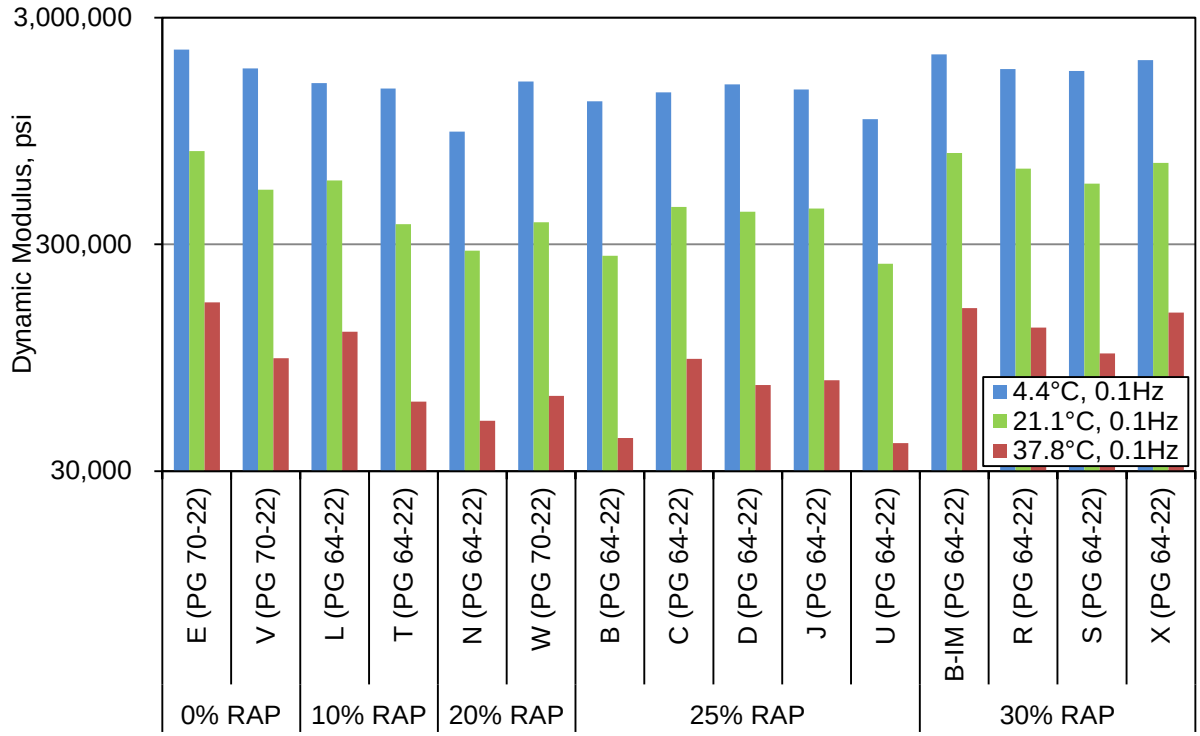


**Figure G1. Dynamic Modulus Values at All Test Temperatures and 0.1 Hz Frequency for the Subset of Cores. RAP = reclaimed asphalt pavement.**

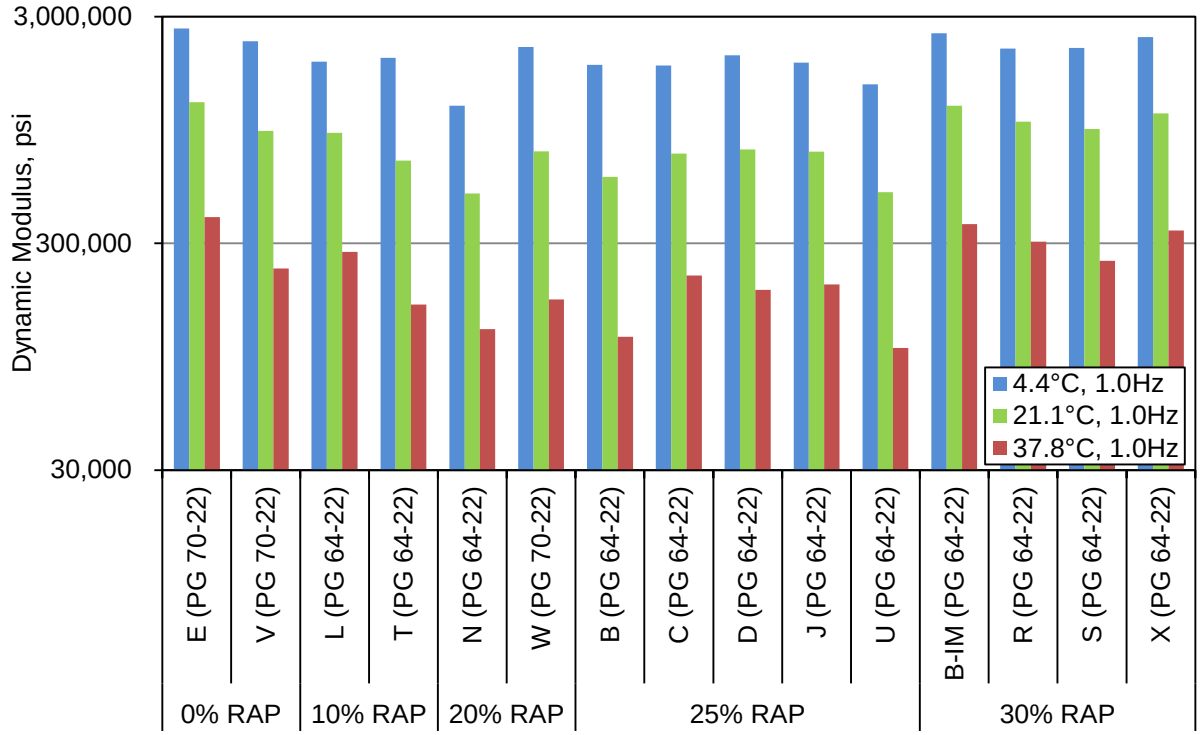


**Figure G2. Dynamic Modulus Values at All Test Temperatures and 1.0 Hz Frequency for the Subset of Cores. RAP = reclaimed asphalt pavement.**

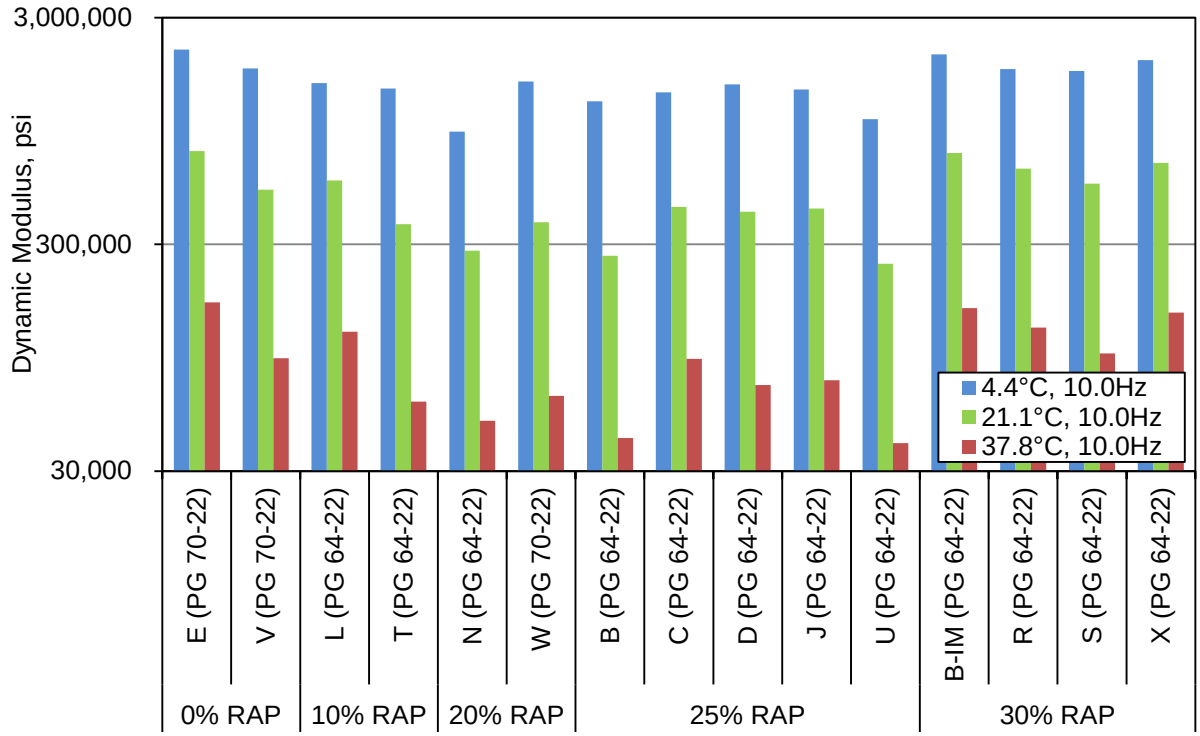


**Figure G3. Dynamic Modulus Values at All Test Temperatures and 10.0 Hz Frequency for the Subset of Cores. RAP = reclaimed asphalt pavement.**

**Table G4. *t*-Test Comparisons of Mixtures at 21.1ºC (70ºF) and 1 Hz (lower left half of table) and 5 Hz (upper right half of table)**

| Section (% RAP) | E (0%) | V (0%) | L (10%) | T (10%) | N (20%) | W (20%) | B (25%) | C (25%) | D (25%) | J (25%) | U (25%) | B-IM (30%) | R (30%) | S (30%) | X (30%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E (0%) | | 0.0331 | 0.0259 | 0.0241 | 0.0103 | 0.0081 | 0.7502 | 0.0791 | 0.0087 | 0.0100 | 0.0088 | 0.0035 | 0.0734 | 0.0424 | 0.4695 |
| V (0%) | 0.0325 | | 0.8089 | 0.1668 | 0.0417 | 0.1069 | 0.0976 | 0.3719 | 0.1194 | 0.0210 | 0.0045 | 0.0030 | 0.1336 | 0.7024 | 0.3342 |
| L (10%) | 0.0179 | 0.3215 | | 0.1521 | 0.0883 | 0.1571 | 0.0791 | 0.4140 | 0.1822 | 0.0960 | 0.0187 | 0.0134 | 0.2083 | 0.6248 | 0.3007 |
| T (10%) | 0.0396 | 0.1854 | 0.2676 | | 0.6443 | 0.5803 | 0.0290 | 0.7997 | 0.5082 | 0.5622 | 0.2607 | 0.4061 | 0.1132 | 0.1658 | 0.0846 |
| N (20%) | 0.0066 | 0.0476 | 0.1729 | 0.8611 | | 0.8455 | 0.0310 | 0.9976 | 0.7135 | 0.7909 | 0.0864 | 0.0700 | 0.0172 | 0.0415 | 0.1132 |
| W (20%) | 0.0123 | 0.1760 | 0.6473 | 0.4006 | 0.3266 | | 0.0246 | 0.9361 | 0.8888 | 0.9830 | 0.0634 | 0.1127 | 0.0419 | 0.0909 | 0.1138 |
| B (25%) | 0.5749 | 0.0459 | 0.0278 | 0.0510 | 0.0080 | 0.0183 | | 0.0924 | 0.0271 | 0.0332 | 0.0185 | 0.0138 | 0.1992 | 0.1147 | 0.6320 |
| C (25%) | 0.0813 | 0.2890 | 0.4745 | 0.9568 | 0.9641 | 0.6154 | 0.1015 | | 0.8795 | 0.9410 | 0.2906 | 0.4541 | 0.2332 | 0.3382 | 0.1692 |
| D (25%) | 0.0079 | 0.1016 | 0.4290 | 0.5335 | 0.4913 | 0.7334 | 0.0113 | 0.7329 | | 0.8446 | 0.0542 | 0.0888 | 0.0441 | 0.0993 | 0.1237 |
| J (25%) | 0.0051 | 0.0109 | 0.2034 | 0.7401 | 0.7678 | 0.3989 | 0.0056 | 0.8897 | 0.6092 | | 0.0148 | 0.0340 | 0.0052 | 0.0125 | 0.1219 |
| U (25%) | 0.0043 | 0.0004 | 0.0272 | 0.2500 | 0.0773 | 0.0382 | 0.0042 | 0.3384 | 0.0413 | 0.0104 | | 0.1712 | 0.0030 | 0.0020 | 0.0500 |
| B-IM (30%) | 0.0027 | 0.0024 | 0.0545 | 0.5503 | 0.2101 | 0.0956 | 0.0028 | 0.6709 | 0.1270 | 0.0936 | 0.0508 | | 0.0013 | 0.0029 | 0.0565 |
| R (30%) | 0.0413 | 0.6614 | 0.2555 | 0.1798 | 0.0519 | 0.1460 | 0.0590 | 0.2657 | 0.0870 | 0.0091 | 0.0001 | 0.0024 | | 0.1735 | 0.5962 |
| S (30%) | 0.0242 | 0.6432 | 0.4370 | 0.1956 | 0.0483 | 0.2318 | 0.0339 | 0.3227 | 0.1305 | 0.0171 | 0.0012 | 0.0033 | 0.3976 | | 0.3739 |
| X (30%) | 0.4275 | 0.3783 | 0.2019 | 0.0817 | 0.0853 | 0.1432 | 0.6191 | 0.1502 | 0.1127 | 0.0949 | 0.0392 | 0.0556 | 0.4280 | 0.3239 | |

Shaded bold cells indicate significant differences in modulus values between sites at a level of significance of $\alpha = 0.05$.

## Repeated Load Permanent Deformation

RLPD tests were performed on eight mixtures using small-scale specimens. The number of mixtures was limited by the availability of cores of suitable thickness with which to prepare test specimens. Removal of Sites K and M resulted in only six mixtures for consideration, of which two were from comparison sites and four from RAP sites. As the specimens never reached tertiary flow, only average slope and intercept results from the secondary flow portion of the response curve are presented for each mixture. Figure G4 indicates that the slope slightly increases with RAP content for these mixtures. The intercept remains relatively constant. Both trends are similar to those observed with the inclusion of Sites K and M.

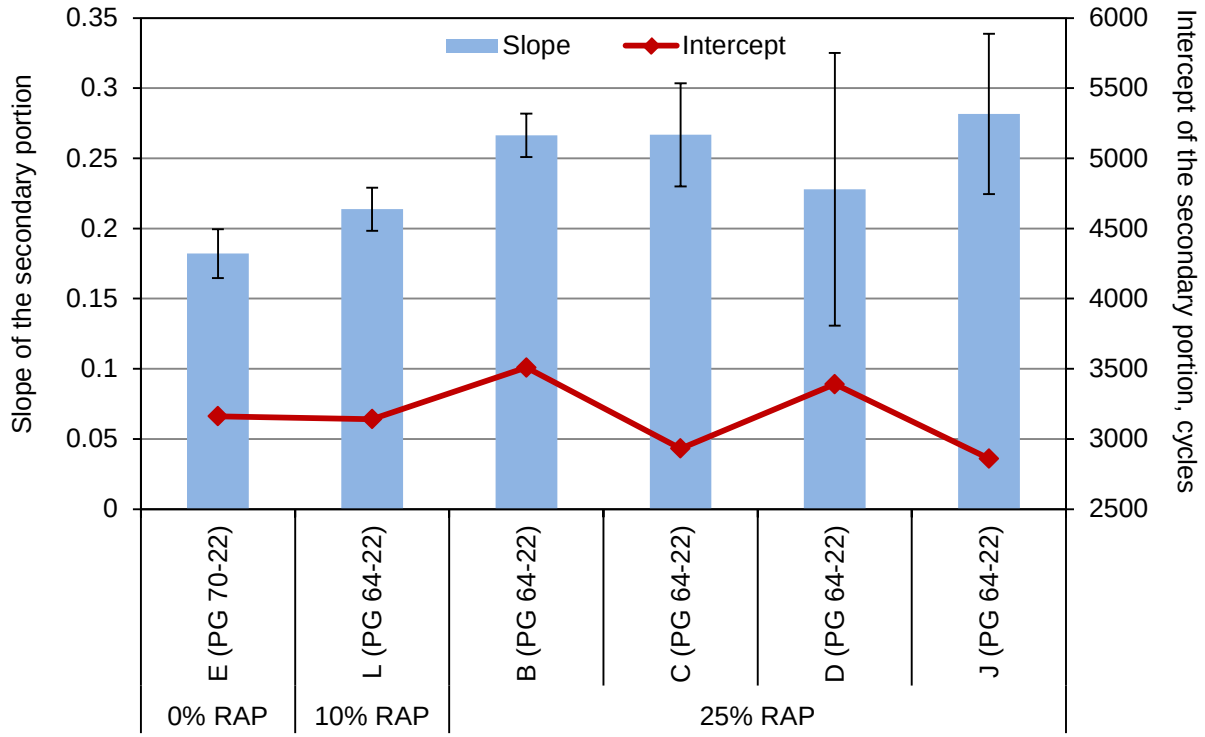


**Figure G4. Average Slope and Intercept of Each Mixture, Grouped By RAP Content. Error bars indicate 1 standard deviation. RAP = reclaimed asphalt pavement.**

## Texas Overlay Test

The Texas overlay test was conducted on 13 mixtures, with at least 4 and as many as 6 replicates tested. Removal of Sites K, M, O, and P from the dataset resulted in 9 sites for further investigation. Figure G5 presents the results of overlay testing for these sites. From Figure G5, it can be seen that Sites E and X, with mixtures containing 0% and 30% RAP, respectively, did not perform as well as the remaining sites, which all averaged more than 1,000 cycles to failure and indicated no significant differences in the results. The COV for Site X was also high, exceeding the 30% target value.

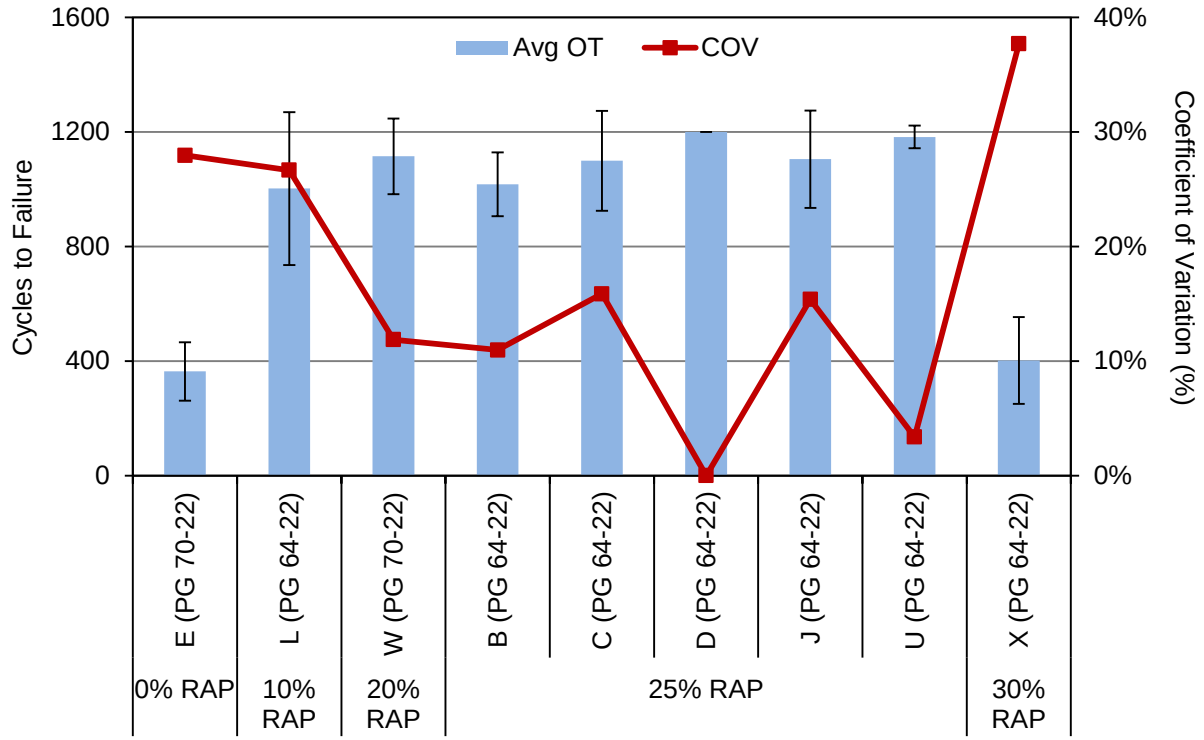


**Figure G5. Overlay Test Results After Removal of Outlier Data. Error bars indicate 1 standard deviation. RAP = reclaimed asphalt pavement.**

## Binder Performance Grading

Analysis of the impact of removing Sites H, K, M, O, and P on binder grading was performed by evaluating the trend in changes in the high and low temperature grade from construction through the in-service period evaluated. Figure G6 shows the trends in high and low failure temperature with increasing RAP content. The trendlines clearly show that the mixtures having less RAP aged over the 6-year period to a greater extent than those having higher RAP contents.

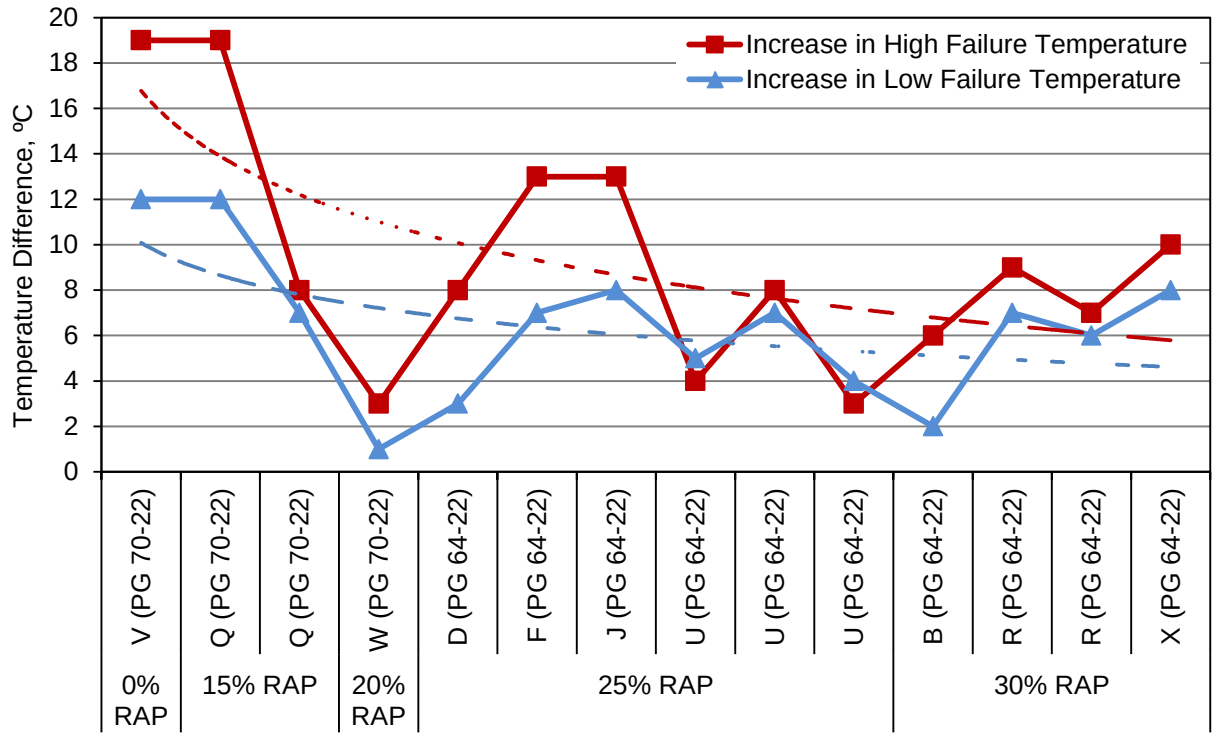


**Figure G6. Increase in High and Low Failure Temperatures With RAP Content. RAP = reclaimed asphalt pavement.**

## Summary

Based on the data analyzed, there does not appear to be any significant impact on the results of this study from the inclusion of either the WMA sites (Sites H, K, and M) or the 21% RAP content sites (Sites O and P).