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IMPROVED MIX DESIGN, EVALUATION, AND MATERIALS MANAGEMENT PRACTICES FOR HOT MIX ASPHALT WITH HIGH RECLAIMED ASPHALT PAVEMENT CONTENT

PRELIMINARY DRAFT FINAL REPORT

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ABSTRACT

In recent years, many highway agencies and paving contractors have increased the percentages of reclaimed asphalt pavement (RAP) used in asphalt paving mixtures. The first objective of this study was to develop recommendations to improve mix design standards to better handle RAP contents between 25 and 55 percent. A laboratory testing plan was executed to answer basic questions about preparing and characterizing RAP materials for mix designs. Mix designs were prepared with materials from different parts of the U.S. with different RAP contents and virgin binders. The mix designs were evaluated with standard Superpave criteria and a set of performance-related tests to further assess their susceptibility to common forms of distress. The report recommends revisions to AASHTO R 35 and M 323 aimed at improving mix design with high RAP contents, and suggests additional tests for further evaluating the mix designs as appropriate for their proposed use.

A second objective of the study was to develop guidelines for RAP management to ensure that high RAP content mixes can be produced with the same uniformity and quality as virgin mixes. Information on good RAP management practices were obtained from a literature review, surveys of current practices, discussions with numerous QC personnel, and analysis of stockpile QC data from across the U.S. From that information, a comprehensive report titled *Best Practices for RAP Management* was prepared as a companion document to this report.

EXECUTIVE SUMMARY

Recycling of asphalt pavements is one of the great success stories of the highway building industry. Although the use of recycled asphalt in new pavements dates back almost 100 years, it did not become a common practice until the late 1970s when asphalt binder prices skyrocketed as a result of the Arab oil embargo. Highway agencies and the asphalt paving industry worked together to develop recycling methods that became part of routine operations for pavement construction and rehabilitation. Motivations for asphalt pavement recycling have always included economic savings and environmental benefits. Economic benefits include materials cost savings from reducing the amount of virgin aggregates and binders in new mixtures as well as reduced costs associated with transporting virgin materials to plant sites. Environmental benefits include reduced emissions and fuel usage associated with extraction and transportation of virgin materials, reduced demands on non-renewable resources, and reduced landfill space for disposal of used pavement materials.

In recent years, highway agencies and the paving industry have again focused attention on increasing the amount of reclaimed asphalt pavement (RAP) materials used in asphalt paving mixtures to offset rising costs of asphalt binder. Industry experts identified several issues that needed to be addressed in order to successfully use higher RAP contents. A key limitation was believed to be a lack of guidelines for processing, handling, and characterizing RAP prior to mix design. It was also felt that the Superpave mix design process needed to be improved to better handle "high RAP" content mixes, defined as mixes containing 25% or more RAP.

The first part of this study was to develop clear guidelines for RAP management to ensure that high RAP content asphalt mixes can be produced with the same uniformity and quality as virgin asphalt mixes. Information on good RAP management practices were obtained from a literature review, surveys of current practices in the industry, discussions with numerous contractor QC personnel, and analysis of contractor stockpile QC data from across the U.S. Based on that information, a comprehensive report titled Best Practices for RAP Management was prepared as a companion document to this report.

The second part of this study was to develop recommendations to improve mix design standards to better handle RAP contents between 25 and 55 percent. The current Superpave mix design standards only briefly address RAP as a mixture component. A laboratory testing plan was executed to answer basic questions about preparing and characterizing RAP materials for mix designs. A series of mix designs were then prepared with materials from four different parts of the U.S. with different RAP contents and different virgin binders. Those mix designs were evaluated with standard Superpave criteria and a set of performance-related tests to further evaluate the mix designs for their susceptibility to common forms of distress.

The Best Practices for RAP Management document includes several important findings and recommendations. RAP stockpile data collected in this study and numerous others have shown that processed RAP from multiple sources is typically more consistent than virgin aggregate. This indicates that requirements to limit RAP to single-source materials are not justified. Using the document's recommended sampling and testing plan and variability guidelines will assure that RAP materials are consistent and suitable for use regardless of how it is collected or processed.

Properties of RAP needed for mix design include its asphalt content, basic RAP aggregate properties, and, when a high RAP content is desired, the true or continuous grade of the recovered RAP binder. The ignition method is more accurate than solvent extraction methods for determining asphalt contents except for certain aggregate types with high mass losses when heated to the high temperatures used in the ignition method. Recovering RAP aggregates using either the ignition method or a solvent extraction procedure is suitable for determining the gradation, specific gravities, and Superpave consensus properties. Estimating the RAP aggregate Gsb by determining its Gse and estimating an asphalt absorption value is not recommended for high RAP contents because this will typically lead to a significant and unconservative error in VMA that will likely be detrimental to mixture performance.

For high RAP content mixes, the current practice requires that the RAP binder be graded following a solvent extraction and recovery procedure. The recovered RAP binder's true grade is determined using standard Superpave binder grading procedures and then used to calculate either the appropriate grade of virgin binder to use in the mix design or the maximum amount of RAP that can be used for a given virgin binder grade. This is still considered the best approach at this time. However, in the end, this study proposes to redefine "high RAP" content mixes as asphalt mixes in which 25% or more of the total binder is from RAP materials. The term "RAP Binder Ratio" is introduced as the ratio of the RAP binder in the mixture divided by the mixture's total binder content, expressed as a decimal to minimize confusion with the traditional RAP content expressed as a percentage.

The experimental phase of the study began with a couple of small lab experiments to determine appropriate methods for drying and heating RAP samples for mix design work. Heating batched samples of RAP to the mixing temperature for 1½ to 3 hours was found to be satisfactory. Heating more than three hours caused additional aging of the RAP binder which may not be apparent in volumetric mix designs, but will likely impact performance-related test results.

The main experimental plan was designed to assess the effects of several factors on mix design properties. Thirty mix designs were prepared using materials from different parts of the U.S. with different RAP contents and different virgin binders. The raw materials were obtained from contractors in New Hampshire, Utah, Minnesota, and Florida. Fractionated RAP was necessary to meet standard Superpave criteria in AASHTO R 35 for all mix designs with 55% RAP. Subsets of the mix designs were further evaluated with a set of performance-related tests to determine for their susceptibility to common forms of distress.

One of the experiments was set up to assess whether or not changing the binder grade or binder source affects mix volumetric properties and therefore the optimum binder content. The results of that experiment were not conclusive. This issue is only important if a mix designer completes a mix design with one binder, then wants to change to another binder source because of supply or cost reasons, or to change binder grades to try to improve mix performance properties.

A limited experiment was performed to assess the effect of using a warm mix asphalt (WMA) technology and decreasing the mixing and compaction temperatures by 19°C (35°F) on a mix design with 55% RAP. The concern addressed by this experiment was the whether or not the lower temperature might affect the activation of the RAP binder. The results showed that the WMA additive and lower temperatures had a negligible effect on the mix's volumetric properties and TSR results. Results of rutting tests and fatigue tests on the mixture with and without WMA were also similar. The dynamic modulus of the WMA was 6 to 15% lower than the HMA, with the larger difference observed at the higher temperature range.

Dynamic modulus tests were conducted on each of the 30 mix designs for two purposes. The first purpose was to evaluate how binder grade, binder source, and RAP content affected mix stiffness. Results showed that the 25% RAP mixes were 30% to 43% higher than companion virgin mixes, with the greatest differences occurring at the intermediate temperature ranges. The 55% RAP mixes were about 25% to 60% stiffer than the virgin mixes with the greatest difference occurring at an intermediate temperature, 21.1°C. The source of the virgin binder was significant only at 21.1°C, and virgin binder grade was significant at 37.8°C and at the lowest test frequency.

The second purpose of dynamic modulus testing was to try to backcalculate the properties of the "effective" or composite RAP and virgin binder using the Hirsch model. This experiment was attempted to answer questions about the degree of blending between the virgin and recycled binders. The analyses clearly showed that this process did not provide useful results. Backcalculated intermediate and high true critical temperatures deviated from measured critical intermediate and high temperatures of binders by as much as 13.1 and 27.8°C, respectively.

Moisture damage susceptibility of the mix designs was evaluated using AASHTO T 283. Although some of the high RAP content mixes did not initially meet the standard 0.80 TSR criteria, adding an antistripping additive generally improved the TSRs above 0.80. In all cases, the tensile strengths of the high RAP content mixes exceeded those of the virgin mixes from the same materials source. This could indicate that some consideration should also be given to minimum tensile strength values to help assess moisture-damage potential.

The confined flow number test was performed on the mix designs to assess their resistance to permanent deformation. None of the samples exhibited tertiary deformation using this method. Therefore, analysis of rutting resistance was based on the total accumulated strain. All the mixes had less than 5% accumulated strain at 20,000 load cycles. Analysis indicated that the total strain was significantly affected by the source of the materials and the high performance grade of the virgin binder, but not by RAP contents.

Mix designs were evaluated for resistance to fatigue cracking based on fracture energy determined from indirect tensile strength tests. The analysis of this this property showed that high RAP content mixes had significantly lower fracture energies than corresponding virgin mixes. Results also showed that mixes with smaller nominal maximum aggregate size (NMAS) mixes also had better fracture energy than larger NMAS mixes. It is important to note that other studies have shown that fracture properties and cracking performance of high RAP content mixes can be improved by either using a softer grade of virgin binder or by using a rejuvenating agent in conjunction with the standard binder grade such that the theoretically blended binders have properties that are appropriate for the specific project climate and traffic.

Potential for thermal cracking was evaluated with two tests: the low-temperature semi-circular bend (SCB) test and the bending beam rheometer (BBR) test on small mix beams cut from gyratory-compacted specimens. Two properties were obtained from the SCB tests: fracture toughness and fracture energy. Ideally, mixes with higher fracture toughness and fracture energy would be expected to perform better than mixes with low fracture properties. The results from the two SCB test properties were conflicting. Compared to the corresponding virgin mixes, the high RAP content mixes generally had higher fracture toughness, but similar or lower fracture energy results. For the BBR results, mixes containing RAP generally had higher stiffness and lower m-values, which theoretically should result in more cracking. However, analysis of the critical cracking temperatures for the climates where the materials were obtained indicated that the high RAP content mixes would perform similar to the corresponding virgin mixes with regard to thermal cracking.

The report recommends several minor, but important revisions to AASHTO R 35 and M 323 aimed at improving mix design with high RAP contents, and suggests additional tests for further evaluating the mix designs as appropriate for their proposed use.

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Draft Final Report

CHAPTER 1 BACKGROUND

Introduction

The economic and environmental advantages of using reclaimed asphalt pavement (RAP) in asphalt mixes have been recognized for decades. Using RAP reduces the cost of purchasing and transporting new aggregate and binder for asphalt mixtures and reduces the energy associated with extracting and processing of those non-renewable natural resources for pavement construction, rehabilitation, and maintenance. However, recent surveys of state highway agencies show that few allow RAP contents above 25% in the surface pavement layer (**Error! Reference source not found.**). In 2007, the Reclaimed Asphalt Pavement Expert Task Group (RAP ETG) identified a list of obstacles that may deter highway agencies or contractors from using higher percentages of RAP in asphalt mixtures. Several obstacles were related to a lack of guidelines for RAP processing and mix design and scarce performance information for "high RAP" content mixes, defined as mixes with 25% or more RAP. The current Superpave mix design procedure, AASHTO R 35-04, briefly addresses RAP as a mixture component. It is believed that one of the issues affecting the usage of RAP is a lack of guidance for developing mix designs that contain RAP and best practices for handling RAP management. Therefore, this study was developed to improve AASHTO R 35-04 with regard to instructions for designing high RAP content mixtures and to develop clear guidelines for RAP management. The RAP management guideline covers best practices for obtaining and processing RAP as well as testing RAP for mix designs.

Project Objectives

The NCHRP 09-46 research panel identified two primary objectives for this study:

1. Adapt AASHTO R 35, *Superpave Volumetric Design for Hot-Mix Asphalt,* and propose changes to the affiliated specification AASHTO M 323, *Superpave Volumetric Mix*

Design for mixtures containing high RAP contents (defined as greater than 25% and possibly exceeding 50%) to include characterization of reclaimed aggregates, characterization of blended binder, and recommended performance tests to ensure quality mixes.

2. Develop practical guidelines for proper RAP management practices.

This research was conducted in three parts. Part I focused on gathering information on best practices for management of RAP materials. This effort resulted in the development of a companion document "Best Practices for RAP Management" and an associated webinar, which are available on the FHWA RAP ETG website: www.moreRAP.us. Part II of this study focused on answering questions about testing methods and preparation of materials for mix designs containing RAP. This effort led to recommended refinements for mix designs containing 25% or more RAP. Part III focused on conducting an experimental plan to evaluate the proposed mix design refinements and to test hypotheses or assumptions made in the development of those refinements.

This final report is organized into four chapters. In addition to the introduction and objectives of the project, this chapter includes a literature review on RAP management and characterization, mix design, laboratory mix performance testing, and field performance of asphalt mixtures containing RAP. Chapter 2 describes the experimental plan and materials. The test results and discussions are covered in Chapter 3. Conclusions and recommendations are provided in Chapter 4.

Literature Review

When conducting research, it is best to begin with a review of available literature to establish the current state of knowledge on the subject. In the past few years, there has been a substantial increase of papers published on high RAP content mixtures. This chapter presents a summary of relevant research and is organized by the following topics: (1) field management of RAP materials, (2) characterizing RAP materials for mix designs, (3) blending of RAP binders and virgin asphalt binders, (4) mix design for mixtures containing RAP, (5) mechanical properties of mixtures containing RAP, and (6) field performance of mixes containing high RAP contents.

Field Management of RAP Materials

RAP management practices vary greatly among HMA producers and from state to state. Decisions in RAP management practices at a plant include choices regarding milling and collecting RAP, segregating RAP from different sources, stockpiling, crushing, fractionation, testing, and mix design. Each of these decisions should be examined with regard to both economics and quality. Best practices for RAP management that enable high percentages of RAP and ensure high quality asphalt mixtures provide the best long-term value.

The National Asphalt Pavement Association's (NAPA) *Information Series 123, Recycling Hot Mix Asphalt Pavements (2)* is a practical guide that addresses sources of RAP, processing, stockpiling, and mix production for HMA containing RAP for various plant configurations. With regard to management and processing RAP the guide states that RAP millings from a single project are typically consistent in composition. These materials are often kept in separate stockpiles and used without further processing other than scalping of particles larger than two inches during the transfer of the materials from the RAP cold fed bin to the transfer belt feeding the mixer during mix production. Many contractors use in-line "lump breakers" to break down the oversize particles or agglomerations of RAP during the RAP feeding process. The guide also states that RAP materials from different sources with different particle sizes and compositions can be made into a very consistent RAP product through careful blending and crushing operations. The key to achieving a homogeneous RAP product from a multiple-source or "composite" pile is to first blend the composite materials with a front-end loader or bulldozer and then to crush the blended material so that the top size is smaller than the maximum aggregate size for the mixes in which the RAP will be used. Advantages of processing small quantities of RAP include the stockpile can be easily sampled and tested to assure consistency and the stockpile can be used before it accumulates moisture from rain. Moisture contents in RAP often range from 7 to 8% which can be a limiting factor in the plant's production rate and control how much RAP can be efficiently used. The guide also recommends using large conical stockpiles rather than wide horizontal stockpiles. RAP stockpiles often form an 8 to 10 inch crust that helps seal the surface and reduce penetration of moisture. The crust is easily broken with the plant's front-end loader, and the RAP under the crust is easy to manage. Sheltering RAP stockpiles is also noted as a way to minimize moisture in RAP.

In 1998, the National Center for Asphalt Technology (NCAT) prepared *Pavement Recycling Guidelines for State and Local Governments (***Error! Reference source not found.***).* This document and training guide provides good information regarding processing of RAP that is consistent with the recommendations from the reference above. Often the maximum particle sizes in RAP limit the amount of RAP that can be used in some mixes. Prior to crushing RAP from multiple source RAP piles, a front-end loader should be used to blend the materials. A variety of crusher types have been used to process RAP into particle sizes that can be used in HMA. Smaller stockpiles are recommended to reduce issues with moisture. The stockpiles should be conical shaped to better shed precipitation and placed on a solid surface to aid drainage from the stockpile. The crust that forms on the outside of the stockpiles also reduces moisture from entering the stockpile.

One of the deliverables from NCHRP 09-12A was a RAP mix design guide for technicians *(4)*. This guide recommends sampling RAP from multiple locations around a RAP stockpile to determine the variability of the RAP material properties. Stockpiling techniques used for virgin aggregates, such as maintaining non-contaminated stockpiles, should be followed for RAP stockpiles. The guide also suggests that single source RAP stockpiles are preferred because they will have more consistent properties.

NAPA's *Quality Improvement Series 124, Designing HMA Mixtures with High RAP Content: A Practical Guide (5)* also contains guidance on sampling RAP stockpiles and analysis of variability. It recommends five to ten samples be collected and tested from each RAP stockpile to characterize the RAP. At a minimum, the asphalt content and gradation of each sample should be checked. When high percentages of RAP are to be used in mix designs, the aggregate and asphalt properties should be determined. A coefficient of variability of less than 15% on key control sieves is considered good. The guide suggests when the coefficient of variability exceeds 20% the percentage of the RAP stockpile used in mixes should be limited or the RAP stockpile reblended to improve uniformity and retested. The benefits of fractionating RAP stockpiles are also discussed in the guide. If a RAP source is separated into fine and coarse stockpiles, then multiple samples should be collected from each stockpile even though it is the same RAP source. Each stockpile should be characterized since the gradations and asphalt contents will differ between a fine and coarse stockpiles. The guide states that using a blend of multiple RAP stockpiles should result in a more consistent mix by averaging out variations in RAP properties.

NCAT conducted a survey on current RAP management practices and RAP variability in 2007 and 2008 *(6)*. The survey collected responses from 81 operations across the USA. Half of the respondents combine all RAP sources into a single stockpile while the other half keep separate stockpiles for each RAP source. Contractors who maintain multiple stockpiles often do so because either the state specifications allow only DOT RAP to be used in mixes for DOT projects, or they do so to better control fines by separating millings from other RAP material, or to improve consistency. RAP processing responses were divided into three categories; crushing to one size, fractionating, or no processing. Seventy-four percent of the respondents only crush to one size. When the RAP is crushed, 52% crush RAP to a maximum particle size of one-half inch. The next most common maximum sizes used for RAP crushing were 5/8 inch and 3/4 inch, at 16% and 11%, respectively. At the time of the survey, only 4% of the respondents were fractionating RAP into two or more sizes. The most common separation is between fine and coarse RAP. The screen that separates the fine and coarse RAP also varies by contractor. Fractionation has been suggested as a method to provide better control of gradations and asphalt content *(7)*. Some states require fractionated RAP for higher RAP content mixtures *(8)*. Stockpiling practices of RAP did not differ from those used for virgin aggregate for 53% of the respondents. Thirty-three percent of the respondents promote moisture drainage by placing RAP stockpile(s) on a slope. Seventeen percent of the respondents stockpile on a paved surface to minimize contamination. Only 9% of the respondents cover their RAP stockpiles to reduce issues with moisture. Forty-three percent of the respondents sample RAP stockpiles to determine gradation and asphalt content once for every 500 tons or less.

Several studies have examined the variability in RAP stockpiles. Table 1 shows data reported by Kallas in 1984 *(9)*. Kandhal et al. *(10)* provided similar data from various locations in Georgia, shown in Table 2.

Table 1 RAP Variability Data from 1984 FHWA Report *(9)*

Location	n	% Passing 2.36 mm		% Passing 0.075 mm		Asphalt Content	
		Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
California	5	69	6.5	11.8	0.34	5.2	0.04
North Carolina	5	72	0.9	8.0	0.11	5.7	0.11
Utah	10	58	2.8	9.9	1.15	6.2	0.44
Virginia	6	52	1.1	13.0	0.30	5.2	0.12

Table 2 RAP Variability Data from NCAT Study in Georgia *(10)*

Location	n	% Passing 2.36 mm		% Passing 0.075 mm		Asphalt Content	
		Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
Newton County	10	47.5	4.95	7.14	0.74	5.52	0.23
Forrest Park	5	3.60[a]	3.41	7.02	1.08	5.46	0.31
Resaca	10	36.4	2.20	8.72	1.36	5.08	0.21
Bryan County	10	42.9	4.63	4.75	0.71	4.83	0.42
Lowndes County	10	49.3	4.82	7.36	0.75	5.60	0.48
Spartan Asphalt	70	58.1	3.5	9.0	0.82	3.80	0.30

[a] This is most likely a typo and should be 36.0.

A more comprehensive study of RAP variability conducted in Florida by the International Center for Aggregate Research *(11)* analyzed RAP and aggregate stockpiles from 13 asphalt plant locations. A summary of stockpile statistics from that study is shown in Table 3. Its analysis found that RAP stockpiles were less variable than virgin aggregates and that increasing the percentage of RAP did not increase the variability of the produced mixtures.

Table 3 RAP Variability Data from ICAR Study in Florida

RAP ID & Description	n	% Passing 2.00 mm		% Passing 0.075 mm		Asphalt Content	
		Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
A2 Millings	18	51.0	3.23	12.6	1.24	5.7	0.32
B3 Crushed	22	63.2	6.25	8.3	0.87	4.7	0.39
C7 Crushed	28	63.4	5.51	8.9	0.95	5.6	0.55
D8 Crushed	32	63.0	5.36	7.7	1.03	5.2	0.27
D12 Crushed	9	60.5	2.64	7.7	0.48	5.1	0.40
D19 Millings	10	49.9	3.58	9.7	1.63	5.7	0.27
E8 Crushed	9	60.9	4.26	8.8	0.96	5.1	0.44
E13 Crushed	22	64.5	4.68	11.0	1.33	5.1	0.27
E16 Crushed	7	62.1	1.95	11.6	0.45	5.7	0.18
E19 Crushed	11	56.4	5.66	9.5	0.68	5.2	0.50
F3 Crushed	7	72.2	2.81	7.2	0.73	5.8	0.13
G5 Crushed	20	69.7	3.81	8.2	0.69	5.2	0.40
H5 Crushed	12	53.3	1.29	10.6	0.64	5.5	0.12
H7 Crushed	12	56.4	1.62	10.2	0.82	5.8	0.23
I7 Crushed	29	50.1	1.66	9.9	1.36	5.1	0.26
J4 Crushed	51	57.2	5.09	7.8	0.50	5.0	0.34
L6 Crushed	7	70.0	2.08	8.0	0.52	5.2	0.10
M5 Millings	11	51.6	4.59	5.5	1.15	6.1	0.37
M16 Millings	4	59.3	0.50	6.6	0.54	5.7	0.26

Nady *(12)* analyzed RAP stockpiles from two Iowa contactors over a four-year period and found that processed "chunk" RAP from multiple sources was just as consistent as millings from single DOT projects. That seems to be supported with the Florida data. He also stated that virgin aggregates from local sources were more variable than RAP stockpiles over the four-year period.

The Texas Transportation Institute (TTI) completed a study in 2009 that documented RAP management practices in Texas and recommended guidelines to control RAP quality and consistency *(13)*. The study found that most Texas contractors combine RAP from multiple sources into a single large stockpile and later process the materials as needed. Processing methods differed greatly among the contractor sites visited; some crushed all RAP to a single top size, and some fractionated the RAP into different sizes. Since millings from large projects are primarily composed of surface layers, screening the material over a 1/2 inch screen will typically yield 70 to 80% passing the 1/2 inch screen. The report notes that most contractors were doing a good job of processing, managing, and testing RAP, but some operations were observed digging into multiple source piles at one location during processing. These operations were not following good practices of blending portions of the multiple-source stockpile together during the crushing and screening processes. Table 4 summarizes the test data obtained from the RAP stockpiles analyzed in the study.

Table 4 Summary of RAP Variability Data from the TTI Study

Stockpile Number	Description	n	% Passing 2.36 mm		% Passing 0.075 mm		Asphalt Content	
			Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
TxDOT 1	unfractionated	7	45.0	4.3	7.6	1.1	5.4	0.2
TxDOT 2	unfractionated	7	46.8	3.3	7.5	0.7	7.9	0.4
Contr. 1	crushed RAP	7	56.3	3.0	11.6	1.1	5.1	0.3
Contr. 2	crushed RAP	7	46.5	5.0	8.1	0.8	4.4	0.2
Contr. 4	coarse RAP	6	15.8	3.1	3.8	0.9	2.4	0.2
Contr. 5	coarse RAP	7	37.0	4.0	3.6	0.5	2.8	0.3
Contr. 5	fine RAP	7	67.8	3.1	6.1	2.1	4.8	0.3

The TTI study included the following recommendations for RAP management:

- eliminate contamination
- separate RAP from different sources when feasible
- avoid over-processing to minimize generating additional fines
- minimize moisture in RAP stockpiles
- thoroughly blend RAP from multiple sources prior to processing

Characterizing RAP Materials for Mix Designs

Aggregates in RAP materials can be recovered for testing either using solvent extractions or the ignition furnace method. The NCAT survey mentioned previously found that the vast majority of contractors use the ignition method to determine RAP asphalt contents and recover the aggregates for sieve analyses. Several studies have examined how to best recover and test aggregates from RAP and how to recover and characterize RAP binder.

Prowell and Carter conducted a study in Virginia to evaluate how aggregate properties were affected by testing materials in an ignition furnace *(14)*. The aggregate properties evaluated were coarse aggregate angularity, fine aggregate angularity, flat and elongated, sand equivalent, aggregate bulk specific gravity (G_{sb}), and gradation. Nine virgin aggregates with varying properties were used to produce a lab-simulated RAP. Only two of the aggregate properties significantly changed after the ignition furnace: sand equivalent and aggregate bulk specific gravity. Comparisons were made between effective specific gravity values, as commonly used for RAP materials in Virginia, and the measured aggregate bulk specific gravity values following the ignition furnace. No attempt was made to adjust the effective specific gravity values using assumed asphalt absorption values. Significant differences were found between the before and after G_{sb} results for six of the coarse aggregate bulk specific gravities and five of the fine aggregate specific gravities. Despite the changes in the aggregate bulk specific gravity results after the ignition furnace, the values were closer to the original (true) values than the effective specific gravity values. This indicated that bulk specific gravity values determined on materials recovered from the ignition furnace may provide more accurate VMA values than using effective specific gravity values for RAP materials.

A study in Arkansas *(15)* also examined changes in gradation and coarse aggregate G_{sb} caused from using the ignition method. Results showed there was little change in gradation and the changes in coarse aggregate G_{sb} could be attributed to testing variability.

A joint study conducted by NCAT and the University of Nevada Reno (UNR) investigated the influence of centrifuge, reflux, and ignition method on recovered aggregate properties *(16, 17)*. Laboratory-produced (simulated) RAP materials were prepared with aggregates from four different sources. Properties (gradation, specific gravities, Superpave consensus properties and others) of the virgin aggregates were compared to those from the recovered aggregates. Based on results with a limited set of aggregates, the researchers made the following recommendations:

- The ignition method provides the most accurate results for the asphalt content of RAP. No aggregate correction factors were used in this study for the ignition method results. The solvent extraction methods do not appear to remove all of the aged binder from RAP, and consequently, RAP asphalt contents using these methods tend to be lower than they actually are.
- The solvent extraction or ignition method may be used to recover the RAP aggregate for gradation analyses. However, the solvent extraction using the centrifuge is recommended for asphalt mixtures with more than 25% RAP.
- The solvent extraction or ignition furnace may be used to recover aggregates for determining coarse aggregate fractured faces and the fine aggregate sand equivalent of RAP material.

- The solvent extraction or ignition furnace may be used to recover RAP aggregates for LA abrasion tests. However, the solvent extraction using the reflux and the ignition furnace are recommended for asphalt mixtures with more than 25% RAP.
- The solvent extraction or ignition furnace may be used to recover RAP aggregates for soundness testing. However, the solvent extraction using the centrifuge is recommended for asphalt mixtures with more than 25% RAP.
- One of the most important properties that must be determined for the RAP is the specific gravity of the RAP aggregate. The RAP aggregate G_{sb} is critical to an accurate determination of VMA, which is a key mix property used in mix design and quality assurance. For high RAP content mix designs, the best method recover the aggregate for determining the RAP aggregate specific gravities is to use a solvent extraction method then test the coarse and fine parts of the recovered aggregate using AASHTO T85 and T84, respectively. The ignition method may also be used to recover the RAP aggregate with the exception of some aggregate types that undergo significant changes in specific gravity when subjected to the extreme temperatures used in the ignition method. In this study, the soft Florida limestone was an example of this problem. Note that all methods used to recover the RAP aggregate are likely to cause small errors in the G_{sb} results. As RAP contents approach 50%, the net effect of the small G_{sb} error could cause the VMA to be off by ± 0.4%. This magnitude of uncertainty is one reason why it may be appropriate to perform additional performance related tests on high RAP mix designs to assure resistance to rutting, moisture damage, fatigue cracking, and low-temperature cracking.
- Another method for estimating the RAP aggregate specific gravity is the approach recommended in NCHRP Report 452. This method was also evaluated in this study and involves determining the maximum theoretical specific gravity (G_{mm}) of the RAP material using AASHTO T 209. From the G_{mm} and the asphalt content of the RAP, the effective specific gravity (G_{se}) of the RAP aggregate can be determined. Although some agencies use the G_{se} for the RAP aggregate in the calculation of VMA, the authors strongly advise against this practice. Other agencies try to correct the G_{se} to an estimated G_{sb} using an assumed value for asphalt absorption. This correction is only reliable when the asphalt absorption can be assumed with confidence. The correction is very sensitive to the assumed asphalt absorption value and can lead to errors in VMA that are 0.5% or more.

Another basic property that must be determined for RAP materials is the binder content. The common methods for determining asphalt contents of asphalt paving mixtures, AASHTO T 164 and AASTO T 308, commonly known as solvent extraction methods and the ignition method, respectively, may be used for RAP. The NCAT-UNR study noted above also evaluated the accuracy and variability of asphalt contents using the centrifuge extraction method, the reflux extraction method, and the ignition method. Laboratory-produced (simulated) RAP materials were prepared with aggregates from four different sources. Trichloroethylene was the solvent used for both the centrifuge and reflux methods, and no correction factor was used in the ignition method. The results showed that all results were significantly lower than the known asphalt contents. The ignition method results were closest to the true asphalt content compared to the two solvent extraction methods.

AASHTO M 323, the current standard for mix designs requires a blending chart analysis to select the virgin binder when RAP contents exceed 25%. In order to complete the blending analysis, the RAP binder properties must be determined. In current practice across the USA, RAP binder properties are not routinely determined because either RAP contents are kept below 25% or because the additional costs of determining the RAP binder properties and the softer grade of virgin binder resulting from the blending analysis diminish the feasibility of using RAP contents above the 25% threshold. The process of determining RAP binder properties includes multiple steps. Some labs prefer to use AASHTO T 319, which was developed in the SHRP program and includes the removal of the binder from the RAP aggregate using a solvent extraction in the first step, followed by recovery of the binder from the solvent. Some labs found the extraction process in AASHTO T 319 to be cumbersome and alternatively use the centrifuge method, AASHTO T 164, Method A, followed by recovery of the binder from a solvent solution using a rotary evaporator, ASTM D 5404. Some labs still use the Abson method, AASHTO T170, for binder recovery. However, it has been criticized for causing additional aging of the binder (*18*). In addition to various extraction and recovery methods, debate also continues about what solvent should be used. In any regard, dealing with solvents like trichloroethylene, toluene, or n-Propyl bromide, and the additional equipment required for recovery of RAP binder have been significant deterrents to using higher RAP contents. The final step in the process is to grade the recovered binder using the Superpave binder performance grading process, AASHTO R 29. NCHRP Project 9-12 concluded that the recovered RAP binder should be graded after conditioning the recovered binder in the rolling thin-film oven. Aging the recovered binder in the pressure-aging vessel is not necessary. This significantly reduces the amount of RAP binder needed for the testing and the time to complete the grading of the RAP binder.

Table 5 summarizes some data on PG grades for recovered RAP binders from several recent studies and data collected by a few states. Data like this may be useful in establishing an appropriate virgin binder grades for different RAP contents within a region that has similar RAP binder properties.

Table 5 RAP Binder Critical Temperatures from Regional Testing and Analyses

Location of Study	No. of Stockpile Samples Analyzed	Parameter	Critical Temperature, °C		
			Avg.	Std. Dev.	Range
Alabama	36	T_{crit} High	91.7	5.2	84.4 to 105.5
		T_{crit} Intermediate	34.1	4.9	25.2 to 42.9
		T_{crit} Low	-12.5	3.7	+0.4 to -21.6
Florida	21	T_{crit} High	94.8	4.6	87.1 to 106.1
		T_{crit} Intermediate	32.3	3.3	24.5 to 38.5
		T_{crit} Low	-15.8	3.2	-9.8 to -23.2
Indiana	33	T_{crit} High	90	5.0	83 to 103
		T_{crit} Low	-11	3.1	0 to -21
Wisconsin	13	T_{crit} High	82.8	3.7	73.5 to 87.1
		T_{crit} Intermediate	26.9	2.3	20.9 to 29.4
		T_{crit} Low	-21.8	2.3	-18.8 to -27.9

Blending of RAP Binders and Virgin Binders

One of the key issues with regard to RAP mix designs is how much blending occurs between the RAP binder and the virgin binder. The following studies have examined this issue.

One of the experimental objectives of NCHRP 09-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System (19)*, dealt specifically with the blending issue. One view of RAP blending has been that RAP simply acts as a black rock and the RAP binder does not blend with the virgin binder, therefore not contributing to bonding the aggregates together. The opposite view is that RAP binder completely blends with the virgin binder and that the composite binder has properties that can be estimated by proportionally combining properties of the RAP binder and the virgin binder. NCHRP 9-12 evaluated the RAP-virgin binder blending issue with an experiment that considered three scenarios of blending. In the first scenario, the black rock scenario, no contribution of the RAP binder was simulated by recovering RAP aggregate and blending it with virgin asphalt and aggregates. By using the reclaimed aggregate in lieu of the RAP, there was no RAP binder to co-mingle with the virgin binder. In the second scenario, RAP was mixed with virgin asphalt and aggregate. This scenario was referred to as the actual practice. In the third scenario, RAP asphalt and aggregate were reclaimed. The reclaimed asphalt was blended with the virgin binder. Completely blending the reclaimed and virgin binders forced total blending of the binders during the mix design process. The specimens made for all three scenarios used the same gradation and total asphalt content. Three RAP materials with different recovered PG grades, two RAP percentages per RAP stiffness, and two virgin binders were used in the experiment. Five mix tests were used to evaluate the mixes for each scenario: frequency sweep at constant height, simple shear at constant height, repeated shear at constant height, indirect tensile creep, and indirect tensile strength. A comparison of the mix test results revealed that the actual practice and the total blending scenarios were the most similar, thus indicating that there is blending of the reclaimed and virgin binder.

The study also examined linearity of the blending between virgin and RAP binder. Multiple RAP percentages and sources of different stiffnesses were used in the evaluation as well as two virgin binders. The RAP percentages evaluated were 0%, 10%, 20%, 40%, and 100%. Three RAP sources varying in PG grades were used; one each from Florida, Connecticut, and Arizona. The two virgin binders used were PG 52-34 and PG 64-22. The blended binders were graded in accordance with Superpave performance grading standards and the results of the different blends were compared. The results were also used to develop blending charts using linear blending equations. The results of the evaluation of the linear blending equations indicated that blending charts could be used successfully when determining the appropriate RAP percentage or virgin binder. This became the basis of the blending procedure in the appendix of AASHTO M 323.

Huang et al. *(20)* took a different approach to evaluate the extent to which RAP binder is active in a new mix. In the first phase of the study, fine RAP material (passing No. 4 sieve) was blended at 10%, 20% and 30% with coarse virgin aggregate (retained on No. 4 sieve) to determine the extent of RAP binder transferred to the coarse aggregate. The virgin aggregate was heated to 190°C and the RAP was added at ambient temperature. The results indicated that approximately 11% of the RAP binder transferred to virgin aggregate during the mixing process. The researchers conceded that in a real mix that included virgin binder, some diffusion has been shown to occur between the RAP binder and virgin binder; thus suggesting that the percentage of RAP binder that will transfer will increase from 11% with time. The second phase of the study evaluated the loss of binder from RAP particles using a staged extraction with trichloroethylene (TCE). The RAP was soaked in the TCE for three periods of three minutes. Each soak/wash period was assumed to remove to layers of asphalt film from the surface of the particles. The results showed that the film thickness removed changed with each successive soak/wash period. The greatest amount of RAP binder was removed after the first soaking period, and the least amount was removed following the second soak period. Based on both experiments, the authors concluded that the percentage of RAP binder that initially blends with virgin binder is low.

In an early RAP-virgin binder blending study using the Superpave binder grading system, Kennedy et al. *(21)* examined the properties of binders made by blending laboratory-simulated RAP binder and virgin binder. The study used laboratory-made RAP binder by aging thin layers of virgin binder in pans. Two laboratory RAP binders were produced and blended with four different virgin binders. Results for one RAP binder indicated that the parameter $G^*/\sin(\delta)$ on RTFO-aged blends was not affected until the RAP binder percentage exceeded 25%. The parameter $G^*/\sin(\delta)$ of the RTFO+PAV-aged binder exhibited differences with 15% or more RAP. The other lab-aged RAP binder resulted in changes in unaged, RTFO, and RTFO+PAV aged properties with as low as 15% RAP (the lowest RAP percentage). The bending beam rheometer creep stiffness results confirmed that the binder stiffness increased with RAP percentage. Performance grading of the blends at the various percentages showed that some of the grades did not change until as much as 55% RAP binder was added while others changed with as low as 15%. Based on the binder tests, a method for determining the optimum amount of RAP was developed. The method consisted of conducting standard Superpave performance grade testing on four binders blends made with different RAP binder percentages. The RAP percentage that meets all criteria will be the selected optimum RAP percentage.

Bonaquist *(***Error! Reference source not found.***)* developed a technique to evaluate blending of virgin and recycled binders in mixtures containing RAP and recycled asphalt shingles (RAS) by comparing laboratory-measured dynamic shear moduli of binders recovered from mixtures to predicted shear moduli using the Hirsch model. Plant-produced mixtures containing RAP and RAS were sampled, and then specimens were fabricated and tested in a Simple Performance Tester to determine the mixtures' dynamic moduli over a range of temperatures and frequencies. Using the Hirsch model, with inputs of the mixture dynamic moduli, VMA, and VFA from the compacted specimens, the predicted shear moduli, |G*|, of the effective binder in the specimens were calculated. These results were plotted on a shear modulus master curve. Next, the binders were extracted and recovered from the specimens. The recovered binders were tested in a DSR using a frequency sweep to determine the binder shear moduli, |G*|. The process of extraction and recovery assures that the recycled binder and virgin binder are completely blended. The measured shear moduli of the recovered (fully blended) were plotted with the predicted moduli from the Hirsch model. When predicted and measured master curves overlap, it can be inferred that the recycled and virgin binders in the plant mix are completely blended. Figure 1 and 2 show the |G*| curves calculated from the mix and measured from the recovered binder for a 5% RAS mixture and a 35% RAP mixture, respectively. The |G*| backcalculated from the RAS mix is lower than the recovered |G*|, indicating that there is not much blending between the RAS binder and the virgin binder. On the contrary, the RAP mixture data shows that the RAP and virgin binders are well blended.

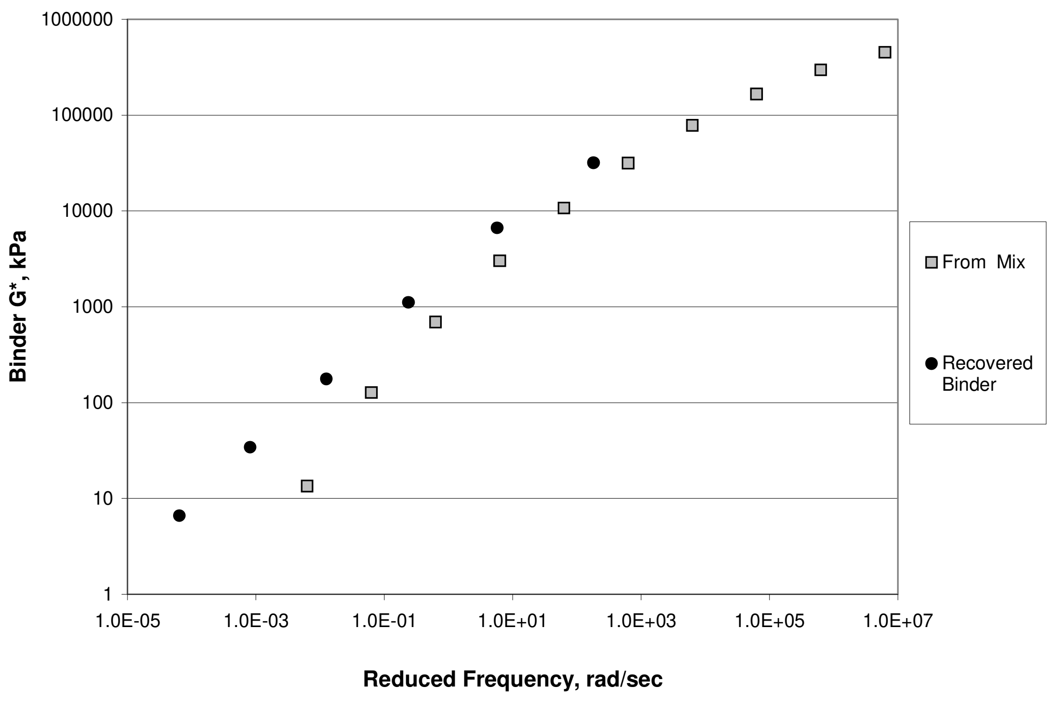


Figure 1 Comparison of Backcalculated and Measured G* for RAS Mixture ***(22)***

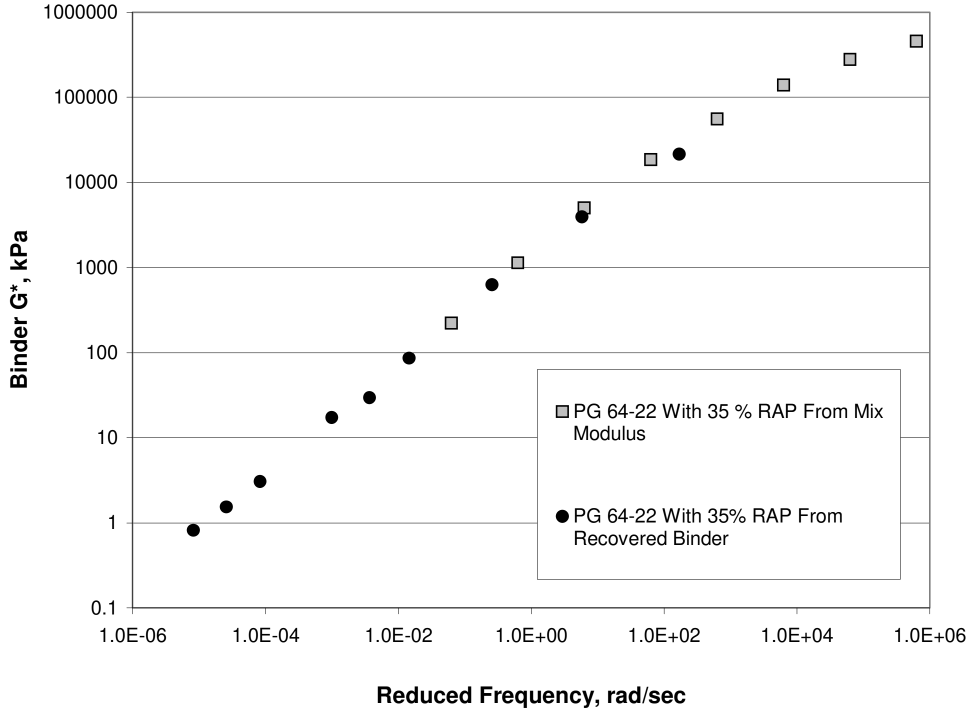


Figure 2 Comparison of Backcalculated and Measured G* for 35% RAP Mixture *(22)*

Mogawer et al. *(23)* used Bonaquist's technique to evaluate eighteen plant-produced mixtures from several northeastern states. This approach indicated that good blending occurred between the RAP and virgin binders in most cases. They commented that plant production parameters affected the degree of blending and the mix properties. McDaniel et al. *(24)* also used Bonaquist's technique to assess the degree of blending for 25 plant mixes containing 15 to 40% RAP from four Indiana contractors and one Michigan contractor. They also found significant blending was evident for the majority of the mixtures containing RAP.

Swiertz et al. *(25)* conducted a study to evaluate a proposed method of estimating the low-temperature properties of hot-mix asphalt blends containing reclaimed asphalt pavement (RAP) and shingles (RAS). The proposed method consisted of testing three sets of bending beam rheometer (BBR) test specimens prepared as follows:

1. Virgin binder tested using standard BBR procedure as described in AASHTO T313,
2. Mortar made from RAP passing the No. 50 sieve and retained on the No. 100 sieve (designated SRAP), and

3. Mortar made from RAP aggregate of the same size as SRAP recovered from the ignition oven, blended with rolling thin-film oven-aged (RTFO) virgin binder at a binder content equal to that of the SRAP (designated RRAP).

The two sets of mortar samples were tested at temperatures corresponding to the low-temperature grade of the virgin binder. The differences between the SRAP and RRAP properties from BBR testing (stiffness (*S*) and *m*-value) were calculated. Since the aggregate and binder content are the same for both sets of specimens, the difference between the test results was theorized to be due solely to the increased stiffness of the RAP binder. This difference was used to shift the virgin binder test results to provide an estimate of the RAP binder properties. The estimated RAP binder properties were then used along with the virgin binder properties to create blending charts for estimating the properties of virgin an RAP binder blends at any proportion.

Additional work was done to determine if the same shifting procedure could be applied to testing low-temperature fracture energy properties using the single-edge notched beam (SENB) test. For this test, specimens were created in a similar manner as before with the addition of a 3-mm notch in the width of the BBR side mold. Materials tested included one RAP source blended with two virgin binders and one RAS source blended with one virgin binder. Samples were tested at -6, -12, and -18°C to measure stress intensity factor K_{IC} and fracture energy, with the load and displacement at failure also reported. Artificially created RAP [virgin binder aged through two cycles of long-term aging in the pressure-aging vessel (PAV) blended with aggregate recovered from RAP burned in the ignition furnace] was used to verify the proposed method for identifying the low-temperature binder properties of HMA containing RAP. The artificial RAP was blended with two virgin binders (PG 64-22 and PG 58-28) at 15 and 25%. The blends were tested using the proposed procedure and the estimated low-temperature properties were compared to BBR test results on binders created by blending the virgin and artificially aged RAP binder. It was found that the proposed procedure could estimate the low-temperature properties of the artificial RAP blends within 1°C of the tested values. When the proposed procedure was used to estimate the low-temperature properties using combinations of actual RAP materials (4 sources) and virgin binder (PG 64-22 and PG 58-28), it was shown that the interaction of RAP and virgin binders was different for different combinations of materials. This implied the current tiered approach to RAP blends may not be valid for all materials. It also implied that current recommendations for an assumed continuous grade rate of change of 0.06°C per percent of RAP binder replacement may not valid for every RAP and virgin binder combination. The procedure was found to work for RAS materials as well as RAP binders and allowed for the estimation of the low-temperature properties of blends containing both RAP and RAS materials. SENB testing could detect changes in the mixture fracture energy of the asphalt mixtures due to the addition RAP and RAS materials, but more work is needed to define what the differences mean.

Researchers at the University of Connecticut *(***Error! Reference source not found.***)* used the indirect tensile strength test to estimate the effective PG binder grade of mixes containing 15 to 25% RAP. Gradation and total asphalt contents were kept the same for the lab virgin and virgin-RAP mixes. Two grades of binder were mixed with the samples before mixing, curing, and compacting specimens. The hypothesis for the experiment was that indirect tensile strength is directly proportional to the PG grade of the composite binder in the mixture. Tensile strengths were determined for the virgin mixes with the two PG binders were plotted versus the PG temperature and connected with a straight line. The intersection of tensile strength of the mix with RAP was then used to determine the effective binder grade of the blended binder, as illustrated in Figure 3. Tensile strengths at 3°C were used to estimate low PG temperatures, and tensile strengths at 38°C were used to estimate the effective high performance grades of the blended binder. The results followed logical trends, but indicated that at low RAP contents, the RAP binder had a negligible effect on the resulting binder grade.

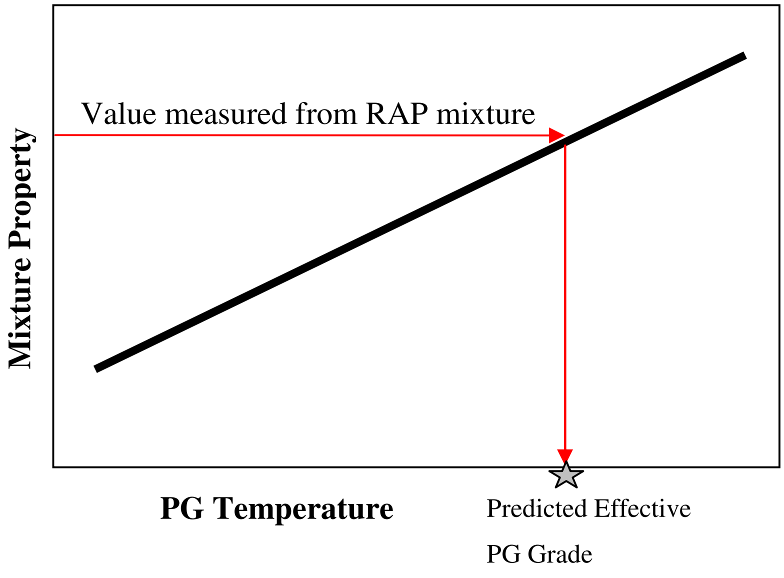


Figure 3 Schematic of Indirect Approach for Identifying the Effective Binder Grade

Research at the University of Minnesota *(27, 28, 29)* used the Bending Beam Rheometer (BBR) to test thin beams (127 mm x 12.7 mm x 6.35mm) of asphalt mixtures to determine their low-temperature creep compliance. The mix samples used in the study contained 0, 20% and 40% RAP, but the hypothesis was that the method could be used on mixes with any RAP content to determine the critical properties of the RAP-virgin composite binder. This approach would eliminate the need for extraction and recovery of RAP binder. A modified Hirsch model was applied to the BBR results using a simple inverse prediction scheme to estimate the component binder creep compliance. A procedure using new blending charts to obtain the critical low temperatures of the binder was proposed. This was considered the more important temperature range for mixes containing RAP since the stiff RAP binder typically increases the low-temperature properties of composite binders. The research concluded that additional work was needed to further refine Hirsch model to obtain reasonable stiffness values and binder *m*-values.

A similar study funded by the Alabama Department of Transportation was conducted by NCAT *(30, 31)*. Four mix tests were evaluated for backcalculating effective binder properties using the Hirsch model. The four mix tests investigated were dynamic modulus, dynamic shear rheometer with torsion bars, bending beam rheometer with mix beams, and the indirect tension relaxation modulus test. Testing included specimens fabricated with 100% virgin aggregates and binders and specimens fabricated with 100% RAP materials from several locations in Alabama. The initial results for backcalculating binder high and intermediate grade properties from dynamic moduli of 100% unmodified virgin mixes or 100% RAP specimens were promising. Relaxation modulus test results were highly variable due primarily to challenges in setting the seating load. Backcalculated high and intermediate temperature binder properties from torsion bar tests did not compare well to measured binder properties for virgin mixes; better match was obtained from samples fabricated with 100% RAP. A sensitivity analysis of dynamic modulus was performed using laboratory-produced mixtures. Experimental factors included asphalt binder grade, RAP source, and RAP content (20%, 35%, and 50%). The results of this analysis indicated that the dynamic modulus and backcalculated binder properties were insensitive to both binder grade and RAP percentage. Testing was also conducted using plant-produced mixtures containing up to 25% recycled materials. For these mixes, the backcalculated effective binder properties did not match well with the properties measured on extracted binders from those mixtures. Michael attributed the differences between backcalculated and measured binder properties to differences in aging conditions and the use of confined dynamic modulus tests *(30)*. Other researchers using the Hirsch model for back calculation of binder properties had used unconfined dynamic modulus tests.

Mix Design for Mixtures Containing RAP

Prior to Superpave, guidelines for mix designs using RAP were included in the Appendix of the Asphalt Institute's MS-2, *Mix Design Methods for Asphalt Concrete and Other Mix Types*, Sixth Edition *(32)*. This manual established many of the principles still used today for designing mixes with RAP. Characteristics of the RAP needed for mix design were the aggregate gradation, the asphalt content, and the viscosity of the recovered binder. The grade (viscosity) of the new asphalt binder was selected based on the asphalt viscosity blending chart. The manual suggests that no change in the new binder is needed for up to 20% RAP and that no more than one grade (i.e., from AC-20 to AC-10) be used when the RAP content is over 21%. Formulas were provided to estimate the percent of new binder to use in the mix design trials.

The current standard for Superpave mix design is AASHTO M 323-07, and the affiliated specification is AASHTO R 35-07. AASHTO M 323 includes guidance on using RAP in Superpave mixes. Most of that guidance was based on NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System.* As previously noted, one of the products from NCHRP 9-12 was *NCHRP Report 452, Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Guide (4)*. This guide provides step-by-step procedures for preparing and designing mixes containing RAP. In general, it recommends that standard Superpave mix design procedures should be followed with a few added details.

- In laboratory mix designs, it is common to fractionate virgin aggregate to individual sieve sizes down to about the No.8 (2.36 mm) sieve. However, RAP materials are not often sieved in the lab for mix design like virgin aggregate, which can lead to inconsistency among specimens.
- For the determination of the specific gravity of the RAP aggregate, the guide recommends running AASHTO T 209 (maximum theoretical specific gravity test) on the as-received RAP, then using the asphalt content of the RAP and calculating the effective specific gravity of the RAP aggregate. The aggregate bulk specific gravity can then be estimated from the effective specific gravity based on an assumed asphalt absorption.

- In batching materials for mix designs, the mass of the RAP binder asphalt must be accounted for using a simple calculation if the asphalt content of the RAP is accurately known.
- Heating RAP should be kept to a minimum to avoid changing the RAP binder properties. This recommendation was based on an experiment to evaluate the effects of heating on RAP. Two RAP sources were used for the evaluation, a very stiff RAP and a low-stiffness RAP. Three heating times were evaluated: 2, 4, and 16 hours at two temperatures, 110°C and 150°C. After heating, RAP binder was recovered and tested with a dynamic shear rheometer to obtain complex shear modulus values. The change in stiffness of these recovered binders was evaluated. Results showed that the time and temperature that caused significant changes in the RAP binder depended on the RAP. Heating stiff RAP for less than four hours at 150°C did not significantly change the RAP binder stiffness, but heating soft RAP at either 110°C or 150°C more than two hours significantly increased the RAP binder stiffness.
- Recommendations for selecting virgin binders are outlined in the guide based on RAP content. For RAP contents below 15%, the virgin binder grade should be the same as for a virgin mix. For intermediate RAP contents between 15 and 25%, the virgin binder should be one full grade lower than for a virgin mix. For RAP contents above 25%, blending charts or equations should be used to determine the appropriate virgin binder grade. These practical recommendations were primarily based on the binder-blending study previously discussed.

Several other researchers have recommended modifications to the mix design procedure for mixtures containing RAP. In some cases, research has identified aspects of mix design and handling of RAP that need to be used but have not become part of test standards or guidelines. This section of the report summarizes the relevant studies and their findings.

One of the most current documents on mix design with high RAP contents is NAPA's *Quality Improvement Series 124, Designing HMA Mixtures with High RAP Content: A Practical Guide* (*5*). Many of the guidelines in this document are consistent with the requirements in AASHTO M 323 for RAP mixes. Some additional recommendations are provided regarding characterizing RAP materials, sample preparation, mechanical property testing, and making mix adjustments for plant production. One suggestion for RAP contents greater than 25% is to characterize RAP binder properties on a regional basis, such as shown in Table 5 of this report, and to develop guidelines or blending charts for selecting virgin binders based on those regional characteristics. The document suggests that mix design for high RAP contents generally follow the conventional process for checking aggregate and volumetric properties but that additional "performance tests" be used to verify that the design has adequate resistance to permanent deformation, thermal cracking, fatigue, and moisture damage. However, the guide acknowledges that few standards or criteria exist for assessing the acceptability of high RAP content mixtures by the performance tests and suggests more research be devoted to this need.

Wu et al. conducted a study to evaluate how temperature affects blends of RAP and virgin materials. The first phase evaluated the effects of temperature on the viscosity of blended binders. RAP binder was recovered and mechanically blended with an AH-70 virgin binder. The RAP binder percentages evaluated were 0%, 25%, 50%, 75%, and 100%. Results of rotational viscosity testing were compared to the varying RAP percentages and temperatures. The test temperatures ranged between 125°C to 185°C. As expected, increasing the amount of RAP binder increased the viscosity at the same test temperature. Results were used to develop the following equation, which could be used to determine the mixing and compaction temperatures for any RAP mixture.

$$\ln T_b = W^{0.5} \ln T_r + (1 - W^{0.5}) \ln T_f \qquad \textbf{[1]}$$

Where,

T_b = Optimum relevant temperature of blended binder

T_r = Optimum relevant temperature of RAP binder

T_f = Optimum relevant temperature of virgin binder

W = Weight percentage of RAP binder

In the second phase of the study, properties of 30% and 50% RAP mixes were compared to virgin mixes. Storage stability data were used to compare the effects of different mixing temperatures. Storage stability consisted of monitoring temperature readings at the time of mixing and then after one hour of storage. The results indicated that the virgin aggregate preheating temperatures needed to be increased when RAP preheating temperatures were decreased to allow for proper mixing and compaction.

A study at Ohio University (*33*) evaluated several loose mix aging conditions and proposed a new method to assess durability of mixtures containing RAP. The first part of the study evaluated different temperatures and times for loose mix conditioning to find the conditions that provided aged binders most similar to binders aged in the rolling thin-film oven and pressure-aging vessel. Conditioning of all loose mix began with two hours at 135°C. Additional conditioning scenarios included four and six hours at 100°C, and three and five hours at 120°C. After conditioning, the binders were recovered using the Abson method with Trichloroethylene. Standard Superpave binder testing was conducted on recovered binders. The results indicated that aging for two hours at 135°C followed by five hours at 100°C resulted in binder properties most similar to RTFO- and PAV-aged binders. That conditioning process was then used to prepare mixtures for the second part of the study.

Part two of the study involved conducting moisture damage susceptibility tests in accordance with AASHTO T 283 on RAP mixes except a new parameter, absorbed energy, was used as the key test parameter instead of tensile strength. Absorbed energy was calculated using the load and deformation of the specimens at failure. The ratio of the average absorbed energy of conditioned specimens to the average absorbed energy of unconditioned specimens was then calculated. A criterion for the acceptable absorbed energy ratio was not established in the report. However, it was recommended that an absorbed energy value of 70 or greater for unaged specimens be considered acceptable and a value of 55 or higher for aged specimens be considered acceptable for determining an appropriate amount of RAP.

NCHRP 09-33 was a recent project to develop a new HMA mix design guide, which has been published as NCHRP Report 673, *A Manual for Design of Hot Mix Asphalt with Commentary (34)*. Chapter 9 of that report deals specifically with RAP. With regard to selecting the virgin binder grade for RAP mixes, the guide follows the current recommendations in AASHTO M323 and acknowledges the assumption that complete mixing occurs between the RAP binder and new binder. Therefore, the resulting blended binder in a mix containing RAP can be estimated from properties of the virgin binder and the RAP binder. The report provides recommendations on assessing the variability of RAP stockpiles and how to consider that variability in establishing feasible RAP contents for mix designs. A companion to the report is a spreadsheet mix design tool, called HMA Tools, for mix designers to use in blending, mix calculations, and for some guidance on mix performance tests.

Mechanical Properties of Mixtures Containing RAP

Several recent studies have evaluated lab-produced and plant-produced RAP mixtures with a variety of mechanical tests. Stroup-Gardiner and Wagner *(35)* conducted an early laboratory study to evaluate the effectiveness of fractionating RAP on mix designs and mechanical properties. RAP was obtained from Minnesota and Georgia and then screened/fractionated over a No. 16 sieve. Mixes were designed above and below the restricted zone with different percentages of coarse and fine RAP. The above restricted zone mixes used only the fine fraction RAP at 15% RAP content. The below restricted zone mixes contained from 15 to 40% total RAP (coarse and fine combined) depending on blend gradation and volumetric limitations. A PG 64-22 virgin binder was used for all mixes. The above restricted zone mixtures were evaluated using low-temperature IDT creep compliance, resilient modulus, tensile strength and moisture damage susceptibility, and Asphalt Pavement Analyzer rut tests. Results indicated that the mixes containing RAP had significantly lower rut depths in the APA tests. Tensile strengths and TSRs were not significantly different between the control mix and the RAP mixes. Compared to the control virgin mix, the RAP mixes were stiffer at all temperatures, but the difference increased at warmer temperatures. At low temperatures, RAP mixes were less compliant at 0 and -10°C, but similar to the control mix at -20°C.

One phase of NCHRP 09-12 investigated the effects of RAP content on mechanical properties of the mixes *(19)*. The materials used in the black rock study were also used in the evaluation of the effects of RAP on HMA. Three RAP sources of varying stiffness and two virgin binders were used to produce mixes that contained 0%, 10%, 20%, and 40% RAP. The mechanical property tests were frequency sweep at constant height, simple shear at constant height, repeated shear at constant height, indirect tensile creep and strength, and beam fatigue tests. The frequency sweep at constant height tests were conducted at 0.01 Hz to 10 Hz, inducing a horizontal strain of 0.005%. The test temperatures employed were 4, 20, and 40°C in accordance with AASHTO TP 7-94. The simple shear at constant height tests were also conducted in accordance with AASHTO TP 7-94 using temperatures of 4, 20, and 40°C. The repeated shear at constant height was also run in accordance with AASHTO TP 7-94 at a test temperature of 58°C. Beam fatigue tests were conducted in accordance with AASHTO TP 8 at 400 and 800 microstrains. The results showed that mix stiffness increased and fatigue life decreases as RAP content increased. Based on these results it was recommended to use a softer virgin binder for high RAP contents to counteract the stiffening effect of the RAP binder. This became the basis of the tiered approach to adjusting the grade of the virgin binder based on the RAP content. NCHRP 09-12 also included an experiment to assess differences between plant- and laboratory-produced mixes. Three tests were used to compare the plant and laboratory mixes: frequency sweep, simple shear, and repeated shear at constant height. The evaluation of the mix tests performed on the laboratory-prepared mix and the plant mix indicated that the samples prepared in the laboratory are representative of plant conditions.

McDaniel et al. conducted a follow up study *(36)* to verify the conclusions from NCHRP 09-12 for materials in the northern Midwest. RAP from three states were used in the study. Laboratory prepared mixes were designed to yield a gradation similar to a plant sampled from each state. The percentages of RAP used varied by source. The Michigan RAP percentages were 0%, 25%, and 40%. The Missouri RAP percentages were 0%, 20%, and 50%. The Indiana RAP source percentages were 0%, 15%, and 50%. The intermediate RAP contents were selected based on the allowed RAP content for the given state. AASHTO TP 2-01 was followed when extracting and recovering the RAP binder. Standard Superpave performance grade testing was conducted on each recovered RAP binder. Asphalt contents and gradations were determined from aggregates recovered by both solvent extractions and the ignition method. The ignition method consistently resulted in higher asphalt contents; however, correction factors were not used. Three mix tests were used to evaluate the mixtures: frequency sweep, repeated shear, and simple shear at constant height tests. The frequency sweep at constant height test was conducted at a range of frequencies from 0.01 Hz to 10 Hz at two test temperatures: 20°C and 40°C. The simple shear at constant height test was conducted at the same test temperatures as the frequency sweep at constant height test and on the same specimens used for the frequency sweep. The repeated shear at constant height was run at 58°C for 5,000 cycles.

The linear binder blending charts recommended in NCHRP 09-12 were shown to be acceptable for the given materials when the recovered RAP binder was RTFO aged. The three-tiered binder recommendations from NCHRP 09-12 were validated for the three RAP sources evaluated. The Superpave binder classifications for the RAP sources evaluated were PG 70-XX, PG 76-XX, and PG 76-28. A complete grading for two of the RAP sources could not be determined due to a lack of material. The results of the recovered blended binders indicated that the high PG grade increased one grade for each of the three mixes containing RAP. The low PG grade changed to one grade warmer for Indiana RAP but did not change for the Michigan and Missouri RAP sources. The frequency sweep for the Indiana mixes resulted in stiffer G* values for the plant and 50% RAP mixes in comparison to the virgin and 15% RAP mixes. The frequency sweep data trends for the Michigan mixes were not consistent. The 40% RAP mix was the stiffest at 40°C, but one of the least stiff mixes at 20°C. Of the Michigan mixes, the virgin mix was consistently the least stiff mix at both temperatures. For the Missouri mixes, the 50% RAP mix was consistently the stiffest, and the virgin was the least stiff at both temperatures for the frequency sweep data. In general, the same results seen for the frequency sweep tests were seen for the simple shear tests. For the repeated shear tests conducted for the Missouri RAP source, as the RAP percentage increased, the shear strain decreased. However, the reverse occurred for the Michigan and Indiana RAP sources. In general, the frequency sweep and simple shear at constant height tests indicated that the mix stiffness increases with higher percentages of RAP. Results of the simple shear at constant height test were highly variable. The results of the repeated shear test indicated the mixes were not prone to rutting. Overall, the results of the study showed that Superpave mixes containing 40 to 50% RAP are feasible and can yield good performing mixes.

Lachance assessed the effects of RAP contents on volumetric properties and several mechanical properties *(37)*. The RAP contents were 0%, 15%, 25%, and 40%. A 19.0 mm mix design was used for all mixes, and the gradations were kept as close as possible. All materials were from New Hampshire, and the virgin binder was a PG 58-28. The analysis of volumetric properties showed that VMA and VFA increased at RAP contents of 25% and 40%. The 25% RAP mixture had a higher optimum asphalt content than the 40% RAP mix. The effect of RAP heating time on volumetric properties was also investigated. RAP for the 40% RAP mixes was heated for different lengths of time and then the volumetric properties compared. The heating times were 2, 3.5, and 8 hours at the mixing temperature (150°C -157°C). The RAP was mixed with virgin materials and compacted using the same compactive effort. Both the air voids and VMA were affected by the different heating times. The air voids increased with heating time. Initially, the VMA decreased from 2 hours to 3.5 hours of heating but then increased from 3.5 to 8 hours of heating. The difference in the VMA was attributed to the RAP particles heating up enough to allow for the particles to break apart and distribute better throughout the mix after 3.5 hours of heating.

The within-set variability of dynamic modulus results increased for 25% and 40% RAP contents. The creep compliance test was conducted at the same five temperatures as the dynamic modulus test, and a creep compliance master curve was also constructed for each mix. The creep compliance for 15% RAP resulted in expected values indicating that there was a decrease in compliance. The creep compliance values for 25% and 40% did not result in typical trends. The researchers attributed the differences to sample variability due to inconsistent RAP gradations since it was not fractionated. Uniaxial creep flow testing was conducted at 45°C with a stress of 600 kPa. The results for the 0% RAP specimens were variable. The variability may have been caused by specimens damaged during previous testing or by an improper load. The creep flow time, the time to reach the tertiary flow, increased for the 15% and 40% RAP mixes. The 25% RAP, which had the highest asphalt content, had a lower creep flow time.

A study from Taiwan evaluated the effects of RAP on binder properties and moisture susceptibility *(38)*. RAP was collected from pavements that were four, six, and ten years old. Binder recovered from these pavements was blended with a virgin binder (AC-10) at percentages 10% to 100%. Binder test results indicated that up to 20% RAP could be used without appreciably altering the virgin binder properties. The blended binders were then used in 30 mixes. One aggregate gradation was used for all 30 mixes. The mixes were tested for moisture susceptibility using AASHTO T 283. It was observed that increasing the RAP content negatively affected the indirect tensile strengths. The absorbed energy (area under the load-displacement curve in the tensile strength test) of conditioned and unconditioned specimens was also determined. The relative energy loss (much like the tensile strength ratio) was found to increase linearly as the RAP binder content increased.

Li et al. *(39)* evaluated ten mixes for low-temperature cracking resistance using the dynamic modulus test and the semi-circular bend (SCB) test. RAP was obtained from two Minnesota sources. Mixes were laboratory prepared with 0%, 20%, and 40% RAP, meeting Minnesota DOTs Superpave criteria. Results showed that the dynamic modulus values increased with increasing RAP percentages. RAP source was not a significant factor for the dynamic modulus at low temperatures; however, it did significantly affect dynamic modulus values at high temperatures. SCB testing was conducted in accordance with the procedure outlined in *(40)*. The fracture energy parameter was used to evaluate the effects of RAP content. The SCB results show that fracture energy decreased as RAP content increased. The control mixtures had the highest fracture energy. The 20% RAP mixtures had similar fracture resistance relative to the control mixtures. However, the mixes with 40% RAP content had significantly lower low-temperature fracture resistance.

Shu et al. *(***Error! Reference source not found.***)* conducted a study to compare several techniques for assessing fatigue properties of Marshall mixes that met Tennessee DOT specifications. Mixes containing 0%, 10%, 20%, or 30% RAP were evaluated. A target asphalt content of 5% was used for all mixes, and the virgin binder content was decreased based on the amount of binder contributed by the RAP. One binder was used, a PG 64-22. Testing included indirect tension (IDT) resilient modulus, IDT creep, IDT strength, and the beam fatigue test. All tests were conducted at 25°C. The IDT strength test was conducted to calculate the strength and toughness index. The minimum dissipated creep strain energy obtained from the IDT creep test and the dissipated creep strain energy threshold obtained from the IDT strength test was used to calculate the energy ratio for each mix. The beam fatigue test was conducted in strain controlled mode at 600 microstrains in accordance with AASHTO T 321. The ratio of dissipated energy change was used to evaluate the fatigue life of the mixes along with the traditional method of establishing failure at 50% reduction of the initial stiffness. It was found that the IDT strengths increased with RAP percentage, but toughness index decreased with increasing RAP percentage, indicating that the mixes became more brittle with greater quantities of RAP. The IDT resilient modulus results indicated the elastic component increased with increasing RAP quantities. However, the dissipated creep strain energy threshold decreased with increasing RAP percentages, which indicates the fatigue life of mixes is negatively affected by the addition of RAP. The energy ratio results also decreased with increasing amounts of RAP. A lower energy ratio means a mix is more likely to crack. However, the beam fatigue results indicated that the higher RAP contents were more resistant to fatigue. Higher plateau values of the ratio of dissipated energy change were observed for mixes containing higher RAP contents. The number of cycles to attain a 50% decrease in stiffness was also greater for the higher RAP percentage mixes than the virgin mix.

A Virginia study evaluated the rutting resistance of nineteen plant-produced asphalt mixtures with up to 25% RAP *(42)*. Dynamic modulus testing was used to characterize stiffness over a range of temperatures. Flow number tests were conducted at 54°C. Mixtures with 25% RAP were generally found to have similar dynamic moduli with the virgin mixtures. Virgin mixes and mixes with 25% RAP had lower flow number results. In general, mixtures containing moderate amounts of RAP (10% and 15%) had better FN results than virgin mixes and mixes with high RAP contents. A statistical analysis showed RAP amount was the most significant factor affecting rutting resistance in the mixtures studied. A linear inverse relationship between RAP and FN fit the data well. The effect of RAP on FN in this study was contrary to the generally expected results, as it showed the rutting resistance to decrease with increased RAP content. Results also showed that as RAP amount increased, there was a downward trend in both effective binder content and rutting parameter ($G^*/\sin\delta$). The authors suggested that the practice of using softer asphalt binders in mixtures with higher RAP contents and the observed decrease in effective asphalt content and $G^*/\sin\delta$ with the higher RAP content mixtures as possible reasons for the observed effect of RAP on flow number.

Hajj et al., at the Western Regional Superpave Center, conducted a study using Nevada mix designs with 0, 15, and 30 % RAP *(43)*. Laboratory mixtures were prepared with three sources of RAP and two binders: a PG 64-22 neat asphalt binder used in the bottom and middle lifts of pavements, and a PG 64-28NV polymer-modified binder used in the surface and underlying lifts of pavement. The "NV" indicated that the binder grading included the standard Superpave binder testing requirements plus additional properties of toughness, tenacity, and ductility on original and RTFO binder at 40°F. Beam fatigue tests were conducted according to AASHTO T 321 at 300, 500, and 700 microns (microstrain). Results showed that the fatigue resistances of polymer-modified mixes were significantly higher than mixtures with unmodified binders regardless of the RAP content. Polymer-modified mixes with 15% and 30% RAP had lower fatigue resistance compared to the virgin polymer-modified mixtures. However, the fatigue resistances of polymer-modified mixtures with 15% and 30% RAP were significantly better than the virgin mixes with neat binder. The authors concluded that RAP can be used in polymer-modified mixtures to offset the additional cost of the polymer while achieving significantly higher fatigue resistance than neat mixtures without RAP.

Mogawer et al. *(23)* evaluated the characteristics of plant-produced hot-mix asphalt (HMA) containing up to 40% RAP. Eighteen mixes (9.5 and 12.5-mm NMAS) were obtained from three contractors located in the Northeastern United States. One contractor used a PG 64-22 for four of the mixes and then adjusted the virgin binder to a PG 58-28 for the two highest RAP content mixes (for a total of six mixes) to evaluate the effect of using a softer virgin binder. Another contractor used a PG 64-28 for four mixes and adjusted to a PG 52-34 for all RAP contents for a total of eight mixes. The third contractor only used a PG 64-28 for its mixes. As part of the mix sampling process, production data were collected, including mixing and discharge temperatures, storage time, and plant type. These data were used to determine if changes in these parameters affected the properties of the RAP mixes. Test specimens were compacted at the plant and in the laboratory to study the effect of reheating the RAP mixes. Testing included extraction and recovery of the RAP mixes using the centrifuge extraction method described in AASHTO T164 Method A and the Abson recovery method described in AASHTO T170. The recovered binders were tested to determine their PG grades. The recovered asphalt binders were also tested in the bending beam rheometer (BBR) and direct tension test (DTT) to determine their low critical cracking temperatures (T_{crit}) according to AASHTO R49. Finally, the recovered binders were tested before and after long-term aging in the pressure-aging vessel (PAV) using the Asphalt Binder Cracking Device (ABCD), which also gives a value of T_{crit}.

Cracking resistance was measured using the Overlay Tester (OT) device at 15°C with a joint opening of 0.06-cm and failure criteria of 93% reduction from the initial load or 1,200 cycles. The OT measures the ability of a mix to resist crack propagation from bottom to top due to a predetermined displacement. The final result of the OT is a measure of cycles to failure. Moisture and rutting susceptibility were tested using the Hamburg Wheel Tracking Device (HWTD) at 50°C. The stripping inflection point (SIP) determined by plotting rut depth versus the number of wheel passes indicates when the mix specimen begins to experience stripping due to moisture damage. Workability of the mixes was measured using a device developed by the Massachusetts Dartmouth Highway Sustainability Research Center. The device measures the workability of an HMA mix using torque measurement principles.

Results from this study showed that it was important to document how RAP mixes are produced and handled, as differences in the recorded production parameters were shown to affect the degree of blending between RAP and virgin binders. Production parameters were also found to affect workability and mixture performance. Reheating of the mixtures was found to impact mixture stiffness compared to mixes that had test specimens compacted at the plant (i.e., not reheated). Reheated RAP mixes also showed decreased sensitivity to increasing RAP content when measured by $|E^*|$. Both the recovered binder and mixture stiffness testing showed that stiffness increased with increasing RAP content and that changing to a softer virgin binder decreased the overall stiffness. Recovered binder testing indicated differences in mix stiffness with increasing RAP content are more pronounced at higher temperatures than at low temperatures. At low temperatures, the ABCD device gave lower T_{crit} values for both the “as-extracted” and PAV-aged recovered binders than the AASHTO R49 procedure. Results for both procedures indicated that the use of a softer virgin binder may improve low temperature properties of the RAP mixes. The OT results showed decreased cracking resistance (lower number of cycles to failure) with increasing RAP content. This trend agrees with the results from both the low-temperature tests on the recovered asphalt binder, which also showed decreased T_{crit} with increasing RAP content. For one of the contractors, the use of a softer PG grade virgin binder did not improve the OT results. The other contractor's mixes did show improved cracking resistance using the softer PG virgin binder. Only one of the RAP mixes (30%) failed the moisture damage test in the HWTD. It was theorized that a low plant discharge temperature for this mix may have been the cause. Workability testing showed that the addition of RAP decreased mixture workability and that the use of a softer virgin binder could improve workability to levels comparable to the control mixes.

McDaniel et al. *(24)* studied the effect of RAP on the performance characteristics of plant-produced HMA mixtures. This study was a continuation of a previous, unpublished study and contained the results of that work as well. The goal of this research was to use the high and low temperature properties of plant-produced RAP to determine if the current tiered guidelines for RAP usage are valid. Plant-produced mixtures were used to include the effects of factors such as plant type, amount of mixing, mixing temperature, etc., all which may affect the amount of blending between RAP and virgin binders. Additional research included a comparison of two methods of extracting and recovering RAP binders and an investigation into the amount of blending that occurs during virgin and RAP binders during production. Four contractors supplied six HMA mixes designed to be as similar as possible (volumetrics, gradation, binder content, etc.). The mixes consisted of a control PG 64-22 mix with no RAP, three PG 64-22 mixes with increasing RAP contents (15, 25, and 40%), and two PG 58-28 mixes with high RAP contents (25 and 40%). The locally available PG 64-22 binder was chosen, along with the PG 58-28, as that was the PG grade required by the current RAP usage guidelines for mixes containing 15 to 25% RAP.

Asphalt binder testing included verification of performance grade of the virgin binders. In addition, frequency sweeps of binder complex shear modulus $|G^*|$ were conducted in the DSR at multiple temperatures for master curve construction. A comparison between the centrifuge extraction method (AASHTO T 164) with Abson recovery (AASHTO T 170) and the combined extraction / recovery procedure described in AASTHO T 319 was also conducted. The centrifuge extractions used methylene chloride (mCl) for the solvent, and the T 319 procedure used an n-propyl bromide (nPB) solution. After recovery, the RAP binders were tested for PG grade and DSR frequency sweeps. Mix testing included a verification of the volumetric properties and mixture dynamic modulus $|E^*|$ using AASHTO TP62. Low-temperature indirect tensile (IDT) creep (-20, -10, and 0°C) and strength (-10°C) testing was performed to measure the thermal cracking behavior of the mixes, and a procedure developed by Christiansen used to calculate a low critical cracking temperature, T_{crit}. Finally, samples from one contractor were sent to the FHWA Turner-Fairbank Highway Research Center (TFHRC) for testing utilizing a newly developed pull-pull fatigue test to study the effect of RAP content and virgin binder on the fatigue life of the mixes.

As expected, the binder testing showed increasing RAP content increased the high temperature properties of the recovered asphalt binders. The low critical temperatures of the recovered binders also increased with increasing RAP binder, but not as much as for the high critical temperatures. Changing the virgin binder to a PG 58-28 caused both the high- and low-temperature grades of the recovered binders to decrease. Overall, the changes in PG grade with increasing RAP contents were less than expected, particularly for the low-temperature grade. The comparison of the extraction / recovery methods did not show any clear pattern as to which might be better. The different methods appeared to affect different binder / RAP combinations differently. It was theorized that this may be due to the normal issues seen with solvent extractions.

Mixture stiffness $|E^*|$ increased with increasing RAP content in most cases, particularly at intermediate and high temperatures. This increase was not always statistically significant for the PG 64-22 mixtures, except at the 40% RAP level (not all of the 40% RAP results were significantly different from the control mix either). Switching from PG 64-22 to PG 58-28 resulted in a reduction in stiffness of the mixes. Also, in many cases, the $|E^*|$ values of the PG 58-28 mixtures were significantly higher at the higher RAP percentage than the lower, which indicated that the stiffening effect of the RAP binder was more significant for the softer virgin binder grade. The addition of RAP did not significantly change the cold-temperature properties for the PG 64-22 mixes containing up to 25% RAP. The 40% RAP PG 64-22 mixtures did show stiffer cold-temperature properties in some cases but were still determined to be acceptable compared to the control mixture. As with the high temperature properties, using the softer virgin binder grade significantly lowered the low-temperature stiffness of the mixes.

Fatigue properties of the RAP mixes did not meet conventional expectations. It was expected that increasing RAP content would decrease the fatigue life of the mixtures. The TFHRC testing did not show this. Mixtures with 40% RAP showed the greatest fatigue life in many cases. Changing to the softer virgin binder increased the fatigue life for the 25% RAP mixtures but did not have as great an effect on the 40% mixtures. The researchers reasoned that since the procedure used for this analysis was fairly new, additional research was needed.

A study by Zhao et al. *(44)* used laboratory performance tests to evaluate the effect of high percentages of RAP on warm-mix asphalt (WMA) mixtures. Rutting resistance, fatigue life, and moisture susceptibility were studied. Four WMA mixtures were designed using the Marshall mix design procedure with 0, 30, 40, and 50% RAP and a PG 64-22 virgin binder. In addition, two HMA control mixtures were designed with 0 and 30% RAP. Aggregate gradations and binder contents were kept similar for all the mixes. HMA and WMA were sampled at the plant, and the WMA specimens were compacted on site to avoid reheating and moisture loss. The HMA test specimens were compacted at a later time. Testing included rut depth in the Asphalt Pavement Analyzer at 50°C and moisture susceptibility using the Hamburg Wheel Tracking Device and AASHTO T 283 with one freeze thaw cycle. Fatigue cracking resistance was measured using the Indirect Tension (IDT) resilient modulus, IDT creep, and IDT tensile strength at 25°C and beam fatigue test at 7°C. The minimum dissipated creep strain energy ($DCSE_f$) from the IDT creep test and the dissipated creep strain energy threshold from the IDT strength test were used to calculate the energy ratio for each mix. The beam fatigue test used a strain level of 300 microstrains and a loading frequency of 10 Hz in accordance with AASHTO T321. From the beam fatigue test, a ratio of dissipated energy change and the number of cycles to 50% of initial stiffness were used to evaluate the fatigue life of the mixes. It was found that rutting resistance was improved by adding RAP to the mixes. The improvement for WMA was greater than that of the HMA mixes. $DCSE_f$ results from the IDT tests showed a slight reduction in the WMA fatigue life with the addition of RAP, but the dissipated energy ratio from the beam fatigue test indicated an improvement in fatigue life. Increasing the RAP content of the HMA mix did not show a significant effect on fatigue measured by either procedure. The number of cycles to 50% of initial stiffness in the beam fatigue device indicated that the addition of RAP increased the fatigue life of the WMA mixes but decreased the fatigue life of the HMA mixes.

Behnia et al. *(45)* conducted a study to assess the effect of RAP on the low-temperature fracture properties of HMA. In particular, the researchers wanted to evaluate the current practice of reducing the virgin binder grade to compensate for the increased stiffness of mixes with high RAP contents. The disk-shaped compact tension test, DC(T) as described in ASTM D7313-07b was chosen for this study because of its simple geometry and ease of specimen preparation. Four RAP sources from the state of Illinois were obtained and tested for binder properties and aggregate gradation using solvent extraction and recovery. A 19-mm NMAS mix was designed for each RAP source using 30% RAP by weight of total mixture and a target asphalt content of 5.9%. The mix designs used a PG 64-22and a PG 58-28. In addition to the RAP mixes, virgin mix designs were also created using the PG 58-28 and PG 64-22 binders. Fracture energy at -12°C was measured for each of the mixes. It was found that there was a significant decrease in fracture energy when 30% RAP was added to the virgin PG 58-28 mix. The virgin PG 58-28 mix test specimens had fracture energy values of approximately 2,000 J/mm^2 while the 30% RAP test specimens had fracture energy values ranging from 540 to 680 J/mm^2. When compared to the virgin PG 64-22 mix fracture energy, the 30% RAP mixes with PG 58-28 were found to have an improvement in fracture energy of around 50%. These findings indicated the RAP mixes with the softer virgin binder had acceptable low-temperature fracture properties compared to the PG 64-22 mix without RAP and that adjusting the virgin binder grade one grade softer was adequate for these materials.

Daniel et al. *(46)* studied the effect of RAP on the extracted asphalt binder properties of plant-produced mixtures. A total of 28 plant-produced HMA mixes were sampled from seven mix plants. The sampled mixes had RAP contents ranging from 0 to 25% and virgin binder grades ranging from a PG 58-34 to a PG 70-22. The percentage of RAP binder replacement (the percentage of the total binder content of the mix taken up by the RAP binder) was calculated for each mix based on the binder content of the RAP and the target total binder content for the mix. This value was referred to as the total reused binder (TRB) and served as a way to normalize the mixes with respect to the different binder contents of the RAP sources and mixes. Extraction and recovery testing was done on the HMA mixes and RAP materials at two separate laboratories. Both laboratories used the centrifuge extraction procedure (AASHTO T176 Method A) and Abson recovery (AASHTO T170) with trichloroethylene as the solvent. Recovered binder samples were tested to determine their performance grade (PG) according to AASHTO M320 and critical cracking temperatures using AASHTO PP-42. The PG grades of the virgin binders were also determined. The findings from the research showed the high-temperature PG grade of the HMA mixes either remained the same or increased by one grade with the addition of up to 25% RAP. The low-temperature PG grades also either stayed the same or changed only one grade. It was noted that even when the low PG grade changed, the actual continuous low-temperature grade only changed by a few degrees. Some of the mixes showed improved low-temperature grades while others showed a decrease in low-temperature grade. Critical cracking temperatures indicated an improvement in thermal cracking performance with increased RAP binder. It was recommended that the TRB value be used to normalize mixtures with respect to asphalt binder properties, as this was a more accurate representation of the amount of RAP binder in the mix than the bulk RAP percentage.

Hajj et al. *(47)* performed a study to evaluate the impact of high RAP content on moisture damage and thermal cracking using Marshall mixes sampled from a project in Manitoba, Canada. The mixes were designed using three RAP contents (0, 15, and 50%). A PG 58-28 binder was used for all the mixes. An additional 50% RAP mix was made using a PG 52-34 virgin binder. All the mixes were designed to have similar gradations and binder contents and were produced at the same plant. In addition to the plant-produced mix, raw materials were collected so that differences between plant mix and laboratory-compacted test specimens could be evaluated. Laboratory test specimens were aged for 4 hours at 275°C prior to compaction while the plant-produced specimens were compacted without additional aging. Testing included extraction and recovery on all of the mixes (plant and laboratory) using the centrifuge extraction method (AASHTO T176 Method A) and rotary evaporator recovery (ASTM D5404). The solvent used was a toluene and ethanol blend. The virgin and recovered asphalt binders were tested to determine their continuous grade temperatures and PG grades according to AASHTO M 320. Compacted mix specimens were subjected to either 0, 1, or 3 freeze thaw cycles and then tested to determine their resistance to moisture damage using the tensile strength ratio (TSR) method described in AASHTO T 283. In addition to TSR, conditioned samples were also tested according to AASHTO TP 62 to assess changes in mixture dynamic modulus, $|E^*|$, due to moisture conditioning. Finally, conditioned test specimens were tested using the Thermal Stress Restrained Specimen Test (TSRST) described in AASHTO TP 10. The TSRST cools a 2”×2”×10” restrained beam of mix at a rate of 10°C/hr and records the temperature and stress at which fracture occurs. The researchers found that at 0 and 15% RAP, the recovered binders met the project binder grade requirement of PG 58-28. The 50% RAP met the high-temperature grade requirement but did not meet the low-temperature requirement, even with the softer virgin binder. Plant-produced test specimens were found to be stiffer in most cases than the laboratory-produced specimens, although overall moisture damage trends and ranking were similar for all the tests performed. In general, the 50% RAP mixes had acceptable resistance to moisture damage. Moisture damage resistance improved with the use of the softer virgin binder. Mix stiffness in the dynamic modulus test increased with increasing RAP content and decreased with decreasing virgin binder stiffness. Dynamic modulus values also decreased with increasing number of freeze-thaw cycles, with the no freeze-thaw condition being the stiffest and the three freeze-thaw cycles being the least stiff. The TSRST results showed no further reduction in fracture stress for the conditioned specimens with increasing RAP content. The TSRST fracture temperatures for the 0 and 15% RAP content specimens were very similar to the virgin binder low critical temperature. The 50% RAP content specimens had TSRST fracture temperatures several degrees warmer than the virgin binder, indicating decreased thermal cracking resistance. Using a softer virgin binder improved the TSRST fracture temperature for the 50% RAP mix. Monitoring of the project site after 13 months of service showed no pavement distresses for any of the mixes evaluated at that time.

Two papers documented testing of moderate and high RAP content surface mixes constructed on the NCAT Test Track in 2009 *(48).* Laboratory tests included APA rutting tests, dynamic modulus, bending beam fatigue, and energy ratio. The APA results corresponded to the effective stiffness of the binder in the mixes. Master curves of dynamic moduli showed the expected effects of the virgin binder grade on the stiffness of the mixtures. Beam fatigue tests indicated that the 45% RAP mixes had lower fatigue lives compared to the 20% RAP mixes, but the authors attributed this to lower effective volumes of asphalt in these mixes.

Two recent laboratory studies at NCAT *(49, 50)* examined several possible ways to improve the durability and cracking resistance of high RAP content mixes. Willis et al. *(49)* evaluated two ways to improve durability of high RAP content mixes. The first approach was simply to increase the asphalt content of the mixes by 0.25% and 0.5%. The second approach was to use a softer virgin binder grade. The study began with 9.5 mm NMAS Superpave mixes designed with 0, 25, and 50% RAP. The initial designs were completed with a PG 67-22 binder. The 25 and 50% RAP mixes were both adjusted by increasing the design binder contents by 0.25% and 0.5%. The original mix designs were also changed by substituting the PG 67-22 virgin binder grade with a PG 58-28. The Energy Ratio test was used to evaluate the mix designs' resistance to top-down cracking. The Overlay Tester was used to assess resistance to reflection cracking, but using a reduced displacement from the Texas standard. Rutting potential was evaluated with the APA. Physically blended binders were evaluated for fatigue resistance using the Linear Amplitude Sweep (LAS test). Results showed that the Energy Ratio decreased (became worse) for the RAP mixes with added virgin binder and when the softer virgin binder grade was used. However, fracture energy did improve for the 25% and 50% RAP mixes when a PG 58-28 binder was used. Overlay Tester results for the 25% RAP mixes significantly improved when the softer virgin binder was used. The average Overlay Tester results for the 50%

RAP mixes with the PG 58-28 virgin binder also improved by three times compared to those with the PG 67-22 binder, but the results were not statistically significant due to the high variability with this test. The APA results for the 25% RAP mix containing the PG58-28 were just above the criteria established for high traffic mixes based on NCAT Test Track results. All other mixes met the NCAT's recommended APA criteria. The LAS testing also indicated that the softer virgin binder improved the fatigue resistance of the composite binder.

The second NCAT study used a rejuvenating agent, Cyclogen L, to restore the performance grade properties of recycled binders. The study evaluated the effect of the rejuvenator on two mixes, one containing 50% RAP, and the other containing 20% RAP and 5% recycled asphalt shingles. A virgin control mix was also included in the experiment. The first part of the study determined that the optimum amount of rejuvenator was 12% of the recycled binder content. This percentage of rejuvenator was needed to restore the properties of the recycled binder to those of the PG 67-22 binder used as the virgin binder for the mix designs. The mix designs with and without the rejuvenator were tested for resistance to moisture damage using AASHTO T 283, rutting with the APA, dynamic modulus after short-term and long-term aging, resistance to top-down cracking using the Energy Ratio procedure, resistance to reflection cracking using the modified Overlay Tester procedure, and resistance to thermal cracking using the IDT creep compliance and strength tests. The results of the mix tests showed that the rejuvenator reduced the mix stiffness, improved all four fracture properties included in the Energy Ratio computation, improved the low-temperature critical cracking temperature. Overlay Tester results also improved for the mixes that included the rejuvenator, but the improvement was not statistically significant due to the poor repeatability of the test. All mixes passed the APA criteria for high traffic pavements. A cost analysis indicated that using the rejuvenator with high recycled binder content mixes is beneficial.

Field Performance of Mixes Containing RAP

This section summarizes studies that have documented and analyzed the field performance of asphalt pavements containing RAP.

Paul *(51)* conducted a study to examine the performance of five early projects containing up to 50% RAP in Louisiana built between 1978 and 1981. The report noted that variations of the recycled mixes during production were similar to those of conventional HMA for all acceptance testing, including gradation, asphalt content, Marshall properties and roadway density. At the time of the report, the oldest project was nine years old and the other four projects were six years old. Analysis included assessment of structural integrity, serviceability index, and a distress type and severity rating. Also, materials from each roadway were sampled to determine mix densification and the asphalt binder quality as measured by absolute viscosity, penetration, and ductility. The study concluded that there was no significant difference between the recycled and control pavements evaluated. The recycled pavements did exhibit slightly more distress with respect to longitudinal cracking.

In 1981, the Arizona Department of Transportation constructed an experimental asphalt concrete overlay project on Interstate 8 in Arizona. The project consisted of eight test sections comparing long-term performance of recycled and virgin asphalt concrete overlays in an arid climate *(52)*. The recycled overlays contained 50% RAP and used a softer grade of virgin binder compared to the virgin mix sections. Roughness, skid number, and cracking data were collected on the test sections over the service life of the project. A visual distress survey was conducted on each section at the end of service life. Performance data through nine years of service indicated that the recycled and virgin asphalt concrete overlays performed similarly.

Five Georgia pavements containing between 10 and 25% RAP were evaluated for up to 2.25 years and compared to virgin HMA sections by Kandhal et al. *(10)*. At the end of the monitoring period, the RAP sections were performing as well as the virgin mix sections. Binder and mix properties at the time of construction were determined. Superpave binder testing and the penetration test were conducted to evaluate the binder properties. The mix properties obtained were air void content, resilient modulus, indirect tensile strength, and confined dynamic creep modulus. The confined dynamic creep modulus results for the RAP and virgin mixes were not statistically significant. The indirect tensile strengths for the virgin mixes were typically greater than those for the RAP mixes.

Eighteen test projects were built across North America as part of Specific Pavement Study 5 (SPS-5) in the Long Term Pavement Performance (LTPP) program. One of the main experimental variables in this study was virgin mix versus mixes containing 30% RAP. The projects were built between 1989 and 1998. West et al. *(53)* examined seven distress parameters from these test pavements, including International Roughness Index (IRI), rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling. Statistical analyses compared the performance of the virgin mix sections directly to companion test sections containing 30% RAP. Overlays using mixes containing 30 % RAP were found to perform as well as overlays with virgin mixes in terms of IRI, rutting, block cracking, and raveling. About a third of the projects had more longitudinal cracking or transverse cracking in the overlays containing RAP compared to the virgin mix overlays.

Carvalho et al. *(54)* analyzed the data from the same LTPP SPS-5 projects using repeated measures analysis of variance and concluded that in the majority of scenarios, RAP mixes performed statistically equivalent to virgin HMA mixes. Analysis of deflections from falling-weight deflectometer tests also indicated that the RAP overlays provide structural improvement equivalent to virgin HMA overlays.

Another study used the data from SPS-5 experiments to conduct a parametric survival analysis to determine the influence of different factors on the initiation of cracking *(55)*. The initiation time for four types of cracks, including the alligator (fatigue) cracks, longitudinal wheel path cracks, non-wheel path longitudinal cracks, and transverse cracks were evaluated. Analyzed factors include overlay thickness, traffic volume, freeze index, mixture type (RAP or virgin) and mill (or no mill) before the overlay. Traffic level was a significant factor for all of the four types of cracks. High traffic levels accelerated the initiation of cracking. Incorporating 30% RAP in the overlay accelerated the initiation of longitudinal cracks in the wheel path, but did not influence the initiation of the other three types of cracking.

Performance of the Texas SPS-5 experimental sections from the LTPP program were analyzed by Hong et al. *(56)* based on about 16 years of data. The test sections containing 35% RAP were compared to the virgin sections in the Texas field project. Comparisons were made with regard to ride quality, transverse cracking, and rutting. The test sections containing RAP had a higher amount of cracking, less rutting, and similar roughness change over time. The overall evaluation revealed that a well-designed mix with 35% RAP could perform as satisfactorily as that produced with virgin materials.

Aguiar-Moya et al. *(57)* also examined the LTPP SPS-5 data from Texas and developed simple performance models for rutting and cracking. The models were used to statistically quantify the effect of RAP on each type of distress and to estimate the expected pavement life of a given overlay. The analyses indicated that there was better rutting resistance when the mixes contained RAP. However, pavements containing RAP developed cracking earlier and at a faster rate. LCCA analysis was performed to compare the economic advantages or disadvantages of using RAP in HMA. The interim results indicated that, under particular scenarios, the use of RAP may not be the most economic choice. The authors recommended that the use of RAP and the percentage of RAP should be determined on a case-by-case analysis.

Maupin et al. *(58)* documented the construction and performance of ten Virginia projects that used mixes containing more than 20% RAP constructed in 2007. A PG 64-22 grade was used for all ten mixes. When possible, control mixes that contained low to no RAP were collected for comparison. No issues were encountered during construction of the projects with the RAP mixes. Beam fatigue tests were conducted in accordance with AASHTO T 321 using a range of strains to determine the fatigue endurance limit. An Asphalt Pavement Analyzer was used to evaluate the rutting susceptibility of the mixes, and moisture susceptibility was evaluated using AASHTO T 283. The results of the mix tests indicated no significant difference between the RAP mixes and the control mixes.

Anderson *(59)* examined the long-term performance data for high RAP content pavement sections from eight states and one Canadian province. The pavements had been in service for more than 10 years and contained at least 20% RAP, and in some cases, contained much higher RAP contents. In each of the case studies, the sections containing RAP were compared to similar pavements built with virgin materials using data obtained by the state highway agency. A field project in Wyoming included sections with 0 to 45% RAP monitored over 12 years. The virgin section started out with a better ride quality and serviceability index and generally maintained a slight edge on performance throughout the evaluation period. Rates of change for pavement condition and ride quality were similar for the different sections. Two high RAP projects in Washington state had comparable performance ratings with other pavements in the state. Pavement maintenance information in Colorado was used to compare a 21-year-old high RAP project to other projects with similar climate and traffic. Anderson summarized that pavements using high RAP contents perform at a comparable level to pavements with virgin materials. On average, the high RAP content sections tended to have more cracking and rutting, but the differences were generally not great enough to substantially affect the long-term performance.

Zaghloul and Holland *(60)* evaluated the long-term performance of 47 pavement sections containing up to 15% RAP in three California environmental zones: desert, mountain, and north coast. Comparisons were made between the performance of the RAP sections and other treatments located within a reasonable distance on the same route. Deterioration models were developed and used to estimate the in-situ structural capacity, distress condition, and roughness condition for all sections at five years of age to normalize comparisons. Service lives were estimated for all treatments based on the field-observed conditions. The results of the analyses indicated that in all three environmental zones, the long-term performance of sections containing RAP appeared to be comparable to other treatments located within a reasonable distance on the same route.

NCAT reported on the construction and performance of test sections containing moderate and high RAP contents at the NCAT Test Track *(48)*. Two test sections built in 2006 included mixes with 20% RAP and four sections used mixes containing 45% RAP. Each mixture contained the same component aggregates and RAP. One of the 20% RAP mixes contained PG 67-22 binder, and the other contained PG 76-22 binder. Different binders in the 45% RAP mixes included PG 52-28, PG 67-22, PG 76-22, and PG 76-22 plus 1.5% Sasobit. All the mixes were placed 2 inches thick as surface layers. Performance of the test sections has been very good. After five years of heavy traffic (over 20 million ESALs), all sections had less than 5 mm of rutting. Changes in surface texture of the test sections were generally consistent with normal wear, but there was a discernible difference with slightly more texture change (an indicator of raveling) associated with stiffer virgin binders. Low-severity cracking was documented in all the sections except for the section containing 20% RAP and PG 67-22 binder. The amount of cracking was also consistent with the virgin binder grade in the RAP sections. The 45% RAP section containing the softest virgin binder had only 3.5 feet of very low-severity cracking. The 45% RAP section with PG 67-22 binder had a total of 13.9 feet of cracking, the 45% RAP section with PG 76-22 had 53.9 feet of crack length, and the 45% RAP section with PG 76-22 and Sasobit had 145.5 feet of total crack length. This led the authors to recommend using a softer virgin binder grade for high RAP content mixes.

In 2009, additional high RAP content test sections were constructed and tested on the NCAT facility. The Mississippi DOT sponsored a section using 45% RAP in the surface and binder layer.

The RAP, gravel, and sand used in the mix designs were from Mississippi. At the end of the 25-month trafficking cycle, the Mississippi test section had only 3 mm of rutting and 61 feet of low-severity cracking. That was slightly better than the performance of the polymer-modified, 15% RAP mix sponsored by the Mississippi DOT in the previous cycle of the NCAT test track.

Another pair of test sections built in 2009 contained 50% RAP in each of the three layers of the 7-inch asphalt pavement structure. One of the 50% RAP sections used a water-injection asphalt foaming process to produce the mixes as WMA. The 50% RAP-HMA and 50% RAP-WMA sections were compared to a virgin mix control section built to the same thickness. Both sections used unmodified PG 67-22 binder, whereas the control section contained all-virgin materials and polymer-modified PG 76-22 binder in the top two layers. These three sections were instrumented with stain gauges at the bottom of the asphalt layers. Pressure plates and temperature probes were also installed in the sections to measure how the sections responded to loads and environmental conditions throughout the cycle. At the end of the cycle, with more than 10 million ESALs applied, all sections had no distresses. The 50% RAP sections had less rutting than the control section. The increased stiffness of the high-RAP mixes resulted in significantly lower critical tensile strains and subgrade pressures relative to the control.

Summary of the Literature Review

RAP Management

RAP management practices vary considerably among asphalt mix producers. Some differences are due to different policies and requirements established by state DOTs. For example, a few states tend to have restrictive RAP practices, such as allowing only RAP from single DOT projects to be used in state mix designs. Some agencies often take ownership of milled materials from rehabilitation projects and then tend to use the material in low-value applications such as equipment yards. Most state highway agencies, however, use a more contractor-friendly approach to RAP by including ownership of the reclaimed pavement as part of the milling operation.

Many contractors collect RAP from a variety of sources into a large stockpile that must be processed to make a RAP material suitable for use in new mix designs. Numerous studies have shown that processing of such multi-source RAP can be made into a consistent material. However, some references recommend that RAP from different sources not be combined.

One common problem with RAP stockpiles is contamination. Contaminants can include dirt, plant material, road debris (tires, crack sealant), paving fabric, tar-sealed pavement, fuel-contaminated mix, and general construction waste. Contamination can occur with single-source RAP stockpiles, but tends to be more prevalent with multiple-source stockpiles.

General methods of RAP processing are shown in Table 6. A common mistake in RAP processing is to crush all RAP to pass a single screen size (e.g., minus ½ inch) so that the RAP can be used in mixes with a range of nominal maximum aggregate sizes. This single-size crushing approach often leads to generating high dust contents, which can limit the amount of the RAP that can be successfully used in mix designs.

Table 6 General Methods of RAP Processing

Type	Description	Suitable Conditions	Possible Concerns
Minimal Processing	Screening only to remove oversized particles (may be accomplished in-line during feed of RAP to the plant)	RAP is from a single source	Single source RAP piles are a finite quantity. When a stockpile is depleted, new mix designs will be needed with another RAP stockpile
Crushing	Breaking of RAP chunks, agglomerations, and or aggregate particles in order to avoid large particles that not break apart during mixing or particles that exceed the mix's NMAS	RAP contains large chunks (anything larger than 2") or RAP aggregate NMAS exceeds the recycled mix's NMAS	Generating excess dust and uncoated surfaces
Mixing	Using a loader or excavator to blend RAP from different sources. Usually done in combination with crushing or fractionating	RAP stockpile contains materials from multiple sources	Good consistency of RAP characteristics must be verified with a RAP QC plan.
Fractionating	Screening RAP into multiple size ranges	High RAP content mixes (above 30 to 40%) are routine	Highest cost, requires additional RAP bin(s) to simultaneously feed multiple fractions

Regardless of the method of processing, the RAP stockpile should be sampled and tested on a routine basis to verify uniformity. A sampling and testing frequency of one per 1,000 tons is recommended.

RAP should be stockpiled such that its moisture content and segregation are minimized. Large conical stockpiles are commonly used for convenience, and they may tend to help shed precipitation, but they are more prone to segregation. Covering stockpiles and placing them on a sloped surface to drain water away from the side used to feed the plant can help reduce moisture contents. Bunkers (two- or three-walled partitions) can help reduce segregation.

The fundamental goal of RAP management should be to optimize the dollar value of the RAP, which suggests spending less money in order to use more RAP without sacrificing mix quality or consistency.

RAP Characterization

In order to use the RAP in a mix design, several basic properties must be determined. The RAP aggregate properties needed are gradation, consensus properties, and bulk specific gravity. Some highway agencies may also require that source properties such as soundness, abrasion resistance, or polishing or mineralogical characteristics be determined if the RAP is intended for use in certain mix types. Most references recommend recovering RAP aggregates using either a solvent extraction procedure or the ignition method in order to determine the necessary properties.

For high RAP content mixes (more than 25% by weight of mix), most guidelines recommend recovering the RAP binder using a solvent extraction and recovery procedure, then determining the true or continuous grade of the binder in accordance with Superpave binder-grading procedures. However, since the RAP binder is already aged, it is not necessary to age the recovered binder in the rolling thin-film oven or the pressure-aging vessel before determining intermediate- and low-temperature properties.

Several recent studies have explored methods to determine properties of RAP binders without having to use risky solvents to extract and recover the RAP binder. Most of the studies have evaluated advanced characterization tests on mixture samples to backcalculate or estimate the properties of the RAP binder. These methods do not appear to have been proven reliable at this time.

Mix Design

Highway agencies typically require mixes containing RAP to meet the same mix design standards as mixes with all virgin materials. Maximum RAP contents allowed by specification vary considerably from state to state. States typically allow higher RAP contents in non-surface layers. Considering the cost advantages of using RAP, it is assumed that mix designers will try to use as much RAP as possible given the constraints of specification limits, RAP availability, plant limitations, etc.

Although the methods for handling and batching RAP in the lab for mix designs should be slightly different than for mixes containing only virgin materials, clear guidance is not provided in current standards. Since RAP has been used in mix designs for decades, actual practices for handling RAP in the lab are most likely learned through experience. Drying and heating RAP materials for preparing samples to perform characterization tests and mix designs can affect the test results. Calculations associated with preparing RAP for lab tests, mix design batches, and determining volumetric properties should be documented and reviewed in mix design training classes.

One key issue still frequently debated is how much blending or comingling occurs between the RAP binder and the virgin binder. Most recent studies clearly indicate that significant blending does occur in most cases. This issue impacts the selection of the virgin binder for high RAP content mixes. The current standard recommends using blending charts or blending equations to estimate the properties of the composite binder based on the proportions and critical temperature of recycled and virgin binders. This approach assumes complete blending and can be used to either select the grade of virgin binder needed to meet the desired properties of the composite binder, or the percentage of recycled binder that can be used with a given virgin binder to meet the composite binder's desired properties.

Mechanical Testing

In current practice, no additional testing is required for mixes containing RAP. Moisture damage susceptibility tests are generally required of most asphalt mix designs, regardless of RAP content. However, researchers have used a variety of tests to evaluate RAP mixtures for resistance to several other forms of pavement distress. Most research that has assessed the impact of RAP on rutting resistance has indicated improved properties for higher RAP content mixes. General measures of stiffness also increased for higher RAP contents. A few studies indicated that RAP had a greater impact on stiffness at high and intermediate temperatures and less of an impact at low temperatures. Most studies that evaluated resistance to cracking indicated RAP mixtures had reduced fatigue life or more brittle behavior. A few studies, however, yielded contradictory results and showed that moderate to high RAP content mixes had greater fatigue life. With regard to low-temperature properties and thermal cracking resistance, mixes containing RAP were generally more susceptible to cracking. Several studies that also examined the effect of using a softer virgin binder with high RAP content mixes found that mix stiffness decreased and fatigue and thermal cracking resistance improved.

In-Service Performance

Numerous studies of in-service pavements containing up to 50% RAP have shown that high RAP content mixtures can provide performance similar to virgin mixes. Good performance with high RAP content mixes has been reported in projects with diverse climates and traffic. Several researchers used the extensive Long-Term Pavement Performance data set to analyze experimental sections built across North America to evaluate RAP mixes compared to virgin mixes. These studies show that overlays containing approximately 30% RAP were performing equal to or better than virgin mixes for most measures of pavement performance. Overall, the recycled mixes in the LTPP experiment did have more wheelpath cracking. That was consistent with observations from other reports. However, in most cases, the extent of cracking for pavements containing high RAP content was acceptable.

Two important findings have emerged from research with high RAP content mixes at the NCAT test track. First, using a softer grade of virgin binder does appear to improve the durability of surface mixes, providing an advantage for better cracking resistance and resistance to raveling. Second, the increased stiffness of high RAP content mixes can be an advantage in structural design by reducing the critical strains in the pavement structure.

CHAPTER 2 RESEARCH PLAN

As described in Chapter 1, this project was conducted in three parts. Part I involved surveying current practices for RAP management, collecting data on RAP stockpile testing, and discussing lessons learned with contractors. Analysis of that information led to the development of the "Best Practices for RAP Management" document and an associated webinar. Part II focused on answering several seemingly simple questions about testing methods for characterizing RAP materials and preparation of materials for mix designs containing RAP. Preliminary laboratory experiments were conducted to evaluate optional methods for characterizing RAP or RAP components. Preliminary experiments were also conducted to evaluate different methods of drying and heating RAP as part of sample preparation. Part III involved evaluating a series of mix designs using sets of materials from the four states. The mix designs were prepared in accordance with AAHTO R35 and M 323 with a few exceptions to be described later. A series of performance tests were conducted on the mix designs to assess their resistance to the major forms of pavement distress.

Part II Preliminary Experiments

RAP Drying Experiment

The first preliminary experiment was conducted to determine the best method to dry samples of RAP obtained from stockpiles. It is common for field samples of RAP to have moisture contents of 5% or more. It is important for that moisture to be removed before characterization tests and before using the RAP in preparation of specimen batches for mix designs.

For the RAP drying experiment, a large sample of RAP from a local plant was obtained and fan-dried in the lab to a constant mass over several days. The sample was then split into four portions of about 24 kg each. Water was added to each portion to obtain a known moisture content of about 5.3%. Two portions were then dried in an oven set at 110°C (230°F), and two samples were fan-dried in the laboratory at ambient temperature. Each sample was weighed periodically to develop a drying curve. After all the moisture was dried from the samples, the binder was recovered from the samples to determine if the drying procedures had affected its PG true grade.

RAP Heating Experiment

The first part of the RAP heating experiment was a simple test to determine how much time is needed for a sample of RAP to reach the set point temperature for mixing. In this experiment, a typical forced-draft oven was set to 182°C (360°F). Ambient temperature RAP samples were placed in the oven and monitored to determine when the samples reached the oven set point temperature. Three samples, 2500 grams each, were put in the oven at different times of the day. A heating curve was developed for the oven and sample size.

The second part of the heating experiment was conducted to evaluate how different methods of heating RAP may affect the characteristics of the RAP binder. A 50/50 blend of virgin aggregate and RAP was prepared using four heating scenarios:

1. RAP and virgin aggregate were heated together for three hours at 179°C (355°F).
2. RAP and virgin aggregate were heated together for 16 hours at 179°C.
3. Virgin aggregate was heated in an oven at 179°C for 3 hours, and the RAP was heated in an oven at 179°C for 30 minutes.
4. Virgin aggregate was superheated to 260°C (500°F) for three minutes, and the RAP was left unheated at ambient laboratory temperature.

Immediately following each heating scenario, the virgin aggregate and RAP were combined and dry mixed, without additional binder, for two minutes. Following mixing, the materials were cooled, then the binder was extracted in accordance with AASHTO T 164 using trichloroethylene and recovered using the rotary evaporator apparatus in accordance with ASTM D 6847. The recovered binder was then graded in accordance with AASHTO R 29 and compared to the performance grade for the RAP binder before heating.

The RAP used in this experiment was obtained from a local contractor's stockpile. Four samples taken from around the stockpile were tested to determine the asphalt content and PG grade of the RAP binder. The average asphalt content was 4.9%, and the average true grade of the RAP binder was 85.1 -15.7. The virgin aggregate used in this experiment was a hard limestone from Calera, AL.

RAP Aggregate Bulk Specific Gravity Experiment

The third experiment was conducted to determine which method should be used for determining the bulk specific gravity of the RAP aggregate. Concurrent to this NCHRP project, NCAT was participating in a joint study with the University of Nevada-Reno to evaluate different options for recovering RAP aggregate for determining a wide range of aggregate properties. A key part of that study involved assessing different methods for determining the RAP aggregate bulk specific gravity.

In that experiment, the RAP aggregate bulk specific gravity values were determined using three approaches:

1. The RAP aggregate was recovered from the centrifuge extraction procedure using trichloroethylene then tested in accordance with AASHTO T84 and/or T85, for fine and coarse aggregate portions, respectively.
2. The RAP aggregate was recovered from the ignition method then tested in accordance with AASHTO T84 and/or T85, for fine and coarse aggregate portions, respectively.
3. The G_{mm} of the as-received RAP was determined in accordance with AASHTO T 209, and the asphalt content of the RAP was determined by the ignition method without an aggregate correction factor. The G_{mm} value and the average asphalt content of the RAP were used calculate the effective specific gravity of the RAP aggregate, G_{se}. The RAP aggregate G_{sb} was then calculated using equation 2.

$$G_{sb}(RAP) = \frac{G_{se(RAP)}}{\frac{P_{ba} \times G_{se\ (RAP)}}{100 \times G_b} + 1} \qquad [2]$$

Since the absorbed asphalt content, P_{ba}, for the RAP was unknown, it was estimated from virgin mix designs from the same locations as the RAP. This approach was described in NCHRP report 452 *(4)*.

Part III High RAP Content Mix Design and Performance Testing

An experimental plan was developed to try to answer five key questions regarding high RAP content mix designs:

1. Are volumetrics affected by a change in the virgin binder grade?
2. Can the compatibility of RAP and virgin binders be assessed in mix design?
3. Do lower mixing temperatures associated with warm mix asphalt technologies affect RAP and virgin binder blending?
4. Can the composite binder (blended or partially blended RAP and virgin binder) be characterized using an indirect method that is based on dynamic modulus of the mix?
5. What do laboratory performance test results tell us about the mix designs with high RAP contents?

Numerous studies have demonstrated that volumetric properties of asphalt mixtures compacted in a fixed-angle (and therefore, a fixed shear strain) Superpave gyratory compactor are rather insensitive to compaction temperature or binder stiffness. Since high RAP content mixes often use a softer grade of virgin binder, it is important to know if the virgin binder grade affects volumetric properties and mix performance test results.

The second question has to do with compatibility of the RAP and virgin binder. Some cases of poor performance of mixes containing RAP have been attributed to incompatibility of the RAP binder and the virgin binder and/or recycling agent. This issue was examined by conducting mix designs using binders of the same performance grade but from different sources. It was assumed if the RAP and virgin binders are not compatible, there would be little or no blending. Although binder incompatibility may not be apparent with volumetric properties, it should be evident in mixture performance tests.

The use of warm mix asphalt has increased dramatically in the past few years and is expected to become the norm for mix production within five years. Some questions have been raised about the possibility that lower mixing temperatures for WMA may not sufficiently activate an aged RAP binder. To address this concern, a mix design with a high RAP content was designed with and without a popular WMA additive. The mixing temperature for the WMA was decreased by 35°F. The differences in mix volumetric properties and performance properties were examined to determine if the lower mixing temperature had an effect.

An important research need was to determine the validity of estimating composite binder properties from dynamic modulus tests. If this technique could be proven, then it would help resolve issues about the degree of blending of virgin and recycled binders, compatibility of binders, and how to best select the appropriate grade of virgin binder. Accordingly, all the mix designs in this study were tested to determine the dynamic moduli in accordance with the recommended standards available at the time the project began. A considerable effort was devoted in this study to the process of back-calculating binder properties from the dynamic modulus data and to comparing those results to known binder properties.

Over the past decade it has become more apparent that the process of designing asphalt mixes needs to move beyond analysis of basic volumetric properties and begin to utilize mechanical property tests that can help us better understand how materials such as RAP, polymers, shingles, fibers, etc. may impact field performance. A few performance tests, such as the Asphalt Pavement Analyzer and Hamburg wheel tracking test, have recently moved out of the research arena and into more routine use for evaluating mix designs. The next generation of mechanical tests, which are more fundamentally sound in engineering principles, are quickly being vetted and refined. One of the challenges established by the research panel for this project was to recommend mixture performance tests to use in evaluating high RAP content mixes for resistance to major forms of pavement distress. This was a daunting task given the numerous tests that have been recommended by numerous researchers for each pavement distress. In the end, the primary factors in deciding which tests to use for this study were 1) what tests appeared to be simple and practical for potential implementation, 2) what tests/properties had some established relation to field performance, and 3) what methods the research team had the capability of performing.

Materials

The experimental plan used materials from four locations in the United States. The materials from the four locations included a variety of aggregate types, binder grades and sources, and RAP of differing characteristics. Representative samples of RAP and virgin aggregates were obtained from contractors' stockpiles in New Hampshire, Utah, Minnesota, and Florida. The contractors also provided samples of the virgin binders they typically use.

New Hampshire Materials

The materials from New Hampshire were obtained from Continental Paving Co. in Londonderry, New Hampshire. Virgin binder grades were an unmodified PG 58-28 and a polymer-modified PG 70-28 commonly used in New Hampshire. The virgin aggregates were granite. No anti-stripping agent was used with these mix designs since they are not commonly used with these materials in New Hampshire. The RAP stockpile received from this location was unfractionated RAP. However, difficulties obtaining satisfactory mix designs with this material led to the need to screen the RAP into a coarse and fine fraction using a lab-screening process. After this lab fractionation, the coarse RAP fraction was graded as 77.3-21.4, and the fine RAP fraction had a true grade of 81.3-18.8.

Utah Materials

The materials from Utah were obtained from Granite Construction Company's Cottonwood Heights plant near Salt Lake City, Utah. The virgin aggregate for this set of materials was granite. Two binders used in this part of Utah were obtained: an unmodified PG 58-28 and a polymer-modified PG 64-34. A coarse RAP and a fine RAP sample were obtained from the contractor. The recovered RAP binder from the coarse RAP was true graded as 83.8-17.0, and fine RAP was true graded as 89.0-32.7. Since this location commonly uses hydrated lime at 1.0% for an anti-stripping additive, all mixes designed with this set of materials included hydrated lime. Evotherm 3G from MeadWestvaco, Inc. was also used with one mix design using the Utah materials to evaluate mix properties and blending of RAP and virgin binders at a lower mixing temperature. Evotherm 3G (formulation K1) was selected because it is easy to use in the laboratory and was not expected to affect volumetric properties. The dosage of the Evotherm 3G was 0.50% of the total binder in the mixes. The additive was added to the binder prior to mixing. Mixing and compaction temperatures for the WMA samples were reduced by approximately 35°F from the respective temperatures for HMA.

Minnesota Materials

The materials from Minnesota were obtained from Harddrives, Inc. in the Minneapolis area. The virgin aggregates included a natural gravel and a granite. The typical virgin binder grade for this location is a PG 58-28. Samples of a coarse and a fine RAP were obtained. The coarse RAP was tested to have a true grade of 72.8-22.7, and the fine RAP had a much higher true grade of 89.2-9.3. Anti-stripping agents are not typically used by this contractor.

Florida Materials

Raw materials from Florida were obtained from Anderson-Columbia Inc. located in Lake City, FL. Coarse and fine virgin aggregate was railed from a granite source in south Georgia. Coarse and fine RAP stockpiles were also sampled. The binder recovered from coarse RAP was tested to have a true grade of 73.8-24.8, and the fine RAP had a true grade of 71.1-26.3. The standard virgin binder for the area is a PG 67-22. ARMAZ LOF 6500 is the anti-stripping agent used in this area and was used in the mix designs with the Florida materials.

Materials Characterization

The materials were characterized as normally done for Superpave mix designs. Virgin aggregates were tested as received for gradation and Superpave aggregate consensus properties. RAP samples were tested to determine asphalt content in accordance with the ignition method, AASHTO T 308, and the centrifuge extraction method, AASHTO T164. The RAP aggregates were retained following the extraction tests for gradations, consensus properties, and specific gravity tests. The recovered aggregates from the ignition method were also retained for gradation and bulk specific gravity. AASHTO T84 and T85 were used to determine the specific gravity of the recovered RAP aggregate, split on the No. 4 sieve for fine and coarse portions, respectively.

Trichloroethylene was used as the solvent for the extractions. RAP binders were recovered with a rotary evaporator in accordance ASTM D5404 and performance graded in accordance with AASHTO M 320-05. A summary of the critical temperatures for the recovered binders is shown in Table 7. Some of the results for coarse and fine portions of RAP from the same source had greater differences than typically seen. The Minnesota fine RAP had a much higher true grade results compared to the coarse RAP at all three critical temperatures. The coarse and fine RAP fractions from Utah were also somewhat different, with the recovered binder from the fine fraction grading lower than the coarse fraction counterpart. The critical temperatures for the coarse and fine Florida RAP binders were more similar, which is common with other fractionated RAP stockpiles tested by NCAT. However, the grade of Florida RAP materials indicates they were not a highly aged RAP since the standard binder grade now used in Florida is a PG 67-22.

Table 7 Performance Grade Critical Temperatures for the RAP Binders

Source	RAP Description	T_{crit} High	T_{crit} Int	T_{crit} Low	PG
NH	Coarse	77.3	23.5	-21.4	76 - 16
	Fine	81.3	28.0	-18.8	76 - 16
	Non-fractionated	80.2	28.1	-20.2	76 - 16
UT	Coarse	83.8	29.3	-17.0	82 - 16
	Fine	89.0	32.7	-12.6	88 - 10
MN	Coarse	72.8	23.7	-22.7	70 - 22
	Fine	89.2	38.1	-9.3	88 - 4
FL	Coarse	73.8	23.6	-24.8	70 - 22
	Fine	71.1	21.7	-26.3	70 - 22

The nine virgin asphalt binders received from the four locations were also graded in accordance with AASHTO M 320-05. Table 8 shows the results of that testing. All the binders met or exceeded the binder grade criteria for which they were identified. Two grades of binder were obtained from the New Hampshire and Utah locations. Ideally, one of the binder grades would have been a conventional binder and the second binder would have been a softer binder grade to assess whether using a softer binder grade, as is commonly required for moderate and high RAP content mixes, affects mix design and performance properties. However, since the contractors did not historically use softer binder grades and, therefore, such binders were not locally available, they provided an alternate binder that was routinely used, which was one or two grades higher on the high temperature end. Thus, these stiffer binders are presumed to be polymer modified binders. Also, for New Hampshire and Utah, binders of the same performance grade but from a different source/supplier were obtained. The primary binder source is identified with an "A" following the PG grade; the secondary source is identified with a "B."

Table 8 True Grade Critical Temperatures for the Virgin Asphalt Binders

Source	ID	T_{crit} High	T_{crit} Int	T_{crit} Low	PG
NH	70-28 A	71.3	19.3	-29.1	70 - 28
	70-28 B	71.4	15.6	-31.9	70 - 28
	58-28 A	61.5	17.4	-29.7	58 - 28
UT	64-34 A	68.2	9.3	-35.5	64 - 34
	64-34 B	70.6	13.9	-34.5	70 - 34
	58-34 A	63.0	11.7	-34.9	58 - 34
	58-34 B	61.2	9.9	-35.9	58 - 34
MN	58-28	60.1	17.4	-29.5	58 - 28
FL	67-22	72.5	21.7	-26.7	70 - 22

Mix Designs

The objective of the mix design effort was to meet the standard Superpave mix design criteria using the materials provided by contractors in four states. For two sets of materials, the goal was to develop 12.5 mm NMAS mix designs with 0, 25, and 55% RAP (by weight of aggregate). For the other two sets, the goal was to develop 9.5 mm and 19.0 mm NMAS mix designs using 0 and 40% RAP (by weight of aggregate). One laboratory compactive effort (75 gyrations) was used for all mixes to reduce experimental factors in the study. This N_{design} corresponds to a traffic level of 0.3 to 3 million design equivalent single axle loads in the current Superpave design procedure. This compactive effort was considered representative of a large proportion of mix designs across the U.S.

The approach to designing the high RAP content mixes in this study followed the familiar steps from the current Superpave approach with some additional testing of the component materials and performance testing. A total of thirty mixes were designed, tested, and evaluated in this study. Many more unsuccessful trial blends were evaluated. A warm mix asphalt technology was also used with one mix design to evaluate the effects of the lower mixing and compaction temperatures on mix properties. Mixes of different nominal maximum aggregate sizes (NMAS) were used to assess the effects of RAP on base, intermediate, and surface mixes. Some of the mix designs were changed only by using a different binder source without changing the PG grade to determine if compatibility of binders would affect mix properties. Mix designs differing only by polymer modification of the virgin binder were also prepared and tested to determine how polymer-modified binders may affect mixes containing RAP.

Mix Performance Testing

A series of mix performance tests was conducted on the mix designs from the Phase III experimental plan to characterize their dynamic moduli and assess the mix's resistance to moisture damage, permanent deformation, fatigue cracking, and low-temperature cracking. Moisture damage susceptibility was evaluated using AASHTO T 283. The flow number test was selected to assess permanent deformation potential. The indirect tension fracture energy test was selected to assess fatigue cracking potential. Two tests, the semi-circular bending (SCB) and bending beam rheometer tests on thin mix beams, were used to evaluate the low-temperature cracking properties of the mixes.

Dynamic Modulus

Dynamic modulus testing was conducted on each of the mix designs for two purposes. The first purpose was to evaluate how changing binder grade, binder source, and RAP content affects mix stiffness over a wide range of temperatures. The second purpose was to try to backcalculate the effective properties of the composite binder using the approach described by Bennert and Dongre *(61)*. Dynamic modulus tests were conducted in accordance with AASHTO TP 62-07 using an IPC Global Asphalt Mixture Performance Tester (AMPT), shown in Figure 4.

Figure 4 IPC Global Asphalt Mixture Performance Tester

Prior to compaction of specimens, loose mixes were short-term aged for 4 hours at 135°C in accordance with AASHTO R 30. Samples were compacted in a Superpave gyratory compactor (SGC) to dimensions of 150 mm in diameter and 170 mm tall. Once cooled, the compacted samples were cut and cored to yield specimens 100 mm in diameter by 150 mm tall. The air void content of the cut and cored specimens was then determined. Cut and cored specimens that had air void contents outside of the range of 7 ± 0.5% were discarded. LVDT mounting studs were glued onto each specimen in 120° intervals around the cut and cored specimens. Once the glue for the LVDT mounting studs dried, a membrane was pulled over the specimen and mounting studs. Specimens were placed in an environmental chamber set at the desired test temperature for a minimum of 3 hours. Four test temperatures were used, starting with the lowest temperature. The four temperatures were 4, 21, 37, and 54°C (40, 70, 100, and 130°F). At each test temperature, the specimens were tested at six frequencies: 0.1, 0.5, 1, 5, 10, and 25 Hz. For each test temperature, the highest frequency was tested first, and the lowest frequency was tested last. A confining pressure of 20 psi was used during testing at all temperatures and frequencies. Triplicate specimens were prepared and tested. To ensure data quality, a maximum coefficient of variation (COV) between replicates was established. If the results for a set exceeded that limit, additional specimens were prepared and tested.

Equations 3 and 4 were used to generate the dynamic modulus master curve for each mix design. Equation 3 is the dynamic modulus equation while Equation 4 shows how the reduced frequency is determined. The regression coefficients and shift factors, which are used to shift the modulus data at various test temperatures to the reference temperature of 21.1°C, are determined simultaneously during the optimization process using the Solver function in a Microsoft Excel® spreadsheet.

$$| \quad ^{*}| = \quad + \frac{\qquad}{(\quad)} \qquad [3]$$

$$\log \quad = \quad \log(\quad) + \log(\quad(\quad)) \qquad [4]$$

where:

- $|E^*|$ = dynamic modulus, psi
- f = loading frequency at the test temperature, Hz
- f_r = reduced frequency at the reference temperature, Hz
- $\alpha, \delta, \beta, \gamma$ = regression coefficients
- $a(T)$ = temperature shift factor

The procedure used to back-calculate the effective binder properties from the dynamic modulus data followed these steps:

Step 1: Mixture Dynamic Modulus Testing: Conduct frequency sweep testing with AMPT as described above.

Step 2: Binder Testing: Extract and recover the binder from the mixtures tested in *Step 1*. Perform dynamic shear rheometer (DSR) testing to develop the binder |G*| master curves. This is the master curve associated with full blending of the virgin and RAP binders. Extract and recover the binder from the RAP and perform DSR testing to develop the RAP binder |G*| master curve. Develop binder |G*| master curves for the virgin binder and typical binders one or two grades higher.

Step 3 Application of the Hirsch Model: Using the Hirsch model (Equation 6), predict the $|G^*|_{binder}$ curve by inputting measured $|E^*|_{mix}$, VMA, and VFA for the mixture. This was accomplished using the *Solver* error minimization function in Microsoft Excel. An example of a measured dynamic modulus master curve and the associated $|G^*|_{binder}$ curve backcalculated using the Hirsch model are shown in Figure 5.

$$|E^*|_{mix} = \left[P_c \left[4{,}200{,}000\left(1-\frac{VMA}{100}\right) + 3\times|G^*|_b\left(\frac{VMA\times VFA}{10{,}000}\right)\right] + \frac{(1-P_c)}{\left(\frac{1-\frac{VMA}{100}}{4{,}200{,}000}+\frac{VMA}{3\times VFA\times|G^*|_b}\right)}\right] \quad [5]$$

where

$$P_c = \frac{\left(20+\frac{3\times VFA\times|G^*|_b}{VMA}\right)^{0.58}}{650+\left(\frac{3\times VFA\times|G^*|_b}{VMA}\right)^{0.58}} \quad [6]$$

$|G^*|_b$ = binder shear modulus, psi

$|E^*|_{mix}$ = mix dynamic modulus (psi) at the corresponding frequency to $|G^*|_{binder}$

VMA = Voids in the Mineral Aggregate, %

VFA = Voids Filled with Asphalt, %

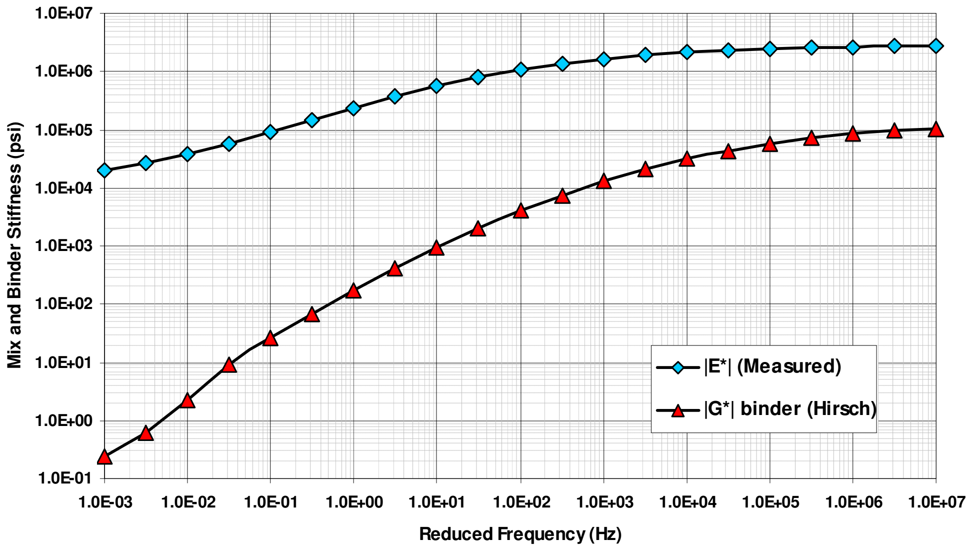


Figure 5 Measured |E*| Master Curve and Binder |G*| Master Curve Backcalculated Using the Hirsch Model

Step 4 Estimate Phase Angle: The backcalculated |G*| values are fit to the Christensen-Andersen model, and then the relationship developed by Geoff Rowe *(62)* (Equation 7 is used to estimate the binder phase angle from the slope of the log:log |G*| versus frequency relationship. This is illustrated in Figure 6.

C-A Phase Angle Fit $$\delta(\omega) = 90\frac{d \ln G^*}{d \ln \omega} \qquad [7]$$

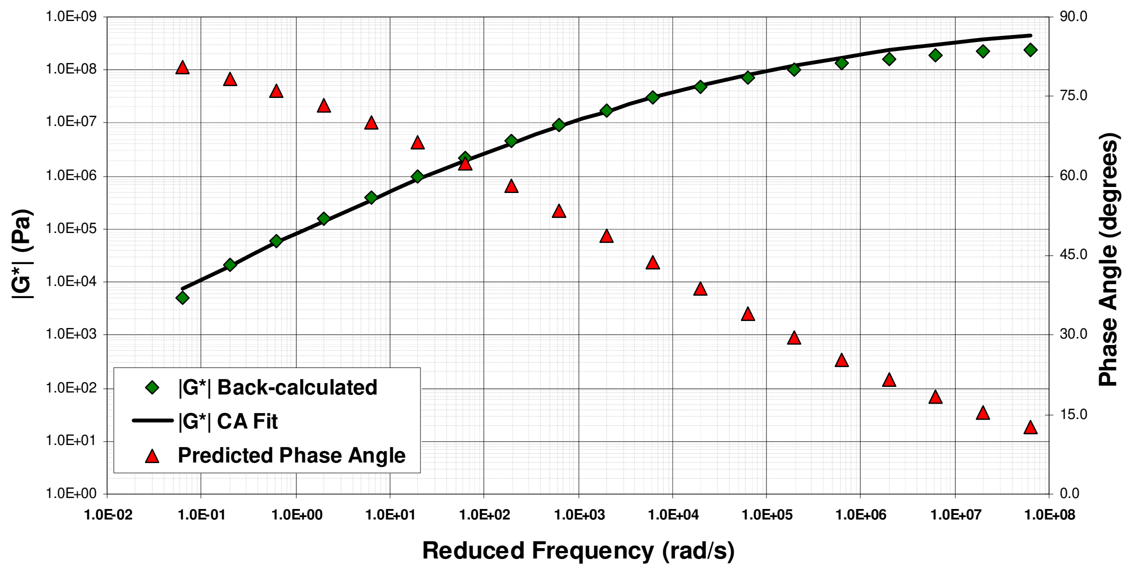


Figure 6 Backcalculated |G*| with C-A Model Fit and Predicted Phase Angle

Step 5 Comparison of Master Curve Data: Compare the |G*| master curves backcalculated from the mixture testing to the |G*| master curves measured on the recovered binder from the mix and RAP and the virgin binder master curves to evaluate the amount of blending.

The dynamic modulus results were analyzed to determine if there are significant differences between the various mix types used in the study and to identify which mix component(s) significantly affect the dynamic modulus values.

Moisture Susceptibility Testing

AASHTO T 283-07, *Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage*, was used to evaluate moisture susceptibility of the mixtures. This test was selected because it is the most common moisture damage susceptibility test in the U.S. and is part of the current Superpave mix design method. As required by this method, the loose mixtures were conditioned for 16 hours at 60°C followed by two hours at the compaction temperature. Specimens were compacted to 7 ± 0.5% air voids with dimensions of 150 mm in diameter and 95 ± 5 mm tall. The conditioned set specimens were saturated to between 70 and 80% and then subjected to one freeze-thaw cycle. Both conditioned and unconditioned specimens were placed in a 25 ± 0.5°C water bath prior to testing. After conditioning, specimens were loaded diametrically at a rate of 50 mm/min. The maximum compressive force was recorded and then the indirect tensile strength and tensile strength ratios were calculated. The ratio of the average tensile strengths of the conditioned specimens to the average tensile strengths of the unconditioned specimens is the tensile strength ratio (TSR). In addition to evaluating the AASHTO T 283 results of each mix against the current AASHTO R 35 tensile strength ratio criterion (a minimum of 0.80), comparisons were made among each source set of the conditioned and unconditioned tensile strengths.

Permanent Deformation Testing

Many highway agencies currently use either the Asphalt Pavement Analyzer or the Hamburg wheel tracking test to evaluate the rutting potential of asphalt mix designs. The flow number test was selected for permanent deformation testing in this study based on recommendations from other recent national studies. At the time this study was initiated, a standard test procedure for flow number did not exist, so a test procedure based on recommendations from NCHRP 9-30A and FHWA was used. This procedure used a confining pressure on the specimens during the test. During the time period this research was conducted, an AASHTO standard was developed for the dynamic modulus test and the flow number test (AAHTO TP 79-09). The standard allows either test to be performed with or without confinement. Some researchers have argued that confined tests better represent the stress state in pavements, particularly lower layers, and that unconfined tests results do not accurately represent the field performance of some mix types such as SMA and asphalt-rubber mixes. However, in recent years, unconfined flow number and dynamic modulus tests have become more popular. Criteria have been recommended for evaluating the results of confined flow number tests, and unconfined dynamic modulus test results are used in mechanistic-empirical pavement analysis programs.

After mixing, loose mix samples were aged for 4 hours at 135°C in accordance with AASHTO R 30. Specimens were compacted to 150 mm diameter by 170 mm in height. The cooled specimens were cut and cored to 100 mm diameter by 150 mm in height. Cut and cored specimens outside of the target air void content of 7 ± 0.5% were discarded. Prior to testing, specimens were preheated to the target testing temperature. The flow number test temperature was 6°C lower than the 50% reliability high pavement temperature from LTPP Bind 3.1 for the location of the respective materials. The deviator stress was 70 psi, and the confining stress was 10 psi as recommended by NCHRP 9-30A. The tests were run for 20,000 cycles.

Statistical analysis of the flow number test results were conducted to evaluate whether or not the mixes containing RAP yield results were similar to the virgin control mixes. Past research and experience indicates that, in most cases, mixes containing RAP perform equal to or better than mixes without RAP in terms of permanent deformation.

Fatigue Cracking Testing Procedure

Other researchers have used a variety of different tests to evaluate the resistance of asphalt mixtures to load-related cracking. There has not been agreement in the asphalt mixture testing community as to which method is best. The research team initially considered the bending beam fatigue test, the Texas Overlay Tester, and the Simplified Viscoelastic Continuum Damage (SVECD) test for this project. The bending beam test is widely used in research, but is impractical as a routine mix design test because of special equipment needed for sample fabrication and the length of time required to obtain test results. The Texas Overlay Tester and the SVECD test were relatively new procedures and other work using these methods at NCAT found the equipment to be unreliable and the test methods to need further development. Therefore, the indirect tensile (IDT) fracture energy test was selected for evaluating the mix designs for resistance to fatigue cracking.

Fracture energy is defined as the area under the stress-strain curve to the point of fracture for the specimen. Physically, it represents the amount of strain energy and dissipated energy due to structural changes (such as micro-cracking) a pavement can absorb prior to failure *(63)*. The magnitude of a mixture's fracture energy has been successfully correlated to amount of fatigue cracking a pavement experienced in the field. Kim and Wen *(63)* conducted a study using the fracture energy of field cores obtained from the WesTrack accelerated pavement testing facility. The calculated fracture energy showed a strong correlation to the amount of fatigue cracking the sections exhibited on the track. For the conditions in the WesTrack study, their results indicated a fracture energy above 3kPa provided excellent resistance to fatigue damage.

For this study, five samples of each mixture were prepared to a thickness between 38 and 50 mm with a target air-void content of 7 ± 0.5%. Samples were both short-term aged (loose mix: 4 hours at 135°C) and long-term aged (compacted specimens: 120 hours at 85°C) to represent in-service aging of a surface layer in the field. The fracture energy tests were conducted at 10°C and a loading ram speed of 50 mm per minute using a servo-hydraulic loading frame (Figure 7). Epsilon gauges were fixed to both faces of the specimens to record horizontal and vertical deformations.

In the analysis of the data, the point of specimen fracture for the fracture energy test was defined using the methodology developed for determining the Florida Energy Ratio *(64)*. Specimen fracture is not defined at the peak load, but rather at the instant at which micro-cracks begin to develop on one of the specimen's faces. This moment is determined by examining the difference in the vertical and horizontal deformations recorded during the strength test plotted versus testing time. As shown in Figure 8, fracture energy is highly dependent on the strain tolerance of the specimen. Analysis was conducted using a software program (ITLT) developed at the University of Florida and Florida DOT. The details regarding the calculation of the fracture energy using this methodology are documented elsewhere *(65)*.

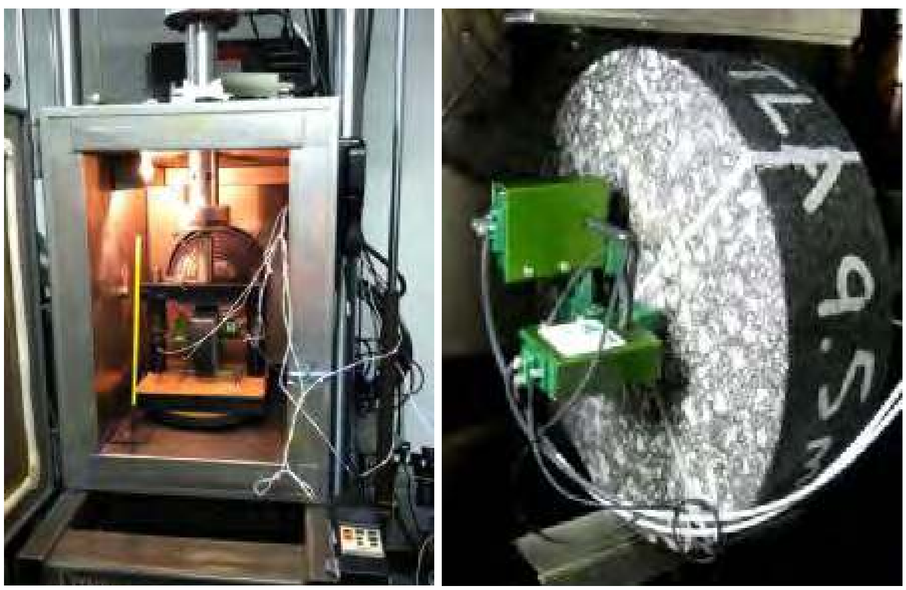


Figure 7 MTS Load Frame and Specimen Setup for Indirect Tension Strength Testing

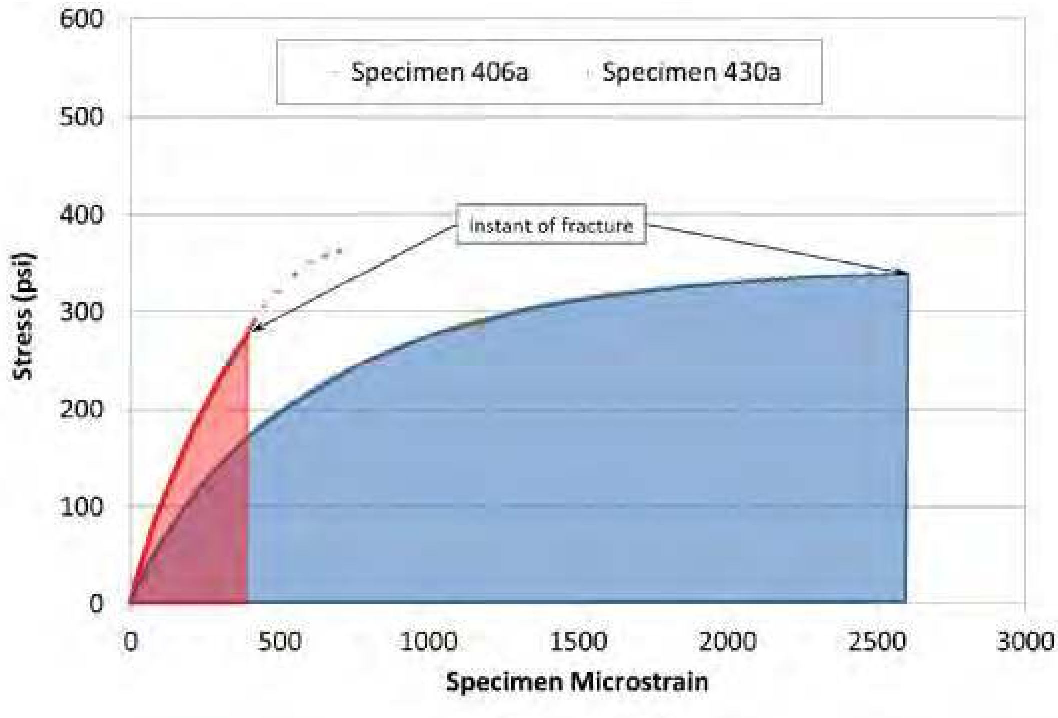


Figure 8 Example Fracture Energy Results

Low-Temperature Cracking Testing

Testing and analysis of low-temperature properties of the mixes were conducted at the University of Minnesota under the direction of Dr. Mihai Marasteanu. Two test methods were used to obtain relevant properties related to the fracture resistance, thermal stress accumulation, and critical low temperature for the asphalt mixtures evaluated in this project: semi-circular bend (SCB) fracture test, and bending beam rheometer (BBR) creep test. Each mixture was tested at three different temperatures for SCB test and at two temperatures for the BBR test, respectively. Three replicates were tested for each mixture at each test temperature. The test temperatures were determined based on the Long Term Pavement Performance (LTPP) temperature database:

- LTPP pavement low temperature (SCB and BBR test)
- 10°C below the LTPP pavement low temperature (SCB test)
- 10°C above the LTPP pavement low temperature (SCB and BBR test)

The LTTP low temperatures represents the pavement low temperature (90% reliability) for the sites where the materials were obtained, and calculated as averages from four locations close to each site. The following temperatures were selected:

- For MN: -24˚C
- For NH: -19˚C
- For UT: -15˚C

Although MN had the lowest temperature, the typical binder used was a PG -28, while for UT, for which the temperature was the highest, the typical binder used had the lowest PG of -34.

The materials received for the project were used to prepare 4 gyratory cylinders (115 mm tall by 150 mm diameter) for each of the 16 different asphalt mixture designs. For the mixtures containing RAP, the RAP was preheated at the mixing temperature for 3 hours prior to mixing. The laboratory loose mix was then short-term aged for 4 hours at 135°C. After aging, all cylinders were compacted in a gyratory compactor to 7±0.5% air voids and then underwent long-term aging (AASHTO R 30-02) for 120 hours at 85°C.

One of the four gyratory cylinders was used to fine-tune the preparation process of the three cylinders used for testing. An SCB slice 25 mm in height and a thin BBR slices of approximately 5 mm height were cut from the remaining three cylindrical specimens, as shown in Figure 9. Cylinder 1 was used to obtain replicates #1 for both BBR and SCB test specimens, for each of the three test temperatures. Cylinder 2 was used to obtain replicates #2, and cylinder 3 was used to obtain replicates #3. For all three cylinders, three slices (two for SCB, and one for BBR) were cut from the middle of each cylinder. The SCB slice cut from cylinders 1, 2, and 3 were symmetrically cut into two semicircular bend samples with a notch of 15mm in length and 2 mm in width.

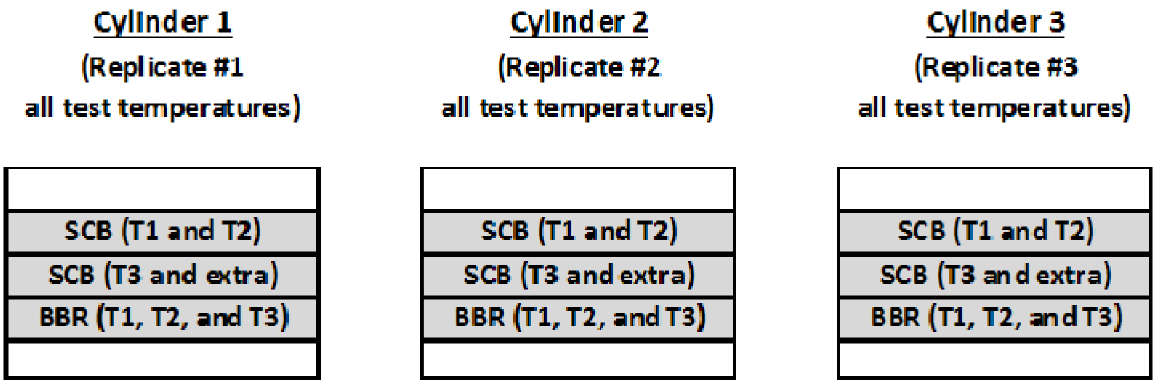


Figure 9 SCB and BBR Test Specimen Preparation

Five BBR thin beams were cut out from the middle of each thin BBR slice. The most uniform three were used for testing (one for each test temperature). Photos of the specimen preparation are shown in Figures 10 to 12.

Figure 10 Specimen Holder for Saw Cutting

Figure 11 Cutting BBR Mixture Beams

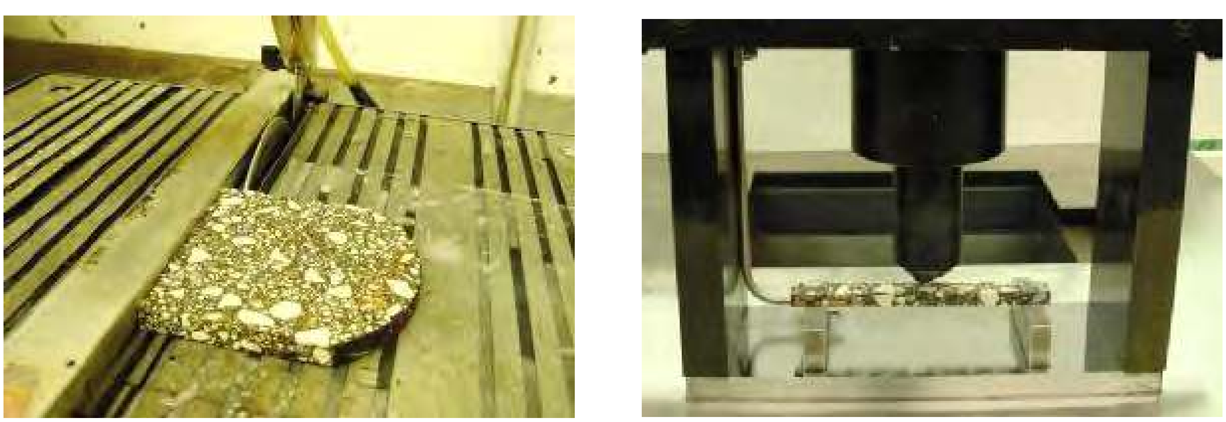


Figure 12 BBR Thin Asphalt Mixture Beams

Semi-circular Bending (SCB) Test

An MTS servo-hydraulic testing system equipped with an environmental chamber was used to perform the SCB test. The half-moon shaped SCB specimens were 25 **± 2 mm** thick. A15 ± 2 mm notch was cut in the center of the flat surface of the SCB specimens, leaving a ligament length (radius minus notch depth) of 135 ± 2 mm. As shown in Figure 13, the SCB samples were symmetrically supported by two fixed rollers with a span of 120 mm. Teflon tape was used to minimize friction between the specimen and the rollers. The load line displacement (LLD) was measured using a vertically mounted Epsilon extensometer.

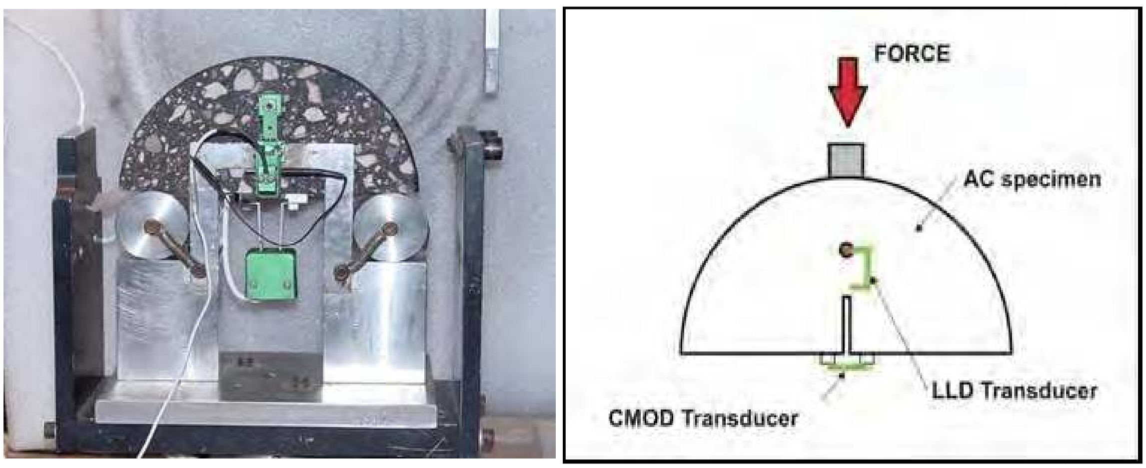


Figure 13 Semi-Circular Bending Test

The crack mouth opening displacement (CMOD) was measured by an Epsilon clip gage attached across the notch on the bottom of the specimen. Further details of the procedure and analysis are provided in the draft procedure for the SCB test included as Appendix A. Considering the brittle behavior of asphalt mixtures at low temperatures, the CMOD signal was used as the control signal to maintain the test stability in the post-peak region of the test. The post peak region, which cannot be measured with other test methods, is critical in calculating the fracture energy and in providing information related to crack propagation. The load and load line displacement (LLD) data were used to calculate the fracture toughness and fracture energy. An example of the load versus LLD for specimens tested at three temperatures is shown in Figure 14. The mode one stress-intensity factor, K_I, adjusts the stress at the crack tip to account for the stress concentration. Fracture toughness is equal to the critical stress-intensity factor, K_{IC}, which is the K_I when the load reaches the maximum value (peak load). Fracture toughness, K_{IC}, quantifies the material's resistance to brittle fracture. A mixture with higher fracture toughness indicates that it is more likely to exhibit ductile failure. The work of fracture, W_f , is the area under the loading-deflection (P-u) curve. The fracture energy, G_f , is obtained by dividing the work of fracture by the ligament area, which is the product of the ligament length and the thickness of the specimen.

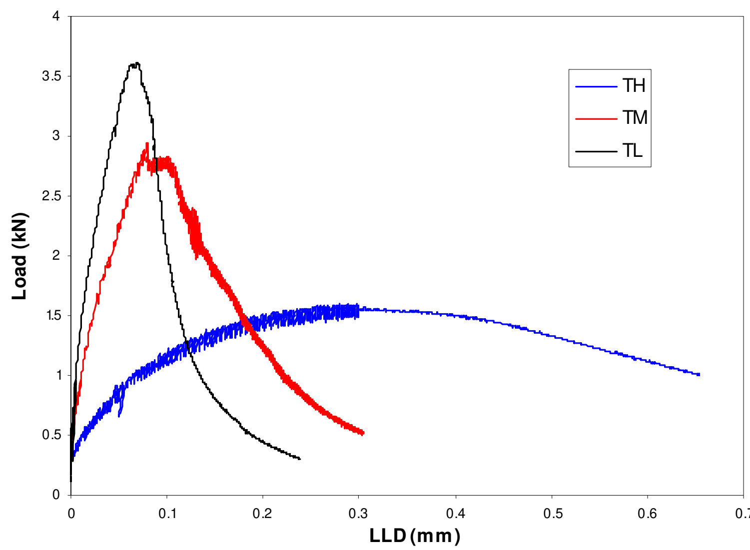


Figure 14 Typical Plot of Load versus Load Line Displacement

Bending Beam Rheometer (BBR) Test

This test method follows the method developed at University of Minnesota under an NCHRP Idea project *(66)* to determine the creep stiffness of thin mixture beams with the BBR equipment commonly used to determine low-temperature properties of asphalt binders for performance grading. The load applied to all mixtures at all test temperatures was approximately 4,000 m·N. The creep stiffness, *S(t)* and the *m*-value, *m(t)* were obtained following the same equations described in the binder BBR test method (AASHTO T313-06). Thermal stresses were also calculated from the BBR mixture creep compliance data, *J(t)* using the following steps:

1. Creep compliance, *J(t),* is obtained from BBR experiments as previously described.
2. Relaxation modulus, *E(t),* is calculated from BBR creep compliance using Hopkins and

Hamming algorithm *(67)*.

3. Relaxation modulus, *E(t),* master curve is generated with the C-A model *(68)*:

$$E(t) = E_g \cdot \left[1 + \left(\frac{t}{t_c} \right)^v \right]^{-w/v} \qquad [8]$$

Where

E_g = Glassy modulus (assumed 30 GPa for asphalt mixtures);

t_c, v, and w = constant parameters in the fitting model

The shift factor expression is:

$$a_T = 10^{C_1 + C_2 \cdot T} \qquad [9]$$

where

C_1 and C_2 = constant fitting parameters;

T = reference temperature, ^{o}C

4. Thermal stresses is calculated from the one-dimensional hereditary integral equation below:

$$\sigma(\xi) = \int_{-\infty}^{\xi} \frac{d\varepsilon(\xi')}{d\xi'} \cdot E(\xi - \xi')d\xi' = \int_{-\infty}^{t} \frac{d(\alpha \Delta T)}{dt'} \cdot E(\xi(t) - \xi'(t))dt' \qquad [10]$$

The equation was solved numerically by using the Gaussian quadrature with 24 Gauss points, as described elsewhere *(69, 70)*.

Thermal stresses can be further used to determine critical cracking temperature, T_{CR}. Two methods are commonly used. In the Dual Instrument Method (DIM), T_{CR} is obtained at the intersection of the thermal stress curve with the strength curves. Since strength tests were not performed in this project, the Single Asymptote Procedure (SAP), was applied. In SAP, strength data is not required *(71)*. A line is fitted to the lowest temperature part of the thermal stress curve, and the intersection with the temperature axis represents T_{CR}, as shown in Figure 15.

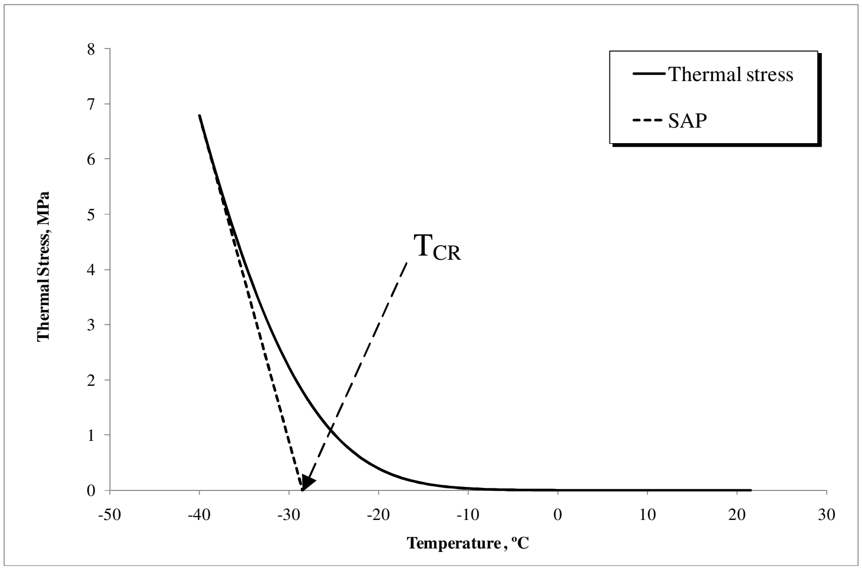


Figure 15 Single Asymptote Procedure (SAP) Method

Table 9 summarizes the mix variables and tests for the mixes using materials from New Hampshire. Mix variables with this set of mixtures included PG grade, source of the virgin binder, and RAP content. The testing plan for these mixes included dynamic modulus testing on all mixes and other performance tests on a subset of the mixes.

Table 9 New Hampshire Mixes and Mix Testing

NMAS (mm)	Virgin PG	Binder Source	RAP %	Mix Testing				
				Dynamic Modulus	*AASHTO T 283*	*Flow Number*	*Fatigue*	*Low Temperature Cracking*
12.5	58-28	A	0					
12.5	58-28	B	0					
12.5	70-28	A	0					
12.5	70-28	B	0					
12.5	58-28	A	25					
12.5	70-28	A	25					
12.5	58-28	A	55					
12.5	58-28	B	55					
12.5	70-28	A	55					
12.5	70-28	B	55					

Table 10 lists the mix factors and tests for the materials from Utah. Variables within this set of mixtures included PG grade, source of the virgin binder, RAP content, and warm-mix asphalt. Dynamic modulus testing was performed on all mix designs with this set of materials. Moisture damage susceptibility flow number, fatigue, and low-temperature cracking testing were conducted on a subset of the mix designs due to budget limitations.

Table 10 Utah Mixes and Mix Testing

Type of Mix	NMAS (mm)	PG	Binder Source	RAP %	Mix Testing				
					Dynamic Modulus	*AASHTO T 283*	*Flow Number*	*Fatigue*	*Low Temperature Cracking*
HMA	12.5	58-34	A	0					
HMA	12.5	58-34	B	0					
HMA	12.5	64-34	A	0					
HMA	12.5	64-34	B	0					
HMA	12.5	58-34	A	25					
HMA	12.5	64-34	A	25					
HMA	12.5	58-34	A	55					
HMA	12.5	58-34	B	55					
HMA	12.5	64-34	A	55					
HMA	12.5	64-34	B	55					
WMA	12.5	58-34	A	55					

The tests conducted on mixes using the Minnesota materials are shown in Table 11. As with the mixes using the Florida materials, the mix variables included NMAS and RAP content. Performance testing included E*, T 283, fracture energy to assess fatigue cracking resistance, and two tests for assessing low-temperature cracking resistance. Flow number tests were not conducted on the Minnesota material mixes due to budget limitations.

Table 11 Minnesota Mixes and Mix Tests

NMAS (mm)	Virgin PG	Binder Source	RAP %	Mix Testing				
				Dynamic Modulus	*AASHTO T 283*	*Flow Number*	*Fatigue*	*Low Temperature Cracking*
9.5	58-28	A	0					
19.0	58-28	A	0					
9.5	58-28	A	40					
19.0	58-28	A	40					

Table 12 summarizes the mixes and mix tests conducted using materials from Florida. Mix variables included NMAS and RAP content. Performance testing included E*, T 283, FN, and fracture energy to assess fatigue cracking resistance. Since thermal cracking is not a problem in Florida, low-temperature cracking tests were not conducted on the Florida mixes.

Table 12 Florida Mixes and Mix Testing

NMAS (mm)	Virgin PG	Binder Source	RAP %	Mix Testing				
				Dynamic Modulus	*AASHTO T 283*	*Flow Number*	*Fatigue*	*Low Temperature Cracking*
9.5	67-22	A	0					
19.0	67-22	A	0					
9.5	67-22	A	40					
19.0	67-22	A	40					

CHAPTER 3 RESULTS AND ANALYSIS

RAP Drying Experiment

Figure 16 shows the drying curves from the RAP drying experiment. These plots show that about six hours were necessary to dry the approximately 24 kg samples using a conventional drying oven temperature of 110°C (230°F) from an initial moisture content of about 5.3%. Fan drying at ambient temperature took about 96 hours. The binders recovered from the RAP samples dried by the two methods had similar PG critical temperatures. The true grade of the RAP binder recovered from the oven dried sample was 103.7 (37.9) -12.1, and the true grade of the binder recovered from the oven dried sample was 102.1 (38.2) -13.1. This indicates that oven drying at 110°C for about six hours did not further age the RAP binder.

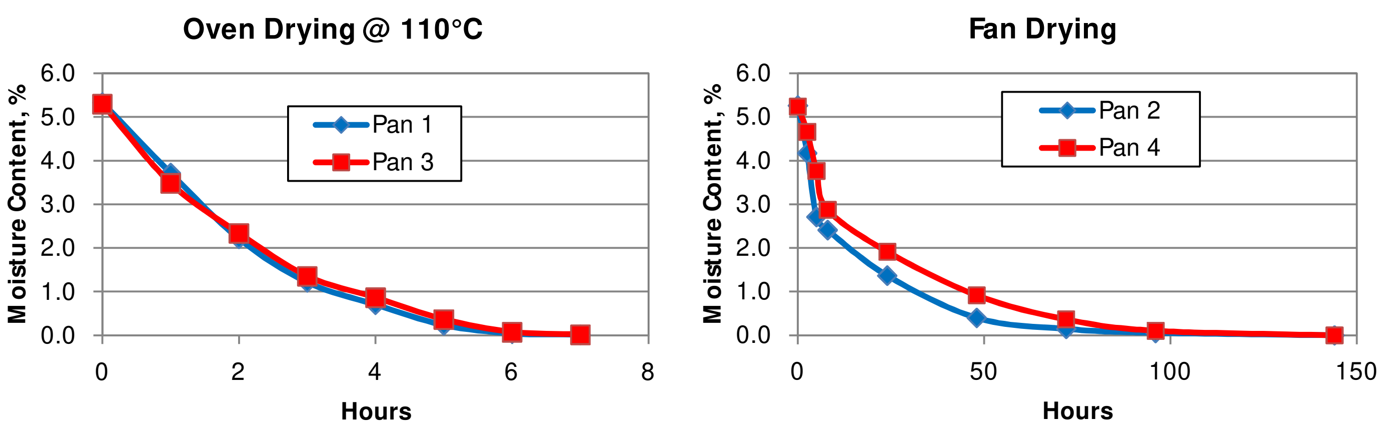


Figure 16 Moisture Content Changes for RAP Dried in an Oven (left) and Fan Drying (right)

RAP Heating Experiment

The RAP heating experiment was performed to determine appropriate heating conditions for RAP during laboratory mix designs. The first part of the heating experiment was to determine the minimum amount of time needed for a sample of RAP to reach the set point temperature of the oven. The sample size used in this experiment was 2,500 grams, which is representative of the sample size needed to make a Superpave gyratory sample with 50% RAP. Figure 17 shows the heating curve developed based on the average of three samples. From this plot, it can be seen that a RAP sample reaches the oven set point temperature in about 1½ hours. Other ovens may take a little more or less time.

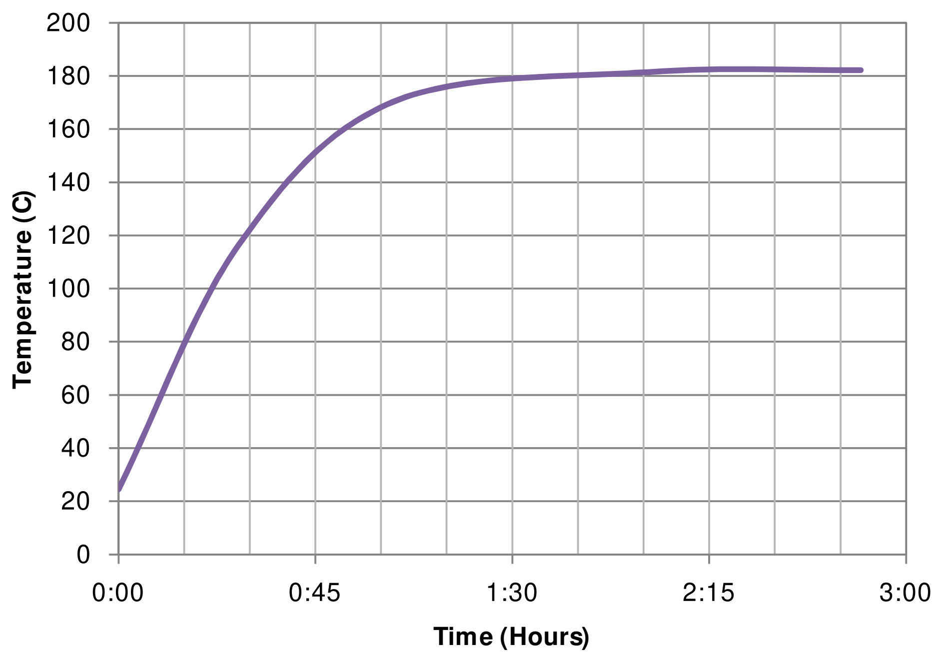


Figure 17 Plot of Time for RAP Sample to Reach Temperature for Mixing

The second heating experiment was to determine how different heating and mixing conditions may affect the properties of the RAP binder. The RAP used in this experiment had an asphalt content of 4.9%, and the average true grade of the RAP binder was 85.1 -15.7. This was a different RAP material from that used in the drying experiment. A 50/50 blend of RAP and virgin aggregate were prepared using four heating scenarios:

1. RAP and virgin aggregate were heated together for three hours at 179°C (355°F).
2. RAP and virgin aggregate were heated together for 16 hours at 179°C (355°F).
3. Virgin aggregate was heated in an oven at 179°C (355°F) for 3 hours, and the RAP was heated in an oven at 179°C (355°F) for 30 minutes.
4. Virgin aggregate was superheated to 260°C (500°F) for three minutes, and the RAP was left unheated at ambient laboratory temperature.

Immediately following each heating scenario, the RAP and virgin aggregate were dry mixed, without additional binder, for two minutes. After mixing and after the materials were cooled, the binder was extracted, recovered, and graded. Since no new binder was added, the theoretical binder content of the mixed materials was 2.45%.

Results of the RAP heating experiment are shown in Table 13. Heating scenario 1 appears to have aged the RAP binder such that the true grade increased a few degrees at the high and low critical temperatures. The extracted asphalt content from this scenario was a little below the theoretical asphalt content of 2.45%. The difference may be attributed to experimental error or to binder that was inadvertently transferred to the mixing bowl and whip. Heating scenario 2 apparently severely aged the RAP binder. Only about one third of the binder could be extracted after soaking in solvent for one hour because the binder had baked onto the RAP aggregate. A sufficient quantity of the binder could not be extracted and recovered to conduct the binder grading. Clearly, placing RAP batches in an oven overnight so mixing can begin first thing in the morning is not a good idea. Heating scenario 3 resulted in the least aging of the RAP binder. The critical high temperature of the recovered binder from this scenario is practically the same as for the original RAP. The critical low temperature was a few degrees lower than the original RAP. This difference is probably due to experimental error. Heating scenario 4, which was intended to simulate plant heating conditions, also appeared to significantly age the RAP binder. The total binder content from the extraction test, however, was close to the expected total binder content of 2.45%. The effect this scenario had on the RAP binder was not expected since the RAP was not heated in an oven, but rather heated only by contact (conduction) from the superheated virgin aggregate. Perhaps this high conductive heat was sufficient to significantly age the binder.

Table 13 Results from RAP Heating Experiment

Heating Scenario	Virgin Heating Time	Virgin Temperature	RAP Heating Time	RAP Temperature	Asphalt Content	Recovered Binder True Grade
1	3 hours	179°C	3 hours	179°C	2.11%	89.3 -13.9
2	16 hours	179°C	16 hours	179°C	0.79%	n.a.
3	3 hours	179°C	30 min	179°C	1.98%	85.0 -17.8
4	3 min	260°C	0	Ambient	2.35%	95.0 -10.0

Some plant experts have suggested that the moisture in RAP converted to steam upon contact with the superheated aggregate creates an inert atmosphere in the plant's mixing zone that reduces further aging of the RAP and virgin binders. In this experiment, the RAP was thoroughly fan dried before mixing, so that hypothesis was not tested. For RAP mix designs by the Louisiana Transportation Research Center, dampened ambient temperature RAP is mixed with superheated aggregate in the laboratory to simulate the conditions in the plant. It is unknown how this process affects aging of the binders.

The results of the two heating experiments indicate that an appropriate heating condition for RAP in preparation for making mix design samples is to place the batched RAP samples in an oven for 1½ to 3 hours.

RAP Aggregate Specific Gravity Experiment

Table 14 shows the RAP aggregate G_{sb} results determined from the three approaches described in Chapter 2. For the backcalculation method, the asphalt absorption values were obtained from the virgin mix designs with the materials from the same source. As can be seen in Table 14, the differences between the G_{sb} results using the first two approaches were very similar in most cases considering that the acceptable range of two results for AASHTO T 84 (fine aggregate G_{sb}) is 0.032 (single operator precision) and 0.025 for AASHTO T 85 (coarse aggregate Gsb). The backcalculated G_{sb} results, however, were much higher than the results from the tests on extraction or ignition recovered aggregates. In several cases, the backcalculated G_{sb} values were about 0.10 higher, which would significantly affect VMA results for high RAP content mixes.

Table 14 RAP Aggregate Bulk Specific Gravity Results Determined by Three Approaches

RAP Source	RAP Fraction	Centrifuge - T84/85	Ignition - T84/85	Backcalculated
New Hampshire	Coarse	2.662	2.653	2.666
	Fine	2.636	2.629	2.680
Utah	Coarse	2.580	2.541	2.631
	Fine	2.583	2.579	2.629
Minnesota	Coarse	2.628	2.623	2.732
	Fine	2.618	2.606	2.739
Florida	Coarse	2.563	2.592	2.659
	Fine	2.565	2.574	2.669

To illustrate the impact of these results, the three different RAP aggregate G_{sb} results were used in the calculation of the total aggregate blend G_{sb} and VMA values for the mix designs that are presented in detail later in the report. The VMA results are shown in Table 15. It can be seen that the impacts of the different RAP aggregate G_{sb} results on VMA were minor if either the centrifuge extraction or the ignition method were used to recover the aggregate before testing the materials in AASTO T84 and T85 for the fine and coarse portions, respectively. At moderate RAP contents (25%), using the backcalculation G_{sb} method inflated the VMA by about 0.4%. However, at higher RAP contents, the backcalculation G_{sb} method resulted in extremely inflated VMA values for most mixes. Using these highly inflated VMAs would likely result in much lower asphalt contents for high RAP content mixes.

Table 15 VMA Results for the High RAP Content Mix Designs Based on the RAP Agg. G_{sb} Values in Table 13

RAP Source	RAP content	NMAS (mm)	Centrifuge - T84/85	Ignition - T84/85	Backcalculated
New Hampshire	25%	12.5	16.1	16.1	16.5
	55%	12.5	15.9	15.8	16.3
Utah	25%	12.5	14.0	13.9	14.4
	55%	12.5	15.1	14.8	16.0
Minnesota	40%	9.4	15.5	15.4	16.9
		19.0	13.3	13.3	14.7
Florida	40%	9.5	15.0	15.2	16.2
		19.0	13.6	13.8	15.0

Based on this analysis, the research team decided to use the RAP aggregate G_{sb} values determined from the Centrifuge - T84/T85 approach in determining volumetric properties for the project mixes. The Ignition - T84/T85 approach would also have been acceptable based on these findings

Volumetric Properties of the Mix Designs

New Hampshire Mix Designs

Eleven mixes were designed using the materials from New Hampshire. The New Hampshire mix designs included 0, 25, and 55% RAP with a PG 58-28 and a PG 70-28 binder. The 0 and 55% RAP content designs were also completed with a PG 58-28 and a PG 70-28 from a second binder source, noted with a "B" following the PG grade. Initially, some difficulty was encountered in obtaining a satisfactory mix design containing 55% RAP because the as-received New Hampshire RAP material was not fractionated. When it was apparent that a successful 55% RAP content mix design could not be obtained with the unfractionated RAP, it was screened in the lab over a No.4 sieve to create a coarse and fine fraction.

Table 16 shows the volumetric properties for the New Hampshire mixes with PG 58-28 binders. The 55% RAP content mix was redesigned for performance testing since the effective asphalt content of the original mix was 0.7% below the effective asphalt contents of the 0 and 25% RAP mixes.

Table 16 Volumetric Properties for the New Hampshire Mixes with the PG 58-28 Binders

	0% RAP	0% RAP	25% RAP	55% RAP Original	55% RAP Original	55%RAP Redesign
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade/Source	58-28A	58-28B	58-28A	58-28A	58-28B	58-28A
Blend Used	2A	2B	4A	1A	1B	3A
½" Stone, %	18	18	30	15	15	18
3/8" Stone, %	37	37	30	0	0	0
DSS, %	12	12	14	10	10	27
WMS, %	20	20	0	10	10	0
Litchfield, %	12	12	0	10	10	0
+ #4 Scrnd RAP (Pb=3.2) %	0	0	0	55	55	31
- #4 Scrnd RAP (Pb=6.05) %	0	0	25	0	0	24
Baghouse fines	1	1	1	0	0	0
Blend G_{sb}	2.696	2.696	2.687	2.672	2.672	2.663
Percent Passing 19.0 mm	100	100	100	100	100	100
Percent Passing 12.5 mm	98.6	98.6	98.5	98.8	98.8	98.6
Percent Passing 9.5 mm	89.0	89.0	88.0	89.7	89.7	88.3
Percent Passing 4.75 mm	56.0	56.0	63.1	51.1	51.1	44.7
Percent Passing 2.36 mm	37.5	37.5	46.8	37.5	37.5	28.6
Percent Passing 1.18 mm	27.2	27.2	36.2	29.8	29.8	22.4
Percent Passing 0.60 mm	18.9	18.9	27.4	22.1	22.1	17.1
Percent Passing 0.30 mm	11.2	11.2	17.7	13.7	13.7	11.8
Percent Passing 0.15 mm	5.6	5.6	8.6	7.4	7.4	7.9
Percent Passing 0.075 mm	3.8	3.8	5.2	4.6	4.6	5.3
Optimum AC, %	5.5	5.6	5.9	5.2	5.3	6.1
AC from virgin binder, %	5.6	5.6	4.4	3.4	3.5	3.7
AC from RAP, %	0	0	1.51	1.76	1.76	2.44
RAP Binder / Total Binder, %	0	0	26	34	33	40
Va, %	4.0	3.7	4.0	4.0	4.1	4.0
VMA, %	15.7	15.5	16.1	14.4	14.4	15.5
Vbe, %	11.7	11.8	12.1	10.4	10.3	11.1
VFA, %	74.5	75.9	75.0	73.0	71.3	74.2
Effective AC, %	5.2	5.0	5.2	4.5	4.4	4.9
Dust / Asphalt Ratio	0.8	0.8	1.0	1.0	1.0	1.1
TSR	0.85	--	0.87	0.90	--	0.81

Table 17 shows the volumetric properties for the New Hampshire mixes with the PG 70-28 binders. The optimum binder contents changed very little when the binder sources were changed. The percentage of RAP binder to total binder was 26% for the mix containing 25% RAP by weight of aggregate. The redesigned 55% RAP mix, which was used in the performance testing evaluations, contained 40% RAP binder.

Table 17 Volumetric Properties for New Hampshire Mixes with the PG 70-28 Binders

	0% RAP	0% RAP	25% RAP	55% RAP Original	55% RAP Original
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	70-28A	70-28B	70-28A	70-28A	70-28B
Blend Used	2C	2A	4B	1C	1D
½" Stone, %	18	18	30	15	15
3/8" Stone, %	37	37	30	0	0
DSS, %	12	12	14	10	10
WMS, %	20	20	0	10	10
Litchfield, %	12	12	0	10	10
+ #4 Scrnd RAP (Pb=3.2) %	0	0	0	55	55
- #4 Scrnd RAP (Pb=6.05) %	0	0	25	0	0
Baghouse fines	1	1	1	0	0
Blend G_{sb}	2.696	2.696	2.687	2.672	2.672
Percent Passing 19.0 mm	100	100	100	100	100
Percent Passing 12.5 mm	98.6	98.6	98.5	98.8	98.8
Percent Passing 9.5 mm	89.0	89.0	88.0	89.7	89.7
Percent Passing 4.75 mm	56.0	56.0	63.1	51.1	51.1
Percent Passing 2.36 mm	37.5	37.5	46.8	37.5	37.5
Percent Passing 1.18 mm	27.2	27.2	36.2	29.8	29.8
Percent Passing 0.60 mm	18.9	18.9	27.4	22.1	22.1
Percent Passing 0.30 mm	11.2	11.2	17.7	13.7	13.7
Percent Passing 0.15 mm	5.6	5.6	8.6	7.4	7.4
Percent Passing 0.075 mm	3.8	3.8	5.2	4.6	4.6
Optimum AC, %	5.6	5.6	5.9	5.2	5.2
AC from virgin binder, %	5.6	5.6	4.4	3.4	3.4
AC from RAP, %	0	0	1.51	1.76	1.76
RAP Binder / Total Binder, %	0	0	26	34	34
Va, %	3.8	3.7	4.0	4.0	4.0
VMA, %	15.5	15.4	16.2	14.5	14.4
Vbe, %	11.7	11.7	12.2	10.5	10.4
VFA, %	75.7	75.9	75.0	72.7	73.0
Effective AC, %	5.0	5.0	5.2	4.5	4.5
Dust / Asphalt Ratio	0.8	0.8	1.0	1.0	1.0
TSR	0.98	--	0.84	0.79	--

Utah Mix Designs

Eleven mixes were designed and tested using the Utah materials, including one warm-mix asphalt (WMA). The Utah mixes contained 0, 25, and 55% RAP and were designed using PG 58-34 and PG 64-34 virgin binders. Summaries of the Utah mix designs are shown in Tables 18 and 19.

Table 18 Volumetric Properties for Utah Mixes with the PG 58-34 Binders

	0% RAP	0% RAP	25% RAP	55% RAP WMA	55% RAP	55% RAP
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	58-34A	58-34B	58-34A	58-34A	58-34A	58-34B
Blend Used	2A	2B	1A	7 WMA	7A	7B
¾” Rock, %	8	8	9	9	9	9
7/16” Blend, %	32	32	29	15	15	15
¼” Chip, %	20	20	14	10	10	10
Type III Sand, %	25	25	9	0	0	0
W. Sand, %	14	14	12	10	10	10
Fine RAP (Pb=6.72), %	0	0	12	15.5	15.5	15.5
Coarse RAP (Pb=5.32), %	0	0	13	39.5	39.5	39.5
H. Lime	1	1	1	1	1	1
Blend G_{sb}	2.610	2.610	2.614	2.603	2.603	2.603
Percent Passing 19.0 mm	100	100	99.9	99.9	99.9	99.9
Percent Passing 12.5 mm	96.2	96.2	95.6	95.4	95.4	95.4
Percent Passing 9.5 mm	89.8	89.8	87.8	86.1	86.1	86.1
Percent Passing 4.75 mm	48.5	48.5	44.9	43.5	43.5	43.5
Percent Passing 2.36 mm	28.7	28.7	28.3	28.0	28.0	28.0
Percent Passing 1.18 mm	20.3	20.3	20.3	20.3	20.3	20.3
Percent Passing 0.60 mm	14.8	14.8	14.8	15.1	15.1	15.1
Percent Passing 0.30 mm	10.3	10.3	10.5	11.2	11.2	11.2
Percent Passing 0.15 mm	6.9	6.9	7.3	8.2	8.2	8.2
Percent Passing 0.075 mm	5.2	5.2	5.6	6.1	6.1	6.1
Optimum AC, %	5.5	6.0	5.7	6.5	6.5	6.1
AC from virgin binder, %	5.5	6.0	4.2	3.5	3.5	3.1
AC from RAP, %	0	0	1.54	3.0	3.0	3.0
RAP Binder / Total Binder, %	0	0	27	46	46	49
Va, %	3.9	4.1	3.7	4.1	3.7	3.7
VMA, %	14.0	15.2	14.1	15.3	15.1	15.0
Vbe, %	10.1	11.1	10.4	11.2	11.4	11.3
VFA, %	72.2	73.4	73.8	73.4	75.4	75.1
Effective AC, %	4.4	4.8	4.5	4.9	4.9	4.9
Dust / Asphalt Ratio	1.2	1.1	1.2	1.2	1.2	1.2
TSR	0.86	--	0.75	0.67	0.71	--

Table 19 Volumetric Properties for Utah Mixes with the PG 64-34 Binders

	0% RAP	0% RAP	25% RAP	55% RAP	55% RAP
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	64-34A	64-34B	64-34A	64-34A	64-34B
Blend Used	2C	2D	1B	7C	7D
¾" Rock, %	8	8	9	9	9
7/16" Blend, %	32	32	29	15	15
¼" Chip, %	20	20	14	10	10
Type III Sand, %	25	25	9	0	0
W. Sand, %	14	14	12	10	10
Fine RAP (Pb=6.72), %	0	0	12	15.5	15.5
Coarse RAP (Pb=5.32), %	0	0	13	39.5	39.5
H. Lime	1	1	1	1	1
Blend Gsb	2.610	2.610	2.614	2.603	2.603
Percent Passing 19.0 mm	100	100	99.9	99.9	99.9
Percent Passing 12.5 mm	96.2	96.2	95.6	95.4	95.4
Percent Passing 9.5 mm	89.8	89.8	87.8	86.1	86.1
Percent Passing 4.75 mm	48.5	48.5	44.9	43.5	43.5
Percent Passing 2.36 mm	28.7	28.7	28.3	28.0	28.0
Percent Passing 1.18 mm	20.3	20.3	20.3	20.3	20.3
Percent Passing 0.60 mm	14.8	14.8	14.8	15.1	15.1
Percent Passing 0.30 mm	10.3	10.3	10.5	11.2	11.2
Percent Passing 0.15 mm	6.9	6.9	7.3	8.2	8.2
Percent Passing 0.075 mm	5.2	5.2	5.6	6.1	6.1
Optimum AC, %	5.9	6.1	6.1	6.2	6.3
AC from virgin binder, %	5.9	6.1	4.6	3.2	3.3
AC from RAP, %	0	0	1.54	3.0	3.0
RAP Binder / Total Binder, %	0	0	25	48	48
Va, %	4.2	4.0	4.0	3.8	4.0
VMA, %	15.2	15.1	15.3	15.4	15.4
Vbe, %	11.0	11.1	11.3	11.6	10.6
VFA, %	71.9	72.7	73.3	75.3	74.0
Effective AC, %	4.8	4.8	4.9	5.1	5.0
Dust / Asphalt Ratio	1.1	1.1	1.1	1.2	1.2
TSR	0.82	--	0.76	0.77	--

Minnesota Mix Designs

Four mixes were designed with the Minnesota materials. Two of the mixes were 9.5 mm NMAS mixes, and the other two were 19.0 mm NMAS mixes. A PG 58-28 binder was used in all the mixes. Table 20 lists the volumetric properties of the mix designs with the Minnesota materials. For the 9.5 mm NMAS mixes, the optimum asphalt contents were similar, within 0.2%. The RAP binder was 33% of the total binder content for the 9.5 mm 40% RAP mix. The optimum asphalt contents for the 19.0 mm NMAS mixes were also similar. Although only the coarse RAP fraction was used in the 19.0 mm mix, the RAP binder was 42% of the total binder.

Table 20 Volumetric Properties for the Minnesota Mixes

	0% RAP	40% RAP	0% RAP	40% RAP
Nominal Max. Agg. Size, mm	9.5	9.5	19.0	19.0
Virgin Binder Grade	58-28	58-28	58-28	58-28
Blend Used	1	3	1	5
ASTM 67s, %	0	0	30	25
½" Chip, %	45	50	20	15
W. Sand, %	0	10	0	20
Pea Gravel, %	15	0	10	0
BA Sand, %	15	0	20	0
Man. Sand, %	25	0	20	0
Coarse RAP (Pb=4.31), %	0	30	0	40
Fine RAP (Pb=4.67), %	0	10	0	0
Blend Gsb	2.631	2.650	2.637	2.651
Percent Passing 25.0 mm	100	100	100	100
Percent Passing 19.0 mm	100	100	98.0	98.2
Percent Passing 12.5 mm	100	98.4	85.6	86.4
Percent Passing 9.5 mm	98.1	92.9	76.6	75.9
Percent Passing 4.75 mm	51.0	48.0	45.1	51.8
Percent Passing 2.36 mm	31.0	34.5	30.8	40.7
Percent Passing 1.18 mm	22.4	26.6	22.4	29.7
Percent Passing 0.60 mm	13.9	19.2	13.2	19.7
Percent Passing 0.30 mm	7.6	11.4	6.8	11.2
Percent Passing 0.15 mm	5.1	6.0	4.4	6.0
Percent Passing 0.075 mm	4.1	3.6	3.6	3.8
Optimum AC, %	6.3	6.1	5.0	5.1
AC from virgin binder, %	6.3	4.1	5.0	3.0
AC from RAP, %	0	2.0	0	2.1
RAP Binder / Total Binder, %	0	33	0	42
Va, %	4.0	4.0	4.1	4.0
VMA, %	16.1	15.5	13.6	13.4
Vbe, %	12.1	11.5	9.5	9.4
VFA, %	75.0	74.7	69.4	70.6
Effective AC, %	5.3	5.0	4.1	4.0
Dust / Asphalt Ratio	0.8	0.7	0.9	0.9
TSR	0.78	1.00	0.85	1.01

Florida Mix Designs

Four mixes were also designed with the Florida materials. The mixes contained either 0 or 40% RAP and were either 9.5 mm or 19.0 mm NMAS. A PG 67-22 binder was used for all the Florida mixes. Table 21 lists the volumetric properties for the Florida mix designs.

Table 21 Volumetric Properties for the Florida Mixes

	0% RAP	40% RAP	0% RAP	40% RAP
Nominal Max. Agg. Size, mm	9.5	9.5	19.0	19.0
Virgin Binder Grade	67-22	67-22	67-22	67-22
Blend Used	7	13	3	7
Sand, %	20	19	17	8
M10, %	15	0	17	0
W10, %	15	0	14	10
67, %	32	21	27	24
78, %	0	0	15	11
89, %	18	20	10	7
Coarse RAP (Pb=5.27), %	0	35	0	20
Fine RAP (Pb=5.95), %	0	5	0	20
Blend Gsb	2.722	2.653	2.736	2.676
Percent Passing 19.0 mm	100	100	96.9	97.3
Percent Passing 12.5 mm	99.6	98.8	87.9	88.5
Percent Passing 9.5 mm	94.3	94.7	73.8	74.3
Percent Passing 4.75 mm	71.3	70.5	51.8	50.9
Percent Passing 2.36 mm	55.8	59.0	41.0	41.8
Percent Passing 1.18 mm	42.0	47.9	32.3	33.8
Percent Passing 0.60 mm	31.7	37.0	25.2	25.8
Percent Passing 0.30 mm	20.8	22.9	16.9	15.7
Percent Passing 0.15 mm	9.4	9.4	7.8	7.2
Percent Passing 0.075 mm	4.6	4.5	4.0	4.0
AC from virgin binder, %	5.4	3.5	4.5	2.9
Optimum AC, %	5.4	5.6	4.5	5.1
AC from RAP, %	0.0	2.1	0.0	2.2
RAP Binder / Total Binder, %	0	38	0	44
Va, %	3.8	4.2	4.1	4.1
VMA, %	15.1	15.0	13.5	13.6
Vbe, %	11.3	10.8	9.4	9.5
VFA, %	72.6	71.8	70.3	70.4
Effective AC, %	4.6	4.6	4.0	4.0
Dust / Asphalt Ratio	1.0	1.0	1.0	1.0
TSR	0.93	0.77	0.91	0.76

For the 9.5 mm NMAS Florida mixes, the optimum asphalt contents were reasonably close, within 0.2%. The RAP binder was 38% of the total binder content. For the 19.0 mm NMAS mixes, even though the gradations were very close, the optimum binder content for the 40% RAP mix was 0.6% higher than the virgin mix.

Effect of Binder Grade and Binder Source

The optimum asphalt contents of the Utah and New Hampshire mixes are shown in Figure 18. The differences in optimum asphalt contents between mixes using the two binder sources and two binder grades are listed in Table 22. The optimum asphalt contents for the Utah mixes were apparently affected by changes in binder source and binder grade. However, there was not a consistent trend for these effects. For example, the optimum asphalt content from the primary source increased when the stiffer binder was used compared to the soft binder for the 0% and 25% RAP mixes, but decreased for the 55% RAP mix. The optimum asphalt content for the virgin Utah mixes with two sources of PG 58-34 binder differed by 0.5%, and with the PG 64-34 binders, differed by 0.2%. The difference between the primary and secondary binders overall for the virgin Utah mix was not substantial, except for the mix containing the soft primary binder compared to the other mixes. The two Utah mixes with 25% RAP used different virgin binder grades. The optimum asphalt content of the mix using the soft binder was 0.4% lower than that of the stiff binder. For the 55% RAP Utah mix, the optimum binder content difference between the mixes containing binders from different sources was 0.4%. All other differences between binder sources and binder types for the Utah and New Hampshire mixes were less than 0.3%.

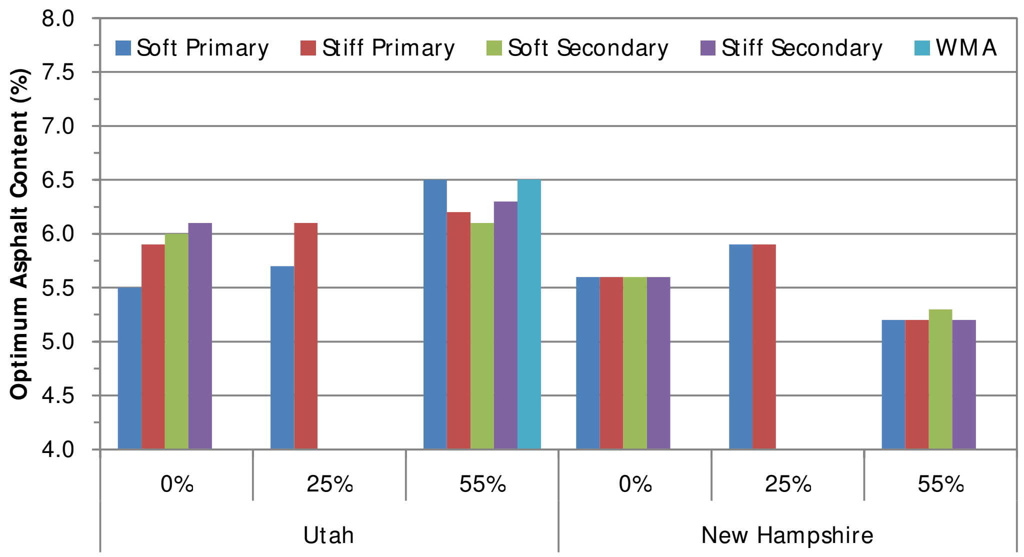


Figure 18 Optimum Total Binder Contents for the Utah and New Hampshire Mixes

Table 22 Optimum Asphalt Content Differences

PG	Materials Source	RAP %	Difference Between Soft Primary and Secondary Binders	Difference Between Stiff Primary and Secondary Binders	Difference Between Soft and Stiff Primary Binders	Difference Between Soft and Stiff Secondary Binders
58-34	UT	0%	-0.5	-0.2	-0.4	-0.1
		25%	--	-0.4	--	--
		55%	0.4	-0.1	0.3	-0.2
58-28	NH	0%	0	0	0	0
		25%	--	0	--	--
		55%	-0.1	0	0	0.1

The effective asphalt contents of the New Hampshire and Utah mixes are shown in Figure 19. The greatest differences in effective asphalt content were observed for the 0 and 25% RAP Utah mixes. All other mixes exhibited reasonable differences between the various binder sources and grades. The fact that the virgin mix designs were among those that had the greatest differences in asphalt contents with the different sources and grades of virgin binder indicates that the differences in optimum asphalt contents were not due to a compatibility problem between virgin and RAP binders.

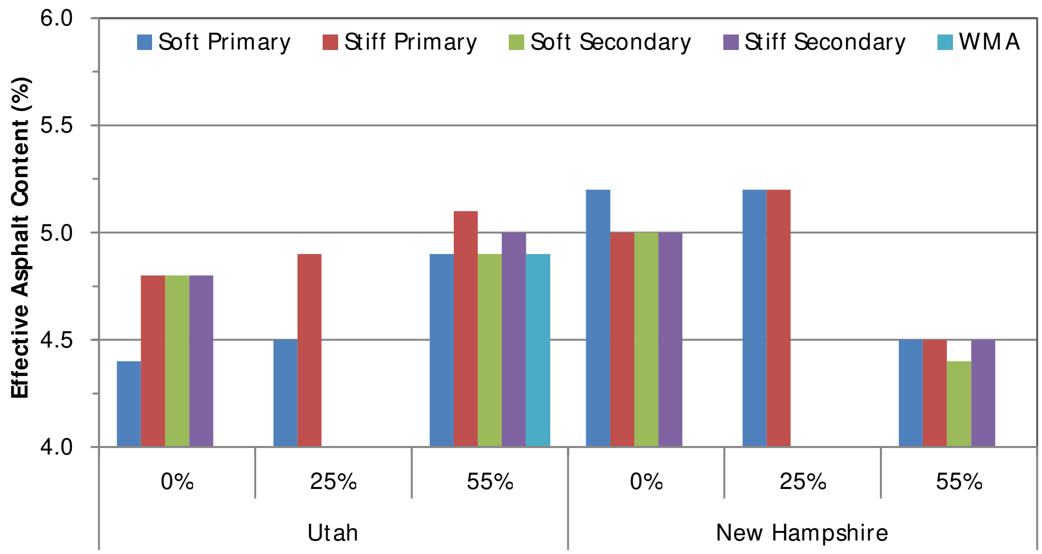


Figure 19 Effective Asphalt Contents of the New Hampshire and Utah Mixes

The voids in the mineral aggregate (VMA) for the New Hampshire and Utah mixes are illustrated in Figure 20. With the exception of the 0 and 25% RAP Utah mixes, the differences were reasonable between mixes with different binder sources and grades.

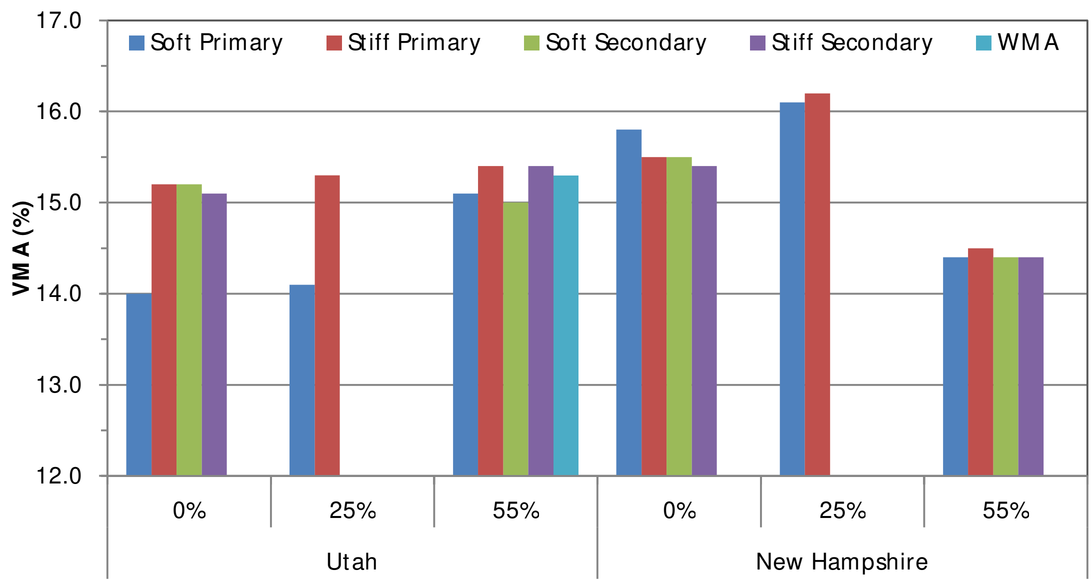


Figure 20 VMA of the Utah and New Hampshire Mixes

Overall, the results were not clear with regard to whether or not changing the binder source or binder grade have an effect on volumetric properties of mix designs. For the Utah materials, significant differences in optimum asphalt contents (up to 0.5%) were obtained for the virgin and 25% RAP mix designs when different binder grades and different binder sources were used. Since these differences in optimum asphalt contents included virgin mix designs, then a problem with compatibility of virgin and RAP binders can be ruled out as a possible cause. For the New Hampshire materials, the mix design results indicate that changing the virgin binder source or the virgin binder grade has little effect on the volumetric properties.

Estimated Effective Binder Grades

Although complete blending of virgin and RAP binders in recycled mixtures has not been proven, most recent research indicates that co-mingling of new and recycled binders does occur to a substantial degree (*19, 22, 23, 24, 36*). Following the assumption of complete blending, which is the basis for high RAP content mix designs in AAHTO M 323, calculations were conducted to predict the effective grade of the composite binder for each mix design. In essence, the calculation is a weighted average of the critical temperatures where the weighting factors are the percentage contribution to the total binder. Results for the New Hampshire mix designs with the primary binder source are summarized in Table 23. Based on this analysis, the most significant impact is on the low critical temperature, where a 2 to 3 degree increase is predicted for the 25% RAP mixtures, and a 2.5 to 3.9 degree increase is predicted for the mixes containing 55% RAP. If virgin binder grades with lower critical temperature PG grades had been available, for example XX-34, the predicted low-temperature grades of the theoretical blends for the RAP mixes would have been very similar to the virgin mixes.

Table 23 Predicted Critical Temperatures of Composite Binders for New Hampshire Mixes

Virgin PG	RAP	Pb_{RAP}/ Pb_{Total}	High T_c	Int. T_c	Low T_c
58-28	0	0	61.5	17.4	-29.7
	25	26	66.6	20.1	-26.9
	55	34	66.6	19.4	-25.8
70-28	0	0	71.3	19.3	-29.1
	25	26	73.2	20.9	-27.2
	55	34	73.2	20.6	-26.6

Results for the Utah mix designs with the primary binder source are summarized in Table 24. For these 55% RAP mixes, the percentages of RAP binder were much higher. Each of the predicted critical temperatures were substantially affected by RAP contents, even at 25%. The increase in the high critical temperatures is not a problem since that improves a mixture's rutting resistance. An increase in the intermediate temperature could mean that the mixture is less fatigue-resistant since the binder is less flexible (a higher temperature is necessary to meet the maximum G*sinδ of 5000 kPa). The substantial increase in low critical temperatures for the mixes containing RAP indicate that the mixtures would be susceptible to thermal cracking at warmer temperatures.

Table 24 Predicted Critical Temperatures of Composite Binders for Utah Mixes

Virgin PG	RAP	Pb_{RAP}/ Pb_{Total}	High T_c	Int. T_c	Low T_c
58-34	0	0	63.0	11.7	-34.9
	25	26	69.2	16.8	-29.6
	55	47	73.6	20.6	-25.8
64-34	0	0	68.2	9.3	-35.5
	25	25	72.7	14.7	-30.4
	55	49	76.8	19.8	-25.6

Predicted composite binder critical temperatures for the Minnesota and Florida mixtures are shown in Table 25. The RAP binder percentage for three of the four 40% RAP mixes was lower than the aggregate content because little or no fine fractionated RAP was used. For both Minnesota mixes, all the predicted composite binder critical temperatures increased by 2 to 5 degrees for the 40% RAP mixes compared to the virgin mixes. For the Florida mixes, the predicted critical temperatures increased slightly for the 9.5 mm NMAS mix, but decreased slightly (improved) for the 19.0 mm NMAS mix. This apparent improvement was due to the relatively unaged binder in the fine fractionated RAP from Florida. The true grade for the recovered RAP binder was 71.1 (21.7) -26.3, which was very close to the virgin PG 67-22 binder from Florida.

Table 25 Predicted True Grade Critical Temperatures for MN and FL Mixes

Source	Virgin PG	NMAS	RAP	Pb_{RAP}/ Pb_{Total}	High T_c	Int. T_c	Low T_c
MN	58-28	9.5	0	0	60.1	17.4	-29.5
			40	33	65.1	20.4	-26.4
		19.0	0	0	60.1	17.4	-29.5
			40	42	64.3	19.5	-27.2
FL	67-22	9.5	0	0	72.5	21.7	-26.7
			40	38	72.8	22.3	-26.1
		19.0	0	0	72.5	21.7	-26.7
			40	44	72.5	22.1	-26.3

Dynamic Modulus Results

Dynamic modulus testing involved laboratory E* testing at four temperatures and six frequencies to develop a master curve for each of the 28 mix designs using the previously described methodology. Analysis of the E* data was conducted separately on mixes from each of the four locations to avoid confounding factors such as RAP characteristics and aggregate mineralogy.

New Hampshire Mixtures

The set of ten mixtures using New Hampshire materials included two binder grades (PG 58-28 and PG 70-28), two binder sources, three RAP contents (0, 25, and 55%), and one NMAS (12.5 mm). The following subsections assess how binder grade, source, and RAP content affected mixture stiffness.

Effect of RAP Content on Mixture Stiffness. Figures 21-23 show the master curves of the ten New Hampshire mixtures sorted by virgin binder grade. Figure 21 presents the master curves of the three mixtures using the PG 58-28A binder, while Figure 22 shows the master curves of the three mixtures using the PG 70-28A binder. Figure 23 shows the virgin and 55% RAP mixtures using both the PG 58-28 and 70-28 binders from source B. From a visual inspection of the master curves, it can be seen that a distinct separation exists between the virgin mix master curves and those of the RAP mixes in the intermediate reduced-frequency range (middle portion of the graphs). All the RAP mixtures were stiffer than their respective virgin mixtures in the intermediate temperature portion of the master curve. The increase in stiffness in this portion of the curve, however, was not always proportional to the amount of RAP in the mixture. When the softer binder was used (Figure 21), the

55% RAP mixture was stiffer than the 25% RAP mixture at intermediate temperatures; however, the converse was true when the stiffer binder was incorporated into the mixture (Figure 22).

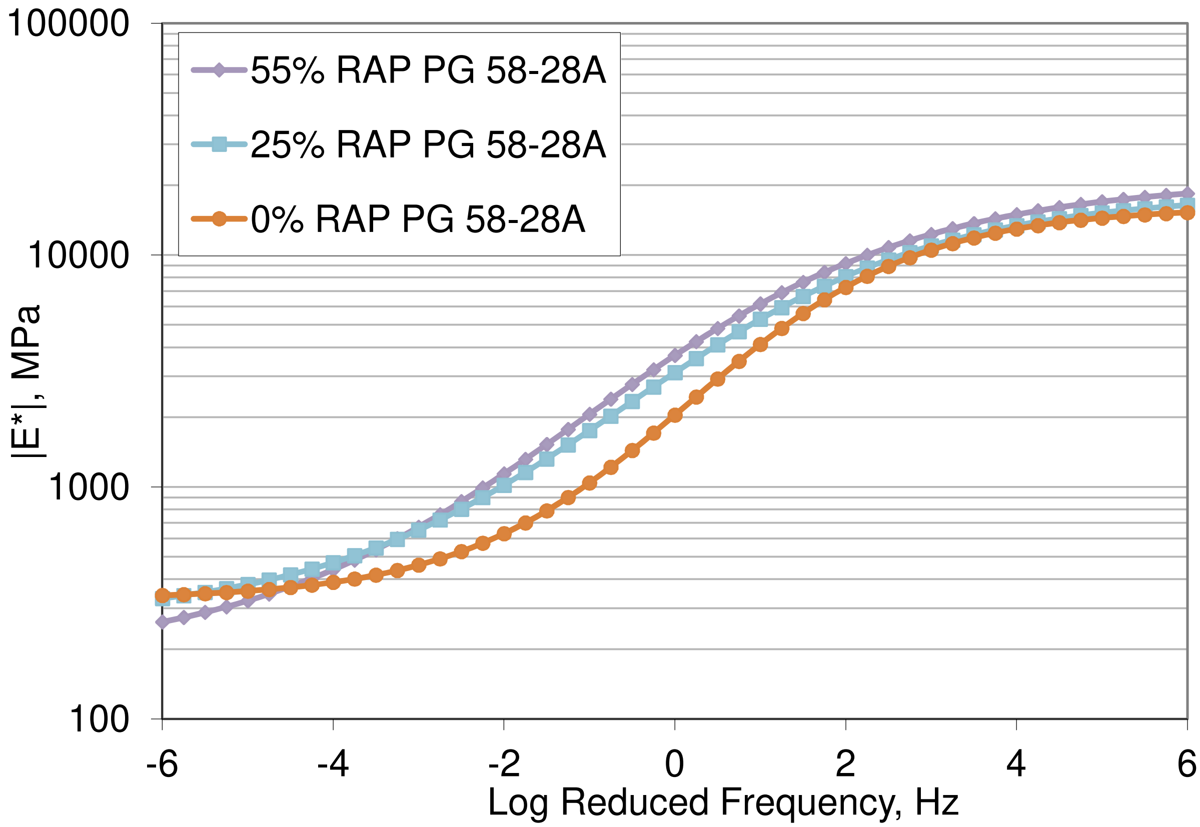


Figure 21 New Hampshire Mixtures using PG 58-28A Master Curves

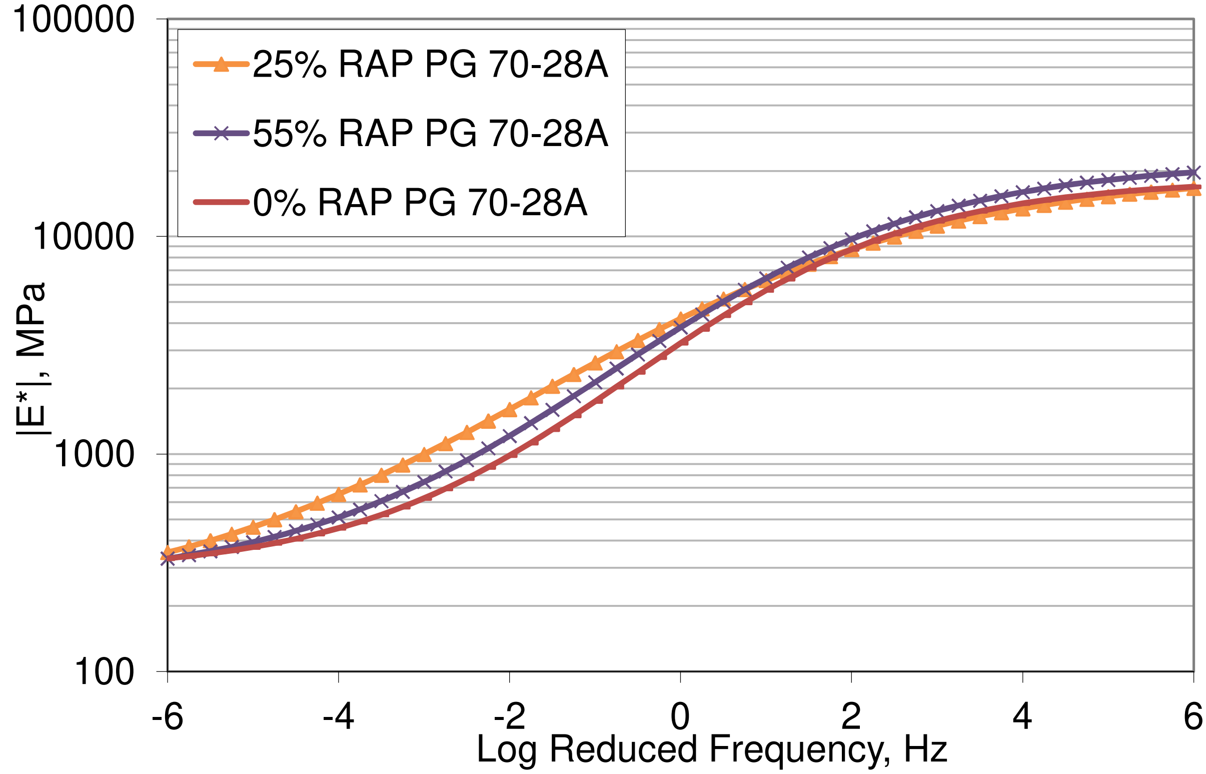


Figure 22 New Hampshire Mixtures using PG 70-28A Master Curves

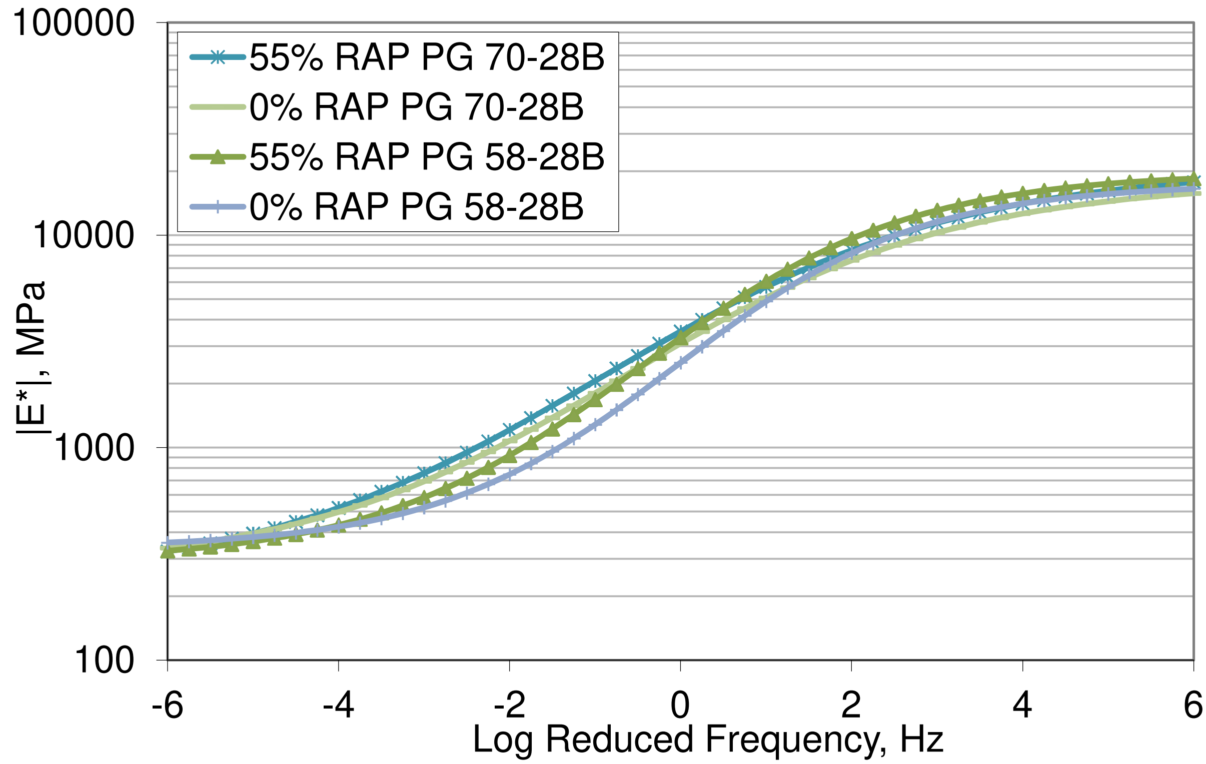


Figure 23 New Hampshire Mixtures using PG 58-28B and PG 70-28B Master Curves

Effect of Virgin Binder Grade on Mixture Stiffness. Figures 24-26 display the New Hampshire mixture master curves by RAP content to assess how the virgin binder grade affects mixture stiffness. From each of these plots, the effect of the binder grade is most apparent at the intermediate reduced frequency range. Master curves appear to converge near the cold and high-temperature regions of the master curves due to limits in the sigmoidal functions used to create the master curves. When visually examining the virgin mixtures in Figure 24, it can be seen that increasing the virgin binder grade of the mixtures from both binder sources increases the stiffness of the mixtures by almost 100%. For the 25% RAP mixtures, shown in Figure 25, increasing the virgin binder by two full grades at the high-temperature range increased the mix stiffness by about 40%. For the 55% RAP mixtures, shown in Figure 26, increasing the virgin binder grade increased the mixture stiffness when using binder source B; however, it did not affect the mixture stiffness when using binder source A. In addition, while the master curves for both 55% RAP mixtures using the PG 58-28 binder and the 55% RAP mix using the PG 70-28A binder converged, the 55% RAP mixture using the PG 70-28 from binder source B was actually the least stiff at the high-temperature range of the master curve. Overall, the results suggest that as RAP content increases, the effect of the virgin binder grade becomes less influential as would be expected due to the higher proportion of reclaimed binder.

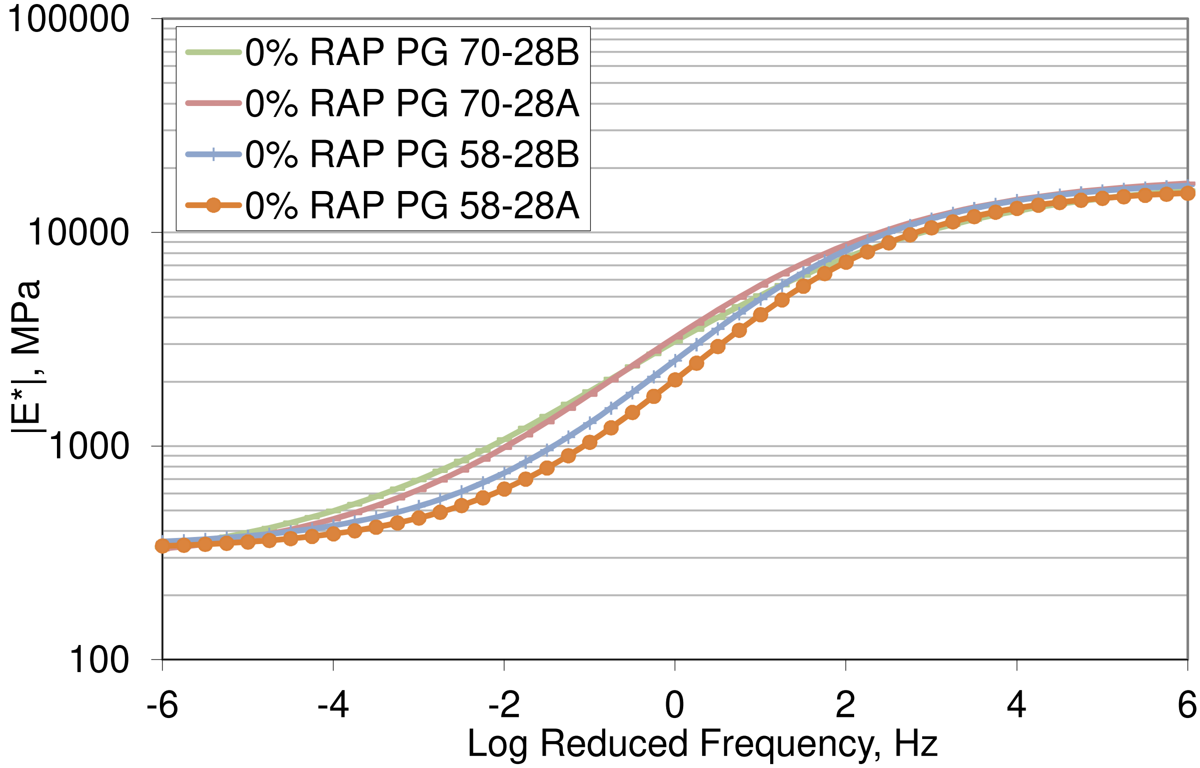


Figure 24 New Hampshire Virgin Mixtures Master Curves

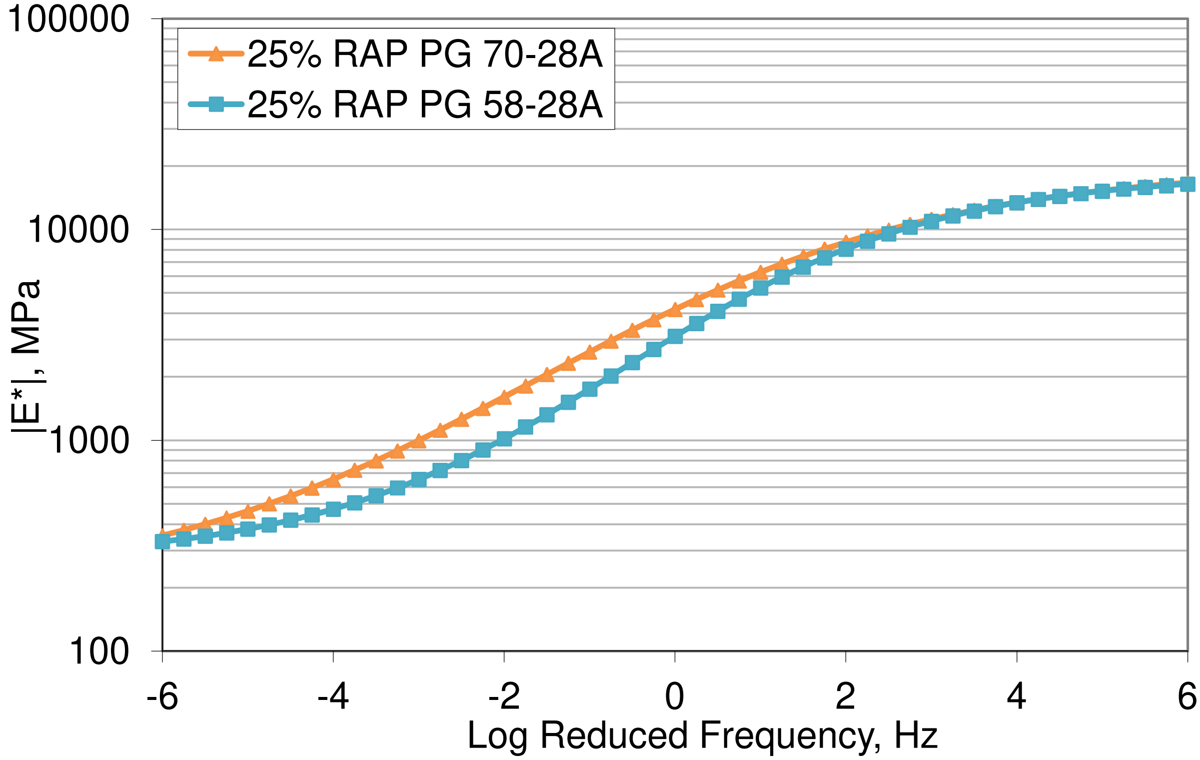


Figure 25 New Hampshire 25% RAP Mixtures Master Curves

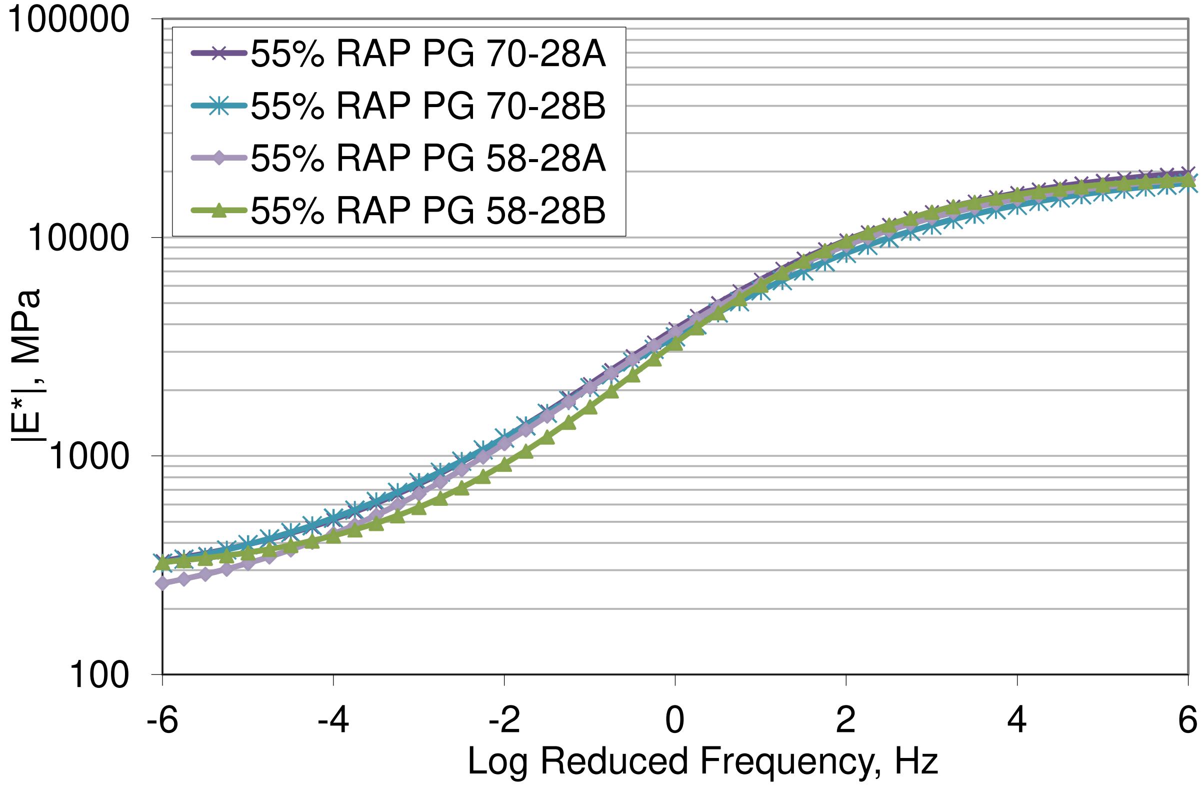


Figure 26 New Hampshire 55% RAP Mixtures Master Curves

Effect of Binder Source on Mixture Stiffness. A final visual analysis of master curves was conducted by comparing the New Hampshire mixtures with similar binder grades from different sources. For the New Hampshire mixtures the true grades of the binders did not vary by more than 4°C at either the high or low critical temperature. These comparisons are presented in Figures 27-30. The results for four virgin mixtures were compared in Figures 27 and 28 for the PG 58-28 binders and PG 70-28 binders, respectively. In Figure 27, the results of the mixture with binder source B appear slightly higher than the E* results for the mixture with source A. An inspection of the average E* values from source B were about 12% higher through the intermediate region of the master curve. At the low-temperature end of the master curves, this difference is reduced to between 5 and 9%. The two master curves converge to stiffnesses within 2 psi of each other at the high-temperature region of the curve.

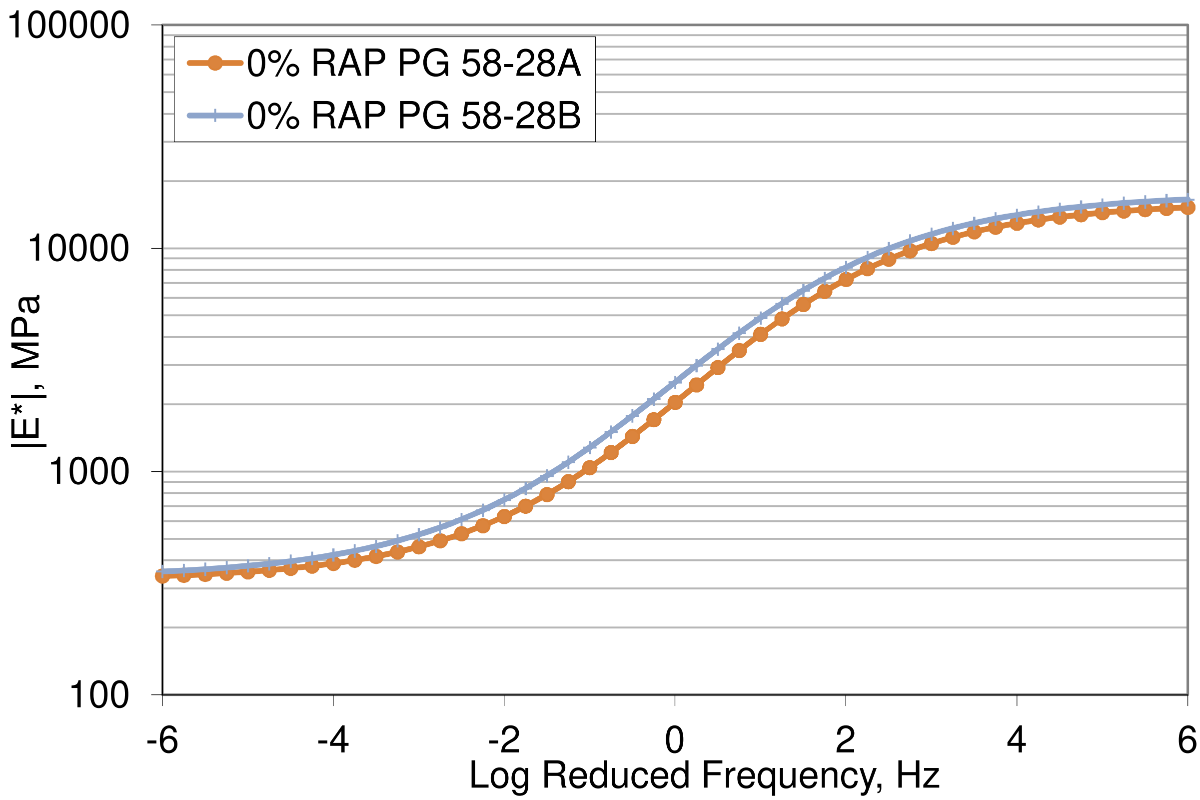


Figure 27 New Hampshire Master Curves for Virgin Mixtures using PG 58-28 Binder

Figure 28 shows a different trend. Using the higher PG grade binders, the master curves of the two mixtures converged at the intermediate temperatures but deviated at the higher and lower temperatures. As with the virgin binder mixtures using the PG 58-28 binders, the maximum difference between mixture stiffness at any point on the master curve was approximately 10%. Based on these results, changing virgin binder source may not significantly affect the stiffness of virgin mixtures.

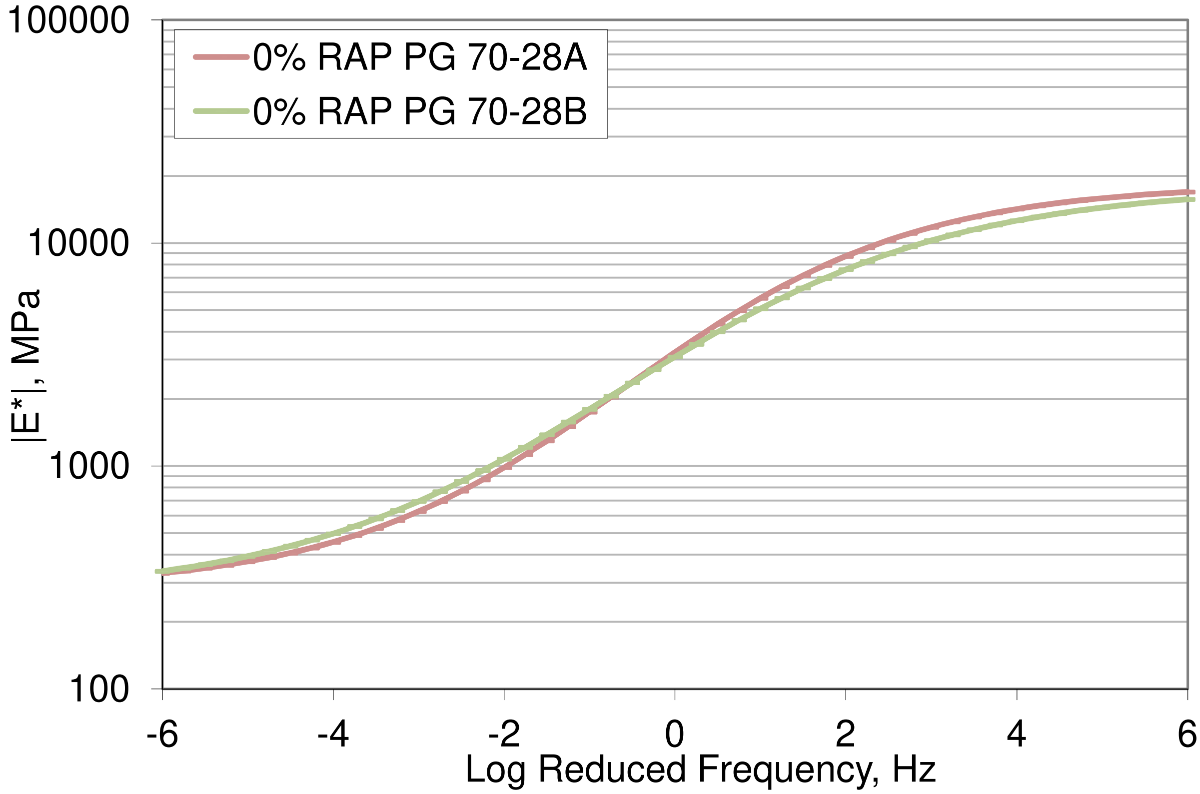


Figure 28 New Hampshire Master Curves for Virgin Mixtures using PG 70-28 Binder

The 55% RAP mixtures also were designed using PG 58-28 and PG 70-28 binders from two different sources. Figure 29 shows the master curves of the two 55% RAP mixtures using the PG 58-28 binders. As can be seen, at the cold temperature, high-frequency portion of the master curve, the mixtures have similar stiffnesses but deviate as the master curves approach the more intermediate and high temperatures. The differences at the intermediate temperatures show the mixture using binder source B are softer by 15 to 20%. However, at the high-temperature, low-frequency section of the master curve, the mixture using binder source B is stiffer by about 20%.

Figure 30 shows the master curves for the two 55% RAP mixtures designed with the PG 70-28 binders. These two master curves are very similar at the high-temperature, low-frequency portion of the curves and through the intermediate temperatures. Even when the mixtures deviate at the right hand side of the master curves (low-temperature, high-frequency), the differences are typically less than 10%.

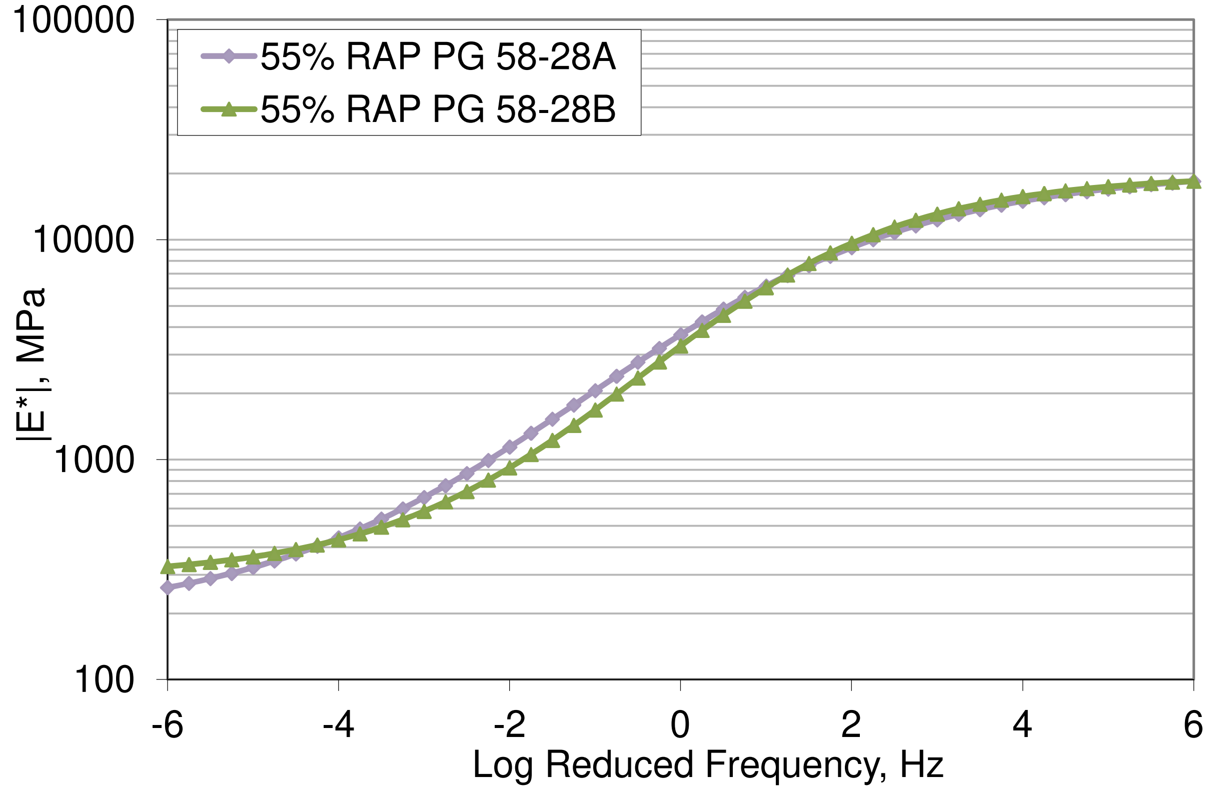


Figure 29 New Hampshire Master Curves for 55% RAP Mixtures using PG 58-28 Binder

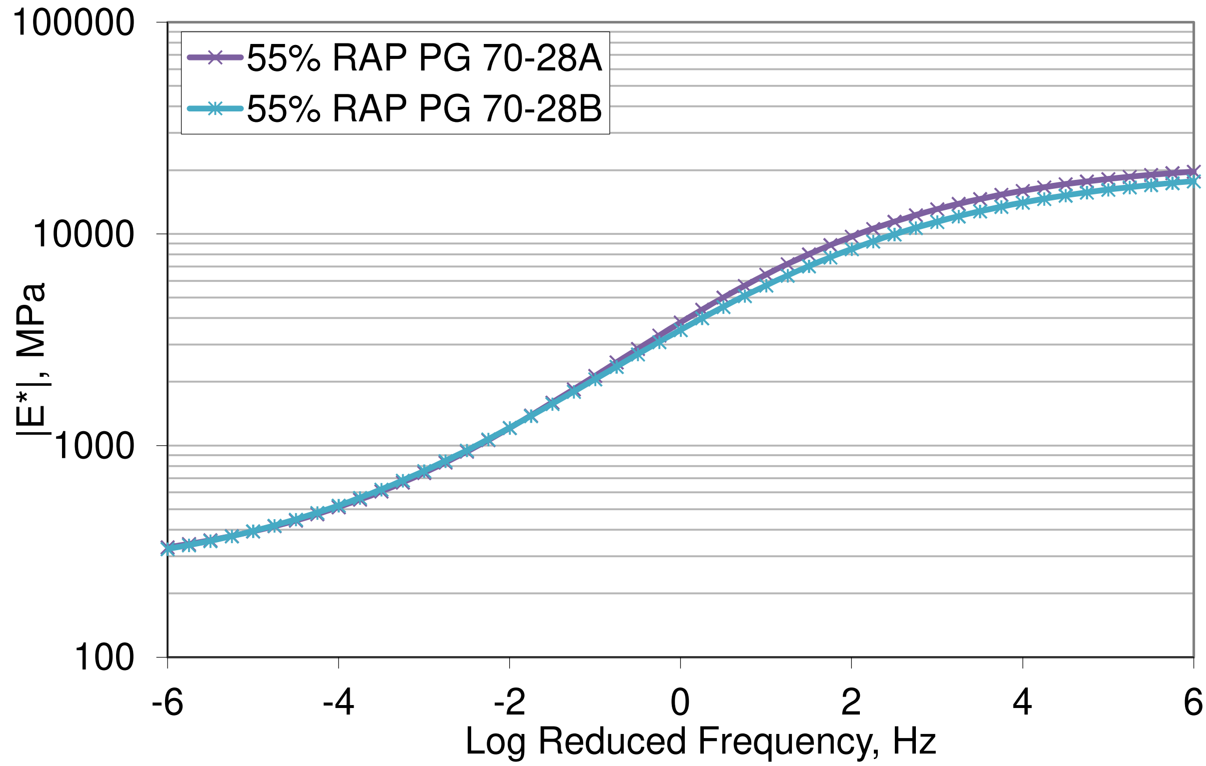


Figure 30 New Hampshire Master Curves for 55% RAP Mixtures using PG 58-28 Binder

As with the effect of the virgin binder grade, which showed less effect on the mixture as RAP content increased, the source of the virgin binder also appeared to make less difference on the mixture stiffness for the 55% RAP mixtures than the virgin mixtures.

To statistically assess the effect of the mix factors on mixture stiffness, a General Linear Model (GLM) ($\alpha = 0.05$) was conducted on the E* data measured at 1 Hz. The frequency of 1 Hz was chosen simply because it was the middle frequency. For this analysis, the binder grade, binder source, and RAP content were chosen as factors for the GLM. The *p*-values for the three factors at the four test temperatures are given in Table 26. The statistical analyses confirm the RAP content is the most critical factor affecting the mixture stiffness for the New Hampshire mixtures at all four temperatures. Binder grade was statistically significant at the intermediate and high temperatures. At the low testing temperature, the binder grade did not significantly influence the mixture stiffness. The least important of the three mixture properties in determining mixture stiffness was binder source. Binder source was statistically significant only at the extreme testing temperatures.

Table 26 New Hampshire E* GLM Results *p*-values

Mix Factor	Test Temperature (°C)			
	4.4	*21.1*	*37.8*	*54.4*
Binder Grade	0.124	0.000	0.000	0.000
Binder Source	0.010	0.428	0.226	0.041
% RAP	0.000	0.000	0.000	0.000

Utah Mixtures

The ten mixtures designed using the materials from Utah included two binder grades (PG 58-34 and PG 64-34), two binder sources, three RAP contents (0, 25, and 55%), and one NMAS (12.5 mm). A mix was developed using a WMA technology to determine how WMA affects mixture stiffness. The following subsections assess how binder grade, source, as well as RAP content and WMA affected dynamic modulus results.

Effect of RAP Content on Mixture Stiffness. Figures 31-33 show the master curves of ten Utah mixtures sorted by binder grade. Figure 31 presents the master curves of the three mixtures using the PG 58-34A binder while Figure 32 shows the master curves of the three mixtures using the PG 64-34A binder. Figure 33 shows the virgin and 55% RAP mixtures using both the PG 58-34 and

64-34 binders from source B. In general, mixes containing RAP had higher stiffness at the right end (low-temperature, high-frequency) and middle (intermediate temperatures) portions of the master curves. At the extreme high-temperature, low-frequency range, most of the mixtures were within approximately 20% of each other. However, the percent difference is not an good indicator of significance at this reduced frequency range since the differences in stiffness between the mixtures was only 10 ksi. For the softer binder from source A, comparing virgin mixture to 25% RAP showed an increase in stiffness; however, increasing the RAP content to 55% made little to no visual difference in the master curves of the two mixtures. For the stiffer binder from source A, an opposite trend was evident. Changing from a virgin mixture to 25% RAP made little difference in the stiffness of the asphalt mixture; however, the 55% RAP content appeared to make a substantial upward shift in the master curve.

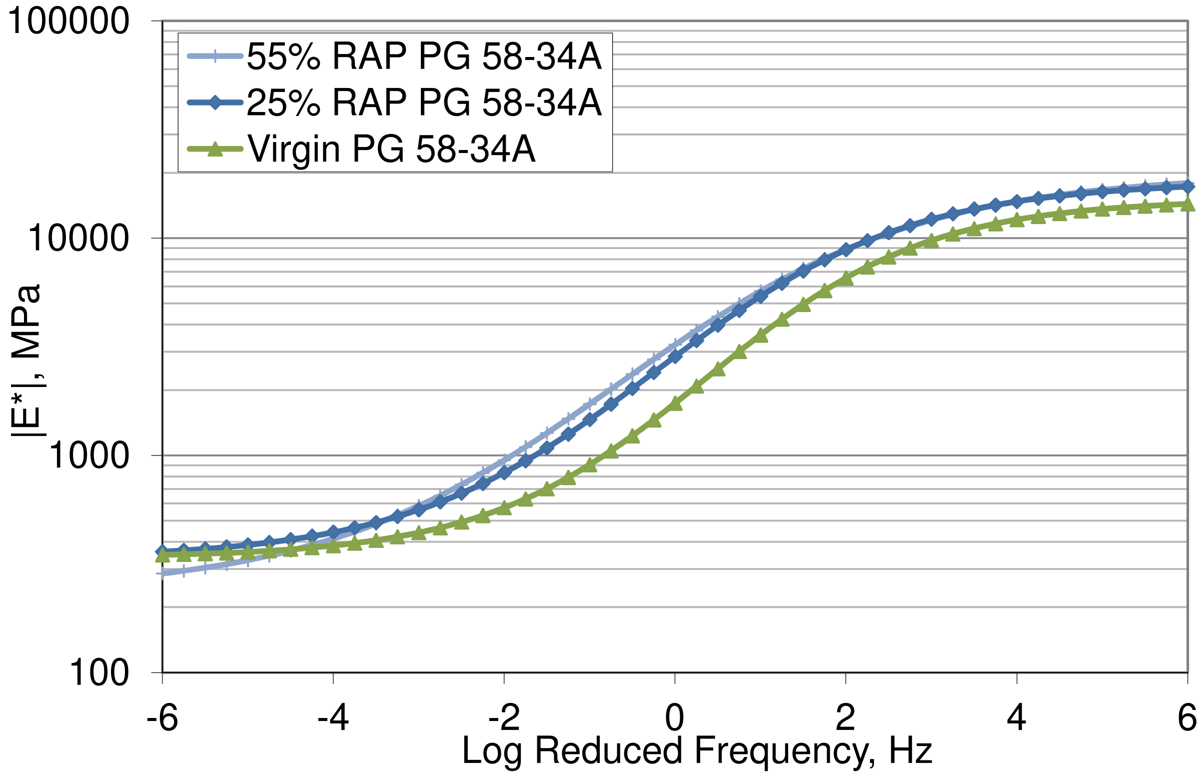


Figure 31 Utah Master Curves for Mixtures Using PG 58-34A

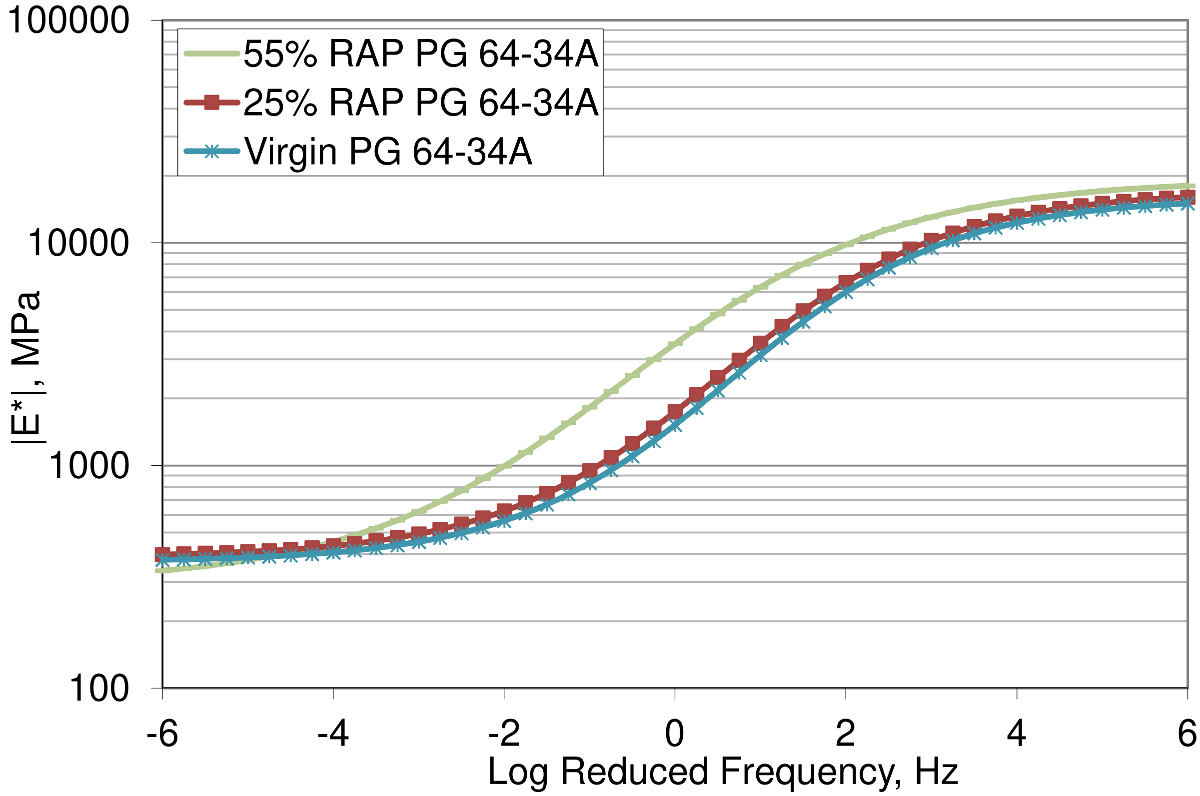


Figure 32 Utah Master Curves for Mixtures Using PG 64-34A

While the same trends were not evident for the mixtures using binders from source B, it can be seen in Figure 33 that the master curves for the 55% RAP content mixes were stiffer at the intermediate and cold temperatures than the corresponding virgin mixtures. Overall, the trend was noticed that mixture stiffness increased for mixtures with higher RAP contents; however, the increase in stiffness was not always proportional or consistent with the amount of RAP used in the mixture.

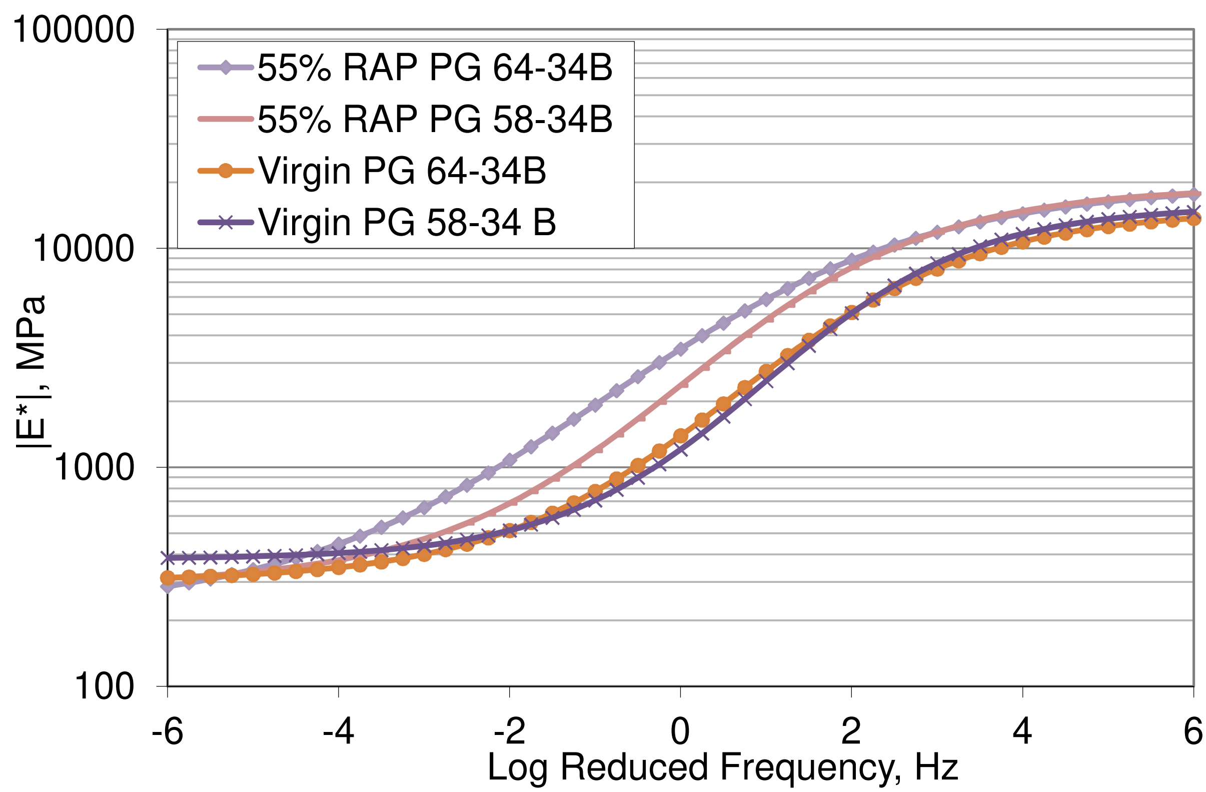


Figure 33 Utah Master Curves for Mixtures Using PG 58-34B and PG 64-34B

Effect of Binder Grade on Mixture Stiffness. Two binder grades were used for the Utah mix designs (PG 58-34 and PG 64-34). Unlike the New Hampshire mixtures, where there was a difference of two performance grades in the critical high temperature of the virgin binders, the difference for Utah binders was only one performance grade. Figures 34-36 show the master curves for the Utah mixtures comparing the effect of virgin binder grades. In Figure 34, it can be seen that the four virgin mixtures had similar master curves at the low-temperature, high-frequency region. At the high-temperature, low-frequency portion of the curve, there is some deviation between the stiffnesses of the mixtures using different binder grades; however, these differences are less than 12%. At the intermediate temperature and frequency portion of the curves, the differences are not very drastic between binder grades, as they are typically less than 10%.

The master curves of the two 25% RAP mixtures with two binder grades are shown in Figure 35. At the extreme temperatures, there is little visual difference in the two master curves. However, at intermediate temperatures, the stiffness increases by over 60% when using a PG 64-34 binder compared to the PG 58-34 binder.

The master curves of the 55% RAP mixtures (Figure 36) presented conflicting results. The mixture using binder source A showed little difference in the stiffness of the mixtures using different binder grades (similar to the virgin mixtures). However, the mixtures using the binders from source B followed the trends seen for the 25% RAP mixtures. The extreme temperatures showed similar mixture stiffnesses; however, a 60% difference in mixture stiffness was seen through the intermediate range of temperatures.

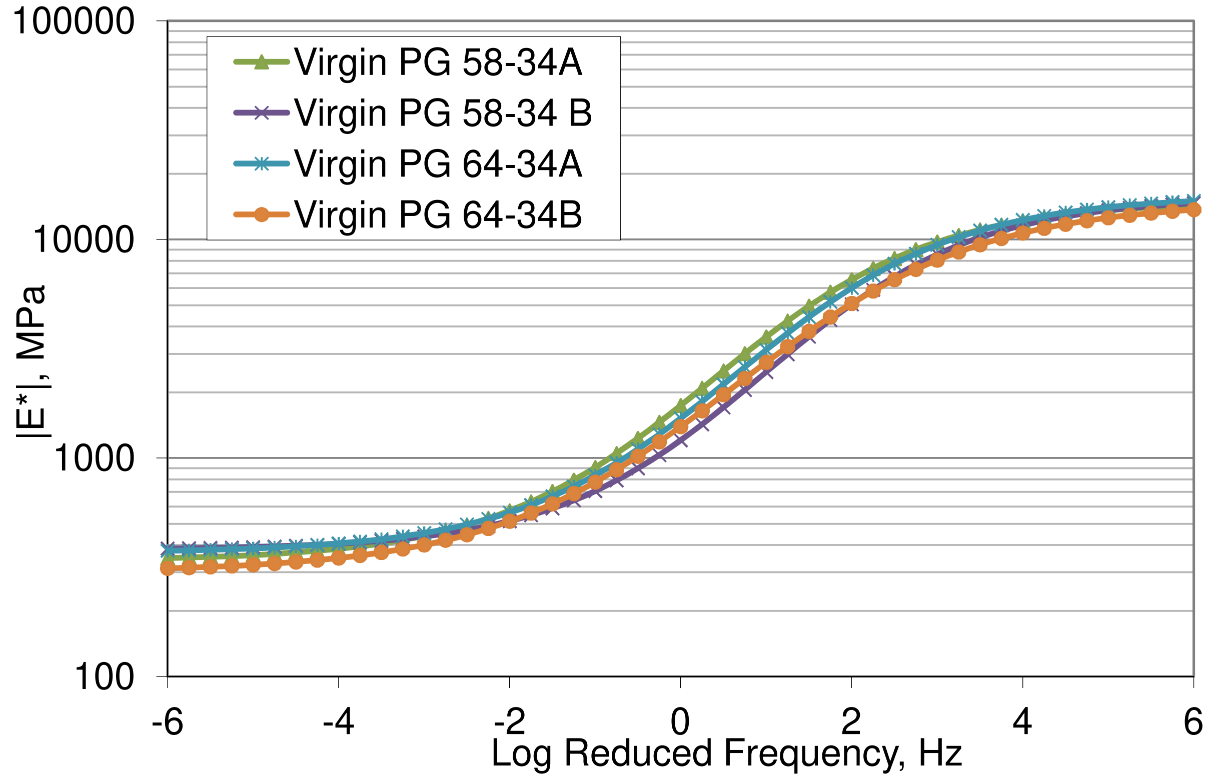


Figure 34 Utah Master Curves for Virgin Mixtures

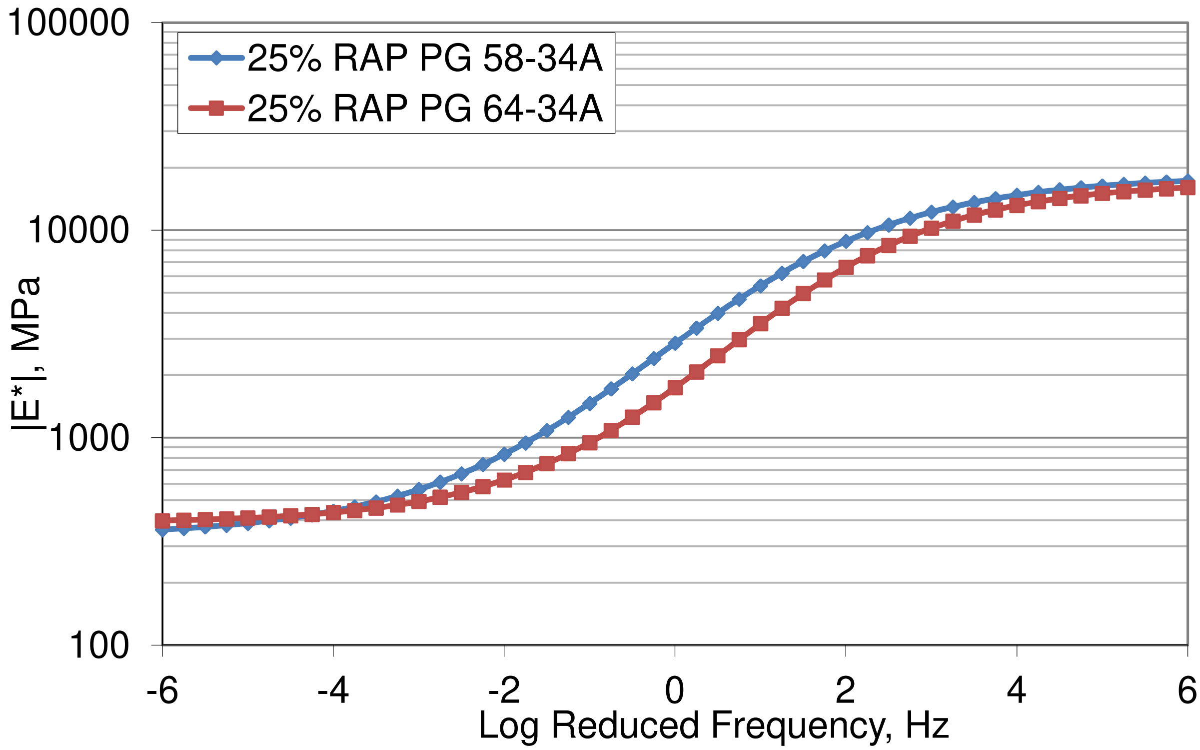


Figure 35 Utah Master Curves for 25% RAP Mixtures

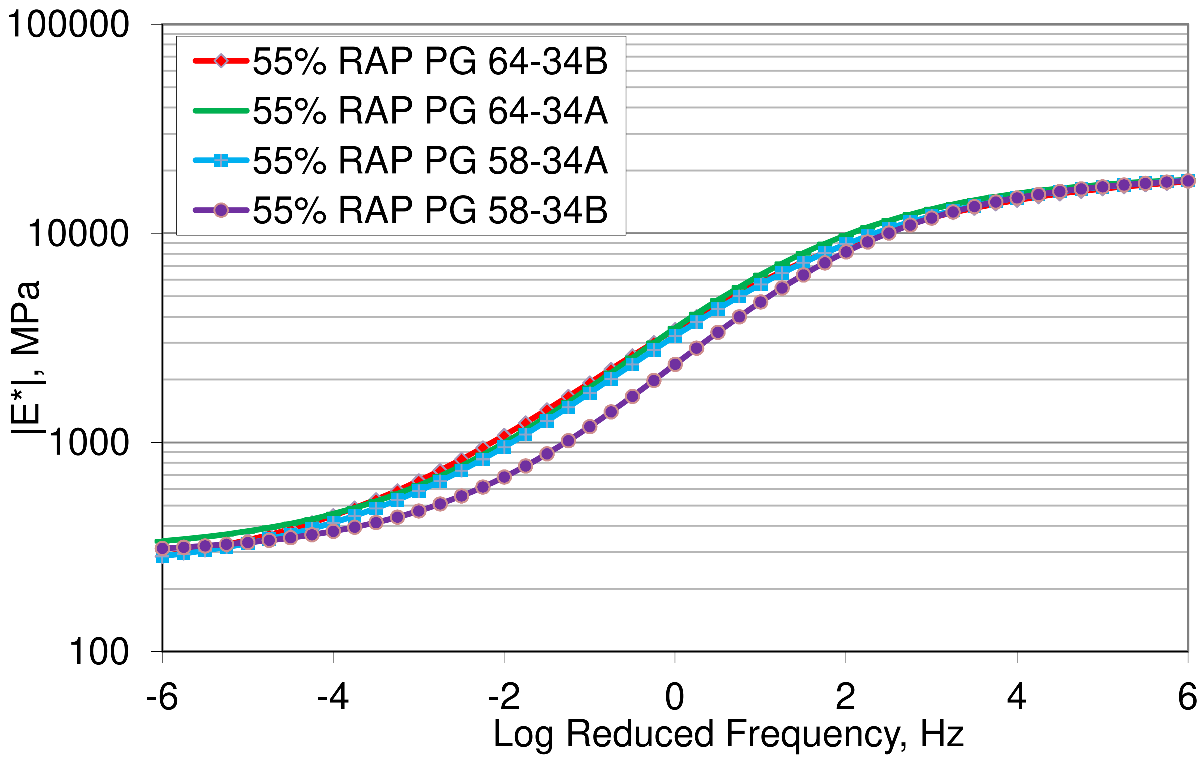


Figure 36 Utah Master Curves for 55% RAP Mixtures

Effect of Binder Source on Mixture Stiffness. Figures 37 and 38 show the master curves for the virgin and 55% RAP mixtures using different binder sources. For the mixtures containing PG 58-34 binders, it can be seen that the master curves of the mixtures from the different binder sources converge at the extreme cold-temperature range of the master curves. At the extreme hot-temperature, low-frequency side of the curves, a 6 to 7 psi difference in mixture stiffness was observed based on the binder source. The greatest deviations in mixture stiffness occur through the intermediate temperature range of the curves. For the virgin mixture, changing from binder source A to B reduced the mixture stiffness by almost 50%. While the reduction in stiffness was not as great for the 55% RAP mixture, the stiffness reduction was still approximately 30%.

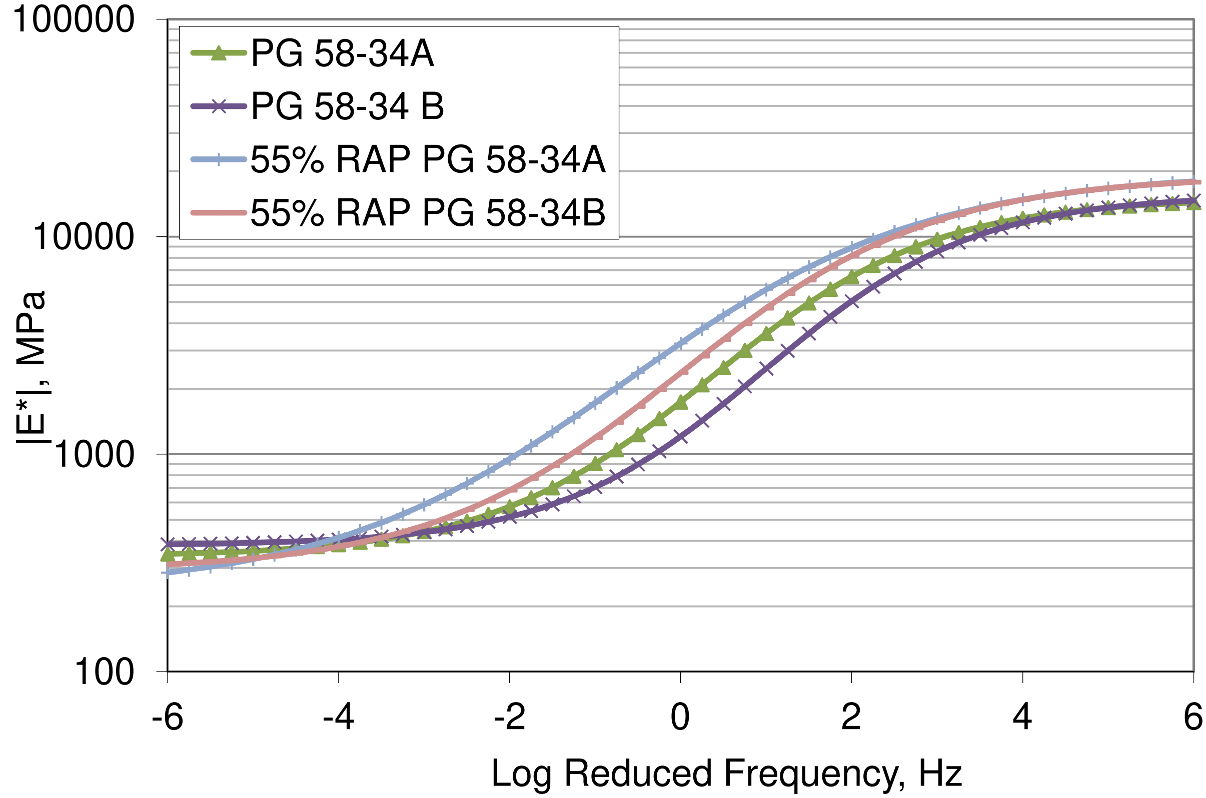


Figure 37 Utah Master Curves for Mixtures with PG 58-34 binders

While the binder source seemed to affect the mixture stiffness of the Utah mixtures containing PG 58-34 binders, little difference was noticed in the master curves of the mixtures containing PG 64-34 binders, as can be seen in Figure 38. It is unknown why this occurred for the mixtures using a softer virgin binder while the mixtures with the stiffer binder were not affected by changing binder source; however, these results emphasize that one must consider the source of the virgin binder when designing mixtures. This is especially critical if dynamic modulus data are to be used in a design methodology such as mechanistic-empirical pavement design.

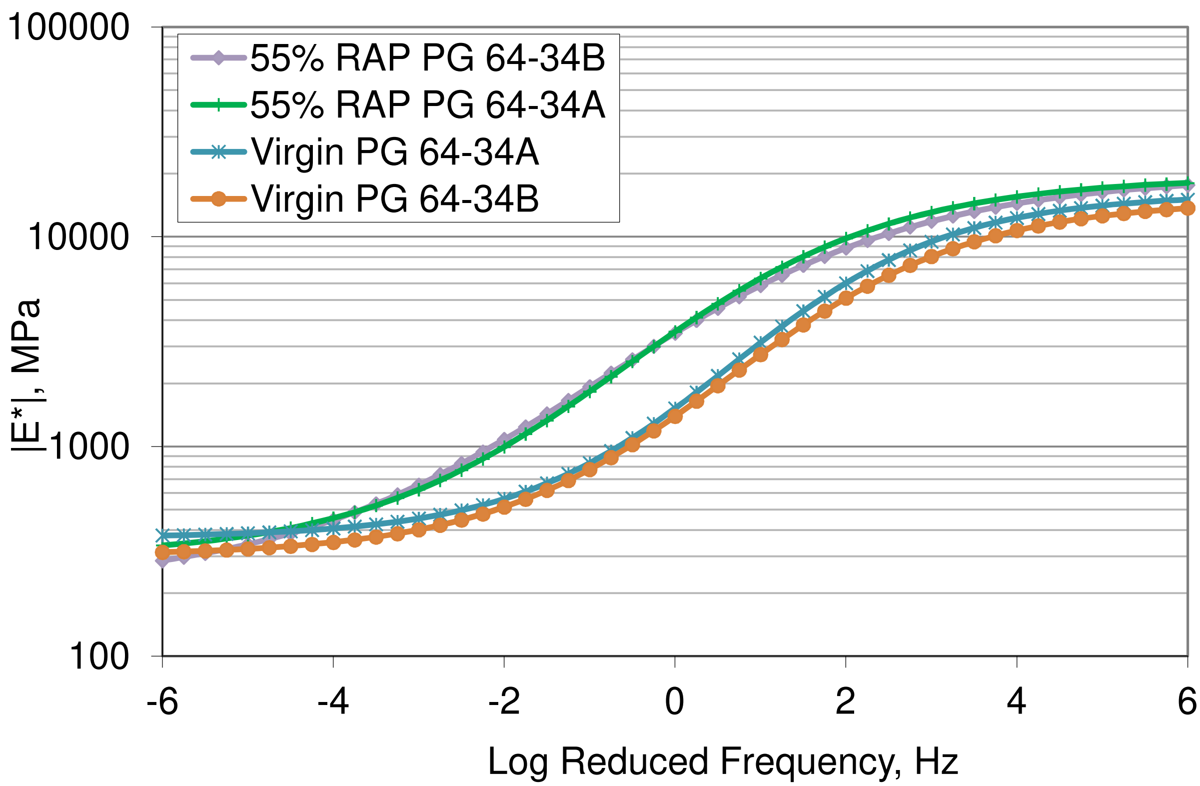


Figure 38 Utah Master Curves for Mixtures with PG 64-34 binders

Effect of WMA on Mixture Stiffness. A final comparison was conducted to determine how WMA affected the mixture stiffness of an asphalt mixture with 55% RAP (Figure 39). As can be seen, the high RAP mixture with WMA presents a similar master curve to the mixture designed and compacted as HMA. Through the intermediate temperatures, the average difference between the HMA and WMA mixtures is approximately 10%. A 15% difference in mixture stiffness was noticed at the hot end of the master curve while the difference at the cold end of the master curve is less than 6%.

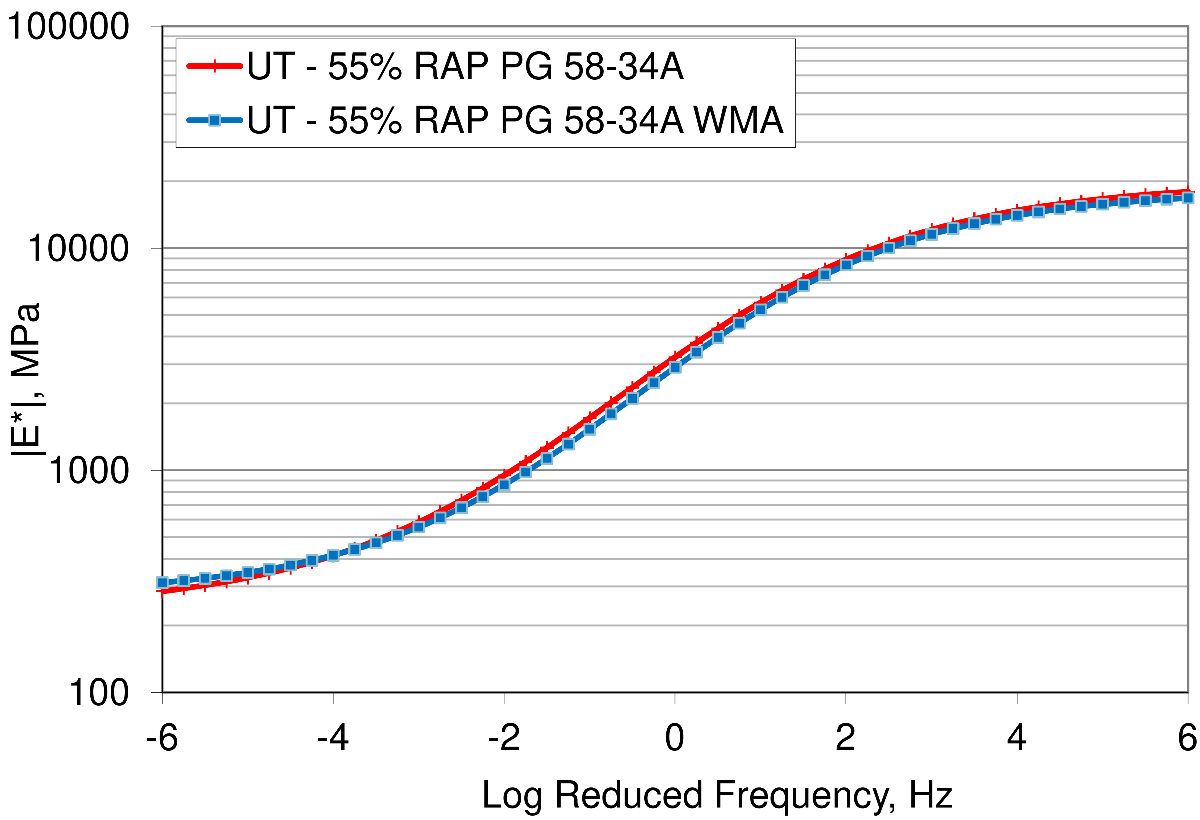


Figure 39 Effect of WMA on Mixture Stiffness

To statistically assess how mix factors affected mixture stiffness through the range of temperatures expected in service, a General Linear Model (GLM) ($\alpha = 0.05$) was conducted on the E* data measured at 1 Hz. For this analysis, the binder grade, binder source, and RAP content were chosen as variables for the GLM. The *p*-values for the three mixture properties at all four temperatures are given in Table 27. RAP content was again the most critical factor affecting mixture stiffness. At all three test temperatures, this factor was statistically significant. The trends showed that increasing RAP content typically increased mixture stiffness. The virgin binder grade of the mixture was statistically significant only at the lowest testing temperature. This differs from the New Hampshire results; however, it is important to remember that the difference between the critical high temperatures of the Utah binders was not as great as the difference between the critical high temperatures of the New Hampshire binders. Additionally, while there were differences in the master curves of the mixtures using the PG 58-34 binder from different sources, the differences in stiffness of the mixtures with the PG 58-34A and PG 58-34B binders were not great enough to make binder source a statistically significant mixture property in this statistical analysis.

Table 27 Utah E* GLM Results *p*-values

Mix Factor	Test Temperature (°C)			
	4.4	*21.1*	*37.8*	*54.4*
Binder Grade	0.047	0.759	0.160	0.445
Binder Source	0.125	0.081	0.196	0.204
% RAP	0.000	0.000	0.000	0.000

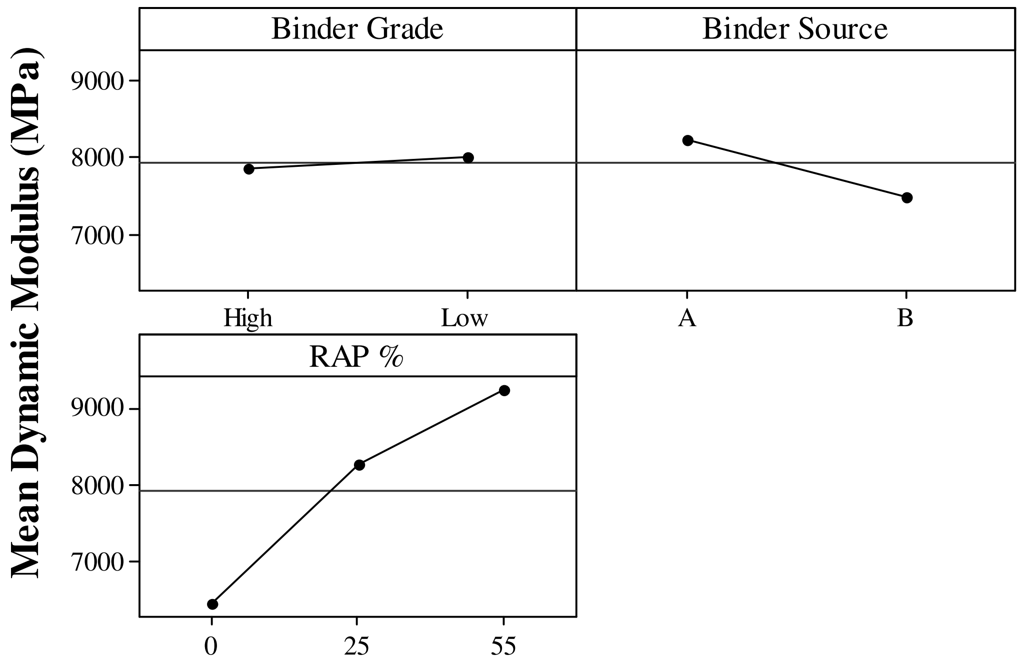
Effects of Mix Design Factors on Dynamic Modulus

An ANOVA was also used to identify the mix factors that significantly affected the dynamic modulus results at each temperature and frequency using the combined data from New Hampshire and Utah. The factors included in the analysis were materials source, RAP percentage, virgin binder source, and virgin binder grade. Table 28 shows the results of the analysis. The cells with diamonds indicate which factors were significant for a given temperature and frequency. It can be seen that the materials source and RAP content were significant across nearly all temperatures and frequencies. The effect of materials source and RAP content are logical. The materials from the two sources had different characteristics, and the mix designs differed by gradations, volumetric properties, and virgin binder grades. Also as expected, mix designs with 55% RAP were significantly stiffer than virgin mixes. Virgin binder source typically was significant at the intermediate temperature of 21.1°C. Virgin binder grade significantly affected most of the dynamic moduli at 37.8°C. The virgin binder grade also significantly affected the dynamic modulus results at the lowest frequency.

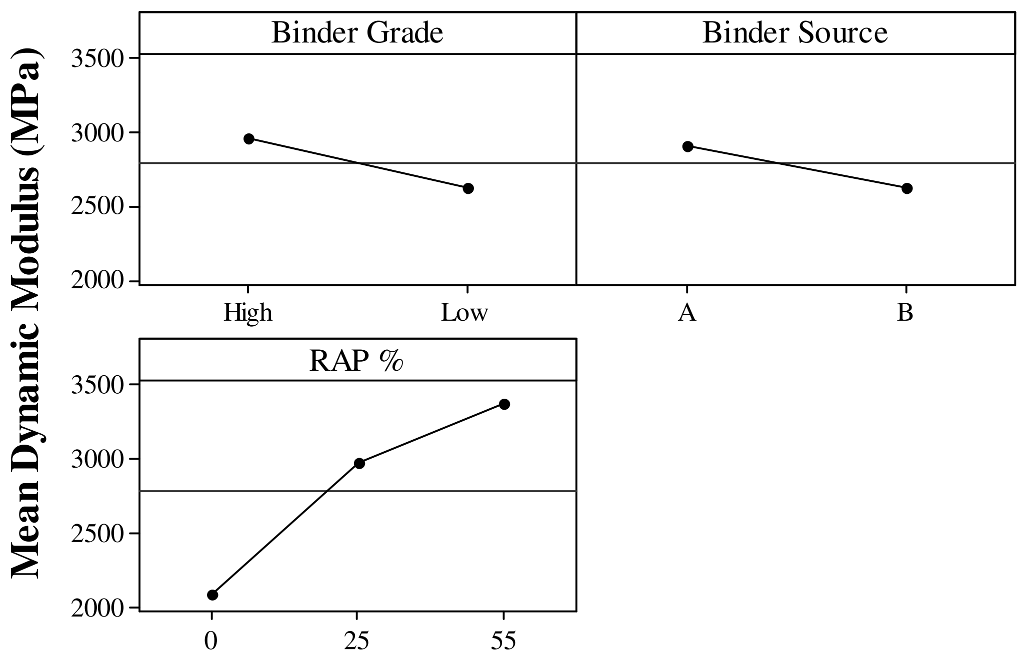
A better sense of the magnitude of the effects of the factors on mix stiffness can be seen in the Main Effects plots in Figure 40. It can be seen that RAP content had the largest impact at all temperatures. Compared to the virgin mixes, the stiffnesses of the 25% RAP mixes were about 30% to 43% higher, with the greatest differences occurring at the intermediate temperature ranges. The 50% RAP mixes were about 25% to 60% stiffer than the virgin mixes with the greatest difference occurring at the 21.1°C. The influence of the virgin binder grade was much more evident at higher temperatures, which is consistent with the fact that the different binder grades used in the mix designs only varied by the high PG number.

Table 28 ANOVA Results for Mixes with Multiple Binder Sources

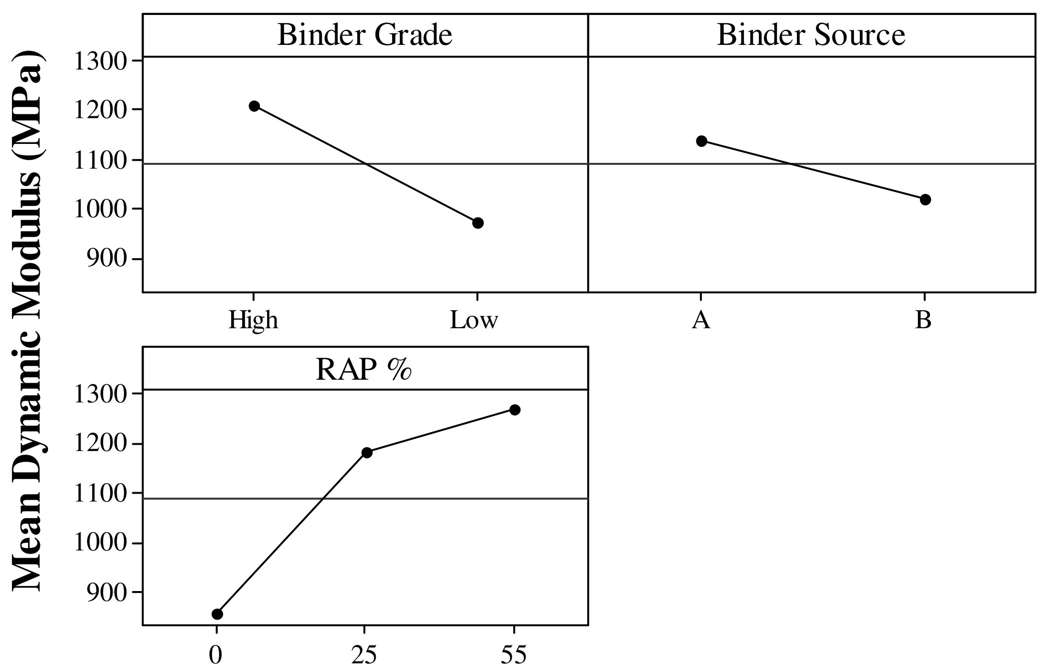
Frequency	Temperature (°C)	Material Source	RAP Percentage	Binder Source	Virgin Binder Grade
25	4.4	♦	♦		♦
	21.1	♦	♦	♦	♦
	37.8	♦	♦		
	54.4		♦		
10	4.4	♦	♦		
	21.1	♦	♦	♦	
	37.8	♦	♦		♦
	54.4		♦		
5	4.4	♦	♦		
	21.1	♦	♦	♦	
	37.8	♦	♦		♦
	54.4		♦		
1	4.4	♦	♦		
	21.1	♦	♦	♦	♦
	37.8	♦	♦		♦
	54.4	♦	♦		
0.5	4.4	♦	♦		
	21.1	♦	♦	♦	♦
	37.8		♦		♦
	54.4	♦	♦	♦	
0.1	4.4	♦	♦		
	21.1	♦	♦		♦
	37.8	♦	♦		♦
	54.4	♦	♦	♦	♦



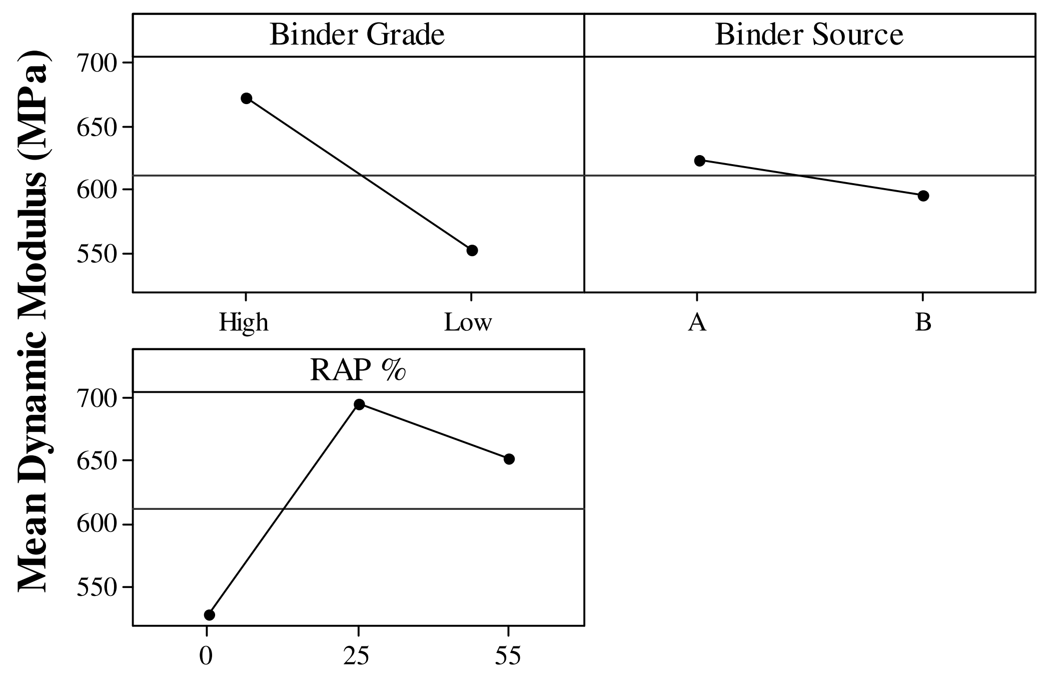
Main Effects Plot for E* at 4.4°C



Main Effects Plot for E* at 21.1°C



Main Effects Plot for E* at 37.8°C



Main Effects Plot for E* at 54.4°C

Figure 40 Main Effects Plots of Experimental Factors on Dynamic Moduli

Minnesota Mixtures

Figure 41 shows the master curves for the four mixtures produced using Minnesota materials. It can be seen that the mastercurves for these four mixtures never really converge. At every point along the master curve, the mixtures with 40% RAP were numerically stiffer than the virgin mixtures. It should also be noted that while the NMAS of the aggregate seemed to have little effect on the E* of the virgin mixtures, the 19.0 mm mixtures with 40% RAP were consistently stiffer than the 9.5 mm mixtures.

To assess how RAP content, virgin binder grade, and binder source affected mixture stiffness through the range of temperatures expected in service, a General Linear Model (GLM) ($\alpha = 0.05$) was completed on the E* data measured at a frequency of 1 Hz. For this analysis, the only terms assessed were NMAS and RAP content. The *p*-values for both factors at all four temperatures are given in Table 29. The statistical analyses confirm the RAP content is again the most critical factor that affects the mixture stiffness for the Minnesota mixtures at three of the four temperatures. The greater the percent RAP in the mixture, the greater the mixture stiffness. The NMAS of the aggregate structure was statistically significant at 4.4 and 37.8°C. However, it was not statistically significant at all four testing temperatures showing the percent RAP in the mixture is consistently the most influential component of mixture stiffness.

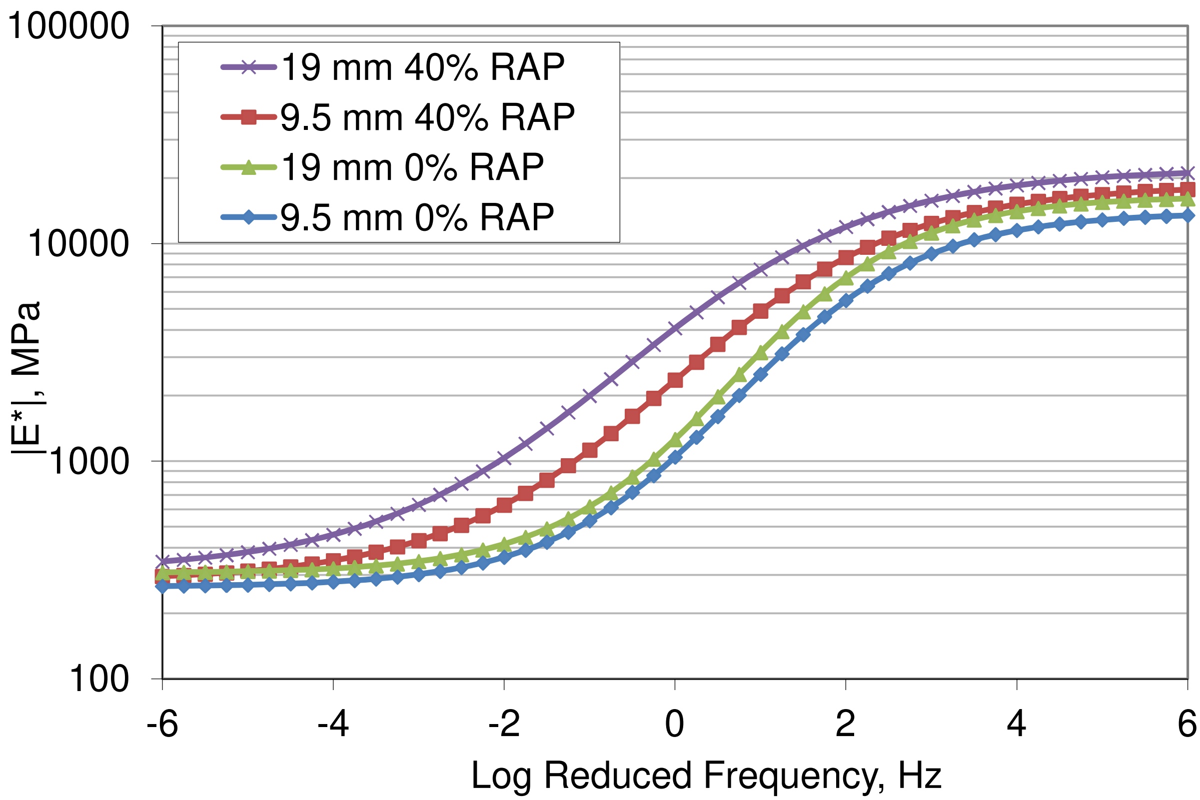


Figure 41 Minnesota Mixture Master Curves

Table 29 Minnesota E* GLM Results *p*-values

Mix Factor	Test Temperature (°C)			
	4.4	*21.1*	*37.8*	*54.4*
NMAS	0.000	0.755	0.018	0.122
% RAP	0.000	0.097	0.001	0.000

Florida Mixtures

Figure 42 shows the master curves for the four mixtures designed using the materials from Florida. It can be seen that the four master curves tend to converge at the right side of the reduced frequency range (representing low-temperature and high-frequency loading). The sigmoidal function used to develop the master curves had two asymptotes, causing the master curves to display at least a small degree of convergence at the intermediate temperatures. However, when the mixtures were tested at intermediate temperatures, clear separation exists between the mixtures produced using virgin aggregate and mixtures produced with 40% RAP. Both the 9.5 and 19.0 mm mixtures with RAP were stiffer than the corresponding virgin mixtures. When tested at the highest temperatures, all four mixtures have stiffness values within 20% psi of each other.

To assess how RAP content, virgin binder grade, and binder source affected mixture stiffness through the range of temperatures expected in service, a General Linear Model (GLM) ($\alpha = 0.05$) was conducted on the E* data measured at 1 Hz. For this analysis, the only terms assessed were NMAS and RAP content. The *p*-values for these factors at all four temperatures are given in Table 30. The statistical analyses confirm the RAP content is the most critical factor affecting the mixture stiffness for the Florida mixtures at all four temperatures. The greater the percent RAP in the mixture, the greater the mixture stiffness. For the low temperature (4.4°C) and the high-intermediate temperature (37.8°C), the NMAS of the aggregate statistically affected the mixture stiffness. However, the aggregate size did not statistically affect mixture stiffness at 21.1 and 54.4°C.

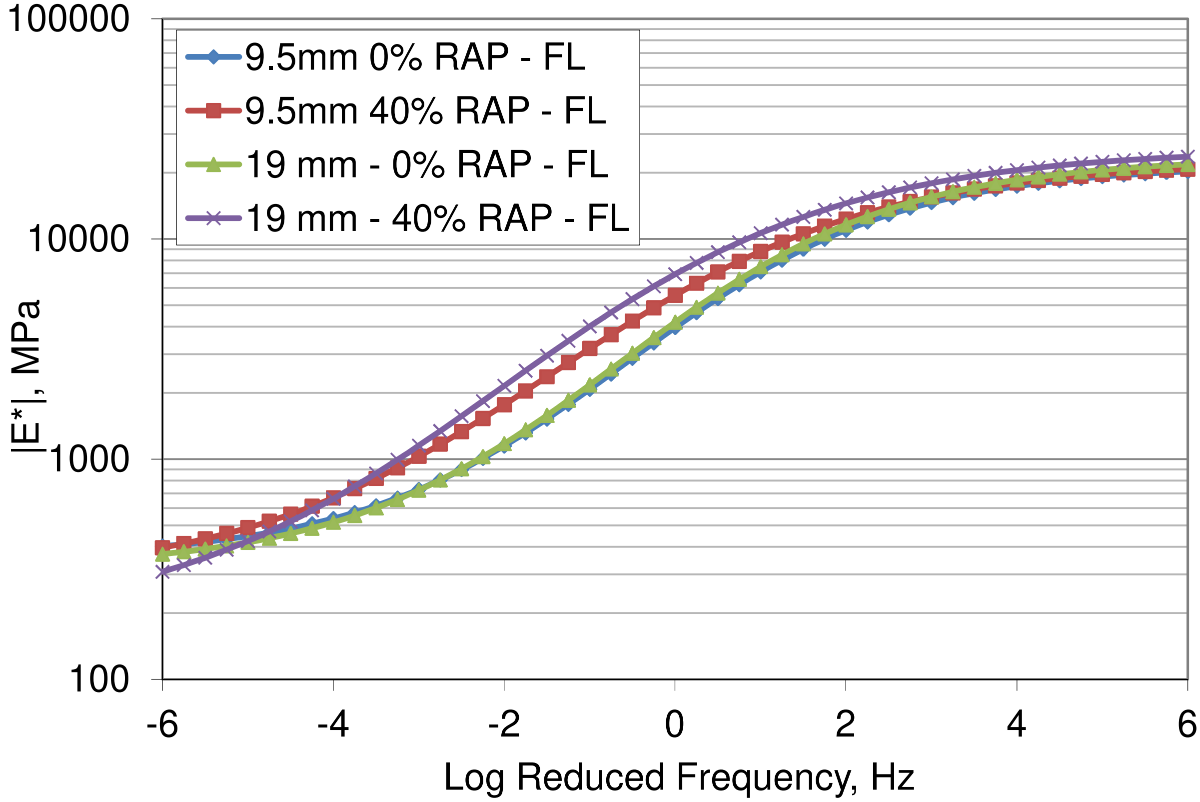


Figure 42 Florida Mixture Master Curves

Table 30 Florida E* GLM Results *p*-values

Mix Factor	Test Temperature (°C)			
	4.4	*21.1*	*37.8*	*54.4*
NMAS	0.000	0.210	0.000	0.313
% RAP	0.000	0.000	0.000	0.002

Backcalculated Effective Binder Grade from Dynamic Modulus Tests

The eight virgin mixtures designed in Phase III were used to initially assess the feasibility of using the backcalculation procedure to determine the effective binder properties of mixtures containing RAP. Virgin mixtures were selected for the initial assessment to avoid the confounding assumption that the extraction and recovery process causes blending of the RAP and virgin binders even though they may not be physically blended in the mixture.

Table 31 shows the measured and predicted critical high and intermediate temperatures as well as the percent error between the measured and predicted values. The "actual" measured critical temperatures shown are from the tank sample virgin binders, so there was no extraction or recovery testing to confound the results. Paired *t*-tests ($\alpha = 0.05$) were used to statistically compare the actual and predicted critical temperatures. The analyses showed the back-calculation statistically under-predicted the actual intermediate temperature ($p = 9.43$ E-07) and statistically over-predicted the actual critical high-temperature grade of the asphalt binders ($p = 0.018$).

Table 31 Actual and Predicted Binder Properties of Virgin NCHRP 9-46 Mixtures

Mixture	Critical Intermediate Temperature, °C			Critical High Temperature, °C		
	Actual	*Predicted*	*% Error*	*Actual*	*Predicted*	*% Error*
FL 19 mm	21.7	13.6	-37.3	72.5	74.7	3.0
FL 9.5 mm	21.7	16.2	-25.3	72.5	83.3	14.9
NH PG 58-28A	17.4	7.8	-55.2	61.5	80.2	30.4
NH PG 58-28B	17.4	5.2	-70.1	60.1	65.2	8.5
NH PG 70-28A	19.3	9.8	-49.2	71.3	73.7	3.4
NH PG 70-28B	15.6	6.2	-60.3	71.4	79.7	11.6
UT 58-34B	9.9	0.9	-90.9	61.2	89.0	45.4
UT 64-34A	9.3	2	-78.5	68.2	63.4	-7.0

A second set of 24 mixtures (Table 32) was also included in the analysis to further assess the backcalculation procedure. These mixtures were produced for the 2009 NCAT Pavement Test Track. Each mixture was sampled during construction and taken to the NCAT laboratory for testing. At the lab, each mixture was reheated for sample preparation in accordance with AASHTO PP 60-09 and then tested for dynamic modulus using AASHTO TP 79-09. These mixtures ranged from virgin mixtures to mixes with high RAP percentages, ground tire rubber, and/or warm-mix asphalt (WMA).

Figure 43 compares the backcalculated versus measured intermediate critical binder temperatures of the 24 test track mixtures. The backcalculation procedure under-predicts 90.6% of the 32 mixtures. On average the model deviated from the measured critical temperature by 7.0°C with a maximum error of 13.1°C and minimum error of 0.4°C.

Figure 44 compares the backcalculated and measured critical high temperatures for the 32 mixtures. While the procedure typically over-predicts the critical high temperature for the laboratory mixtures (87.5%), the model under-predicts 96% of the critical high temperatures when using plant-produced mixtures. The average absolute deviation for the backcalculation high-temperature procedure was 10.5°C. The minimum and maximum errors were 1°C and 27.8°C, respectively. These data suggest the backcalculation procedure returns errors of at least 1.5 performance grades. These errors would either grossly underestimate or overestimate the high-temperature performance of each binder.

One possible explanation for this error is an extrapolation error. The maximum testing temperature using AASHTO TP 79-09 is 45°C to ensure data quality. However, the high temperature assessed in these analyses was at least 15°C greater than the maximum testing temperature. The extrapolation procedure used to obtain binder stiffness at temperatures well above the measured mixture stiffness could influence the accuracy of the model.

Table 32 Actual and Predicted Binder Properties of 2009 NCAT Test Track Mixtures

	Critical Intermediate Temperature, °C			Critical High Temperature, °C		
Mixture	*Actual*	*Predicted*	*% Error*	*Actual*	*Predicted*	*% Error*
9.5 mm PG 76-22	21.9	11.4	-47.0	81.7	65.9	-19.3
19 mm PG 76-22	21.9	10.0	-56.7	85.1	69.3	-18.6
19 mm PG 67-22	24.4	16.9	-30.7	77.4	76.4	-1.3
12.5 mm PG 67-22	20.0	15.4	-23.0	69.4	68.3	-1.6
9.5 mm PG 88-22	17.5	17.1	-2.3	93.5	80.6	-13.8
19 mm PG 88-22	17.5	17.9	2.3	93.5	67.0	-28.3
SMA PG 70-22	15.5	13.6	-12.3	71.8	66.0	-8.1
12.5 mm PG 70-22	15.5	18.3	18.7	71.8	74.3	3.5
9.5 mm 50% RAP	29.4	19.7	21.8	87.8	73.3	-16.5
19.0 mm 50% RAP	32.4	25.3	-21.6	95.0	83.7	-11.9
9.5 mm 50% RAP/WMA	29.4	35.8	21.8	83.8	90.3	7.8
19 mm 50% RAP/WMA	32.1	24.3	-24.3	88.7	86.4	-2.6
SMA PG 76-22	25.5	15.4	-39.6	78.6	69.3	-11.8
12.5 mm 40% RAP	18.6	28.5	53.2	90.0	85.1	-5.4
12.5 mm PG 76-22	19.1	16.6	-13.1	76.6	70.4	-8.1
12.5 mm Rubber Modified	20.3	17.9	-11.8	81.7	71	-13.1
9.5 mm PG 76-22 WMA Foaming	23.2	11.4	-50.9	82.9	63.8	-22.2
19 mm PG 76-22 WMA Foaming	19.9	14.6	-26.6	86.6	67.5	-22.1
19 mm PG 67-22 WMA Foaming	20.5	13.9	-32.2	75.6	68.4	-9.5
9.5 mm PG 76-22 WMA Additive	22.6	11.1	-50.9	80.3	56.6	-29.5
19 mm PG 76-22 WMA Additive	20.3	12.4	-38.9	82.5	66.1	-19.9
19 mm PG 67-22 WMA Additive	21.8	15	-31.2	73.7	67.6	-8.3
9.5 mm Natural Asphalt	20.3	15.1	-25.6	80.5	67.8	-15.8
19 mm Natural Asphalt	20.7	19.5	-5.8	81.5	77.1	-5.4

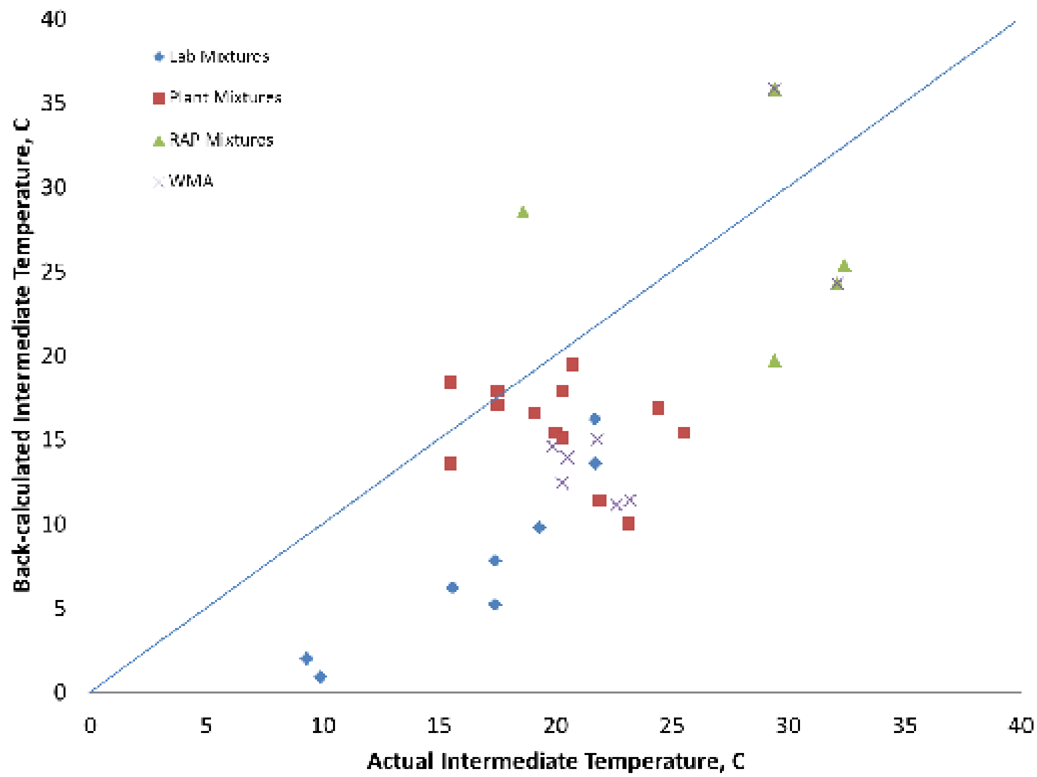


Figure 43 Comparison of Backcalculated and Measured Critical Intermediate Temperatures

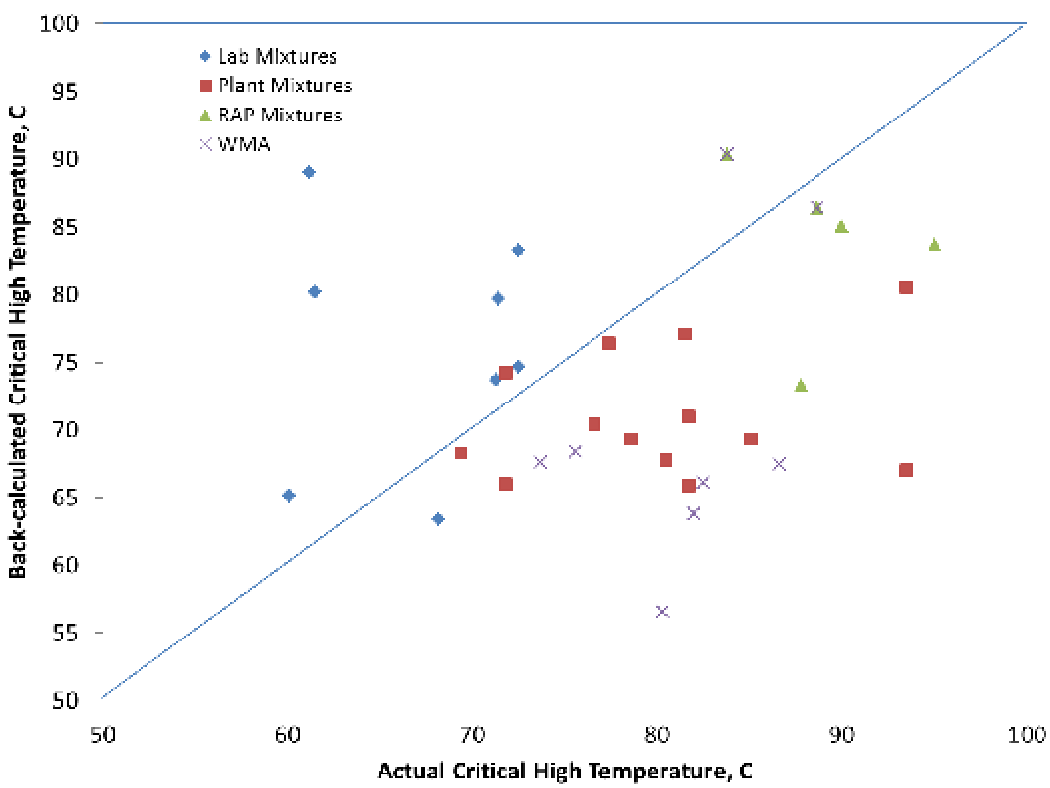


Figure 44 Comparison of Backcalculated and Measured Critical High Temperatures

Additional analyses were conducted to determine if the errors may have originated from either poor G* or δ predictions by comparing the measured and predicted G* and δ at the high performance grade temperature closest to the true high and intermediate temperature grades of the binder. The comparisons of measured and predicted G* and δ for the high-temperature backcalculation procedure are shown in Figures 45 and 46. The figures revealed a few discernible trends in the data. The results suggest the backcalculation procedure over-predicts the G* value of laboratory mixtures while it under-predicts the G* of plant-produced mixtures. The average error for G* was 13.1% or approximately 0.22 kPa. From Figure 46 it can be seen that the backcalculation methodology consistently under-predicted (for 84% of the mixtures) the phase angle of the binders at high temperatures. The average percent error of the model was only 10.1%, but this resulted in under-predicting the phase angle on average by 8.5°.

Figures 47 and 48 graphically compare the backcalculated and measured G* and δ at intermediate temperatures. While the model typically over-predicted the lab mixtures G* at high temperatures, the models only over-predicted G* for two plant mixtures and one RAP mix at intermediate temperatures. The remainder of the mixtures had G* values that were under-predicted. The average G* error was -50.8%. The average difference in measured and backcalculated G* values was 4033 kPa. Twenty-nine of the 32 mixtures had phase angles that were over-predicted at intermediate temperatures. The average error was 14.3% or 5.8°.

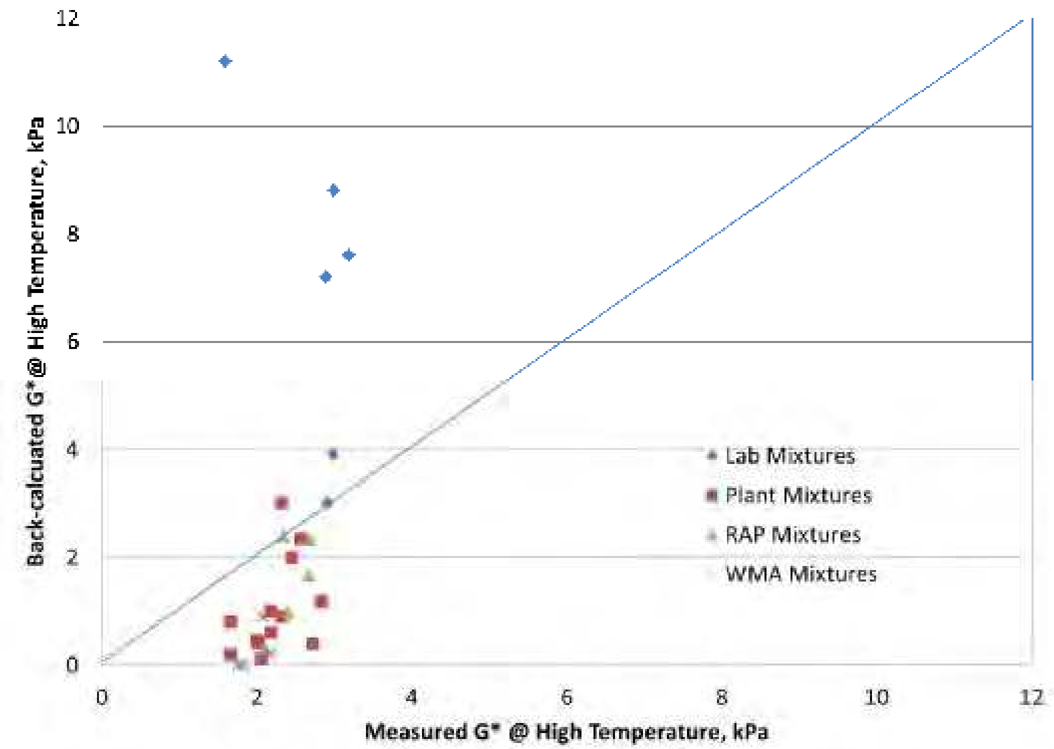


Figure 45 Measured and Backcalculated G* at High Temperatures

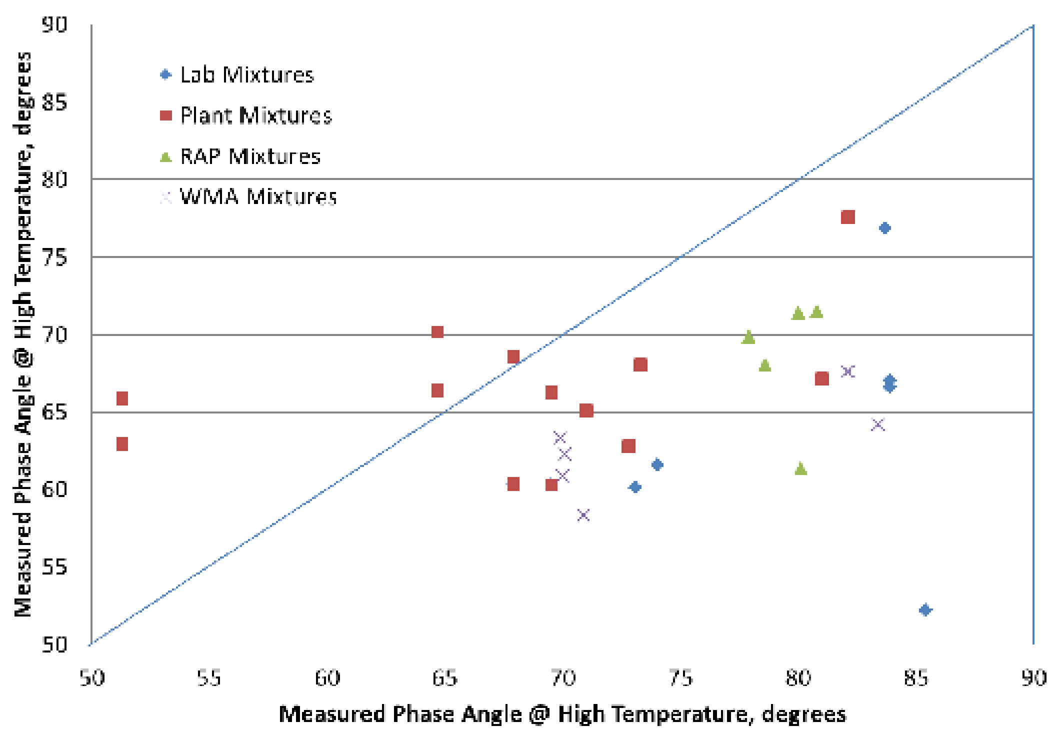


Figure 46 Backcalculated and Measured Phase Angles at High Temperatures

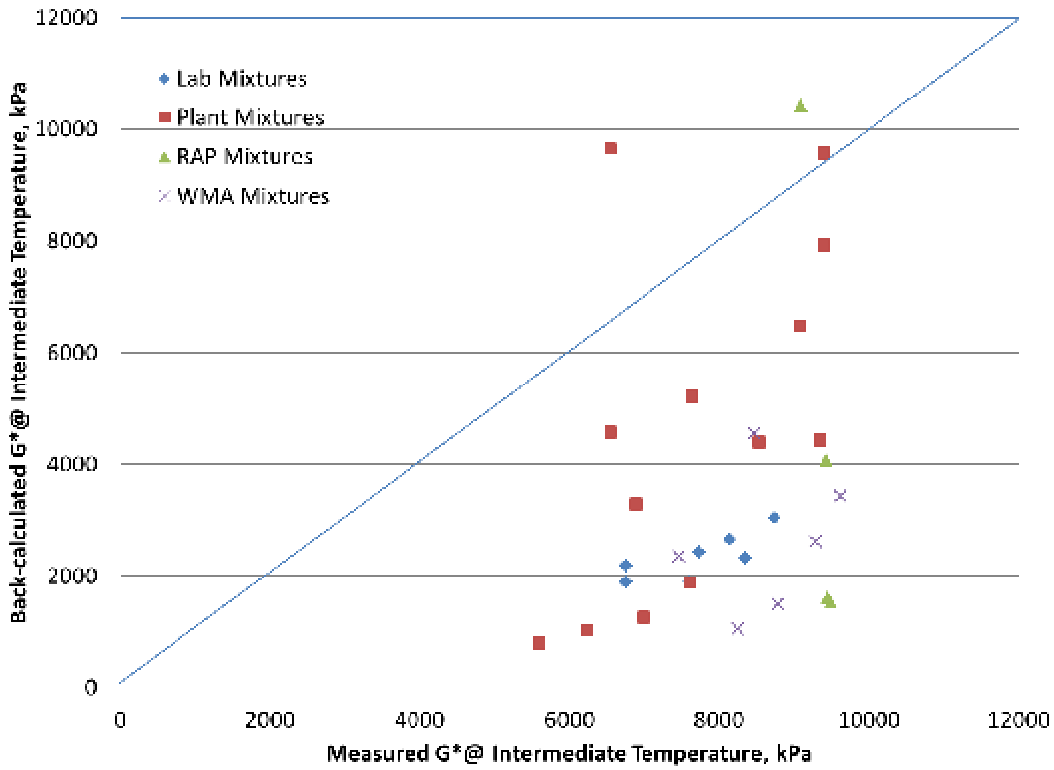


Figure 47 Backcalculated and Measured G* at Intermediate Temperatures

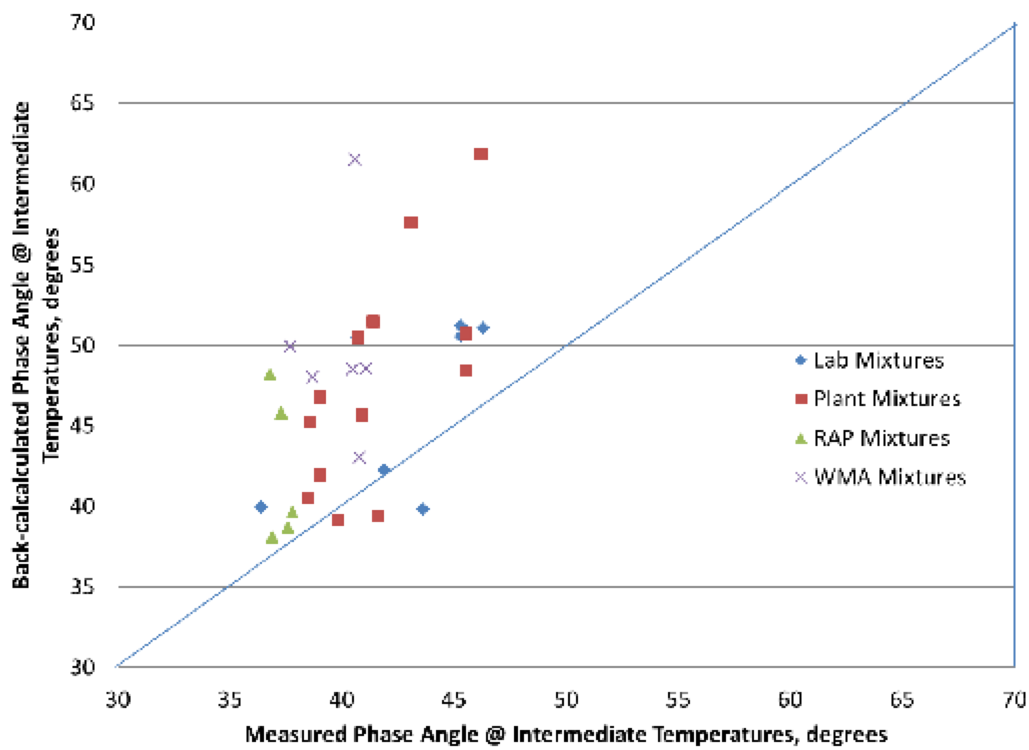


Figure 48 Backcalculated and Measured Phase Angles at Intermediate Temperatures

The results of these analyses show the process used for backcalculating the effective binder properties of asphalt binders from dynamic modulus test results is not suitable for use without significant improvements. The backcalculated critical intermediate and high temperatures deviated from the measured critical intermediate and high temperatures by as much as 13.1 and 27.8°C, respectively. These differences were due to errors in backcalculating the G* and phase angle of the asphalt binders from the dynamic modulus data using the Hirsch and C-A models. The errors at the high critical temperature properties could be due to extrapolating the model to at least 15°C beyond measured data. Due to the consistency and magnitude of these deviations, the backcalculation methodology for predicting effecting binder properties from asphalt mixture dynamic modulus testing is neither practical nor effective.

Moisture Damage Susceptibility Results

New Hampshire Mix Designs

Results of the moisture damage testing for the mixes with New Hampshire materials are illustrated in Figure 49. This bar graph shows average conditioned and unconditioned tensile strengths plotted against the y-axis on the left side, and tensile strength ratios (TSRs) shown as black diamonds plotted against the secondary y-axis on the right side of the chart. It can be seen that TSRs for some of the mix designs were less than the AASHTO R35 minimum criteria of 0.80 when no antistrip additive (ASA) was used. As noted previously, the contractor who provided these materials generally does not use antistripping additives. After adding 0.5% (by weight of virgin binder) AkzoNobel Wetfix 312, the TSRs improved to above 0.80. It can also be seen that the mixtures containing high RAP contents generally had higher tensile strengths, which is expected due to the contribution of stiffer RAP binder. In most cases, mixes with PG 70-28 virgin binder had higher unconditioned tensile strengths compared to the same design with the PG 58-28 virgin binder.

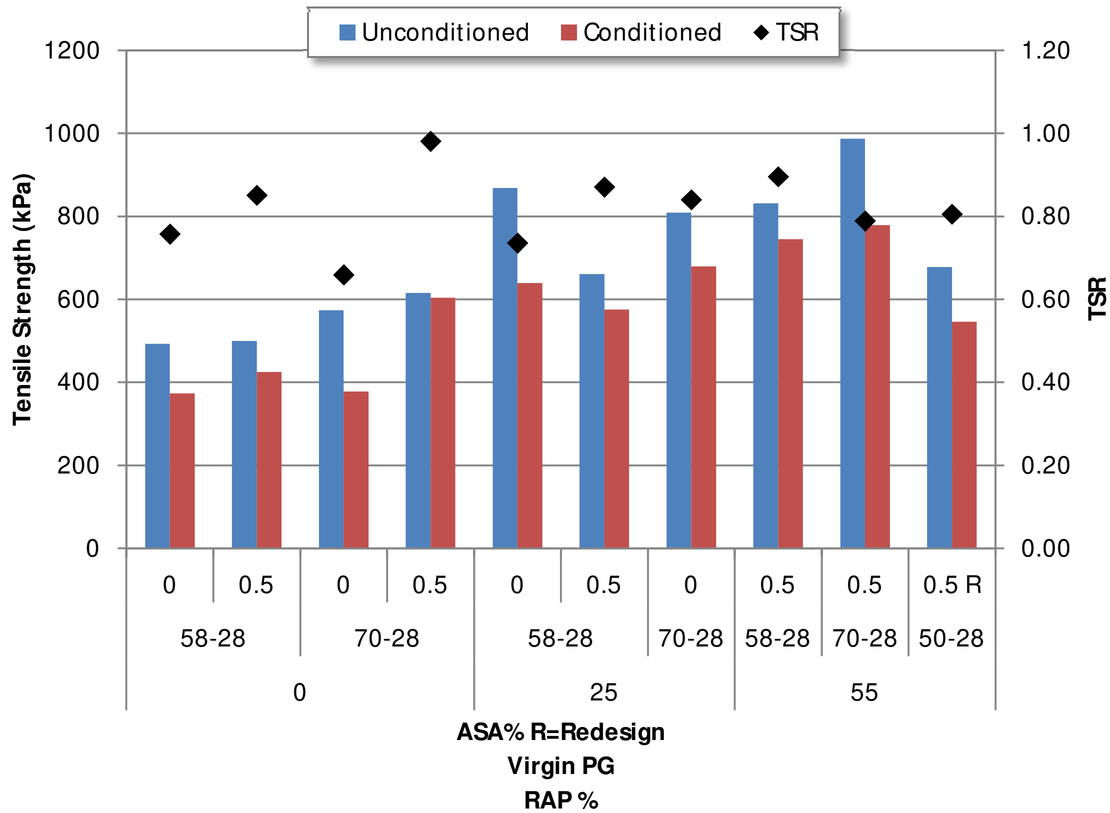


Figure 49 Moisture Damage Susceptibility Results for the New Hampshire Mixes

Figure 50 shows a similar bar chart for the Utah mix designs. All of these mixes contained 1% hydrated lime by weight of total aggregate, as typically used by the contractor who supplied these materials. No additional antistrip additive was added to mixes and retested for this set when TSRs were below 0.80. Note that Utah DOT uses the Hamburg test to evaluate resistance to moisture damage. Although several of the high RAP content mixes did not meet the 0.80 TSR criteria, conditioned and unconditioned tensile strengths increased substantially as RAP contents increased. This is a good case to support the argument that TSR values should not be used solely to assess moisture damage potential. A few states allow a lower TSR criteria if the tensile strengths are maintained above a certain threshold. For example, the Georgia DOT will allow TRS as low as 0.70 as long as conditioned and unconditioned tensile strengths are above 689 kPa (100 psi). States that use a softer PG grade of binder should have lower tensile strength criteria.

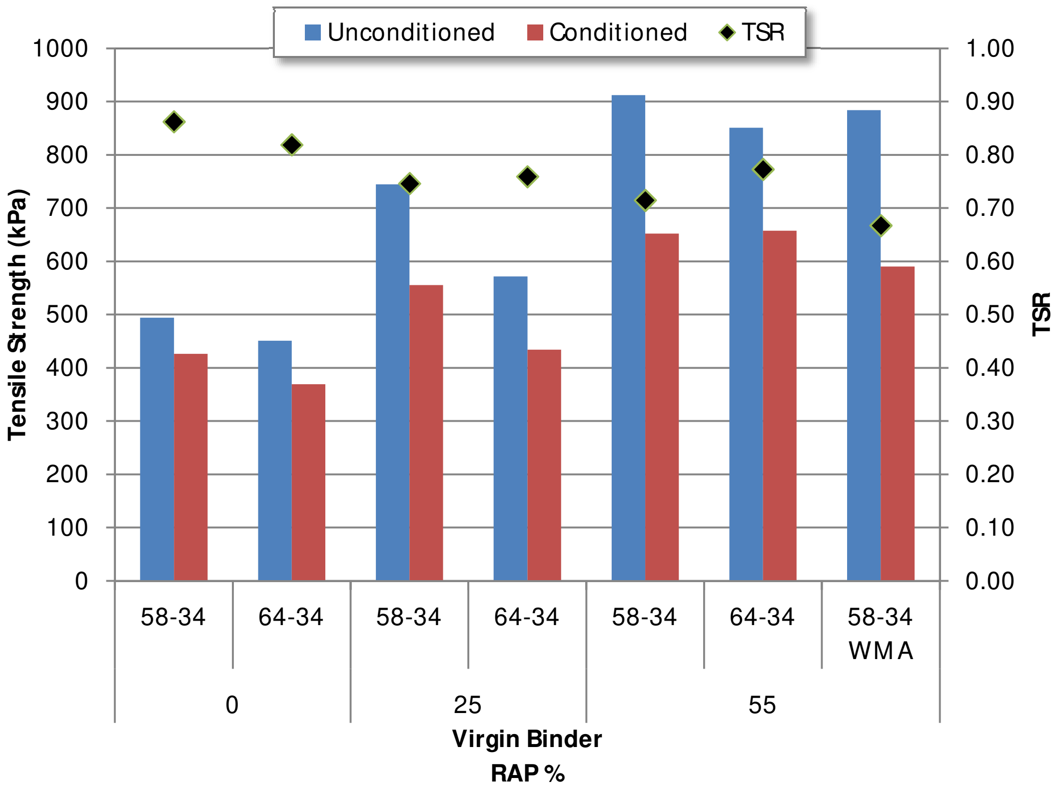


Figure 50 Moisture Damage Susceptibility Results for Utah Mixes

Moisture damage susceptibility results for the Minnesota mixes are illustrated in Figure 51. The TSR for the virgin 9.5 mm NMAS was 0.78. All other mixtures met the TSR criteria. The contractor who supplied these materials does not use antistripping additives. The mixtures containing RAP had significantly higher tensile strengths and showed no strength losses due to the conditioning procedure in AASHTO T 283.

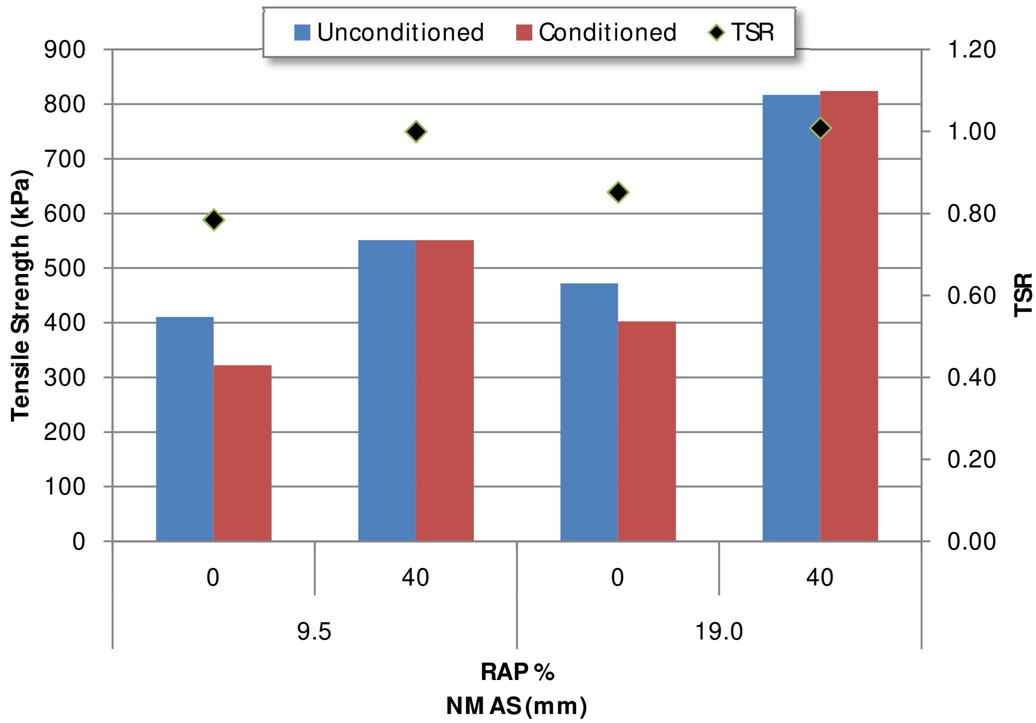


Figure 51 Moisture Damage Susceptibility Results for Minnesota Mixes

Figure 52 shows the bar graph of TSR results for the Florida mixes. The two virgin mixtures met the TSR criteria. In comparison, tensile strengths for the mixes with 40% RAP were higher than the virgin mix counterparts, but TSRs were lower, even when the antistrip dosage was increased from 0.5 to 0.75% by weight of the virgin binder. The virgin binder for these two mix designs was 62% and 56% of the total binder for the 9.5 mm and 19.0 mm NMAS mixes, respectively. Therefore, as percentages of the total binder, the antistrip dosages were 0.31% and 0.47% for the 9.5 mm mix, and 0.28% and 0.42% for the 19.0 mm mixes. Mix designers should keep in mind that higher dosages of liquid antistrip agents may be needed for high RAP content mixes when the antistrip agent is added to the virgin binder in order to supplement the binder contributed by the RAP.

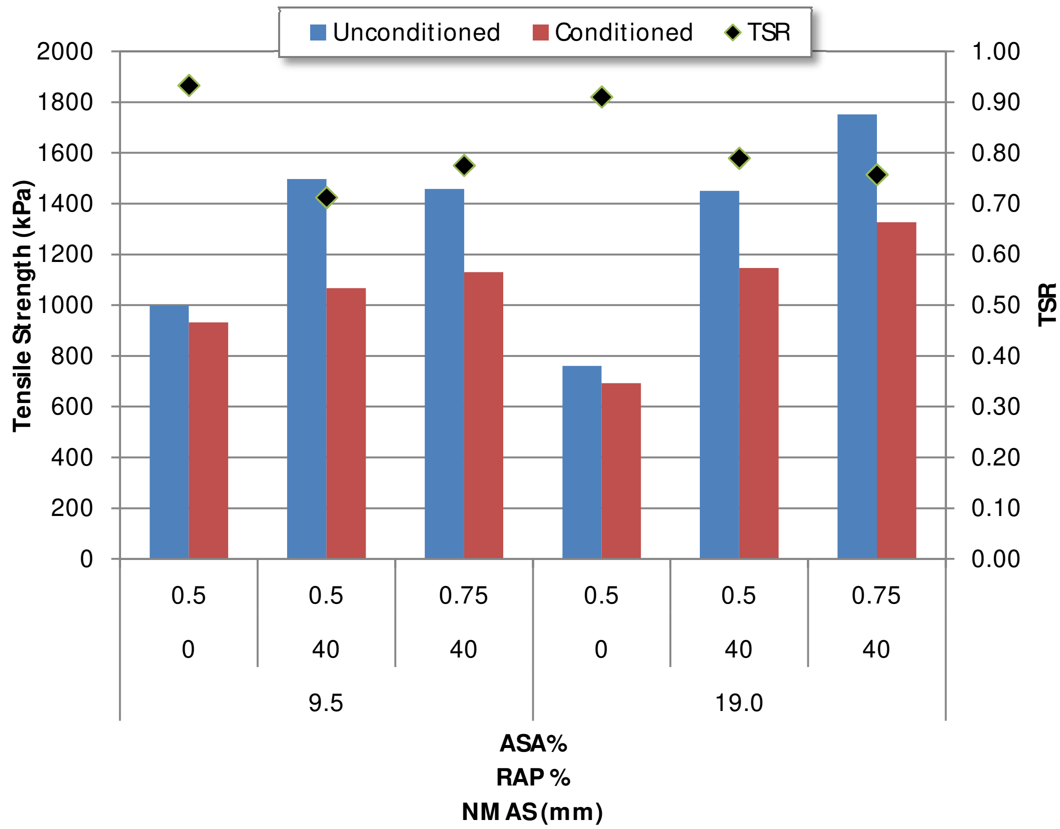


Figure 52 Moisture Damage Susceptibility Results for Florida Mixes

Overall, high RAP content mixes generally had higher conditioned and unconditioned tensile strengths than virgin mixes. The higher tensile strengths are due to the contribution of the stiffer aged RAP binder. In several cases, the TSRs of the high RAP content mixes were lower than for the virgin mixes and even dropped below the criterion of 0.80 required in AASHTO M323. Adding antistripping additive was usually sufficient to improve the TSRs above 0.80.

Flow Number Results

Plots of total accumulated permanent strain versus test cycles were constructed for each mix to visually evaluate the Flow Number test results. Figure 53 shows the average results for the 55% RAP mixes from New Hampshire as an example. The initial region of deformation, up to about 1,000 cycles, represents seating and densification (volume decrease). The second region of the deformation is characterized by a relatively constant rate of strain versus cycles. Lower slopes indicate that a mix is stable (i.e., there is not a substantial amount of shifting of particles in the mix after initial deformation). Permanent deformation failure is identified by a third region also known as tertiary flow. The point where the third region begins is the flow number. None of the tests conducted in this study exhibited a third region partially due to the use of a confining pressure in the tests.

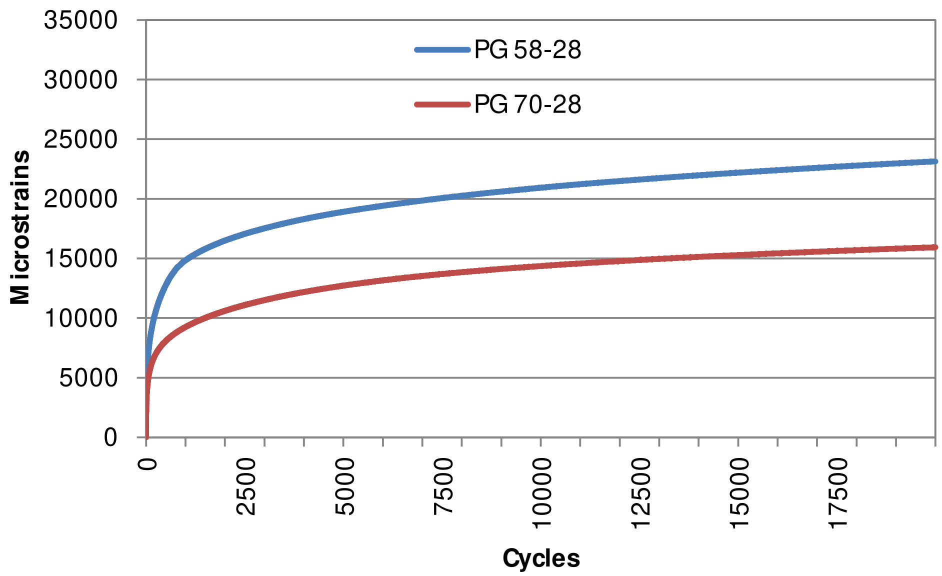


Figure 53 Comparison of Average Flow Number Results for New Hampshire Mixes

Since none of the Flow Number test results exhibited tertiary flow, test results were evaluated based on the total accumulated strain at 20,000 cycles and the slope of the change in accumulated strain between 10,000 and 20,000 cycles. These results are summarized in Table 33. The coefficients of variation for accumulated microstrain and slopes of secondary deformation are mostly below 15%, which indicate that the test results are reasonably repeatable. For the set that had the poorest repeatability (Utah 25% RAP with PG 64-34 binder), an additional specimen was tested, but including this data did not improve the coefficient of variation.

Table 33 Summary of Flow Number Test Results

Source	NMAS	RAP%	Total Pb%	Virgin High PG	Microstrain @ 20,000 Cycles			Slope 10k to 20k Cycles		
					Avg.	Std. Dev.	CV	Avg.	Std. Dev.	CV
NH	12.5	0	5.6	58	28,614	4,718	16%	0.33	.066	20%
		55	5.2		22,464	1,273	6%	0.22	.025	11%
		0	5.6	70	16,344	558	3%	0.14	.007	5%
		55	5.2		15,789	721	5%	0.15	.022	15%
UT	12.5	0	5.5	58	19,200	1,991	10%	0.26	.028	11%
		25	5.7		25,980	2,205	8%	0.25	.030	12%
		55	6.5		21,080	2,207	10%	0.21	.018	9%
		55	6.5	58 WMA	15,546	1,812	12%	0.14	.011	8%
		0	5.9	64	23,629	2,134	9%	0.23	.022	10%
		25	6.1		14,468	5,802	40%	0.12	.066	55%
		55	6.2		19,150	2,255	12%	0.18	.020	11%
FL	9.5	0	5.4	67	35,823	4,663	13%	0.57	.120	21%
		40	5.6		43,011	1,142	3%	0.79	.032	4%
	19.0	0	4.5		37,453	2,664	7%	0.50	.048	10%
		40	5.1		36,027	7,098	20%	0.59	.016	3%

Figure 54 shows a plot of the total accumulated microstrain versus the slope of the deformation between 10,000 and 20,000 cycles. It can be seen that the two parameters are closely related. In the interest of brevity, further analysis of Flow Number results was limited to the accumulated microstrain data.

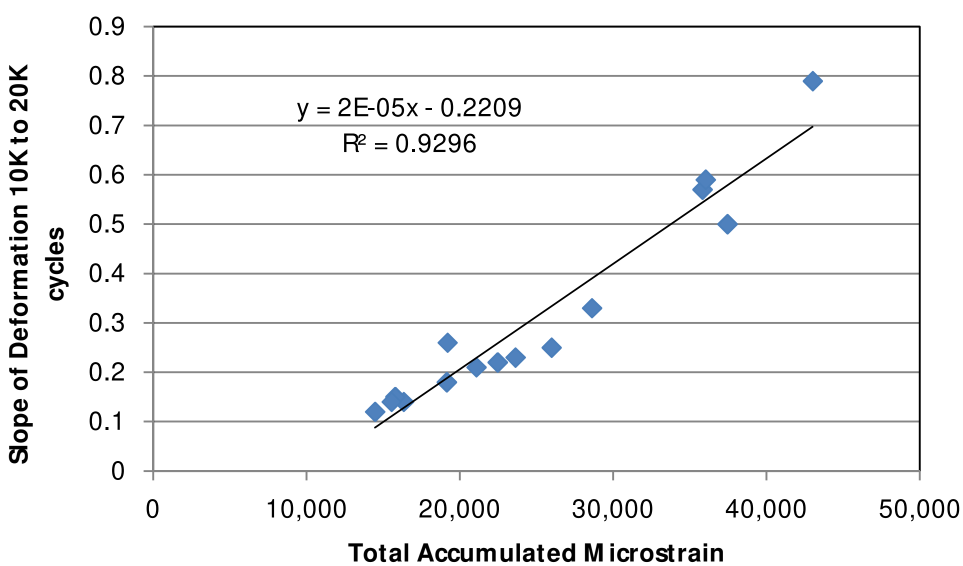


Figure 54 Correlation of Confined Flow Number Output Parameters

New Hampshire Mix Designs

Figure 55 shows the accumulated strain at 20,000 cycles for the New Hampshire mixes. As can be seen, the mixes containing 50% RAP had lower accumulated strain than their virgin mix counterparts for each grade of virgin binder. The accumulated strain for the mix with the higher PG virgin binder was less than that for the mix with the lower PG binder, as expected. Virgin and high RAP mixes with unmodified virgin binders had higher accumulated strain than the polymer-modified binder mixes.

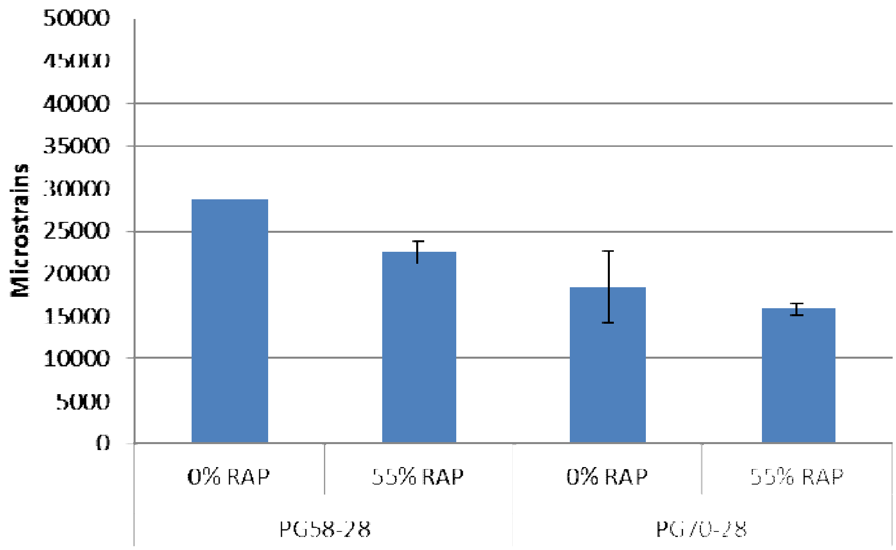


Figure 55 Comparison of Total Accumulated Strain of New Hampshire Mixes

Utah Mix Designs

Figure 56 illustrates the total accumulated strain at 20,000 cycles for the Utah mixes. Note that the flow number tests were conducted only using binders from the primary source. For the mixes with the PG 58-34 binder, some of the results seem a little odd. The mix containing 55% RAP had similar results to the virgin mix despite the high proportion of RAP binder. This is likely due to the higher total asphalt content of the 50% RAP mix compared to the virgin mix design. The 50% RAP mix had an optimum total asphalt content of 6.5%, whereas the virgin mix had 5.5%. The mix containing the WMA technology exhibited lower accumulated strain than the companion HMA. This is unusual since mixes with WMA typically have less resistance to permanent deformation due to less aging of the asphalt binder resulting from lower mixing and compaction temperatures. It is also not clear why the 25% RAP mix had greater deformation than the virgin mix.

For the mix designs with the PG 64-34 binder, the accumulated strain for the 25% RAP mix was the lowest, but the results were more variable than those for other mix sets. The 55% RAP mix had less total deformation than the virgin mix even though its asphalt content was 0.3% higher.

Comparing the results of the mixes with the different binder grades shows that the virgin mix with the unmodified binder had less deformation than the corresponding mixes with the polymer binder. This seemingly unusual result may be explained by the lower asphalt content for the virgin mix with the PG 58-34 binder. The optimum asphalt content for the virgin mix with PG 58-35 was 5.5%, compared to 5.9% for the same mix design with the PG 64-34 binder. For the 25% and 55% RAP mixes, the total deformation decreased, as expected, when the higher PG binder was used.

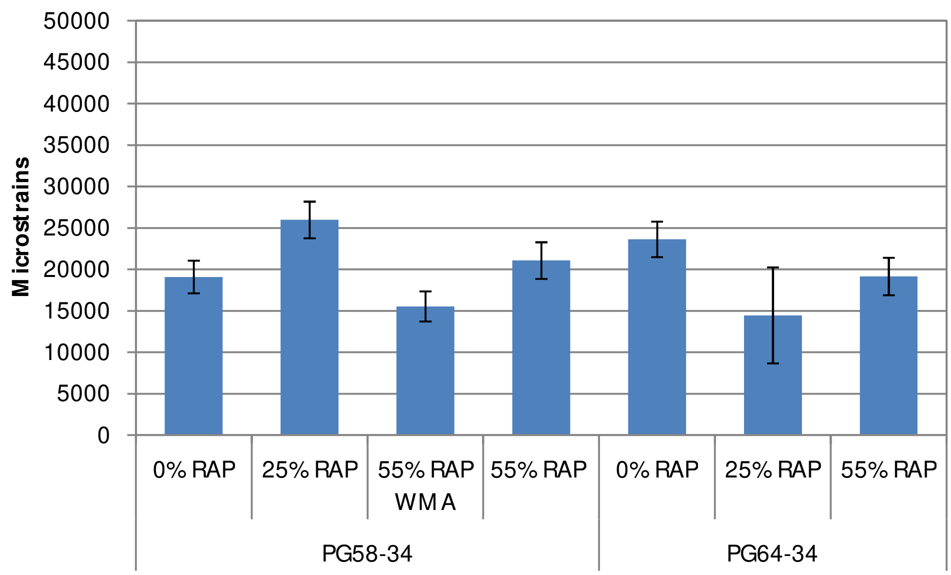


Figure 56 Comparison of Total Accumulated Strain for Utah Mixes

Florida Mix Designs

The accumulated strain for the virgin and 40% RAP content mixes using the Florida materials are shown in Figure 57. The 9.5 mm NMAS 40% RAP content mix had greater accumulated strain than its virgin mix counterpart. The accumulated strains for the 19.0 mm NMAS mixes were similar.

It is important to recall that the Florida RAP was apparently from unaged material; the Florida RAP binder graded very similar to the virgin binder. Therefore, in this case, the mixes with RAP would not be expected to be stiffer or more resistant to permanent deformation.

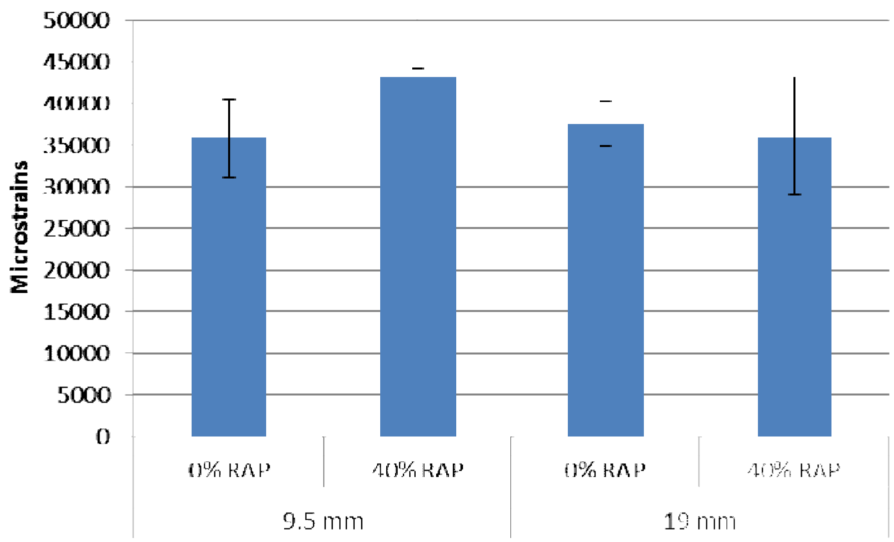


Figure 57 Total Accumulated Strain for Florida Mixes

Statistical Analysis of Flow Number Results

Analysis of variance was conducted to determine which factors significantly affected the total accumulated strain at 20,000 cycles. The factors that were considered were mix source (New Hampshire, Florida, and Utah), NMAS (9.5, 12.5, and 19.0 mm), RAP percentage (0, 40, and 55%), and virgin binder high performance grade (58, 64, and 70°C). A level of significance of 0.05 was used. The ANOVA identified materials source and high virgin binder grade as significant factors. An interaction plot of the factors affecting the flow number results is shown in Figure 58.

Summary of Flow Number Results

The confined flow number test was conducted to assess the resistance to permanent deformation of mix designs from three of the four locations. Analysis was based on the total accumulated strain at 20,000 cycles. All the mixtures had less than 50,000 microstrain, or 5% strain. However, no criteria have been recommended for total accumulated strain from confined flow number test results. The ANOVA indicated that both mix source and high performance grade of the virgin binder significantly affect the accumulated strain. This indicates that the selection of virgin binder can affect the permanent deformation of RAP mixtures.

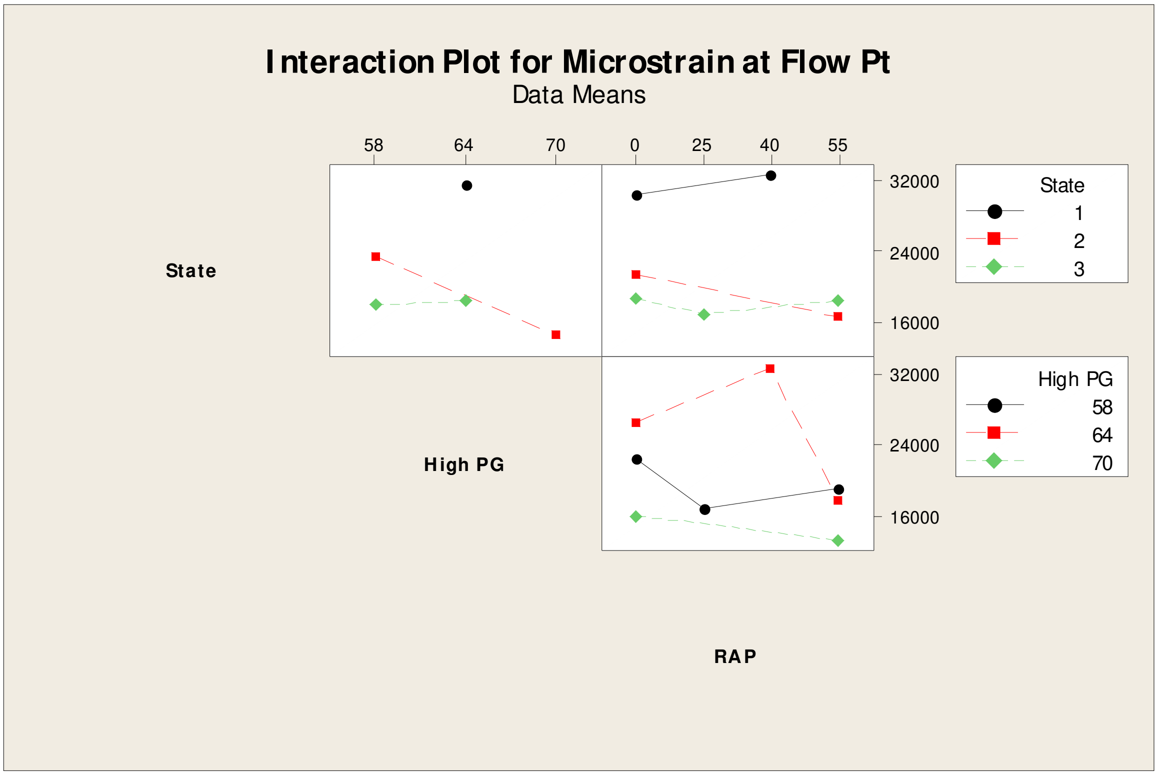


Figure 58 Interaction Plot of Accumulated Microstrain for Flow Number Tests

Fatigue Cracking

Mixes from each of the four locations were evaluated for resistance to fatigue cracking using the IDT fracture energy property based on a testing temperature of 10°C. All samples were short-term and long-term aged prior to testing. The IDT fracture energy tests were performed only on mix designs using the primary binder sources. Research using mixes from Westrack indicated that very good fatigue performance was observed for mixes having an IDT fracture energy of 3.0 KJ/m^3. However, the test temperature and specimen failure criteria used in that research differs from the conditions used in this project. Therefore, an assessment of the impact of the experimental factors can only be made on a relative basis.

New Hampshire Mix Designs

A summary plot of the IDT fracture energy results for the mix designs using materials from New Hampshire is shown in Figure 59. Although the repeatability of the results was poor for several mix designs, as indicated by the one-standard deviation whisker bars, the average fracture energy results for the virgin mixes were higher than for the mix designs containing RAP. The mix designs with 55% RAP had slightly higher average fracture energy results compared to the mix designs containing 25% RAP. The mix designs with the unmodified virgin binder appear to have slightly higher fracture energy results compared to the corresponding mixes with the polymer-modified virgin binder. A statistical analysis of these factors was conducted by combining the data from the New Hampshire and Utah mixes.

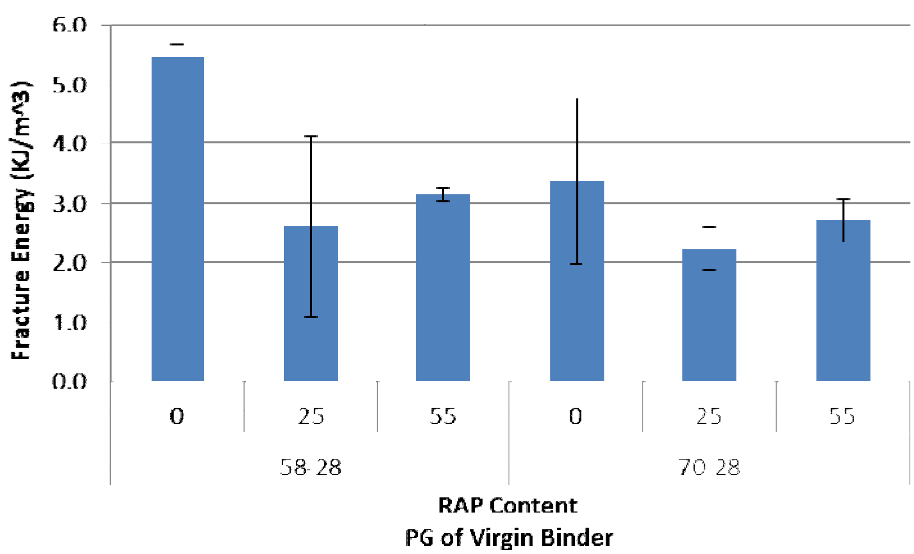


Figure 59 IDT Fracture Energy Results for Mix Designs Using New Hampshire Materials

Utah Mix Designs

Indirect tensile fracture energy results for the Utah mix designs are shown in Figure 60. As with the New Hampshire mix designs, the virgin mix designs had higher fracture energy results. The fracture energy of the 55% RAP mix with the PG 64-34 binder was much lower than other mixes. It is unclear if this result is anomalous or if it correctly represents the cracking resistance of the mix design. The mix design with the softer, unmodified virgin binder has a much higher fracture energy.

Other mix design properties, such as the effective asphalt content and the predicted effective binder grade, are not substantially different for these two mixes. The use of the Evotherm WMA appears to provide a slight improvement in fracture energy.

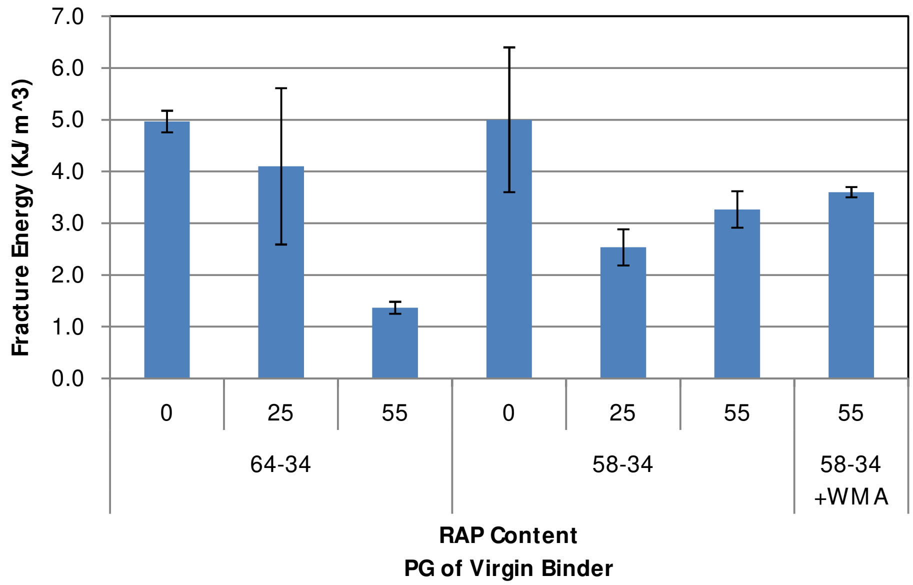


Figure 60 IDT Fracture Energy Results for Mix Designs Using Utah Materials

To examine the statistical significance of mix factors on fracture energy, an ANOVA was conducted with the combined data from New Hampshire and Utah. The factors in the analysis were materials source (New Hampshire or Utah), virgin binder grades, and RAP content. The ANOVA results, shown in Table 34, indicate that RAP content was the most significant factor, followed by the source of the materials. The *p*-value for virgin binder grade was just above the 0.05 level of significance. The interaction of materials source and RAP content was not significant. The main effects plot, shown in Figure 61, illustrates the magnitude of the effect of RAP content and source on fracture energy. As evident in the previous plots, the fracture energy of the virgin mixes was significantly higher than the 25% and 55% RAP mixes. Although these data indicate that the high RAP content mixes are more susceptible to fracture than the virgin mixes, a critical value has not been established for fracture energy for the conditions used in this study.

Table 34 ANOVA Output for IDT Fracture Energy of New Hampshire and Utah Mixes

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Material Source	1	0.8585	3.9621	3.9621	4.35	0.046
Virgin Binder Grade	3	4.2818	7.5661	2.5220	2.77	0.059
RAP %	2	31.0556	31.0556	15.5278	17.04	0.000
Material Source*RAP %	2	3.7222	3.7222	1.8611	2.04	0.147
Error	30	27.3378	27.3378	0.9113		
Total	38	67.2559				

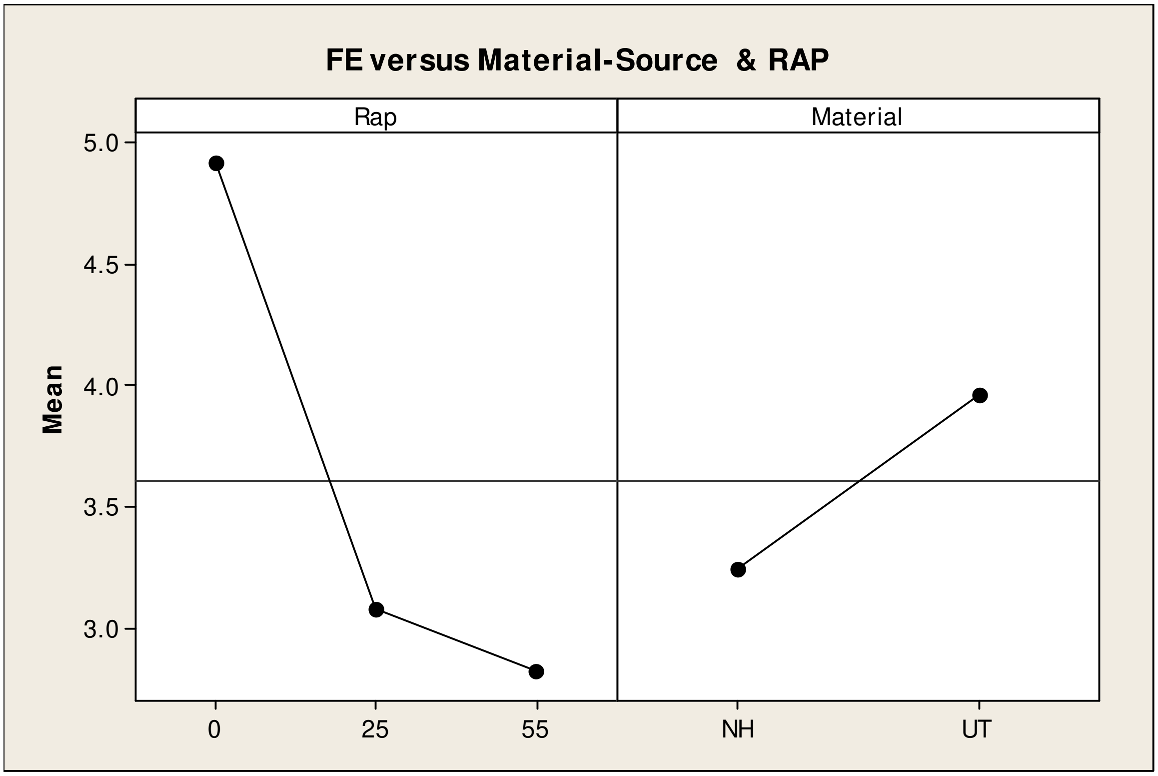


Figure 61 Main Effects Plot of Significant Factors on IDT Fracture Energy Results for New Hampshire and Utah Mixes

Minnesota Mix Designs

Figure 62 shows the fracture energy results for the mix designs with the materials from Minnesota. As with the previous mix designs, the virgin mixes have higher fracture energies than the mixes containing RAP. It can also be seen that the 9.5 NMAS mixes have higher fracture energies than the 19.0 NMAS mixes. This is likely due to the higher effective asphalt contents for the smaller NMAS mixes.

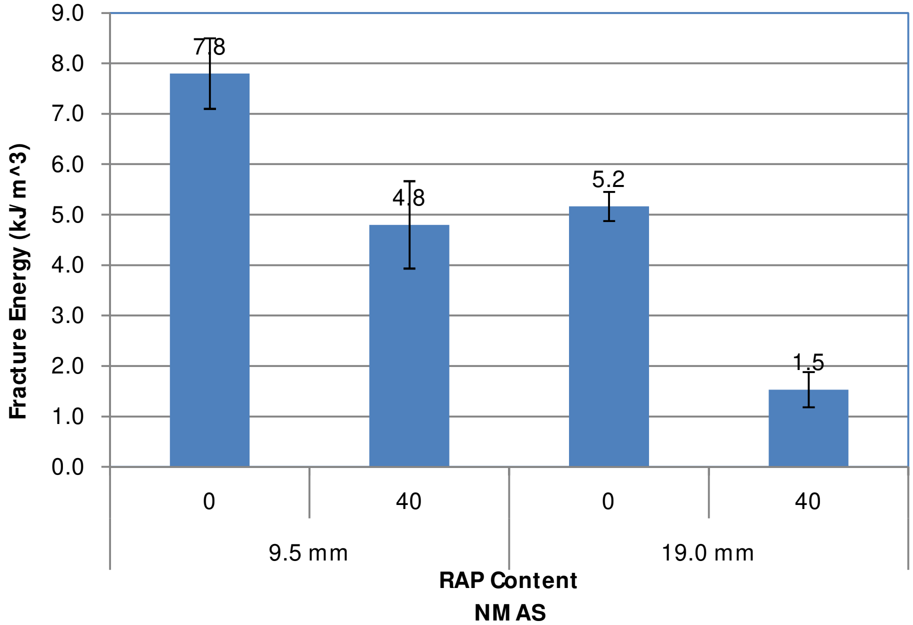


Figure 62 IDT Fracture Energy Results for Minnesota Mix Designs

Florida Mix Designs

IDT fracture energy results are shown in Figure 63. The mix designs containing 40% RAP had very low fracture energy results compared to the Florida virgin mixes and relative to all the other mixes tested in this study. This is particularly surprising given that the Florida RAP was PG graded to be very similar to the virgin binder from Florida. Other properties, such as the tensile strengths from TSR tests and dynamic modulus tests of these mixes at low temperatures were not unusual. If there had been a problem with compatibility of the RAP and virgin binders, it should have been evident in the other tests.

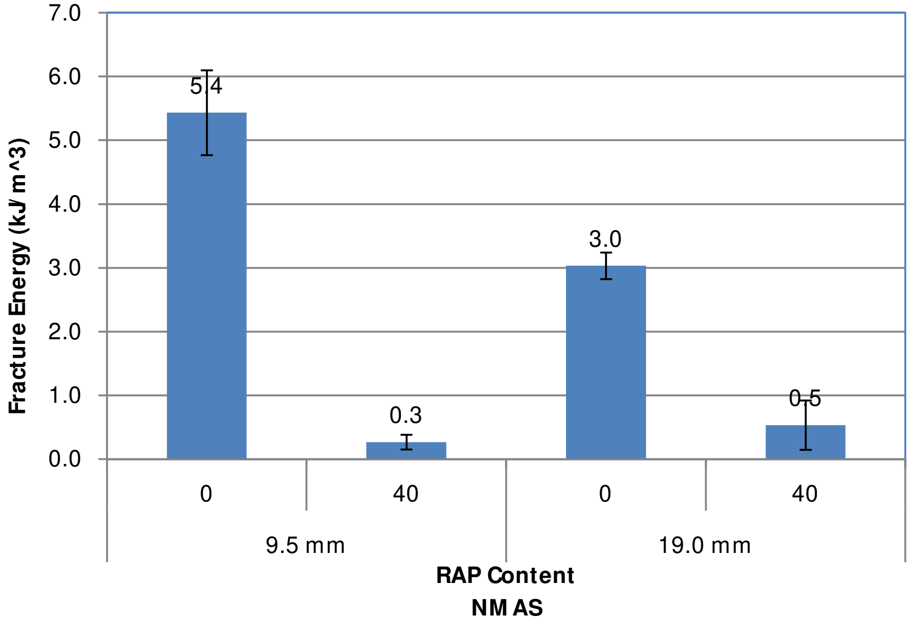


Figure 63 IDT Fracture Energy Results for Florida Mix Designs

ANOVA results for the mix factors that affected IDT fracture energy for the Minnesota and Florida mixes are shown in Table 35. All factors and interactions were significant except for the interaction between RAP percentage and materials source. Based on the *F* value, RAP clearly had the greatest effect. That is consistent with the ANOVA on IDT fracture energy for the New Hampshire and Utah mix designs.

Table 35 ANOVA Output for IDT Fracture Energy of Florida and Minnesota Mixes

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Material-Source	1	37.750	37.750	37.750	147.32	0.000
NMAS	1	24.200	24.200	24.200	94.44	0.000
% RAP	1	76.684	76.684	76.684	299.25	0.000
Material-Sou*NMAS	1	5.320	5.320	5.320	20.76	0.000
Material-Sou*% RAP	1	0.400	0.400	0.400	1.56	0.229
NMAS*% RAP	1	1.550	1.550	1.550	6.05	0.026
Material-Sou*NMAS *% RAP	1	4.084	4.084	4.084	15.94	0.001
Error	16	4.100	4.100	0.256		
Total	23	154.090				

The interaction plot of the main factors for this experiment is shown in Figure 64. This plot also illustrates the fact that the 9.5 mm mixes had more fracture energy than the 19.0 mm mixes. If

IDT fracture energy is a good indicator of fatigue resistance, then smaller NMAS mixes should be used in pavement structures where high tensile strains occur.

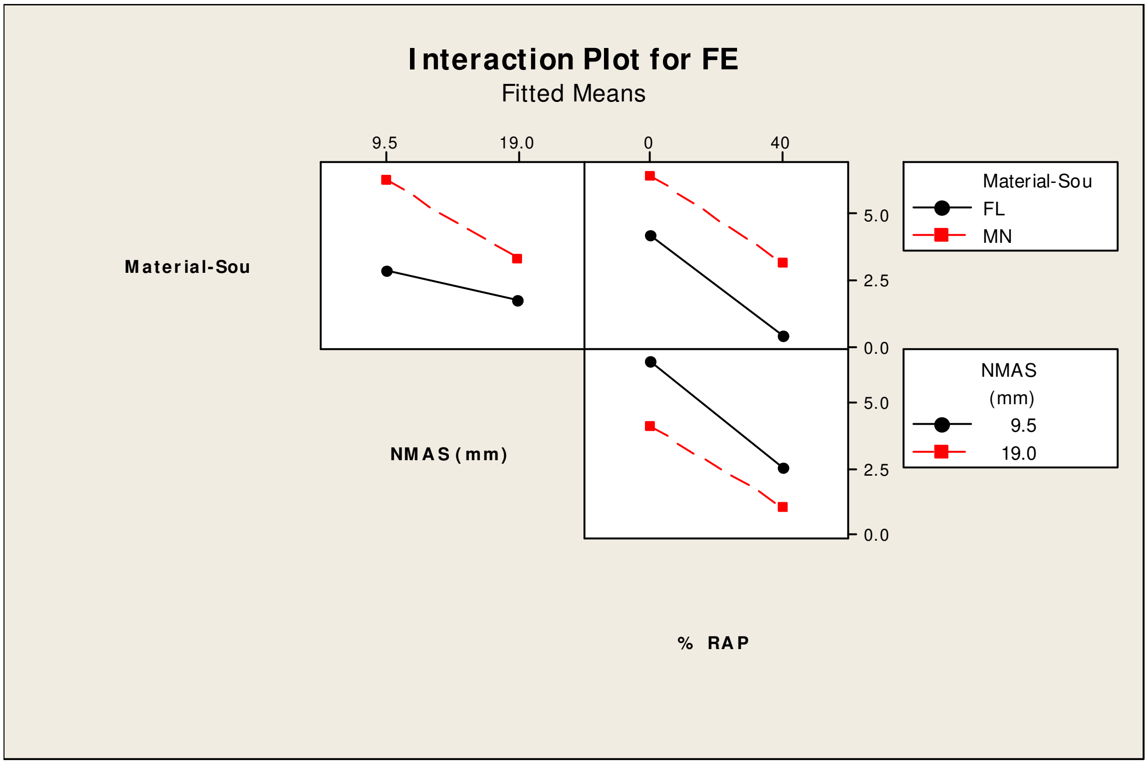


Figure 64 Interaction Plot of Main Factors for Fracture Energy for Minnesota and Florida Mixtures

Low-Temperature Cracking

The mix designs were evaluated for resistance to thermal cracking resistance using two tests and four properties:

- Fracture toughness, K_{IC}, and fracture energy, G_f, were computed from SCB test data.
- Creep stiffness, *S(t),* and *m*-value, *m(t),* at 60 seconds were computed from BBR test data.

The mix designs from the three sources were tested for low-temperature properties. The Florida mix designs were not evaluated for thermal cracking properties since this is not a distress that occurs in that state. For the mix designs from the other three locations, three replicates were tested. The primary analysis was to test the null hypothesis that low-temperature properties of high RAP content mixtures do not significantly differ from the corresponding virgin asphalt concrete mixture from the same source.

New Hampshire Mixtures

The experimental variables for the New Hampshire mixtures were:

- Low temperature with three different levels in SCB test: -9˚C (control), -19˚C, and -29˚C
- Low temperature with two different levels in BBR test: -9˚C (control) and -19˚C
- RAP content with three different levels: 0% (control), 25%, and 55%.

SCB test results. The SCB test data were used to compute fracture toughness, K_{IC}, and fracture energy, G_f, according to the previously described methods. The results are reported in Table 36 and graphically presented in Figures 65 and 66. Most coefficients of variation (CV) values were less than 25, which is reasonable for fracture testing of asphalt mixtures. In most cases, K_{IC} increased with increasing RAP contents and a decrease in temperature. On the contrary, G_f decreased at lower temperatures. Note that in these figures, the whiskers represent one standard deviation for the test results.

Table 36 Mean and Coefficient of Variation of Fracture Parameters for NH Mixtures

Binder	Temp (˚C)	RAP (%)	K_{IC} (MPa•m$^{0.5}$)		G_f (kJ/m^2)	
			Mean	CV[%]	Mean	CV[%]
PG58-28A	-9	0	0.630	12	0.737	4
		25	0.755	15	0.689	37
		55	0.871	12	0.589	26
	-19	0	0.773	7	0.449	9
		25	0.839	9	0.488	15
		55	0.834	14	0.417	11
	-29	0	0.823	7	0.307	6
		25	0.928	9	0.300	23
		55	1.052	9	0.383	3
PG70-28A	-9	0	0.618	9	0.554	32
		25	0.639	2	0.441	28
		55	0.689	6	0.478	25
	-19	0	0.825	13	0.502	17
		25	0.829	7	0.416	4
		55	0.786	6	0.413	18
	-29	0	0.974	10	0.332	17
		25	1.016	13	0.345	6
		55	0.843	12	0.315	13

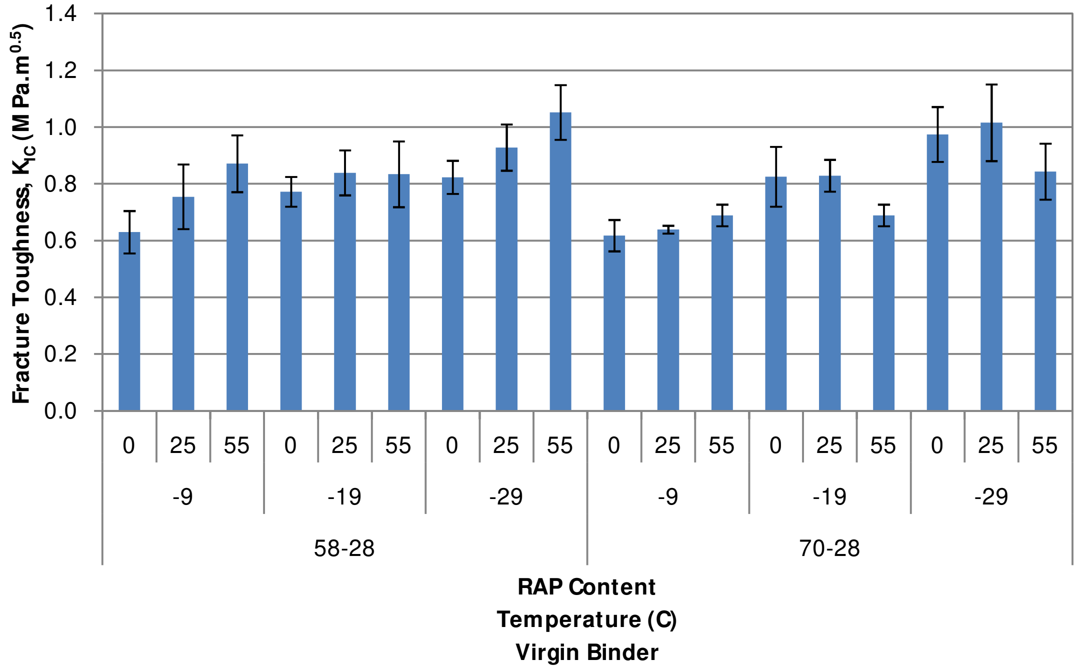


Figure 65 Fracture Toughness Results for New Hampshire Mixtures

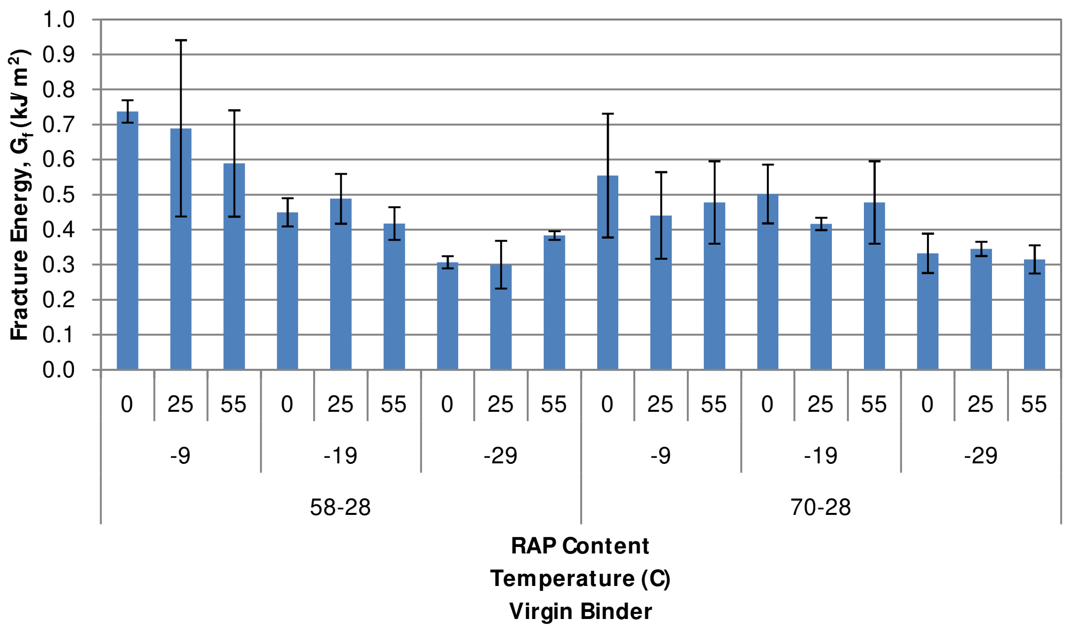


Figure 66 Fracture Energy Results for New Hampshire Mixtures

In the statistical analysis, K_{IC} and G_f were set as dependent variables, and RAP content and temperature were set as independent variables. ANOVA was performed at 5% of significance level for each binder grade to reduce the number of terms and unexpected errors. Table 37 and Table 38 show results of ANOVA from the SCB test.

Table 37 Results of ANOVA on SCB Properties for NH binder PG 58-28A

Response: K_{IC}

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.630	0.051	12.353	0.000	Significant
Temp-19	0.143	0.072	1.986	0.063	
Temp-29	0.193	0.072	2.681	0.015	Significant
RAP 25%	0.125	0.072	1.736	0.100	
RAP 55%	0.241	0.072	3.347	0.004	Significant

Response: G_f

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.737	0.061	12.082	0.000	Significant
Temp-19	-0.288	0.087	-3.310	0.004	Significant
Temp-29	-0.430	0.087	-4.943	0.000	Significant
RAP 25%	-0.048	0.087	-0.552	0.584	
RAP 55%	-0.149	0.087	-1.713	0.103	

Table 38 Results of ANOVA on SCB Properties for NH binder PG 70-28A

Response: K_{IC}

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.618	0.047	13.149	0.000	Significant
Temp-19	0.207	0.066	3.136	0.006	Significant
Temp-29	0.356	0.066	5.394	0.000	Significant
RAP 25%	0.021	0.066	0.318	0.754	
RAP 55%	0.071	0.066	1.076	0.294	
Temp*RAP	-0.202	0.093	-2.172	0.044	Significant

Response: G_f

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.554	0.054	10.259	0.000	Significant
Temp-19	-0.052	0.076	-0.684	0.502	
Temp-29	-0.222	0.076	-2.921	0.009	Significant
RAP 25%	-0.114	0.076	-1.500	0.154	
RAP 55%	-0.077	0.076	-1.013	0.329	

For mixes with the PG 58-28A binder, no differences in K_{IC} were found between intermediate temperature and control temperature and between 25% and 0% of RAP content. However, at the lowest temperature level and 55% RAP content, a significant increase was observed compared to the control mix. For G_f, significant differences were found at two different levels of temperature, but no differences were found for different RAP contents (0%, 25%, and 55%). Also, no significant interactions terms were observed for K_{IC} and G_f.

For mixes with the PG 70-28A binder, significant increase in K_{IC} was observed with temperature decrease. However, no differences were found among different RAP contents. For G_f, significant difference was found only at the lowest temperature level (Temp-29).

BBR test results. Creep stiffness and *m*-value at 60 seconds were calculated from BBR experimental data. The data is reported in Table 39 and plots are presented in Figures 67 and 68. As with the SCB test results, most values of coefficient of variation were less than 25%, which is reasonable for creep testing of asphalt mixtures. From Figures 10 to 13, higher values of *S*(60s) and lower values of *m*(60s) were observed with decrease of temperature, respectively, which means asphalt mixtures become stiffer and less able to relax stresses as temperature decreases. A small number of test results were considered outliers and were removed from the analysis.

Table 39 Results of BBR Tests for New Hampshire Mixtures

Binder	Temp [°C]	RAP [%]	*S*(60s) [MPa]		*m*(60s)	
			Mean	CV[%]	Mean	CV[%]
PG 58-28A	-9	0	8,604	7	0.264	6
		25	12,133	6	0.214	4
		55	6,997	15	0.175	4
	-19	0	10,129	14	0.115	16
		25	27,036	12	0.166	3
		55	10,315	16	0.091	7
PG 70-28A	-9	0	11,960	21	0.211	3
		25	10,103	16	0.157	16
		55	11,388	15	0.201	14
	-19	0	21,217	15	0.160	11
		25	22,942	11	0.169	3
		55	17,921	16	0.111	36

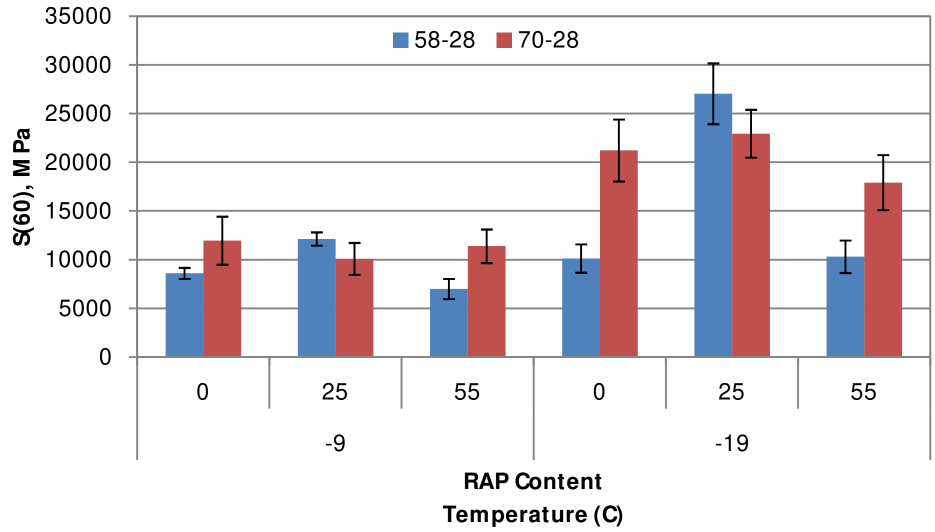


Figure 67 BBR Stiffness Results for New Hampshire Mixes

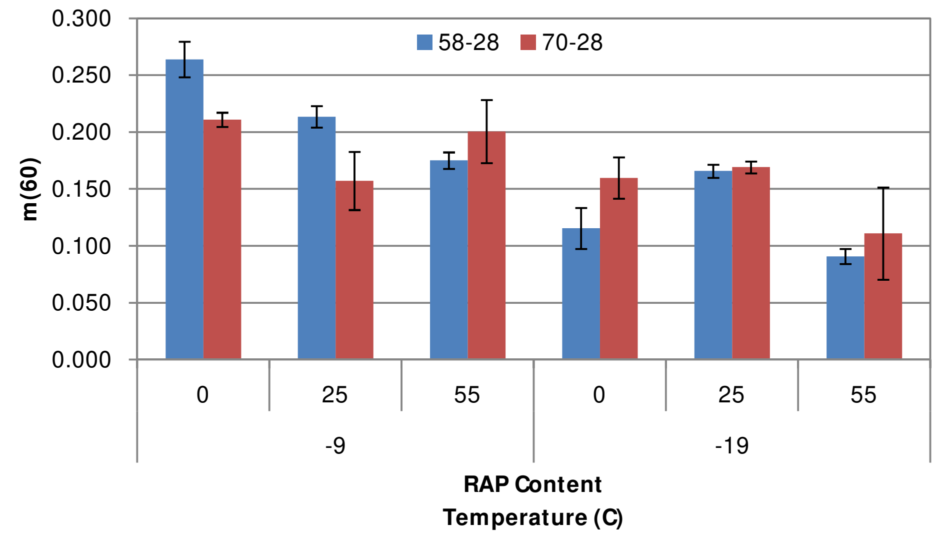


Figure 68 BBR *m*-Value Results for New Hampshire Mixes

A similar ANOVA procedure was performed for *S*(60s) and *m*(60s). To reduce residual errors, *Log S*(60s) was used rather than *S*(60s). All the computed results are shown in Tables 40 and 41, respectively.

Table 40 Results of ANOVA on BBR Parameters for NH binder PG 58-28A

Response: LogS(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	3.934	0.031	126.903	0.000	Significant
Temp-19	0.068	0.044	1.545	0.147	
RAP 25%	0.149	0.044	3.386	0.005	Significant
RAP 55%	-0.092	0.044	-2.091	0.058	
Temp*RAP	0.278	0.062	4.484	0.001	Significant

Response: m(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.264	0.007	37.714	0.000	Significant
Temp-19	-0.149	0.009	-16.556	0.000	Significant
RAP 25%	-0.050	0.009	-5.556	0.000	Significant
RAP 55%	-0.089	0.009	-9.899	0.000	Significant
Temp*RAP	0.065	0.013	5.000	0.000	Significant

Table 41 Results of ANOVA on BBR Parameters for NH binder PG 70-28A

Response: LogS(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	4.072	0.040	101.800	0.000	Significant
Temp-19	0.252	0.056	4.500	0.001	Significant
RAP 25%	-0.071	0.056	-1.268	0.232	
RAP 55%	-0.019	0.056	-0.339	0.745	
Temp*RAP	-0.054	0.084	-0.643	0.534	

Response: m(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.211	0.013	16.231	0.000	Significant
Temp-19	-0.051	0.018	-2.833	0.015	Significant
RAP 25%	-0.054	0.018	-3.000	0.012	Significant
RAP 55%	-0.010	0.018	-0.556	0.574	
Temp*RAP	0.063	0.025	2.520	0.029	Significant

For the New Hampshire mixes with PG 58-28 binders, a significant increase in *S*(60s) was found only for the 25% RAP content mix because of high *S*(60s) values at temperature -19˚C. A significant decrease in *m*(60s) was observed for both levels of RAP content. However, no differences in *S*(60s) were observed in the different RAP contents for mixes using the PG 70-28A binder. Even though lower stress-relaxation ability was observed in the 25% RAP content mix, no significant difference in stress-relaxation ability was observed compared to the 55% RAP content mix.

Thermal stresses and the critical cracking temperature, T_{CR}, using the SAP (Single Asymptote Procedure) method were computed from BBR mixture tests. In computing thermal stresses, two temperature drop rates of asphalt mixture were considered: 1°C/h and 10°C/h. The results are reported in Table 42 and plotted in Figure 69 and 70.

Table 42 Thermal Stress at -19°C and Critical Cracking Temperature for NH Mixtures

Binder type	RAP [%]	σ_{-19} [MPa]		T_{CR} [° C]	
		1° C/h	10° C/h	1° C/h	10° C/h
PG58-28A	0	1.1	2.4	-20.59	-17.33
	25	3.3	5.2	-20.48	-15.63
	55	1.7	2.9	-23.13	-20.67
PG70-28A	0	3.1	4.9	-22.52	-18.58
	25	3.4	5.0	-20.67	-16.48
	55	3.0	4.9	-21.80	-18.53

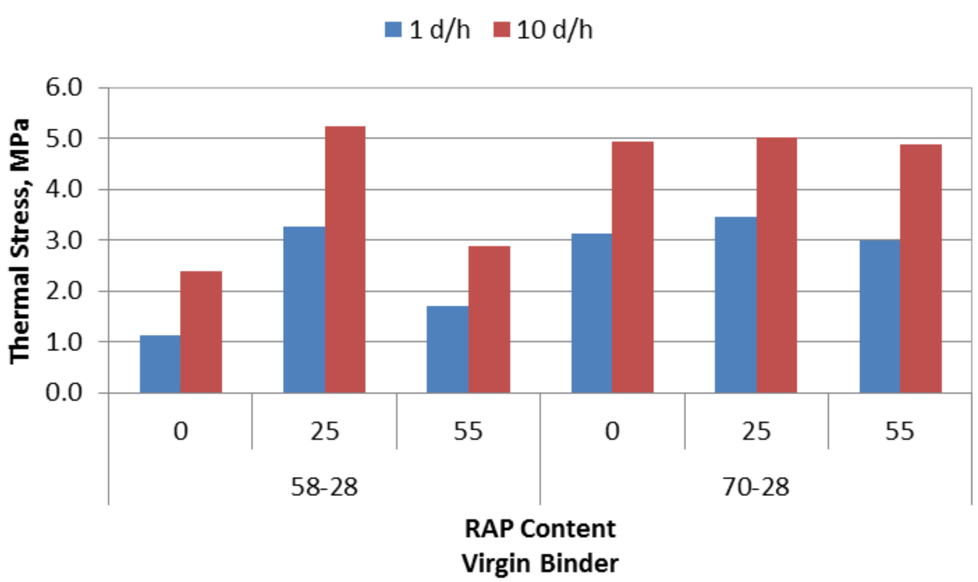


Figure 69 Thermal Stresses at -15°C for 1° and 10°/hr Cooling Rates for the NH Mixtures

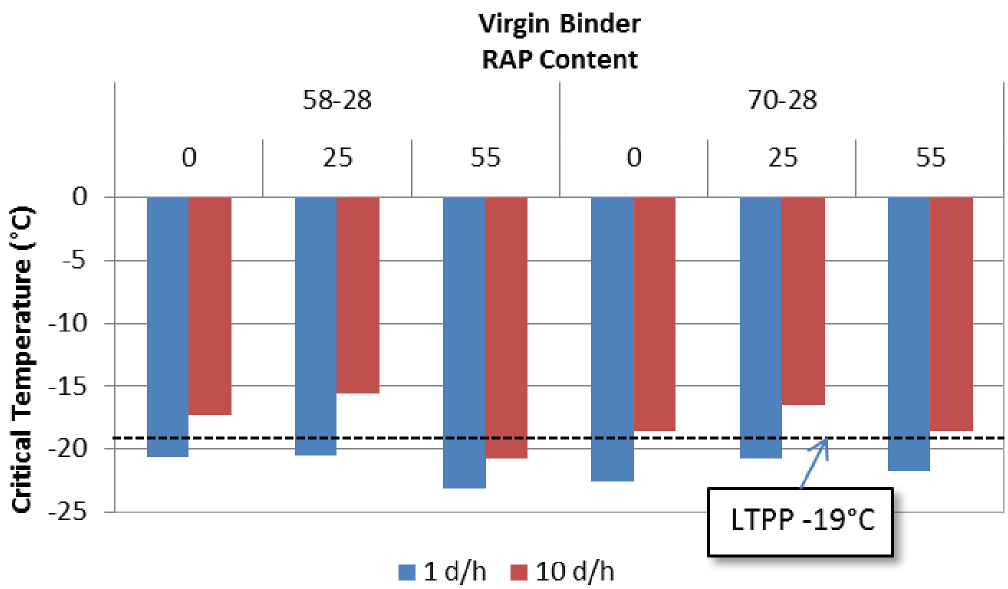


Figure 70 Critical Cracking Temperatures for the New Hampshire Mixtures

In Figure 70, it can be seen that the different RAP contents and binder grade do not have a significant effect on the critical cracking temperature for the New Hampshire mixes. In addition, for the 1˚C/h temperature drop rate, all the calculated T_{CR} values were lower than 98% reliability LTPP critical temperature (-19˚C) for this location. However, only the 55% RAP content mix with PG58-28A was lower than the LTPP temperature for a 10˚C/h temperature drop rate. For mixes with the PG 70-28 binder, thermal stresses were not affected by RAP content. Among the mixtures with PG 58-28 binder, the highest stresses were observed for the mixture with 25% RAP.

Utah Mixes

The experimental variables for the UT mixture were:

- Low temperature with three different levels in SCB test: -5˚C (control), -15˚C, and -25˚C
- Low temperature with two different levels in BBR test: -5˚C (control) and -15˚C
- RAP content with three different levels: 0% (control), 25%, and 55%.

SCB Test Results. The binder types (PG 58-34A and PG 64-34A) were different from the ones used for NH mixtures, thus, direct comparison was not possible. The means and CVs for the

Utah mixtures' fracture parameters are reported in Table 43. As with the New Hampshire results, repeatability of the results was reasonable. Average values of K_{IC} and G_f are plotted in Figures 71 and 72. As before, the whiskers represent one standard deviation for the mixture set.

Table 43 Mean and Coefficient of Variation (CV) of Fracture Parameters for Utah Mixtures

Binder	Temp (°C)	RAP (%)	K_{IC} (MPa•m$^{0.5}$)		G_f (kJ/m^2)	
			Mean	CV[%]	Mean	CV[%]
PG 58-34A	-5	0	0.440	18	1.258	1
		25	0.458	5	0.778	16
		55	0.752	3	0.908	7
	-15	0	0.800	10	1.110	9
		25	0.771	10	0.603	20
		55	0.956	7	0.491	2
	-25	0	1.032	9	0.521	5
		25	0.921	6	0.488	10
		55	0.741	23	0.238	6
PG 64-34A	-5	0	0.302	4	0.791	16
		25	0.458	5	0.980	3
		55	0.718	21	1.297	28
	-15	0	0.604	5	1.117	23
		25	0.855	24	0.938	26
		55	0.871	18	0.468	36
	-25	0	0.971	4	0.650	11
		25	1.022	4	0.718	7
		55	0.795	7	0.268	23

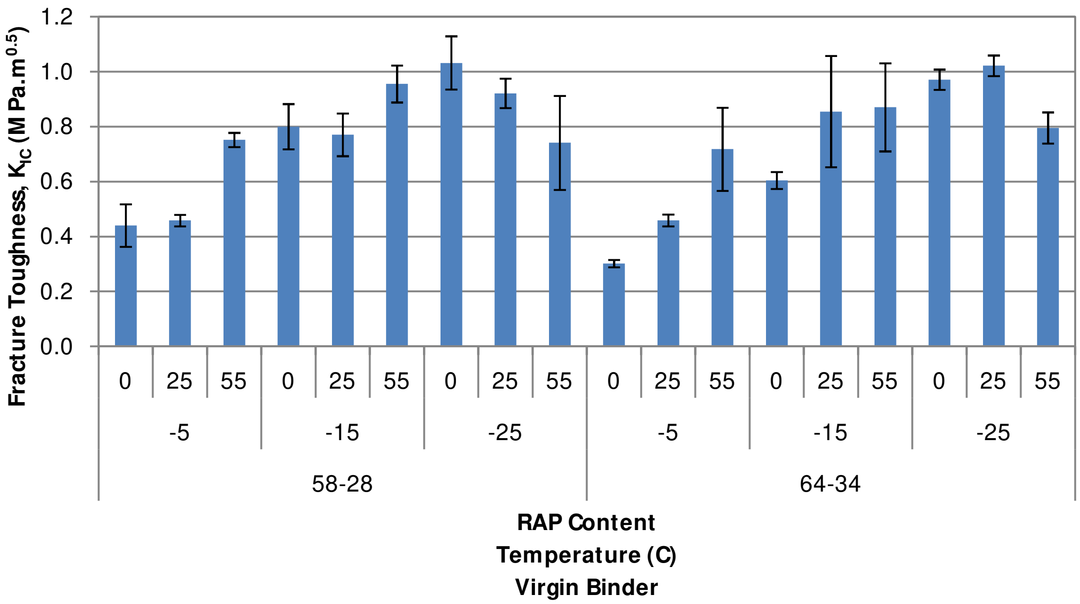


Figure 71 SCB Fracture Toughness Results for Utah Mixtures

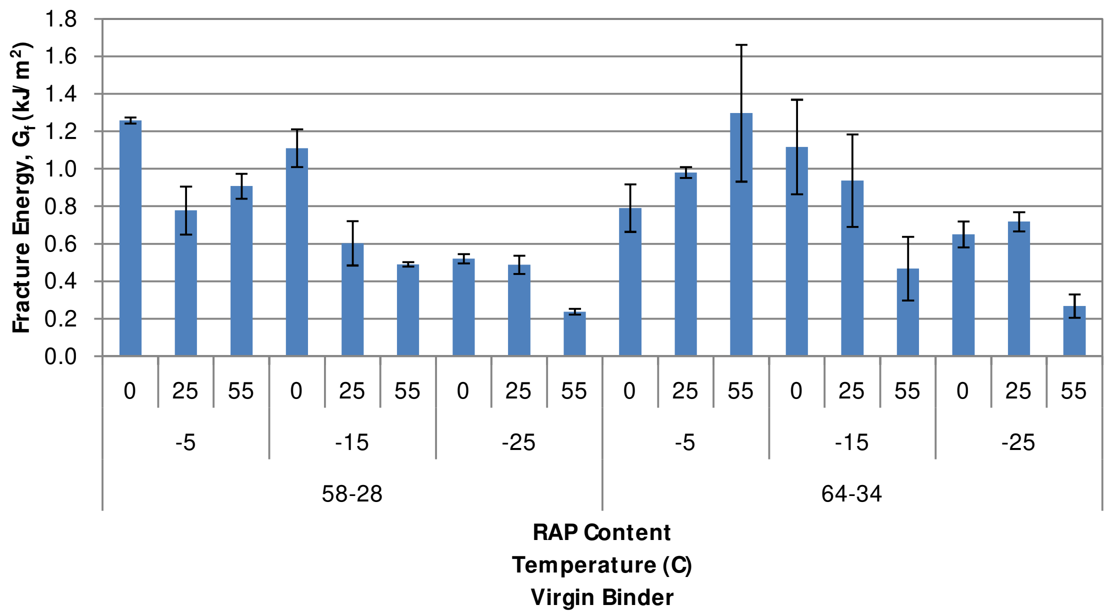


Figure 72 SCB Fracture Energy Results for Utah Mixtures

For both binders (PG 58-34A and PG 64-34A), as the RAP content increased, fracture toughness increased, except at the lowest temperature, -25˚C. However, fracture energy generally decreased with increasing RAP contents and decreased at lower temperatures. In the case of binder PG64-34A, fracture energy was highest for the 55% RAP content mixes at the warmest test temperature, -5˚C.

Tables 44 and 45 present the results of the ANOVA for the mixtures with the two grades of virgin binder. For the mixtures containing the PG 58-34A virgin binder, a statistically significant increase in fracture toughness was observed at the two low temperatures and 55% of RAP content. However, no differences in K_{IC} were observed between 25% of RAP content and the control group. Contrary to K_{IC}, a significant decrease of G_f was observed as temperature decreased and RAP content increased. For mixes using the PG64-34A binder, no differences of K_{IC} and G_f were found between 0% and 25% RAP content. The two temperature levels significantly affected fracture toughness. However, fracture energy was negatively affected at -15˚C, but was not significantly different at the lowest temperature. Significant interactions between temperature and RAP were observed in all test cases.

Table 44 Results of ANOVA on SCB Properties for UT binder PG 58-34A

Response: K_{IC}

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.440	0.049	8.980	0.000	Significant
Temp-15	0.360	0.070	5.143	0.000	Significant
Temp-25	0.592	0.070	8.457	0.000	Significant
RAP 25%	0.018	0.070	0.257	0.803	
RAP 55%	0.311	0.070	4.443	0.000	Significant
Temp*RAP	-0.602	0.099	-6.081	0.000	Significant

Response: G_f

Parameter	Coefficient	Std. Error	t	p-value	Significance
Intercept	1.258	0.042	29.952	0.000	Significant
Temp-15	-0.147	0.060	-2.450	0.025	Significant
Temp-25	-0.737	0.060	-12.283	0.000	Significant
RAP 25%	-0.480	0.060	-8.000	0.000	Significant
RAP 55%	-0.350	0.060	-5.833	0.000	Significant
Temp*RAP	0.448	0.085	5.271	0.000	Significant

Table 45 Results of ANOVA on SCB Properties for UT binder PG64-34A

Response: K_{IC}

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.302	0.060	5.033	0.000	Significant
Temp-15	0.302	0.084	3.595	0.002	Significant
Temp-25	0.669	0.084	7.964	0.000	Significant
RAP 25%	0.156	0.084	1.857	0..082	
RAP 55%	0.416	0.084	4.952	0.000	Significant
Temp*RAP	-0.592	0.126	-4.698	0.000	Significant

Response: G_f

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.791	0.102	7.755	0.000	Significant
Temp-15	0.326	0.144	2.264	0.037	Significant
Temp-25	-0.140	0.144	-0.972	0.344	
RAP 25%	0.190	0.144	1.319	0.204	
RAP 55%	0.507	0.161	3.149	0.006	Significant
Temp*RAP	-0.889	0.215	-4.135	0.001	Significant

BBR test results (UT). The results of *S*(60s) and *m*(60s) for the Utah mixes are reported in Table 46. Plots are presented in Figures 73 and 74. The CVs were reasonable for most of the mix sets. In a few limited cases, outliers were removed to reduce errors in the statistical analysis. For each of the binder grades, *S*(60s) increased with higher RAP contents and at lower temperatures. For *m*(60s), higher RAP contents and lower temperatures also reduced the mixes' abilities to relax under stress.

Table 46 Mean and Coefficient of Variation (CV) of *S*(60s) and *m*(60s) for UT Mixtures

Binder type	Temp [°C]	RAP [%]	*S*(60s) [MPa]		*m*(60s)	
			Mean	CV[%]	Mean	CV[%]
PG 58-34A	-5	0	2720	15	0.384	9
		25	5636	23	0.317	7
		55	5687	11	0.238	3
	-15	0	11604	0	0.267	9
		25	15184	13	0.237	9
		55	23561	15	0.210	6
PG 64-34A	-5	0	1889	16	0.409	4
		25	3325	18	0.325	13
		55	7202	10	0.242	1
	-15	0	7525	18	0.308	8
		25	12729	13	0.235	17
		55	14191	8	0.179	2

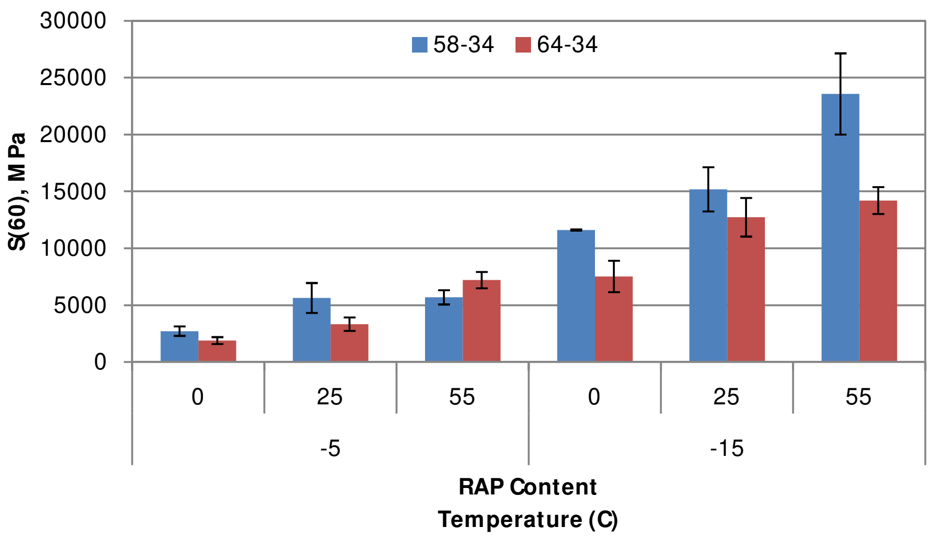


Figure 73 BBR Stiffness Results for Utah Mixes

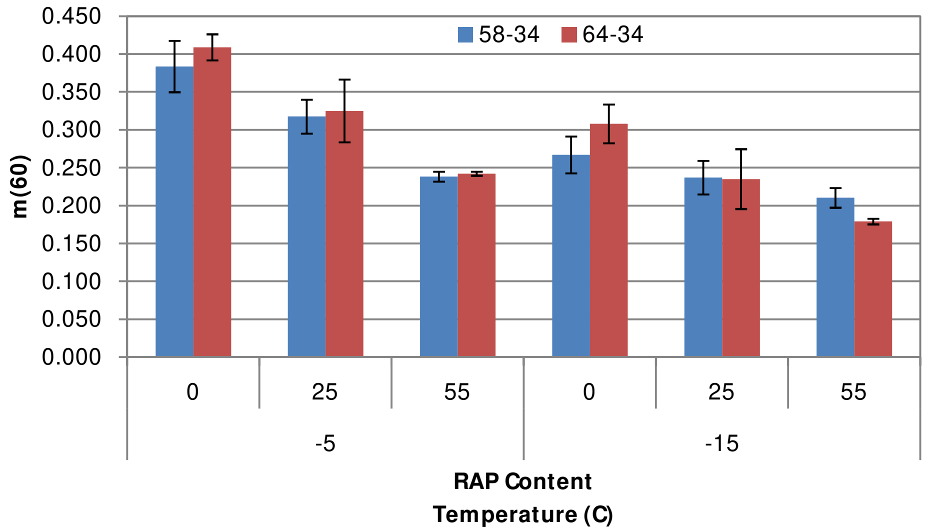


Figure 74 BBR *m*-Values for the Utah Mixes

Similar to the previous section, *S*(60s) and *m*(60s) were set as dependent variables, and RAP and temperature were set as independent variables in the statistical analysis. Also, the original scale of *S*(60s) was converted into *log* scale similar to the previous section. ANOVA results are shown in Tables 47 and 48. It can be seen that each parameter had a significant effect on *S*(60s) and *m*(60s). Lower temperatures and higher RAP content significantly increased *S*(60s) and decreased *m*(60s) .

Table 47 Results of ANOVA on BBR Parameters for Utah Mixes with PG 58-34A

Response: LogS(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	3.431	0.037	92.730	0.000	Significant
Temp-15	0.633	0.052	12.173	0.000	Significant
RAP 25%	0.311	0.052	5.981	0.000	Significant
RAP 55%	0.322	0.052	6.192	0.000	Significant
Temp*RAP	-0.197	0.074	-2.662	0.021	Significant

Response: m(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.384	0.013	29.538	0.000	Significant
Temp-15	-0.117	0.018	-6.500	0.000	Significant
RAP 25%	-0.066	0.018	-3.667	0.003	Significant
RAP 55%	-0.146	0.018	-8.111	0.000	Significant
Temp*RAP	0.089	0.026	3.423	0.005	Significant

Table 48 Results of ANOVA on BBR Parameters for Utah Mixes with PG 64-34A

Response: LogS(60)

Parameter	Coefficient	Std. Error	t	p-value	Significance
Intercept	3.272	0.038	86.105	0.000	Significant
Temp-15	0.599	0.053	11.302	0.000	Significant
RAP 25%	0.245	0.053	4.623	0.001	Significant
RAP 55%	0.584	0.053	11.019	0.000	Significant
Temp*RAP	-0.304	0.080	-3.800	0.003	Significant

Response: m(60)

Parameter	Coefficient	Std. Error	t	p-value	Significance
Intercept	0.409	0.016	25.563	0.000	Significant
Temp-15	-0.101	0.023	-4.391	0.001	Significant
RAP 25%	-0.084	0.023	-3.652	0.003	Significant
RAP 55%	-0.167	0.023	-7.261	0.000	Significant

The results of computed thermal stress and T_{CR} are shown in Table 49; plots are presented in Figures 75 and 76, respectively. Figure 75 shows that the buildup of stresses is significantly influenced by the rate of the temperature drop. Higher RAP contents also lead to greater stress accumulation. Surprisingly, the mixes with the softer high PG binder builds up greater thermal stresses than the stiffer high PG binder.

The results shown in Figure 76 indicate that the estimated critical cracking temperature for all mixtures, except the 55% RAP mix with PG 58-34 binder subjected to a fast cooling rate, are well below the 98% reliability LTPP low temperature for the climate at this location. This suggests that despite the apparent negative impact that RAP has on thermal cracking properties, the mixtures may still be resistant to thermal cracking.

Table 49 Thermal Stress at -15°C and Critical Cracking Temperature for Utah Mixtures

Binder type	RAP [%]	σ_{-15} [MPa]		T_{CR} [°C]	
		1°C/h	10°C/h	1°C/h	10°C/h
PG 58-34A	0	0.32	0.86	-26.5	-22.1
	25	1.13	2.40	-25.7	-21.3
	55	1.28	2.57	-19.7	-15.2
PG 64-34A	0	0.15	0.48	-29.7	-26.0
	25	0.49	1.13	-25.4	-21.2
	55	1.18	2.36	-24.7	-21.0

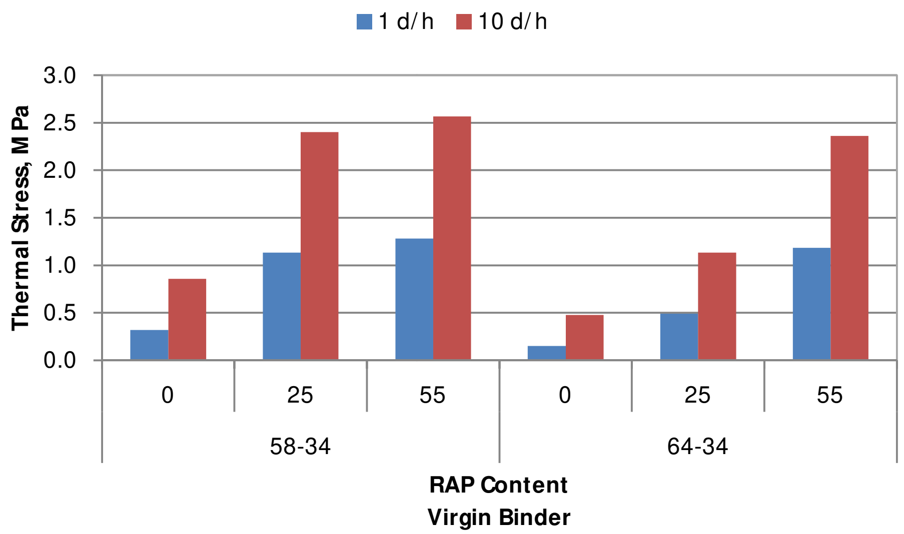


Figure 75 Thermal Stresses at -15°C for 1°/hr and 10°/hr Cooling Rates for Utah Mixes

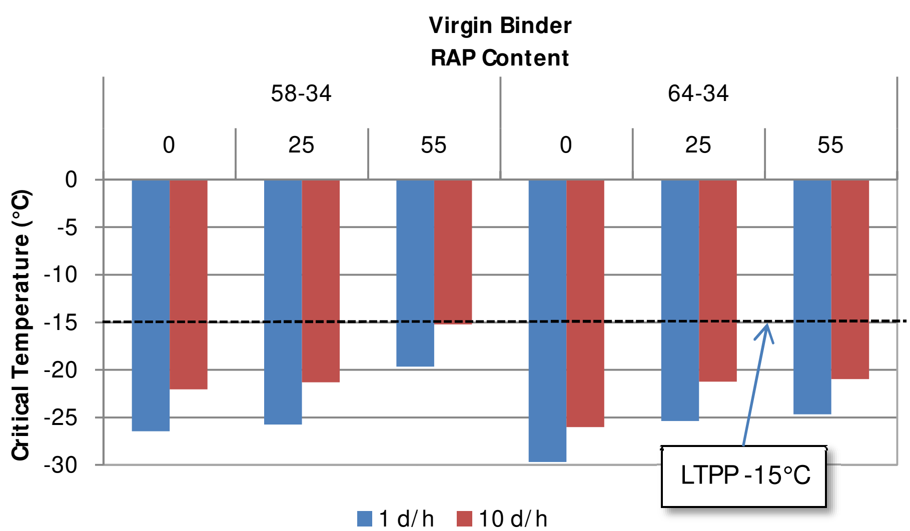


Figure 76 Estimated Critical Cracking Temperatures for Utah Mixes

Minnesota Mixes

The experimental variables for the MN mixture were:

- Low temperature with three different levels in SCB test: -14˚C (control), -24˚C, and -34˚C
- Low temperature with two different levels in BBR test: -14˚C (control) and -24˚C
- RAP content with two different levels: 0% (control) and 40%.

- Nominal Maximum Aggregate Size: 9.5 mm (control) and 19.5 mm

For the Minnesota mixture set, only one binder was used: 58-28B; therefore, binder effects were not evaluated. However, a new experimental variable was introduced: the nominal maximum aggregate size (NMAS) with two different levels: 9.5 mm and 19.0 mm. The other experimental variables consisted of three temperature levels: high, intermediate, and low (-14˚C, -24˚C, and -34˚C) for the SCB test, and two temperature levels (-14˚C and -24˚C) for BBR test, as well as two different RAP content levels: 0% and 40% for the SCB and BBR test.

SCB test results for Minnesota mixtures. The fracture toughness and fracture energy results for the Minnesota mixes are shown in Table 50, and the plots are presented in Figures 77 and 78, respectively.

Table 50 Mean and Coefficient of Variation of Fracture Parameters for MN Mixtures

NMAS	Temp [˚C]	RAP [%]	K_{IC} [MPa·m$^{0.5}$]		G_f [kJ/m^2]	
			Mean	CV[%]	Mean	CV[%]
9.5 mm	-14	0	0.574	10	0.577	9
		40	0.742	7	0.554	18
	-24	0	0.610	15	0.325	8
		40	0.816	8	0.318	19
	-34	0	0.656	17	0.235	8
		40	0.711	2	0.216	22
19.0 mm	-14	0	0.737	7	0.421	23
		40	0.715	6	0.458	23
	-24	0	0.858	12	0.358	14
		40	0.896	11	0.400	20
	-34	0	0.738	16	0.186	17
		40	0.692	11	0.200	26

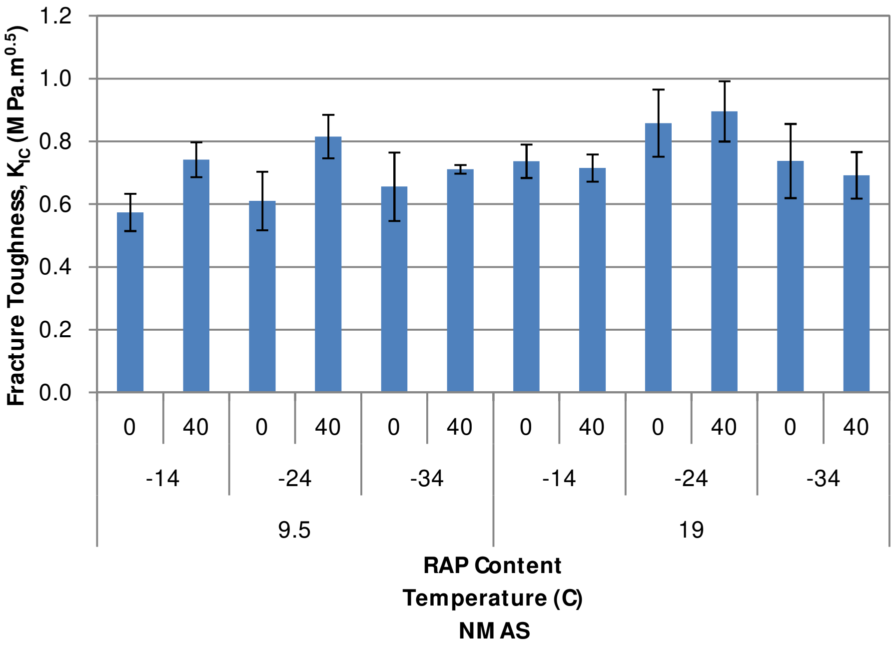


Figure 77 SCB Fracture Toughness Results for Minnesota Mixes

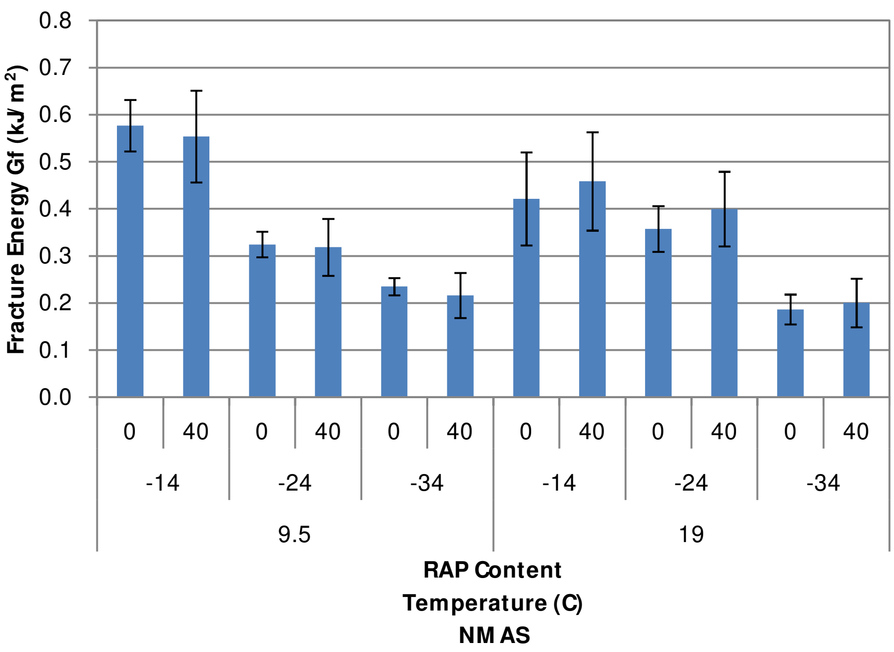


Figure 78 SCB Fracture Energy Results for Minnesota Mixes

For the 9.5 mm mixes, similar values of K_{IC} were observed among different test temperatures. The 40% RAP mixtures had slightly higher values of K_{IC} than the virgin mixes. For the 19.0 mm mixes, virgin and 40% RAP mixtures had similar fracture toughness results. Fracture toughness values were highest at the intermediate test temperature.

As with the mixtures from NH and UT, smaller fracture energy values were observed at lower test temperatures. However, virgin and 40% RAP content mixtures had similar results at each temperature for both NMAS.

Table 51 shows the results of ANOVA on fracture energy and fracture toughness for the MN mixtures. It was observed that K_{IC} for the 19 mm 40% RAP mixture was significantly higher compared to the virgin 9.5 mm mixture. The two lower temperatures resulted in an increase of K_{IC}, but only the intermediate temperature was significant. In addition, the interaction between RAP and NMAS was observed. For fracture energy comparisons, the two lower temperatures resulted in significant decrease of G_f; however, no significant change in G_f was found between the mixtures with different RAP contents (0% and 40%). The larger NMAS mixture had significantly lower G_f compared to the smaller NMAS, and the interaction between temperature and NMAS was significant.

Table 51 Results of ANOVA on SCB Properties for MN Mixtures

Response: K_{IC}

Parameter	**Coefficient**	**Std. Error**	***t***	***p*-value**	**Significance**
Intercept	0.577	0.034	16.971	0.000	Significant
Temp-24	0.103	0.034	3.029	0.005	Significant
Temp-34	0.007	0.034	0.206	0.830	
RAP 40%	0.143	0.039	3.667	0.001	Significant
NMAS 19.0mm	0.164	0.039	4.205	0.000	Significant
RAP*NMAS	-0.152	0.055	-2.764	0.010	Significant

Response: G_f

Parameter	**Coefficient**	**Std. Error**	***t***	***p*-value**	**Significance**
Intercept	0.562	0.027	20.815	0.000	Significant
Temp-24	-0.244	0.036	-6.778	0.000	Significant
Temp-34	-0.340	0.036	-9.444	0.000	Significant
RAP 40%	0.007	0.021	0.333	0.720	
NMAS 19.0mm	-0.126	0.036	-3.500	0.001	Significant
Temp*NMAS	0.183	0.050	3.660	0.001	Significant

BBR test results (MN). The test results of *S*(60s) and *m*(60s) for the Minnesota mixes are shown in Table 52 and in Figures 79 and 80, respectively. The CVs were reasonable and similar to the results for the mix designs using materials from the other two locations. Higher values of *S*(60s) and lower values of *m*(60s) were observed with a decrease in temperature. In the case of *m*(60s) comparisons, it can be seen in Figure 79 that stresses build up in specimens as temperature decreases due to a reduced ability to creep. For NMAS 9.5 mm, lower values of *m*(60s) were observed with an increase of RAP content at -14˚C; however, contrary to the previous case, higher or similar values of *m*(60s) were found with an increase of RAP content at -24˚C.

A similar ANOVA procedure was performed; however, some *S*(60s) and *m*(60s) data were erased because they were considered outliers. ANOVA results are presented in Table 53. It can be observed that both temperature and RAP significantly affected *S*(60s) and *m*(60s) compared to the control group. *S*(60s) was significantly affected by NMAS, but *m*(60s) was not.

Table 52 Mean and Coefficient of Variation of *S*(60s) and *M*(60s) for MN Mixes

NMAS	Temp [˚C]	RAP [%]	*S*(60s) [MPa]		*m*(60s)	
			Mean	CV[%]	Mean	CV[%]
9.5 mm	-14	0	5949	13	0.231	7
		40	7892	4	0.172	8
	-24	0	7656	7	0.060	16
		40	16751	7	0.098	15
19.0 mm	-14	0	6525	10	0.179	17
		40	21955	16	0.186	9
	-24	0	21438	18	0.115	17
		40	22514	4	0.112	8

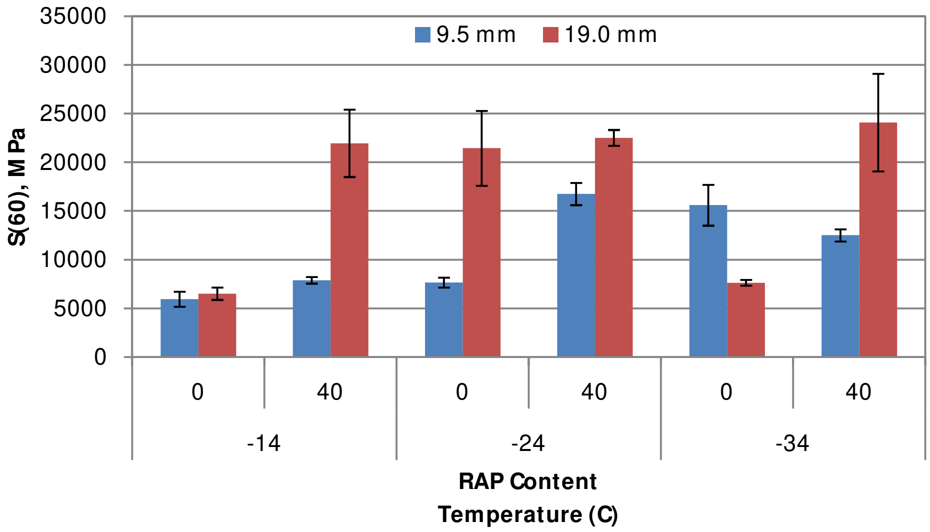


Figure 79 BBR Stiffness Results for Minnesota Mixes

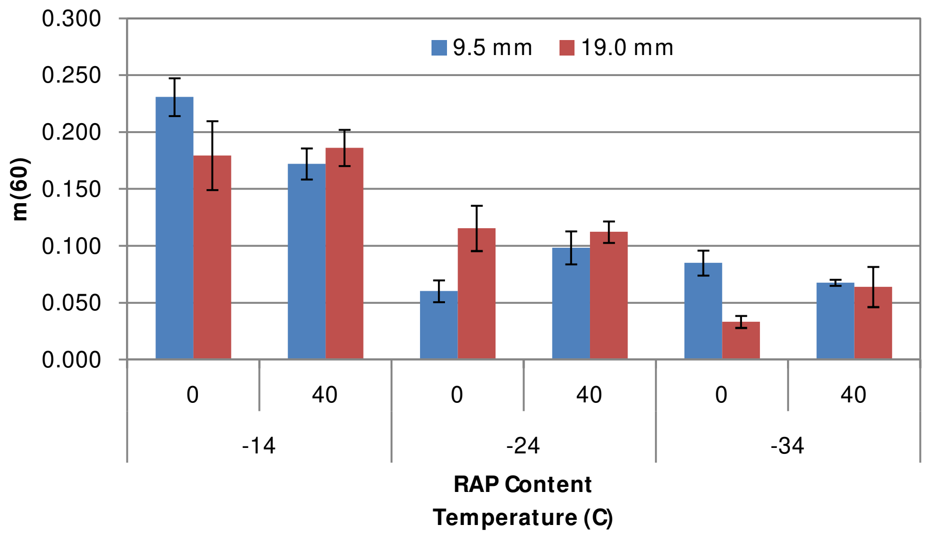


Figure 80 BBR *m*-value Results for Minnesota Mixes

Table 53 Summary of ANOVA on BBR Parameters for Minnesota Mixtures

Response: LogS(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	3.700	0.065	56.923	0.000	Significant
Temp-24	0.290	0.094	3.085	0.009	Significant
RAP 40%	0.268	0.087	3.080	0.009	Significant
NMAS 19	0.184	0.087	2.115	0.053	Significant

Response: m(60)

Parameter	Coefficient	Std. Error	*t*	*p*-value	Significance
Intercept	0.220	0.013	16.923	0.000	Significant
Temp-24	-0.144	0.019	-7.579	0.000	Significant
RAP 40%	-0.038	0.018	-2.111	0.052	Significant
NMAS 19	-0.030	0.018	-1.667	0.109	
Temp*NMAS	0.053	0.022	2.409	0.031	Significant

Comparison of thermal stress and critical cracking temperature for Minnesota mixes. The effect of RAP content on thermal stress during cooling and the estimated critical cracking temperatures were also analyzed. Results are reported in Table 54 and presented in Figures 32 and 33, respectively. As expected, thermal stresses were higher for the faster cooling rate. For both NMAS, the mixes containing RAP also had higher thermal stresses than the virgin mix counterparts. The 40% RAP content mix had unusually high thermal stresses relative to all other mixes in this study. This result is not consistent with the properties from the SCB tests, which did not show any unusual trends for this mixture.

Table 54 Thermal Stress at -24°C and Critical Cracking Temperature for MN Mixes

NMAS	RAP [%]	σ_{-24} [MPa]		T_{CR} [°C]	
		1d/h	10d/h	1d/h	10d/h
9.5mm	0	0.86	1.81	-26.7	-24.0
	40	2.14	3.52	-25.7	-23.0
19.0mm	0	1.99	3.27	-22.0	-21.4
	40	10.72	13.16	-5.7	-5.3

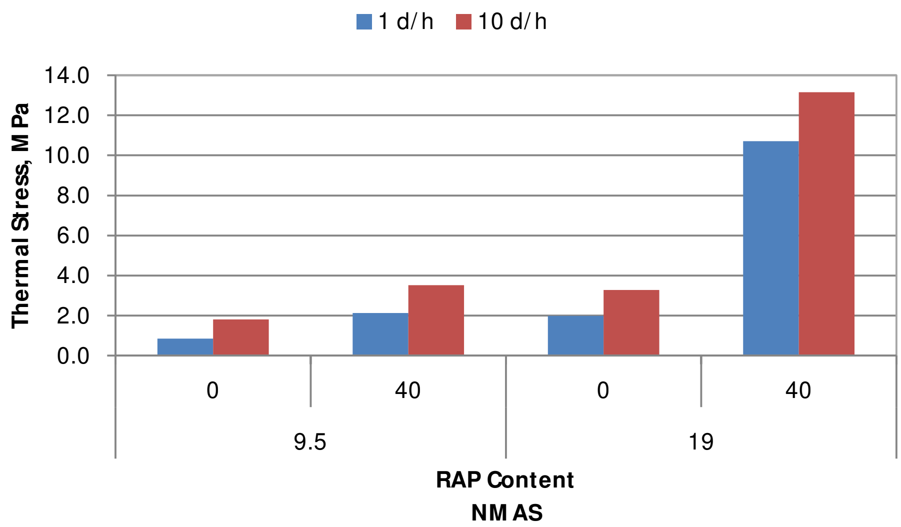


Figure 80 Thermal Stresses at -15°C for 1°/hr and 10°/hr Cooling Rates for MN Mixes

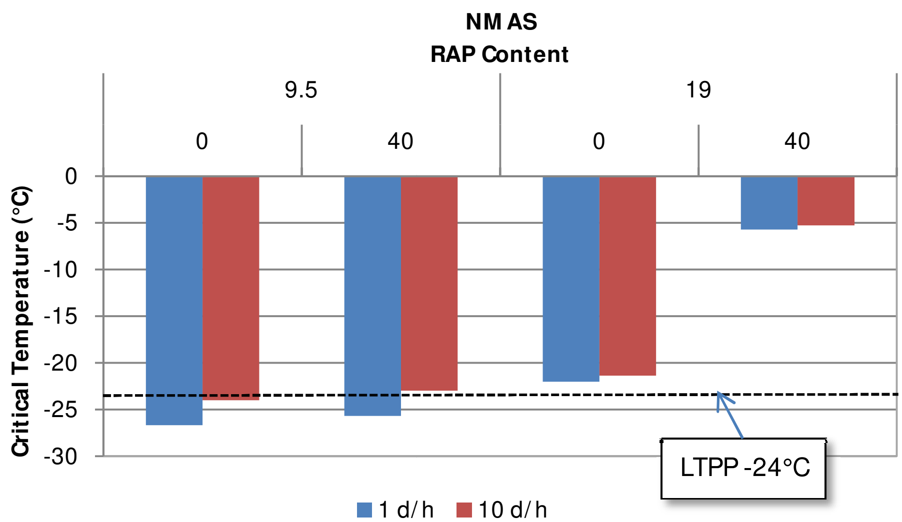


Figure 81 Estimated Critical Cracking Temperatures for MN Mixes

Summary of Low-Temperature Properties

A summary of the effect of RAP content on the low-temperature properties for each of the mix designs is shown in Table 55. It can be seen that the mixes with 55% RAP had significantly higher fracture toughness, K_{IC}, than the corresponding virgin mixes, except when the mixes contained the polymer-modified binder. The SCB fracture energy was not significantly affected by RAP content except in the Utah mixes. For those mix designs, mixes with RAP often yielded lower fracture energies. Therefore, the SCB properties do not provide a consistent effect for mixes with high RAP contents. In the BBR results, mixes with RAP generally had higher stiffness and lower *m*-values, which theoretically should result in more cracking.

Table 55 Summary of the Effect of RAP Content on Low-Temperature Properties

Virgin Binder	SCB K_{IC}	SCB G_f	BBR *S*(60s)	BBR *m*(60s)
New Hampshire				
PG 58-28	55% ↑	Not significant	25% ↑	25 & 55% ↓
PG 70-28	Not significant	Not significant	Not significant	25% ↓
Utah				
PG 58-34	55% ↑	25 & 55% ↓	25 & 55% ↑	25 & 55% ↓
PG 64-34	55% ↑	55% ↓	25 & 55% ↑	25 & 55% ↓
Minnesota				
PG 58-28	40% ↑	Not significant	40% ↑	40%↓

However, estimates of the critical cracking temperatures of the mix designs based on the BBR results compared to the critical temperatures in the climates where the materials were obtained indicate that the all the mix designs using Utah materials should perform well with respect to thermal cracking. The New Hampshire mixes would also be expected to do well except for a very rapid temperature drop. Even then, the high RAP content mixes would be expected to perform similar to the virgin mixes. For the Minnesota mixes, the 9.5 mm mixes with or without RAP would be expected to perform similarly. However, the 19.0 mm mix with 40% RAP appears to be much more susceptible to thermal cracking.

CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings from the literature review and the results of the experimental work. It is organized by the logical progression in which RAP materials are obtained, tested, and used in the mix design, and the mix designs are evaluated. The chapter ends with recommendations for revising the current AASHTO standards for Superpave mix design to better guide users on how to deal with high RAP content asphalt mixes.

RAP Management

Information on good RAP management practices were obtained from the literature review, surveys of current practices, discussions with numerous contractor QC personnel, and analysis of contractor stockpile QC data from across the U.S. Based on that information, a comprehensive report titled *Best Practices for RAP Management* was prepared and is included as a companion document to this report. Some of the more important findings and recommendations from that document are summarized here.

Some references have recommended not combining RAP collected from different sources due to concern that it will result in greater variability in the RAP stockpile. Milled RAP from a single project typically will have a consistent gradation and asphalt content. Such stockpiles of single-source RAP generally require only screening to remove oversized particles. It is generally accepted that RAP particles larger than 2 inches should be screened out because the larger particles (chunks of pavement or agglomerations) may not break apart during the mixing process.

Several previous studies and data collected from contractors during this project have shown that processing RAP collected from multiple sources can result in a material that is often more consistent than virgin aggregate. This information is evidence to dispute the requirement that RAP be limited to single-source materials. A recommended RAP sampling and testing plan and variability criteria provided below should provide assurance that the RAP is consistent regardless of how it was collected or processed.

A summary of different processes used to produce a consistent RAP product is shown in Table 56. It is often appropriate to combine different processes, such as mixing and crushing. A common mistake in RAP processing is to crush all RAP to pass single a single screen size (e.g., minus ½ inch) so that the RAP can be used in mixes with a range of nominal maximum aggregate sizes. This single-size crushing approach often leads to generating high dust contents, which can limit the amount of the RAP that can be successfully used in mix designs.

Table 56 Summary of RAP Processing Options

Type	Description	Suitable Conditions	Possible Concerns
Minimal Processing	Screening only to remove oversized particles (may be accomplished in-line during feed of RAP in the plant)	RAP from a single source	Single source RAP piles are a finite quantity. When a stockpile is depleted, new mix designs will be needed with another RAP stockpile
Crushing	Breaking of RAP chunks, agglomerations, and or aggregate particles in order to avoid large particles that may not break apart during mixing or particles that exceed the mix's NMAS	RAP contains large chunks (anything larger than 2") or RAP aggregate NMAS exceeds the recycled mix's NMAS	Generating excess dust and uncoated surfaces
Mixing	Using a loader or excavator to blend RAP from different sources. Usually done in combination with crushing and/or fractionating	RAP stockpile contains materials from multiple sources	Good consistency of RAP characteristics must be verified with a RAP QC plan
Fractionating	Screening RAP into multiple size ranges	High RAP content mixes (above 30 to 40%) are routine	Highest cost, requires additional RAP bin(s) to simultaneously feed multiple fractions

Contamination of RAP stockpiles is a common complaint. Contaminants can include dirt, road debris (tires, crack sealant), paving fabric, plant material, tar-sealed pavement, fuel-contaminated mix, and general construction waste. Contamination can occur with single-source RAP stockpiles, but tends to be more prevalent with RAP collected from different sources. Perhaps this is because the collection of RAP from multiple sources is not well monitored because it is known that the collected material will have to be extensively processed later. However, contamination is best avoided by inspecting the materials before they are unloaded on the unprocessed stockpile. Contaminated materials are better suited for use as shoulder fill or other non-asphalt mix applications.

Regardless of the how the RAP is collected, processed, or stored, it should be sampled and tested on a routine basis to assess uniformity. A sampling and testing frequency of one per 1,000 tons is consistent with QC requirements for virgin aggregates and will provide sufficient information to determine whether a problem exists with the material's consistency

Characterizing RAP Materials for Mix Design

Once RAP stockpile samples are obtained, they must be dried before testing. A simple comparison of the amount of time necessary to dry typical samples of RAP with about 5% moisture using an oven set at 110°C and fan drying at ambient temperature showed the oven drying took six hours, and fan drying took about 96 hours. Oven drying at 110°C for six hours did not further age the RAP binder.

Properties of RAP materials that are needed for mix design include basic RAP aggregate properties, the asphalt content, and, if the RAP content is considered "high," the true or continuous grade of the recovered RAP binder may be needed.

Most references recommend recovering RAP aggregates using either a solvent extraction procedure or the ignition method in order to determine the needed properties. Gradation and consensus properties of the recovered aggregate may be affected to a minor degree by solvent extraction or the ignition method, but generally not enough to appreciably affect the mix design or the amount of RAP that can be used. Some agencies may also require that aggregate source properties such as soundness, abrasion resistance, or polishing or mineralogical characteristics be determined if the RAP is to be used in surface mixes.

With regard to the bulk specific gravity of the RAP aggregate, this is a key property since it is used in the calculation of VMA, the most important volumetric criteria to ensure mix durability. The current AASHTO standard for Superpave mix design suggests that the following three methods are acceptable for determining the RAP aggregate specific gravity:

1. Recovery of the RAP aggregate using the ignition method (AASHTO T 308) followed by conducting AASHTO T84 and T85 for specific gravity of the fine and coarse aggregate portions, respectively.
2. Recovery of the RAP aggregate using the solvent extraction (AASHTO T 164) followed by conducting AASHTO T84 and T85 for specific gravity of the fine and coarse aggregate portions, respectively.
3. Estimating the RAP aggregate bulk specific gravity using the following process:

a. conduct the maximum theoretical specific gravity test (i.e., the Rice method) on samples of the RAP following AASHTO T 209.
b. calculate the effective specific gravity of the RAP aggregate from the asphalt content, G_{mm} of the RAP, and an assumed value for specific gravity of the binder, G_b.

$$G_{se}(RAP) = \frac{100 - P_{b(RAP)}}{\dfrac{100 - P_{b(RAP)}}{G_{mm(RAP)} \times G_b}}$$

c. calculate the RAP aggregate bulk specific gravity using the formula:

$$G_{sb}(RAP) = \frac{G_{se(RAP)}}{\dfrac{P_{ba} \times G_{se\,(RAP)}}{100 \times G_b} + 1}$$

Where P_{ba} (asphalt absorption) also has to be assumed based on historical records of mixes with the same raw materials.

These three options were evaluated in a joint study by the University of Nevada-Reno and NCAT and in this project. Results from this study showed that method 1 and 2 provided similar G_{sb} values, but method 3 provided substantially different G_{sb} values from a practical point of view. As shown in the UNR-NCAT study, the accuracy of method 3 is highly dependent on how well the percentage of absorbed asphalt can be estimated. For the 25% RAP content mixes, using method 3 inflated the VMA by about 0.4%. For the 55% RAP content mixes, method 3 resulted in extremely inflated VMA values for most mixes. Using inflated VMAs would likely result in low asphalt contents for high RAP content mixes and ultimately in significant pavement performance problems. Based on these findings, method 3 is not recommended. For consistency with other research at NCAT, method 2 was used in this project.

The most popular method for determining the asphalt content of RAP is the ignition method. Several studies have shown that the ignition method provides more accurate results for asphalt content compared to solvent extraction methods from many aggregate types, even when no aggregate correction factor is used for RAP samples in the ignition method. However, regions that have not found the ignition method suitable for asphalt content determinations due to the reaction of dolomitic aggregates at high temperatures should use solvent extractions for determining RAP asphalt contents.

For high RAP content mixes, most studies support the current standard that recommends recovering the RAP binder using a solvent extraction and recovery procedure, then determining the true or continuous grade of the binder in accordance with Superpave binder grading procedures. There are several disadvantages of this method since it involves handling potentially hazardous solvents. Many researchers have attempted to use properties of mix or mortar tests and to estimate properties of the RAP binder. At this time, these techniques have not been proven reliable.

Field Performance of High RAP Content Mixes

In service performance of asphalt pavements containing up to 50% RAP in projects with diverse climates and traffic have been very positive. Several researchers examined data from experimental sections in the Long-Term Pavement Performance program to compare overlays with RAP mixes and virgin mixes. Those studies have shown that the overlays containing 30% RAP have performing equal to or better than virgin mixes for most measures of pavement performance. Overall, the overlays containing RAP had more wheelpath cracking, but the extent of cracking was acceptable.

Recent findings from research with high RAP content mixes at the NCAT test track indicate that using a softer grade of virgin binder improves the cracking and raveling resistance of surface mixes. Pavement response measurements under heavy traffic also show that the increased stiffness of high RAP content mixes can be an advantage in structural design by reducing the critical tensile strains in the pavement structure.

Mix Designs Using High RAP Contents

Results of heating experiments showed that an appropriate method to heat batched samples of RAP in preparation for making mix design samples is to place the samples in an oven at the mixing temperature for 1½ to 3 hours. Heating RAP samples for more than three hours may cause excessive aging of the RAP binder. This finding is consistent with other studies. Although the effect of overheating RAP may not be apparent in the volumetric mix design process, the additional aging will likely impact performance-related test results.

The primary experimental plan was designed to answer five questions:

1. Are volumetrics affected by a change in the virgin binder grade?

2. Can the compatibility of RAP and virgin binders be assessed in mix design?
3. Does lower mixing temperatures associated with warm mix asphalt technologies affect RAP and virgin binder blending?
4. Can the composite binder (blended or partially blended RAP and virgin binder) be characterized using an indirect method that is based on dynamic modulus of the mix?
5. What do laboratory performance-related test results tell us about the mix designs with high RAP contents?

The materials for this study were obtained from four locations in the United States that included a variety of aggregate types, binder grades and sources, and RAP materials with different characteristics. Contractors from New Hampshire, Utah, Minnesota, and Florida provided materials and example mix designs. Thirty mix designs meeting the requirements of AASHTO R 35 were completed with the materials. Twelve of those mix designs were virgin mixes to provide a basis of comparison in the analyses. Fractionated RAP was provided by three of the four contractors. It was necessary to fractionate the fourth RAP material in order to obtain satisfactory mix designs with 55% RAP. In some cases, only the coarse RAP fractions were used for higher RAP content mixes in order to meet the Superpave mix design criteria. Many of the experiments used subsets of the mix designs in order to keep the project with the budget constraints.

The experimental results to determine whether or not changing the binder grade or binder source affects mix design volumetric properties were not conclusive. For one source of materials, significant differences in optimum asphalt contents (up to 0.5%) were obtained for virgin and 25% RAP mix designs when different binder grades and different binder sources were used. However, it is unlikely that the binder source or grade change was responsible for the variations in the optimum asphalt contents for this source of materials since the effects were not consistent for the mix designs with different RAP contents. Mix design results for the second set of materials in this experiment clearly indicate that changing the virgin binder source or the virgin binder grade had a negligible effect. This issue is only important if a mix designer completed a mix design with one binder, then wanted to change to another binder source due to supply or economic reasons, or to change binder grades to try to improve mix performance properties.

The experiment to assess the impact of using WMA and a lower mixing temperature with a high RAP content mix was very limited since WMA was included as a variable with only one mix design containing 55% RAP. Including a WMA additive and decreasing the mixing and compaction temperatures by 19°C (35°F) had a negligible effect on the mix's volumetric properties and TSR results. The WMA mix had slightly better rutting test results and the fatigue results were similar to that of the HMA. The dynamic modulus of the WMA was 6 to 15% lower than the HMA, with the larger difference observed at the higher temperature range.

Dynamic modulus tests were performed on all mix designs for two purposes. The first purpose was to evaluate how binder grade, binder source, and RAP content affected mix stiffness. The second purpose was to try to backcalculate effective binder properties using the Hirsch model. Results showed that dynamic modulus was significantly affected by RAP content and source. Compared to the virgin mixes, stiffnesses of the 25% RAP mixes were about 30% to 43% higher, with the greatest differences occurring at the intermediate temperature ranges. The 55% RAP mixes were about 25% to 60% stiffer than the virgin mixes with the greatest difference occurring at the 21.1°C. Virgin binder source was significant at 21.1°C, and virgin binder grade was significant at 37.8°C and for results at the lowest frequency.

The analyses of backcalculated effective binder properties using dynamic modulus test results and the Hirsch model clearly show that this process did not provide useful results. The backcalculated intermediate and high true critical temperatures deviated from the measured critical intermediate and high temperatures by as much as 13.1 and 27.8°C, respectively.

The mix designs' resistance to moisture damage was evaluated by AASHTO T 283. Several of the high RAP content mixes did not meet the standard 0.80 TSR criteria. Adding an antistripping additive was usually sufficient to improve the TSR above 0.80. In all cases, the conditioned and unconditioned tensile strengths of the high RAP content mixes exceeded those of the virgin mixes from the same materials source. This is a good argument to support the case that TSR values should not solely be used to assess moisture-damage potential. A few states allow a lower TSR criteria if the tensile strengths are maintained above a certain threshold. For example, the Georgia DOT allows TSR as low as 0.70 if the conditioned and unconditioned tensile strengths are above 689 kPa (100 psi). States that use a softer PG grade of binder would need to use a lower tensile strength criterion.

The confined flow number test was performed on the mix designs to assess their resistance to permanent deformation. Using the confined test, none of the samples exhibited tertiary deformation. Therefore, analysis of rutting resistance was based on the total accumulated strain at 20,000 cycles. All the mixtures had less than 50,000 microstrain, or 5% strain. An ANOVA indicated that the total strain was significantly affected by the source of the materials and the high performance grade of the virgin binder, but not RAP content.

Mix designs were evaluated for resistance to fatigue cracking based on fracture energy determined from indirect tensile strength tests. Specimens were long-term oven-aged before testing. Fracture energy is the amount of strain energy and dissipated energy a mixture can absorb up to the point when cracking is initiated. The fracture energy results showed that the virgin mixes have significantly better fracture energy than high RAP content mixes. Smaller nominal maximum aggregate size mixes also had better fracture energy than larger NMAS mixes.

Resistance to thermal cracking was evaluated with two tests: the low-temperature semi-circular bend (SCB) test and the bending beam rheometer (BBR) test on small mix beams cut from gyratory-compacted specimens. The SCB test yields two properties: fracture toughness and fracture energy. Ideally, mixes with higher fracture toughness and fracture energy would be expected to perform better than mixes with low fracture properties. However, the experimental results from the SCB test were conflicting. Compared to the corresponding virgin mixes, the high RAP content mixes generally had higher fracture toughness, but similar or lower fracture energy results. For the BBR results, mixes with RAP generally had higher stiffness and lower *m*-values, which theoretically should result in more cracking. Yet further analysis of the critical cracking temperatures for the climates where the materials were obtained indicates that the high RAP content mixes would perform similar to the corresponding virgin mixes with regard to thermal cracking.

It is important to note that other studies have shown that fracture properties and cracking performance of high RAP content mixes can be improved by either using a softer grade of virgin binder or by using a rejuvenating agent in conjunction with the standard binder grade such that the theoretically blended binders have properties that are appropriate for the specific project climate and traffic.

Recommendations

Based on the findings from the literature review and the results of the experimental work, the following recommendations are offered.

1. High RAP contents should be defined more clearly. This study has used the conventional practice of describing RAP contents as the percentage of RAP aggregate in the total aggregate blend. However, it seems that it would be more appropriate to distinguish mixes containing

RAP by the proportion of RAP binder to the total binder. Some highway agencies now use the term "RAP binder replacement" to convey this idea. The research team prefers the term "RAP binder ratio" because the word "replacement" infers that virgin binder is replaced with RAP binder. Replacing virgin asphalt with recycled binder is not what we really do in mix designs with RAP materials. Rather what we want to identify with this term is the portion of the total binder content that comes from the RAP. The former RAP Expert Task Group defined "high RAP content mixes" as asphalt mixes containing 25% or more RAP. The research team proposes to redefine high RAP content mixes as asphalt mixes in which 25% or more of the total binder is from RAP materials, or in other words asphalt mixes having a RAP binder ratio ≥ 0.25.

2. RAP stockpiles should be sampled for quality control testing and characterizing the RAP for mix designs with the aid of a loader or other power equipment to make miniature sampling stockpiles. The miniature sampling stockpiles shall be flattened with blade of the equipment in a back-dragging technique. Each sample shall be obtained by taking at least three portions from the flattened surface with a square-end shovel. The miniature stockpile sampling method will minimize variations in samples due to segregation. This technique shall be repeated at different locations around the main RAP stockpile. Do not combine samples obtained from different locations around the main stockpile since they will be used to determine the amount of variability within the main stockpile. Reduce samples to appropriate test-size portions using the mechanical splitter method described in AASHTO R 47.
3. Figure 82 shows a flow chart for the proposed sampling and testing of RAP stockpiles for high RAP content mix designs. Table 57 provides the proposed test methods, sampling frequencies, and variability guidelines.

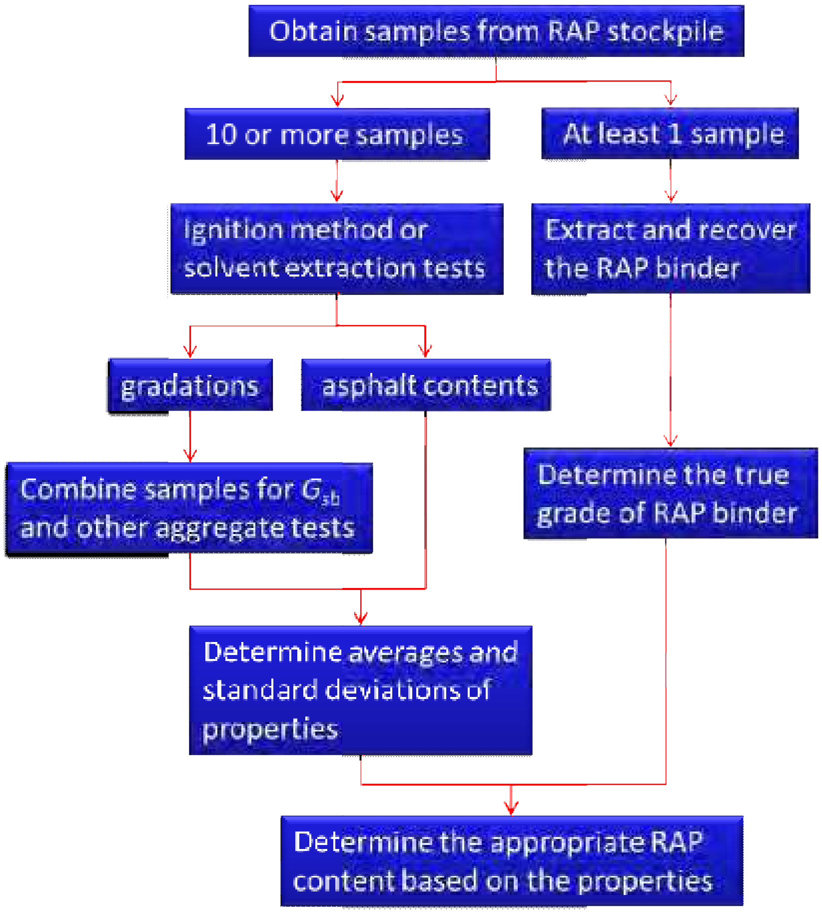


Figure 82 Flow Chart for Proposed Sampling and Testing RAP Stockpiles

Table 57 Proposed RAP Sampling and Testing Guidelines for High RAP Content Mixes

Property	Test Method(s)	Frequency	Minimum Number of Tests per Stockpile	Maximum Standard Deviation
Asphalt Content	AASHTO T 164 or AASHTO T 308	1 per 1000 tons	10	0.5
Recovered Aggregate Gradation*	AASHTO T 30	1 per 1000 tons	10	5.0 all sieves 1.5 on 75 micron
Recovered Aggregate Bulk Specific Gravity	AASHTO T 84 and T 85	1 per 3000 tons	3	0.030**
Binder Recovery and PG Grading	AASHTO T 319 or ASTM D 5404 and AASHTO R 29	1 per 5000 tons	1	n.a.

* Samples for Superpave aggregate consensus properties or other aggregate testing needs may be obtained by combining the tested aggregates following sieve analyses.
**This is a preliminary value based on limited data and possible impacts to VMA for high RAP content mixes

4. The study found that the current standards for Superpave mix design are applicable to high-RAP content mixes with a few minor, but important changes, as described below. The proposed revisions to AASHTO R 35 and M 323 are shown in Appendix B and C, respectively.
5. Selection of the grade of virgin binder for high RAP content mixes should be based on knowledge of the true grade of the RAP binder, the high and low critical temperatures for the project location and pavement layer, and one of the following:
    a. the approximate ratio of RAP binder divided by the total binder content
    b. the high and low critical temperatures for the available virgin binder(s)

    Note that the high and low critical temperatures for a project location and pavement layer can be determined using LTPP Bind version 3.1

    If the RAP binder ratio (RBR) is known, determine the appropriate virgin binder grade using the following formula:

$$(\text{virgin}) = \frac{(\quad)\ (\quad \times \ (\qquad))}{(\quad)} \qquad [11]$$

    Where:

    T_c *(virgin)* = critical temperature (high or low) of the virgin asphalt binder

    T_c *(need)* = critical temperature (high or low) needed for the climate and pavement layer.

    RBR = RAP Binder Ratio - the ratio of the RAP binder in the mixture divided by the mixture's total binder content. The mixture's total binder content is an unknown prior to mix design but can be estimated based on historical data for the aggregate type and NMAS.

    T_c *(RAP Binder)* = Critical temperature (high or low) of the RAP binder determined from extraction, recovery, and PG grading.

    If the virgin binder grade is known, determine the maximum RAP binder ratio using the following formula:

$$. = \frac{(\quad)\ (\quad)}{(\qquad)\ (\quad)} \qquad [12]$$

6. At the present time, the only strong recommendation for performance testing of mix designs is to require moisture-damage testing of all mixes, regardless of RAP content. Agencies should specify either AASHTO T 324 (Hamburg), AASHTO T 283 (TSR) or some variation thereof, as well as appropriate criteria based on historical performance. A rutting test for high RBR mixes seems unnecessary unless a softer grade of virgin binder or rejuvenator is used. In that case, one of several suitable tests could be required, including AASHTO TP 63-07 (Asphalt Pavement Analyzer), AASHTO T 324 (Hamburg), or AASHTO TP 62-07 (Flow Number). If the Flow Number test is selected, the unconfined test and the criteria recommended in NCHRP report 673 or NCHRP report 691, for HMA or WMA, respectively, should be followed. For high RBR surface mixes to be used in climates prone to thermal cracking, agencies may consider either the SCB test, as used in this study, or the disc-shaped compact tension (DCT) test for assessing low-temperature properties. The national pooled-fund study *Investigation of Low Temperature Cracking in Asphalt Pavements, Phase II* (*71*) recommended these procedures and accompanying specification criteria as well as an improved thermal cracking model for asphalt pavements. Although no fatigue test can be recommended at this time, it is an important need and worthy of further research and development. The use of any test to assess load-related cracking potential of asphalt mixes, regardless of RAP content, should be done only to gather additional information on the resulting properties of mixes and not to accept or reject mixes until further research is able to establish how the property is related to field performance.

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APPENDIX A

DRAFT STANDARD FOR SEMI-CIRCULAR BEND TEST

APPENDIX B

PROPOSED CHANGES TO AASHTO R 35 FOR HIGH RAP CONTENT MIXES

APPENDIX C

PROPOSED CHANGES TO AASHTO M 323 FOR HIGH RAP CONTENT MIXES