1/12/2012

ERRATA

"Investigation of Low- and High-Temperature Properties of Plant-Produced RAP Mixtures"

Publication No. FHWA-HRT-11-058

Dear Customer:
Technical and editorial corrections were made to this report after the report was originally published. The following table shows the modifications that were made to this report.

List of Changes

Location	**Correction**
Technical Report Documentation Page	Changed report date in box 5 from "December 2011" to "January 2012."
List of Tables, page vi	Replaced second "table 11" with "table 12" and updated remaining table numbers throughout the list of tables and the report.
Page 5, first paragraph	Removed "Arab."
Page 9, second paragraph	Replaced "0.37 inches" with "$^{3}/_{8}$ inches."
Page 9, fourth paragraph	Changed "0.37-inch" to "$^{3}/_{8}$-inch." Changed "0.09-, 0.05-, and 0.02-inch ((9.5-, 2.36-, 1.18-, and 0.6-mm)" to "No. 8, No. 16, and No. 30." Changed "0.09-inch (2.36-mm)" to "No. 8."
Page 10, first paragraph	Replaced "90.7" Mg with "90 Mg."
Page 10, second paragraph	Replaced "18.93-L" with "20-L."
Page 10, bulleted list	Replaced "18.93-L" with "20-L" and "3.79-L" with "4-L."
Page 10, table 2	Removed "and Evansville, IN" from plant location for contractor 2.
Page 11, second to last bullet	Changed "18.93-L" to "20-L." Changed "239 °F" to "240 °F." Changed "289.4 °F" to "290 °F."
Page 11, last bullet	Changed "39.2, 69.8, 98.6, and 129.9 °F (4, 21, 37, and 54.4 °C)" to "40, 70, 100, and 130 °F (4, 21, 37, and 54 °C)."
Page 12, last paragraph	Changed "University of Wisconsin—Madison" to "University of Wisconsin-Madison."
Page 13, second paragraph under "Summary of Phase I Results"	Changed "0.5-inch" to "$^{1}/_{2}$-inch."

Page 13, fourth paragraph	Changed “129.9 °F” to “130 °F.” Changed “54.4 °C” to “54 °C.” Changed “68 °F” to “70 °F.”
Page 13, fifth paragraph	Changed “37.4 °F” to “5.4 °F.” Changed “42.8 °F” to “10.8 °F.” Changed “35.6 °F” to “3.6 °F.”
Page 14, first paragraph under “Mixture Volumetrics”	Replaced “…in table 3 through table 5” with “…in table 3 through table 6.”
Page 15, first paragraph	Changed “4 percent” to “4.0 percent,” “15 percent” to “15.0 percent,” and “0.37-inch” to “$^{3}/_{8}$-inch.”
Page 16, last paragraph	Changed “0.18- and 0.09-inch (4.75- and 2.36-mm)” to “No. 4 and No.8.”
Page 17, first paragraph	Changed “0.003-inch (0.075-mm)” to “No. 200.” Changed “0.18-inch (4.75-mm)” to “No. 4.”
Page 17, second paragraph	Changed “0.18-inch (4.75-mm)” to “No.4.”
Page 19, first paragraph	Changed “43,511.31 to 58,015.08 psi” to “43,500 to 58,000 psi.” Changed “2,900,754 to 4,351,131 psi” to “2,900 to 4,350 ksi.”
Page 24, first paragraph	Changed “35.6 or 37.4 °F” to “3.6 or 5.4 °F.” Changed “39.2 °F” to “7.2 °F.” Changed “33.8 °F” to “1.8 °F.”
Page 24, third paragraph	Changed “41 to 44.6 °F” to “9 to 12.6 °F.” Changed “35.6 to 39.2 °F” to “3.6 to 7.2°F.”
Page 24, fifth paragraph	Changed “33.8 to 35.6 °F” to “1.8 to 3.6 °F.”
Page 24, sixth paragraph	Changed “33.8 to 35.6 °F” to “1.8 to 3.6 °F.” Changed “39.2 °F” to “7.2 °F.”
Page 25, first paragraph	Changed “35.6 °F” to “3.6 °F” in two instances.” Changed “35.6 to 37.4 °F” to “3.6 to 5.4 °F.”

Page 37, second paragraph	Changed "…in table 11 through table 14" to "…in table 12 through table 15." Changed "129.9 °F" to "130 °F." Changed "54.4 °C" to "54 °C."
Page 40, first paragraph	Changed "129.9 °F (54.4 °C)" to "130 °F (54 °C)."
Page 41, third paragraph	Changed "…in table 15 through table 19" to "…in table 16 through table 20."
Page 43, first paragraph	Changed "35.6 to 39.2 °F" to "3.6 to 7.2 °F." Changed "39.2 to 42.8 °F" to "7.2 to 10.8 °F."
Page 50, first paragraph	Changed "…in table 20" to "…in table 21." Changed "35.6 °F" to "3.6 °F." Changed "39.2 °F" to "7.2 °F." Changed "33.8 °F" to "1.8 °F."
Page 59, fourth paragraph	Changed "…in table 21 and table 22" to "…in table 22 and table 23." Changed "table 14" to "table 15."
Page 59, last paragraph	Changed "69.8 °F" to "70 °F" in two instances. Changed "table 23" to "table 24."
Page 64, bulleted list	Changed "69.8 and 82.4 °F" to "70 and 82°F."
Page 65, bulleted list	Changed "33.8 to 37.4 °F" to "1.8 to 5.4 °F." Changed "35.6 °F" to "3.6 °F."

Investigation of Low- and High-Temperature Properties of Plant-Produced RAP Mixtures

PUBLICATION NO. FHWA-HRT-11-058

JANUARY 2012

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

As asphalt prices fluctuate, reclaimed asphalt pavement (RAP) use mitigates variability in material costs, making RAP a valuable commodity for use in asphalt pavements. Understanding the performance of pavements containing high amounts of RAP (greater than 25 percent) is important to State highway agencies across the United States. The addition of high RAP typically stiffens an asphalt mixture, making fatigue and low-temperature performance properties a concern. This report documents a two-phase study that evaluated performance properties of high RAP mixtures. This study is unique because it evaluates plant-produced mixtures with high RAP contents (25 and 40 percent) and different binders (performance grade (PG) 64-22 and a softer PG58-28 binder). A control mixture with no RAP was also evaluated. Mixture volumetrics, binder performance grade, and performance tests, such as dynamic modulus, indirect tensile test, and fatigue, were performed to evaluate the behavior of different mixtures. In addition to insight on the performance of high RAP and plant-produced mixtures, this study provides information regarding RAP content limits, blending of virgin and RAP binders, and the extraction and recovery process. This report will be of interest to those involved in asphalt pavement mix design, as well as the design and construction of asphalt pavements.

Butch Wlaschin
Director, Office of Pavement Technology

Jorge E. Pagán-Ortiz
Director, Office of Infrastructure Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-11-058	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Investigation of Low- and High-Temperature Properties of Plant-Produced RAP Mixtures	5. Report Date January 2012 6. Performing Organization Code
7. Author(s) Rebecca S. McDaniel, Ayesha Shah, and Gerald Huber	8. Performing Organization Report No.
9. Performing Organization Name and Address North Central Superpave Center Purdue University P.O. Box 2382, 1205 Montgomery Street West Lafayette, IN 47906	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-08-P-00165
12. Sponsoring Agency Name and Address Office of Pavement Technology and Office of Infrastructure R&D Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296	13. Type of Report and Period Covered Final Report, 2008–2011 14. Sponsoring Agency Code HIPT-10 and HRDI-10

15. Supplementary Notes
The FHWA Contracting Officer's Technical Representative (COTR) was Audrey Copeland, HRDI-10.

16. Abstract
Asphalt prices, supply issues, and growing interest in sustainable construction practices are leading to increased use of reclaimed asphalt pavement (RAP) in greater amounts and in more types of mixes. When using more than 15–20 percent RAP under most current specifications (State and national), contractors must change the virgin binder grade added to the mix. This frequently means using a less commonly available binder, which may be more expensive.

This report provides analysis of the results of testing plant-produced hot mix asphalt (HMA) containing various levels of RAP and different grades of virgin binder. The study was undertaken initially to examine the effects of RAP on low-temperature properties of mixtures. In phase I of the study, mixes produced by one contractor in 2006 were tested. The results suggest that the addition of RAP stiffened the mix, but probably not to the extent expected based upon linear blending. There is evidence from other research that also suggests that there are cases when linear blending does not apply. Consequently, in phase II of the project, four more contractors replicated the experiment in their HMA plants. The objectives of the study were also expanded to include an evaluation of the extent of blending of the RAP and virgin binders in plant-produced mixtures.

17. Key Words Asphalt pavement, Pavement recycling, Reclaimed asphalt pavement, RAP, Recycled asphalt, Pavement performance	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 101	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed pages authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

INTRODUCTION **1**

OBJECTIVES **3**

BACKGROUND **5**
- **RATIONALE BEHIND CURRENT SPECIFICATIONS** **5**
- **CURRENT ISSUES** **6**

RESEARCH APPROACH **9**
- **MIX DESIGN, PRODUCTION, AND SAMPLING** **9**
- **LABORATORY TESTING PLAN, TEST PROCEDURES, AND DATA ANALYSIS** **11**
- **COLLABORATIONS** **12**

TEST RESULTS AND DISCUSSION **13**
- **SUMMARY OF PHASE I RESULTS** **13**
- **MIXTURE VOLUMETRICS** **14**
- **BINDER TEST RESULTS** **20**
- **|*E**| TEST RESULTS** **25**
  - Statistical Analysis 37
  - Estimation of Blending 39
- **IDT TEST RESULTS** **41**
- **COMPARISON OF BINDER EXTRACTION/RECOVERY TECHNIQUES** **51**
- **FHWA FATIGUE TESTING AND DATA ANALYSIS** **59**

OVERALL OBSERVATIONS AND CONCLUSIONS **65**

APPENDIX A **67**
- **CONTRACTOR MIX DESIGNS AND/OR QC DATA** **67**

APPENDIX B **73**
- **BINDER CRITICAL TEMPERATURES** **73**

APPENDIX C **79**
- **ANALYSIS OF BLENDING** **79**

ACKNOWLEDGEMENTS **91**

REFERENCES **93**

LIST OF FIGURES

Figure 1. Graph. Number of gyrations to achieve 7 percent AV ... 19
Figure 2. Graph. Example master curves ... 20
Figure 3. Graph. Comparison of high critical temperatures ($T_{c,\ \mathrm{DSR}}$) for binders recovered from plant mixtures ... 23
Figure 4. Graph. Comparison of low critical temperatures ($T_{c,\ \mathrm{BBR}}$) for binders recovered from plant-produced mixtures (based on BBR m-value = 0.300) ... 23
Figure 5. Graph. Mix modulus of PG64-22 mixes from contractor 1 ... 26
Figure 6. Graph. Mix modulus of control and PG58-28 mixes from contractor 1 ... 26
Figure 7. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 1 ... 27
Figure 8. Graph. Mix modulus of PG64-22 mixes from contractor 2 ... 27
Figure 9. Graph. Mix modulus of control and PG58-28 mixes from contractor 2 ... 28
Figure 10. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 2 ... 29
Figure 11. Graph. Mix modulus of PG64-22 mixes from contractor 3 ... 30
Figure 12. Graph. Mix modulus of control and PG58-28 mixes from contractor 3 ... 31
Figure 13. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 3 ... 32
Figure 14. Graph. Mix modulus of PG64-22 mixes from contractor 4 ... 33
Figure 15. Graph. Mix modulus of control and PG58-28 mixes from contractor 4 ... 34
Figure 16. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 4 ... 34
Figure 17. Graph. Mix modulus of PG64-22 mixes from contractor 5 ... 35
Figure 18. Graph. Mix modulus of control and PG58-28 mixes from contractor 5 ... 36
Figure 19. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 5 ... 36
Figure 20. Graph. Example of thorough blending (mix 5B) ... 39
Figure 21. Graph. Example of poor blending (mix 4D) ... 40
Figure 22. Graph. IDT stiffness and pavement cracking temperature for contractor 1 ... 43
Figure 23. Graph. IDT strength and pavement cracking temperature for contractor 1 ... 44
Figure 24. Graph. IDT stiffness and pavement cracking temperature for contractor 2 ... 45
Figure 25. Graph. IDT strength and pavement cracking temperature for contractor 2 ... 45
Figure 26. Graph. IDT stiffness and pavement cracking temperature for contractor 3 ... 46
Figure 27. Graph. IDT strength and pavement cracking temperature for contractor 3 ... 47
Figure 28. Graph. IDT stiffness and pavement cracking temperature for contractor 4 ... 48
Figure 29. Graph. IDT strength and pavement cracking temperature for contractor 4 ... 48
Figure 30. Graph. IDT stiffness and pavement cracking temperature for contractor 5 ... 49
Figure 31. Graph. IDT strength and pavement cracking temperature for contractor 5 ... 50
Figure 32. Graph. Comparison of binder recovered using different solvents for mix A ... 52
Figure 33. Graph. Comparison of binder recovered using different solvents for mix B ... 53
Figure 34. Graph. Comparison of binder recovered using different solvents for mix C ... 53
Figure 35. Graph. Comparison of binder recovered using different solvents for mix D ... 54
Figure 36. Graph. Comparison of binder recovered using different solvents for mix E ... 54
Figure 37. Graph. Comparison of binder recovered using different solvents for mix F ... 55
Figure 38. Graph. Comparison of binders recovered using different procedures and same solvent for mix A ... 56
Figure 39. Graph. Comparison of binders recovered using different procedures and same solvent for mix B ... 56

Figure 40. Graph. Comparison of binders recovered using different procedures and same solvent for mix C ... 57
Figure 41. Graph. Comparison of binders recovered using different procedures and same solvent for mix D ... 57
Figure 42. Graph. Comparison of binders recovered using different procedures and same solvent for mix E ... 58
Figure 43. Graph. Comparison of binders recovered using different procedures and same solvent for mix F ... 58
Figure 44. Graph. Fatigue life for mixtures at 69.8 °F (21 °C) and 400 με. ... 63
Figure 45. Graph. DSR critical temperatures—mixes with PG64-22 binder ... 73
Figure 46. Graph. DSR critical temperatures—mixes with PG58-28 binder ... 73
Figure 47. Graph. DSR critical temperatures—mixes with 25 and 40 percent RAP ... 74
Figure 48. Graph. BBR critical temperatures—mixes with PG64-22 binder ... 74
Figure 49. Graph. BBR critical temperatures—mixes with PG58-28 binder ... 75
Figure 50. Graph. BBR critical temperature—mixes with 25 and 40 percent RAP ... 75
Figure 51. Graph. TSAR™ critical temperature—mixes with PG64-22 binder ... 76
Figure 52. Graph. TSAR™ critical temperature—mixes with PG58-28 binder ... 76
Figure 53. Graph. TSAR™ critical temperature—mixes with 25 and 40 percent RAP ... 77
Figure 54. Graph. Contractor 2 evaluation of blending from master curves: mix A ... 79
Figure 55. Graph. Contractor 2 evaluation of blending from master curves: mix B ... 79
Figure 56. Graph. Contractor 2 evaluation of blending from master curves: mix C ... 80
Figure 57. Graph. Contractor 2 evaluation of blending from master curves: mix D ... 80
Figure 58. Graph. Contractor 2 evaluation of blending from master curves: mix E ... 81
Figure 59. Graph. Contractor 2 evaluation of blending from master curves: mix F ... 81
Figure 60. Graph. Contractor 3 evaluation of blending from master curves: mix A ... 82
Figure 61. Graph. Contractor 3 evaluation of blending from master curves: mix B ... 82
Figure 62. Graph. Contractor 3 evaluation of blending from master curves: mix C ... 83
Figure 63. Graph. Contractor 3 evaluation of blending from master curves: mix D ... 83
Figure 64. Graph. Contractor 3 evaluation of blending from master curves: mix E ... 84
Figure 65. Graph. Contractor 3 evaluation of blending from master curves: mix F ... 84
Figure 66. Graph. Contractor 4 evaluation of blending from master curves: mix A ... 85
Figure 67. Graph. Contractor 4 evaluation of blending from master curves: mix B ... 85
Figure 68. Graph. Contractor 4 evaluation of blending from master curves: mix C ... 86
Figure 69. Graph. Contractor 4 evaluation of blending from master curves: mix D ... 86
Figure 70. Graph. Contractor 4 evaluation of blending from master curves: mix E ... 87
Figure 71. Graph. Contractor 4 evaluation of blending from master curves: mix F ... 87
Figure 72. Graph. Contractor 5 evaluation of blending from master curves: mix A ... 88
Figure 73. Graph. Contractor 5 evaluation of blending from master curves: mix B ... 88
Figure 74. Graph. Contractor 5 evaluation of blending from master curves: mix C ... 89
Figure 75. Graph. Contractor 5 evaluation of blending from master curves: mix D ... 89
Figure 76. Graph. Contractor 5 evaluation of blending from master curves: mix E ... 90
Figure 77. Graph. Contractor 5 evaluation of blending from master curves: mix F ... 90

LIST OF TABLES

Table 1. Experimental design for each plant showing mix designations 10
Table 2. Participating contractors and plant details 10
Table 3. Mixture volumetrics for contractor 2 14
Table 4. Mixture volumetrics for contractor 3 15
Table 5. Mixture volumetrics for contractor 4 15
Table 6. Mixture volumetrics for contractor 5 15
Table 7. Comparison of measured and design binder contents 18
Table 8. Virgin and recovered binder properties for contractor 2 21
Table 9. Virgin and recovered binder properties for contractor 3 21
Table 10. Virgin and recovered binder properties for contractor 4 22
Table 11. Virgin and recovered binder properties for contractor 5 22
Table 12. Statistical analysis of moduli at 25 Hz from contractor 1 37
Table 13. Statistical analysis of moduli at 25 Hz from contractor 2 38
Table 14. Statistical analysis of moduli at 25 Hz from contractor 4 38
Table 15. Statistical analysis of moduli at 25 Hz from contractor 5 38
Table 16. IDT results for contractor 1 41
Table 17. IDT results for contractor 2 42
Table 18. IDT results for contractor 3 42
Table 19. IDT results for contractor 4 42
Table 20. IDT results for contractor 5 43
Table 21. Change in T_{crit} (°C) with the addition of RAP 51
Table 22. $|E^*|$ and phase angle data for PG 58-28 mixtures 61
Table 23. $|E^*|$ and phase angle data for PG64-22 mixtures 62
Table 24. Overall summary of fatigue life 63
Table 25. Contractor 1 mix designs 67
Table 26. Contractor 2 job mix formula (JMF) and QC test results 68
Table 27. Contractor 3 QC test results 69
Table 28. Contractor 4 mix designs 70
Table 29. Contractors mix designs and QC results 71

INTRODUCTION

Asphalt prices, supply issues, and growing interest in sustainable construction practices are leading to increased use of reclaimed asphalt pavement (RAP) in greater amounts and in more types of mixes. However, when using more than 15–20 percent RAP under most current specifications (State and national), contractors must change the virgin binder grade added to the mix. This frequently means using a less commonly available binder, which may be more expensive.

This report provides an analysis of the results of testing plant-produced hot mix asphalt (HMA) containing various levels of RAP and different grades of virgin binder. The study was initially undertaken to examine the effects of RAP on low-temperature properties of mixtures. In phase I of the study, mixes produced by one contractor in 2006 were tested. The results suggested that the addition of RAP stiffened the mix, but not to the extent expected based on linear blending.(1) There is evidence from other research that suggests that there are cases where linear blending does not apply.(2) Consequently, in phase II of the project, four more contractors replicated the experiment in hot mix plants.(3) The objectives of the current study were expanded to include an evaluation of the extent of blending of the RAP and virgin binders in plant-produced mixtures.

OBJECTIVES

The goal of this project was to improve the understanding of the performance characteristics of HMA mixtures with RAP at high, intermediate, and low temperatures and to provide knowledge regarding plant-produced HMA mixtures with RAP.

The specific objectives of this project were as follows:

- Validate the results from phase I of this project.
- Assess the current guidelines for RAP usage by determining the low- and high-temperature properties of plant-produced HMA with varying RAP contents and virgin binder grades.
- Further investigate the amount of blending that occurs between the RAP binder and virgin binder during plant production.

BACKGROUND

Recycling asphalt mixtures became widely practiced in the United States in the 1970s, spurred by high petroleum prices and limited availability caused by the oil embargo of 1973. The increased availability of cold milling machines also promoted recycling in some areas of the country. By the late 1970s, technology was developed to allow recycle ratios as high as 100 percent, although HMA typically contained at most 25–40 percent RAP. Due to fluctuating petroleum prices, recycling is becoming even more attractive. There is interest in using higher RAP contents and in using RAP in more mixtures.

RATIONALE BEHIND CURRENT SPECIFICATIONS

The presence of RAP binder in a mixture is generally acknowledged to increase the mix stiffness at all temperatures and frequencies of loading, although the amount of stiffening may be negligible at low RAP contents. For mixtures that contain high amounts of RAP, there may be substantial increases in stiffness. At high temperatures, an increase in stiffness is considered advantageous because it helps resist permanent deformation. At low and intermediate temperatures, an increase in stiffness may reduce resistance to cracking.

The current American Association of State Highway and Transportation Officials (AASHTO) guidelines require a change in the binder grade when more than 15 percent RAP is added to a mix.[(4)] They were developed through National Cooperative Highway Research Program (NCHRP) project 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*, which was concluded in 2000 by the North Central Superpave Center (NCSC) and the Asphalt Institute.[(5)] The data from that study showed that when 15–20 percent RAP was added to a mix, the stiffening effect of the oxidized RAP binder started to become significant. Dropping the virgin binder grade by one increment on both the high- and low-temperature grades counteracted this stiffening effect, resulting in a mixture that behaved similarly to one without RAP and with the design binder grade. If more than 25–30 percent RAP was added, the effect of the RAP binder became even more significant. At that level, testing the RAP binder was recommended to evaluate what virgin binder should be used or how much RAP could be added with a given virgin binder grade. As more RAP is added to a mix, the amount of RAP binder also increases, potentially stiffening the mix even more.

The extent of blending of the virgin and RAP binders is expected to have an effect on stiffness. If the new and old asphalt binders are homogenized, the mixture may have increased stiffness and may crack at low temperatures. If little blending occurs, the mixture may behave as if it contains only the virgin binder. As a result, low-temperature cracking might not occur, but the lack of stiffening by the RAP binder may contribute to high-temperature rutting. NCHRP project 9-12 found that a significant amount of blending occurred between the hardened RAP binder and the added virgin binder in the materials studied. Total blending of the RAP and virgin binders is highly unlikely, but the NCHRP project 9-12 research showed that enough blending occurred that the mixture testing results were not statistically different from total blending.[(5)] If little or no blending occurs for any reason, the mix properties will be strongly influenced by the virgin binder grade.

Current specifications in Indiana and many other States conform to the requirements of AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design*, and AASHTO R 35, *Standard Practice for Superpave Volumetric Mix Design for Hot Mix Asphalt*.[4,6] Both standards were revised to incorporate RAP mixes based on the results of NCHRP project 9-12 and input from various State highway agencies as well as the Federal Highway Administration (FHWA) Asphalt Mixture Expert Task Group (ETG). Those specifications include the following three tiers of RAP content based on the mass of RAP in the total mix:

- **Up to 15 percent RAP**: No change is required in the virgin binder grade.
- **Over 15–25 percent RAP**: The virgin binder grade should be one grade softer at both high and low temperatures.
- **Over 25 percent RAP**: Blending charts should be developed to determine either the amount of RAP that can be used with a given virgin binder or the appropriate virgin binder grade to use for a desired RAP content.

The final NCHRP 9-12 report includes recommendations for different tiers depending on the low-temperature grade of the RAP binder. If the binder was very stiff (PGXX-10 or higher), lower amounts of RAP could be used before changing the binder grade (10 and 15 percent). Conversely, if the RAP binder was softer (PGXX-22 or lower), higher RAP contents could be used (20 and 30 percent).[5] The FHWA Asphalt Mixture ETG determined that there were not enough data points to include this in the AASHTO specifications. The asphalt binder requirements that were subsequently adopted represent a middle ground based on the results of the laboratory testing. They also agree well with the interim recommendations that had been made previously by the Asphalt Mixture ETG based on extensive experience with Marshall mixes.[7]

A regional pooled fund study in the Midwest studied three more RAP sources with contents up to 50 percent. That study showed that the NCHRP results generally held true for the materials tested.[2] The study also included a comparison of plant-produced mixes to a linear blending chart. In two of the three cases evaluated, linear blending worked well. However, in the third case, the mixture was consistently stiffer than expected based on linear blending, which possibly showed the effects of plant production variables.

CURRENT ISSUES

Anecdotal evidence to date suggests that the AASHTO M 323 tiers generally work well in many cases, but there is also some evidence that these break points may not be appropriate in all cases. The actual amount of blending that occurs in a mixture depends on many factors, including the stiffness of the RAP binder, the compatibility of the virgin and RAP binders, and specifics of the hot mix production, including plant type (batch or drum), type and amount of mixing (pugmill or drum), mixing temperature, mix handling (live bottom trucks or dump trucks, shuttle buggies, windrow and pickup, as well as dumping straight into the paver hopper), etc.[2] Laboratory-produced mixtures may not reflect the effects of all of these factors, so testing plant-produced mixtures, which is not typically done in routine practice, would be more realistic.

As contractors use more RAP, two issues have become increasingly important. The effects of RAP on the low-temperature grade are a concern, particularly to agencies in more severe Northern climates that may have to deal with increased cracking later in the service life of the pavement. The increased stiffness of the mix generally provided by the addition of RAP is beneficial at high temperatures but may be detrimental at low temperatures. Conversely, there is some evidence that the addition of oxidized binders may not have as great an effect on low-temperature properties as it does on high-temperature properties.[2] Experiences in Missouri and Minnesota suggest that recycled shingles do not have as great an effect on low-temperature properties as on high-temperature properties. The effects of RAP may be similar since both may contain highly oxidized binders.[8,9] Another issue for contractors is the RAP content at which the binder grade must be changed. For contractors in Indiana, where this work was conducted, the use of greater than 15 percent RAP required the use of a PG58-28 virgin binder. This binder grade is typically more expensive than PG64-22, which is routinely used with 15 percent RAP or less in that market.

The issue of binder grade changes is also a concern to agencies. If RAP does not stiffen the mix to the extent expected, the resulting mixture may be too soft for the intended purpose. Similarly, if there are cases where the plant-produced mix with RAP is stiffer than expected, as seen in the regional pooled fund study, the mix may be more prone to cracking.[2]

Bonaquist et al. suggests that there are some cases where RAP and shingles do not blend with virgin materials to the extent expected.[10,11] Bonaquist et al. used the complex dynamic modulus ($|E^*|$) of plant-produced mix and $|E^*|$ of the binder recovered from the mixture to estimate the blending between the virgin and RAP binder. The binder modulus and mixture volumetric properties were input into the Hirsch predictive model to estimate what the mix modulus would be if total blending occurred during production.[12] It is assumed that the recovered binder from the mix represents complete blending between the virgin and RAP binder. If the measured and estimated mix master curves overlap, the blending of recycled and virgin binders is nearly complete. If the curves do not overlap, there is incomplete blending. Bonaquist et al. has examples of incomplete blending, particularly with shingles, but also with RAP.[10] Since Bonaquist et al.'s technique uses test results from plant-produced mixes, the potential variables introduced by the plant also play a role in the amount of blending that occurs.

Because of the lingering questions about the amount of blending that occurs between the RAP and virgin binders, the effects of RAP on mixture properties (especially at low temperatures), and the point(s) at which the virgin binder grade should be adjusted, the research project summarized in this report was undertaken.

RESEARCH APPROACH

This section describes the approach used in both phase I and phase II of the current study to evaluate the effects of RAP on the properties of plant-produced asphalt mixtures. The results from phase I are summarized in the next section, and full details are provided in the final unpublished report. Where appropriate, the results from testing mixes produced by the phase I contractor are combined with those of the phase II contractors for completeness.

MIX DESIGN, PRODUCTION, AND SAMPLING

In phase II of this study, four contractors replicated the experiment conducted by one contractor in phase I of this experiment. Each contractor designed six mixtures, as shown in table 1, to be as similar as possible. The mixes are SUperior PERforming Asphalt PAVEments (Superpave®) mixes with a nominal maximum aggregate size (NMAS) of $^3/_8$ inches (9.5 mm). Each contractor's set of mixes used one source of RAP, one set of virgin aggregates, and one source of each of two binder grades. That is, each binder grade was from one source per plant, although the different binder grades may have come from different sources. The RAP contents ranged from zero (the control mix) to 40 percent, as shown in table 1.

The contractors generally did a complete mix design on one mixture and then altered the binder grade or aggregate/RAP stockpile percentages to fill the other cells. These alternate mixes were typically verified to conform substantially to the mix design requirements with a one-point mix design. The mix designs and/or quality control (QC) testing results provided by the contractors are in appendix A of this report.

In almost all cases, the mix design gradations for a given contractor agreed within a range of 3 percent or less on each sieve. Consequently, variations in the voids in the mineral aggregate (VMA) and sometimes total binder content occurred as the aggregate properties changed when RAP was added to the mixtures. One contractor used exactly the same mix design gradation for all six mixes and varied the binder content to achieve 4 percent air voids (AV) at design. The greatest differences in the gradations were for contractor 1. Those mix designs agreed within less than 3 percent except on the $^3/_8$-inch (9.5-mm) No. 8, No. 16, and No. 30 sieve. None of the mixes from contractor 1 were consistently higher or lower than the others, even where the greatest ranges occurred. That is, the higher RAP contents did not necessarily yield finer mixes or vice versa. Contractors 1 and 4 provided coarse mix designs, whereas contractors 2, 3, and 5 offered fine mixes (compared to the primary control sieve control point of 46 percent passing the No. 8 sieve).[(4)]

Two different binder grades, PG58-28 and PG64-22, were used. PG64-22 is the standard binder for the area, and PG58-28 is the grade that would be selected for the 25 percent RAP content mixtures. For the 40 percent RAP content mixtures, a blending chart would be required to determine the appropriate virgin binder grade according to the current AASHTO standards.[(4)]

Table 1. Experimental design for each plant showing mix designations.

Asphalt Binder Grade	RAP			
	0 Percent	**15 Percent**	**25 Percent**	**40 Percent**
PG 64-22	Mix A	Mix B	Mix C	Mix D
PG 58-28			Mix E	Mix F

Note: Blank cells indicate that the binder grade and RAP percentage mix was not evaluated.

The mixes were produced through the contractors' hot mix plants (over as short a time frame as practical) using any processing they typically use with RAP mixes. It was requested that approximately 100 T (90 Mg) of each mixture be produced before sampling. The contractors placed the mixes wherever they could, typically on commercial or local road projects.

The contractors sampled the mixes from a truck at the plant and stored the samples in sealed 5-gal (20-L) buckets. The contractors also sampled the RAP stockpile and virgin binder. The following minimum samples were requested:

- **RAP**: Three 5-gal (20-L) buckets.
- **Loose mix**: Eight 5-gal (20-L) buckets per mix.
- **Liquid**: Two 1-gal (4-L) paint cans of each grade of asphalt binder.
- **Compacted samples**: Three field-mixed plant lab-compacted gyratory samples per mix.

The contractors were asked to provide information on the maximum theoretical specific gravity of each mix, binder content, gradation, plant type, tonnage, and any RAP processing techniques used. In some cases, this level of detail was not provided.

The details of the contractors who agreed to participate in this study and information about their plants are provided in table 2. RAP from Michigan would have been produced originally using a softer binder grade than the Indiana sources because of the climate and prevailing specifications.

Table 2. Participating contractors and plant details.

Contractor	Plant Location	Plant Type	Processing
1	Indianapolis, IN	Gencor counterflow drum with embedded burner	Minus one-half in screened
2	Ada, MI	CMI parallel flow drum	Minus five-eighths in crushed/screened
3	Huntington, IN	ASTEC, Inc. double drum	Minus one-half in screened
4	Evansville, IN	CMI parallel flow drum	Minus one-half in screened
5	Leesburg, IN	Two drums (aggregate dryer with separate mixing drum)	Minus one-half in crushed/screened

LABORATORY TESTING PLAN, TEST PROCEDURES, AND DATA ANALYSIS

The laboratory testing plan was designed to examine the following:

- Verification of mixture volumetrics and compliance with applicable standards (including binder grade).
- Assessment of the high- and low-temperature mixture properties and the effect of increasing RAP content on those properties.
- Examination of the degree of blending of the RAP and virgin binders in the plant-produced mixtures.

The following tests were conducted on various samples:

- **Volumetric data on plant-produced and compacted mixture samples**. The maximum specific gravity (G_{mm}) was measured on two samples of each mixture according to AASHTO T 209, and the results were averaged for AV content determination.(13) The bulk specific gravity (G_{mb}) was measured according to AASHTO T 166.(14) AV content was determined using the measured maximum theoretical and G_{mb} of the mixtures. The G_{mb} and AV content of all laboratory compacted samples was also determined to ensure compliance with the sample requirements for the mechanical tests being conducted. Compaction of the specimens was conducted according to AASHTO T 312.(15)

- **Verification of virgin binder grade**. Tank samples of each virgin binder were tested for compliance with the AASHTO M 320 high- and low-temperature grades.(16) Frequency sweeps and temperature sweeps using the dynamic shear rheometer (DSR) were conducted on the original binder to determine the complex shear modulus ($|G^*|_m$).(17) Two replicates were tested for each binder and averaged to develop the master curves for the binders. Three replicates were tested at low temperatures in the bending beam rheometer (BBR) after rolling thin film oven (RTFO) and pressure-aging vessel aging.(18–20) These data were used to determine the true (or continuous) grade of the binder.

- **Determination of mixture properties**. Lab-compacted mixture samples were tested for their high- and low-temperature properties. To do so, 5-gal (20-L) buckets of the plant-produced mix were heated to approximately 240 °F (115 °C) for typically 1 h, which was just long enough to soften the mix for splitting. Samples of the loose mix were conditioned for 2 h at the compaction temperature (290 °F (143 °C)) before compaction into gyratory specimens. The gyratory specimens were then cut to the proper size for the specific mix tests to be performed.

    - Four replicates for each mix (compacted to 7 ±0.5 percent AV) were tested for $|E^*|$ using the universal testing machine (UTM-25) developed by Industrial Process Controls, Ltd. Samples were tested at 40, 70, 100, and 130 °F (4, 21, 37, and 54 °C) at the frequency range specified in AASHTO TP 62.(21) These results were then used to develop master curves in Microsoft Excel®, which show the trends in $|E^*|$ as a function of reduced frequency. The modulus of the mixtures can be related to pavement rutting at high temperatures and fatigue cracking at intermediate temperatures.

  - The mixes were also tested at low temperatures for indirect tensile (IDT) creep compliance and strength (specified in AASHTO T 322) to estimate the effects of RAP content and properties on the thermal cracking behavior of the resulting mix.(22) Creep compliance tests were conducted for 100 s on three replicates (compacted to 7 ±0.5 percent AV) at -4, 14, and 32 °F(-20, -10, and 0 °C). Following the creep compliance tests, the same samples were tested for IDT strength at 14 °F (-10 °C). These data were used to determine the critical cracking temperatures (T_{crit}) of the mixes.

- **Extraction and recovery of binder**. The binder from each RAP source and mixture was extracted and recovered according to AASHTO T 319 using n-propyl bromide (nPB).(23) The recoveries in phase I were conducted using methylene chloride (mCl) and the Abson procedure, which is discussed later in this report.(24) The recovered binders were then tested for complex modulus (|*G**|) in the DSR.(17) This information was used according to Bonaquist's method of evaluating binder blending.(11) The recovered binders were also tested at low temperatures as described above for virgin binders (except without RTFO aging since they had been through a hot mix plant).

- **Comparison of extraction/recovery techniques**. Samples of selected mixtures were also extracted according to AASHTO T 164 and recovered using the Abson method with mCl, as done in phase I of this study.(25,24) They were also extracted with nPB for comparison to the AASHTO T 319 results.(23) The Abson recovered binders were then tested in the DSR, and the properties were compared to those of binders recovered according to AASHTO T 319. This was done to assess the impact of the extraction/recovery technique/solvent on the resulting binder properties. The Abson recovery technique was used in phase I of this study and may have contributed to the observed results.(24)

COLLABORATIONS

The research team provided samples of one contractor's mixtures (set of six) to the FHWA Turner-Fairbank Highway Research Center (TFHRC) for study. Researchers at TFHRC performed fatigue testing on these materials, utilizing a pull-pull fatigue test as a part of their research. Those results are summarized later in this report.

Samples were also provided to Dr. Hussain Bahia from the University of Wisconsin-Madison, for his use in a RAP mortar testing procedure. Those results will be reported by Dr. Bahia separately as part of his overall project. |*E**| and binder testing data were shared with Dr. Jo Daniel at the University of New Hampshire as she developed plans for a pooled fund study of plant-produced RAP mixtures in the Northeast. Lastly, samples of binders recovered from one set of mixes were provided to Dr. Eric Kalberer at the Western Research Institute for Atomic Force Microscopy compatibility testing.

TEST RESULTS AND DISCUSSION

This section describes and discusses the results of the testing conducted.

SUMMARY OF PHASE I RESULTS

The unpublished phase I study entitled *Testing to Support Low-Temperature Performance Properties of Hot Mix Asphalt Containing Reclaimed Asphalt Pavement (RAP)* was conducted in 2006 and 2007. The test results from phase I are included in this report with the results from phase II, when applicable, for completeness. However, a brief summary of the phase I results is provided in this section. The full results from phase I are available in a paper presented at the Transportation Research Board.(1)

One contractor in Indiana produced six different mixtures using two different binder grades and up to 40 percent RAP, as shown in table 1, on two consecutive days in May 2006. The RAP was screened into coarse and fine fractions on a $^1/_2$-inch (12.5-mm) screen, with only the fine fraction added to the new mixture. Samples were taken of each plant-produced mix and tested for low-, intermediate-, and high-temperature properties. The mixture tests included the following:

- $|G^*|_m$.
- $|E^*|$.
- IDT strength.
- Creep stiffness.

In addition, samples of the RAP and the virgin binders were obtained. The binders were recovered from the RAP sample and the plant-produced mixtures using a solvent recovery process and were tested in the DSR to determine the binder complex shear modulus ($|G^*|_b$).(24)

The high-temperature mixture testing showed that both $|G^*|_m$ and $|E^*|$ increased as the RAP content increased. The increase was not statistically significant at 15 percent RAP, but $|E^*|$ increased by approximately 100 percent at 100 and 130 °F (37.8 and 54 °C) when 40 percent RAP was added to the mix. At 70 °F (20 °C), $|E^*|$ of the 40 percent RAP mix was only about 12 percent higher than the control. Changing the virgin binder grade to PG58-28 at the higher RAP content lowered $|G^*|_m$ and $|E^*|$.

Low-temperature testing in the IDT tester showed that, in general, as the RAP content increased, the stiffness and strength of the mixes also increased, but the differences were not statistically significant. T_{crit} became less negative as the RAP content increased, indicating that the mixes with higher RAP content had lower thermal cracking resistance than the control or 15 percent RAP mix. The 25 percent RAP mix with PG64-22 had a T_{crit} only 5.4 °F (3 °C) warmer than the control mix. With the addition of 40 percent RAP and the same binder grade, T_{crit} was approximately one binder grade (10.8 °F (6 °C)) warmer than the control. Lowering the virgin binder grade to PG58-28 was beneficial in improving T_{crit}, but the improvement was only about 3.6 °F (2 °C) compared to mixes with the same RAP content but with PG64-22.

Binder tests were also performed to look at the extent of blending of the RAP and virgin binders. The binders from the RAP and from the plant-produced mixtures were extracted and tested in the DSR. The virgin binder was also tested. This testing showed that the amount of RAP in the mix had a small effect on the stiffness of the binder. The stiffness of the binder recovered from the plant-produced mixes was slightly higher than the stiffness of the virgin binder itself, but the stiffening did not occur as rapidly as expected. The recovered RAP binder was much stiffer than either the virgin binder or the binder from the mixtures with RAP. The binders recovered from the mixes with PG64-22 were somewhat stiffer than the mixes with PG58-28 at the same RAP content, as expected.

While the phase I results indicated that the addition of RAP increased the mix and recovered binder stiffnesses, which could improve the rutting resistance of the mix but decrease the cracking resistance, the stiffness did not increase as quickly as expected. The results of phase I highlighted some challenges in using high amounts of RAP, as well as the uncertainty of what occurs between the RAP and virgin binders during plant production (i.e., the extent of blending). In phase II, the study was expanded to more HMA plants to substantiate or refute the findings of phase I. The remainder of this report summarizes the results of phase II (combined with the phase I results where applicable).

MIXTURE VOLUMETRICS

The mixture volumetrics measured in the NCSC lab on plant-produced lab-compacted specimens are shown in table 3 through table 6. Mix volumetrics and compacted gyratory samples were not requested of the phase I contractor. In addition, one phase II contractor did not submit samples. The G_{mb} and asphalt contents that were used in calculating the volumetrics were provided by the contractors. The asphalt contents were verified by reflux extraction of plant-produced mixtures in the NCSC lab.

Table 3. Mixture volumetrics for contractor 2.

Mix ID	Percent RAP	Grade	G_{mm}	G_{mb}	Percent AV	Percent VMA	Percent of voids filled with asphalt (VFA)
2A	0	PG64-22	2.459	2.326	5.4	17.4	69.0
2B	15		2.467	2.387	3.0	15.3	80.3
2C	25		2.462	2.355	4.3	16.4	73.6
2D	40		2.456	2.402	2.2	14.8	85.1
2E	25	PG58-28	2.455	2.373	3.3	15.8	79.0
2F	40		2.456	2.424	1.3	14.0	90.7

Table 4. Mixture volumetrics for contractor 3.

Mix ID	Percent RAP	Grade	G_{mm}	G_{mb}	Percent AV	Percent VMA	Percent VFA
3A*	0	PG64-22	2.463	—	—	—	—
3B	15		2.460	—	—	—	—
3C*	25		2.466	—	—	—	—
3D	40		2.466	—	—	—	—
3E*	25	PG58-28	2.487	—	—	—	—
3F	40		2.471	—	—	—	—

* Indicates that water was found in the buckets.
— Indicates that production pills were not provided.

Table 5. Mixture volumetrics for contractor 4.

Mix ID	Percent RAP	Grade	G_{mm}	G_{mb}	Percent AV	Percent VMA	Percent VFA
4A	0	PG64-22	2.454	2.370	3.4	14.3	76.2
4B	15		2.446	2.356	3.7	14.9	75.4
4C	25		2.441	2.386	2.3	14.1	83.8
4D	40		2.452	2.391	2.5	13.9	82.2
4E	25	PG58-28	2.441	2.372	2.9	14.6	80.4
4F	40		2.454	2.402	2.1	13.5	84.4

Table 6. Mixture volumetrics for contractor 5.

Mix ID	Percent RAP	Grade	G_{mm}	G_{mb}	Percent AV	Percent VMA	Percent VFA
5A	0	PG64-22	2.444	2.351	3.8	16.4	76.8
5B	15		2.467	2.365	4.1	16.1	74.4
5C	25		2.435	2.360	3.1	16.4	81.0
5D	40		2.444	2.390	2.2	15.6	85.8
5E	25	PG58-28	2.441	2.351	3.7	16.7	77.9
5F	40		2.432	2.382	2.0	15.8	87.1

Volumetric requirements for these mixes included AV (4.0 percent), VMA (15.0 percent for $^{3}/_{8}$-inch (9.5-mm) mixes), and VFA (no more than 80 percent or less depending on traffic level, which was not defined for this experiment). Note that gradation is not a quality parameter in Indiana and was not determined in the NCSC lab. For each mix, one truck sample was taken to collect all the mix needed for testing at NCSC, so it was essentially one sample. Some mixes did not meet the design volumetric requirements, as shown in the tables above. General QC limits for multiple tests would be ±0.3 percent asphalt binder and ±1.0 percent AV. However, for single tests, these ranges would more typically be ±0.5 percent asphalt binder and ±1.5 percent AV.

In general, AV tended to be lower as the percent RAP increased. A review of the volumetric data also shows that VMA decreased as RAP content increased. To further investigate the cause of the low AV, samples of the plant-produced mixes from contractors 2 through 5 were extracted using the reflux extraction. This was done for speed and because the binders were not going to be recovered and tested. These data are summarized in table 7. The binder contents were all found to be within 0.3 percent with four exceptions. For contractor 2, mix B had a binder content that was 0.4 percent lower than the design, and mix F was 0.6 percent higher. For contractor 3, mix B was 0.4 percent higher. For contractor 4, mix D was 0.4 percent higher. For the other mixes, the difference from the design binder content ranged from -0.3 to 0.3 percent, with most binder contents within 0.2 percent of the design.

Contractors 2, 3, and 5 performed routine QC test results, although this was not required because of the relatively small quantities of mix produced and the rapid change from one mix to the next. These data, which are included in appendix A of this report, were examined in light of the low AV contents measured on some of the mixes in the NCSC lab. The data from all three contractors reflected higher G_{mm} values than measured in the NCSC lab. This, in turn, yielded higher AV contents. The contractors used the dry back method to determine when the sample was dry, whereas the NCSC lab did not. The dry back method is an optional supplementary procedure in AASHTO T 209 that can be used to correct for absorbed water during the G_{mm} determination.(13) Also, the NSCS lab had to reheat the samples, while the contractors did not. These reasons and normal testing variability likely explain the differences that were observed.

There was generally better correlation between the G_{mb} values reported by NCSC and the contractors, with most results comparing within the a range of 0.017.(14) The comparison of results was better with contractor 5 than contractor 2 for unknown reasons. Contractor 5's results were always lower than NCSC but only by 0.007 or less. Contractor 2's results were lower by 0.015–0.030, except in the case of mix C, where the results were higher by 0.015.

These differences in the measured volumetric properties, especially in the G_{mm} values, explain the observed differences in AV and VMA as measured by the contractors and the NCSC lab. The AV content and VMA were higher for contractor 2, except for mix C, which resulted in lower VFA. AV was higher and VMA was similar for contractor 5. The contractors' data showed a general trend of VMA decreasing with increasing RAP content, similar to that observed in the NCSC data.

In the case of contractor 3, since gyratory specimens compacted at the plant lab during construction were not provided, the corresponding volumetric data from the NCSC lab is not available except for G_{mm} data. The G_{mm} data were generally higher than for the NCSC lab, as was also observed with contractors 2, 3, and 5. Contractor 3's QC results showed AV ranging between 2.4 and 6.8 percent, which was fairly similar to the ranges observed with the other contractors. The lowest AV content was observed for the 40 percent RAP mix with PG58-28, and the highest was observed for the control mix.

QC data from the contractors were also examined to look at the variation in gradations between mixes. Contractor 2 provided individual mix designs for each of the six mixes. The mix design gradations compared within 3 percent on each sieve size. The QC data for each mix were compared to the mix design for that mix. The measured percentage passing individual sieves ranged from 1.6 percent, which was less than the design, to 3.2 percent greater than the design. The biggest variance from the design occurred at the No. 4 and No. 8 sieve sizes.

Contractor 3 did not provide the actual mix design values but indicated that the aggregate gradations were designed to closely agree. The binder content was varied to produce 4 percent AV. Contractor 3's QC data showed that the six mixes had gradations that compared within a range of 2 percent on the No. 200 sieve to 7.3 percent on the No. 4 sieve. This seems to be a reasonable level of variation considering the small quantities of mix produced, which did not allow much time for dialing in the plant.

The QC data for contractor 5 also showed reasonable variation for small quantities of mix. Four mix designs were provided. The 25 and 40 percent RAP mixes had the same design regardless of binder grade. A comparison of the QC data to the mix designs shows that the greatest variation from the design gradation occurred on the No. 4 sieve, where the actual gradation was as much as 9.7 percent finer than the design. The gradations on other sieves compared within 1 percent coarser to 5 percent finer than the design.

The binder contents measured by the contractors agreed with the mix designs within 0.3 percent. As noted in the discussion of table 7, the NCSC data showed similar results except in a few cases. All of the data suggest that the mixes were not over asphalted.

The NCSC data and the contractors' QC data showed that there was a general trend of decreasing VMA with increasing RAP content, which is partly caused by low AV. Excess asphalt binder is not the main cause of the low AV. This is significant in that asphalt binder properties and asphalt binder content more strongly control cracking behavior than do the aggregate properties. During analysis of the low-temperature cracking predictions, consideration will be given to mixtures with asphalt contents that differ markedly from the design.

For the mixture tests in this study, the specimens were compacted to 7 ±1 percent AV by varying the gyration level. Generally, there is a relationship between the number of gyrations required to reach 7 percent AV and AV at the design number of gyrations. Figure 1 shows the data from the mixes in this study. Mixtures with lower AV require fewer gyrations to achieve 7 percent AV.

Table 7. Comparison of measured and design binder contents.

Contractor	Mix	Percent AV (Plant Compacted)	Measured Binder Content (Percent)	Design Binder Content (Percent)	Difference from Design*
2	2A	5.4	5.7	5.9	-0.2
	2B	3.0	5.5	5.9	-0.4
	2C	4.3	6.2	5.9	+0.3
	2D	2.2	6.1	5.9	+0.2
	2E	3.3	5.9	5.9	0
	2F	1.3	6.5	5.9	+0.6
3	3A	—	5.9	5.7	+0.2
	3B	—	6.1	5.7	+0.4
	3C	—	5.7	6.0	-0.3
	3D	—	5.8	5.7	+0.1
	3E	—	6.0	5.7	+0.3
	3F	—	5.9	5.9	0
4	4A	3.4	5.5	5.6	-0.1
	4B	3.7	5.3	5.3	0
	4C	2.3	5.6	5.4	+0.2
	4D	2.5	5.6	5.2	+0.4
	4E	2.9	5.6	5.4	+0.2
	4F	2.1	5.4	5.2	+0.2
5	5A	3.8	5.6	5.6	0
	5B	4.1	5.7	5.6	+0.1
	5C	3.1	5.5	5.6	-0.1
	5D	2.2	5.6	5.6	0
	5E	3.7	5.5	5.6	-0.1
	5F	2.0	5.8	5.6	+0.3

* The difference equals the design binder content minus the measured binder content.
— Indicates that data were not available for this contractor.

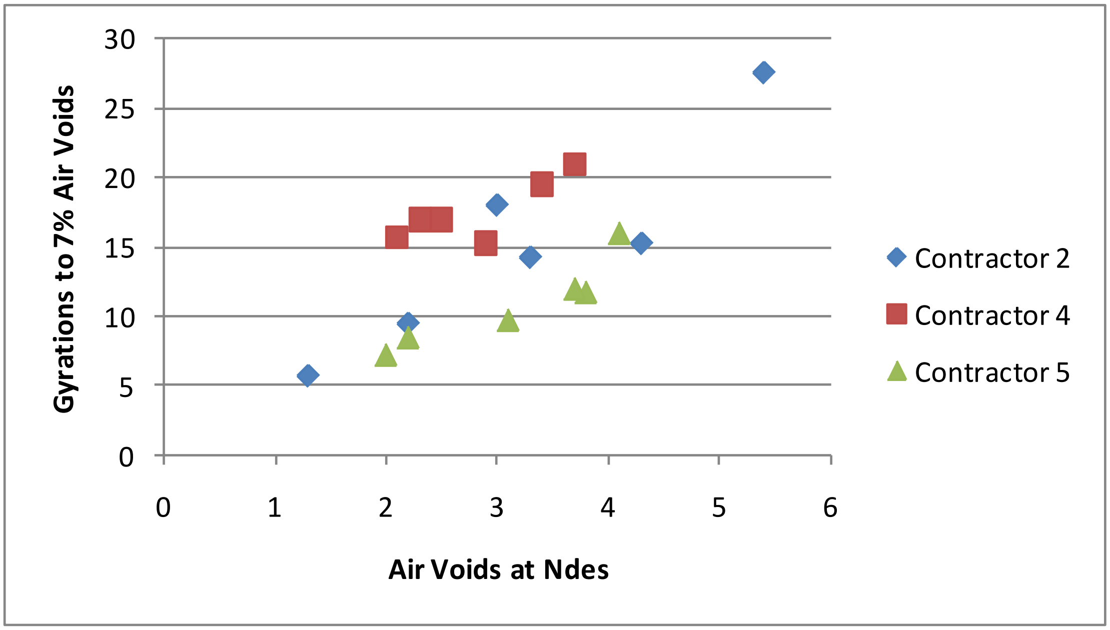
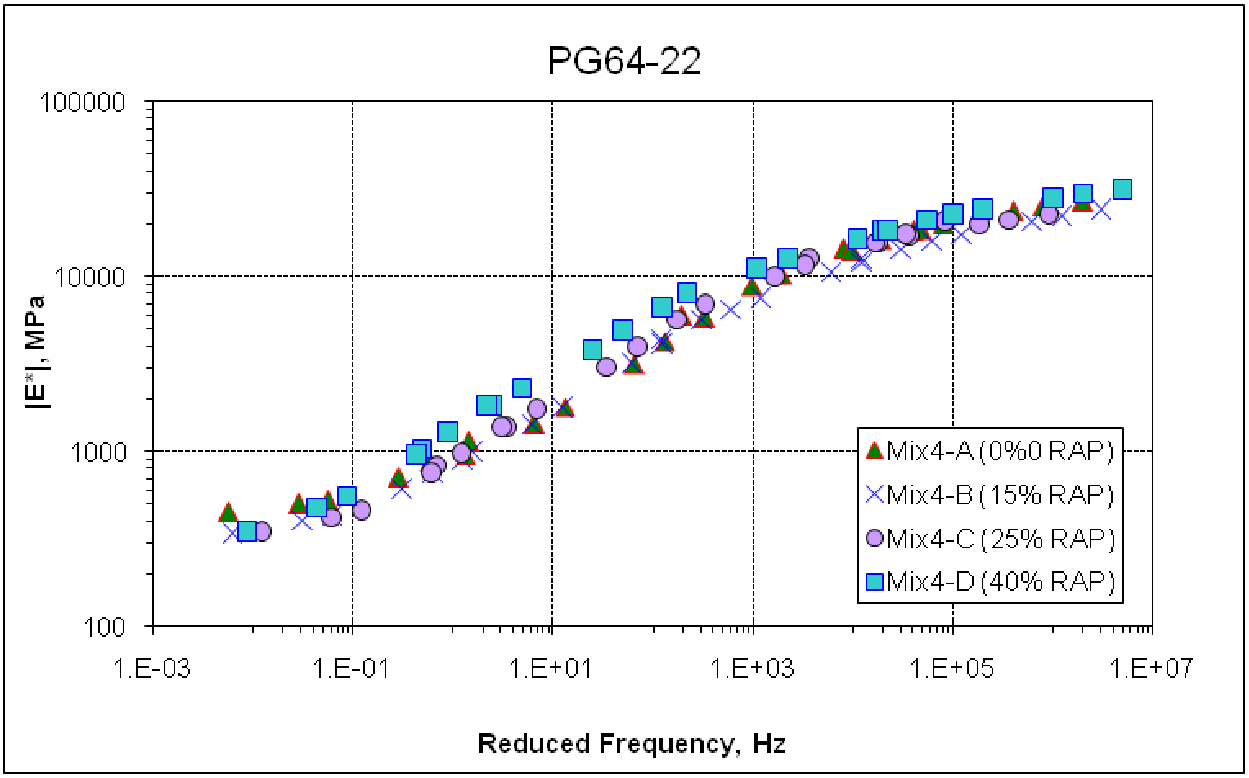


Figure 1. Graph. Number of gyrations to achieve 7 percent AV.

The cause of low AV in some of the mixtures is related to the aggregate skeleton (low VMA). High-temperature properties would be influenced more by a low number of gyrations to achieve 7 percent AV. This should be especially true for rut testing results. For |*E**|, the effect should be less so. Consider the |*E**| data shown in figure 2. At low frequencies where the asphalt binder properties were less dominant, the mixture stiffness was about 43,500 to 58,000 psi (300 to 400 MPa). At higher frequencies where the asphalt binder properties were more dominant, the stiffness is about 2,900 to 4,350 ksi (20,000 to 30,000 MPa), which is an increase of 70 times. Most of this increase is related to the binder properties.

In summary, because asphalt content is generally within a normal target value, the low-temperature and fatigue results of the study should not be unduly affected by mixtures with low AV. |*E**| data should also be relatively unaffected by low design AV.



1psi = 0.0069 MPa

Figure 2. Graph. Example master curves.

BINDER TEST RESULTS

The results of testing the virgin and recovered RAP and mix binders from each phase II contractor are shown in table 8 through table 11. Note that this testing was not performed in phase I; only DSR master curves were developed. The right-hand column summarizes the results from the analysis of the binder direct tension data and the BBR using the Thermal Stress Analysis Routine (TSAR™) software to determine T_{crit}. The results of testing the binders recovered from the mixtures in phase II are shown in figure 3 and figure 4. More graphs that show the results of testing the recovered binders are included in appendix B of this report.

Table 8. Virgin and recovered binder properties for contractor 2.

ID	Grade	High-Temperature Grade (DSR)	Low-Temperature Grade (BBR)	True Grade	T_{crit} (TSAR™)
Virgin binders	PG64-22	67.4	-24.2	PG67-24	
	PG58-28	60.7	-28.3	PG60-28	
RAP		85.8	-15.0	PG86-15	
2A	PG64-22	74.2	-22.1	PG74-22	-22.0
2B		75.5	-21.9	PG75-21	-21.9
2C		74.6	-21.8	PG74-21	-21.5
2D		74.7	-21.3	PG74-21	-21.5
2E	PG58-28	72.1	-24.1	PG72-24	-28.6
2F		73.4	-23.3	PG73-23	-25.9

Note: Blank cells indicate that there are no data for the virgin or RAP binders.

Table 9. Virgin and recovered binder properties for contractor 3.

ID	Grade	High-Temperature Grade (DSR)	Low-Temperature Grade (BBR)	True Grade	T_{crit} (TSAR™)
Virgin binders	PG64-22	66.4	-24.8	PG66-24	
	PG58-28	61.1	-28.9	PG61-28	
RAP		83.4	-17.0	PG83-17	
3A	PG64-22	71.3	-22.5	PG71-22	-18.9
3B		74.1	-21.8	PG74-21	-20.9
3C		74.7	-21.4	PG74-21	-20.2
3D		70.2	-20.3	PG70-20	-19.8
3E	PG58-28	75.5	-21.3	PG75-21	-22.3
3F		72.4	-24.5	PG72-24	-23.5

Note: Blank cells indicate that there are no data for the virgin or RAP binders.

Table 10. Virgin and recovered binder properties for contractor 4.

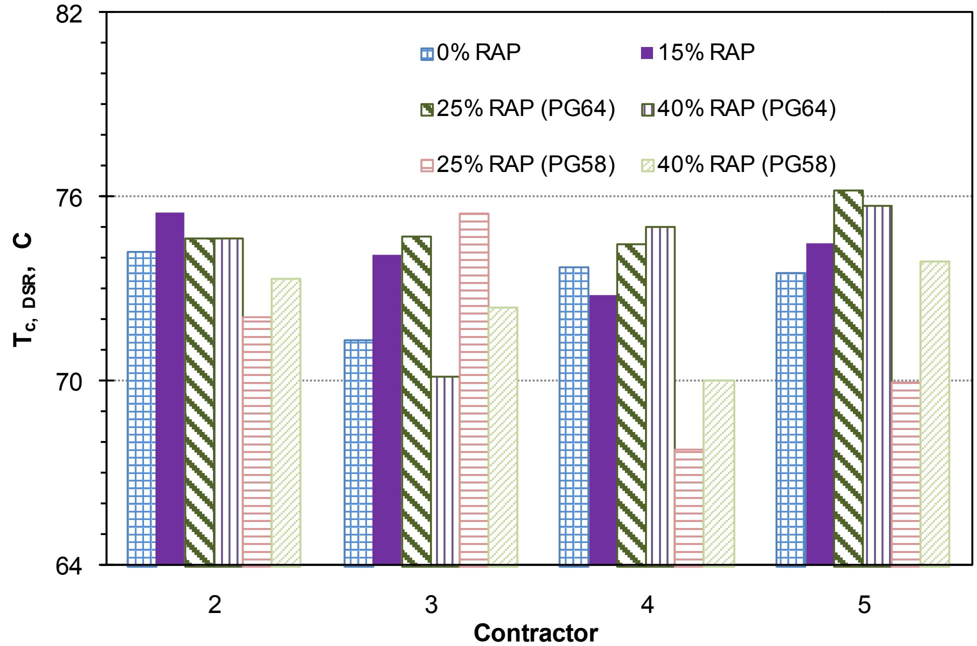
ID	Grade	High-Temperature Grade (DSR)	Low-Temperature Grade (BBR)	True Grade	T_{crit} (TSAR™)
Virgin Binders	PG64-22	67.4	-24.2	PG67-24	
	PG58-28	60.7	-28.3	PG60-28	
RAP		80.9	-20.9	PG80-20	
4A	PG64-22	73.7	-20.5	PG73-20	-22.6
4B		72.8	-20.8	PG72-20	-22.5
4C		74.4	-20.5	PG74-20	-20.1
4D		75.0	-19.6	PG75-19	-20.2
4E	PG58-28	67.8	-24.2	PG67-24	-26.2
4F		70.0	-23.3	PG70-23	-23.4

Note: Blank cells indicate that there are no data for the virgin or RAP binders.

Table 11. Virgin and recovered binder properties for contractor 5.

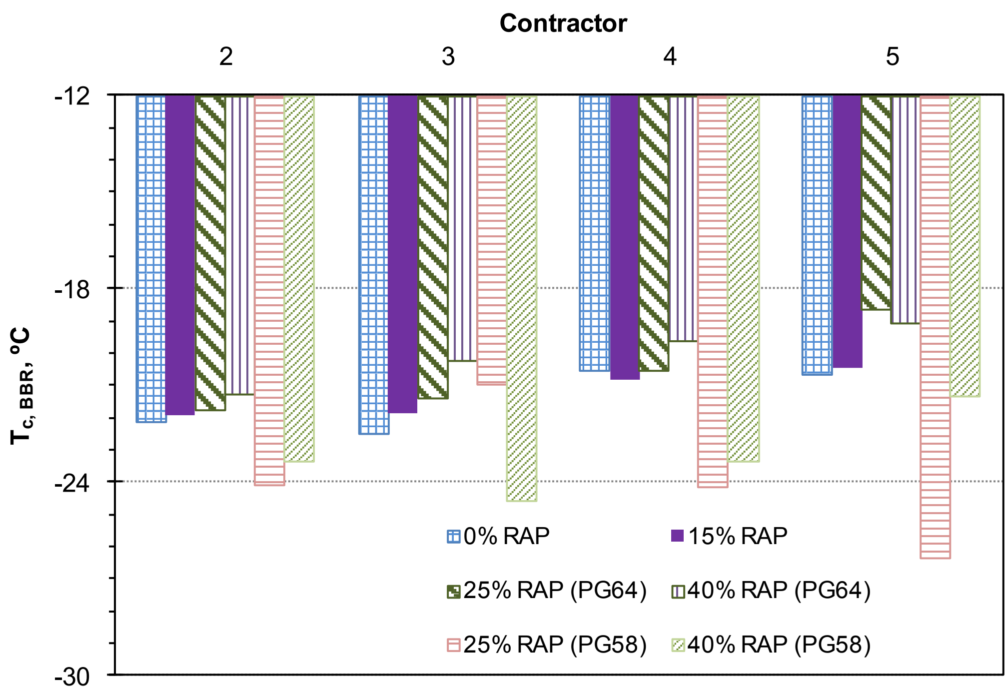
ID	Grade	High-Temperature Grade (DSR)	Low-Temperature Grade (BBR)	True Grade	T_{crit} (TSAR™)
Virgin Binders	PG64-22	66.2	-23.0	PG66-23	
	PG58-28	59.7	-29.9	PG59-29	
RAP		89.6	-9.7	PG89-9	
5A	PG64-22	73.5	-20.6	PG73-20	-20.2
5B		74.5	-20.5	PG74-20	-20.2
5C		76.2	-18.6	PG76-18	-20.8
5D		75.7	-19.1	PG75-19	-19.3
5E	PG58-28	69.9	-26.3	PG69-26	-24.8
5F		73.9	-21.3	PG73-21	-24.2

Note: Blank cells indicate that there are no data for the virgin or RAP binders.



°F = °C(1.8) + 32

Figure 3. Graph. Comparison of high critical temperatures ($T_{c,\ DSR}$) for binders recovered from plant mixtures.



°F = °C(1.8) + 32

Figure 4. Graph. Comparison of low critical temperatures ($T_{c,\ BBR}$) for binders recovered from plant-produced mixtures (based on BBR m-value = 0.300).

From these tables and figures, it can be observed that the virgin binders all met the specified grade. Most of the virgin binders had a "cushion" of a few degrees exceeding the required critical temperature by 3.6 or 5.4 °F (2 or 3 °C) (e.g., the true grade of a nominal PG64-22 was PG66-24). Occasionally, this factor of safety was as much as 7.2 °F (4 °C). Meeting the low-temperature grade with the PG58-28 binder appeared to be somewhat more challenging for the binder supplier than meeting the PG64-22 binder. The cushion on the low-temperature grade was less than 1.8 °F (1 °C) for two of the virgin binders. The low-temperature grades predicted by BBR alone and by the TSAR™ analysis were similar. True grades (continuous grades) may be more meaningful when analyzing test results than simply the standard PG grades. The greater cushion on the PG64-22 properties may have helped improve the test results of the mixes with that binder grade compared to the mixes with PG58-28, which had little or no cushion. That is, the greater cushion on the PG64-22 grade binder could help lessen the stiffening effect of higher RAP contents to a greater extent than the PG58-28 grade could accommodate.

Extracting and recovering the binder from the mixes forces blending of the virgin and RAP binders if they have not already blended in the mix. Therefore, it would be expected that as the percentage of RAP in the mix increases (moving from mix A with no RAP to mix D with 40 percent RAP), the high- and low-temperature grades would be expected to increase (i.e., the low-temperature grade would be expected to become less negative).

A comparison of the binder recovered from mix A with the virgin PG64-22 (see table 8 through table 11) shows that the plant processing (and possibly the process of extraction and recovery) increased the high-temperature grade of the binder by 9 to 12.6 °F (5 to 7 °C). The low-temperature grade also increased by 3.6 to 7.2 °F (2 to 4 °C). This result is not necessarily surprising. Previous research by Galal and White showed that binders recovered from plant-produced mixes in Indiana were stiffer than the RTFO tests on virgin binder would suggest they would be.[26] While that is only one study, it was conducted in the same State and included some of the same plants involved in the current study.

During phase I of the current study, the RTFO-aged virgin PG64-22 was found to be stiffer than the binder recovered from the plant-produced control mix that contained the same binder and no RAP. The binder was recovered using the Abson recovery procedure with mCl solvent.[24] That difference in the extraction/recovery procedure was the impetus for the extraction/recovery comparison conducted in phase II, which is discussed later in this report.

When comparing the mixes made with PG64-22 and differing RAP contents (mixes A through D), a slight increase in the high- and low-temperature grades can generally be observed, but the change is fairly minimal (1.8 to 3.6 °F (1 to 2 °C)) (see figure 3 and figure 4). In the case of contractor 3, no consistent pattern in the results was observed, but the results were from mixes where some buckets had water in them. The presence of water could possibly have affected the results.

When the mixes with PG58-28 (mixes E and F) were compared to the mixes with PG64-22 at the same RAP content (mixes C and D, respectively), the use of the softer binder typically decreased the high- and low-temperature grades by half a grade or more. The exception was contractor 3, where the high-temperature grade increased by 1.8 to 3.6 °F (1 to 2 °C) when the virgin binder grade decreased. The low-temperature grade for contractor 3's mixes either stayed the same (for the 25 percent RAP mixes) or decreased by 7.2 °F (4 °C) (for the 40 percent RAP mixes) when the softer binder was used.

These data suggest that if total, or nearly total, blending of the RAP and virgin binders occurred in these mixes, the effect on the low-temperature properties of the blended binder would not be extreme. Increasing the RAP content from zero to 25 percent without changing the binder grade resulted in no more than a 3.6 °F (2 °C) increase in the low true temperature grade (excluding the results of mix 3). Increasing the RAP content to 40 percent with no binder grade change also increased the low-temperature grade no more than 3.6 °F (2 °C). The mixes with PG58-28 exhibited recovered low-temperature binder properties that were typically 3.6 to 5.4 °F (2 to 3 °C) lower (more negative) than the corresponding mixes with PG64-22 and similarly better than the control mix with no RAP.

Mixture testing is necessary to determine if the mixtures behave as if total, or nearly total, binder blending has occurred. The mixture test results are presented next.

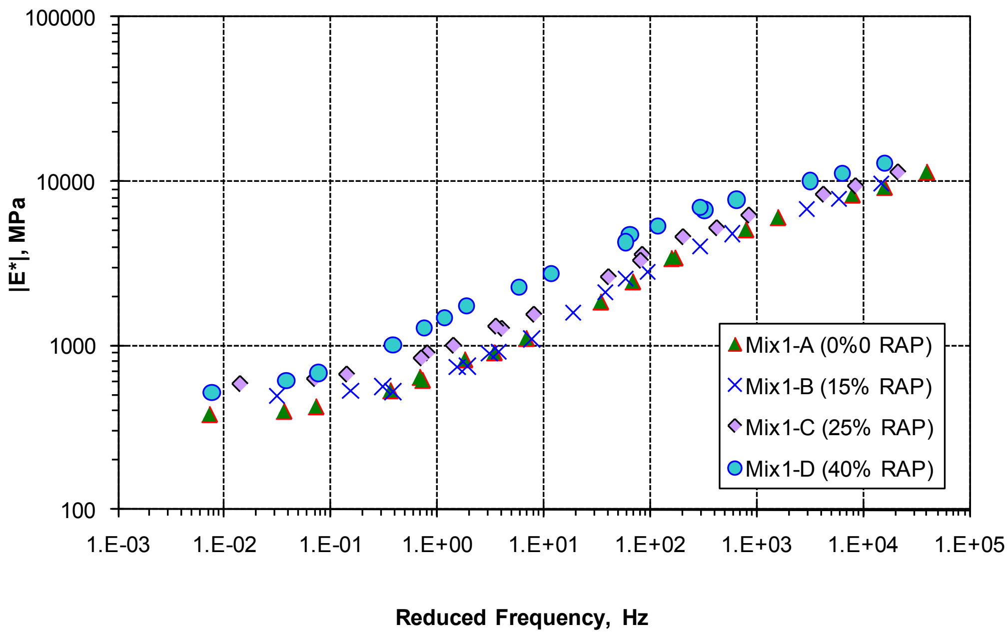
|*E**| TEST RESULTS

At least four replicates of each mix (at each RAP content and binder grade, including mixes A through E) were produced and tested for |*E**|. The results are summarized in figure 5 through figure 19. Statistical analysis of the |*E**| data is provided in the next section.

The figures illustrate the change in stiffness (|*E**|) of the mixes versus changes in the loading frequency on a log-log scale. Because frequency of loading and temperature are inversely related for asphalt materials, the figures reflect the behavior at different temperatures. High moduli occurred at high frequencies or low temperatures and are represented on the right side of the graphs. Low moduli occurred at high temperatures or low frequencies and are shown on the y-axis. At intermediate temperatures or loading frequencies, the mix moduli would also be intermediate.

For each set of mixtures (from one contractor), there are three graphs. The first graph compares the four mixes produced with PG64-22. It compares the control mix with no RAP to the three mixes with increasing RAP content (15, 25, and 40 percent) with the same binder grade. The second graph compares the control mix to the two mixes with PG58-28, which contain 25 and 40 percent RAP. The third graph compares the mixes with 25 and 40 percent RAP but with different PGs.

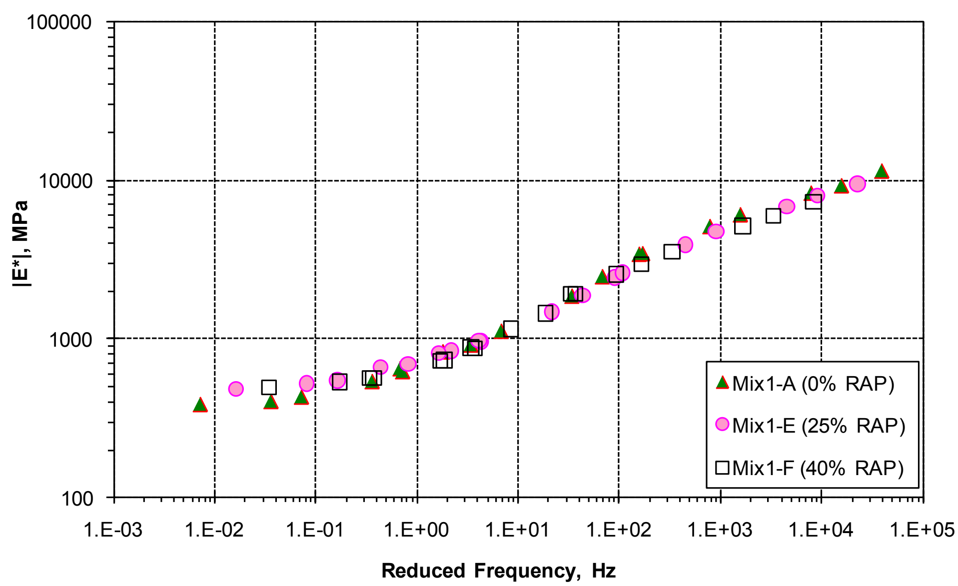
For contractor 1, adding 15 percent RAP (mix B) increased the stiffness compared to control mix A (see figure 5). The mix with 25 percent RAP was much stiffer, especially at intermediate and high temperatures, and the 40 percent RAP mix was also slightly stiffer. As a result, this mix behaved as expected.



1psi = 0.0069 MPa

Figure 5. Graph. Mix modulus of PG64-22 mixes from contractor 1.

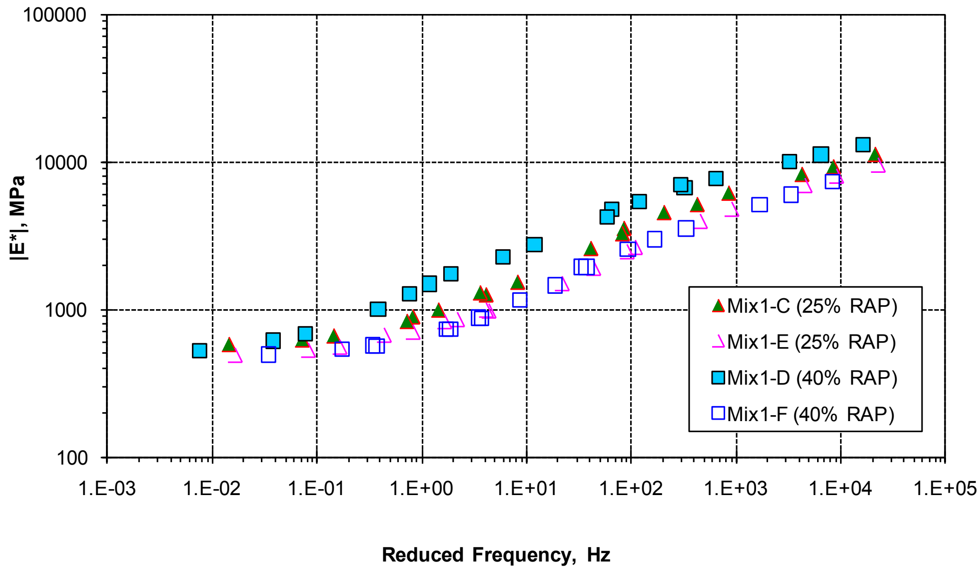
Figure 6 compares the control mix to the PG58-28 mixes from contractor 1. Changing the binder grade helped make the higher RAP content mixes more comparable to the control mix. They were more similar to the control than mixes C and D in figure 5. In this case, the control mix was not as stiff as the RAP mixes at high temperatures (low frequencies) and was comparable at low temperatures (high frequencies).



1psi = 0.0069 MPa

Figure 6. Graph. Mix modulus of control and PG58-28 mixes from contractor 1.

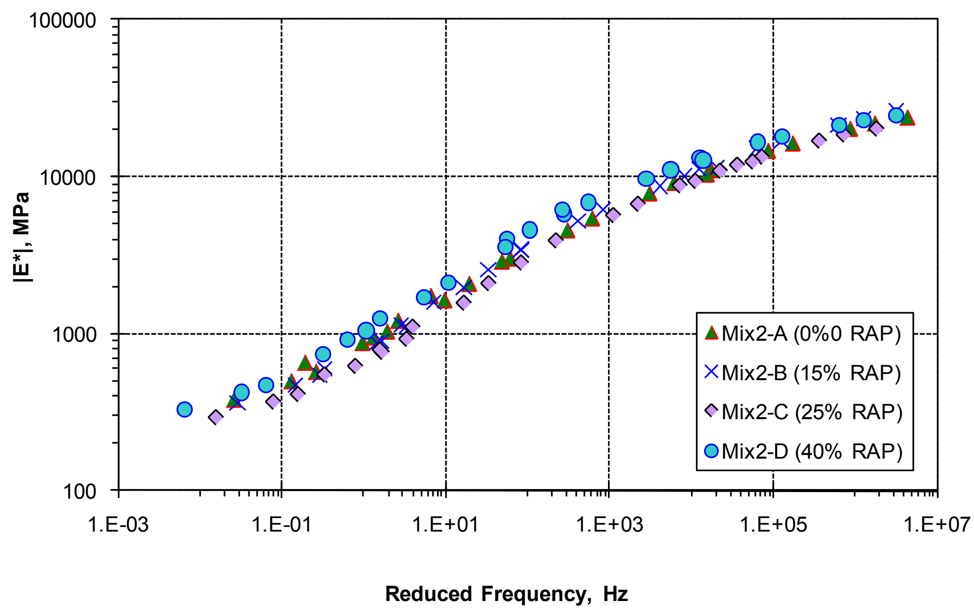
Figure 7 shows that changing the virgin binder grade in mixes with 25 and 40 percent RAP impacted the mix stiffness. There was a greater decrease in stiffness for the 40 percent RAP mixes than for the 25 percent RAP mixes. The two mixes with PG58-28 had similar stiffness.



1psi = 0.0069 MPa

Figure 7. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 1.

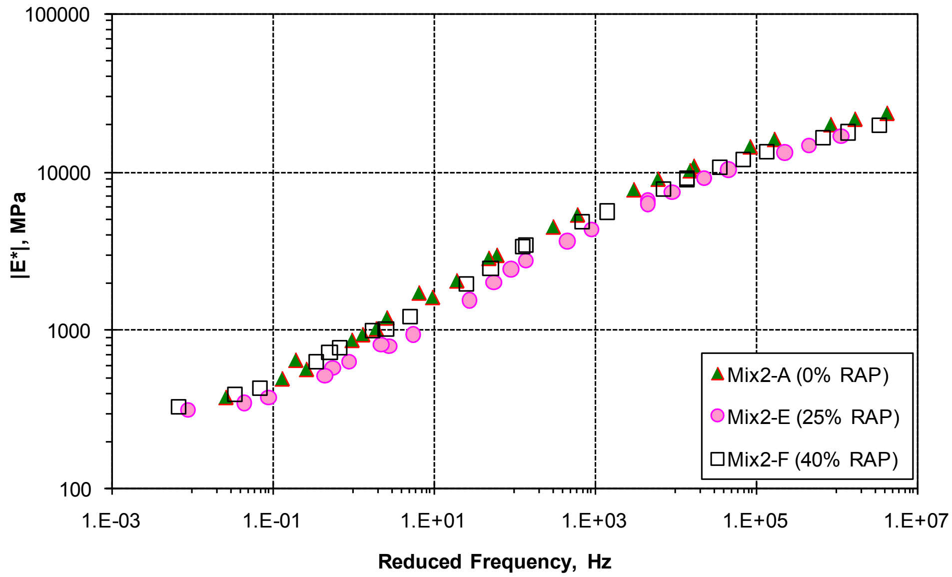
Figure 8 shows the mixes from contractor 2 with PG64-22. There was little change in stiffness of the mixes with zero, 15, and 25 percent RAP. The 40 percent RAP mix was the stiffest mix, especially at intermediate and higher temperatures.



1psi = 0.0069 MPa

Figure 8. Graph. Mix modulus of PG64-22 mixes from contractor 2.

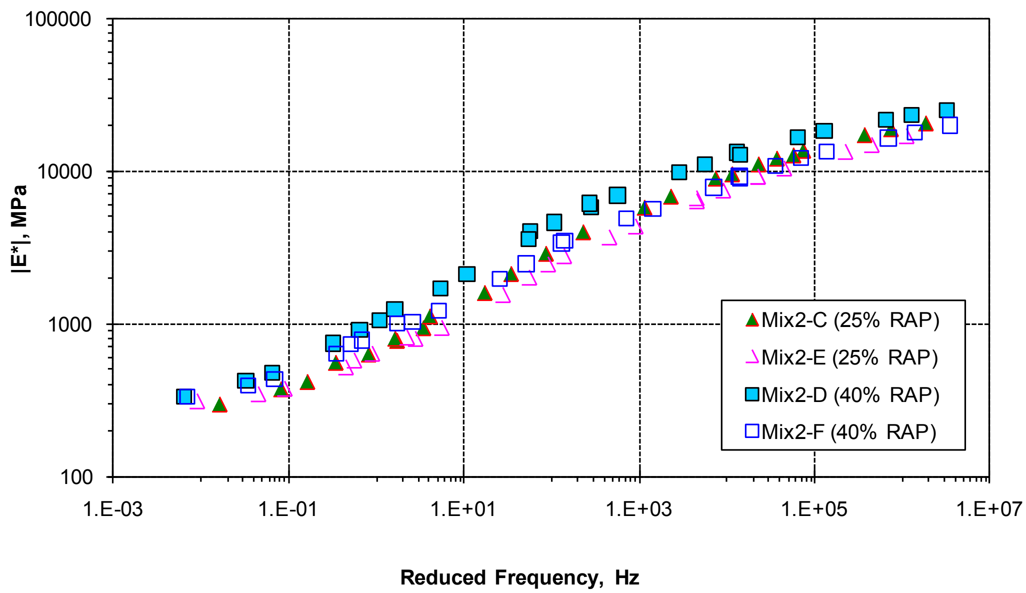
The comparison of the control mix to the mixes with PG58-28 from contractor 2 in figure 9 shows that the control and 40 percent RAP mixes were generally comparable. The control mix was somewhat stiffer than the PG58-28 mixes at low temperatures. The 25 percent RAP mix was less stiff than the control and 40 percent RAP mixes, especially at high and intermediate temperatures.



1psi = 0.0069 MPa

Figure 9. Graph. Mix modulus of control and PG58-28 mixes from contractor 2.

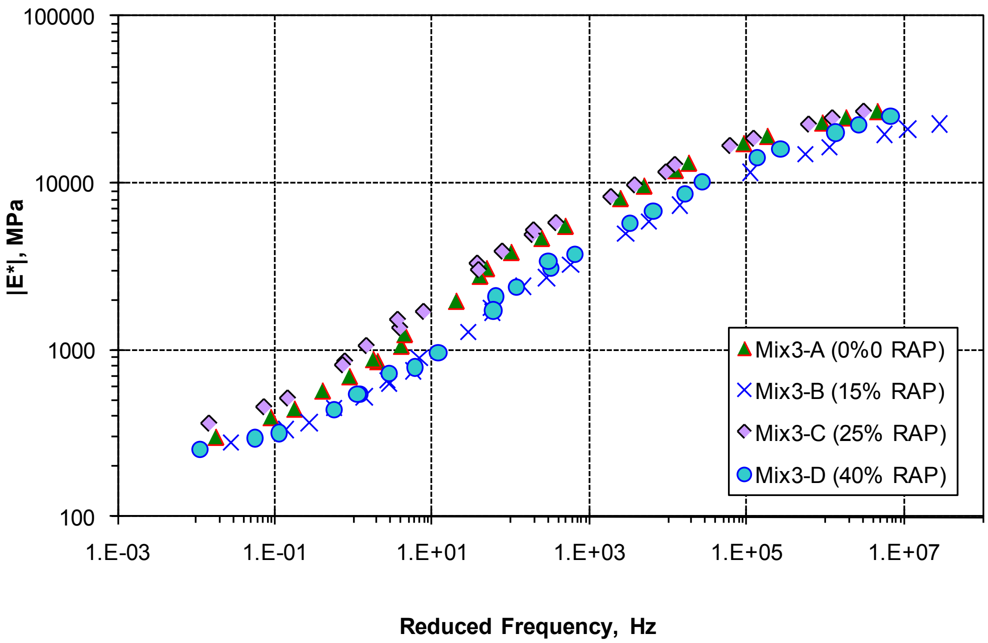
Figure 10 shows that the use of a softer binder grade softened the mix. The effect was especially pronounced for the 40 percent RAP mix. The 40 percent RAP mix contained more hardened RAP binder that could blend with, and be softened by, the virgin binder. The mix with 40 percent RAP and PG58-28 was generally stiffer than either mix with 25 percent RAP; however, those three mixes were similar at low temperatures (and were all softer than the 40 percent RAP mix with PG64-22).



1psi = 0.0069 MPa

Figure 10. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 2.

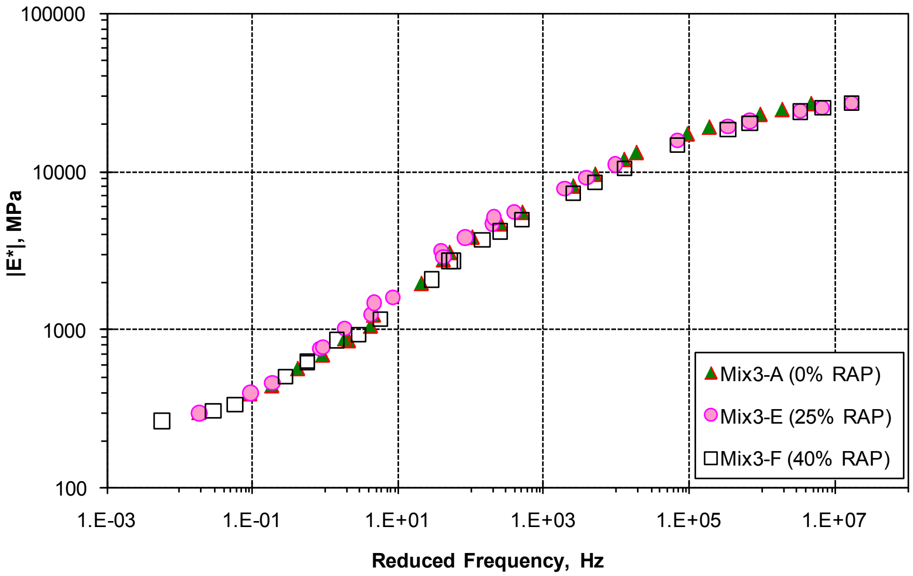
For contractor 3, mixes A, C, and E had visible water in the buckets when opened in the laboratory. The effects of the water on the test results are unknown. Given that, the results in figure 11 indicate that the mix with 15 percent RAP was the least stiff mix. The 25 percent RAP mix with PG64-22 was stiffer than the control, and the mix with 40 percent RAP and PG64-22 was similar to the 15 percent RAP mix at high temperatures and somewhat stiffer at intermediate and low temperatures.



1psi = 0.0069 MPa

Figure 11. Graph. Mix modulus of PG64-22 mixes from contractor 3.

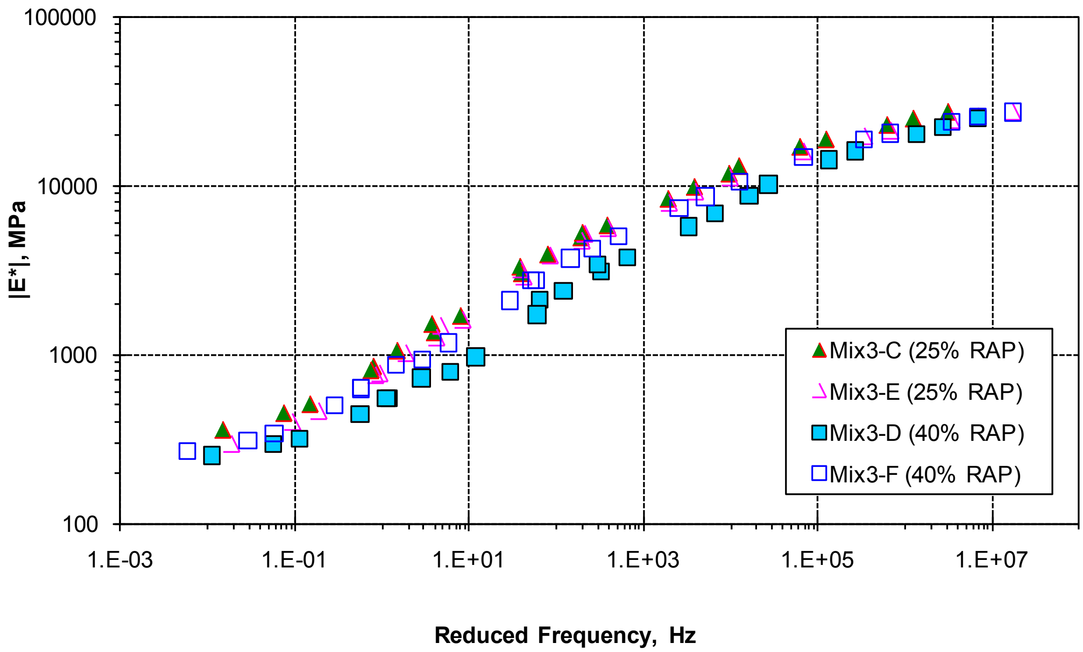
Figure 12 indicates that the mix with 25 percent RAP and PG58-28 from contractor 3 was slightly stiffer than the control at intermediate temperatures and similar at low and high temperatures. The 40 percent RAP mix with PG58-28 was similar to the control at all temperatures. However, mixes A and E had visible water, so these results are questionable.



1psi = 0.0069 MPa

Figure 12. Graph. Mix modulus of control and PG58-28 mixes from contractor 3.

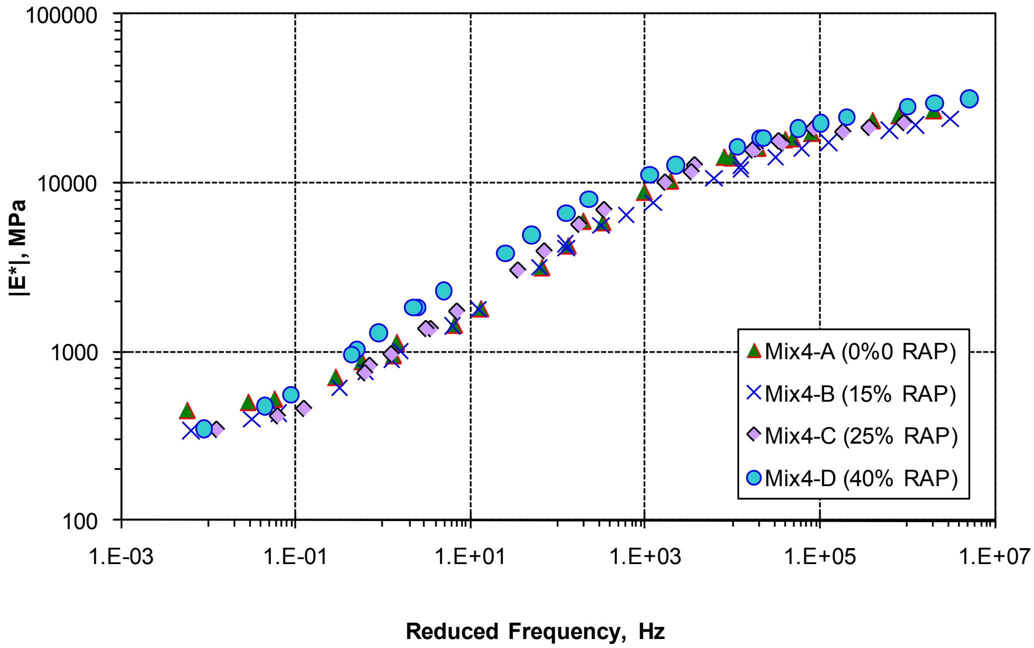
Figure 13 shows that a softer virgin binder grade decreased the mix stiffness slightly at 25 percent RAP. For the 40 percent RAP mixes, the mix with PG58-28 (mix F) demonstrated higher stiffness than the mix with PG64-22 (mix D), which was contrary to expectations.



1psi = 0.0069 MPa

Figure 13. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 3.

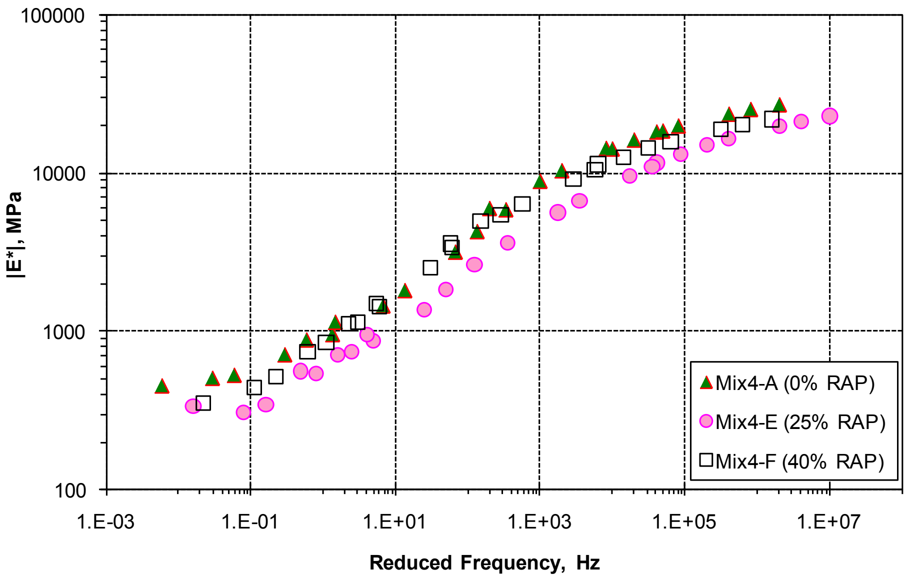
In the case of contractor 4's mixes in figure 14, the 15 percent RAP mix was not as stiff as the control. However, the 25 percent RAP mix was similar to the control, and the 40 percent RAP mix was stiffer. At low temperatures, the 40 percent RAP mix could be more susceptible to thermal cracking than the control or the lower RAP content mixes.



1psi = 0.0069 MPa

Figure 14. Graph. Mix modulus of PG64-22 mixes from contractor 4.

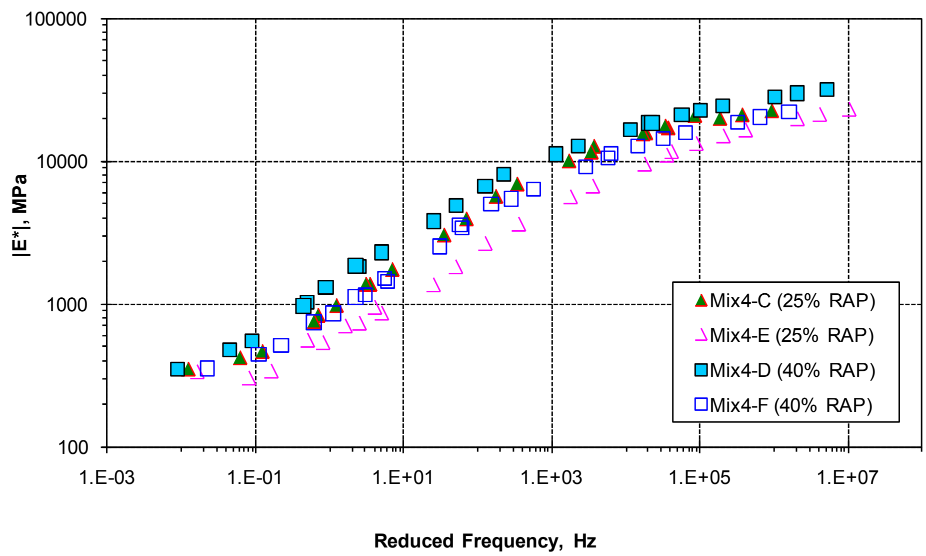
Figure 15 shows that the mix with 25 percent RAP and PG58-28 was not as stiff as the control mix. The mix with 40 percent RAP was also not as stiff as the control at low and high temperatures, but it was much stiffer than the 25 percent RAP mix.



1psi = 0.0069 MPa

Figure 15. Graph. Mix modulus of control and PG58-28 mixes from contractor 4.

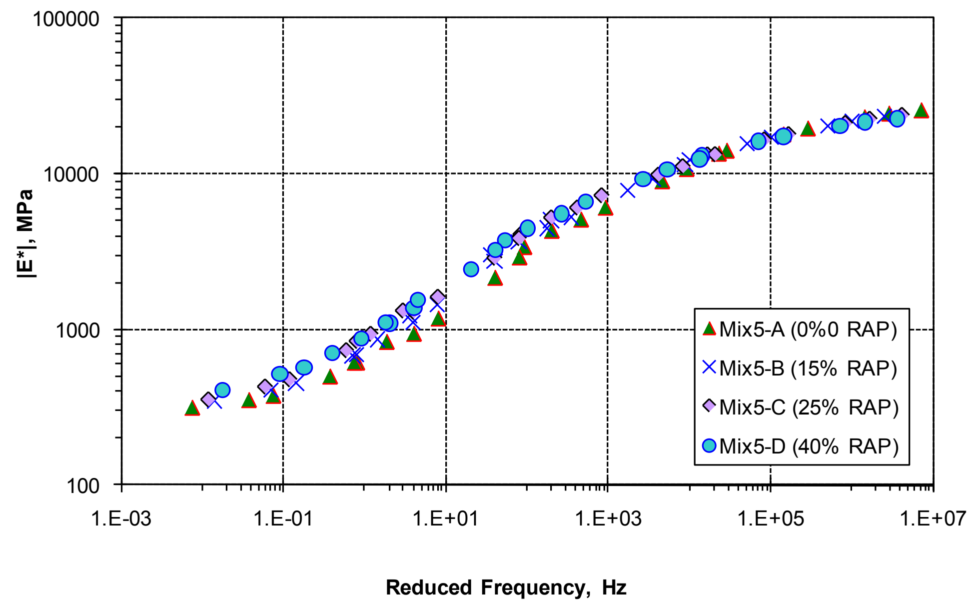
Figure 16 compares the 25 and 40 percent RAP mixes with different binder grades. The effect of the softer binder grade is visible for both RAP contents.



1psi = 0.0069 MPa

Figure 16. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 4.

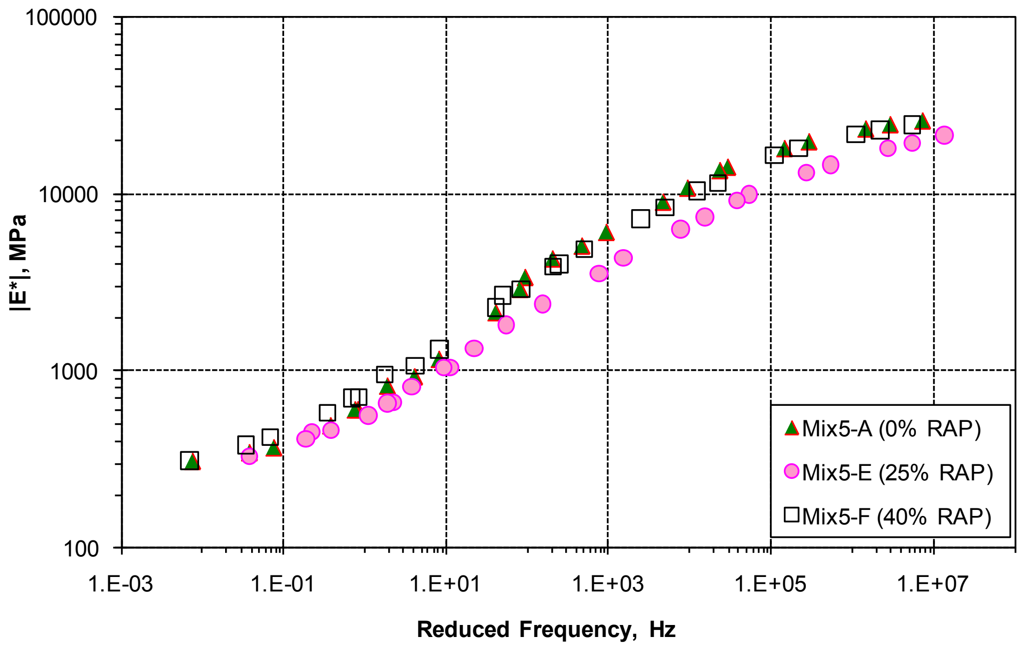
In the case of the results for contractor 5 in figure 17, all of the mixes with PG64-22 were similar in stiffness at low temperatures. As the RAP content increased, the stiffness at low temperatures (high frequencies) decreased slightly, which may have been an effect of the mix volumetrics (see table 6). As the RAP content increased, AV decreased. While all |*E**| test specimens were compacted to 7 ±0.5 percent AV, the difference in AV at a standard compaction level (50 or 75 gyrations) suggests weakening of the mix structure. At high temperatures, the stiffness increased slightly as the RAP content increased.



1psi = 0.0069 MPa

Figure 17. Graph. Mix modulus of PG64-22 mixes from contractor 5.

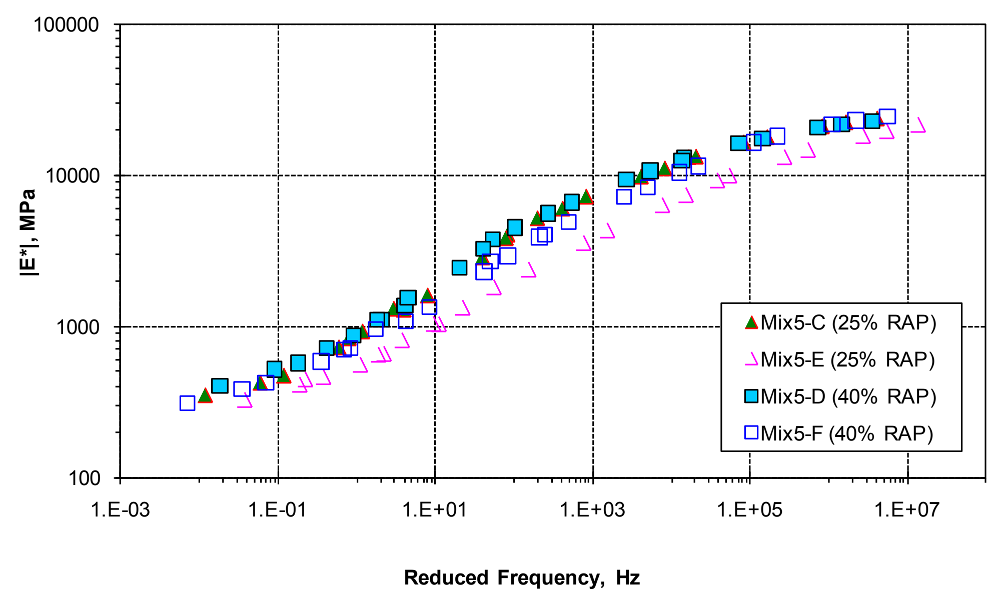
Figure 18 shows a comparison of the control mix to the mixes with PG58-28 from contractor 5. The mix with 25 percent RAP was not as stiff as the control, but that the mix with 40 percent RAP was similar to the control.



1psi = 0.0069 MPa

Figure 18. Graph. Mix modulus of control and PG58-28 mixes from contractor 5.

In figure 19, the effect of the softer binder grade is apparent in the mixes with 25 percent RAP and less obvious for the 40 percent RAP. However, even at 40 percent RAP, the mix with PG58-28 had a slightly lower |*E**| than the comparable mix with PG64-22.



1psi = 0.0069 MPa

Figure 19. Graph. Comparison of mix moduli of PG64-22 and PG58-28 from contractor 5.

Statistical Analysis

In order to quantify the differences between the mixes, the $|E^*|$values at 25 Hz were analyzed statistically to see if the differences were significant. Analysis of variance (ANOVA) was performed to determine if significant differences were observed between the four mixes with PG64-22 binder and between the two mixes with PG58-28 at different test temperatures. If the ANOVA indicated significant differences, a Bonferroni comparison of means test was conducted to determine which mixes were significantly different from the others. The comparison of means test categorizes results that are not significantly different together in the same group.

A summary of the results is shown in table 12 through table 15. The analysis was not performed on the results from contractor 3 because of the unknown effect of the water in the samples. In the tables, the null hypothesis was that the means of the mixes with the same virgin binder grade were not significantly different (e.g., the moduli of mixes A through D were not different). A *p*-value less than the significance level of 0.05 indicated that there was a significant difference. If the *p*-value was less than 0.05, the comparison of means test was run to group the data. The results of this test are shown in the column labeled "Inference," where the mixes that were not significantly different were grouped together. For example, contractor 1's mixes at 70 °F (20 °C) fell into two groups: mixes A, C, and D and mixes A, B, and C. Mixes A, C, and D were not significantly different from each other, and mixes A, B, and C were not significantly different from each other. Because these groups overlapped so much, no clear distinction could be made. However, at higher temperatures, mix D was significantly different from mixes A, B, and C. Also for contractor 1, mixes E and F were significantly different from each other at 39.2 and 130 °F (4 and 54 °C), but they were marginally not significantly different at 100 °F (37.8 °C) (although the *p*-value was only slightly greater than 0.05).

Review of the data from the other contractors shows that, in most cases, the mixes with the PG64-22 did not have significantly different moduli. If there was a significant difference, mix D with 40 percent RAP was different from the others. There are several instances where the mixes with PG58-28 were significantly different; this increase in significance may have been due in part to the fact that only two mixes were being compared.

Table 12. Statistical analysis of moduli at 25 Hz from contractor 1.

Mix	Binder	Temp. (°C)	Hypothesis	*p*-value	Inference
1	PG64-22	20	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0032	[D=A=C]; [A=C=B]
		37.8	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0002	[D]; [A = B = C]
		54.4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0010	[D]; [A = B = C]
1	PG58-28	4	$\mu_E = \mu_F$	0.0421	Significantly different (SD)
		37.8	$\mu_E = \mu_F$	0.5066	Not significantly different (NSD)
		54.4	$\mu_E = \mu_F$	0.0258	SD

°F = °C(1.8) + 32

Table 13. Statistical analysis of moduli at 25 Hz from contractor 2.

Mix	Binder	Temp. (°C)	Hypothesis	*p*-value	Inference
2	PG64-22	4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.1211	NSD
		21	$\mu_A = \mu_B = \mu_C = \mu_D$	0.3117	NSD
		37.8	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0000	[D]; [A = B = C]
		54.4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0618	NSD
2	PG58-28	4	$\mu_E = \mu_F$	0.0557	NSD
		21	$\mu_E = \mu_F$	0.0660	NSD
		37.8	$\mu_E = \mu_F$	0.0293	SD
		54.4	$\mu_E = \mu_F$	0.0688	NSD

°F = °C(1.8) + 32

Table 14. Statistical analysis of moduli at 25 Hz from contractor 4.

Mix	Binder	Temp. (°C)	Hypothesis	*p*-value	Inference
4	PG64-22	4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.1548	NSD
		21	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0221	[A = B = C = D]
		37.8	$\mu_A = \mu_B = \mu_C = \mu_D$	0.4002	NSD
		54.4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0016	[D]; [A = B = C]
4	PG58-28	4	$\mu_E = \mu_F$	0.7388	NSD
		21	$\mu_E = \mu_F$	0.6209	NSD
		37.8	$\mu_E = \mu_F$	0.0009	SD
		54.4	$\mu_E = \mu_F$	0.0101	SD

°F = °C(1.8) + 32

Table 15. Statistical analysis of moduli at 25 Hz from contractor 5.

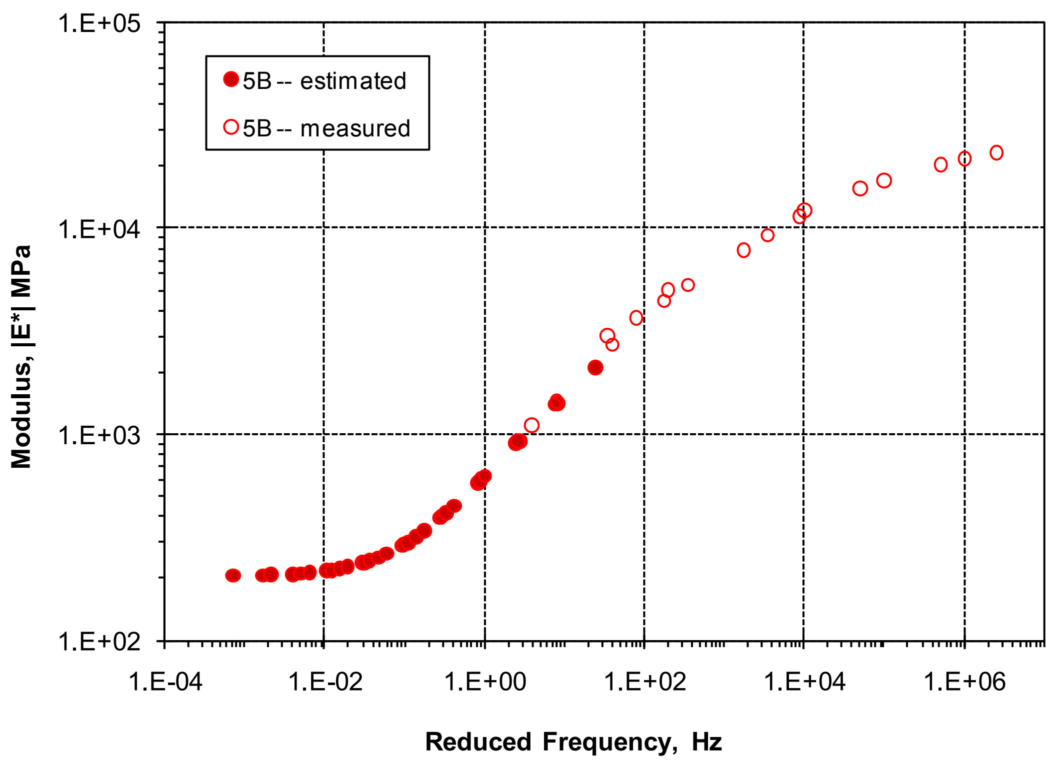
Mix	Binder	Temp. (°C)	Hypothesis	*p*-value	Inference
5	PG64-22	4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.6712	NSD
		21	$\mu_A = \mu_B = \mu_C = \mu_D$	0.5484	NSD
		37.8	$\mu_A = \mu_B = \mu_C = \mu_D$	0.2594	NSD
		54.4	$\mu_A = \mu_B = \mu_C = \mu_D$	0.0414	[A = B]; [B = C = D]
5	PG58-28	4	$\mu_E = \mu_F$	0.1174	NSD
		21	$\mu_E = \mu_F$	0.0872	NSD
		37.8	$\mu_E = \mu_F$	0.0173	SD
		54.4	$\mu_E = \mu_F$	0.2678	NSD

°F = °C(1.8) + 32

Estimation of Blending

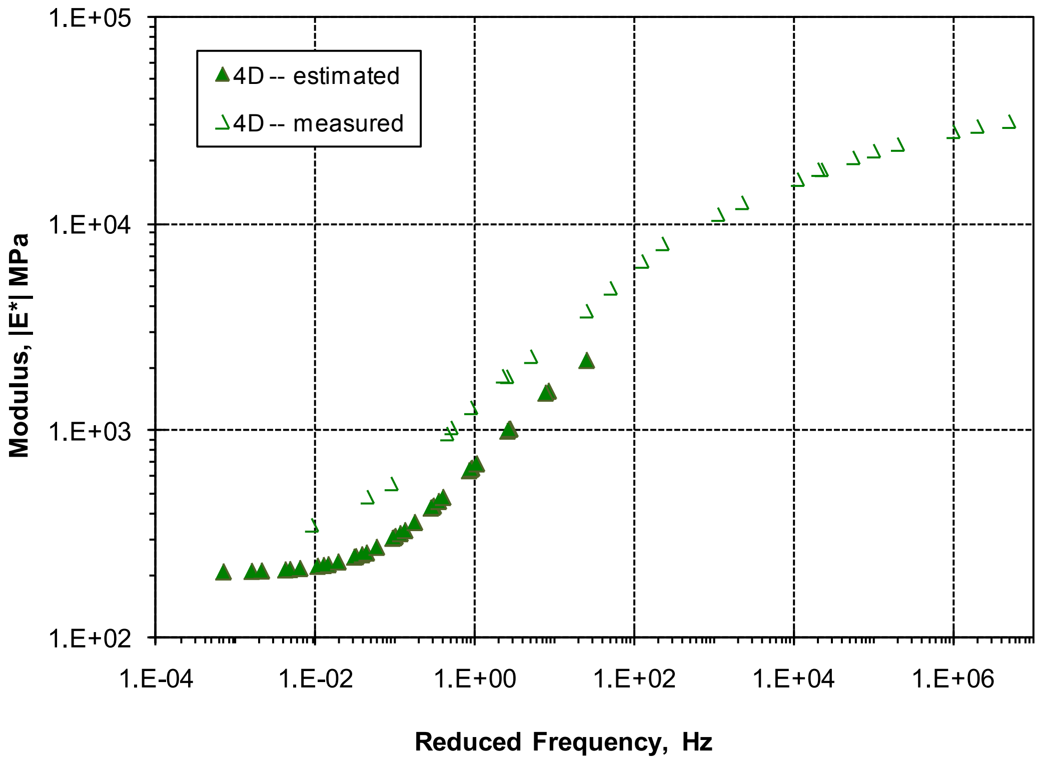
The binder and mixture testing results were used together following Bonaquist's approach for estimating binder blending in the mix.[10,11] The recovered binder test results and mixture volumetrics were used with the Hirsch model to estimate what the mix modulus would be if the RAP and virgin binders were completely blended.[12] The extraction and recovery process served to fully blend the binders. This estimation was then compared to the measured mix moduli over a range of temperatures through the mix master curve. Substantial overlap of the estimated and measured master curves indicates thorough blending. If there is overlap in the curves, the binder in the mix is acting as if it is a thorough blend of the RAP and virgin binders. If the two curves do not overlap, the binder is not acting like a total blend of the virgin and RAP binders. An example of good mixing is showed in figure 20, which shows the results for mix B (15 percent RAP) for contractor 5. An example of poorer blending is shown in figure 21 for mix D (40 percent RAP) for contractor 4.

All of the results for all six mixes from each of the phase II contractors are shown in appendix C. A general description of the results follows.



1psi = 0.0069 MPa

Figure 20. Graph. Example of thorough blending (mix 5B).



1psi = 0.0069 MPa

Figure 21. Graph. Example of poor blending (mix 4D).

At the time this testing was completed, the research team used the standard test temperatures and frequencies. The team has since learned that Dr. Bonaquist does not recommend testing at the highest temperature used here (130 °F (54 °C)) because of possible machine compliance issues. Some of the graphs in appendix C (figure 63, figure 68, figure 74, figure 75, and figure 77) show a slight upward curve in the measured modulus master curve at this high temperature, probably caused by machine compliance issues. Also, it would have been preferable to run the binder tests at different frequencies to ensure a greater overlap of the estimated and measured test frequencies. Future testing in this lab will follow these recommendations.

With those limitations, information still needs to be gathered from this analysis. In general, the mixes from contractor 2 showed substantial blending of the old and new binders, with the exception of the 40 percent RAP mixes, especially with PG64-22. Good blending was also observed for five of the mixes and partial blending for the 15 percent RAP mix from contractor 3; however, the impact of water in the samples is unknown. The comparison of estimated and measured moduli for contractor 4 was not as good, possibly indicating less blending of the RAP and virgin binders. The results for contractor 5 also indicated that substantial blending occurred in these mixes. In total, three out of four sets of data exhibited fair to good blending between the RAP binder and the virgin binder, and the fourth set is not as good at the higher RAP contents. Out of 24 mixes, three exhibited poor blending, one exhibited partial blending, and 20 exhibited good blending.

IDT TEST RESULTS

All of the mixes produced by the five contractors were tested at low temperatures in the indirect tension test.[22] In that test, the mixture's creep compliance (stiffness) and strength were evaluated. These values were used to estimate T_{crit} of the mixes. Neither stiffness nor strength alone can be used to determine when a mixture will crack. A stiff material will not crack if its strength is great enough, and a weaker material will not crack if it is not too stiff. A spreadsheet developed by Don Christensen called LTStress was used to calculate T_{crit} based on estimating when the tensile stresses that build up in a pavement (calculated based on the mixture stiffness) exceed the tensile strength of the mix.[27]

Three individual specimens of each mix were tested for creep stiffness at -4, 14, and 32 °F (-20, -10, and 0 °C). Following creep testing, strength testing was conducted on one of these specimens at each of the temperatures. The data were then input into LTStress for analysis.

The data for each contractor are reflected in two graphs each (see figure 22 through figure 31). The first graph in each pair shows the stiffness of the six mixes and the estimated pavement cracking temperature. The second graph shows the mix strength and the same estimated pavement cracking temperature. The data are also tabulated in table 16 through table 20.

LTStress uses a Gauss-Newton nonlinear least squares procedure to estimate the creep compliance master curve. This is an iterative procedure, and sometimes the data do not converge. In that case, there is a break in the line of T_{crit} and stiffness data shown below (see mix 4D). In all cases, the AV content of the samples tested were in the range of 7 ±1 percent.

Table 16. IDT results for contractor 1.

Mix	Binder	Strength, kPa (psi)	Coefficient of Variation (Percent)	Stiffness at 60 s (GPa)	Pavement Cracking Temperature, °F (°C)
1A	PG64-22	3,145 (456)	10.8	18.4	-22 (-30)
1B	PG64-22	3,238 (470)	11.2	20.9	-15 (-26)
1C	PG64-22	3,169 (459)	5.5	18.3	-18 (-28)
1D	PG64-22	3,870 (561)	10.8	24.8	-8 (-22)
1E	PG58-28	2,903 (421)	14.6	18.8	-21 (-30)
1F	PG58-28	3,210 (465)	6.2	20.1	-14 (-26)

1 psi = 6.89 × 10^{-6} GPa

Table 17. IDT results for contractor 2.

Mix	Binder	Strength, kPa (psi)	Coefficient of Variation (Percent)	Stiffness at 60 s (GPa)	Pavement Cracking Temperature, °F (°C)
2A	PG64-22	3,657 (530)	5.2	28.1	-3 (-20)
2B	PG64-22	3,704 (535)	5.4	18.4	-32 (-36)
2C	PG64-22	3,687 (535)	3.0	21.3	-18 (-28)
2D	PG64-22	3,737 (542)	5.9	25.9	-8 (-22)
2E	PG58-28	3,436 (498)	9.7	18.8	-18 (-28)
2F	PG58-28	3,923 (569)	4.4	12.1	-39 (-40)

1 psi = 6.89 × 10^{-6} GPa

Table 18. IDT results for contractor 3.

Mix	Binder	Strength, kPa (psi)	Coefficient of Variation (Percent)	Stiffness at 60 s (GPa)	Pavement Cracking Temperature, °F (°C)
3A*	PG64-22	3,440 (499)	10.8	24.1	-4 (-20)
3B	PG64-22	3,352 (486)	4.2	25.8	-4 (-20)
3C*	PG64-22	3,567 (517)	13.0	31.1	-2 (-19)
3D	PG64-22	3,181 (461)	14.7	30.3	-2 (-19)
3E*	PG58-28	3,643 (526)	11.5	23.4	-5 (-21)
3F	PG58-28	3,414 (495)	5.7	28.8	-4 (-20)

1 psi = 6.89 × 10^{-6} GPa

* Indicates that the buckets had water in them.

Table 19. IDT results for contractor 4.

Mix	Binder	Strength, kPa (psi)	Coefficient of Variation (Percent)	Stiffness at 60 s (GPa)	Pavement Cracking Temperature, °F (°C)
4A	PG64-22	2,884 (418)	7.7	25.9	-3 (-19)
4B	PG64-22	2,936 (426)	20.0	21.2	-6 (-21)
4C	PG64-22	3,153 (457)	8.4	22.6	-4 (-20)
4D	PG64-22	3,318 (481)	9.2	*	*
4E	PG58-28	3,072 (445)	6.3	21.9	-9 (-23)
4F	PG58-28	3,431 (498)	0.3	25.2	-10 (-23)

1 psi = 6.89 × 10^{-6} GPa

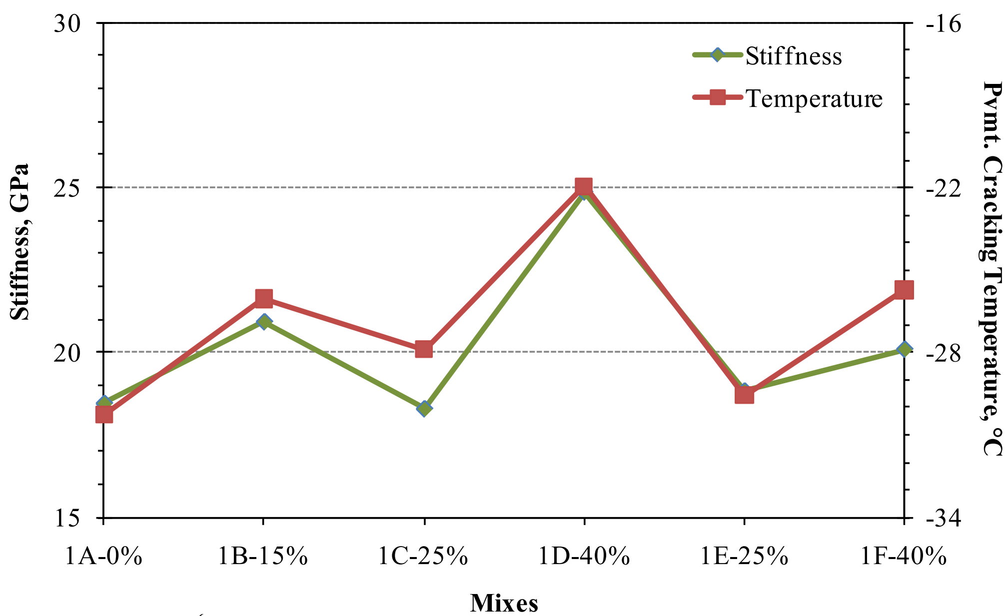
* Indicates data did not converge.

Table 20. IDT results for contractor 5.

Mix	Binder	Strength, kPa (psi)	Coefficient of Variation (Percent)	Stiffness at 60 s (GPa)	Pavement Cracking Temperature, °F (°C)
5A	PG64-22	2,927 (424)	25.6	21.4	-15 (-26)
5B	PG64-22	2,982 (432)	18.3	27.3	-1 (-18)
5C	PG64-22	3,146 (456)	4.4	26.9	-4 (-20)
5D	PG64-22	3,319 (481)	8.9	22.1	-8 (-22)
5E	PG58-28	2,976 (431)	7.1	19.3	-9 (-23)
5F	PG58-28	3,096 (449)	8.3	20.2	-7 (-22)

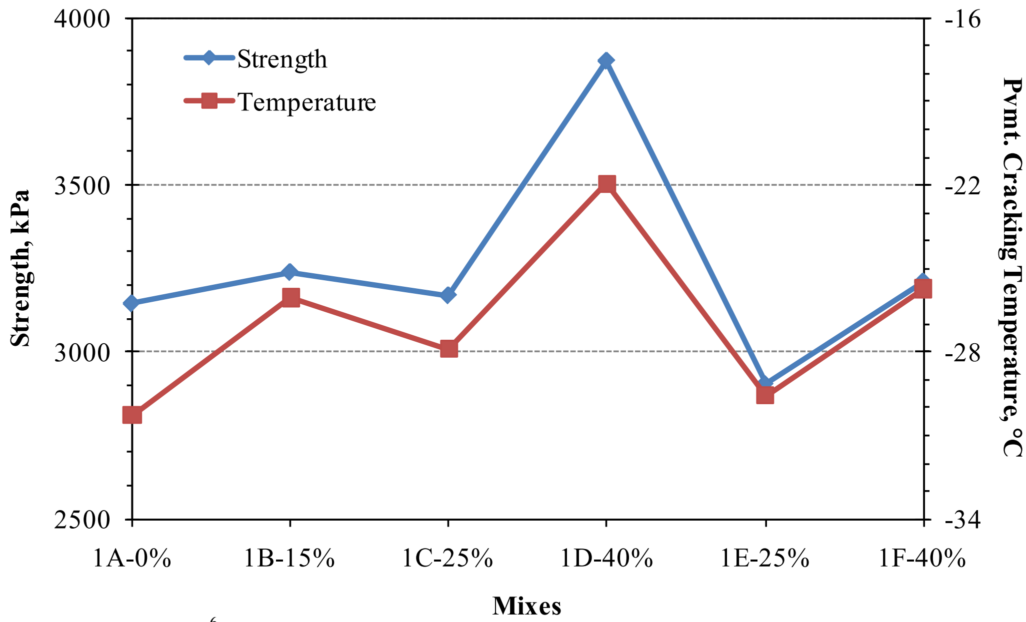
1 psi = 6.89 × 10^{-6} GPa

Figure 22 and figure 23 show the results for contractor 1. The results indicate that the stiffness of the 15 percent RAP mix with PG64-22 binder was somewhat higher than the control. The 25 percent RAP mix was similar to the control, while the 40 percent RAP mix was stiffer than the control. The strengths of the PG64-22 mixes followed a similar trend. T_{crit} was slightly warmer than the control (3.6 to 7.2 °F (2 to 4 °C)) for the 15 and 25 percent RAP mixes and 7.2 to 10.8 °F (4 to 6 °C) warmer for the 40 percent RAP mix. The stiffnesses and strengths of the mixes with PG58-28 were similar to the 15 and 25 percent RAP mixes with PG64-22, as were the cracking temperatures.



1 psi = 6.89 × 10^{-6} GPa
°F = °C(1.8) + 32

Figure 22. Graph. IDT stiffness and pavement cracking temperature for contractor 1.



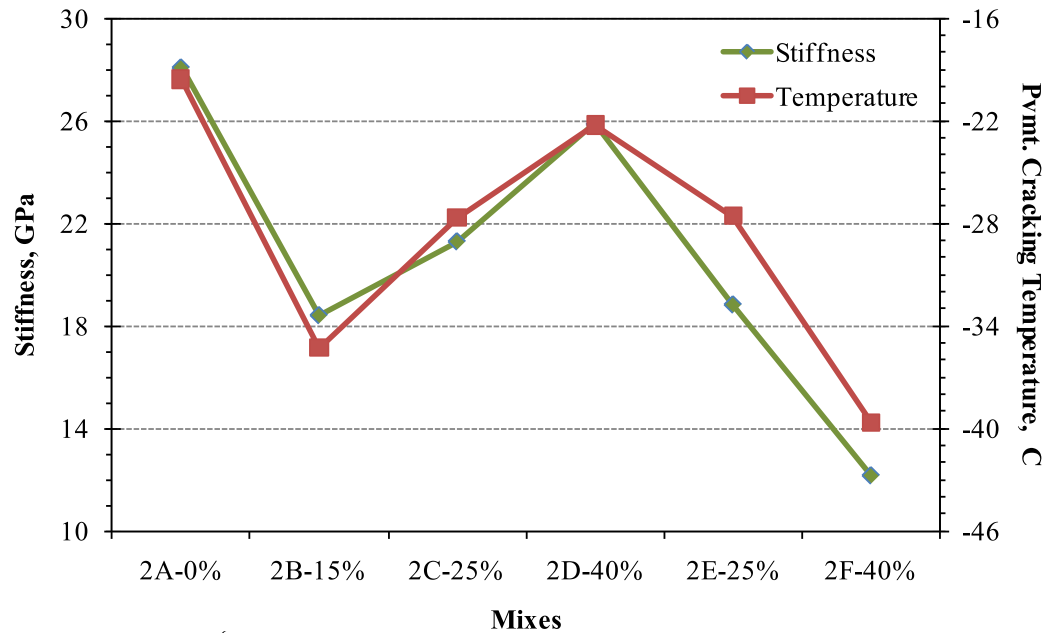
1 psi = 6.89×10^{-6} GPa
°F = °C(1.8) + 32

Figure 23. Graph. IDT strength and pavement cracking temperature for contractor 1.

The data for contractor 2's mixes, shown in figure 24 and figure 25, indicate that the addition of 15 percent RAP reduced the mix stiffness and pavement cracking temperature, despite the fact that the 15 percent RAP mix was 0.4 percent low in binder. Additional amounts of RAP, up to 40 percent, caused an increase in the stiffness and cracking temperature. The strength was relatively constant for mixes A through D. Large differences in the mix strength would not be expected since the same binder was used in all four mixes and low-temperature cracking is highly binder dependent.

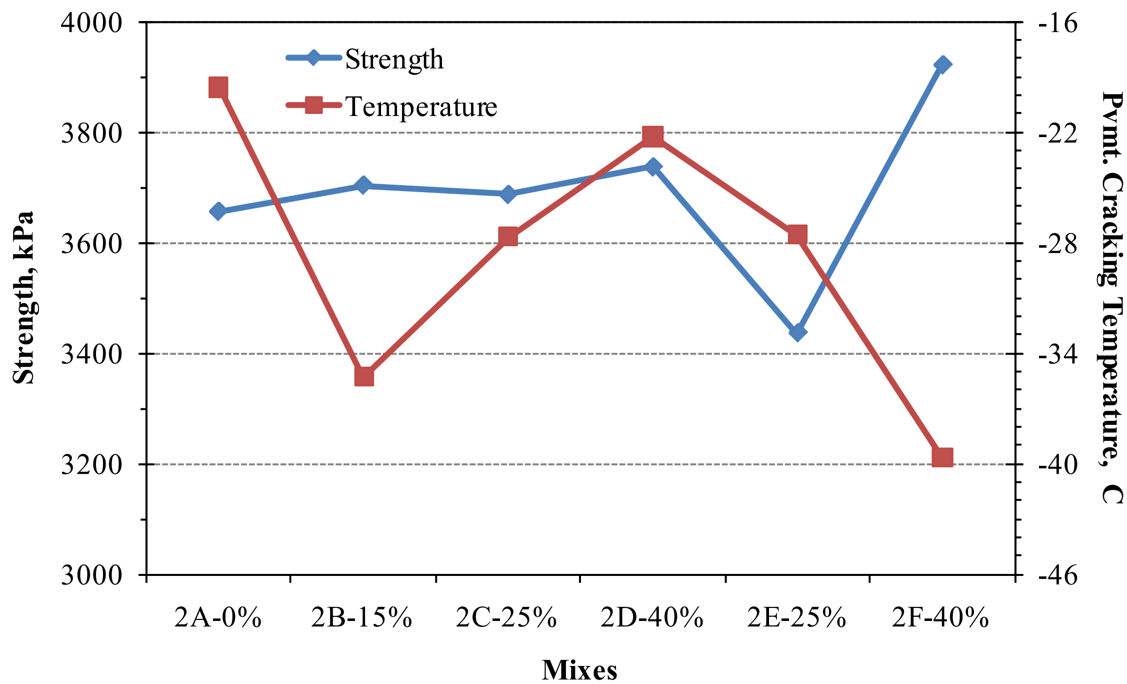
When the binder grade was changed to PG58-28, the stiffness and pavement cracking temperature decreased. The stiffness of the mix with 25 percent RAP and PG58-28 was comparable to the 15 percent RAP mix with PG64-22. The cracking temperature of mix E was similar to that of the 25 percent RAP mix with the stiffer binder. Surprisingly, mix F, which has 40 percent RAP and PG58-28 binder, was even less stiff and had a lower T_{crit} than any of the other mixes. This mix had the highest deviation in the binder content and was 0.6 percent higher than the design. The low cracking temperature of about -40 °F (-40 °C) was due in part to the high strength of that mix in conjunction with the low stiffness and may have been related to the high binder content.

These results correspond fairly well to the $|E^*|$ master curve analysis presented earlier in this report. Mix A was consistently stiffer than mixes B and C but was similar to mix D, especially at lower temperatures. Mixes E and F were both less stiff than the control mix.



1 psi = 6.89 × 10^{-6} GPa
°F = °C(1.8) + 32

Figure 24. Graph. IDT stiffness and pavement cracking temperature for contractor 2.



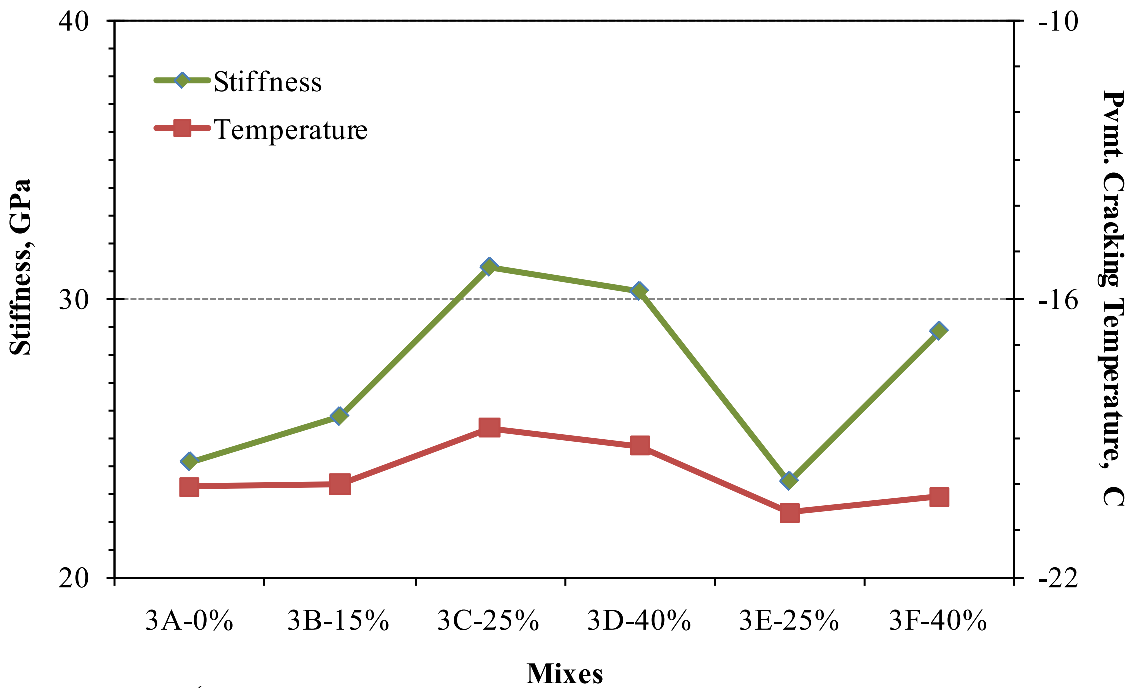
1 psi = 6.89 kPa
°F = °C(1.8) + 32

Figure 25. Graph. IDT strength and pavement cracking temperature for contractor 2.

Analysis of the IDT test results for contractor 3 show little change in the estimated pavement cracking temperature for any of the mixes. In terms of stiffness, the control mix was slightly less stiff than mix B, and the addition of more RAP caused an increase in the stiffness of mix C (see figure 26). Mix D had comparable stiffness to mix C. Mix E, with the softer binder, had comparable stiffness to the control mix, and mix F was somewhat stiffer.

The strengths of these mixes were somewhat more variable than some of the other mixes (see figure 27). The 40 percent RAP mixes with the PG58-28 binder tended to have higher strengths than their companion mixes with PG64-22. The 15 percent RAP mix had lower strength than the control mix.

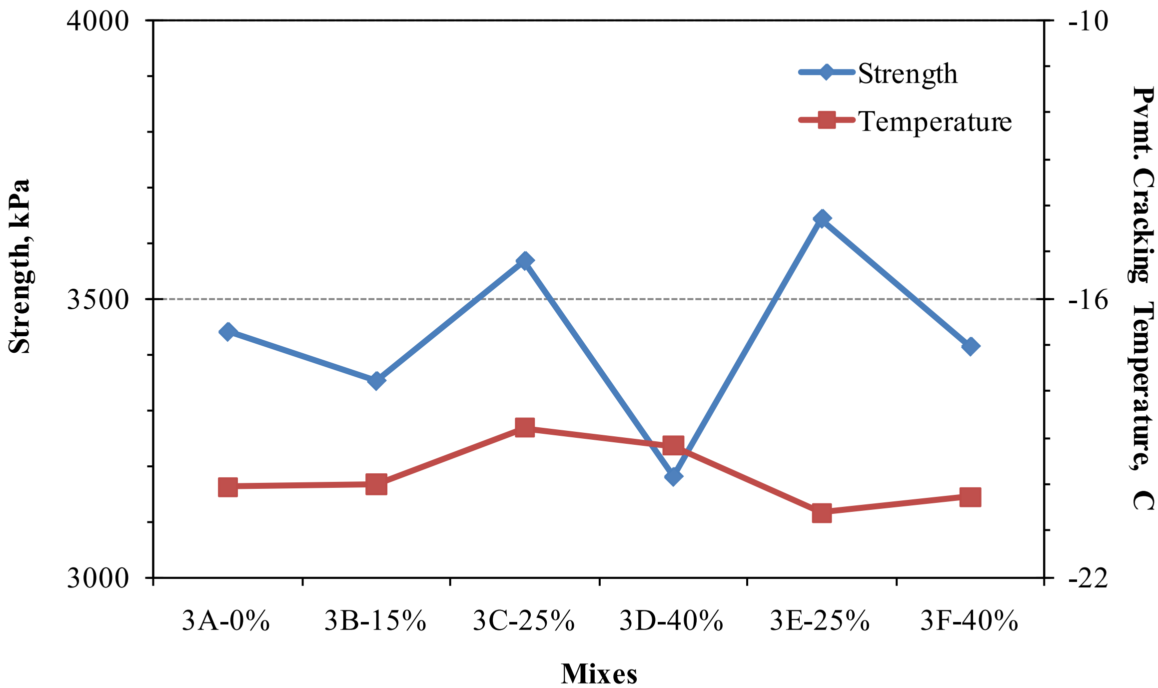
The unknown effects of visible water in mixes A, C, and E from contractor 3 may make these results questionable. In addition, mix B had binder content 0.4 percent higher than design, which did not appear to have had a major impact on these results.



1 psi = 6.89×10^{-6} GPa

°F = °C(1.8) + 32

Figure 26. Graph. IDT stiffness and pavement cracking temperature for contractor 3.



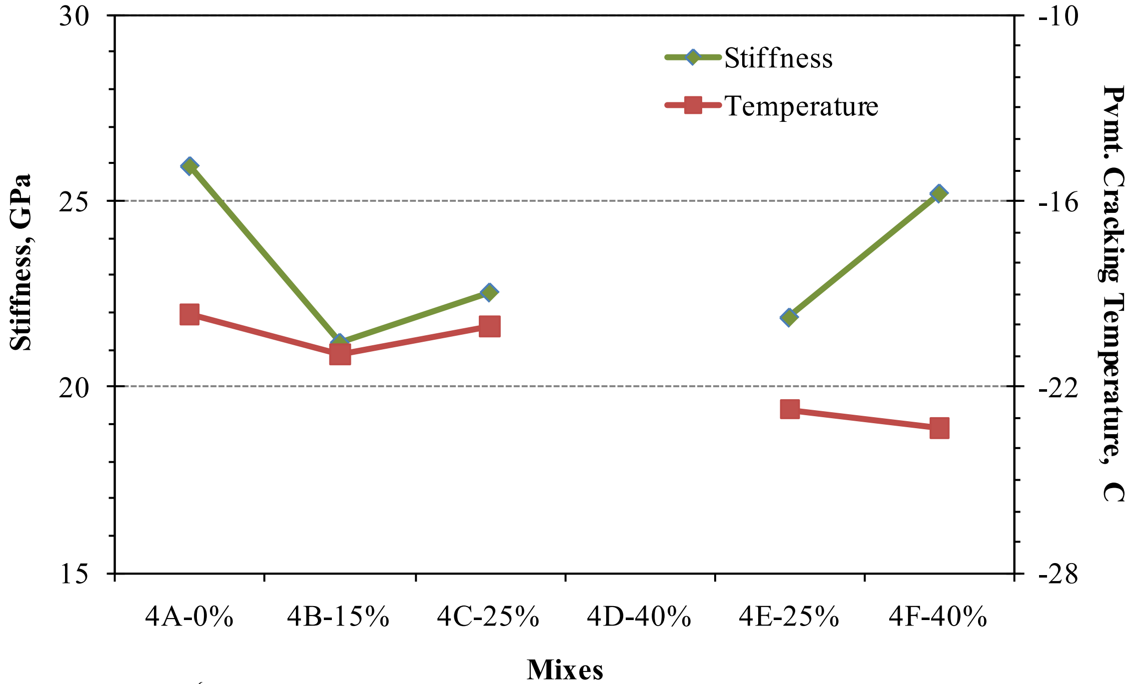
1 psi = 6.89 kPa
°F = °C(1.8) + 32

Figure 27. Graph. IDT strength and pavement cracking temperature for contractor 3.

The mixes from contractor 4 show an example of a dataset that did not converge (see figure 28 and figure 29). Satisfactory results could not be obtained for mix D. There is no obvious problem with the data itself (i.e., no obvious outlier(s) and a lack of excessive variability in the results), but the data would not converge. Mix D had 0.4 percent higher binder than designed, which should not have affected how the data converged. The overall interpretation of data was not affected since that data point was not considered.

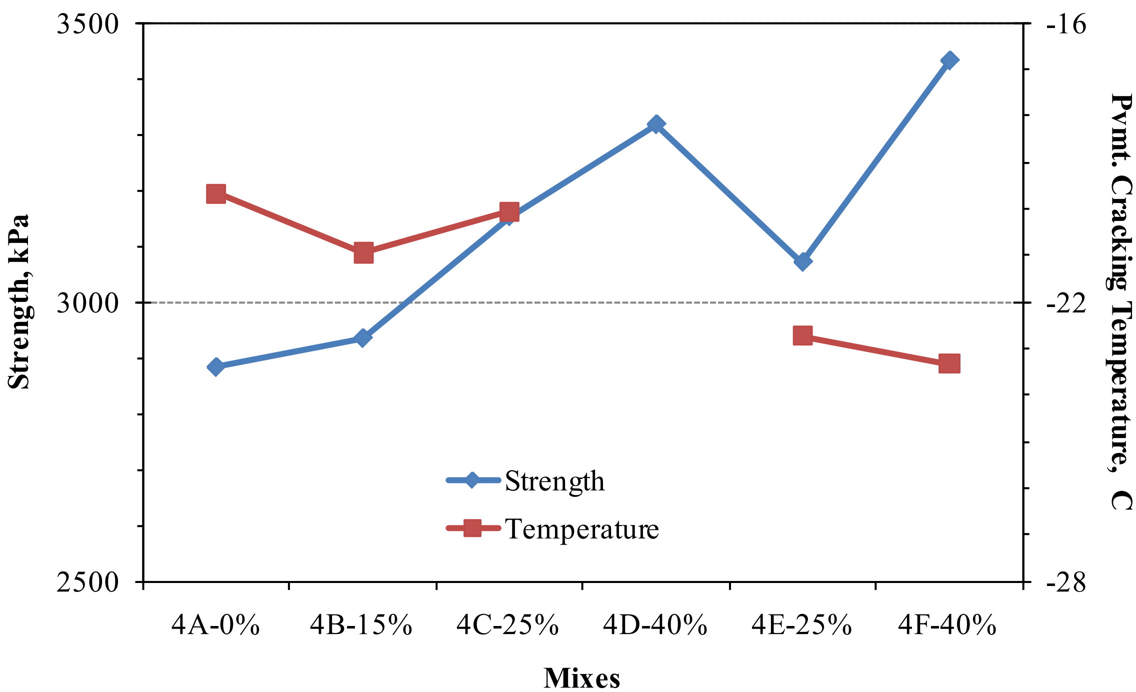
The data that could be analyzed showed a decrease in stiffness from the control to 15 percent RAP followed by an increase (though still less stiffness than the control) for mix C. Mix E had similar stiffness to mixes B and C. Mix F was stiffer than mix E, likely showing the stiffening effect of the RAP. Mix F was still not as stiff as the control, possibly reflecting the influence of the softer binder grade.

The strength data showed a steady increase in the strength as the RAP content increased in the mixes with PG64-22. The mixes with PG58-28 had comparable or higher strengths than their companion mixes, and mix F had greater strength than mix E. There was little change in the pavement cracking temperature for the mixes with the same binder grades.



1 psi = 6.89 × 10^{-6} GPa
°F = °C(1.8) + 32

Figure 28. Graph. IDT stiffness and pavement cracking temperature for contractor 4.

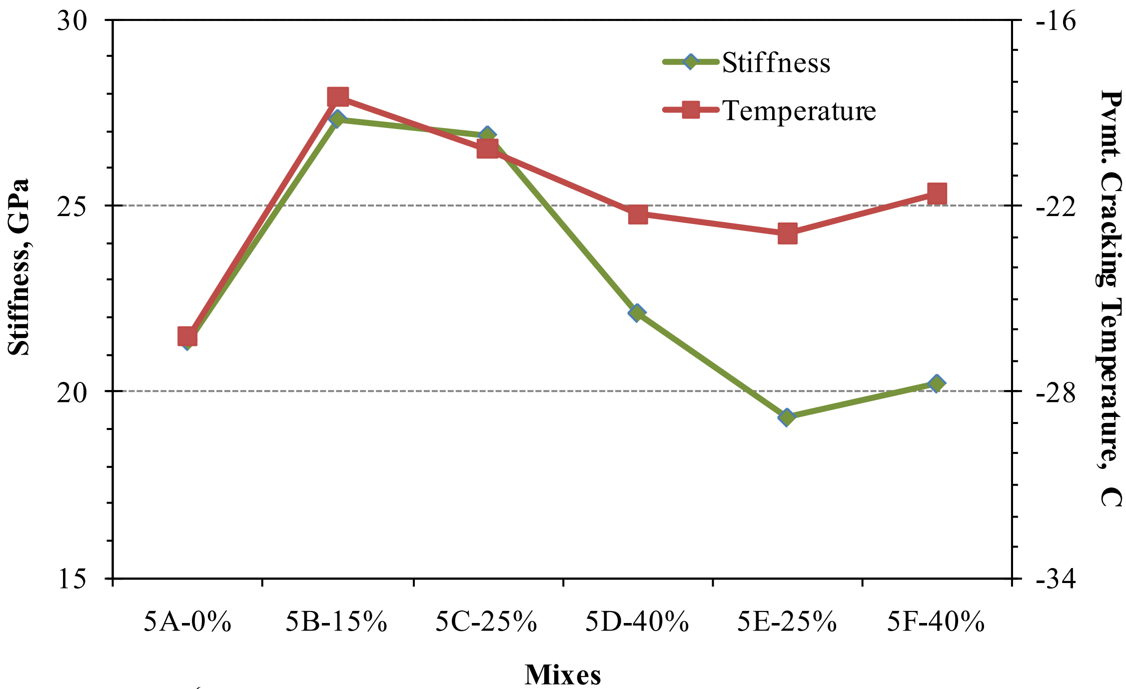


1 psi = 6.89 kPa
°F = °C(1.8) + 32

Figure 29. Graph. IDT strength and pavement cracking temperature for contractor 4.

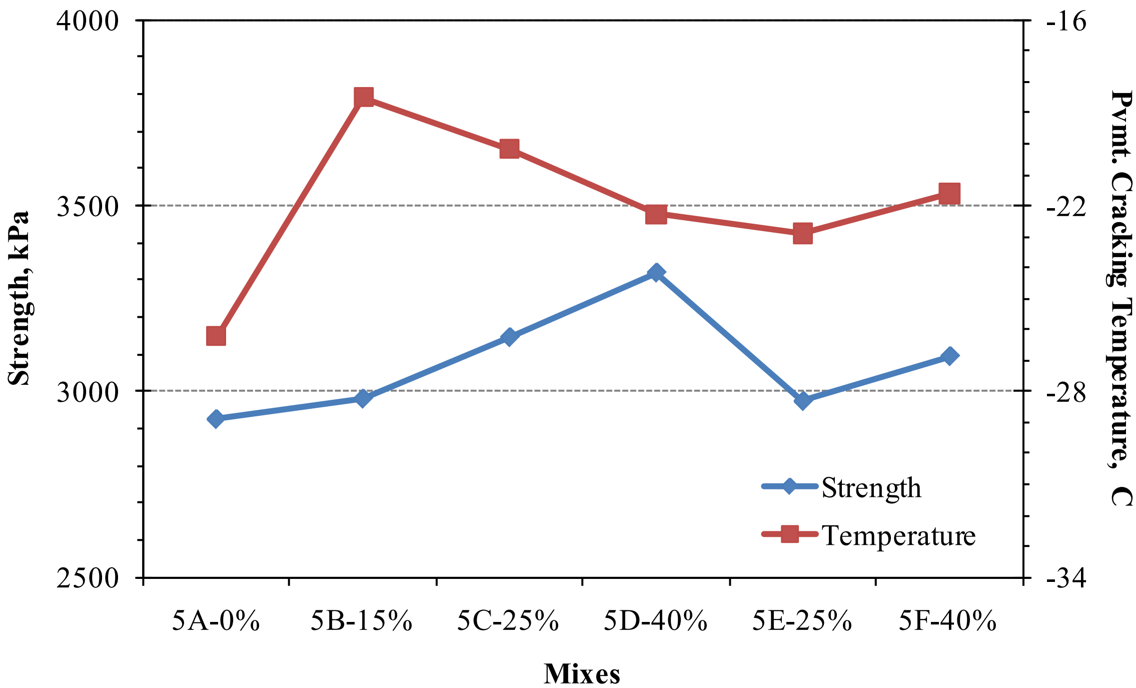
The results for contractor 5 are illustrated in figure 30 and figure 31. The stiffness of these mixes increased from the control to the 15 percent RAP mix and then remained relatively constant when the RAP content increased to 25 percent with the PG64-22 binder. As the RAP content increased to 40 percent, the stiffness decreased. The stiffness of the two mixes with PG58-28 binder were lower than any of the PG64-22 mixes. Mix F was slightly stiffer than mix E, possibly reflecting the influence of the increased RAP content.

The mixes from contractor 5 showed a steady increase in the mix strength with increasing RAP content for a given binder grade. The strength of mix E with 25 percent RAP and the softer binder was similar to that of mix B with a stiffer binder and only 15 percent RAP. Mix F with the softer binder and 40 percent RAP had a slightly lower strength than mix C with 25 percent RAP and the stiffer binder. In this case, the control mix had a more negative T_{crit} than any of the RAP mixes, even compared to the mixes with the softer binder grade.



1 psi = 6.89 × 10^{-6} GPa
°F = °C(1.8) + 32

Figure 30. Graph. IDT stiffness and pavement cracking temperature for contractor 5.



1 psi = 6.89 kPa
°F = °C(1.8) + 32

Figure 31. Graph. IDT strength and pavement cracking temperature for contractor 5.

To summarize the low-temperature mixture testing results, the changes in T_{crit} for the different contractors and mixes are shown in table 21. Contractor 2's data are shown but were not included in calculating the average because the strength was higher than the other results for unknown reasons, and the strength did not change from zero to 40 percent RAP. The addition of RAP, in this case, led to a significant improvement in the low-temperature cracking, which did not seem reasonable. This table shows that, on average, the addition of 15 to 25 percent RAP without altering the binder grade changed T_{crit} by about 3.6 °F (2 °C). The addition of 40 percent RAP without a grade change increased T_{crit} by about 7.2 °F (4 °C). When the virgin binder grade was changed, the addition of 25 percent RAP had virtually no effect on the cracking temperature. Additionally, using 40 percent RAP only changed the cracking temperature by 1.8 °F (1 °C) compared to the control. This lends support for lowering the binder grade for 40 percent RAP but not lowering the binder grade for 25 percent RAP.

Table 21. Change in T_{crit} (°C) with the addition of RAP.

Contractor	PG64-22				PG58-28	
	0 Percent RAP	15 Percent RAP	25 Percent RAP	40 Percent RAP	25 Percent RAP	40 Percent RAP
1	—	4	2	8	0	4
2	—	-16	-8	-2	-8	-20
3	—	0	1	1	-1	0
4	—	-2	-1	DNC	-4	-4
5	—	8	6	4	3	4
Average	—	2.5	2	4.3	-0.5	1.0

DNC = Did not converge.
— Indicate no data for the control (i.e., zero percent RAP).

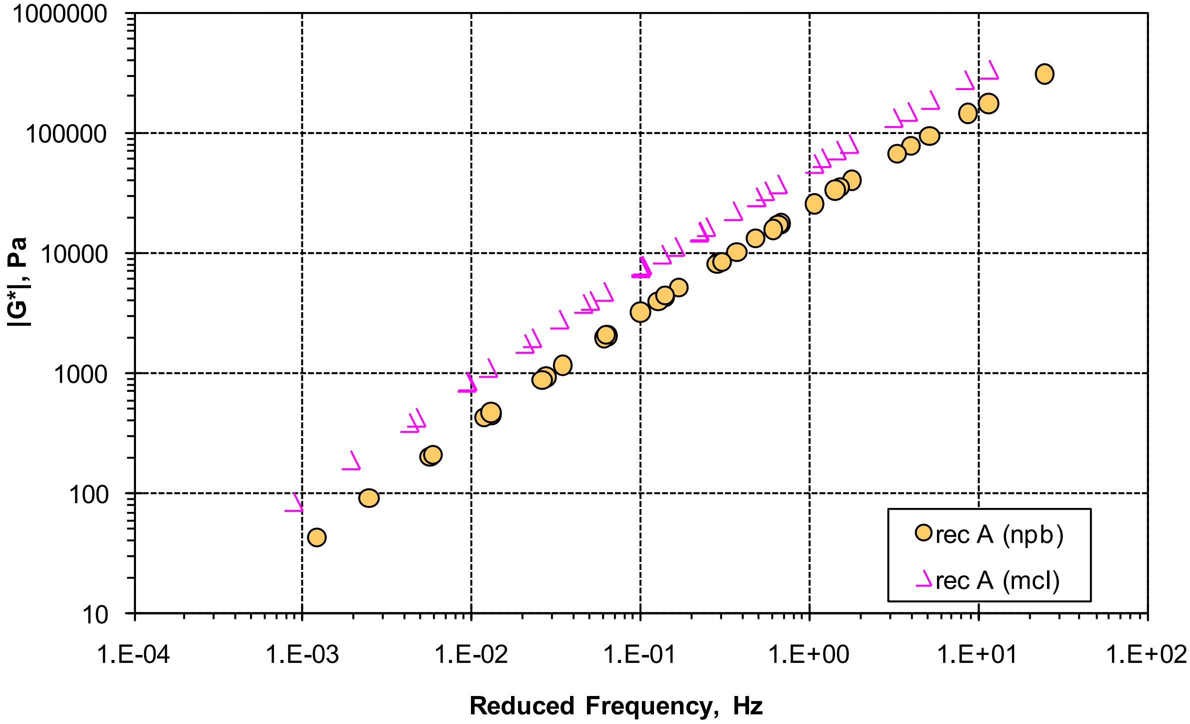
COMPARISON OF BINDER EXTRACTION/RECOVERY TECHNIQUES

The AASHTO T 319 extraction and recovery procedure was recommended in NCHRP 9-12 because research showed the method yielded less change in the binder properties before and after extraction/recovery compared to the Abson method.[23,5] AASHTO T 319 uses a rotating extraction vessel with baffles inside to bathe the mix in solvent and remove the binder. The binder is then recovered from the solution through a rotavapor. NCSC uses nPB as the solvent. Few labs in the United States are equipped to run the AASHTO T 319 procedure. However, some labs use the rotavapor for recoveries. Most labs already had the equipment for other extraction and recovery techniques before the AASHTO T 319 procedure was developed, and the impetus to change is not strong.

In phase I of this report, the Abson recovery procedure was used with reagent grade mCl.[24] The recovered binder properties were then determined by NCSC, and master curves were developed. Those master curves showed an increase in the stiffness of the recovered binders as the RAP content increased. The binder recovered from the control mix was not as stiff as the RTFO-aged virgin binder. Binders were also recovered from the control mix and mix C (25 percent RAP with PG64-22) by NCSC using the AASHTO T 319 procedure with nPB. For those two mixes, the binders recovered using AASHTO T 319 were stiffer than those recovered using the Abson recovery procedure.[24]

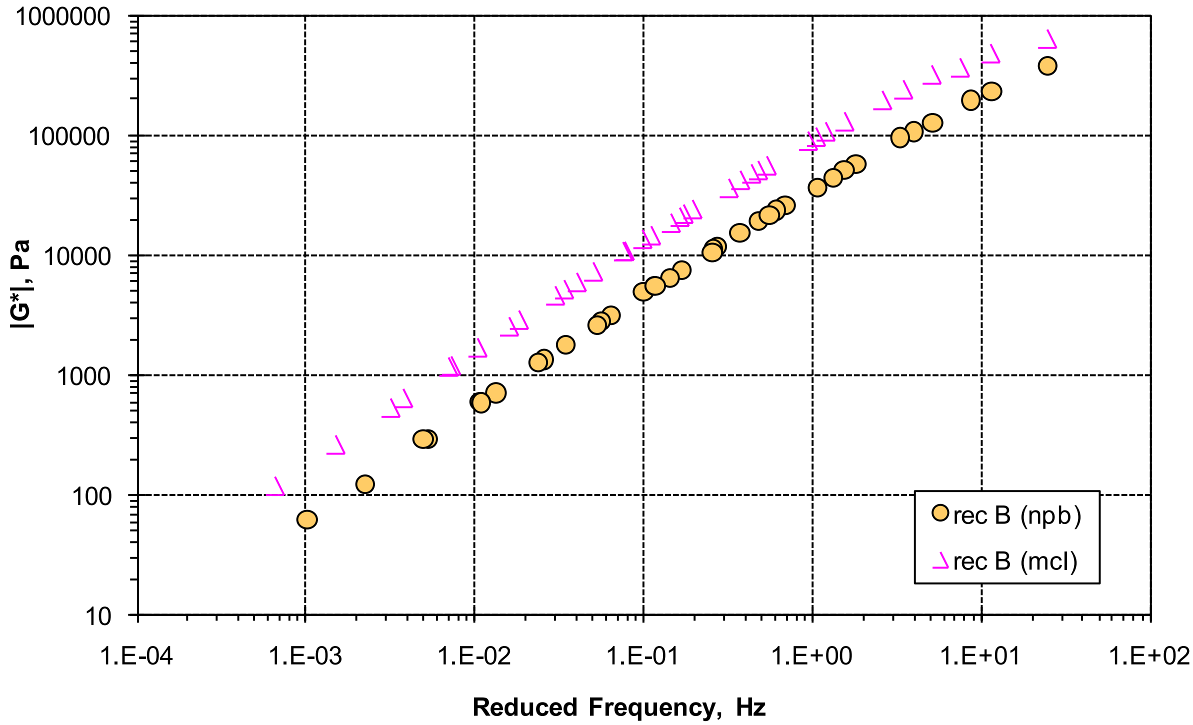
Blends of binders were also prepared in phase I to simulate total blending in the 25 and 40 percent RAP mixes with PG64-22. The binders recovered from the RAP in the proper proportions with RTFO-aged PG64-22 were blended. NCSC then compared the blended binders to binders recovered from the mixes with the same RAP content and binder. The DSR results from the pairs (blended and actual mix) were similar.

Since phase I utilized a different extraction/recovery procedure and solvent than the NCHRP research, it seemed appropriate to investigate the potential differences in phase II. Therefore, one set of six mixtures was selected (based on having adequate samples for testing). Mix samples were sent for extraction and recovery using the same Abson procedure but using mCl for one set of extractions, as performed in phase I, and using the Abson with nPB for comparison purposes. A companion set was extracted and recovered at NCSC using the AASHTO T 319 procedure with nPB. The recovered binders were returned to NCSC where DSR testing was performed to develop master curves. The master curves in figure 32 through figure 37 reflect a comparison between the binders recovered using mCl and those recovered using nPB. The results were compared to see if there was a consistent relationship between the stiffness of the binders recovered using the different solvents.



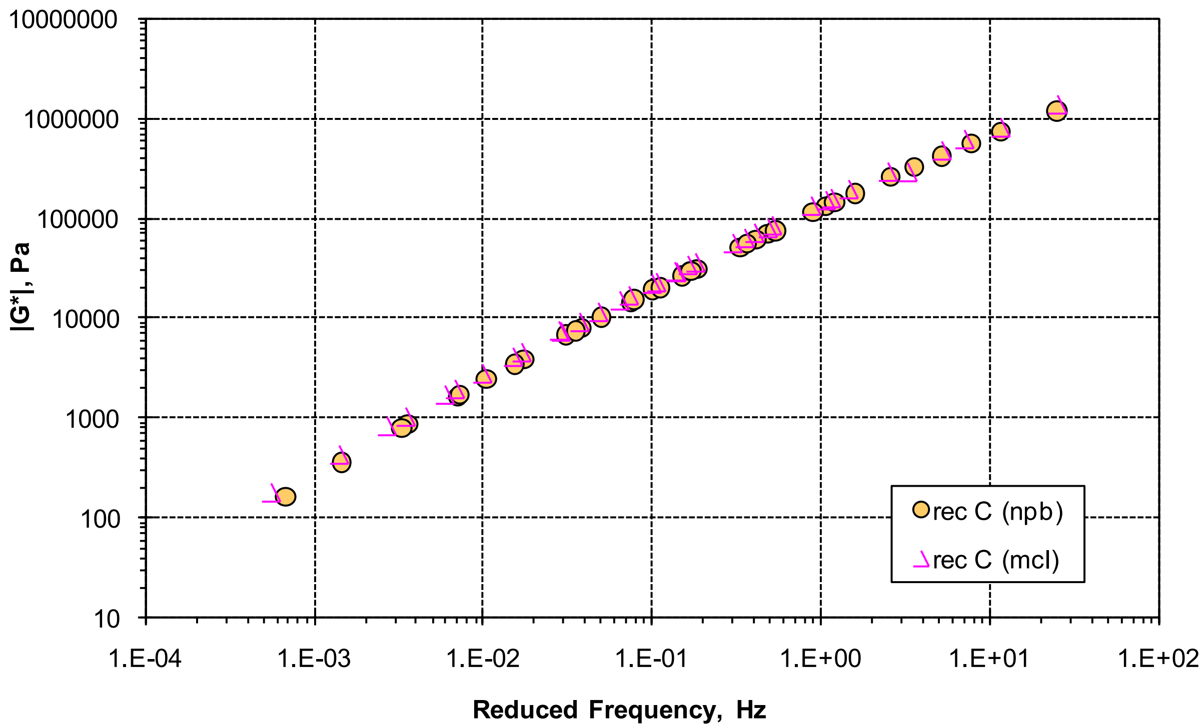
1 psi = 6,894.76 Pa

Figure 32. Graph. Comparison of binder recovered using different solvents for mix A.



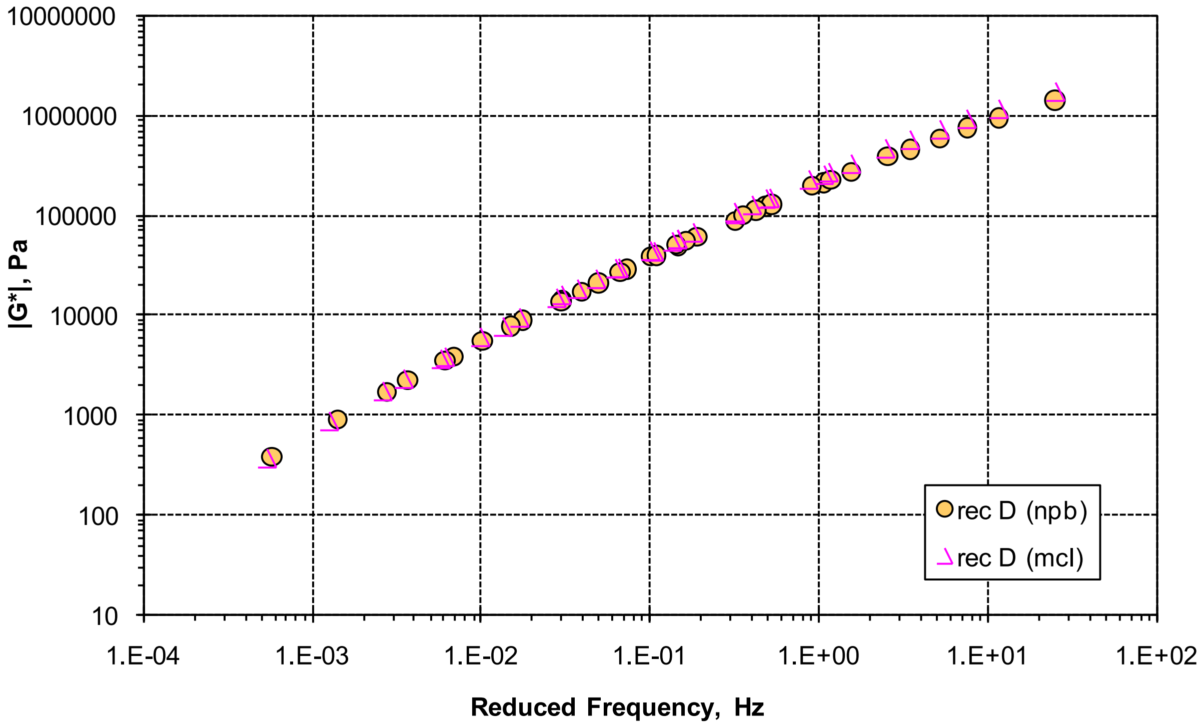
1 psi = 6,894.76 Pa

Figure 33. Graph. Comparison of binder recovered using different solvents for mix B.



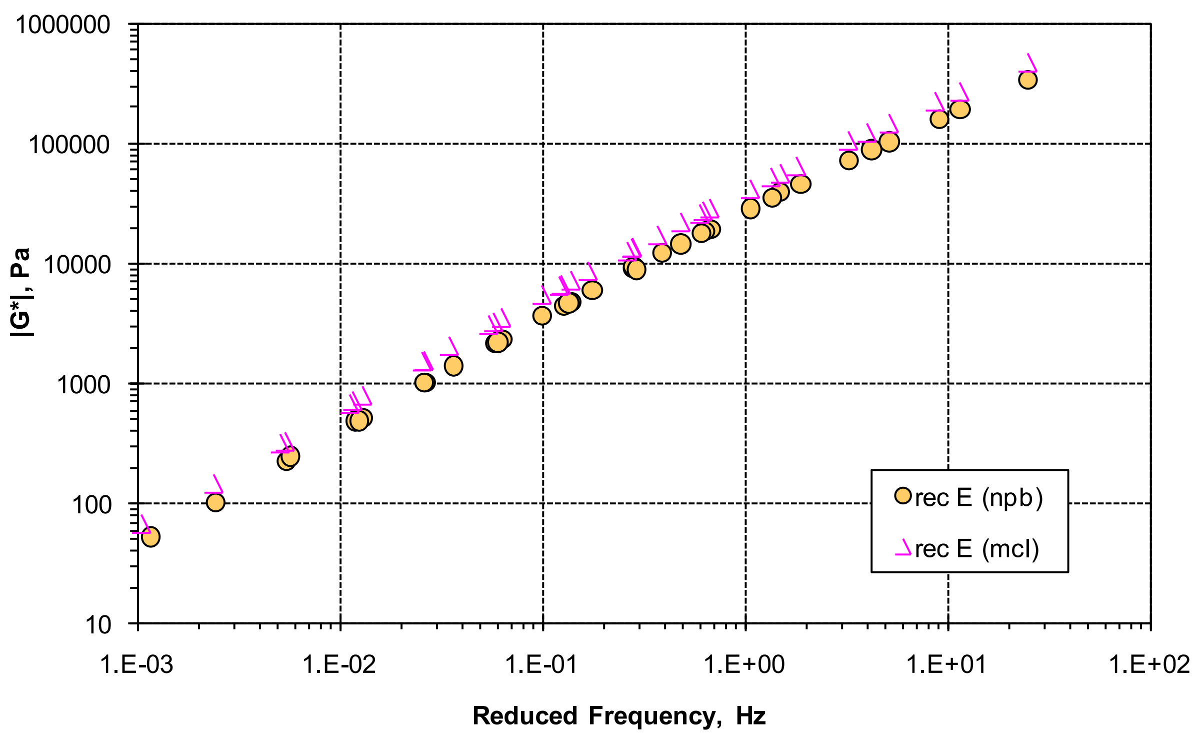
1 psi = 6,894.76 Pa

Figure 34. Graph. Comparison of binder recovered using different solvents for mix C.



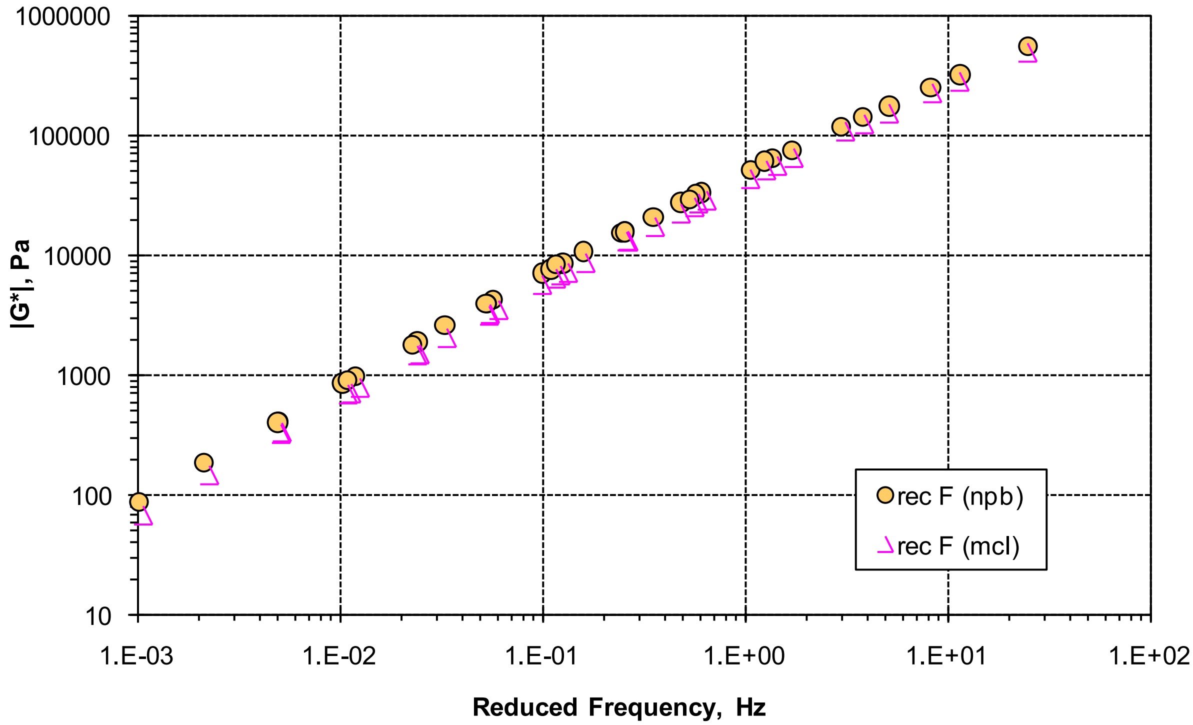
1 psi = 6,894.76 Pa

Figure 35. Graph. Comparison of binder recovered using different solvents for mix D.



1 psi = 6,894.76 Pa

Figure 36. Graph. Comparison of binder recovered using different solvents for mix E.

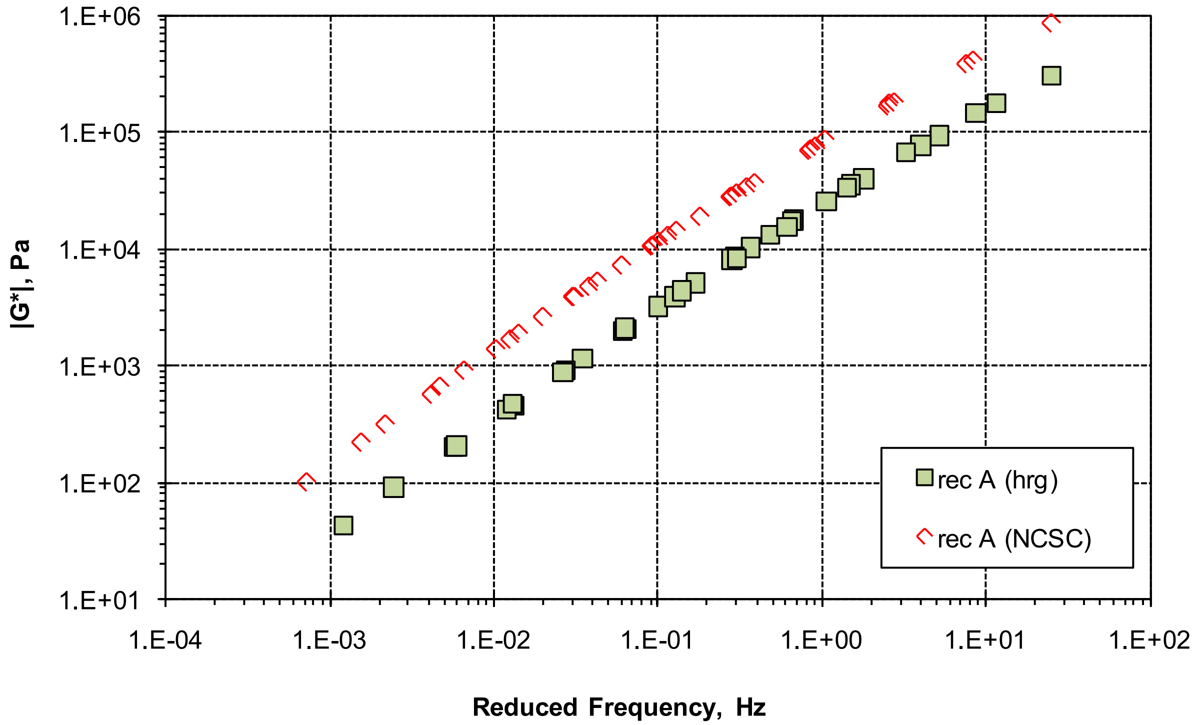


1 psi = 6,894.76 Pa

Figure 37. Graph. Comparison of binder recovered using different solvents for mix F.

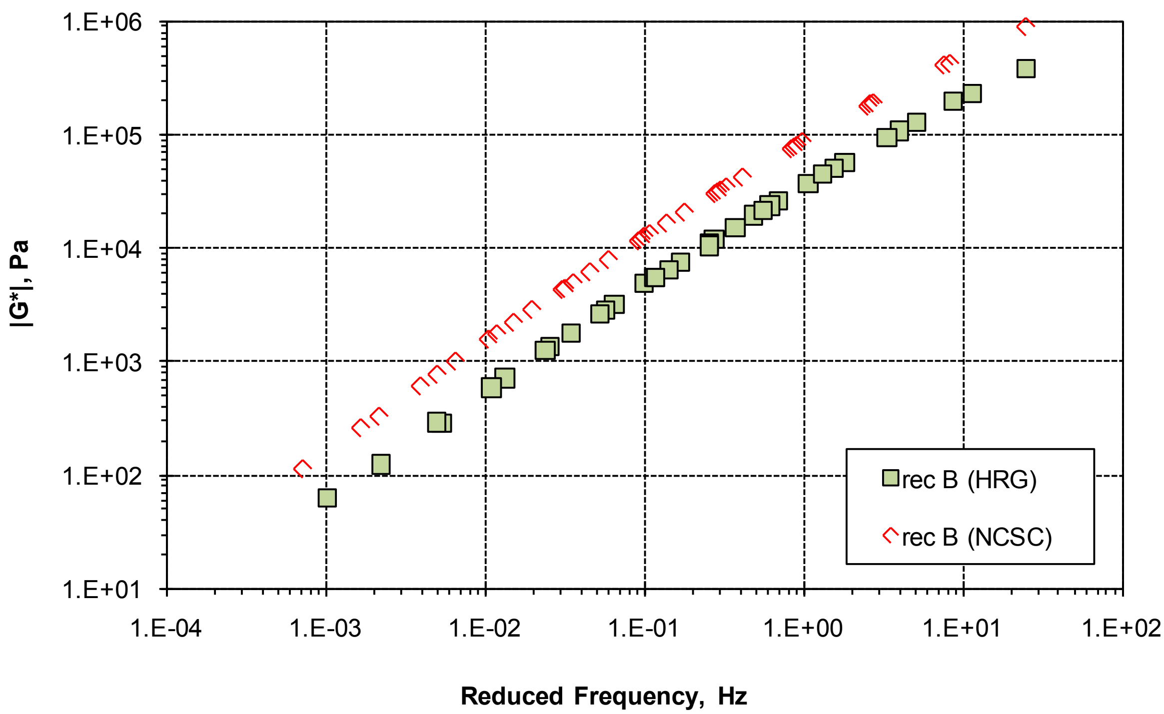
There does not appear to be a consistent trend in the comparison of the binder properties relative to the solvent used in the Abson procedure.(24) For mixes A, B, and E, the binder extracted/recovered with the Abson procedure and mCl was stiffer than the binder from the Abson procedure with nPB. For mixes C and D, the binders were virtually the same. For mix F, the binder recovered with nPB was somewhat stiffer than that recovered with mCl. The effect of the solvent does not appear to be related to the virgin binder grade either (e.g., mixes E and F with PG58-28 yielded opposite comparisons).

Figure 38 through figure 43 show a comparison of the binders recovered using nPB and the Abson procedures, as well as the AASHTO T 319 procedure at NCSC. The trends were not consistent, although they appear to be more consistent than the effect of the solvent. The binders recovered by NCSC using the AASHTO T 319 procedure were stiffer than those recovered using the Abson procedure for mixes A, B, E, and F. Mix C yielded the same results regardless of the procedure, and mix D was less stiff using AASHTO T 319 than the Abson procedure. Since the research that led to the AASHTO standards was based on using the AASHTO T 319 method, it is the method preferred by NCSC.



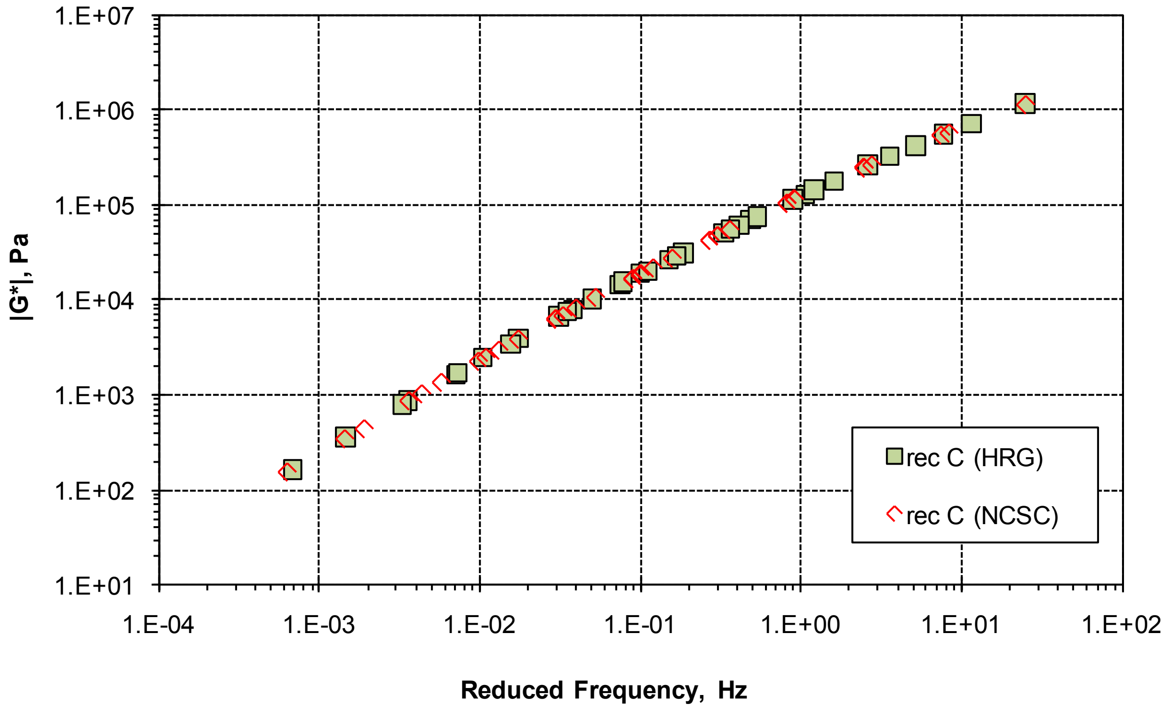
1 psi = 6,894.76 Pa

Figure 38. Graph. Comparison of binders recovered using different procedures and same solvent for mix A.



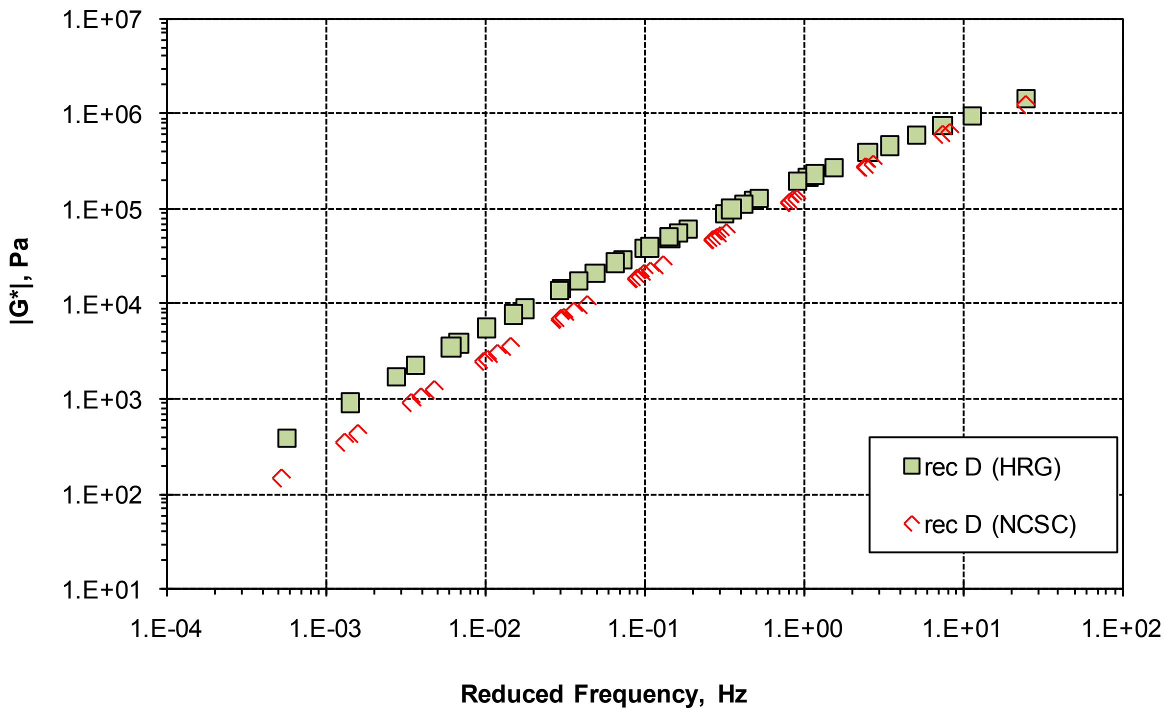
1 psi = 6,894.76 Pa

Figure 39. Graph. Comparison of binders recovered using different procedures and same solvent for mix B.



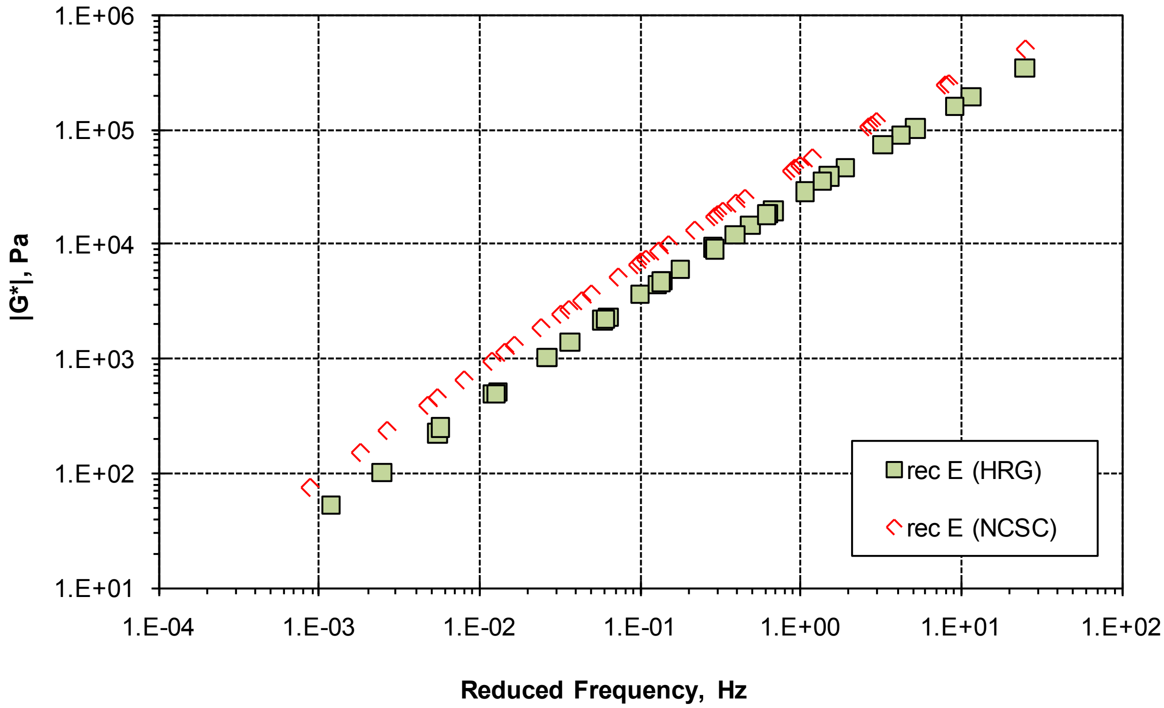
1 psi = 6,894.76 Pa

Figure 40. Graph. Comparison of binders recovered using different procedures and same solvent for mix C.



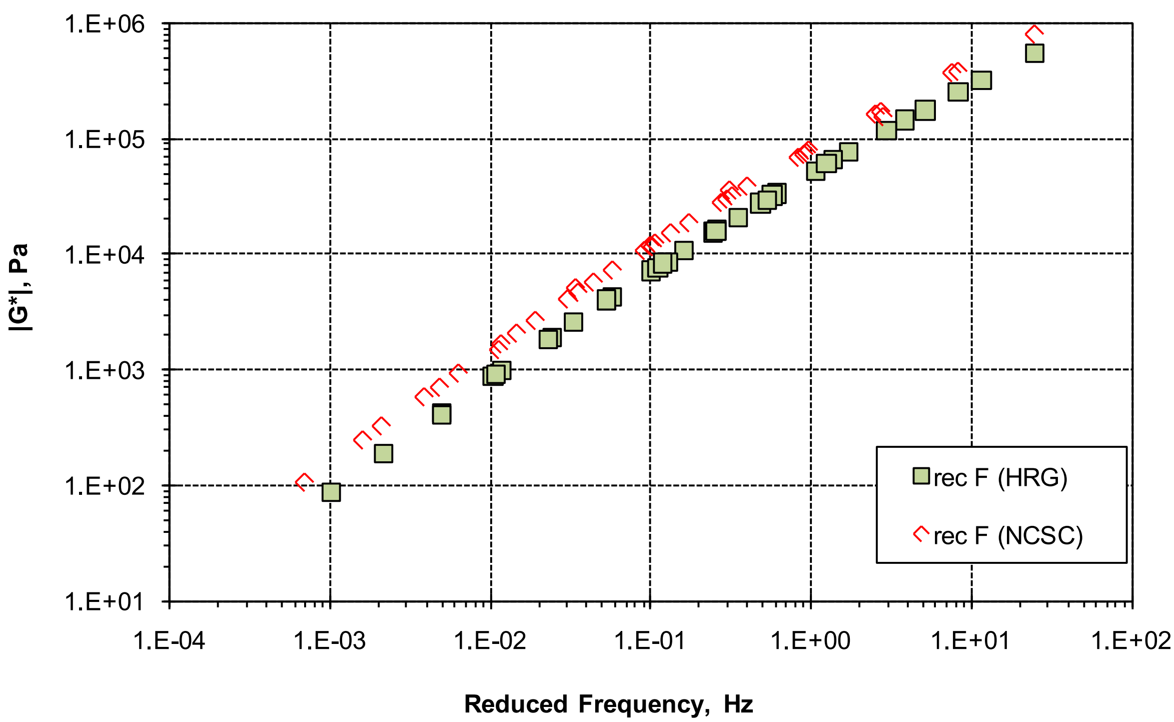
1 psi = 6,894.76 Pa

Figure 41. Graph. Comparison of binders recovered using different procedures and same solvent for mix D.



1 psi = 6,894.76 Pa

Figure 42. Graph. Comparison of binders recovered using different procedures and same solvent for mix E.



1 psi = 6,894.76 Pa

Figure 43. Graph. Comparison of binders recovered using different procedures and same solvent for mix F.

FHWA FATIGUE TESTING AND DATA ANALYSIS

As mentioned previously in this report, samples of one set of plant-produced mixes were provided to TFHRC for fatigue testing. Samples from contractor 5 were provided because more material was available from that contractor.

The TFHRC personnel performed the simplified viscoelastic continuum damage protocol on the six mixes from contractor 5.[28] This procedure utilizes a cyclic axial pull-pull test to evaluate the susceptibility of an asphalt mixture to fatigue damage. They also performed $|E^*|$ testing since the phase angle was needed for the analysis of relaxation. A brief summary of the results is provided in this report, and full results are available in the unpublished FHWA report, *RAP Mixtures S-VECD Fatigue Characterization Testing and Data Analysis Summary*.

Samples of the plant-produced mixtures were transported in metal buckets with rubber lid seals to TFHRC where they were reheated to remove the mix from the pails. The loose material was stirred, split, divided into pans, and heated to 275 °F (135 °C) before compaction in the gyratory. Samples were cored, and the AV content determined. Samples with AV contents of 7 ±0.5 percent were tested after long-term oven aging for 5 days at 185 °F (85 °C).

Two replicates of each mix were tested for $|E^*|$ using the standard Asphalt Mixture Performance Test compression protocol. The results are shown in table 22 and table 23.[29] The data were then used to develop $|E^*|$ master curves. The results showed that the PG64-22 mixes with 15, 25, and 40 percent RAP were 24, 20, and 24 percent stiffer than the control, respectively. The phase angle decreased 3–6 percent as the RAP content increased. The PG58-28 mixtures were less stiff than their companion mixes with PG64-22. The stiffness of the PG58-28 mixes increased by 3 percent, and the phase angle decreased by 1 percent when the RAP content increased from 25 to 40 percent. Based on $|E^*|$ data, it was concluded that the binder grade was much more significant than the RAP content. The researchers also noted that while there did appear to be an effect of the RAP on the stiffness, especially for the PG64-22 mixes, the effect was not proportional to the RAP content. These conclusions agree with the trends but not the proportions in figure 17, figure 18, and table 15.

The direct tension cyclic fatigue testing was performed at 59 and 70 °F (15 and 21 °C). The tests at 70 °F (21 °C) were conducted at two strain levels. The test was conducted with a constant actuator displacement, which produced an increasing displacement in the test specimen as measured by four linear variable differential transformers affixed to the specimen. The actuator displacements were determined by trial and error to target failure within 1,000 cycles (high strain) and 10,000 cycles (low strain). After the fatigue testing, the data were processed mathematically to estimate the reduction in modulus and damage characteristic curve at different temperatures and strain levels. The predicted number of cycles to failure to a defined fatigue value, in this case 50 percent reduction in modulus (pseudostiffness), can be determined (full details are provided in the unpublished FHWA report *RAP Mixtures S-VECD Fatigue Characterization Testing and Data Analysis Summary*). The predicted number of cycles to failure for the various mixtures at different temperatures and loading times for one particular strain and temperature scenario is illustrated in figure 44. The individual ranking of the mix changed depending on the strain and temperature conditions, as illustrated in table 24, from higher to lower performance from left to right. The overarching observations hold true where mixes with the softer PG58-28 binder performed better than the PG 64-22 mixes and the higher RAP content performed better than the lower contents. The repeatability of the determinations was reportedly satisfactory. The coefficient of variation for the number of cycles to failure was below 30 percent in all cases except for the PG64-22 mix with 25 percent RAP, which had a coefficient of variation of 34 percent.

At the time that this report was written, the TFHRC team further analyzed the fatigue data for more explicit definitions of failure rather than the classic, arbitrary criteria of 50 percent reduction in modulus (pseudostiffness). Research showed that the point of localization, which is the point where microcracking coalesces into macrocracking, can occur at different values of modulus reduction depending on the type of mix (e.g., NMAS, binder grade, degree of aging, RAP content, etc.).(28) During the test, this occurs at the point where the phase angle reaches a maximum and then drops to mechanistically reflect localization and a more true definition of fatigue failure. It is unknown at the time this report was written, but the refined analysis could reorient the fatigue life ranking of the mixtures with respect to RAP contents.

Table 22. |*E| and phase angle data for PG 58-28 mixtures.**

Temperature (°C)	Frequency (Hz)	25 Percent RAP		40 Percent RAP	
		|*E**| (MPa)	Phase Angle (Degree)	|*E**| (MPa)	Phase Angle (Degree)
4.4	0.1	8,537	16.7	9,218	15.2
	0.5	11,225	13.3	11,757	12.1
	1	12,428	12.2	12,853	11.1
	5	15,020	10.0	15,246	9.2
	10	16,137	9.2	16,267	8.5
	20	17,556	8.5	17,617	7.8
21.1	0.1	2,671	28.2	2,970	27.7
	0.5	4,198	24.9	4,537	24.0
	1	4,953	23.8	5,263	22.7
	5	7,047	19.9	7,317	18.9
	10	8,074	18.5	8,303	17.6
	20	9,506	16.5	9,698	15.8
37.8	0.1	514	30.6	564	31.8
	0.5	990	31.3	1,091	32.1
	1	1,301	31.6	1,415	32.2
	5	2,292	30.6	2,476	30.5
	10	2,834	30.1	3,062	29.7
	20	3,693	28.9	3,949	28.2
54.4	0.1	110	28.0	106	28.8
	0.5	213	30.5	207	31.5
	1	306	30.6	291	32.5
	5	610	32.6	595	34.6
	10	807	33.9	789	35.9
	20	1,101	36.5	1,087	38.7

°F = °C(1.8) + 32
1psi = 0.0069 MPa

Table 23. |*E| and phase angle data for PG64-22 mixtures.**

Temperature (^oC)	Frequency (Hz)	0 Percent RAP		15 Percent RAP		25 Percent RAP		40 Percent RAP	
		|*E**| (MPa)	Phase Angle (Degree)	|*E**| (MPa)	Phase Angle (Degree)	|*E**| (MPa)	Phase Angle (Degree)	|*E**| (MPa)	Phase Angle (Degree)
4.4	0.1	10,311	13.8	11,427	12.8	11,436	12.3	11,707	11.5
	0.5	12,816	11.0	14,064	10.1	14,014	9.7	14,034	9.3
	1	13,824	10.0	15,163	9.2	15,110	8.9	14,960	8.5
	5	16,050	8.3	17,530	7.6	17,376	7.4	16,962	7.1
	10	16,971	7.7	18,515	7.1	18,339	6.8	17,740	6.7
	20	18,149	7.0	19,906	6.5	19,589	6.3	18,791	6.6
21.1	0.1	3,484	26.7	4,049	25.4	4,072	24.9	4,325	24.7
	0.5	5,241	22.7	5,878	21.4	5,933	20.8	6,240	20.3
	1	6,062	21.2	6,754	20.0	6,819	19.4	7,087	18.8
	5	8,247	17.4	9,101	16.3	9,075	15.9	9,289	15.2
	10	9,231	16.0	10,172	15.0	10,154	14.6	10,256	13.8
	20	10,611	14.2	11,663	13.4	11,668	13.1	11,573	12.4
37.8	0.1	608	33.0	776	31.9	854	32.3	888	32.7
	0.5	1,234	32.5	1,492	31.5	1,596	31.6	1,663	31.8
	1	1,612	32.1	1,940	31.3	2,019	31.2	2,109	31.3
	5	2,787	29.9	3,267	28.8	3,335	28.2	3,498	28.1
	10	3,401	28.9	3,964	27.7	4,022	27.0	4,202	26.8
	20	4,320	26.8	4,958	25.9	5,075	25.0	5,264	24.7
54.4	0.1	116	30.0	138	30.3	152	30.6	154	31.2
	0.5	225	32.3	279	32.5	307	32.1	312	32.7
	1	325	32.5	402	32.9	426	32.7	439	33.1
	5	671	34.3	822	34.0	853	34.1	887	34.6
	10	898	35.5	1,093	34.9	1,121	35.1	1,171	35.5
	20	1,230	37.9	1,497	36.7	1,512	37.0	1,590	37.3

°F = °C(1.8) + 32
1psi = 0.0069 MPa

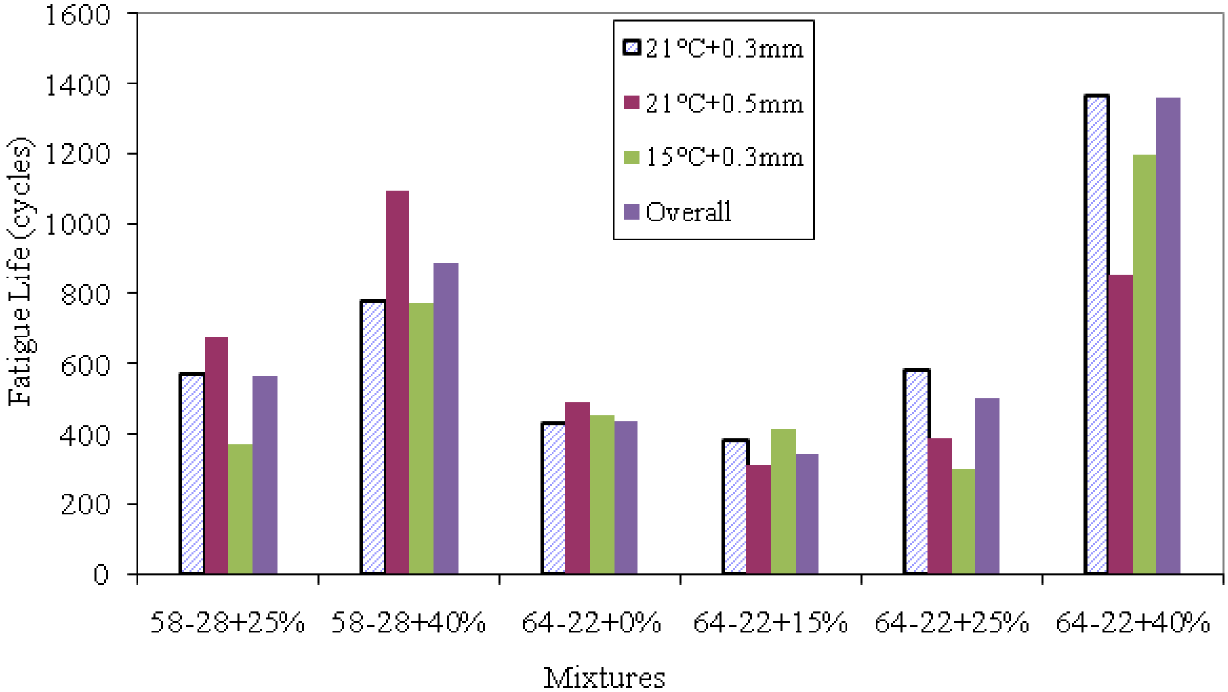


Figure 44. Graph. Fatigue life for mixtures at 69.8 °F (21 °C) and 400 με.

Table 24. Overall summary of fatigue life.

Temperature (°C)	Strain (με)	Fatigue Life (Cycles) Ranking (High to Low)					
21	100	PG58-28 40 percent RAP	PG58-28 25 percent RAP	PG64-22 40 percent RAP	PG64-22 0 percent RAP	PG64-22 25 percent RAP	PG64-22 15 percent RAP
	200	PG58-28 40 percent RAP	PG64-22 40 percent RAP	PG58-28 25 percent RAP	PG64-22 0 percent RAP	PG64-22 25 percent RAP	PG64-22 15 percent RAP
	400	PG64-22 40 percent RAP	PG58-28 40 percent RAP	PG58-28 25 percent RAP	PG64-22 0 percent RAP	PG64-22 25 percent RAP	PG64-22 15 percent RAP
28	100	PG58-28 25 percent RAP	PG58-28 40 percent RAP	PG64-22 0 percent RAP	PG64-22 40 percent RAP	PG64-22 15 percent RAP	PG64-22 25 percent RAP
	200	PG58-28 40 percent RAP	PG58-28 25 percent RAP	PG64-22 40 percent RAP	PG64-22 0 percent RAP	PG64-22 15 percent RAP	PG64-22 25 percent RAP
	400	PG58-28 40 percent RAP	PG58-28 25 percent RAP	PG64-22 40 percent RAP	PG64-22 0 percent RAP	PG64-22 25 percent RAP	PG64-22 15 percent RAP

°F = °C(1.8) + 32

Note: Squares that are shaded the same color are ranked approximately equal in fatigue life.

The predicted cycles to failure suggest that the mixes with 40 percent RAP had the greatest fatigue life, which is contrary to expectations. Furthermore, the PG64-22 mix with 40 percent RAP had an even higher fatigue life than the PG58-28 mix with 40 percent RAP. The PG58-28 mix with 25 percent RAP had improved fatigue performance compared to the PG64-22 mix with the same RAP content, which is more in line with conventional wisdom that a softer binder may have improved fatigue performance. Within the PG64-22 mixes, the addition of 15 percent RAP had a slight negative effect on fatigue, while the mixes with 25 and 40 percent RAP showed superior fatigue life compared to the control regardless of the virgin binder grade.

Based on the test results, the following general conclusions were made:

- The fatigue life at a given strain level increased as temperature increased, but the fatigue life did not increase as much at lower temperatures.

- At the two lower temperatures tested, the predicted fatigue life was virtually the same for all six mixtures regardless of binder grade or RAP content.

- The mixtures with PG58-28 binder had greater fatigue resistance at lower strains at 70 and 82 °F (21 and 28 °C) than the companion mixes with PG64-22. This effect was more pronounced when 25 percent RAP was added to the mix than when 40 percent RAP was added. At higher strains, there was little to no significant difference in the fatigue life for the 40 percent RAP mixes. In some cases, the mix with PG64-22 and 40 percent RAP (mix D) had higher fatigue resistance than the mix with PG58-28 and 40 percent RAP (mix F).

- For the mixes with PG64-22 (mixes A through D), the mix with 40 percent RAP exhibited higher fatigue resistance in every set of test conditions except one. The control mix had the second highest fatigue life, and the mixes with 15 and 25 percent RAP had similar fatigue lives.

The testing and analysis protocol used is complex and relatively new. Additional testing and analysis is necessary to fully appreciate the implications of the data on fatigue life predictions and the effects of other mix variables on the results. There may be other factors that affect these results and analysis.

The fatigue testing data provide intermediate temperature testing results to supplement the previously reported high- and low-temperature testing data. The mixture testing data plus the binder test results and blending analysis lead to the observations and conclusions in the following section.

OVERALL OBSERVATIONS AND CONCLUSIONS

Based on the results presented in this report, the following observations and conclusions were made:

- Test results on binders extracted and recovered from the plant-produced mixes showed that, in general, as the RAP content in the mixture increased, the high-temperature grade of the recovered binder also increased, but only by a few degrees (1.8 to 5.4 °F (1 to 3 °C)).

- As the RAP content increased, the low-temperature grade of the recovered RAP binders also increased, but not as much as the high-temperature grade.

- The use of a softer virgin binder grade typically decreased both the high- and low-temperature grades of the recovered binders by half a grade or more.

- Increasing the RAP content to 25 percent changed the recovered binder low-temperature grade by no more than 3.6 °F (2 °C) compared to the binder recovered from the virgin mix (with no RAP).

- The low-temperature grades determined by analysis of the BBR data and by the TSAR™ analysis were in close agreement, using the direct tension data and the BBR data to calculate T_{crit}.

- Examination of the mixture $|E^*|$ data reveals that, in general, an increase in the RAP content caused an increase in the modulus of the mix, especially at intermediate and high temperatures. However, this finding was not consistent across every set of mixes, possibly reflecting the important contributions of other factors to the mix modulus.

- Statistical analysis of the dynamic moduli at 25 Hz showed that in most cases, there was no significant difference in the moduli of mixes with PG64-22 and varying RAP contents. In cases where there was a statistically significant difference, the 40 percent RAP mix differed from the other RAP contents. These findings suggest that the RAP content can possibly be increased to 25 percent before changing the virgin binder grade, but a grade change should be incorporated when increasing the RAP content to 40 percent. The findings are considered representative of mixtures produced in hot mix plants in Indiana using virgin asphalt binders and RAP typically found in Indiana.

- Use of a softer virgin binder grade typically reduced the stiffness of the mixes.

- The moduli of the PG58-28 mixes with 25 and 40 percent RAP were often statistically different.

- Comparison of the measured mix moduli to those predicted based on the recovered binder master curves and the mixture volumetrics suggests that significant blending of the RAP and virgin binders occurred in 16 of the 20 mixes that contained RAP. Data from contractor 4 showed incomplete blending between the PG64-22 virgin binder and the higher RAP contents. More research is needed to validate this approach to estimating blending.

- IDT test results on the mixtures showed only slight effects on T_{crit} for mixes containing up to 25 percent RAP and PG64-22. The 40 percent RAP mixes with PG64-22 had warmer (less negative) T_{crit} in two cases, and the data did not converge in one case, so the cracking temperature could not be determined. In these mixes, the predicted cracking temperatures were approximately the same as the design low-temperature binder grade (i.e., around -7.6 °F (-22°C)), so would presumably be acceptable.

- T_{crit} of the mixes with PG58-28 were much lower than those of the comparable mixes with PG64-22 in two of five cases. In the other cases, they were comparable. It is not clear whether cracking temperatures of -14.8 °F (-26 °C) or lower are necessary.

- The extraction/recovery process and solvent did not show a clear pattern. That is, binders recovered using the AASHTO T 319 procedure with nPB were not consistently stiffer or softer than those recovered using the Abson procedure with mCl or nPB. As a result, the extraction/recovery/solvent variables do not explain the unexpected results of phase I. Any extraction/recovery procedure is problematic.

- The fatigue testing results do not conform to expectations. While the softer virgin binder grade resulted in an increase in the fatigue life at 25 percent RAP, it did not have as strong an impact on the 40 percent RAP mixes.

- The mixes with 40 percent RAP exhibited the greatest fatigue lives in many cases, which was an unexpected result.

- The fatigue life increased as temperature increased at a given strain level, but fatigue life was less sensitive at lower temperatures.

- At the two lower temperatures tested, the predicted fatigue life was the same for all six mixtures regardless of RAP content or virgin binder grade.

- More work is needed to investigate the effects of RAP content on fatigue life.

- Additional research should be conducted on plant-produced mixtures from different places with varying RAP and virgin material properties to examine the effects of these variables over a wider inference range.

- Other agencies should be advised to review their typical materials, especially RAP stockpiles, to determine their own course of action.

APPENDIX A

CONTRACTOR MIX DESIGNS AND/OR QC DATA

Table 25. Contractor 1 mix designs.

Label	1A	1B	1C	1D	1E	1F
Mix	PG 64-22 0 percent RAP	PG 64-22 15 percent RAP	PG 64-22 25 percent RAP	PG 64-22 40 percent RAP	PG 58-28 25 percent RAP	PG 58-28 40 percent RAP
9.5 mm (percent passing)	93.2	96.3	97.8	98.9	97.8	98.9
4.75 mm (percent passing)	62.0	63.8	61.2	63.2	61.2	63.2
2.36 mm (percent passing)	43.7	42.0	35.8	36.3	35.8	36.3
1.18 mm (percent passing)	30.3	31.1	25.8	26.2	25.8	26.2
0.6 mm (percent passing)	20.1	21.9	17.8	18.2	17.8	18.2
0.3 mm (percent passing)	9.6	10.2	9.8	10.9	9.8	10.9
0.15 mm (percent passing)	5.0	5.4	6.0	7.3	6.0	7.3
0.075 mm (percent passing)	3.7	4.4	5.1	6.2	5.1	6.2
Asphalt content (percent)	5.5	5.4	5.5	5.5	5.5	5.5
G_{mm}	2.482	2.481	2.475	2.482	2.475	2.483
G_{mb}	2.383	2.382	2.377	2.386	2.377	2.385
AV (percent)	4.0	4.0	4.0	3.9	4.0	3.9
VMA (percent)	15.2	15.2	15.2	15.1	15.2	15.1
VFA (percent)	73.7	73.6	74.0	74.3	74.0	73.9
Effective asphalt content (percent)	4.8	4.8	4.9	4.8	4.9	4.8
Dust-to-binder ratio	1.0	1.0	1.0	1.3	1.0	1.3

1 inch = 25.4 mm

Table 26. Contractor 2 job mix formula (JMF) and QC test results.

Label	JMF	2A	2B	2C	2D	2E	2F
Mix	All Mixes	PG 64-22 0 percent RAP	PG 64-22 15 percent RAP	PG 64-22 25 percent RAP	PG 64-22 40 percent RAP	PG 58-28 25 percent RAP	PG 58-28 40 percent RAP
12.5 mm (percent passing)	100	99.58	100	99.58	100	99.8	99.77
9.5 mm (percent passing)	95.1	96.34	95.6	96.62	95.92	95.29	94.27
4.75 mm (percent passing)	76.6	79.78	78.58	78.11	79.78	78.47	77.16
2.36 mm (percent passing)	61.3	63.91	63.41	62.95	64.18	63.12	61.39
1.18 mm (percent passing)	48.9	50.92	50.3	49.86	50.75	50.28	48.55
0.8 mm (percent passing)	37.3	39.44	39.03	38.72	39.29	39.08	37.4
0.3 mm (percent passing)	18.7	19.72	19.99	19.76	20.67	20.03	19.99
0.15 mm (percent passing)	8.3	6.94	7.39	7.78	8.83	8	9.13
0.075 mm (percent passing)	5.8	4.24	4.54	4.93	5.86	5.11	6.25
Asphalt content (percent)	5.86	5.84	5.84	5.97	6.19	5.81	5.75
G_{mm}	2.474	2.478	2.474	2.467	2.462	2.466	2.47
AV (percent)	4	6.75	4.72	3.91	3.09	4.34	2.56
VMA (percent)	15.71	17.99	1635	15.99	15.63	16.26	14.49
VFA (percent)	74.5	62.47	73.93	75.57	80.23	73.29	82.33
Dust-to-binder ratio	1.14	0.84	0.9	0.95	1.08	1.01	1.25

1 inch = 25.4 mm

Table 27. Contractor 3 QC test results.

Label	3A	3B	3C	3D	3E	3F
Mix	PG 64-22 0 percent RAP	PG 64-22 15 percent RAP	PG 64-22 25 percent RAP	PG 64-22 40 percent RAP	PG 58-28 25 percent RAP	PG 58-28 40 percent RAP
37.5 mm (percent passing)	100	100	100	100	100	100
25.0 mm (percent passing)	100	100	100	100	100	100
19.0 mm (percent passing)	100	100	100	100	100	100
12.5 mm (percent passing)	100	100	100	100	100	100
9.5 mm (percent passing)	96.2	95.6	97.1	95.9	97.1	97.4
4.75 mm (percent passing)	71.4	68.5	75.8	71.2	73.2	74.2
2.36 mm (percent passing)	48.6	48.1	53.4	50.5	51.4	53.2
1.18 mm (percent passing)	32.7	33.4	36.6	35.3	36.5	37.8
0.60 mm (percent passing)	21.2	22.4	24.4	23.6	25.4	26.5
0.30 mm (percent passing)	10.1	11.5	12.5	12.1	13.7	14.7
0.15 mm (percent passing)	4.8	5.7	6.1	5.9	7	7.6
0.075 mm (percent passing)	3.5	4.2	4.5	4.4	5.1	5.5
Asphalt content (percent)	5.7	5.7	6	5.7	5.7	5.9
AV (percent)	6.8	3.9	5.2	4.8	3.6	2.4
VMA (percent)	17.8	16.1	17.4	16.9	16.0	15.6
G_{mb}	2.310	2.371	2.351	2.357	2.398	2.410
G_{mm}	2.479	2.468	2.480	2.477	2.487	2.471

1 inch = 25.4 mm

Table 28. Contractor 4 mix designs.

Label	4A	4B	4C/4E	4D/4F
Mix	PG 64-22 0 percent RAP	PG 64-22 15 percent RAP	PG 64-22/ PG 58-28 25 percent RAP	PG 64-22/ PG 58-28 40 percent RAP
12.5 mm (percent passing)	100	100	100	100
9.5 mm (percent passing)	96	96.1	95.6	95.9
4.75 mm (percent passing)	56	56.6	59.3	57.4
2.36 mm (percent passing)	34.5	33.6	35.7	34.2
1.18 mm (percent passing)	27.3	25.4	27.2	26
0.6 mm (percent passing)	17.7	16.9	18.5	17.5
0.3 mm (percent passing)	8.6	8.4	10.5	9.2
0.15 mm (percent passing)	4.4	4.9	7.3	5.9
0.075 mm (percent passing)	4.1	4.5	6.6	5.3
Asphalt content (percent)	5.6	5.3	5.2	5.4
G_{mm}	2.441	2.451	2.453	2.444
AV (percent)	4	4	4	4
VMA (percent)	15.3	15	15.2	15.5
VFA (percent)	73.9	73.3	73.7	74.2
Dust-to-binder ratio	0.8	0.9	1.3	1.0

1 inch = 25.4 mm

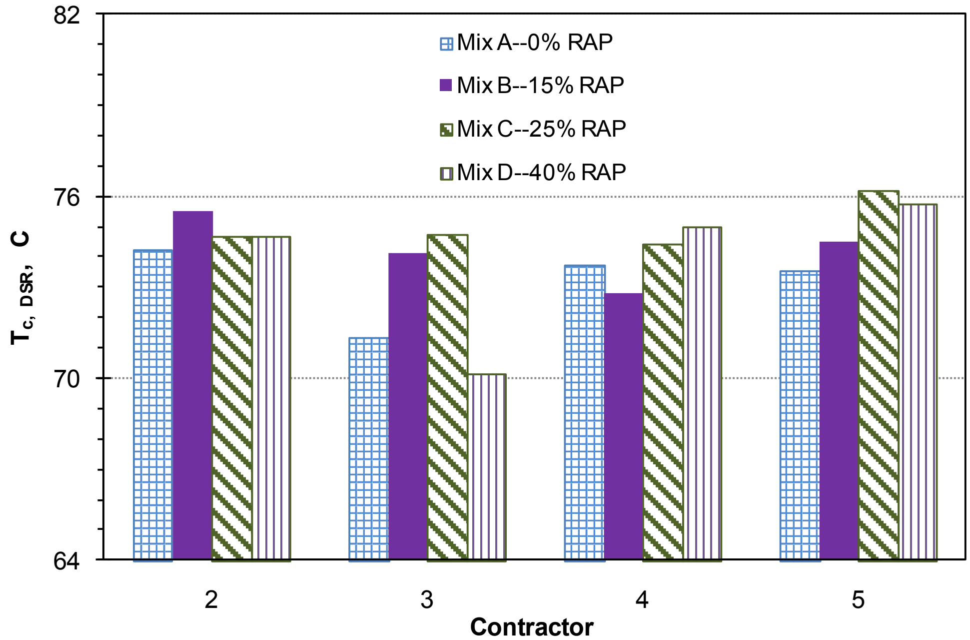
Table 29. Contractors mix designs and QC results.

Label	JMF A	5A	JMF B	5B	JMF C	5C	JMF D	5D	JMF E	5E	JMF F	5F
Mix	PG 64-22 0 Percent RAP		PG 64-22 15 Percent RAP		PG 64-22 25 Percent RAP		PG 64-22 40 Percent RAP		PG 58-28 25 Percent RAP		PG 58-28 40 Percent RAP	
12.5 mm (percent passing)	100.00	100.00	99.99	100.00	99.99	100.00	99.98	100.00	99.99	100.00	99.98	100.00
9.5 mm (percent passing)	98.97	98.95	98.71	100.00	98.05	99.79	97.09	98.89	98.05	98.95	97.09	99.11
4.75 mm (percent passing)	68.56	73.28	67.94	74.25	67.81	75.04	65.56	72.28	67.81	73.48	65.56	75.32
2.36 mm (percent passing)	49.41	50.74	49.14	49.73	51.61	52.82	48.54	50.22	51.61	51.40	48.54	53.74
1.18 mm (percent passing)	36.56	36.04	36.42	34.73	38.09	37.54	36.21	36.13	38.09	36.43	36.21	38.73
0.6 mm (percent passing)	25.28	24.62	25.32	23.97	25.96	26.03	25.45	25.69	25.96	25.27	25.45	27.46
0.3 mm (percent passing)	13.74	12.76	14.02	13.24	14.16	14.45	14.63	14.66	14.16	13.90	14.63	15.51
0.15 mm (percent passing)	6.49	5.95	6.94	6.40	6.88	6.81	7.84	7.47	6.88	6.42	7.84	7.69
0.075 mm (percent passing)	4.70	3.80	5.09	4.09	4.89	4.46	5.93	5.17	4.89	4.16	5.93	4.94
Asphalt content (percent)	5.60	5.61	5.60	5.63	5.60	5.80	5.60	5.90	5.60	5.40	5.60	5.70
G_{mm}	2.47	2.47	2.47	2.47	2.47	2.46	2.49	2.47	2.47	2.45	2.49	2.46
AV (percent)	3.80	4.86	3.90	4.13	4.00	4.20	3.90	3.10	4.00	4.20	3.90	3.20
VMA (percent)	15.50	16.40	15.40	16.10	15.80	16.50	15.70	15.50	15.80	16.50	15.70	15.90

1 inch = 25.4 mm

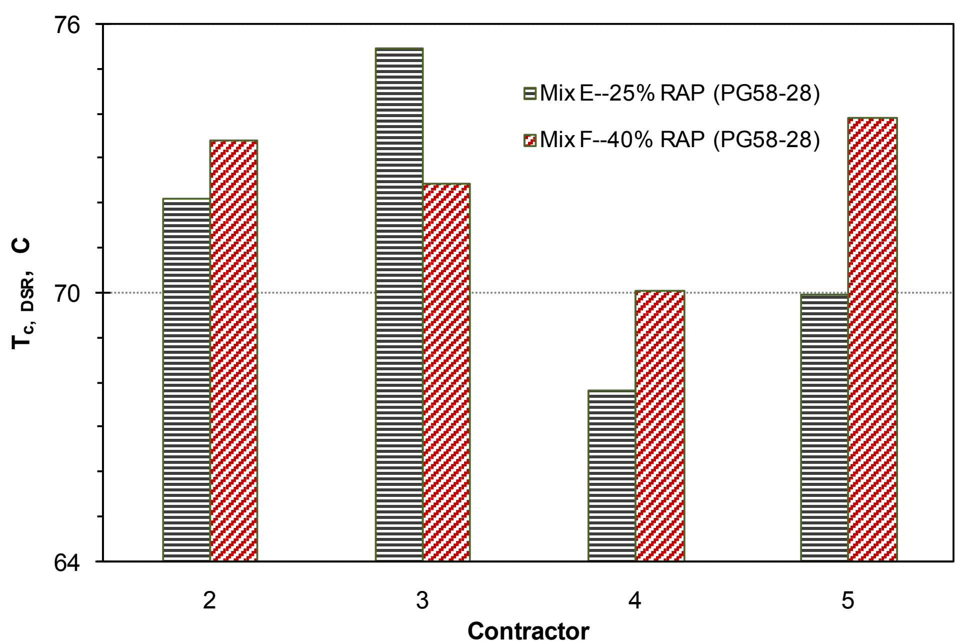
APPENDIX B

BINDER CRITICAL TEMPERATURES



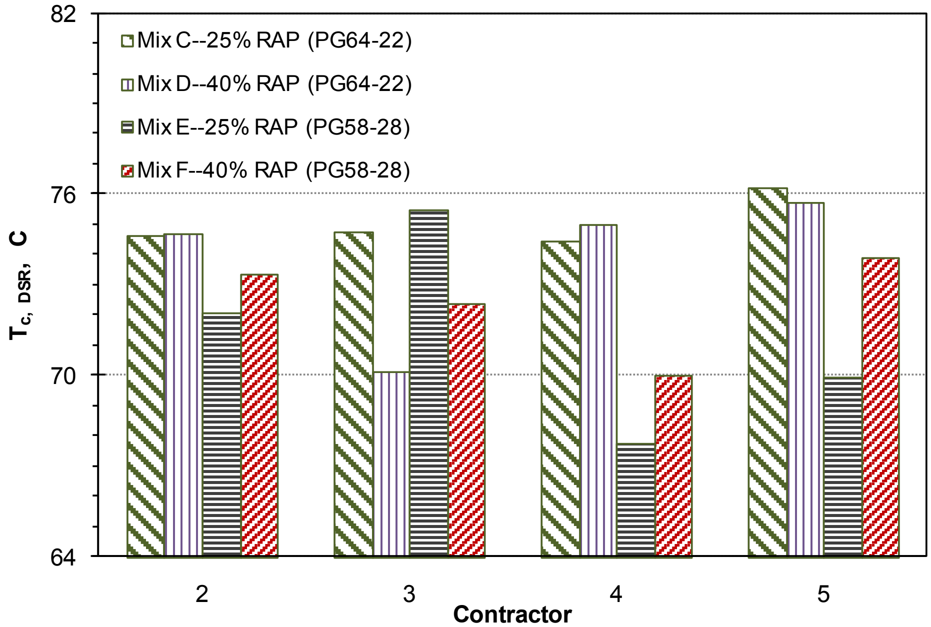
°F = °C(1.8) + 32

Figure 45. Graph. DSR critical temperatures—mixes with PG64-22 binder.



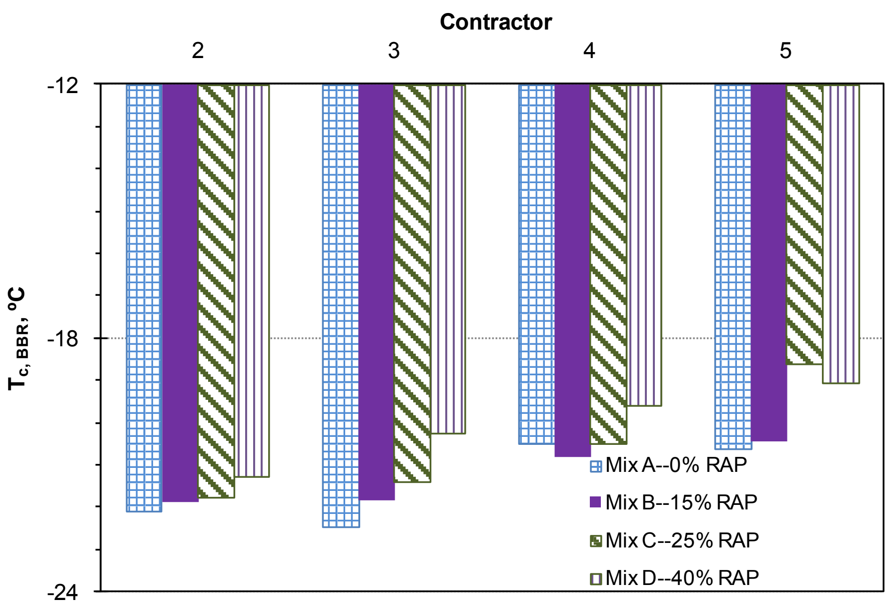
°F = °C(1.8) + 32

Figure 46. Graph. DSR critical temperatures—mixes with PG58-28 binder.



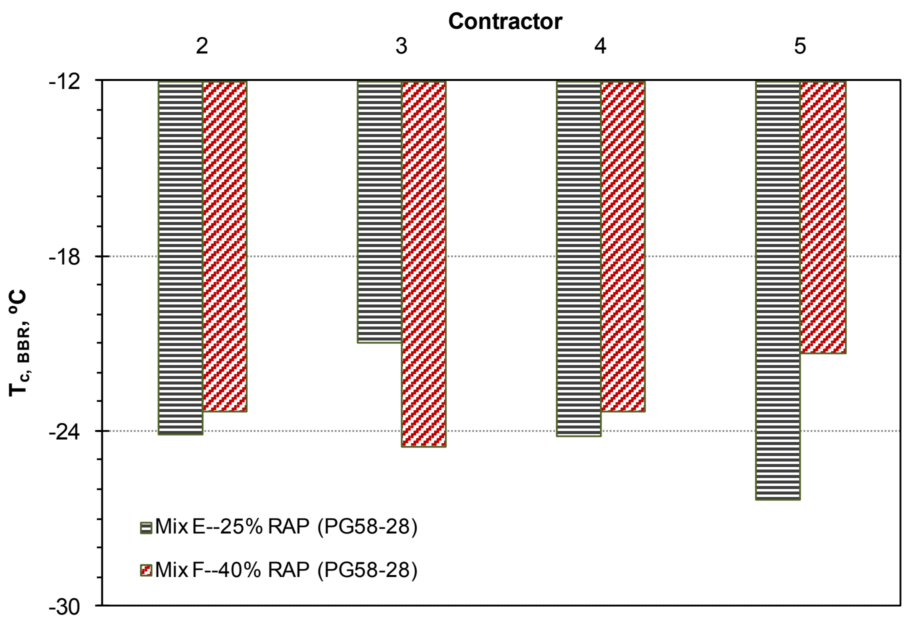
°F = °C(1.8) + 32

Figure 47. Graph. DSR critical temperatures—mixes with 25 and 40 percent RAP.



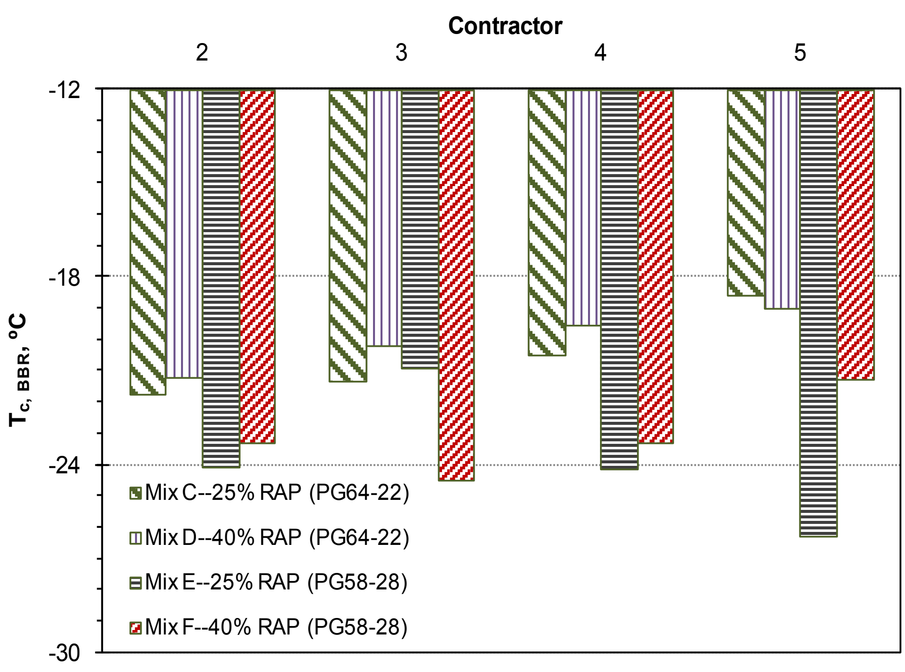
°F = °C(1.8) + 32

Figure 48. Graph. BBR critical temperatures—mixes with PG64-22 binder.



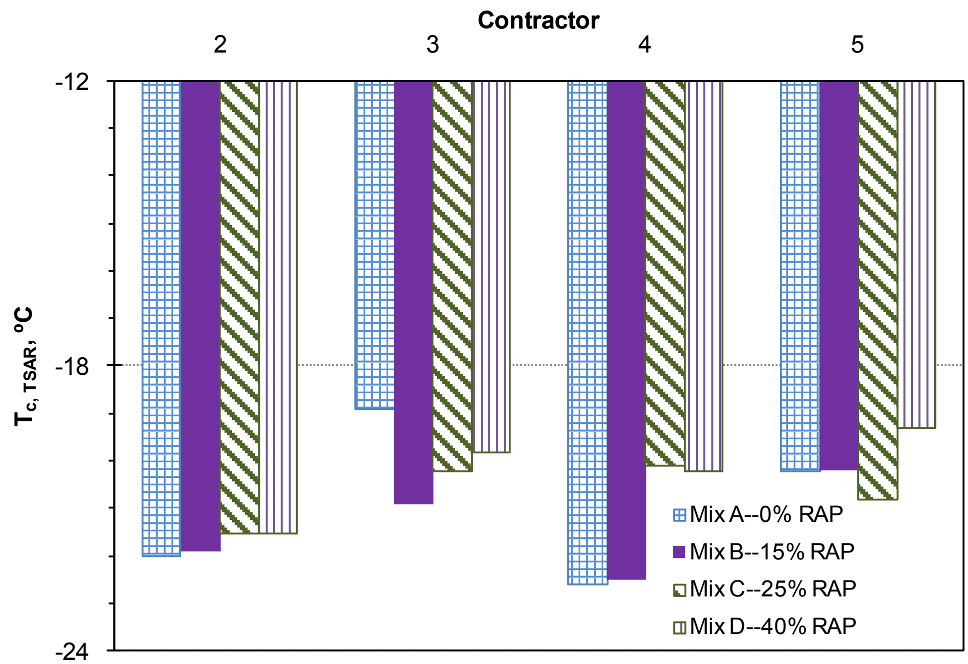
°F = °C(1.8) + 32

Figure 49. Graph. BBR critical temperatures—mixes with PG58-28 binder.



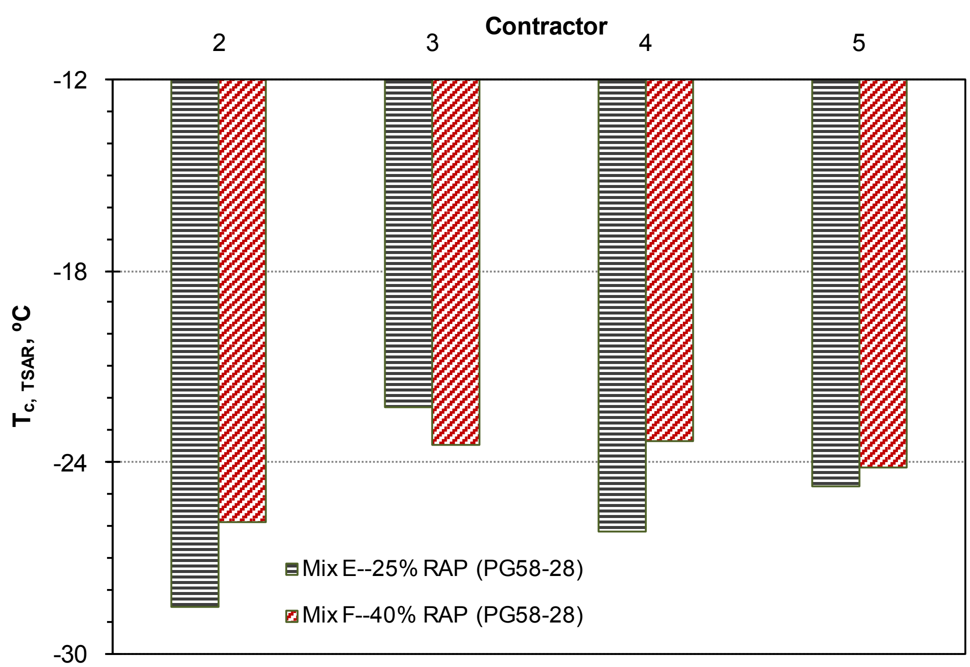
°F = °C(1.8) + 32

Figure 50. Graph. BBR critical temperature—mixes with 25 and 40 percent RAP.



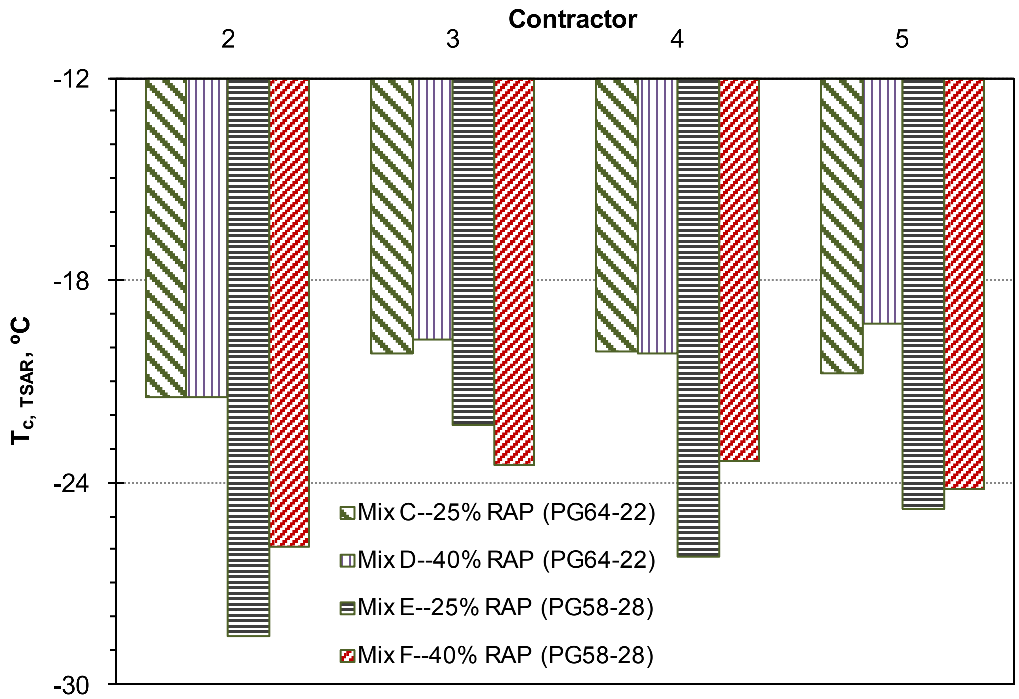
°F = °C(1.8) + 32

Figure 51. Graph. TSAR™ critical temperature—mixes with PG64-22 binder.



°F = °C(1.8) + 32

Figure 52. Graph. TSAR™ critical temperature—mixes with PG58-28 binder.

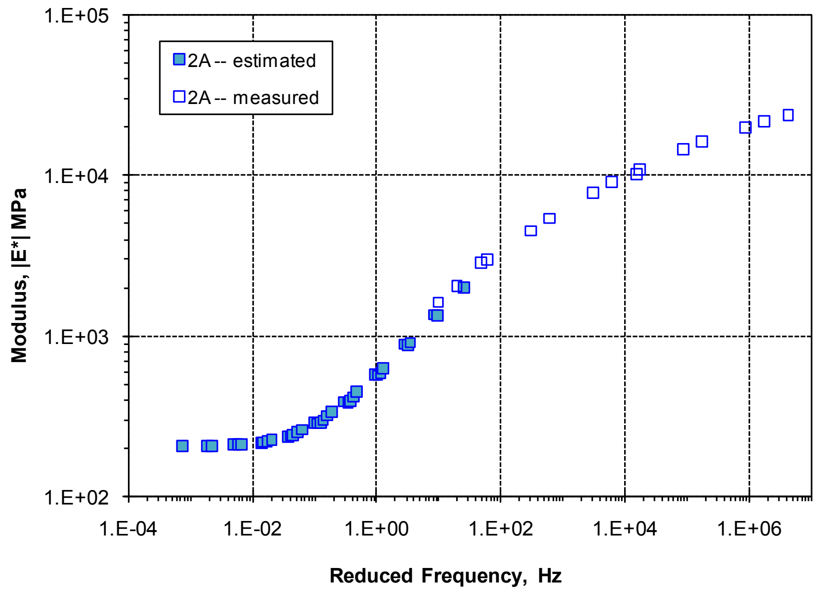


°F = °C(1.8) + 32

Figure 53. Graph. TSAR™ critical temperature—mixes with 25 and 40 percent RAP.

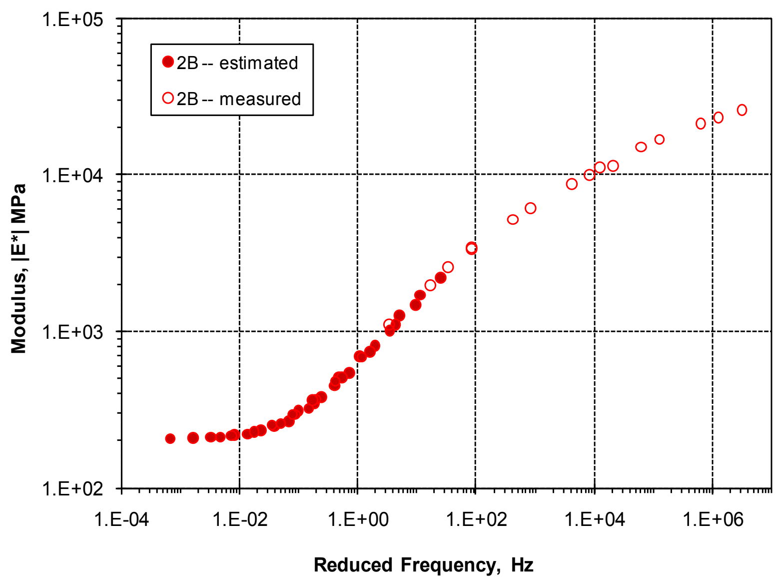
APPENDIX C

ANALYSIS OF BLENDING



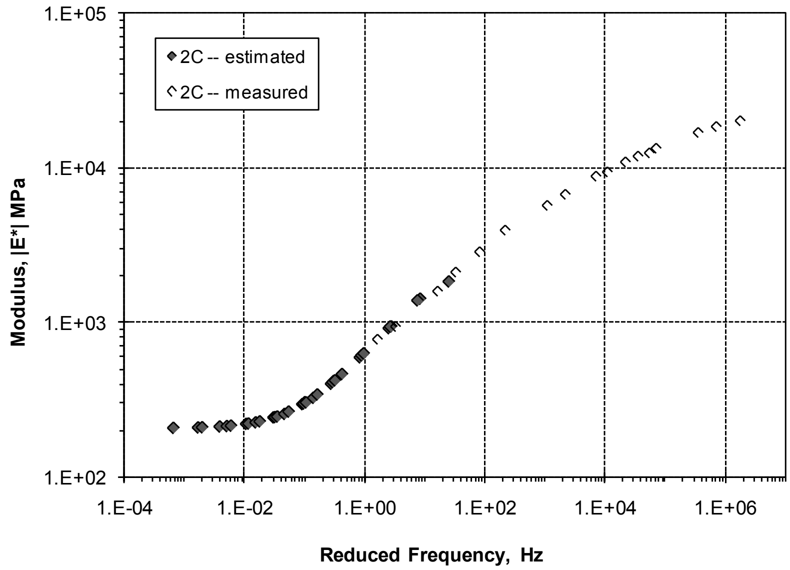
1psi = 0.0069 MPa

Figure 54. Graph. Contractor 2 evaluation of blending from master curves: mix A.



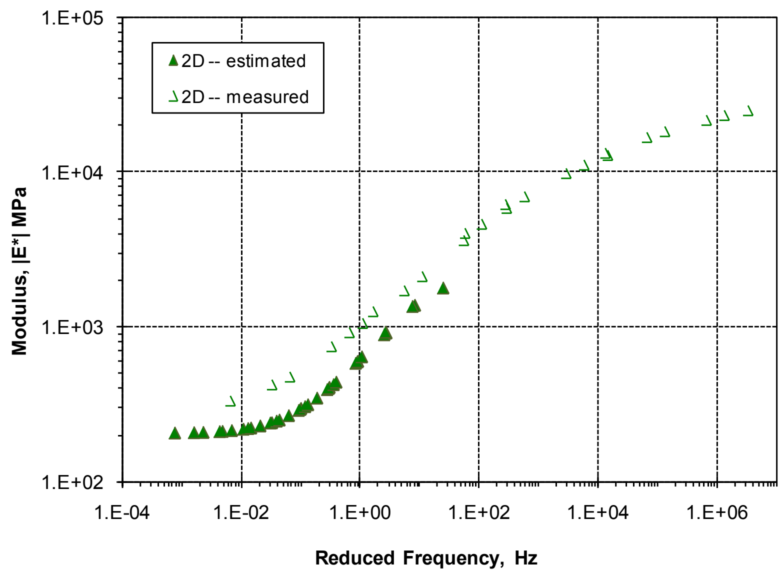
1psi = 0.0069 MPa

Figure 55. Graph. Contractor 2 evaluation of blending from master curves: mix B.



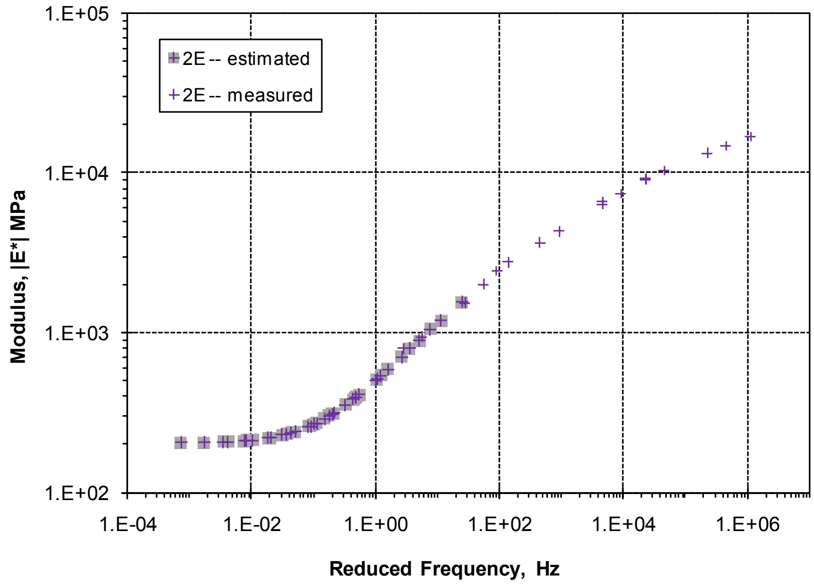
1psi = 0.0069 MPa

Figure 56. Graph. Contractor 2 evaluation of blending from master curves: mix C.



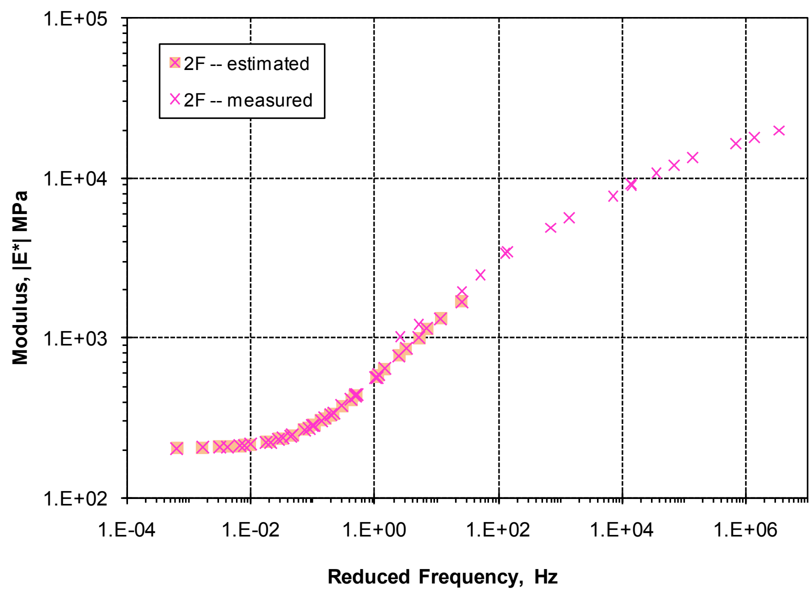
1psi = 0.0069 MPa

Figure 57. Graph. Contractor 2 evaluation of blending from master curves: mix D.



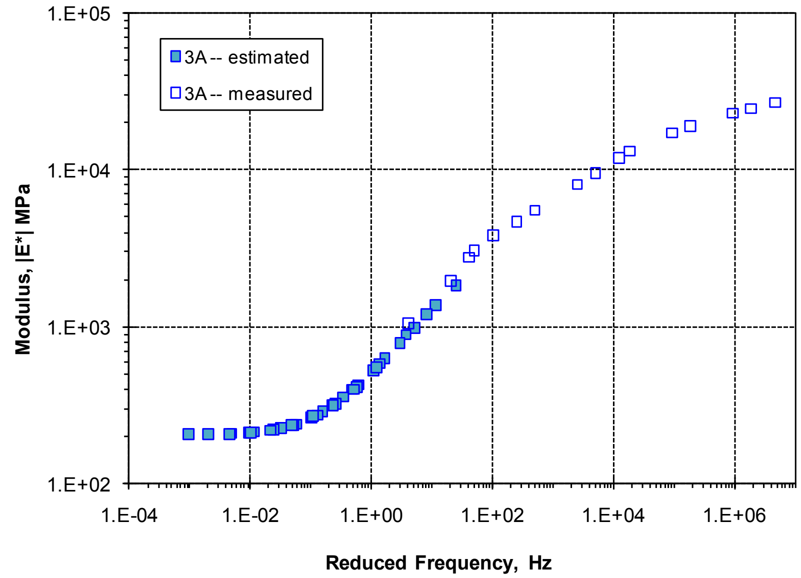
1psi = 0.0069 MPa

Figure 58. Graph. Contractor 2 evaluation of blending from master curves: mix E.



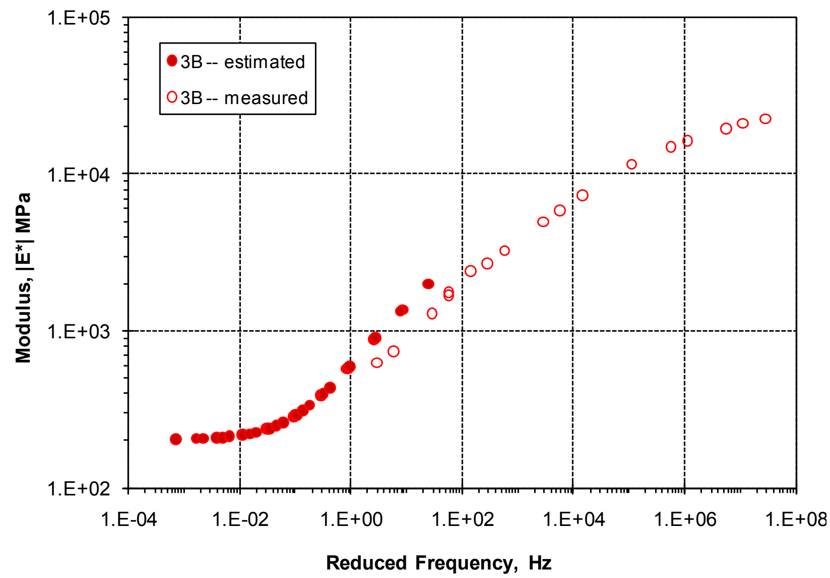
1psi = 0.0069 MPa

Figure 59. Graph. Contractor 2 evaluation of blending from master curves: mix F.



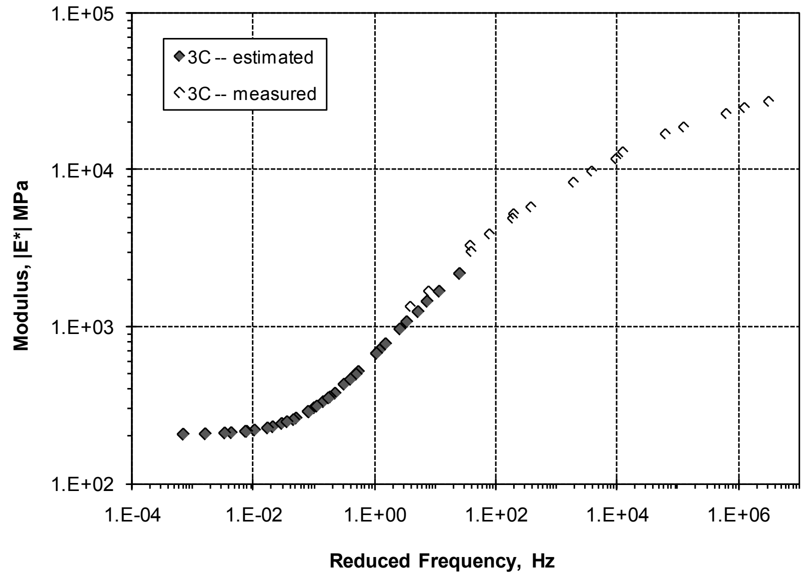
1psi = 0.0069 MPa

Figure 60. Graph. Contractor 3 evaluation of blending from master curves: mix A.



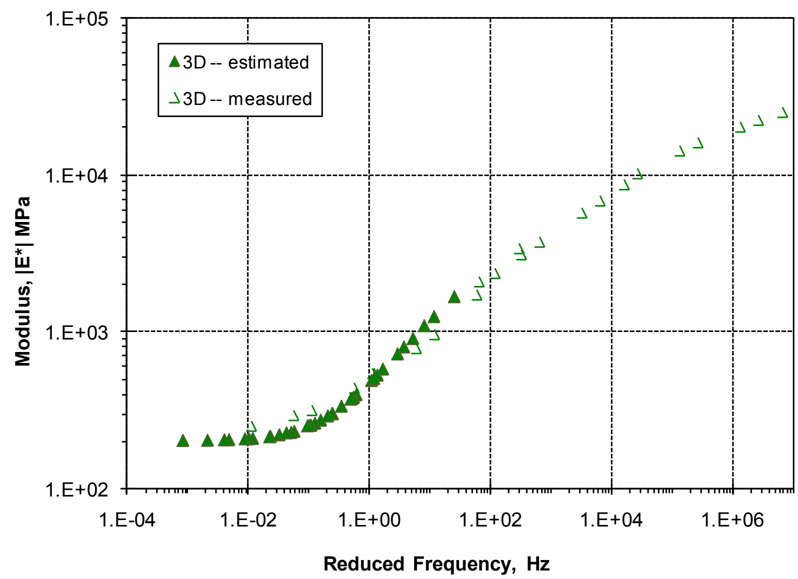
1psi = 0.0069 MPa

Figure 61. Graph. Contractor 3 evaluation of blending from master curves: mix B.



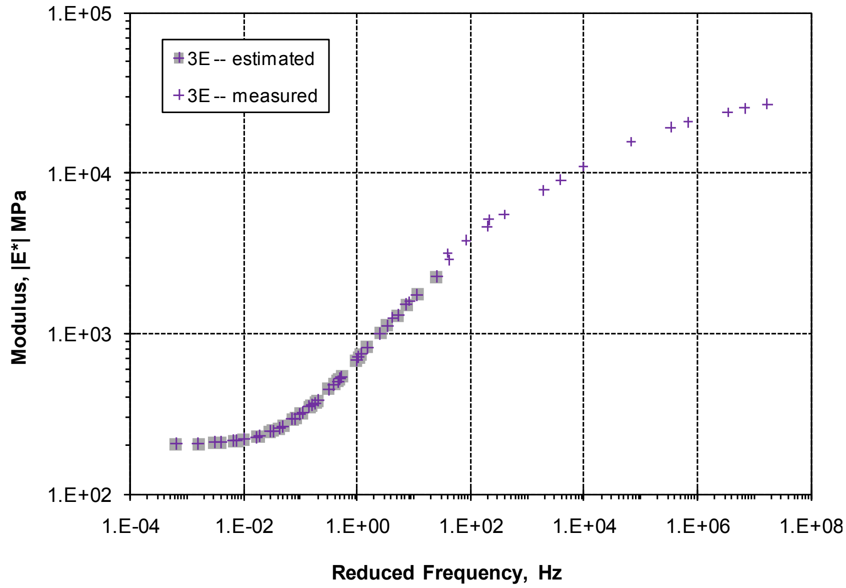
1psi = 0.0069 MPa

Figure 62. Graph. Contractor 3 evaluation of blending from master curves: mix C.



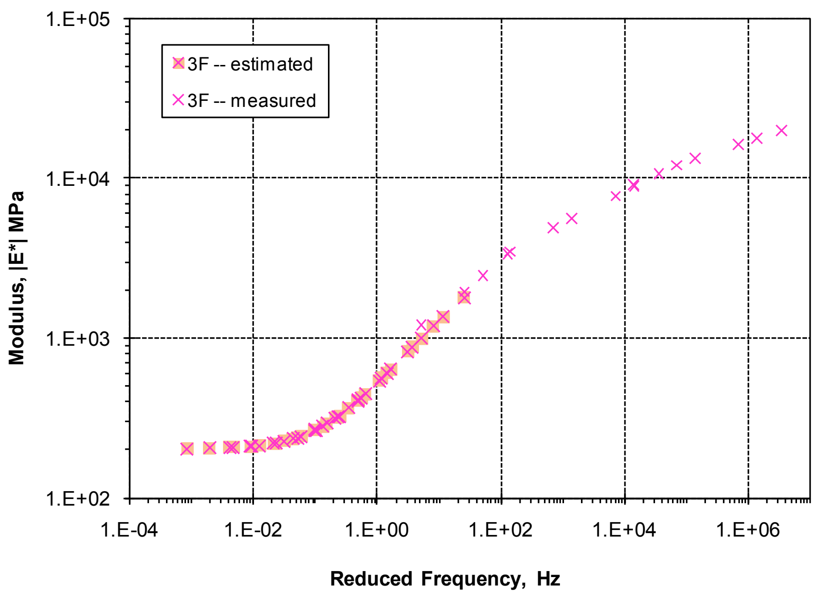
1psi = 0.0069 MPa

Figure 63. Graph. Contractor 3 evaluation of blending from master curves: mix D.



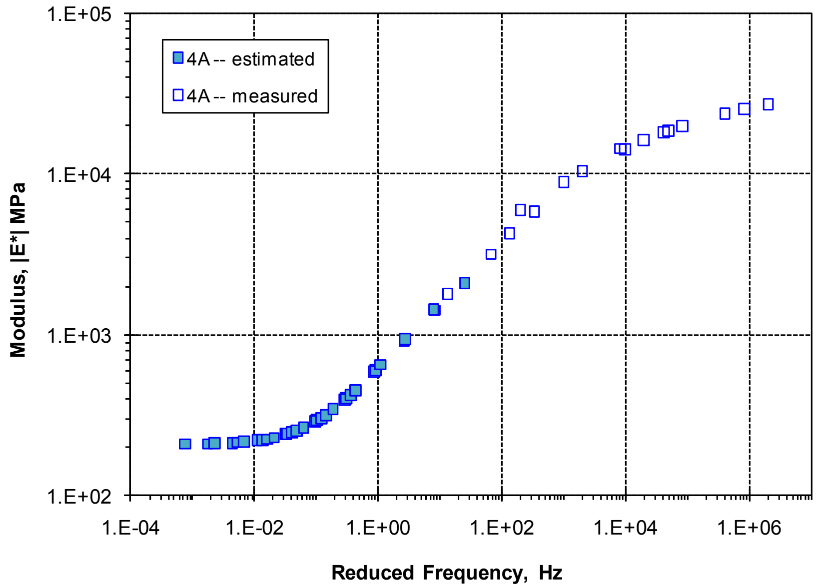
1psi = 0.0069 MPa

Figure 64. Graph. Contractor 3 evaluation of blending from master curves: mix E.



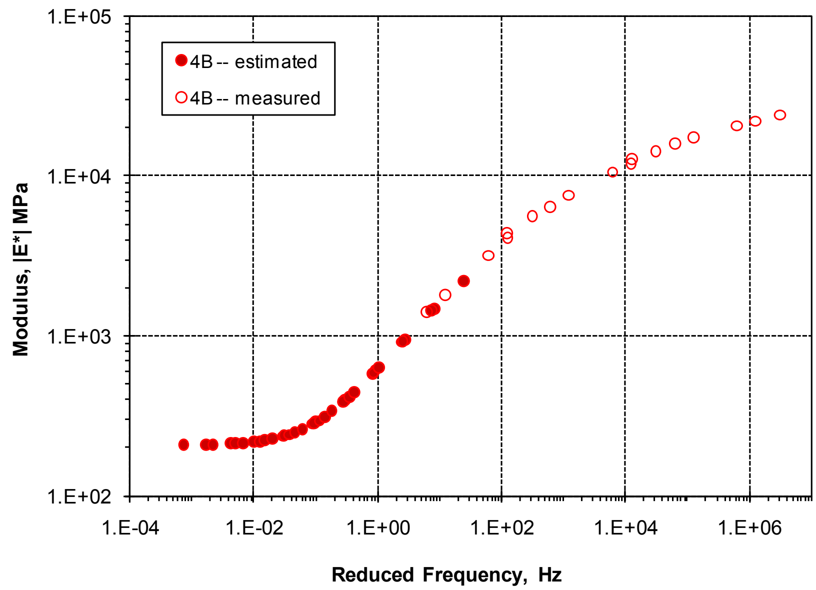
1psi = 0.0069 MPa

Figure 65. Graph. Contractor 3 evaluation of blending from master curves: mix F.



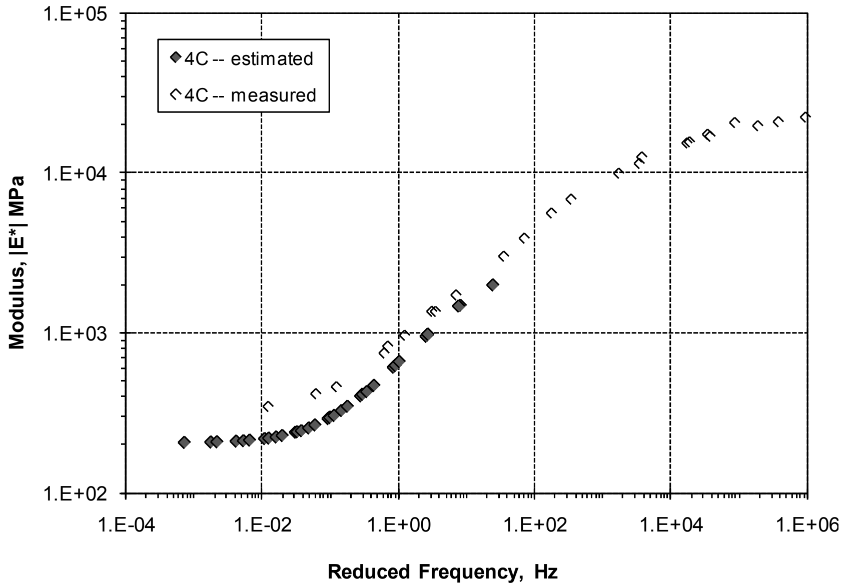
1psi = 0.0069 MPa

Figure 66. Graph. Contractor 4 evaluation of blending from master curves: mix A.



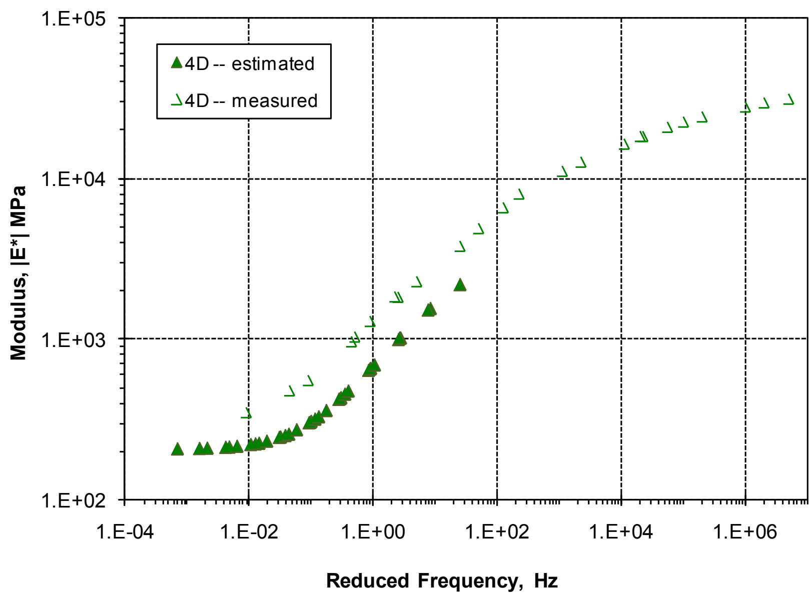
1psi = 0.0069 MPa

Figure 67. Graph. Contractor 4 evaluation of blending from master curves: mix B.



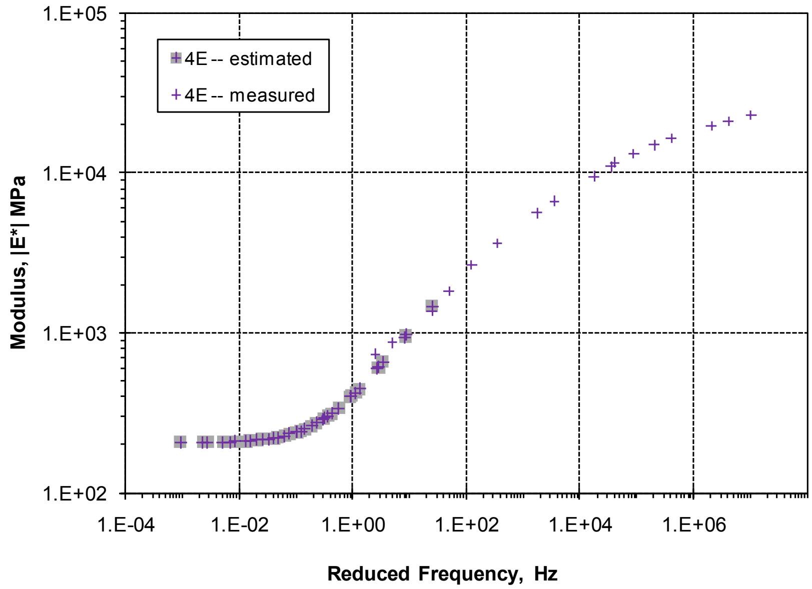
1psi = 0.0069 MPa

Figure 68. Graph. Contractor 4 evaluation of blending from master curves: mix C.



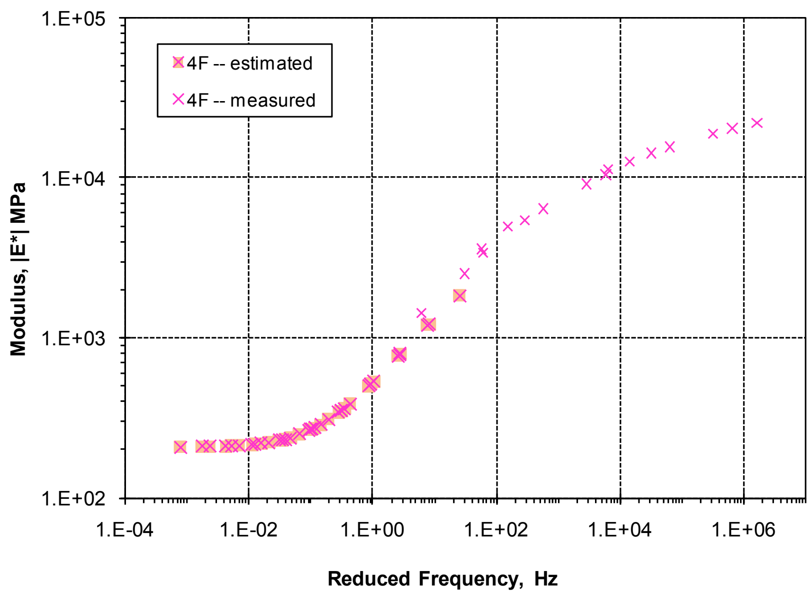
1psi = 0.0069 MPa

Figure 69. Graph. Contractor 4 evaluation of blending from master curves: mix D.



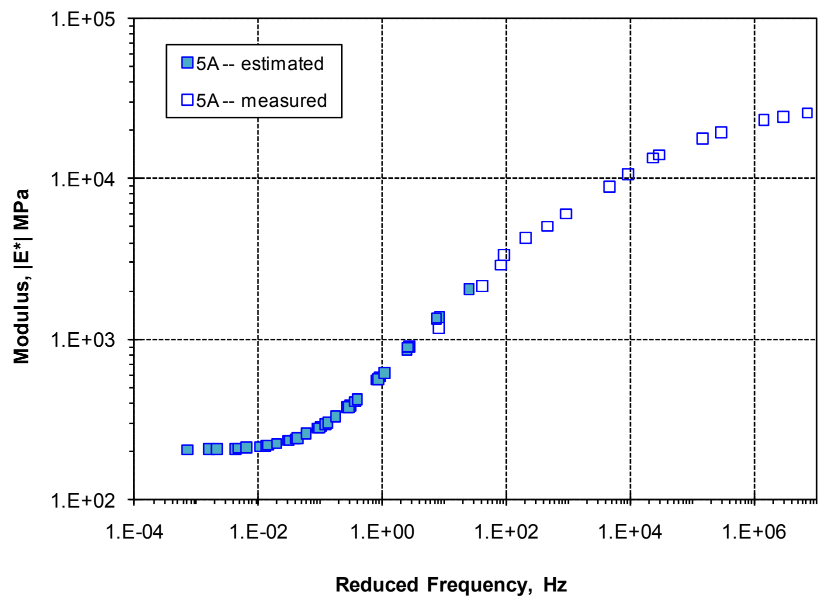
1psi = 0.0069 MPa

Figure 70. Graph. Contractor 4 evaluation of blending from master curves: mix E.



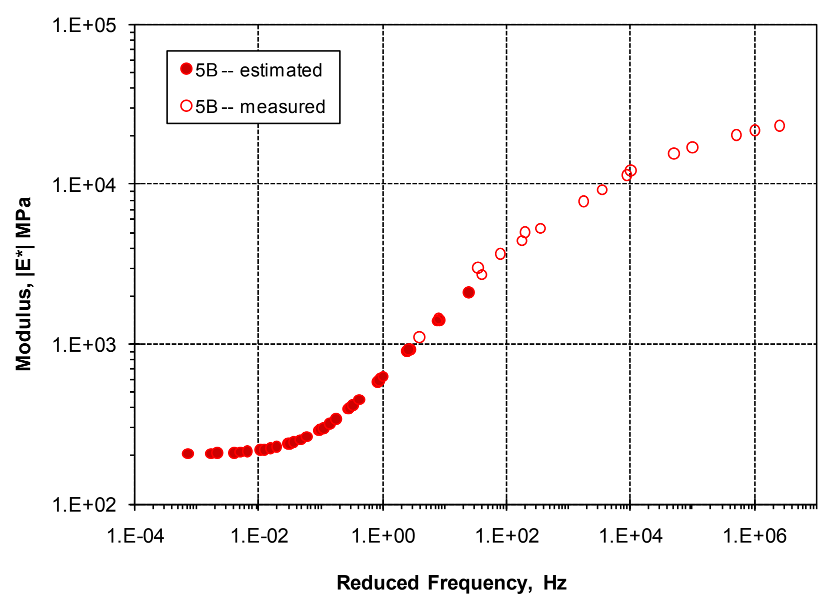
1psi = 0.0069 MPa

Figure 71. Graph. Contractor 4 evaluation of blending from master curves: mix F.



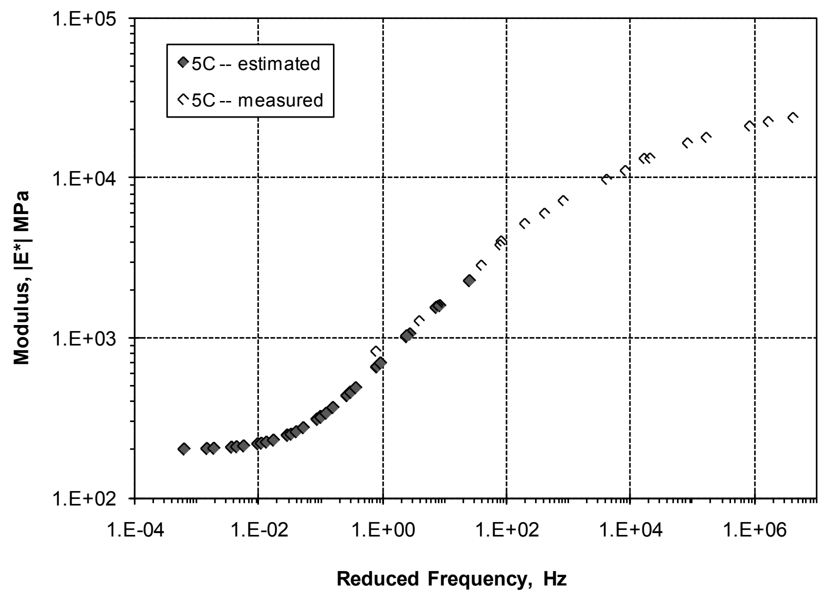
1psi = 0.0069 MPa

Figure 72. Graph. Contractor 5 evaluation of blending from master curves: mix A.



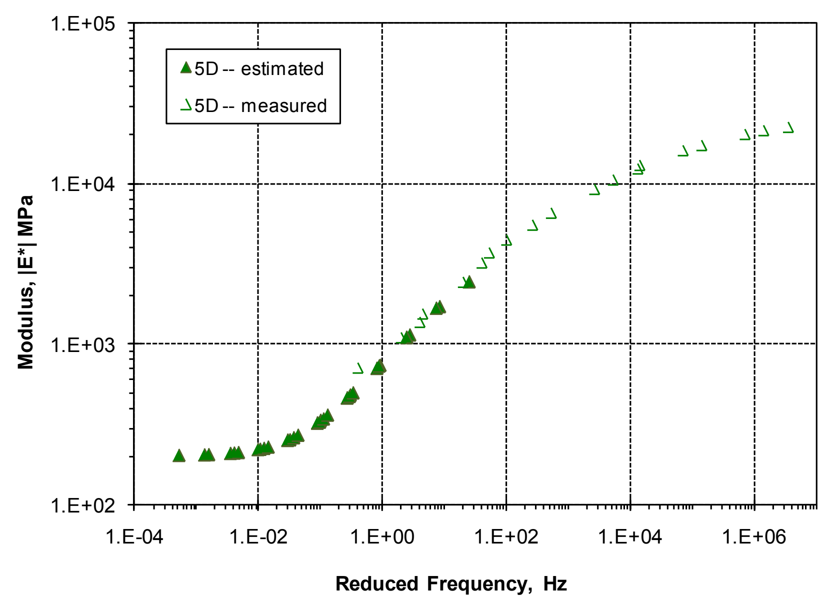
1psi = 0.0069 MPa

Figure 73. Graph. Contractor 5 evaluation of blending from master curves: mix B.



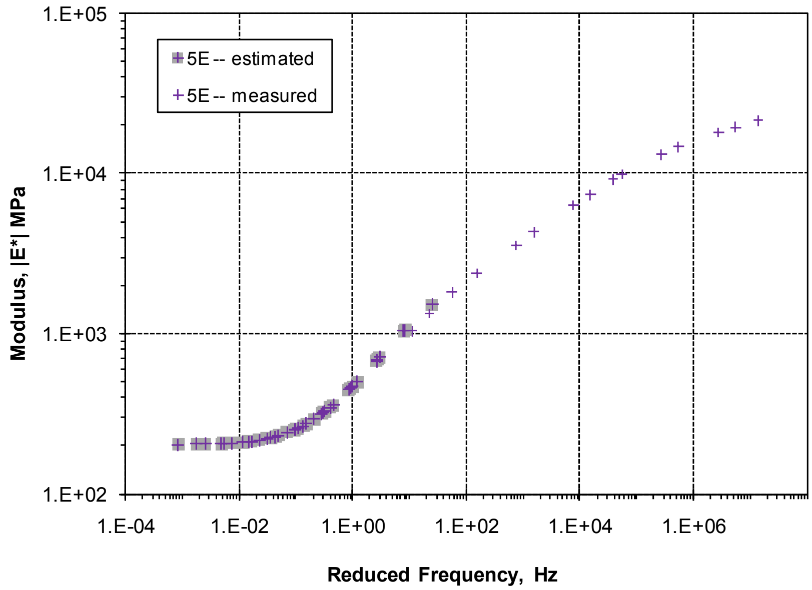
1psi = 0.0069 MPa

Figure 74. Graph. Contractor 5 evaluation of blending from master curves: mix C.



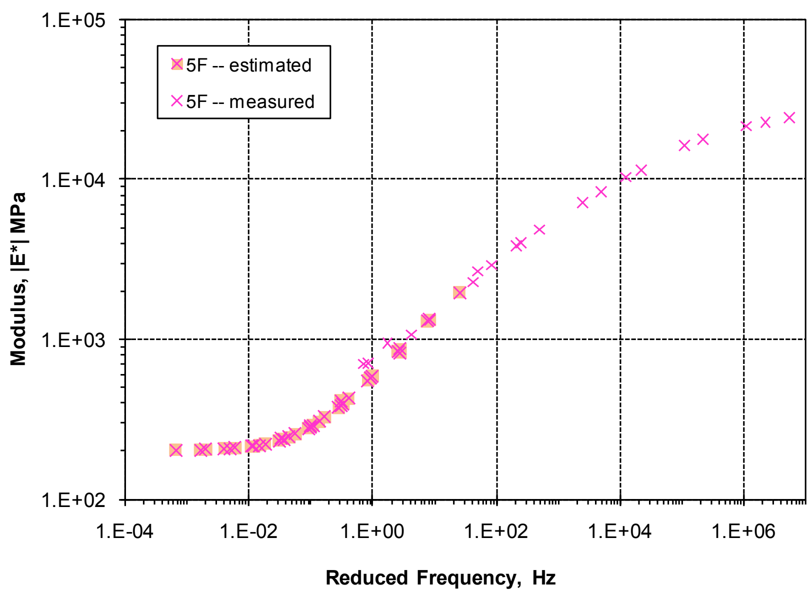
1psi = 0.0069 MPa

Figure 75. Graph. Contractor 5 evaluation of blending from master curves: mix D.



1psi = 0.0069 MPa

Figure 76. Graph. Contractor 5 evaluation of blending from master curves: mix E.



1psi = 0.0069 MPa

Figure 77. Graph. Contractor 5 evaluation of blending from master curves: mix F.

ACKNOWLEDGEMENTS

The researchers would like to thank the contractors who put so much effort into designing, producing, and sampling the mixtures evaluated for this report and in phase I of this project. This was not an insignificant amount of effort, and it is greatly appreciated. In addition, the members of the Asphalt Pavement Association of Indiana and Brad Cruea and Don Lecklitner, assisted the research effort by arranging and supporting a technician for several months to perform binder extractions, recoveries, and binder testing. Josh Clark was extremely helpful and productive. Andrew Szabat, a Purdue University undergraduate, completed the extractions/recoveries. His assistance and patience is also appreciated.

The following individuals provided technical review of this report: Nelson Gibson, John Bukowski, Victor (Lee) Gallivan, Andy Mergenmeier, and John D'Angelo. Their efforts are appreciated.

REFERENCES

1. Shah, A., McDaniel, R.S., Huber, G.A., and Gallivan, V.L. (2007). "Investigation of Properties of Plant-Produced RAP Mixtures," *Transportation Research Record 1998*, 103–111, Transportation Research Board, Washington, DC.

2. McDaniel, R., Soleymani, H., and Shah, A. (2002). *Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications: A Regional Pooled Fund Project,* North Central Superpave Center, West Lafayette, IN.

3. McDaniel, R.S. and Shah, A. (2008). *Investigation of Low and High Temperature Properties of Plant-Produced RAP Mixtures: Phase II Work Plan*, Contract No. DTFH61-08-P-00165, North Central Superpave Center, West Lafayette, IN.

4. AASHTO M 323. (2007). *Standard Specification for Superpave Volumetric Mix Design*, American Association of State Highway and Transportation Officials, Washington, DC.

5. McDaniel, R.S., Soleymani, H., Anderson, R.M., Turner, P. and Peterson, R. (2000). *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method*, Web Document 30, National Cooperative Highway Research Program, Washington, DC. Obtained from: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w30-a.pdf. Site last accessed August 29, 2011.

6. AASHTO R 35. (2009). *Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*, American Association of State Highway and Transportation Officials, Washington, DC.

7. Superpave Mixture Expert Task Group. (1997). *Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP)*, 5, Federal Highway Administration, Washington, DC.

8. Schroer, J. (2007). *Asphalt Shingles in HMA: Missouri DOT Experience*, Presentation at NCAUPG North Central Hot Mix Asphalt Technical Conference, Springfield, IL. Obtained from: http://cobweb.ecn.purdue.edu/~spave/NCAUPG/Activities/2007/Presentations/Schroer%20MoDOT%20-%20Asphalt%20Shingles%20in%20HMA.pdf. Site last accessed August 29, 2011.

9. Ordorff, D. (2007). *RAP & Recycling of Asphalt Shingles: A Contractor's Experience*, Presentation at North Central Asphalt User/Producer Group North Central Hot Mix Asphalt Technical Conference, Springfield, IL. Obtained from: http://cobweb.ecn.purdue.edu/~spave/NCAUPG/Activities/2007/Presentations/Ordorff%20Recycling%20Shingles.pdf. Site last accessed August 29, 2011.

10. Bonaquist, R. (2005). *New Approach for the Design of High RAP HMA*, Presentation at NEAUPG Meeting, Burlington, VT. Obtained from: www.neaupg.uconn.edu/pdf/neaupg_oct2005_bonaquist.pdf. Site last accessed December 20, 2010.

11. Bonaquist, R. (2007). “Can I Run More RAP?,” *Hot Mix Asphalt Technology*, *12*(5), National Asphalt Pavement Association, Lanham MD.

12. Christensen, D., Pellinen, T., and Bonaquist, R. (2003). “Hirsch Model for Estimating the Modulus of Asphalt Concrete,” *Journal of the Association of Asphalt Paving Technologists*, *72*, 97–121.

13. AASHTO T 209. (2009). *Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)*, American Association of State Highway and Transportation Officials, Washington, DC.

14. AASHTO T 166. (2007). *Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens*, American Association of State Highway and Transportation Officials, Washington, DC.

15. AASHTO T 312. (2009). *Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor*, American Association of State Highway and Transportation Officials, Washington, DC.

16. AASHTO M 320. (2009). *Performance-Graded Asphalt Binder*, American Association of State Highway and Transportation Officials, Washington, DC.

17. AASHTO T 315. (2009). *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*, American Association of State Highway and Transportation Officials, Washington, DC.

18. AASHTO T 313. (2009). *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*, American Association of State Highway and Transportation Officials, Washington, DC.

19. AASHTO T 240. (2009). *Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)*, American Association of State Highway and Transportation Officials, Washington, DC.

20. AASHTO R 28. (2007). *Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)*, American Association of State Highway and Transportation Officials, Washington, DC.

21. AAASHTO TP 62. (2009). *Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA)—Revision 1*, American Association of State Highway and Transportation Officials, Washington, DC.

22. AASHTO T 322. (2007). *Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*, American Association of State Highway and Transportation Officials, Washington, DC.

23. AASHTO T 319. (2008). *Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*, American Association of State Highway and Transportation Officials, Washington, DC.

24. AASHTO T 170. (2000). *Recovery of Asphalt from Solution by Abson Method*, American Association of State Highway and Transportation Officials, Washington, DC.

25. AASHTO T 164. (2008). *Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt (HMA)*, American Association of State Highway and Transportation Officials, Washington, DC.

26. Galal, K., White, T.D., and Hand, A. (2000). *Second Phase Study of Changes in In-Service Asphalt*, Report No. FHWA/IN/JTRP-99/07Joint Transportation Research Program, Purdue University, West Lafayette, IN.

27. Christensen, D. (1998). "Analysis of Creep Data from Indirect Tension Test on Asphalt Concrete," *Journal of Association of Asphalt Paving Technologists*, *67*, 458–492, St. Paul, MN.

28. Hou, T., Underwood, B.S., and Kim, Y.R. (2010). "Fatigue Performance Prediction of North Carolina Mixtures Using the Simplified Viscoelastic Continuum Damage Model," *Journal of the Association of Asphalt Paving Technologists*, *80*, 35–80.

29. American Association of State Highway and Transportation Officials. (2010). "AASHTO TP 79: Determining the Dynamic Modulus and Flow Number for HMA Using the Asphalt Mixture Performance Tester (AMPT)," *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 30th Ed., AASHTO, Washington, DC.

HRDI-10/01-12(WEB)E