2002

Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications: A Regional Pooled Fund Project

Rebecca McDaniel

Hamid Soleymani

Ayesha Shah

Final Report

FHWA/IN/JTRP-2002/6

Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications

A Regional Pooled Fund Project

Sponsored
by

Illinois Department of Transportation
Indiana Department of Transportation
Iowa Department of Transportation
Michigan Department of Transportation
Minnesota Department of Transportation
Missouri Department of Transportation
Wisconsin Department of Transportation

Conducted
by

Rebecca S. McDaniel
Technical Director

Hamid Soleymani
Post-Doctoral Research Associate

Ayesha Shah
Research Engineer

North Central Superpave Center
P. O. Box 2382
1205 Montgomery Street
West Lafayette, IN 47906

Joint Transportation Research Program
Project No. C-36-56E
File No. 2-13-5
SPR-2143

Purdue University
West Lafayette IN 47907
May 2002

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2002/6	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications: A Regional Pooled Fund Study		**5. Report Date** May 2002 **6. Performing Organization Code**
7. Author(s) Rebecca McDaniel, Hamid Soleymani, and Ayesha Shah		**8. Performing Organization Report No.** FHWA/IN/JTRP-2002/6
9. Performing Organization Name and Address Joint Transportation Research Program 1284 Civil Engineering Building Purdue University West Lafayette, IN 47907-1284		**10. Work Unit No.** **11. Contract or Grant No.** SPR-2143
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

This regional pooled fund project was conducted to investigate the performance of Superpave asphalt mixtures incorporating RAP. This study was closely coordinated with a national study on the same topic (NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*). Specifically, this regional project looked at typical materials from the North Central United States to determine if the findings of NCHRP 9-12 were valid for Midwestern materials and to expand the NCHRP findings to include higher RAP contents.

Three RAP materials from Indiana, Michigan and Missouri were evaluated. Mixtures were designed and tested in the laboratory with each RAP, virgin binder and virgin aggregate at RAP contents up to 50%. The laboratory mixtures were compared to plant produced mixtures with the same materials at the medium RAP content of 15-25%. Binder and mixture tests were performed.

Briefly, the results showed that mixtures with up to 50% RAP could be designed under Superpave, provided the RAP gradation and aggregate quality were sufficient. In some cases, the RAP aggregates limited the amount of RAP that could be included in a new mix design to meet the Superpave volumetric and compaction requirements. Linear binder blending charts were found to be appropriate in most cases. In general, increasing the RAP content of a mixture increased its stiffness and decreased its shear strain, indicating increased resistance to rutting. It is important to consider the RAP aggregate gradation and quality in the mix design, since a poor aggregate structure could reduce mixture stiffness and ultimately performance.

Provided the RAP properties are properly accounted for in the material selection and mix design process, Superpave mixtures with RAP can perform very well.

17. Key Words Reclaimed Asphalt Pavement, RAP, recycling, Superpave, hot mix asphalt, rutting	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	69	

Form DOT F 1700.7 (8-69)

INDOT Research

TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

TRB Subject Code:31-8 Bituminous Materials Recycling *May 2002*
Publication No.: FHWA/IN/JTRP-2002/6, SPR-2143 *Final Report*

Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications: A Regional Pooled Fund Project

Introduction

States in the North Central region of the United States made extensive use of reclaimed asphalt pavement (RAP) prior to the implementation of Superpave. As the Superpave mix design system was implemented, however, the use of RAP decreased. Although Superpave did not rule out the use of RAP, there were no clear guidelines on how to incorporate RAP in Superpave mixtures. In addition, the states and industry were learning the new system and adjusting to the new, frequently tighter Superpave specifications, so there was some reluctance to add another variable to the process.

It was anticipated, however, that there would be renewed interest in using RAP once the use of Superpave became more routine. For this reason, seven states in the North Central region initiated a pooled fund research project to address the use of RAP in Superpave mixtures with typical North Central materials. The seven states were Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri and Wisconsin.

This regional pooled fund project was closely coordinated with National Cooperative Highway Research Project 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*, which was conducted by the North Central Superpave Center at Purdue University and the Asphalt Institute. Specifically, the regional study looked at typical materials for the North Central United States to determine if the findings of NCHRP 9-12 were valid for Midwestern materials and to expand the NCHRP findings to higher RAP contents.

The objectives of this regional project, then, were to:

- Expand the research conducted under NCHRP 9-12 to examine more materials, particularly those common to the North Central region,
- Investigate higher proportions of RAP in the mixtures, and
- Focus on mixture properties and the effects of RAP on those properties.

The objectives were addressed by comparing mixtures produced in the laboratory with different proportions of RAP and virgin materials. Three RAP sources were investigated at RAP contents up to 50%. Indiana, Michigan and Missouri provided RAP and virgin materials for use in the study. For each RAP source, a laboratory mix was also compared to a plant-produced mix with the same RAP content. Binder and mixture tests were performed following protocols established in NCHRP 9-12..

Findings

The study demonstrated that acceptable Superpave mixtures can be designed with up to 50% RAP. Aggregate quality and gradation in the RAP material may limit the amount of RAP that can be incorporated.

Linear blending charts, as recommended in NCHRP 9-12, were found to be appropriate for estimating the effects of RAP binder on the blended binder properties, in most cases. Linear blending charts were not strictly correct when testing the binder from the plant mixes and from the RAPs as if they were original, unaged binders. These binders had in fact been aged to some extent during production and service. The errors, however, were typically small and conservative. Linear approximations were very accurate for the RTFO and RTFO-PAV aged materials from Michigan and Missouri.

For the Indiana materials when tested as original, RTFO and RTFO-PAV aged, the binder from the plant-produced mix was significantly stiffer than expected. This behavior was also observed in testing the plant-produced mixture from Indiana in the Superpave shear tests. This was not observed with any of the other materials investigated in the regional study nor in NCHRP 9-12. One possible explanation for this behavior is that this particular plant caused increased aging during production. The Indiana materials were one year older than the materials from Michigan and Missouri and may have aged during storage, but this seems less likely than plant differences.

The results support the concept of a tiered approach to RAP usage. Adding 20 to 25% RAP raised the high temperature grade of the plant-produced mixture by one increment. Under the recommended tiers, this amount of RAP could be used by dropping the virgin binder grade by one increment to counteract the stiffening effect of the RAP binder. Low amounts of RAP (up to about 15%) could be used with no change in the virgin binder grade.

Shear testing of the mixtures generally showed that the higher the RAP content, the higher the mixture stiffness and the lower the shear strains. Higher RAP content mixtures could be expected to perform better in terms of rutting resistance due to this increased stiffness, provided the mixtures are properly designed and constructed. The RAP binder and aggregate properties need to be accounted for in the design.

The results of this regional study were generally consistent with the NCHRP 9-12 findings. This implies that the results and the recommendations of the national study can be implemented with confidence in the North Central region.

Implementation

The results of this study indicate that RAP mixtures can be designed using typical North Central materials and can be expected to perform well. States should consider allowing the use of RAP, if they do not already do so, under the newly revised AASHTO provisional standards MP2, PP28 and TP2. This regional research shows that mixtures using up to 50% RAP can be successfully designed. Based on these results states should, at the very least, allow RAP at levels comparable to pre-Superpave levels and may consider increasing the allowable RAP contents. Other considerations, such as durability or acceptable friction for surface courses, will also come into play when determining allowable RAP contents.

Discussions of RAP mixture design should be added to existing mix design courses and certification training. The NCSC has already incorporated this type of training in its mixture courses.

Local agencies should also be made aware of these findings through state paving conferences, LTAP Centers and other channels. The addition of RAP can help to offset the perceived higher costs of Superpave mixtures while still providing good performance for low volume roads. Mixtures designed for low volume roads should be designed for durability, so all mixtures need to be designed for appropriate traffic levels. This may be especially true for mixtures with higher RAP contents since the stiffening effect of the RAP could negatively impact durability and fatigue behavior unless the virgin binder grade and total binder content are selected to account for this effect.

Individual states should consider evaluating their own materials to assess typical RAP binder grades and aggregate gradations. These two factors can affect the resulting mixture properties and limit the amount of RAP that can be successfully incorporated.

Field validation of the findings is recommended, but is not as critical as with many other research efforts based on past experience that shows RAP mixtures can perform well.

Two topics for future research related to the use of RAP include the effects of rejuvenators on blended binder and mixture properties and the effects of different types of hot mix plants.

Contacts

For more information:

Dr. Rebecca S. McDaniel
Principal Investigator
Technical Director
North Central Superpave Center
Purdue University
West Lafayette IN 47907
Phone: (765) 463-2317
Fax: (765) 497-2402

Indiana Department of Transportation
Division of Research
1205 Montgomery Street
P.O. Box 2279
West Lafayette, IN 47906
Phone: (765) 463-1521
Fax: (765) 497-1665

Purdue University
Joint Transportation Research Program
School of Civil Engineering
West Lafayette, IN 47907-1284
Phone: (765) 494-9310
Fax: (765) 496-1105

Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications

Final Report

A Regional Pooled Fund Project
Sponsored by:

Illinois Department of Transportation
Indiana Department of Transportation
Iowa Department of Transportation
Michigan Department of Transportation
Minnesota Department of Transportation
Missouri Department of Transportation
Wisconsin Department of Transportation

Conducted by:

Rebecca S. McDaniel, Technical Director
Hamid Soleymani, Post-Doctoral Research Associate
Ayesha Shah, Research Engineer
North Central Superpave Center
P. O. Box 2382, 1205 Montgomery Street
West Lafayette, IN 47906

May 2002

Table of Contents

List of Tables

List of Figures

Abstract

This regional pooled fund project was conducted to investigate the performance of Superpave asphalt mixtures incorporating RAP. This study was closely coordinated with a national study on the same topic (NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*). Specifically, this regional project looked at typical materials from the North Central United States to determine if the findings of NCHRP 9-12 were valid for Midwestern materials and to expand the NCHRP findings to include higher RAP contents.

Three RAP materials from Indiana, Michigan and Missouri were evaluated. Mixtures were designed and tested in the laboratory with each RAP, virgin binder and virgin aggregate at RAP contents up to 50%. The laboratory mixtures were compared to plant produced mixtures with the same materials at the medium RAP content of 15-25%. Binder and mixture tests were performed.

Briefly, the results showed that mixtures with up to 50% RAP could be designed under Superpave, provided the RAP gradation and aggregate quality were sufficient. In some cases, the RAP aggregates limited the amount of RAP that could be included in a new mix design to meet the Superpave volumetric and compaction requirements. Linear binder blending charts were found to be appropriate in most cases. In general, increasing the RAP content of a mixture increased its stiffness and decreased its shear strain, indicating increased resistance to rutting if the virgin binder grade was unchanged. It is important to consider the RAP aggregate gradation and quality in the mix design, since a poor aggregate structure could reduce mixture stiffness and ultimately performance.

Provided the RAP properties are properly accounted for in the material selection and mix design process, Superpave mixtures with RAP can perform very well.

INTRODUCTION

States in the North Central region of the United States made extensive use of reclaimed asphalt pavement (RAP) prior to the implementation of Superpave. As the Superpave mix design system was implemented, however, the use of RAP declined. Although Superpave did not rule out the use of RAP, there were no clear guidelines on how to use RAP in Superpave mixtures. The states and industry were also adjusting to the new, frequently tighter Superpave specifications, so there was some reluctance to add another variable to the process.

It was anticipated that there would be renewed interest in utilizing RAP again once the use of Superpave became more routine and mix designers became more comfortable with the new controls on mixtures. For this reason, seven states in the North Central region initiated a regional pooled fund research project in late 1996 at the North Central Superpave Center to investigate the use of RAP in Superpave mixtures with typical materials from the region. The seven states were Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri and Wisconsin.

Continued use of RAP in Superpave pavements is desired because:

- RAP has performed well in the past and there is no reason to believe it will not perform well in Superpave mixtures as well, if properly accounted for in the mix design;
- use of RAP is economical and can help to offset the increased initial costs sometimes associated with Superpave binders and mixtures; and
- use of RAP conserves natural resources, and not reusing RAP could cause disposal problems and increased costs.

For these reasons, in 1997 a subgroup of the FHWA Superpave Mixtures Expert Task Group developed interim guidance for the use of RAP based on past experience (1). These guidelines established a tiered approach for RAP usage. Up to 15% RAP could be used with no change in binder grade. Between 15 and 25% RAP, the virgin binder grade should be decreased one increment (6°) on both the high and low temperature grades. Above 25% RAP, blending charts should be used to determine how much RAP can be used.

Shortly before FHWA approved this regional pooled fund project, the National Cooperative Highway Research Program (NCHRP) let research contract number 9-12 to investigate *The Incorporation of Reclaimed Asphalt Pavement in the Superpave System*. The North Central Superpave Center (NCSC) and its partner, the Asphalt Institute, were selected to conduct the NCHRP research. (The objectives and findings of that project will be described in detail later.)

The regional study was then seen as complimentary to the NCHRP research, not a duplication of effort. The regional study allowed the evaluation of materials and issues typical to the North Central region by building on the work conducted under NCHRP 9-12.

This report summarizes the findings of NCHRP 9-12, particularly as they pertain to the North Central region, and documents the additional research conducted as part of the regional pooled fund project.

PROBLEM STATEMENT

The original problem statement (2) read:

> Research is needed to determine how RAP can be accommodated in the Superpave volumetric mix design procedure. The effects of RAP on the binder grade and mixture properties need to be determined. Because the Superpave binder specifications will be implemented in most states before the Superpave volumetric mix design process, determination of the effects of RAP on binder grade is most critical.

This is very similar to the problem statement for NCHRP 9-12 (3), which follows:

> This research addresses issues related to how RAP can be accommodated in the Superpave system. The effects of RAP on the binder grade (low, intermediate and high) and mixture properties are evaluated.

In light of the fact that the NCSC would be conducting the NCHRP research, the focus of this regional effort was shifted from determining how to accommodate RAP, which would be done under NCHRP 9-12, to expanding the NCHRP findings and verifying their applicability to typical North Central materials.

OBJECTIVES

The original objectives of this pooled fund research project were to:

- determine the effects of aged binder from RAP on combined binder grade,
- determine the effects of aggregates from RAP on combined design aggregate structure and mixture volumetrics,
- estimate the effects of RAP usage on mixture performance, and
- review and revise guidelines for the use of RAP in Superpave mixtures.

The stated objectives of NCHRP 9-12 were:

> To develop guidelines for incorporating RAP in the Superpave system on a scientific basis and prepare a manual for RAP usage that can be used by laboratory and field technicians. This research effort considers the effects of RAP on binder grade, aggregate parameters, and resulting mixture properties and performance. Recommendations are made regarding the incorporation of RAP in the Superpave system and procedures for mixture design and material selection. A plan for the implementation of the recommended procedures is also offered…. The products of the research include proposed revisions to applicable AASHTO standards, a manual for technicians and guidelines for specifying agencies. (3)

Again, since the work originally proposed under this regional effort would essentially be completed under NCHRP 9-12, the objectives of the regional effort were shifted towards the following:

- expanding the research conducted under NCHRP 9-12 to examine more materials, particularly those common to the North Central region of the United States,
- investigating higher proportions of RAP in the mixtures, and
- focusing more on the mixture properties than the binder properties of the mixtures.

SUMMARY OF NCHRP 9-12 RESEARCH FINDINGS

The following briefly summarizes the results of NCHRP 9-12 to put the regional project in perspective.

It seems likely that when the aged binder from RAP is combined with new binder, it will have some effect on the resultant binder grade. At low RAP percentages, the change in binder grade may be negligible. At higher percentages, however, the effects of the RAP may become significant. How do you account for the effects of the RAP binder and how much RAP can you add before its effects become significant?

The aggregate in the RAP may also affect mixture volumetrics and performance. The design aggregate structure, crushed coarse aggregate content, dust proportion and fine aggregate angularity should take into account the aggregate from the RAP. Again, at low RAP percentages, the effects may be minimal, but how much can be added?

One recurring question regarding RAP is whether it acts like a "black rock." If RAP acts like a black rock, the aged binder will not combine, to any appreciable extent, with the virgin binder and will not change the binder properties. If this is the case, then the premise behind blending charts, which combine the properties of the old and new binders, is void. This question had not been raised in the regional project and, in fact, became an intensive and important part of NCHRP 9-12.

These questions were addressed through the NCHRP Project 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*. The full report is available on the NCHRP website (3). Guidelines for the use of RAP were published (4), as was a technicians' manual (5). Recommendations from this research were incorporated into revised AASHTO provisional standards, published in April 2001 (6). The provisionals revised to include considerations of RAP were:

MP2 *Specification for Superpave Volumetric Mix Design*
PP28 *Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)*
TP2 *Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*

NCHRP Experimental Approach

The research approach used in NCHRP 9-12 followed three coordinated paths. The same materials were examined in each path, for the most part. One path investigated the question of whether RAP is a “black rock” or whether the aged RAP binder actually blends with the virgin binder added. Another path focused on binder issues, such as how best to extract, recover and test the RAP binder, how to select the best virgin binder grade or RAP content to use, and the applicability of the Superpave binder tests to RAP binders. The last path examined the effects of RAP on mixture properties. The findings are summarized separately below.

The three RAP materials evaluated under NCHRP 9-12 included a low binder stiffness RAP from Florida, a medium stiffness RAP from Connecticut and a high stiffness RAP from Arizona. The distinction in RAP binder stiffness was made based on the recovered viscosity. Pertinent binder properties are listed in Table 1.

Two different virgin binders were used in the study; one was a PG52-34 and the other a PG64-22. Both were from Midwestern suppliers.

All three RAPs had an asphalt content of roughly 5% (4.9% for CT, 5.0% for FL and 5.3% for AZ).

Table 1 NCHRP RAP Binder Properties

Source	Viscosity @ 60°C, Poise	PG Grade	Critical Temperatures (High, Low) °C
Florida	23,760	PG 82-22	82, -22
Connecticut	65,192	PG 82-16	82, -16
Arizona	124,975	PG 88-4	89, -9

For the NCHRP testing, each RAP was blended with a common virgin aggregate. The virgin coarse aggregate used was a typical Kentucky limestone. A Kentucky natural sand was used as the fine aggregate. These aggregates are the lab standards used at the Asphalt Institute. The gradations were manipulated to keep the gradation of the blends of virgin and RAP materials as consistent as possible during testing. For the black rock study, the source of the aggregate in the three different cases (i.e. whether virgin or RAP) was also kept constant at the level appropriate for the RAP content being tested. The virgin and RAP materials were blended to produce a 12.5mm nominal mix.

Black Rock Study

The NCHRP research effort was directed first at resolving the issue of whether RAP acts like a black rock or whether there is, in fact, some blending that occurs between the old, hardened RAP binder and the added virgin binder. This question was addressed by fabricating mixture specimens simulating actual practice, black rock and total blending. The so-called “black rock” and “total blending” cases represent the possible extremes. If RAP were a "black rock," the mixture properties would depend on the virgin binder with no effect of the RAP binder. The “black rock” case therefore, was simulated by extracting the binder from a RAP mixture then blending the recovered RAP aggregate in the proper proportions with virgin aggregate and *only* the virgin binder. The "actual practice" samples were prepared as usual by adding the RAP with its coating intact to virgin aggregate and virgin binder. The "total blending" samples were fabricated by extracting and recovering the RAP binder and blending it into the virgin binder, then combining the blended binder with the virgin and RAP aggregates. All the samples were prepared on the basis of an equal volume of total binder.

Three different RAPs, two different virgin binders and two RAP contents (10 and 40%) were investigated in this phase of the project. The different cases of blending were evaluated through the use of various Superpave shear tests at high temperatures and indirect tensile creep and strength tests at low temperatures.

The results of this phase of the research indicated no significant differences between the three different blending cases at low RAP contents (10%). Not enough RAP binder was present to significantly alter the mixture properties. At higher RAP contents (40%), however, the differences became significant. In general, the "black rock" case demonstrated lower stiffnesses and higher deformations than the other two cases. The "actual practice" and "total blending" cases were not significantly different.

These results provide compelling evidence that RAP does not act like a black rock. It seems unreasonable to suggest that total blending of the RAP binder and virgin binder ever occurs, but partial blending apparently occurs to a significant extent.

This means that at high RAP contents the hardened RAP binder must be accounted for in the virgin binder selection. The use of blending charts for determining either the virgin binder grade or the maximum allowable amount of RAP is a valid approach since blending does occur. Procedures for extracting and recovering the RAP binder with minimal changes in its properties and then developing blending charts are detailed in the final report (3) and manual for technicians (5). The recommended extraction/recovery procedure uses either toluene and ethanol, as specified in AASHTO TP2, or an n-propyl bromide solvent, which was proven suitable for use. Modifications to AASHTO TP2 were suggested based on this research and were adopted by AASHTO. The revised provisional test procedure is in the April 2001 AASHTO provisional standards book (6).

The findings also support the concept of a tiered approach to RAP usage since the effects of the RAP binder are negligible at low RAP contents. This is very significant since it means that lower amounts of RAP can be used without going to the effort of testing the RAP binder and developing a blending chart. The procedures for developing blending charts were perfected during the second portion of the project, the binder effects study.

The researchers felt the RAP materials investigated in this study were sufficiently representative, and the findings so compelling, that this portion of the project was not repeated for the North Central materials. Logically, one would expect harder binders to blend less readily than softer binders. The RAP from Arizona was very hard, incorporating a stiff virgin binder that had "baked" in a desert environment. Yet this hard RAP still showed clearly that blending occurred to a significant effect when new binder was added.

This portion of the NCHRP study was also extremely involved, time consuming and expensive, requiring large numbers of extractions and recoveries to yield enough RAP binder for the total blending case samples and aggregate for the black rock case.

Binder Effects Study

This phase of the NCHRP research investigated the effects of the hardened RAP binder on the blended binder properties and lead to recommended procedures for testing the RAP binder and the development of blending charts. This portion of the research was conducted at the Asphalt Institute.

The same three RAPs and two virgin binders were evaluated in this phase of the project at RAP binder contents of 0, 10, 20, 40 and 100%. The blended binders were tested according to the AASHTO MP1 binder tests.

The results show that the MP1 tests are applicable to RAP binders and linear blending equations are appropriate. The recovered RAP binder should be tested in the DSR to determine its critical high temperature as if it were unaged binder. The rest of the recovered binder should then be RTFO aged; linear blending equations are not appropriate without this additional aging. The high temperature stiffness of the RTFO-aged binder should then be determined. The remaining MP1 tests at intermediate and low temperatures should then be performed as if the RAP binder were RTFO and PAV aged. The RAP binder does not need to be PAV aged before testing for fatigue or low temperature cracking, as would be done for original binder. Conventional Superpave methods and equipment, then, can be used with the recovered RAP binder. (Above 40% RAP, or so, some non-linearity begins to appear.) Since PAV aging is not necessary, the testing process is shortened by approximately one day.

The binder effects study also supports the tiered usage concept. At low RAP contents, the effects of the RAP binder are negligible. At intermediate levels, the effects of the RAP binder can be compensated for by using a virgin binder that is one grade softer on both the high and low temperature grades. The RAP binder stiffens the blended binder. At higher RAP contents, a blending chart should be used to either determine the appropriate virgin binder grade or to determine the maximum amount of RAP that can be used with a given virgin binder. The research suggests that the limits of the three tiers could vary depending on the recovered binder stiffness. Higher RAP contents could be used if the recovered RAP binder stiffness is not too high. This is, however, based on limited data and needs more validation before it is accepted at a national level.

These findings mean that, for the most part, conventional equipment and testing protocols can be used with RAP binders. The tiered approach allows for the use of up to 15 to 25% RAP without extensive testing. Higher RAP contents can also be used when additional testing is conducted.

The recovered RAP binders from the North Central region were characterized using the procedures developed in NCHRP 9-12 and analyzed to determine if the blending equations are applicable.

Mixture Effects Study

The same three RAPs and two virgin binders were used in this portion of the NCHRP research to investigate the effects of RAP on the resulting mixture properties. Shear tests and indirect tensile tests were conducted to assess the effects of RAP on mixture stiffness at high, intermediate and low temperatures. Beam fatigue testing was also conducted at the Asphalt Institute at intermediate temperatures. RAP contents of 0, 10, 20 and 40% were evaluated.

All of the tests indicated a stiffening effect from the RAP binder at higher RAP contents. At low RAP contents the mixture properties were not significantly different from those of mixtures with no RAP. The shear tests indicated an increase in stiffness and decrease in shear deformation as the RAP content increased. This would indicate that higher RAP content mixtures (with no change in binder grade) would exhibit more resistance to rutting, provided the aggregates are of acceptable quality. The indirect tensile testing also showed increased stiffness for the higher RAP content mixtures, which could lead to increased low temperature cracking, if no adjustment is made in the virgin binder grade. Beam fatigue testing also supported this conclusion since beam fatigue life decreased for higher RAP contents, when no change was made in the virgin binder grade.

The significance of these results is that the concept of using a softer virgin binder with higher RAP contents is again supported. The softer binder is needed to compensate for the increased mixture stiffness and help improve the fatigue and low temperature cracking resistance of the mixture. The results also support the tiered concept since low RAP contents, below 20%, yield mixture properties that are statistically the same as the virgin mixture properties.

Because the aggregates used in the North Central region may differ more from those used in other parts of the country than the binders, more emphasis was placed on investigating the effects of increased RAP quantities on mixture properties, particularly at high temperatures where the aggregate effects become more important.

Overall Conclusions from NCHRP 9-12

The findings of this research effort largely confirm current practice. The concept behind the use of blending charts is supported. A tiered approach to the use of RAP is found to be appropriate. The advantage of this approach is that relatively common levels of RAP can be used without extensive testing of the RAP binder. If the use of higher RAP contents is desirable, conventional Superpave binder tests can be used to determine how much RAP can be added or which virgin binder to use.

The properties of the aggregate in the RAP may limit the amount of RAP that can be used. The RAP aggregate properties, with the exception of sand equivalent value, should be considered as if the RAP is another aggregate stockpile, which it in fact is. The mixtures being recycled presumably met specifications when constructed, so certain minimum aggregate properties and mixture properties were met. Past specifications, however, likely differed from Superpave specifications. In the mix design, the RAP aggregates should be blended with virgin aggregates so that the final blend meets the consensus properties. Also in the mix design, the RAP binder should be taken into account and the amount of virgin binder added should be reduced accordingly.

Many specifying agencies will find that these recommendations largely agree with past practice and concepts. These results should not be surprising, perhaps, since the asphalt binders and mixtures are largely the same as were previously used. This research effort, however, should give the agencies confidence in extending the use of RAP to Superpave mixtures.

The products of this research include revisions to several AASHTO specifications; procedures for extracting and recovering the RAP binder, testing the RAP binder and developing blending charts, and designing RAP mixtures under the Superpave system; a manual for laboratory and field technicians; guidelines for the use of specifying agencies; and an implementation plan for moving these results into practice.

SUMMARY OF LITERATURE REVIEW

A review of the literature shows that there has not been a great deal of published research about RAP using the Superpave binder or mixture test protocols. There simply has not been enough time since the Superpave products debuted for much research to have been initiated or completed. We can, however, learn from past projects that used some of the Superpave procedures or that studied related topics using other specifications and test methods.

The research by Harvey et al. (7) is one of the few projects to use Superpave mixture tests. That research showed that the repetitive shear test at constant height and beam fatigue tests are sensitive to changes in mixture and binder properties. Mixtures evaluated in repetitive shear were compacted using rolling wheel compaction since the Superpave Gyratory Compactor had not yet been developed, but that would not be anticipated to significantly alter the results. Rolling wheel compaction is necessary for fabricating beam fatigue specimens in the lab.

Other studies (8, 9, and 10) exhibit the variety of results obtained in past research. For example, Tam et al. (8) found that mixes with RAP are less resistant to thermal cracking than non-recycled mixtures, while Kandhal et al. (9) found no significant difference in cracking performance, and Sargious and Mushule (10) found that a recycled mixture performed better than a virgin mixture in terms of cracking. The mixture behavior is responsive to binder properties at low, intermediate and high temperatures. A binder selected to perform well at high temperatures may not necessarily perform well at low temperatures. These studies were conducted with penetration or viscosity graded asphalts. The Superpave binder system gives us a tool to investigate the binder effects over a range of temperatures and aging conditions and should, therefore, allow us to better select the appropriate binder blend (RAP + virgin) for a given situation. The study by Sargious and Mushule did use a softer asphalt for the recycled mix than for the control mix, which may have rejuvenated the RAP, resulting in the improved performance noted.

Resilient modulus has been used in many studies to evaluate RAP mixtures (10, 11, 12, 13 and 14). This test method could be evaluated further, but it is not a preferred method of evaluation. Variability of test results, especially between labs, has posed problems in interpreting the data. The tests used in NCHRP 9-12 proved to be capable of differentiating between RAP and virgin mixtures and had reasonable repeatability. Those tests will also be used in this regional research effort.

Many studies (14, 15, 16 and 17) document the fact that recycled mixtures can perform at least as well as conventional mixtures. Improved extraction, recovery and binder testing procedures should allow even better selection of the right binder for a recycled mixture leading to improved performance.

Several studies of solvents and extraction/recovery techniques have been completed (18, 19, 20, 21, 22 and 23). That research supports the use of the Rotavapor or SHRP methods over the Abson. Further work done as a part of the NCHRP 9-12 binder effects study confirms these findings and proposes additional modification to improve the SHRP method even more. The method recommended in NCHRP 9-12 was used to extract and recover the RAP binders for testing in this regional study.

REGIONAL POOLED FUND WORK PLAN

The remainder of this report describes the work conducted under the regional pooled fund project. The analysis, conclusions and recommendations will tie together the NCHRP and regional pooled fund study results.

The objectives of the regional effort were modified as described earlier to expand on the NCHRP findings without duplicating effort. This study, then, looks at the use of Midwestern RAP, aggregate and binder materials at RAP contents up to 50%. The main focus of the research is on the effects of RAP on mixture properties, though some binder evaluations are presented.

Experimental Design

In contrast to the work under NCHRP 9-12, which was intended to be national in scope, this regional effort focuses on typical Midwestern materials. The intent is to closely examine regional materials and evaluate the applicability of the national findings on a regional level.

One illustration of this different approach is apparent in the experimental design of the project, as shown in Table 2. Since NCHRP was broad in scope, each of the three RAPs evaluated was tested with a common set of virgin aggregates and two virgin binders. This allowed comparisons of the effects of differing RAP stiffness levels. One common control mix, using only the virgin Kentucky aggregates, was used throughout the national study. In the case of the regional study, however, no effort is made to compare across RAP sources. That is, the Michigan RAP mixes are compared to each other and to the mix prepared in the laboratory using only the Michigan virgin aggregates and virgin binder. Similarly, the Missouri materials are compared only to each other, and the Indiana materials only to each other.

The regional study was also designed to expand the NCHRP findings to higher RAP contents. The original plan was to evaluate medium and high RAP contents as compared to mixes made with only the virgin components from each state. The medium RAP content was not fixed, but varied to match the plant-produced mix from each source. The high RAP content was planned to be 50%, which is about the highest RAP content used in the region (except for relatively rare specialty applications that may use up to 100% RAP). In the case of the Michigan RAP, however, the researchers could not fabricate an acceptable mix using 50% RAP. The RAP was apparently too fine to allow the use of such a high percentage. The high RAP content for Michigan, then, was selected at 40%, while the Missouri and Indiana materials had a high RAP content of 50%.

In summary, Table 2 illustrates the experimental design and quantifies the actual RAP contents used in the study. Comparisons are made within a row. That is, for a given RAP source, the change in mixture properties with changing RAP content is evaluated, and laboratory mixtures are compared to plant-produced mixtures in an attempt to verify the approach. Due to the differences noted above between the mixtures produced from the various RAP sources, comparisons between rows may not be valid.

Table 2 RAP Contents Evaluated in Study

Mix Source	Laboratory			Plant
RAP Content	Low	Medium	High	Medium
IN	0%	15%	50%	15%
MI	0%	25%	40%	25%
MO	0%	20%	50%	20%

MATERIALS

Three RAPs from the North Central region were evaluated in this study: one from Indiana, one from Michigan and one from Missouri. This section describes the properties of each RAP and mixture with RAP.

Binder Properties

The RAP binder from each RAP source was extracted and recovered according to the procedures refined in NCHRP 9-12 (now published as AASHTO TP2-01). The average recovered RAP binder properties are summarized in Tables 3 through 5. These tables also show the test results for the virgin binder and binder extracted from the plant-produced mixtures.

Table 3 Virgin, Recovered RAP and Plant Mix Binder Properties - Indiana

Aging	Property	Temp, C	Virgin	RAP*	Plant
Original	G*/sinδ kPa	52	6.88	44.93	31.95
		58	3.13	17.10	12.84
		64	1.56	6.94	5.47
		70	0.88	3.06	2.41
		76	0.47	1.40	1.09
RTFO	G*/sinδ kPa	52	15.68	51.69	34.66
		58	6.82	19.33	13.84
		64	3.24	7.96	5.58
		70	1.51	3.29	2.61
		76	0.85	1.49	1.15
PAV	G*sinδ kPa	16	4934		9763
		19	3425		6550
		22	2326	7191	3893
		25	1554		2273
		28	1043	2676	1440
	BBR Stiffness MPa	-12	118	686	188
		-18	235	724	341
		-24	361		
	BBR m-value	-12	0.426	0.629	0.384
		-18	0.379	0.312	0.315
		-24	0.320		

* Recovered RAP binders without additional aging were tested as if RTFO and PAV aged.

Table 4 Virgin, Recovered RAP and Plant Mix Binder Properties - Michigan

Aging	Property	Temp, C	Virgin	RAP*	Plant
Original	G*/sinδ kPa	52	3.02	30.55	12.15
		58	1.34	11.98	4.93
		64	0.62	7.82	2.31
		70	0.32	3.45	1.04
		76	0.18	1.61	0.85
RTFO	G*/sinδ kPa	52	6.24	34.82	11.55
		58	2.69	18.03	4.54
		64	1.27	7.69	1.95
		70	0.59	3.12	0.93
		76	0.30	1.59	0.45
PAV	G*sinδ kPa	16	3414		4436
		19	2356		2758
		22	1600	10038	1666
		25	1036		946
		28	664	4608	507
	BBR Stiffness MPa	-12	80	NA	87
		-18	196	NA	162
		-24	370	NA	NA
	BBR m-value	-12	0.457	NA	0.453
		-18	0.480	NA	0.351
		-24	0.318	NA	NA

*Recovered RAP binders without additional aging were tested as if RTFO and PAV aged.
NA = No binder available for testing

Table 5 Virgin, Recovered RAP and Plant Mix Binder Properties - Missouri

Aging	Property	Temp, C	Virgin	RAP*	Plant
Original	G*/sinδ kPa	52	3.02		17.76
		58	1.34	37.07	7.27
		64	0.62	18.34	3.22
		70	0.32	5.34	1.49
		76	0.18	3.46	0.72
		82		1.69	
		88		0.80	
RTFO	G*/sinδ kPa	52	6.24		12.67
		58	2.69	33.77	5.26
		64	1.27	16.73	2.32
		70	0.59	8.50	1.06
		76	0.30	3.51	0.52
		82		1.74	
PAV	G*sinδ kPa	16	5844		5966
		19	3945		3972
		22	2612	4926	2481
		25	1192		1537
		28	1074	2336	892
	BBR Stiffness MPa	-12	138	49	124
		-18	312	340	258
		-24	424		
	BBR m-value	-12	0.439	0.370	0.449
		-18	0.385	0.293	0.409
		-24	0.255		

* Recovered RAP binders without additional aging were tested as if RTFO and PAV aged.

Aggregate and Mixture Properties

Asphalt contents were determined after solvent extraction and after the ignition oven for each source and for the aggregate extracted from the RAP and from the plant-produced mix, for comparison purposes. Each determination in Table 6 below represents the average of three replicates.

Table 6 RAP and Plant-Mix Asphalt Contents

Source	Indiana	Michigan	Missouri
RAP by Solvent	4.7%	3.8%	4.4%
RAP by Ignition	6.3%	5.3%	4.7%
Plant Mix by Solvent	4.5%	5.6%	4.5%
Plant Mix by Ignition	6.0%	6.4%	5.3%

Because limited samples were available, no aggregate correction factors were determined for the ignition oven asphalt content determinations. It can be seen, then, that the uncorrected ignition oven results indicate a higher asphalt content than the solvent extraction for both the RAPs and plant mixes. This underscores the need to properly calibrate the ignition oven for the aggregates in the mixture. The asphalt contents are generally in the range of 4 to 6%, as expected.

The properties of the plant-produced mixtures containing RAP are shown in Table 7. For comparisons of various RAP contents, the gradation of the virgin aggregates added was adjusted so that the RAP-virgin aggregate blend would match the plant-produced mixture gradation. The total binder content was also kept constant for each mixture.

Table 7 Plant-Produced Mixture Properties

Property	Percent Passing		
Percent Passing Sieve	Indiana	Michigan	Missouri
25.0 mm	100.0	100.0	100.0
19.0 mm	92.2	100.0	100.0
12.5 mm	73.8	90.0	96.8
9.5 mm	62.4	65.2	87.6
4.75 mm	38.7	32.2	69.6
2.36 mm	29.6	22.8	29.4
1.18 mm	17.2	18.7	16.7
600 μm	10.5	14.9	13.3
300 μm	6.7	10.4	9.6
150 μm	5.3	6.0	6.8
75 μm	3.5	4.5	5.7
Binder Content	5.0%	5.5%	4.2%
Binder Grade	PG64-28	PG52-28*	PG58-28
RAP Content	15%	25%	20%
N_{des}	126	96	**
VMA	14.9	13.9%	15.5

*PG58-28 required for project, dropped to 52-28 for this RAP content per specifications.
** This mix was actually a Marshall design but otherwise met Superpave requirements.

DISCUSSION OF TESTS AND RESULTS

Binder Tests

Routine PG binder tests were performed on each binder from each source. The virgin binder was tested conventionally. The RAP and plant mix binders were extracted, recovered, then tested as recommended in NCHRP 9-12. That is, the recovered binders were tested as original binders in the DSR at high temperatures. The recovered binders were then RTFO aged and tested as RTFO in the DSR at high temperatures. The recovered binders were further tested in the DSR at intermediate temperatures and in the BBR at low temperatures as if they had been RTFO and PAV aged. This data was previously summarized in Tables 3 through 5.

From the data in these tables, it is possible to determine the critical temperatures and the PG grade of each binder. The critical temperatures are the test temperatures at which the binder just meets the Superpave requirement. They can be thought of as the temperature at which the binder goes from passing to failing to meet the specification limit. The critical temperatures, based on DSR measurements, are summarized in Table 8. (Keep in mind that the low critical temperatures for stiffness and m-value are ten degrees warmer (less negative) than the low temperature binder grade.) There was not enough binder left from all of the sources to fully characterize the recovered RAP binder, but the test results that were obtained are provided for information. It is recommended that individual states test a variety of RAP sources to determine typical RAP grades in their state. Testing can also be done on a project-by-project basis when higher RAP contents are desired.

Table 8 Critical Temperatures and Binder Grades

	Critical Temperatures, °C								
	Indiana			Michigan			Missouri		
Property	Virgin	Plant	RAP	Virgin	Plant	RAP	Virgin	Plant	RAP
RAP Content	0	15	100	0	25	100	0	20	100
Original G*/sin δ	68.9	76.4	77.5	57.8	71.1	84.7	60.8	73.8	86.6
RTFO G*/sin δ	67.6	71.7	73.6	60.1	63.4	79.6	60.1	64.6	80.4
G*sin δ	15.9	20.8	24.9	11.5	15.0	27.6	17.3	17.5	21.8
Stiffness	-21.1	-16.4	NA	-21.5	-29.0	NA	-17.6	-17.2	-19.9
m-value	-26.2	-25.3	-24.2	-24.7	-21.0	NA	-21.9	-17.4	-20.2
Temp. Range	67-31	71-26	73-??	57-31	63-31	79-??	60-27	64-27	80-29
PG Grade (MP1)	64-28	70-22	70-??	52-28	58-28	76-??	58-22	64-22	76-28

NA = Not enough binder available for replicate testing.

The low temperature grade of the Indiana RAP binder could not be determined, but it was likely a -6 or higher. The BBR test was conducted at -12 and -18ºC and the stiffness exceeded 600 mPa at both temperatures. There was insufficient material to retest at a warmer temperature. There was not enough binder to test any low temperature properties of the Michigan RAP.

Examination of the last row of Table 8 shows the effect of RAP on the final binder grade. Comparison of the grades of the virgin binder with the binder from the plant-produced mix shows that the addition of RAP increased the high temperature grade by one increment. There was no detrimental effect of the RAP on the low temperature grade for the Michigan and Missouri materials. The Indiana plant mix did have a low temperature grade one increment warmer than the virgin binder grade (-22 vs. -28).

The critical temperatures from the DSR results in Table 8 are plotted in Figures 1 through 3. In each figure, the virgin binder critical temperatures are plotted on the y-axis at 0% RAP and the recovered RAP binder properties are plotted at 100% RAP. The recovered plant-mix binder properties are plotted at the appropriate RAP content for that mixture. If a linear blending equation is appropriate for estimating the blended RAP-virgin binder properties, these three points should lie on a straight line. Examination of Figures 1 through 3 shows that in most cases, the points do lie on a straight line.

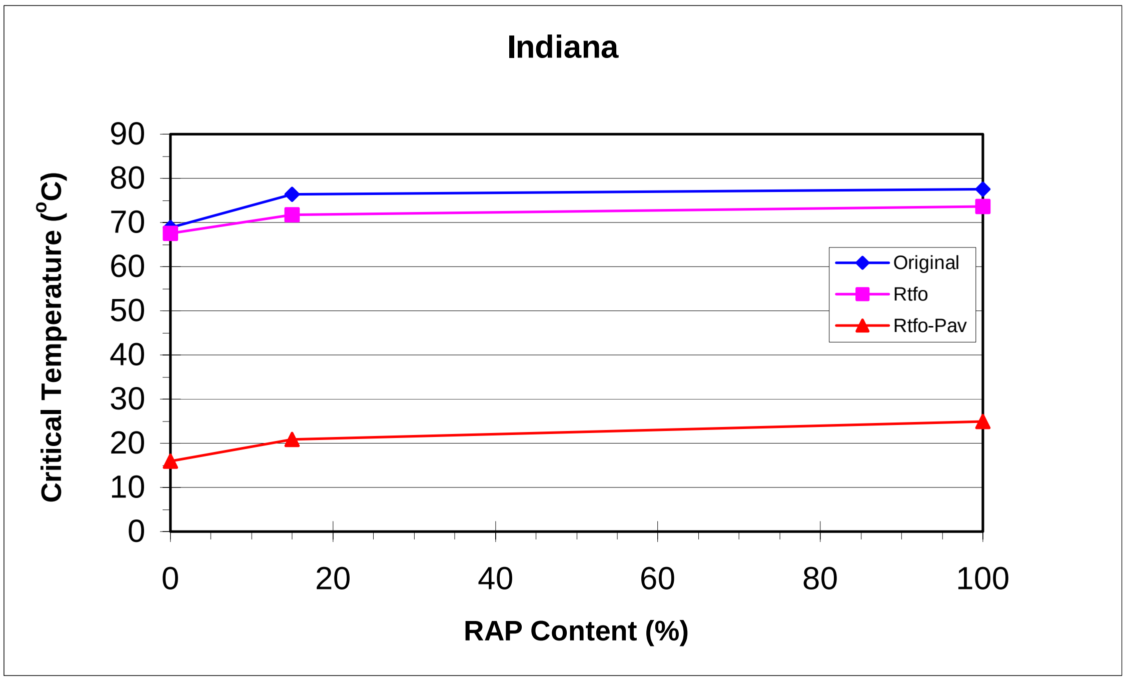


Figure 1 Critical Temperatures vs. RAP Content - Indiana

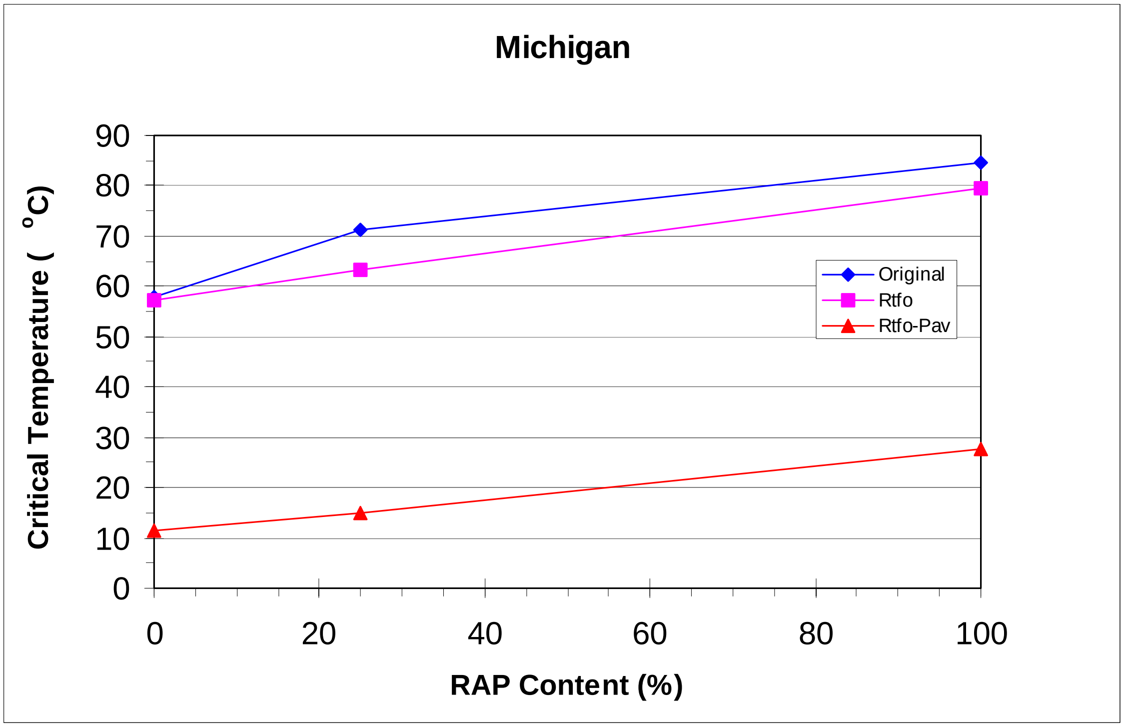


Figure 2 Critical Temperatures vs. RAP Content - Michigan

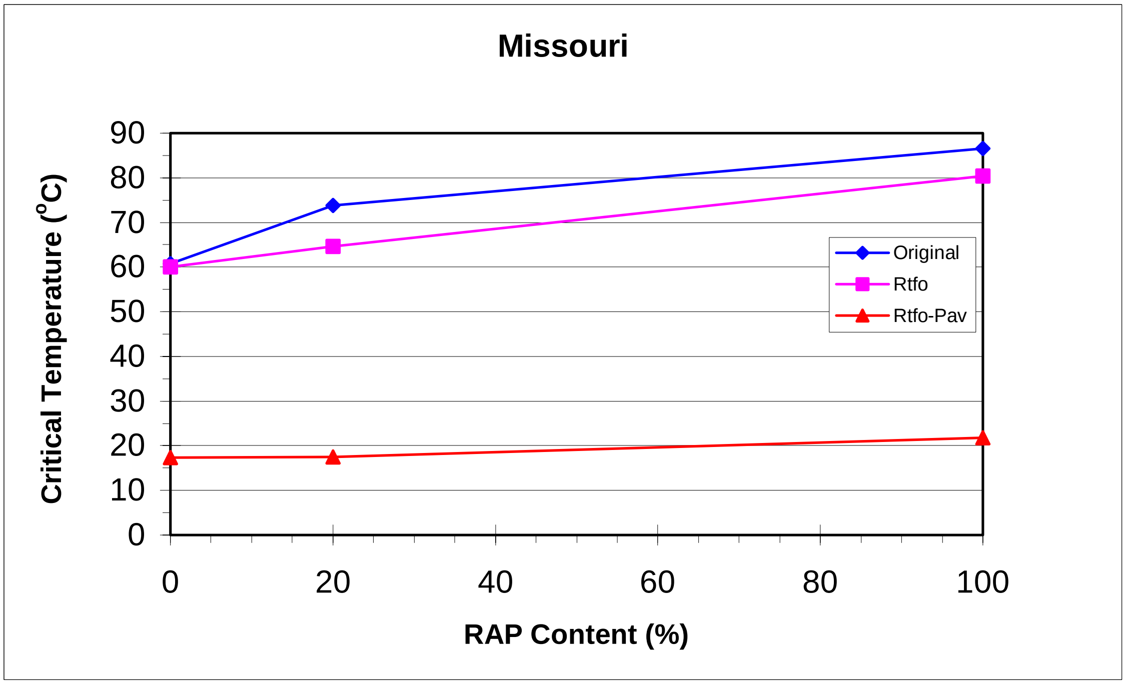


Figure 3 Critical Temperatures vs. RAP Content - Missouri

The critical temperatures for the binders tested as original material, however, do not exhibit a strictly linear relationship. When the plant-produced and RAP binders are tested as original material, they have in fact been aged already during production and, in the case of the RAP, by in-service aging. The high temperature stiffnesses, then, are higher than that of the virgin, unaged binder. This implies that a linear blending equation based on testing the RAP binder as original material may underestimate the plant mix's binder grade by as much as one PG grade, as detailed in Table 9. This trend is observed for all three RAP sources.

In addition, the Indiana materials do not adhere strictly to a linear relationship when tested as RTFO and RTFO-PAV aged. The critical temperatures of the plant mix are slightly higher than they should be for a true linear equation. As Table 9 shows, this error is about three degrees, or one-half of a binder grade difference. This trend is not observed for the Michigan and Missouri RAP sources. It may reflect differences in the aging produced in different hot mix plants. This particular Indiana plant may have aged the mix more than was observed in the three mixtures evaluated in NCHRP 9-12 or the Michigan and Missouri mixes evaluated here. In addition the Indiana materials are older than the others and may have experienced additional aging during storage.

Table 9 Estimated vs. Measured Critical Temperatures – Recovered Binder from Plant Mix

Binder Aging	Indiana			Michigan			Missouri		
	Est	Meas	Diff	Est	Meas	Diff	Est	Meas	Diff
Original	70.2	76.4	6.2	64.5	71.1	6.6	66.0	73.8	7.8
RTFO	68.5	71.7	3.2	63.0	63.4	0.4	64.2	64.6	0.4
RTFO-PAV	17.3	20.8	3.5	15.5	15.0	0.5	18.2	17.5	0.7

Est = Estimated critical temperature based on linear blending.
Meas = Critical temperature based on testing recovered binder from plant mix.
Diff = |Estimated – Measured Critical Temperature|

Linear equations for the RTFO and RTFO-PAV aged materials for the Michigan and Missouri mixtures are excellent approximations, agreeing within one degree. In the case of Indiana, the approximation is still good, but is off by up to 3 degrees. It should be noted, however, that the RAP content in this mixture is only 15%, which is below the threshold where blending equations are recommended. In fact, the current recommendations are to allow up to 15% RAP to be used without changing the binder grade. Even this amount of RAP stiffened the resulting blend, but only by a few degrees. This can be observed by comparing the slopes of the blending curves. The Indiana blending curves are much flatter than the Michigan and Missouri curves.

Mixture Tests

Mixtures were analyzed using the Superpave shear tester. The specific tests conducted were the Frequency Sweep test at Constant Height (FS), the Simple Shear test (SS) and the Repeated Shear at Constant Height tests (RSCH). These tests had proven to be very informative and sensitive to changes in the mixture properties during the NCHRP 9-12 research and in other work. (24, 25)

Frequency Sweep Test at Constant Height (FS)
The Frequency Sweep at Constant Height (FS) test is conducted by applying a repeated shear load producing a strain of 0.005% in a horizontal direction while applying an axial stress to keep the specimen height constant. The frequency sweep test allows determination of the complex shear modulus (G*) and phase angle (δ) of a mixture at a wide range of frequencies from 0.01 Hz to 10Hz and at 4, 20 and 40°C (AASHTO TP7-94, *Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device*, Procedure E). For this work, tests were conducted at only 20 and 40ºC. At 10 Hz and 40°C, a modulus (G*) value of about 35,000 to 50,000 psi or higher generally indicates a good mix while values below about 22,000 psi generally indicate poor performance. Values between 22,000 and 50,000 psi fall in a gray area and could be either good or bad. (These values are used by the Asphalt Institute as rough guidelines and were presented to the Mixture Expert Task Group in September 1997.)

Simple Shear at Constant Height (SS)
The Simple Shear at Constant Height (SS) test applies a single, controlled stress to the specimen while an axial load keeps the specimen height constant. The shear load ramps up at 70 kPa/sec to the specified shear load, which varies for different test temperatures. The load is then held constant for ten seconds. After ten seconds, the load ramps down at 25 kPa/sec. The maximum shear deformation is the primary data item of interest (AASHTO TP7-94 Procedure D).
In this study, the SS test was conducted on the same samples immediately after the FS test at the same temperature (20 and 40°C). Guidelines for acceptable shear deformation values have not been established.

Repeated Shear at Constant Height (RSCH)
In the Repeated Shear at Constant Height test (RSCH), a repeated, stress-controlled shear load is applied to the specimen while an axial stress is applied to keep the specimen height constant. The shear stress is applied in repeated haversine pulses. The load is applied for 0.1 second followed by a 0.6-second rest period. The test is typically run to 5000 cycles or 5% permanent shear strain. This testing was conducted at 58ºC for this study. The plastic shear strain at 5000 cycles is the parameter of interest from this test (AASHTO TP7-94, Procedure C). Permanent shear strain of less than 1% is generally considered excellent, 1 to 2% is good, 2 to 3% is fair, 3 to 5% is questionable and more than 5% is poor, according to the guidelines used by the Asphalt Institute and others.

The frequency sweep and simple shear tests are conducted on the same specimens, which are compacted to 7% air voids. This air void content approximates that typically achieved in the field after construction. The repeated shear at constant height test is conducted on specimens compacted to 3% air voids. This is intended to represent the state of the pavement after many years of densification under traffic. The repeated shear test looks at the possibility that a mixture will become plastic late in its service life and exhibit tertiary flow, the sudden, dramatic increase in deformation that may occur at low air void contents.

Results

Frequency Sweep Testing

The results of frequency sweep testing at 20 and 40ºC are illustrated in Figures 4 through 13 below and shown in entirety in Appendix A. The coefficient of variation (COV) on all of these test results is 20% or less, unless otherwise noted, which is quite good for this type of testing.

Figures 4 through 7 show some typical replicate data to illustrate the type of repeatability generally observed. Figures 8 through 13 show the average test results for the RAPs from each state at 20 and 40ºC. Each point shown in Figures 8 through 13 represents the average of four to six tests. The results are discussed in detail state by state below.

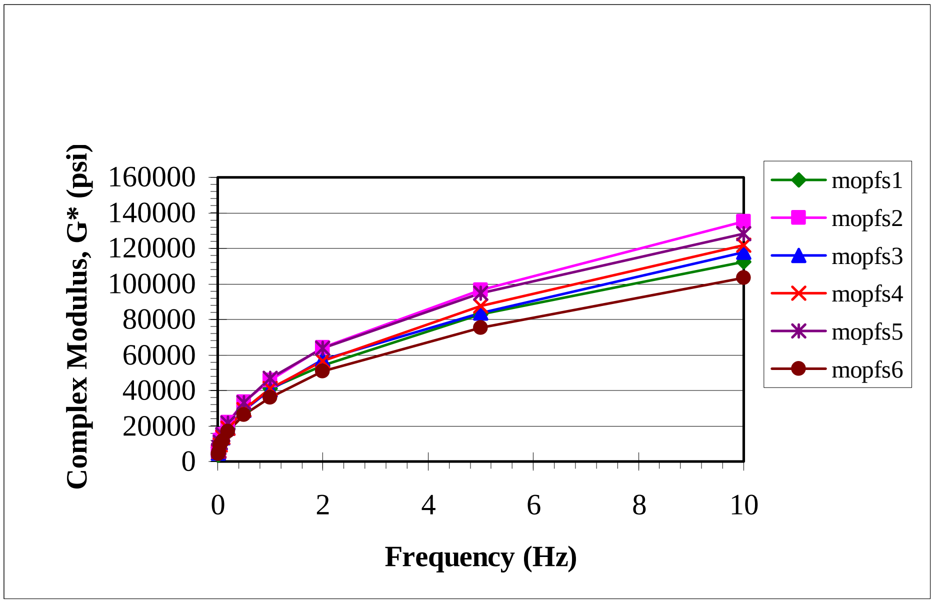


Figure 4 Frequency Sweep Results for Missouri Plant Mix Replicates (40ºC)

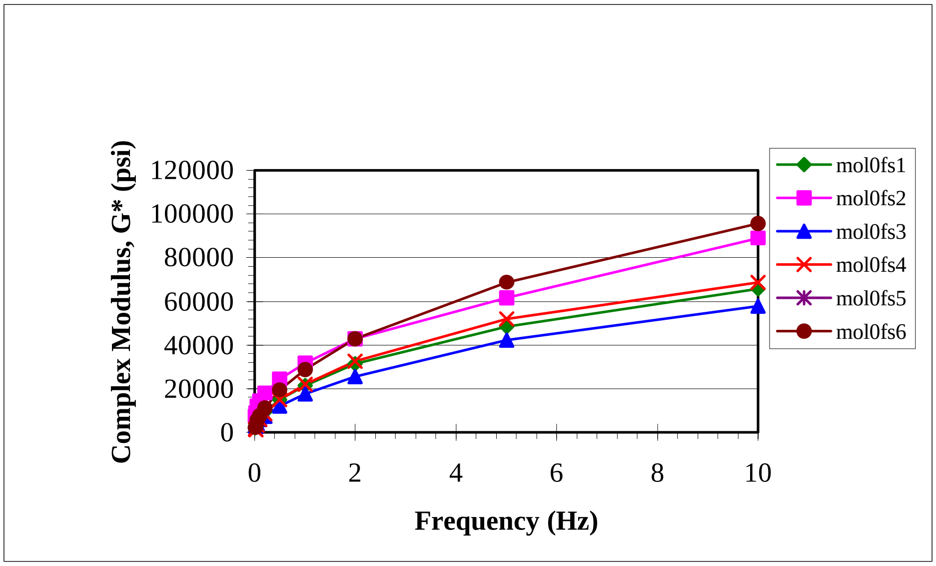


Figure 5 Frequency Sweep Results for Missouri Lab Mix Replicates, 0% RAP (40ºC)

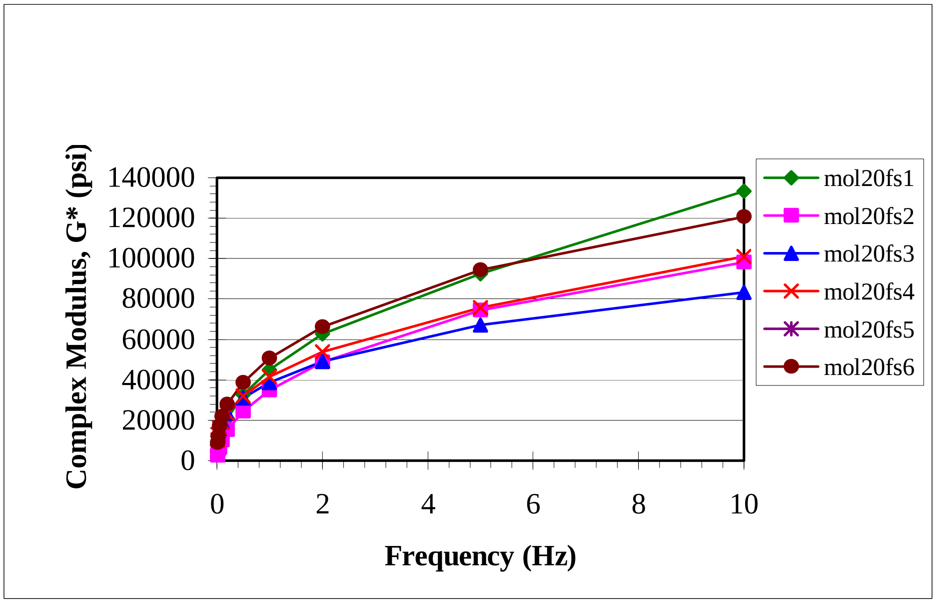


Figure 6 Frequency Sweep Results for Missouri Lab Mix Replicates, 20% RAP (40ºC)

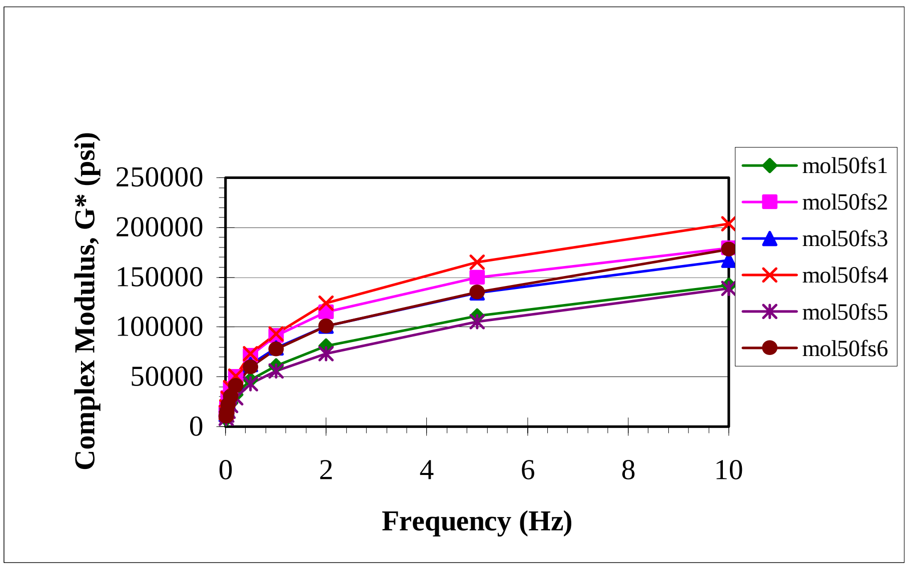


Figure 7 Frequency Sweep Results for Missouri Lab Mix Replicates, 50% RAP (40ºC)

The results from Indiana, shown in Figures 8 and 9, and summarized in Figure 10 and Table 10, are unusual in that the plant mix stiffness is significantly higher than any of the lab-produced mixes, even the 50% RAP mix. This trend is not seen in the other states, nor was it seen in NCHRP 9-12. In fact, a mini-experiment in NCHRP 9-12 showed that lab-produced mixes compared extremely well to plant-produced mixes at the same RAP content. The higher stiffnesses of the plant mix from Indiana may mirror the higher critical temperatures noted for the binder recovered from the plant-mix. This particular plant may have produced increased aging of the plant mix. It should also be noted that this mix was placed in 1997 and is one year older than the Michigan and Missouri mixes. It seems unlikely that substantially more aging of the Indiana mix could have occurred in one year of storage under similar conditions, but is a possibility. The Indiana RAP and virgin binder were also held in storage for an additional year, with no apparent detrimental effects.

The Indiana lab mix results are more in line with expectations, based on previous experience. The lab mixes at 0 and 15% RAP show similar stiffnesses. Although the 0% RAP mix has a slightly higher average stiffness than the 15% RAP, there is no significant difference in the stiffnesses, due to the inherent variability in this type of testing. It is also possible that the virgin aggregates are of higher quality and angularity than the RAP aggregates, so the virgin mixture may have a better aggregate skeleton, yielding a higher stiffness than the RAP mix. As the RAP content is increased to 50%, the stiffness increases significantly, as expected, due to the stiffening effect of the RAP binder.

The Indiana FS results at 40ºC indicate that all of these mixes would be rated as good according to the rough guidelines established by the Asphalt Institute. The stiffness values are greater than 22,000 psi in all cases. The plant mix and the lab mix at 50% RAP would both be rated as excellent, since their stiffnesses are in excess of 50,000 psi.

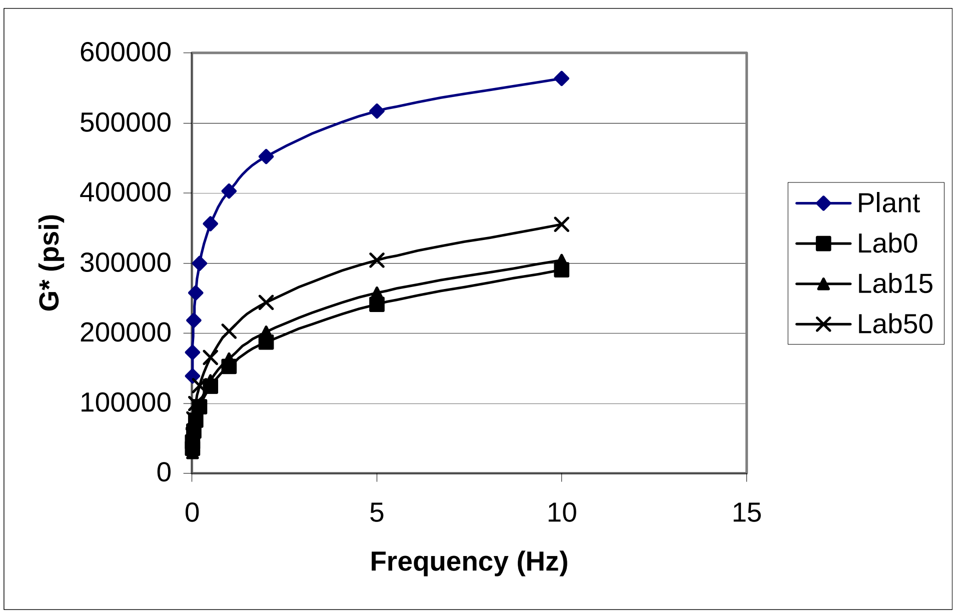


Figure 8 Average Frequency Sweep Results for Indiana Mixes (20ºC)

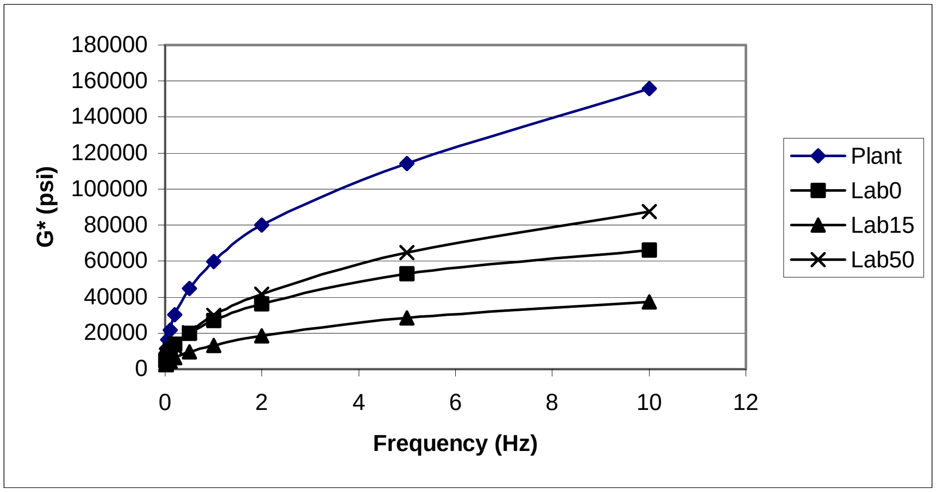


Figure 9 Average Frequency Sweep Results for Indiana Mixes (40ºC)

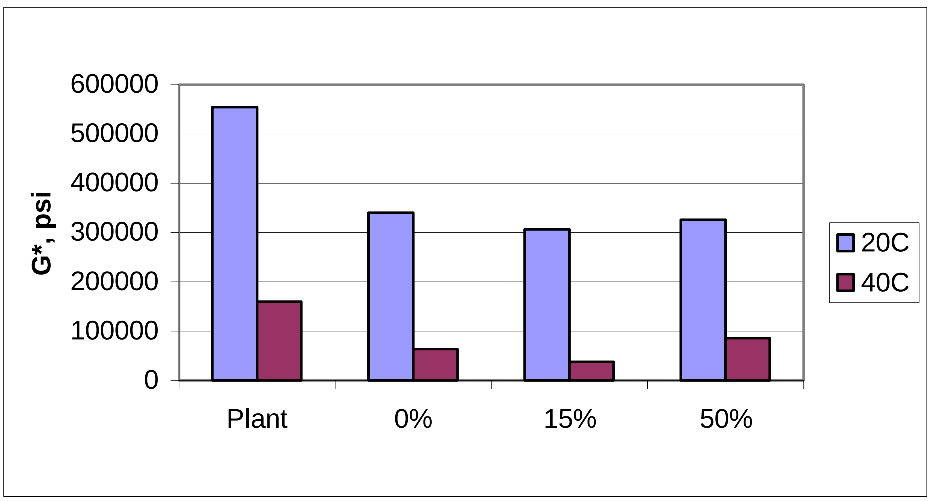


Figure 10 Summary of Complex Shear Moduli from Frequency Sweep at 10 Hz, Indiana

Table 10 Summary of Complex Shear Moduli (psi) at 10Hz, Indiana Mixes

Temperature	Plant	Lab, 0% RAP	Lab, 15% RAP	Lab, 50% RAP
20ºC	563,312	289,966	304,183	355,048
40ºC	155,803	66,166	37367	87,419

The FS results from Michigan are shown in Figures 11 and 12, and summarized in Figure 13 and Table 11. The data at 20ºC was quite variable, perhaps due to the high stiffness. The coefficient of variation of the plant mix was 34% and the 25% RAP lab mix had a COV of 25%. The other two mixes had COVs at 20ºC of 15 and 8%. The results for the plant mix were so variable, in fact, that it could not be determined which values were possible outliers. At 20ºC the plant mix yields a much higher stiffness than the lab mixes, but this trend is not observed at 40ºC. This, plus the fact that the binder data did not show evidence of increased age hardening, seems to indicate that this data is not reliable.

At 40ºC the data appears more logical. The plant mix has a stiffness similar to the lab mixes at 0 and 25% RAP. As the RAP content increases in the lab, the stiffness increases. Using the Asphalt Institute's rough guidelines at 10 Hz and 40ºC, the lab mixes with 25% and 40% RAP would be expected to have good rutting resistance since their moduli are greater than 35,000 psi. The plant mix and lab mix without RAP fall in the gray area between 22,000 and 35,000 psi.

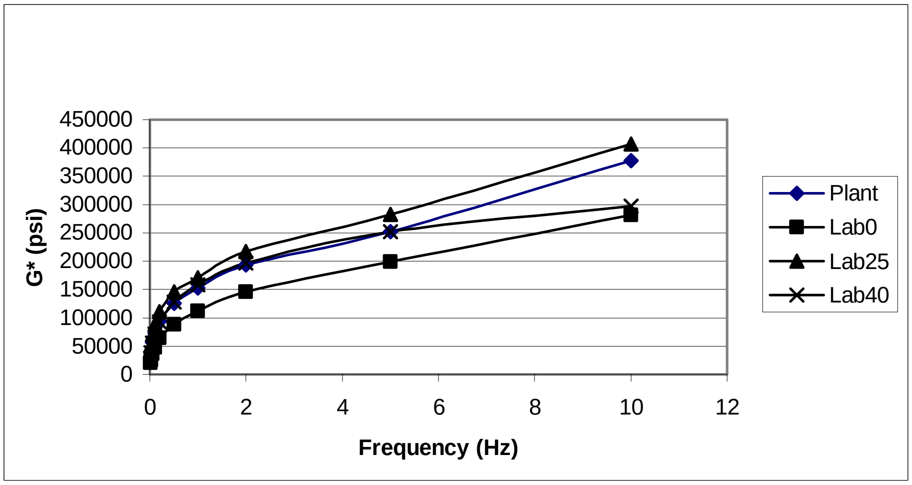


Figure 11 Average Frequency Sweep Results for Michigan Mixes (20ºC)

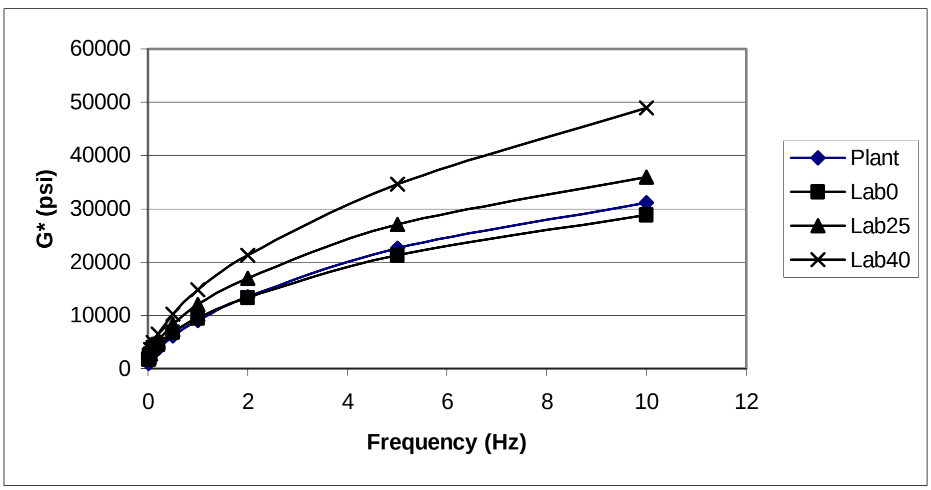


Figure 12 Average Frequency Sweep Results for Michigan Mixes (40ºC)

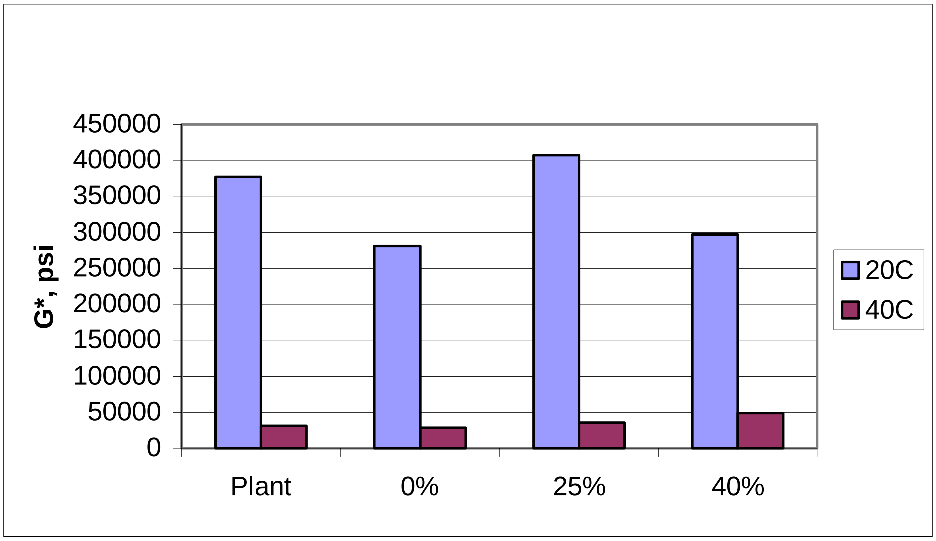


Figure 13 Summary of Complex Shear Moduli from Frequency Sweep at 10 Hz, Michigan

Table 11 Summary of Complex Shear Moduli (psi) at 10Hz, Michigan Mixes

Temperature	Plant	Lab, 0% RAP	Lab, 25% RAP	Lab, 40% RAP
20ºC	377,154	281,139	406,986	297,109
40ºC	31,197	28,832	36,002	48,971

The data from Missouri also shows the trend of increasing stiffness as the RAP content increases at both 20 and 40ºC. The plant and lab mixes at 20% are not significantly different, but the mix with no RAP is substantially softer. At 40ºC, there is a significant difference between the results for the individual mixes.

All of the Missouri mixes, regardless of RAP content, have stiffnesses in excess of 50,000 psi at 40ºC, which would imply that they could be expected to have excellent resistance to rutting.

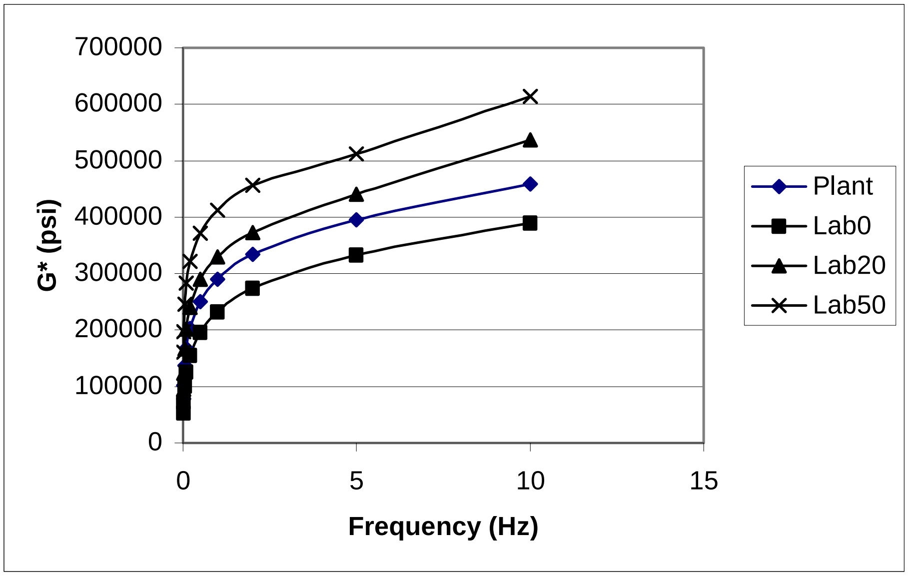


Figure 14 Average Frequency Sweep Results for Missouri Mixes (20ºC)

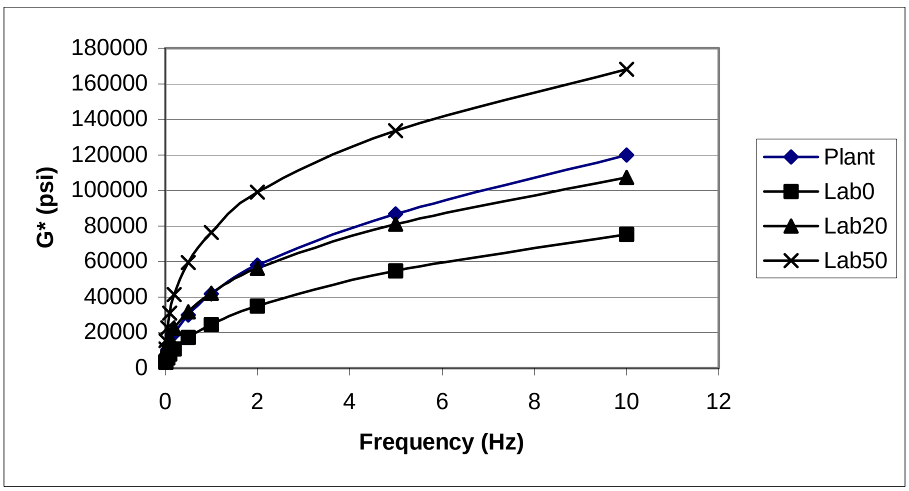


Figure 15 Average Frequency Sweep Results for Missouri Mixes (40ºC)

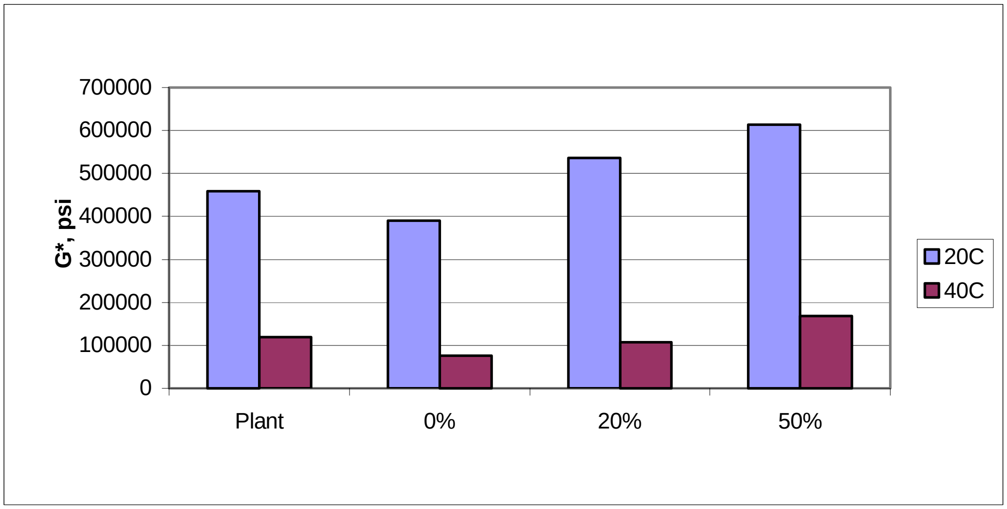


Figure 16 Summary of Complex Shear Moduli from Frequency Sweep at 10 Hz, Missouri

Table 12 Summary of Complex Shear Moduli (psi) at 10Hz, Missouri Mixes

Temperature	Plant	Lab, 0% RAP	Lab, 20% RAP	Lab, 50% RAP
20ºC	458,283	390,118	536,511	613,493
40ºC	119,852	75,295	107,307	168,104

Simple Shear Test Results

For the most part, the simple shear test results correspond to the frequency sweep test results. That is, the mixtures with the highest stiffness values (G*) in the frequency sweep test exhibit the lowest shear strains in the simple shear test, as logic would dictate. This does not hold true in all cases, however, as will be discussed below. Since the simple shear test imparts one shear load to the specimen, rather than a repeated load as in the frequency sweep or repeated shear tests, the results tend to be more variable; they are not averaged over repeated loadings. Past experience with this type of testing at the NCSC generally shows more logical and repeatable data is obtained with the frequency sweep and repeated shear tests than with simple shear.

The results from Indiana at 20°C, for example, shown in Figure 17, indicate that the plant mix, which had the greatest stiffness, exhibited the lowest shear deformation as expected. The lab mixes, however, are reversed from what would be expected. The 50% RAP mix, which had the highest stiffness of the lab mixes, also had the highest shear deformation. The 0% RAP mix, which had the lowest stiffness in the frequency sweep test, showed the lowest shear deformation. Similar results were obtained at 40ºC, as shown in Figure 18. Because of high variability in the test results, the differences between the three lab mixes are not statistically significant. Replicate test results for a given mix varied in some cases as much as 500%. That is, the highest maximum shear strain observed was five times the lowest observed shear strain for the 0% RAP lab mix at 20ºC. The 50% RAP mix at 20ºC had replicate test results that varied by about 400%. The plant mix had a variability between replicate results of about 200% and was significantly different from the lab mixes. Figure 19 illustrates the more typical variability observed between replicate test results for this type of testing.

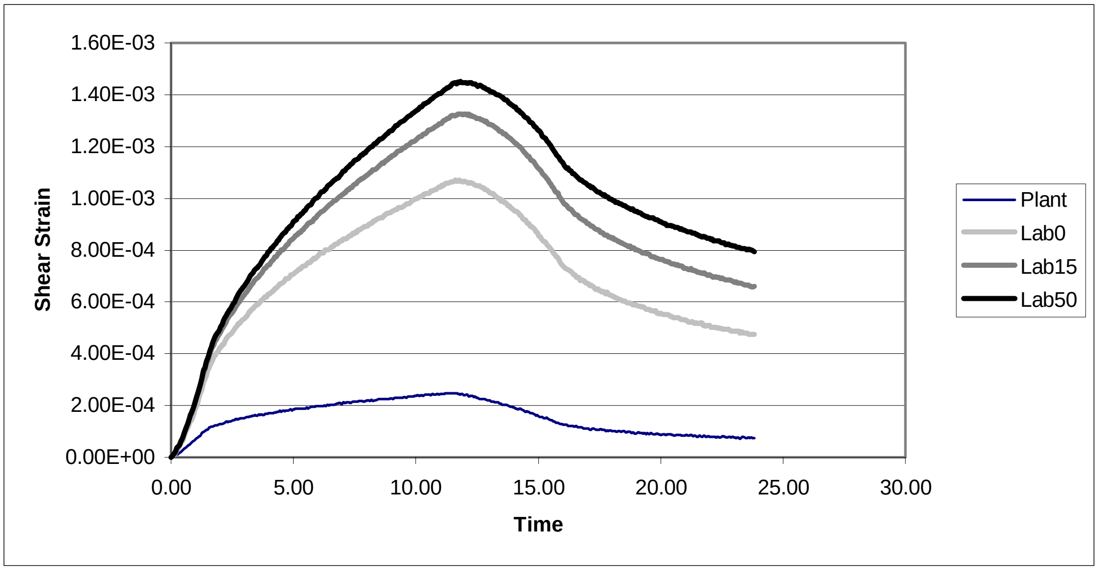


Figure 17 Average Shear Strains for Indiana Mixes at 20ºC

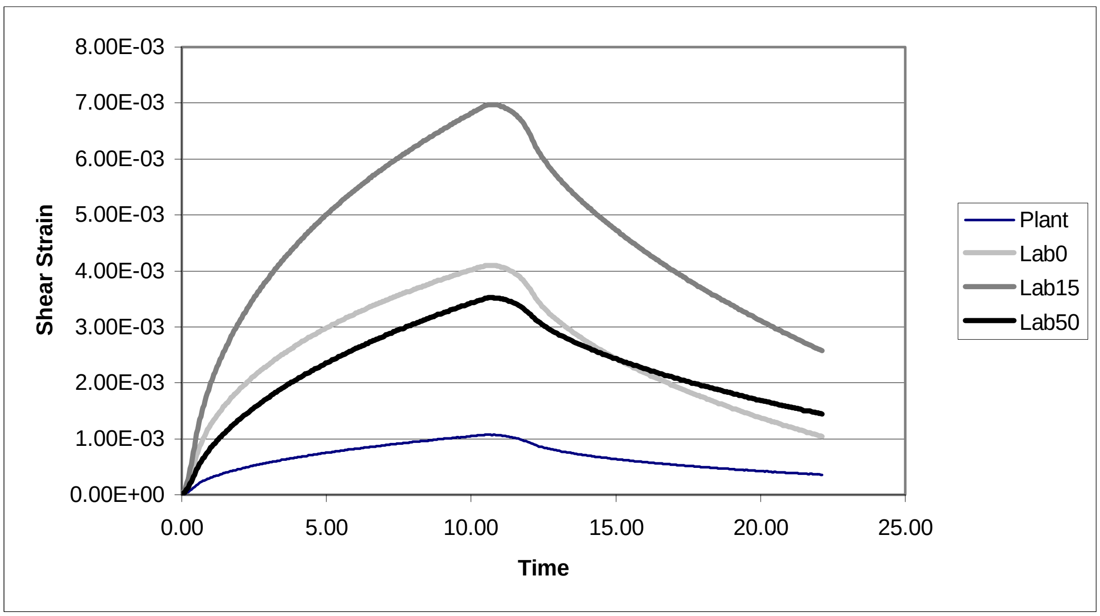


Figure 18 Average Shear Strains for Indiana Mixes at 40ºC

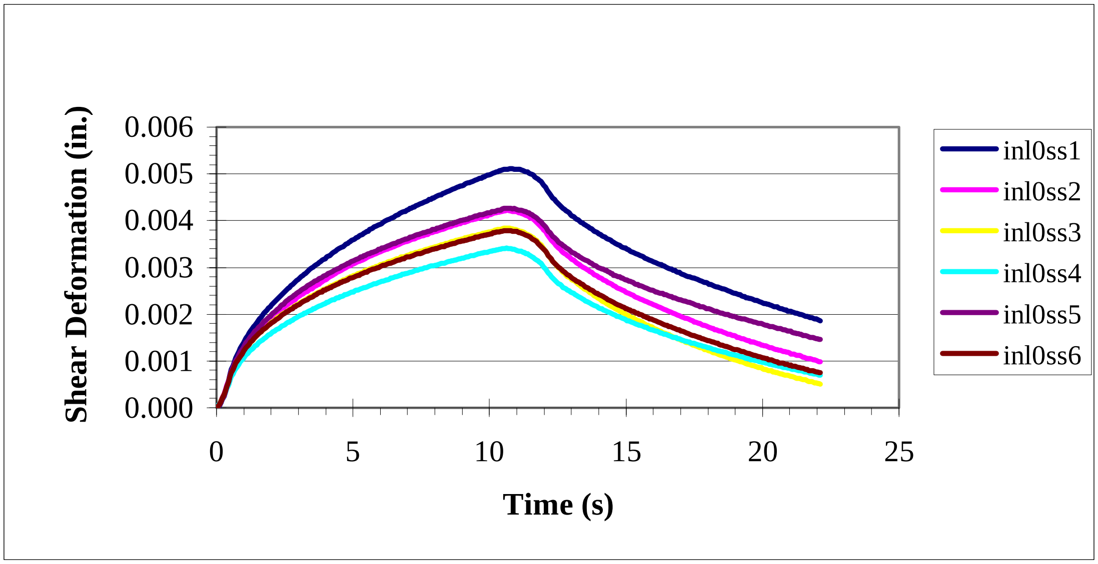


Figure 19 Examples Showing Typical Variability in Replicate Test Results

The data from the Michigan mixes also shows high variability, though not as high as the Indiana data. Differences between the highest and lowest values for replicate test results was typically around 200% or less.

The results at 20ºC conform to expectations. The lab mixes demonstrate decreasing maximum shear strains as the RAP content increases, which also agrees with increasing complex modulus from the frequency sweep test. The strain for plant mix was between that of the 0% RAP and 25% RAP lab mixes, as was its stiffness.

At 40ºC the results are not as consistent. The plant mix exhibited the highest shear strain but had the second highest stiffness. This is likely due to the variability in both the tests, but especially with the simple shear test. The lab mixes with 25 and 40% RAP would be expected to have good resistance to rutting based on the FS stiffness values, and these two mixes also show the lowest shear strains. The plant mix and 0% RAP lab mix exhibited higher shear strains; these mixes fell in the gray area in terms of FS stiffness.

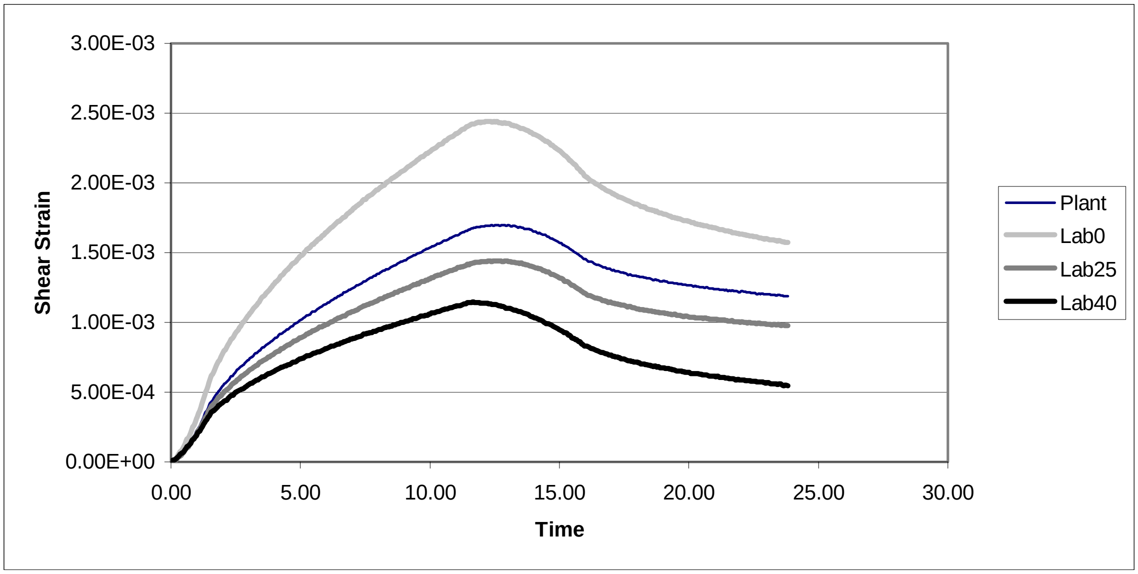


Figure 20 Average Shear Strains for Michigan Mixes at 20ºC

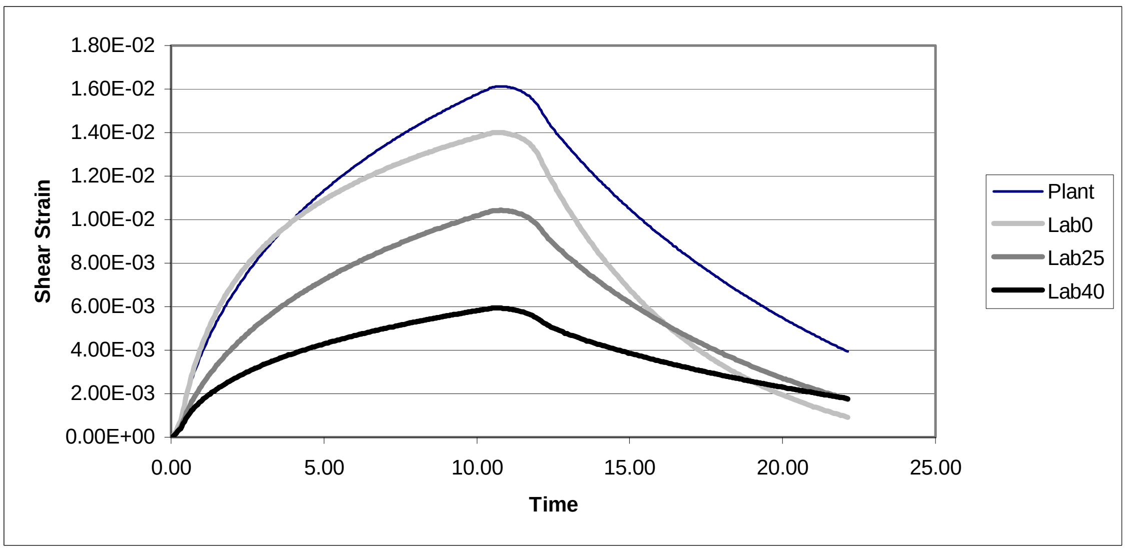


Figure 21 Average Shear Strains for Michigan Mixes at 40ºC

The Missouri mixes are consistent with expectations. The stiffest mixtures also exhibit the lowest shear strains at both 20 and 40ºC. At 40ºC the plant mix had a slightly lower shear strain than the 20% RAP lab mix although it had a slightly higher stiffness. The difference between the shear strains and the stiffnesses of these two mixes is not significant at this temperature.

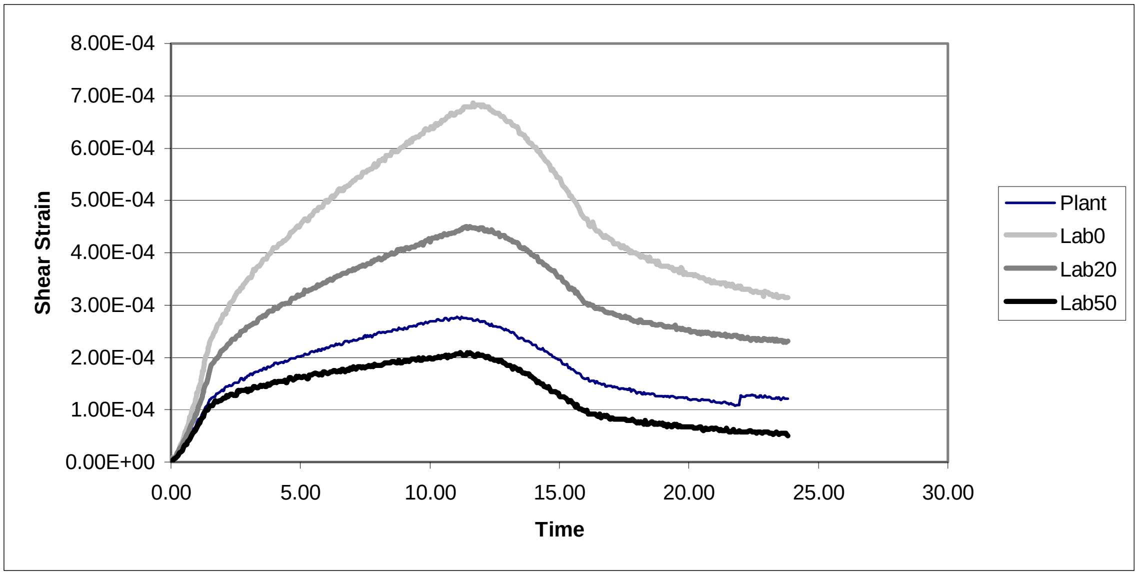


Figure 22 Average Shear Strains for Missouri Mixes at 20ºC

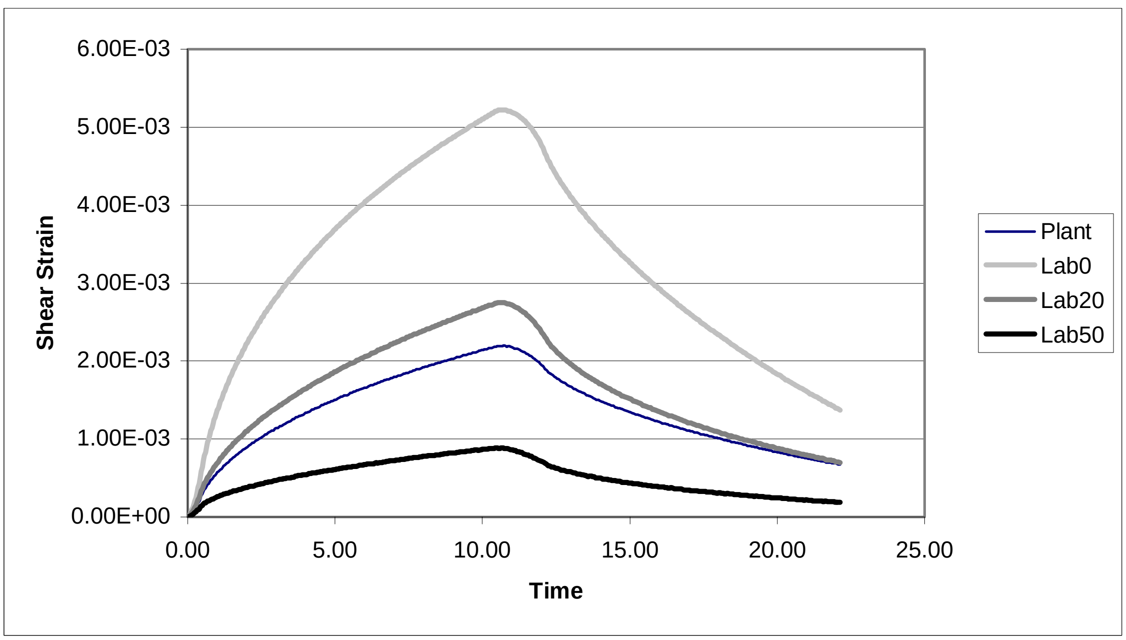


Figure 23 Average Shear Strains for Missouri Mixes at 40ºC

Repeated Shear at Constant Height Testing

This testing was conducted at 58ºC, much higher than the other shear tests, which were conducted at 20 and 40ºC. At this high a temperature, the binders, and hence the mixtures, tend to be very soft. This test is also conducted at 3% air voids, versus 7% air voids for the other shear tests. The test has proven very effective in the past at differentiating between mixtures.

None of the mixtures tested from any source exhibited any signs of tertiary flow. In addition, most exhibited low shear strains, which are considered indicative of good performance.

The Indiana results are shown in Figure 24. All of the average shear strains at 5,000 cycles are between 1 and 2% strain (0.01 to 0.02 in/in), which indicates good performance. The plant mix exhibits strain levels comparable to the lab mix with 50% RAP throughout the test, again showing the higher than expected stiffness for the Indiana plant mix. The lab mix with no RAP has a lower strain value. This may indicate that the virgin aggregates develop a better aggregate structure than the RAP aggregates. The lab mix with 15% RAP shows the highest shear strain. This may indicate a slight degradation in the mix quality when the RAP aggregates are added to the mix. This degradation, though, is not enough to compromise the expected mix performance. The fact that the 50% RAP mix showed a decrease in the shear strain may be due to the increase in the binder stiffness when that much aged binder is included in the mix. The increased binder stiffness may be compensating for the slight degradation in the aggregate skeleton.

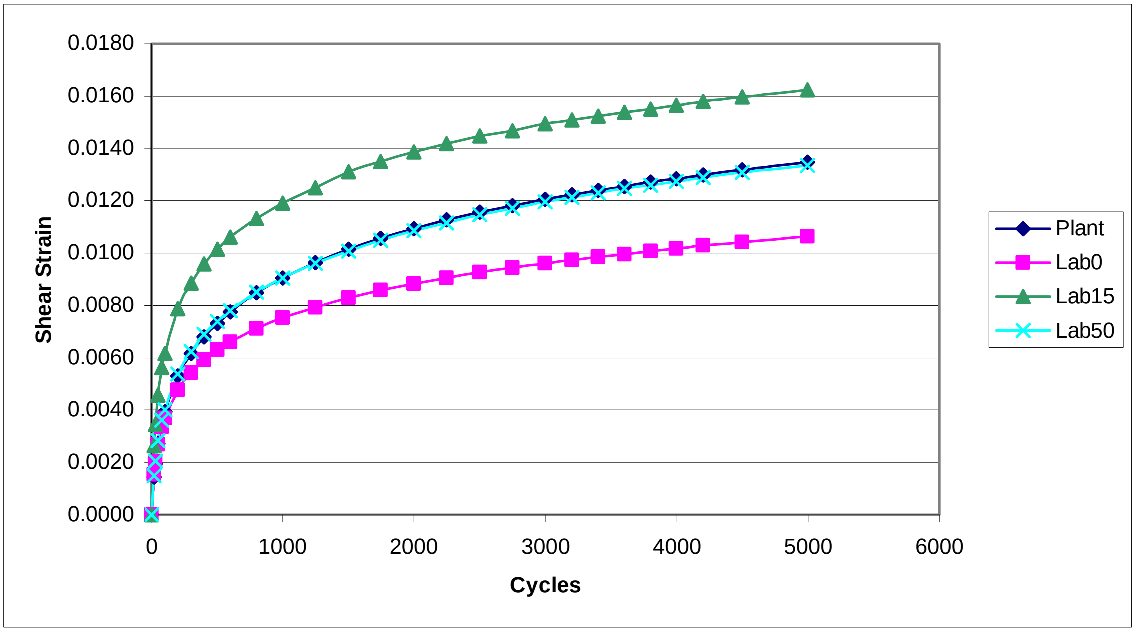


Figure 24 Average Shear Strain from RSCH Test, Indiana Mixes

The results of testing the Michigan materials are shown in Figure 25. The mixture with the highest RAP content exhibits the highest shear strain, which was in excess of 2% strain (greater than 0.02 in/in), indicating only fair performance. As the RAP content decreases, the strains also decrease. The plant mix exhibited strain values between those of the 25 and 40% RAP mixes.

The strain values for the plant, 0% RAP and 25% RAP mixes were all between 1 and 2% strain, indicating good performance.

The explanation for the observed trends may again lie with the aggregates. As mentioned earlier, the maximum amount of this particular RAP that could be incorporated was 40%. Repeated attempts to design a mix with 50% RAP were unsuccessful. An acceptable aggregate structure could not be developed with large amounts of this RAP. This was detected during the mix design phase by unacceptable void contents and poor compaction parameters (density at N_{ini}, N_{des} and N_{max}). Up to 25% RAP, however, could be used and still provide good performance comparable to a virgin mix. For this mix, therefore, it may be conjectured that stiffening the binder by the addition of RAP cannot counteract the weakening of the aggregate structure caused by the RAP aggregates.

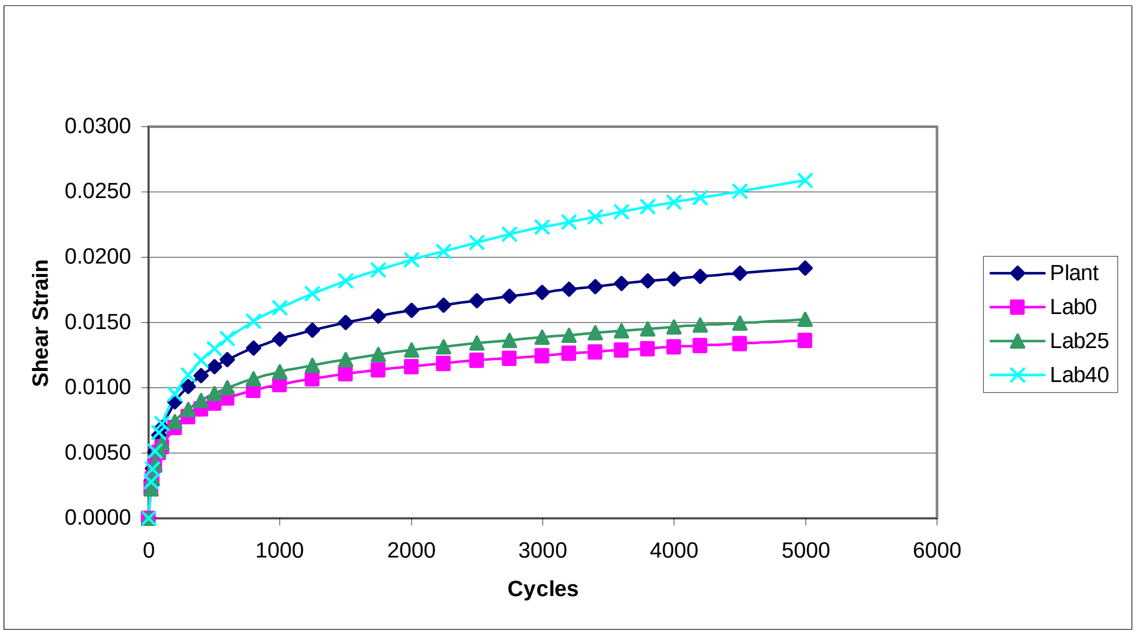


Figure 25 Average Shear Strain from RSCH Test, Michigan Mixes

The Missouri mixes again exhibit behavior that conforms more closely to expectations, as shown in Figure 26. In this case, as the RAP content increases, the shear strain decreases. In fact, increasing the RAP content from 20 to 50% improves the expected performance from good to excellent. This apparently indicates the stiffening effect of the RAP binder. The plant produced mix falls neatly into line with strains between those of the 20% and 50% RAP mixes produced in the lab.

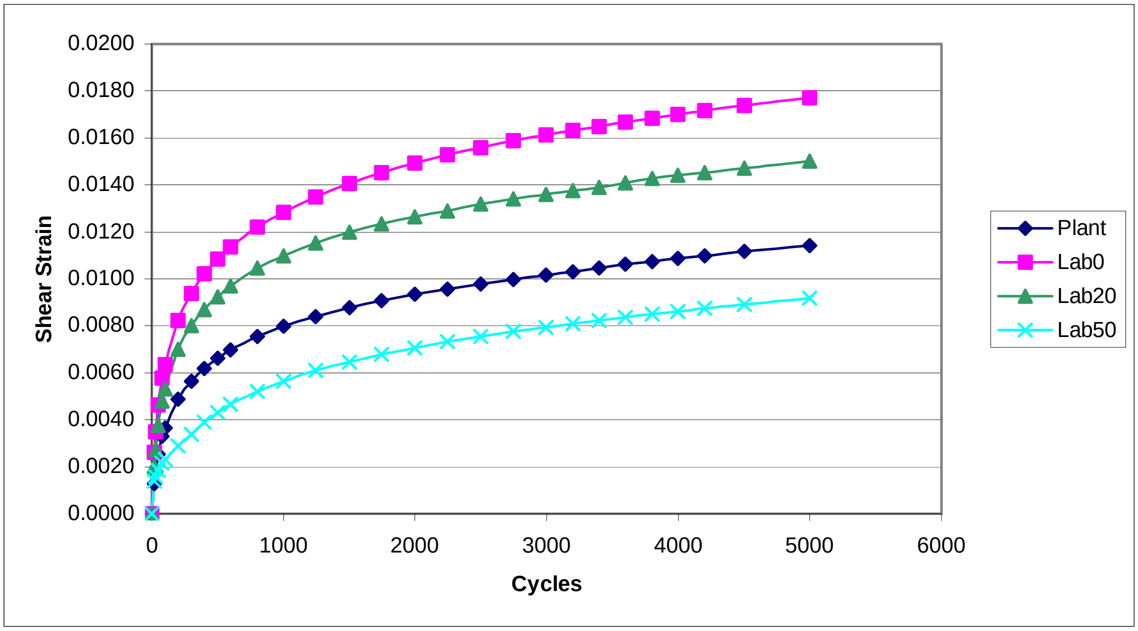


Figure 26 Average Shear Strain from RSCH Test, Missouri Mixes

CONCLUSIONS

This study of typical North Central region RAP mixes leads to the following conclusions.

1. Using the materials in this study, acceptable Superpave mixtures could be designed with up to 40 or 50% RAP. Excessively fine RAP gradations may limit the amount of RAP that can be incorporated in a new Superpave mixture. Depending on the quality of the aggregates in the RAP and traffic level, even higher RAP contents may be feasible, however, mixes with very high RAP contents have historically been relatively rare.
2. A limited comparison of solvent extractions to ignition oven asphalt content determinations underscored the need to properly calibrate the ignition ovens for the aggregates being tested.
3. Linear blending charts proved appropriate for estimating the effects of the RAP binder on blended binder properties, in most cases. Testing the binder from plant mix and RAP materials as if they were unaged (original) binders is not strictly correct since some aging has in fact occurred. The errors, however, were generally small and conservative (i.e. stiffness was underestimated by about one-half grade).
4. Linear approximations for RTFO and RTFO-PAV aged materials were very accurate, except for the Indiana materials. For the Indiana materials, when tested as original, RTFO and RTFO-PAV aged, the binder from the plant-produced mix was significantly stiffer than expected.
5. Adding 20 to 25% RAP raised the high temperature grade of the plant mixed material by one increment. This is consistent with the tiered approach which allows up to 25% RAP to be used by dropping the virgin binder grade by one increment. The Indiana mix with 15% RAP also showed an increase in the binder grade although this falls in the tier where no change in the virgin binder grade is recommended. The increased binder grade is likely due to the excessive stiffness of the plant-produced mix.
6. In general, frequency sweep testing on the mixtures showed that the higher the RAP content, the higher the mixture stiffness due to the effect of the hardened RAP binder. The plant mixes from Michigan and Missouri were similar in stiffness to lab-produced mixes at the same RAP content. The Indiana mixes produced in the lab showed a similar trend of increasing stiffness with increasing RAP content. The plant-produced mix from Indiana, however, was significantly stiffer than expected.
7. The mixture simple shear test results showed higher variability than any of the other mixture shear tests. This is likely due to the fact that the test consists of one load application whereas the frequency sweep and repeated shear tests involve multiple loads that can serve to “smooth” the data. This high variability made interpretation of the data difficult.
8. Simple shear tests in general agreed with the frequency sweep results. That is, the mixes with the highest stiffnesses in the frequency sweep testing also exhibited the lower shear strains, as expected. In some cases, however, significant departures from the expected trends were observed, such as with the Indiana lab mixes and Michigan mixes at 40ºC. This is likely due to the high variability in the simple shear test results.
9. None of the mixtures tested exhibited tertiary flow in the repeated shear at constant height test at 58ºC. Most of the mixes tested would be expected to perform well in terms of rutting resistance. The Michigan mix with 40% RAP demonstrated only fair performance in the repeated shear test, most likely due to the aggregate structure.

10. Repeated shear testing appears to show the influence of changes in the aggregate structure with the addition of RAP as opposed to the increase in binder stiffness. In some cases of the repeated shear testing, such as with the Indiana and Michigan mixtures, increasing the RAP content lead to a slight decrease in performance, presumably because changes in the aggregate structure had a greater effect than the stiffening of the binder phase. This reinforces the need to consider the quality, shape and gradation of the RAP aggregate as part of the overall aggregate framework.
11. The Indiana materials showed consistently that the plant-produced mix and binder extracted from that mix were stiffer than expected. These results were not consistent with any of the other testing in this study nor with the findings in NCHRP 9-12. Two possible explanations for this apparent anomaly are that this particular plant caused increased aging during production and that additional aging of the plant mix occurred during one additional year of storage. Plant aging appears to be a more plausible explanation.
12. The addition of RAP can lead to improved rutting resistance by stiffening the binder, provided the mixtures are properly designed and constructed. This stiffening effect can be counteracted by decreasing the binder grade. Care should be taken to ensure that the RAP binder and aggregate properties are appropriately accounted for in the mix design process.
13. The results are generally consistent with the findings from NCHRP 9-12. Those national results and the revised AASHTO specs can be applied to typical North Central materials with confidence.

RECOMMENDATIONS

These results generally show that hot mix asphalt mixtures with RAP can perform well, provided the mixtures are properly designed and constructed. In addition, the results from this regional study indicate that mixes with higher RAP contents (up to 50% RAP) can be designed under the Superpave system. There are some remaining questions, however, that should be considered by agencies or addressed through additional research.

- This study looked at a very limited set of materials. Individual states should consider evaluating their own materials to assess typical RAP binder grades and gradations.
- Neither this study nor the NCHRP research addressed the issue of rejuvenating agents and their effect on the blended binder grade. Additional research is needed.
- Field verification of these findings is necessary. The states are encouraged to monitor the performance of the mixtures tested here to determine if the mixes are resistant to rutting and cracking. Based on past experience that shows recycled mixtures can perform well, no significant problems are expected, provided the mixtures are properly designed and constructed.
- The results from Indiana show an apparent anomaly in the stiffness of the plant-produced mixture. This raises the issue of the effects of various plant types and production variables on the resulting mixtures. No comparisons were made here or in NCHRP 9-12 of the effects of batch plants versus drum plants, for example. As more states move towards warranties and testing as-produced mixture properties, implementing a truly simple performance test for testing actual production mixtures becomes more important.

IMPLEMENTATION SUGGESTIONS

The results of this study indicate that RAP mixtures can be designed using typical North Central materials and can be expected to perform well. States should consider allowing the use of RAP, if they do not already do so, under the newly revised AASHTO provisional standards MP2, PP28 and TP2. This regional research shows that mixtures using up to 50% RAP can be successfully designed. Based on these results states should, at the very least, allow RAP at levels comparable to pre-Superpave levels and may consider increasing the allowable RAP contents. Other considerations, such as durability or acceptable friction for surface courses, will also come into play when determining allowable RAP contents.

Discussions of RAP mixture design should be added to existing mix design courses and certification training. The NCSC has already incorporated this type of training in its mixture courses.

Local agencies should also be made aware of these findings through state paving conferences, LTAP Centers and other channels. The addition of RAP can help to offset the perceived higher costs of Superpave mixtures while still providing good performance for low volume roads. Mixtures designed for low volume roads should be designed for durability, so all mixtures need to be designed for appropriate traffic levels. This may be especially true for mixtures with higher RAP contents since the stiffening effect of the RAP could negatively impact durability and fatigue behavior unless the virgin binder grade and total binder content are selected to account for this effect.

REFERENCES

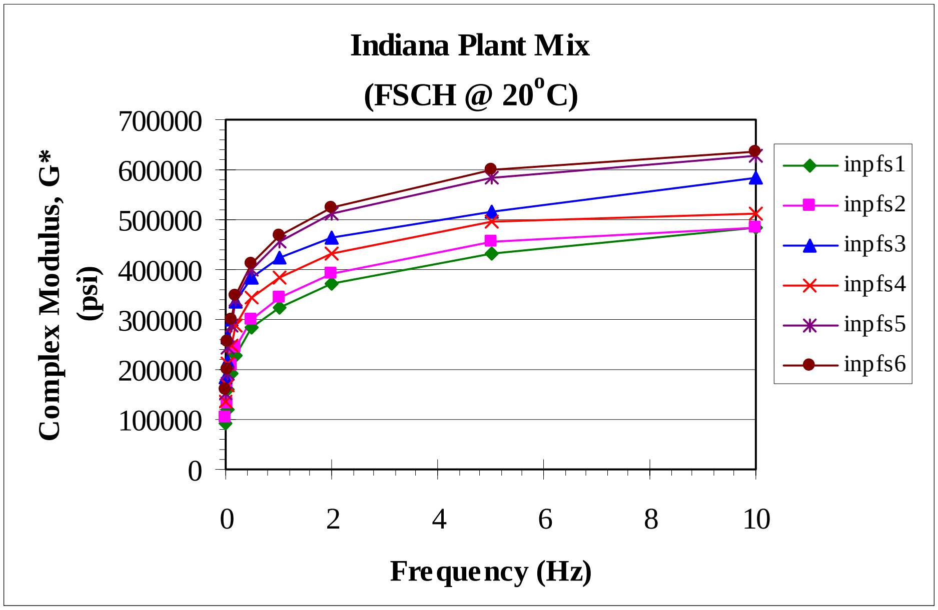
1. Federal Highway Administration, Superpave Mixture Expert Task Group, "Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP)." Washington, D.C. (1997) 5 pp.
2. McDaniel, Rebecca, and Jan Olek, Regional Pooled Fund Project Proposal, *Use of Reclaimed Asphalt Pavement Under Superpave Specifications*, July 1996.
3. McDaniel, Rebecca S., and R. Michael Anderson, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines*. National Cooperative Highway Research Program, Washington, D.C. (October 2000) 17 pp.
4. McDaniel, Rebecca S., Hamid Soleymani, R. Michael Anderson, Pamela Turner and Robert Peterson, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method*. National Cooperative Highway Research Program, Washington, D.C. (October 2000).
5. McDaniel, Rebecca S., and R. Michael Anderson, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*. National Cooperative Highway Research Program, Washington, D.C. (October 2000), 49 pp.
6. American Association of State Highway and Transportation Officials, "Provisional Standards." AASHTO, Washington, D.C. (June 1996).
7. Harvey, J., T. Lee, J. Sousa, J. Pak, and C. L. Monismith, "Evaluation of Fatigue and Permanent Deformation Properties of Several Asphalt-Aggregate Field Mixes Using Strategic Highway Research Program A-003A Equipment." Transportation Research Record, No. 1454, Transportation Research Board, Washington, D.C. (1994) pp. 123-133.
8. Tam, K. K., P. Joseph, and D. F. Lynch, "Five-Year Experience of Low-Temperature Performance of Recycled Hot Mix." Transportation Research Record, No. 1362, Transportation Research Board, Washington, D.C. (1992) pp. 56-65.
9. Kandhal, P. S., S. S. Rao, D. E. Watson, and B. Young, "Performance of Recycled Hot-Mix Asphalt Mixtures in Georgia." Transportation Research Record, No. 1507, Transportation Research Board, Washington, D.C. (1995) pp. 67-77.
10. Sargious, M., and N. Mushule, "Behaviour of Recycled Asphalt Pavements at Low Temperatures." Canadian Journal of Civil Engineering, Vol. 18, National Research Council of Canada, Ottawa (1991) pp. 428-435.
11. Noureldin, A. S., and L. E. Wood, "Laboratory Evaluation of Recycled Asphalt Pavement Using Nondestructive Tests." Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 92-100.
12. Amirkhanian, S. N., and B. Williams, "Recyclability of Moisture Damaged Flexible Pavements." Journal of Materials in Civil Engineering, Vol. 5, No. 4, American Society of Civil Engineering, New York (1993) pp. 510-530.
13. Terrel, R. L. and D. R. Fritchen, "Laboratory Performance of Recycled Asphalt Concrete," American Society for Testing and Materials, STP 662, Recycling of Bituminous Pavements, ASTM, Philadelphia, PA (1977) pp. 104-122.
14. Epps, J.A., Little, D.N., O'Neal, R.J., and Galling, B.M., "Mixture Properties of Recycled Central Plant Materials," ASTM, STP 662, Recycling of Bituminous Pavements, ASTM, Philadelphia, PA 1997, pp. 68-103.
15. Hossain, M., D. G. Metcalf, and L. A. Scofield, "Performance of Recycled Asphalt Concrete Overlays in Southwestern Arizona." Transportation Research Record, No. 1427, Transportation Research Board, Washington, D.C. (1993) pp. 30-37.

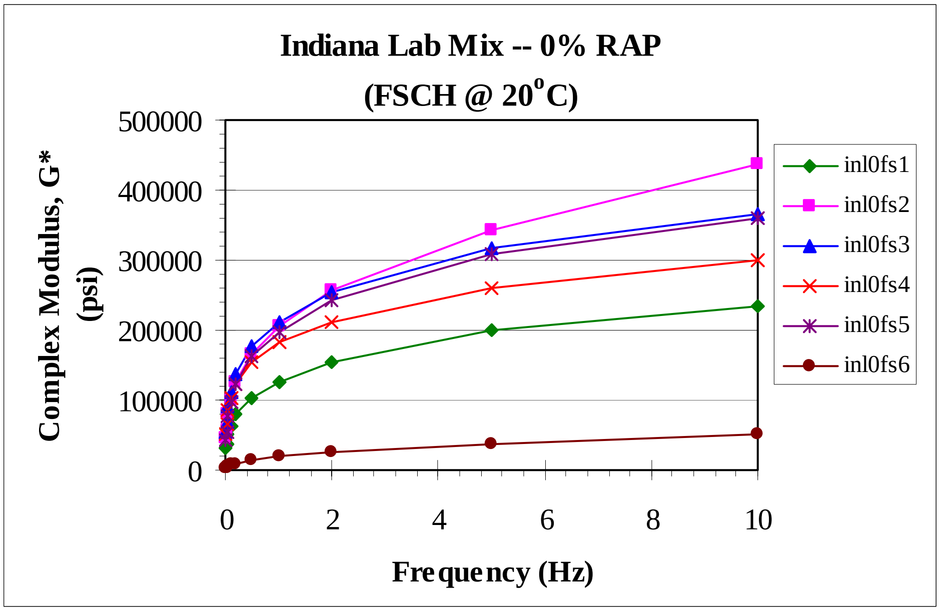
16. Paul, H. R., “Evaluation of Recycled Projects for Performance.” Asphalt Paving Technology, Vol. 65, Journal of the Association of Asphalt Paving Technologists, St. Paul, Minnesota (1996) pp. 231-254.
17. Servas, V.P., M. A. Ferreira, and P. C. Curtayne, “Fundamental Properties of Recycled Asphalt Mixes,” Sixth International Conference on Structural Design of Pavement, Ann Arbor, Michigan (July 1987) pp. 455-465.
18. Burr, B. L., R. R. Davison, C. J. Glover, and J. A. Bullin, “Solvent Removal from Asphalt.” Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 1-8.
19. Cipione, C. A., R. R. Davison, B. L. Burr, C. J. Glover, and J. A. Bullin, “Evaluation of Solvents for Extraction of Residual Asphalt from Aggregates.” Transportation Research Record, No. 1323, Transportation Research Board, Washington, D.C. (1991) pp. 47-52.
20. Peterson, G. D., R. R. Davison, C. J. Glover, and J. A. Bullin, “Effect of Composition on Asphalt Recycling Agent Performance.” Transportation Research Record, No. 1436, Transportation Research Board, Washington, D.C. (1994) pp. 38-46.
21. Burr, B. L., R. R. Davison, H. B. Jemison, C. J. Glover, and J. A. Bullin, “Asphalt Hardening in Extraction Solvents.” Transportation Research Record, No. 1323, Transportation Research Board, Washington, D.C. (1991) pp. 70-76.
22. Burr, B. L., C. J. Glover, R. R. Davison, and J. A. Bullin, “New Apparatus and Procedure for the Extraction and Recovery of Asphalt Binder from Pavement Mixtures.” Transportation Research Record, No. 1391, Transportation Research Board, Washington, D.C. (1993) pp. 20-29.
23. Burr, B. L., R. R. Davison, C. J. Glover, and J. A. Bullin, “Softening of Asphalts in Dilute Solutions at Primary Distillation Conditions.” Transportation Research Record, No. 1436, Transportation Research Board, Washington, D.C. (1994) pp. 47-53.

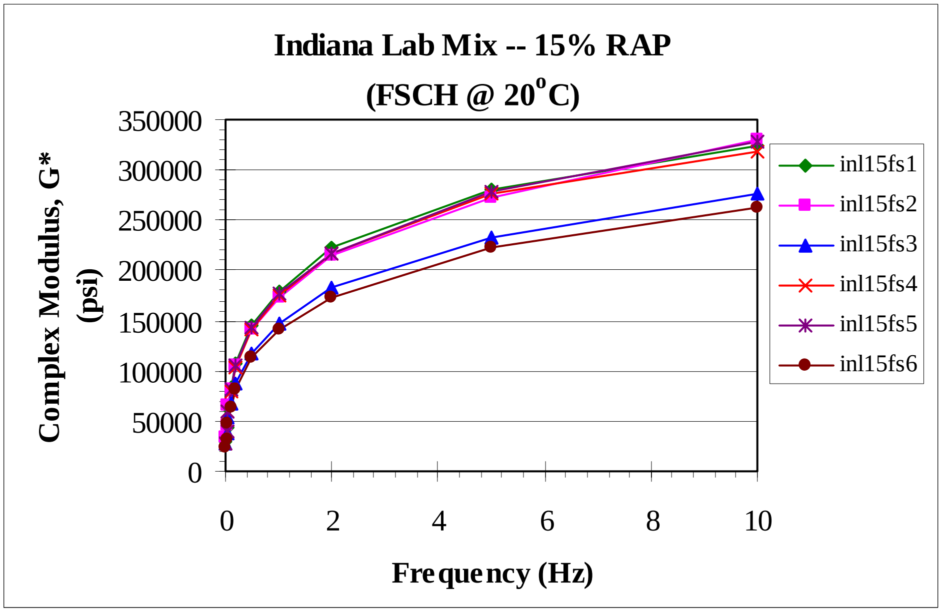
APPENDICES

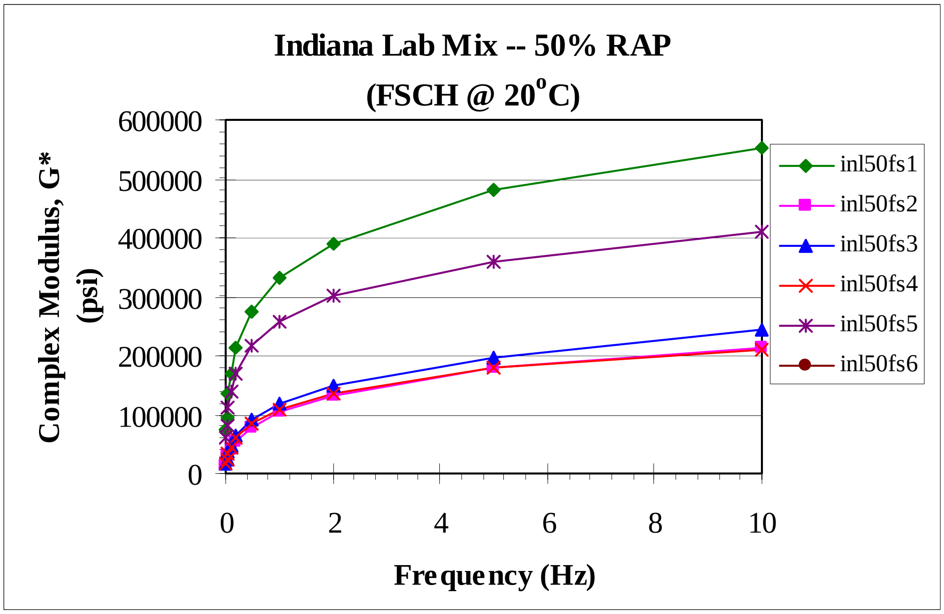
A. Frequency Sweep Results at 20 and 40°C
B. Simple Shear Results at 20 and 40°C
C. Repeated Shear Results at 58°C

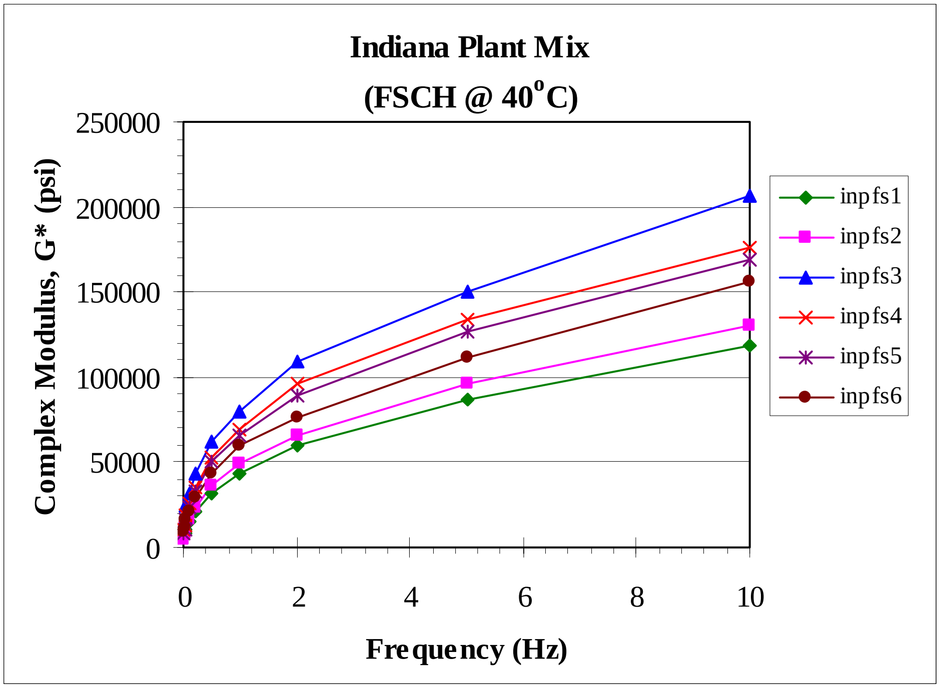
APPENDIX A – Frequency Sweep Results at 20 and 40°C



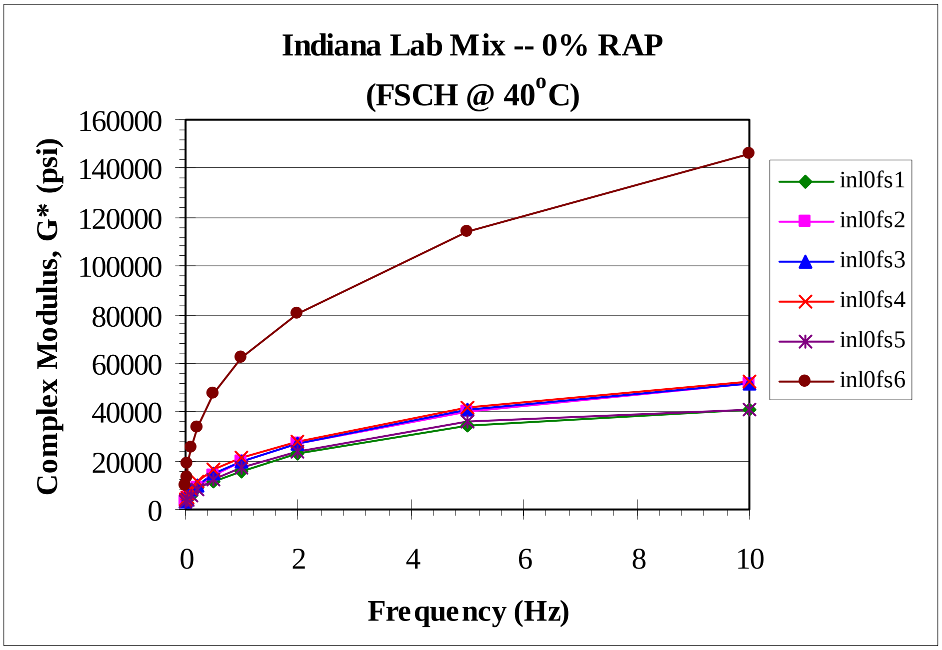



Indiana Lab Mix -- 15% RAP
(FSCH @ 20°C)
Complex Modulus, G* (psi)
350000
300000
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
Frequency (Hz)
inl15fs1
inl15fs2
inl15fs3
inl15fs4
inl15fs5
inl15fs6

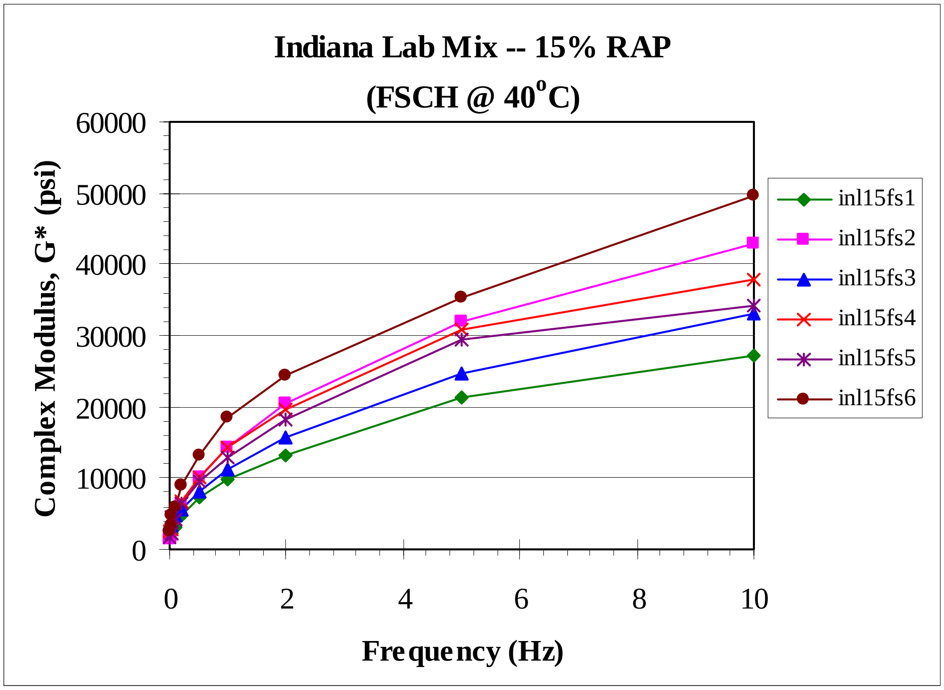

Indiana Lab Mix -- 50% RAP
(FSCH @ 20°C)
Complex Modulus, G* (psi)
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
inl50fs1
inl50fs2
inl50fs3
inl50fs4
inl50fs5
inl50fs6

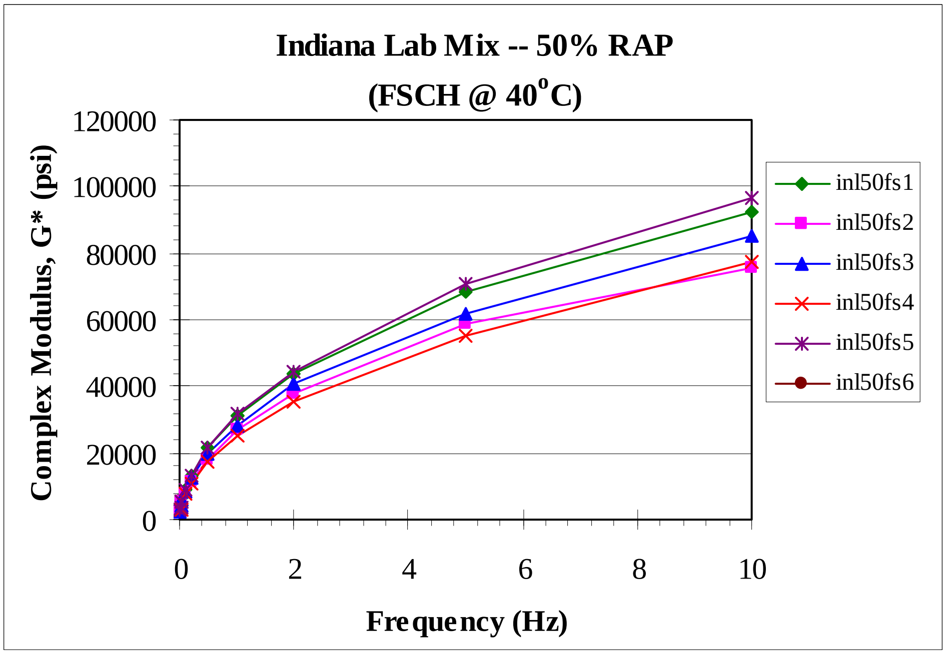


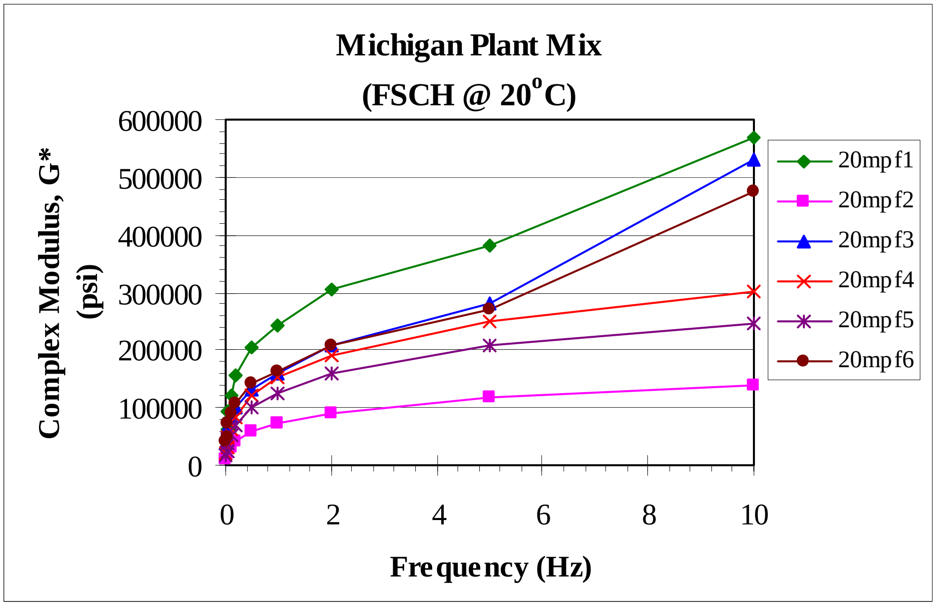
Indiana Plant Mix
(FSCH @ 40°C)
250000
200000
150000
100000
50000
0
Complex Modulus, G* (psi)
0
2
4
6
8
10
Frequency (Hz)
inpfs1
inpfs2
inpfs3
inpfs4
inpfs5
inpfs6

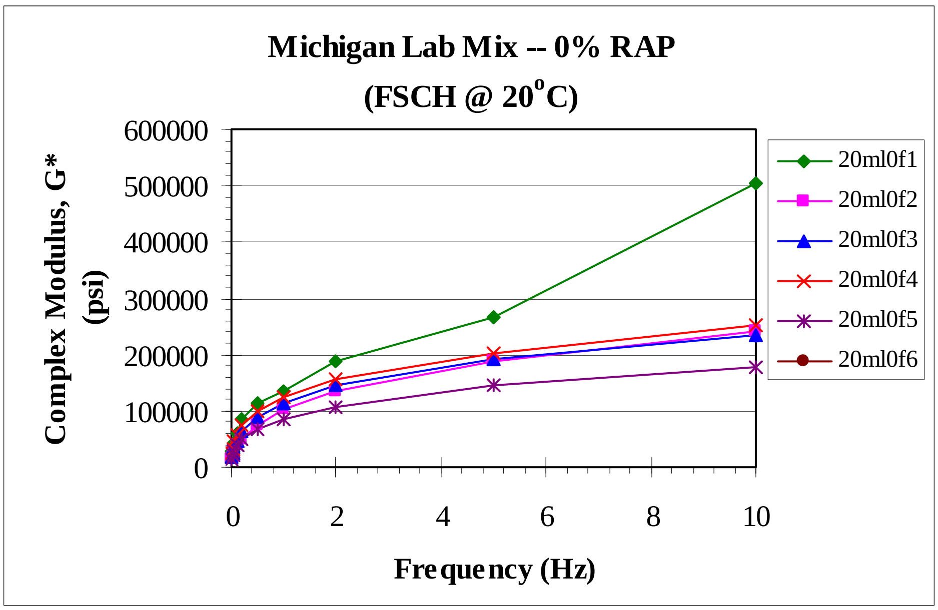


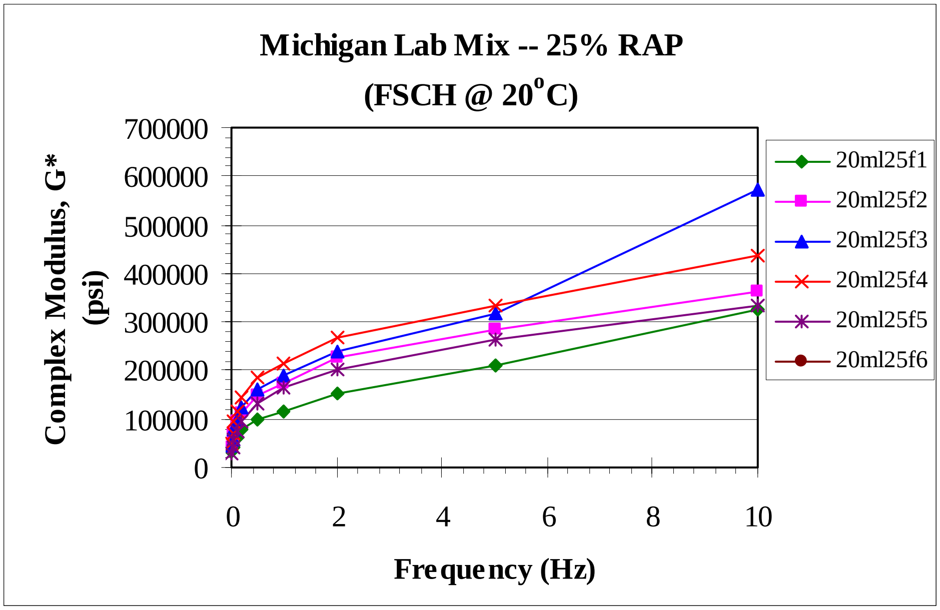
Indiana Lab Mix -- 0% RAP
(FSCH @ 40°C)
160000
140000
120000
100000
80000
60000
40000
20000
0
Complex Modulus, G* (psi)
0
2
4
6
8
10
Frequency (Hz)
inl0fs1
inl0fs2
inl0fs3
inl0fs4
inl0fs5
inl0fs6

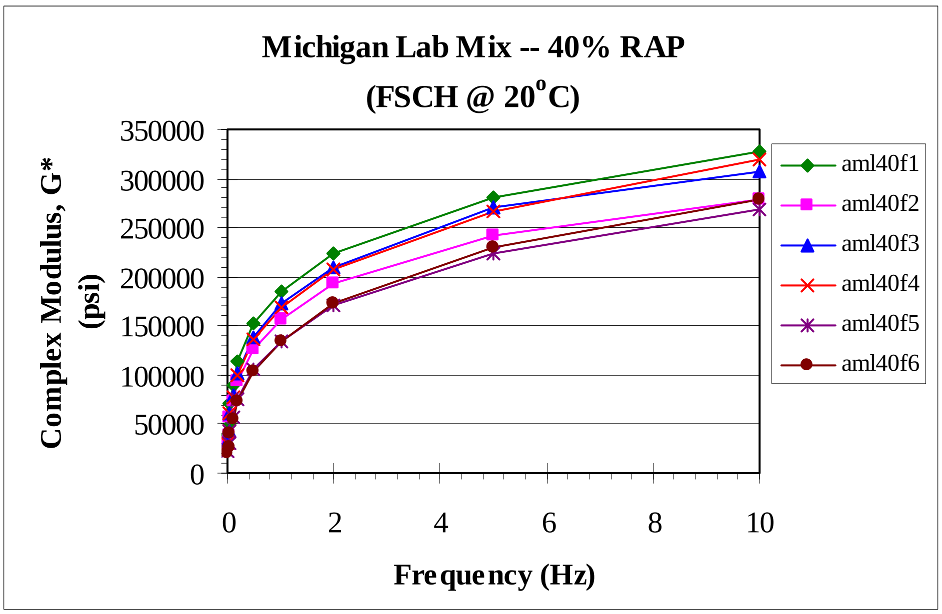

Indiana Lab Mix -- 15% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
Frequency (Hz)
0
10000
20000
30000
40000
50000
60000
0
2
4
6
8
10
inl15fs1
inl15fs2
inl15fs3
inl15fs4
inl15fs5
inl15fs6

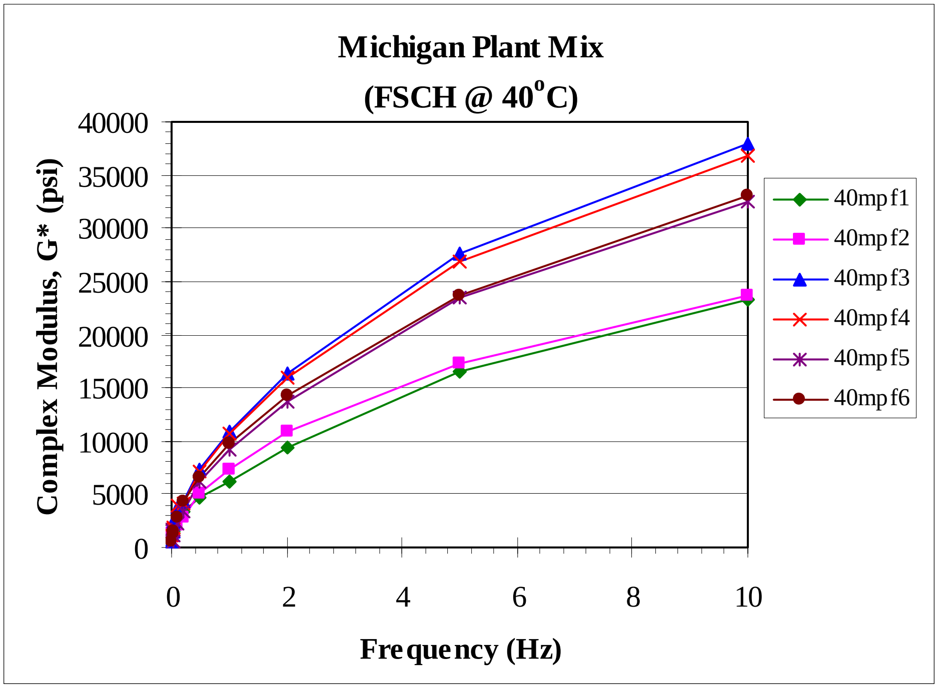

Indiana Lab Mix -- 50% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
Frequency (Hz)
0
20000
40000
60000
80000
100000
120000
0
2
4
6
8
10
inl50fs1
inl50fs2
inl50fs3
inl50fs4
inl50fs5
inl50fs6

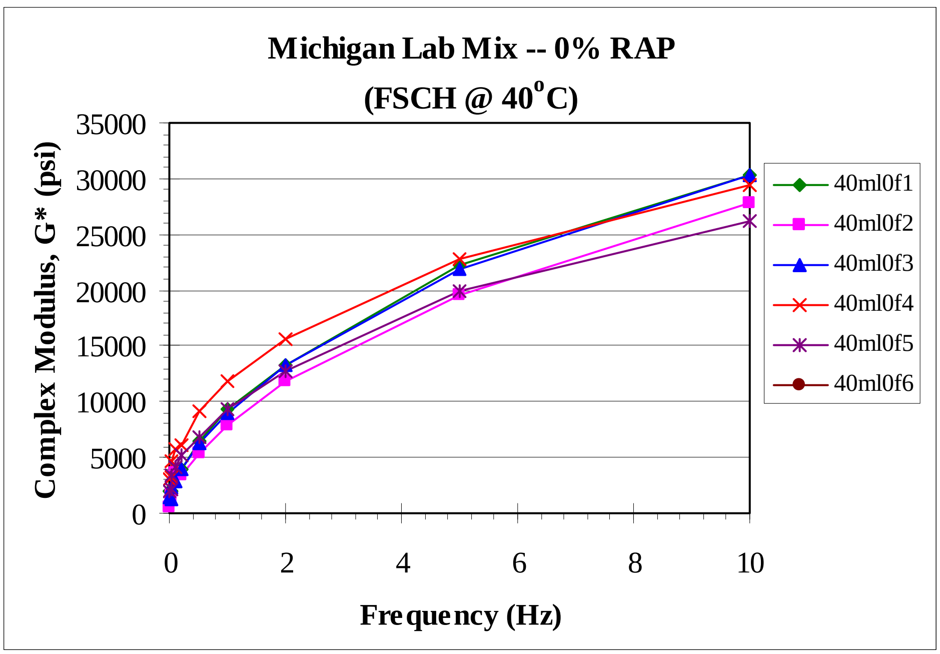

Michigan Plant Mix
(FSCH @ 20°C)
Complex Modulus, G* (psi)
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
20mpf1
20mpf2
20mpf3
20mpf4
20mpf5
20mpf6

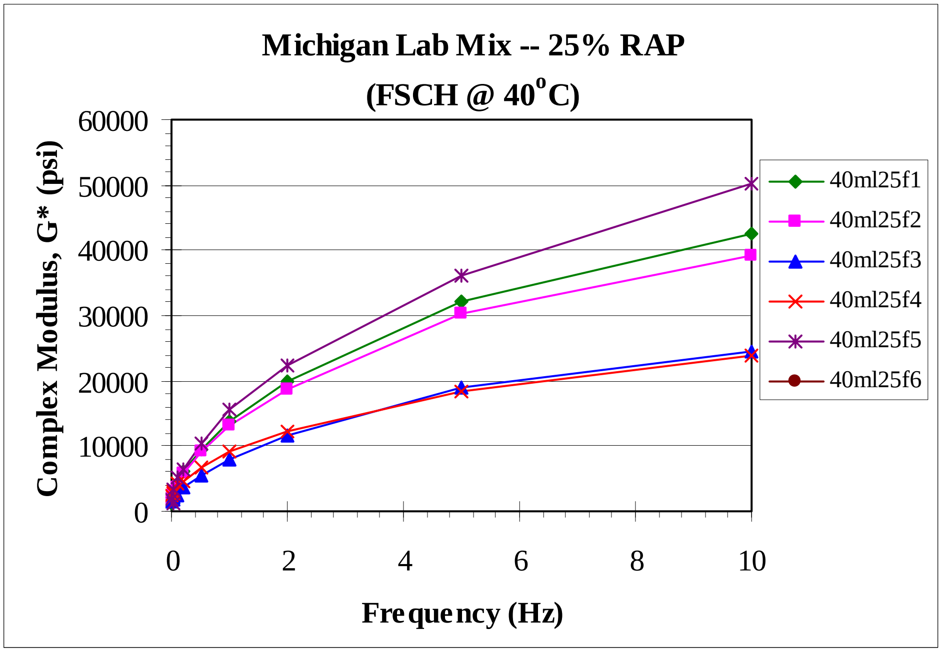

Michigan Lab Mix -- 0% RAP
(FSCH @ 20°C)
Complex Modulus, G* (psi)
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
20ml0f1
20ml0f2
20ml0f3
20ml0f4
20ml0f5
20ml0f6


Michigan Lab Mix -- 25% RAP
(FSCH @ 20°C)
Complex Modulus, G* (psi)
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
20ml25f1
20ml25f2
20ml25f3
20ml25f4
20ml25f5
20ml25f6

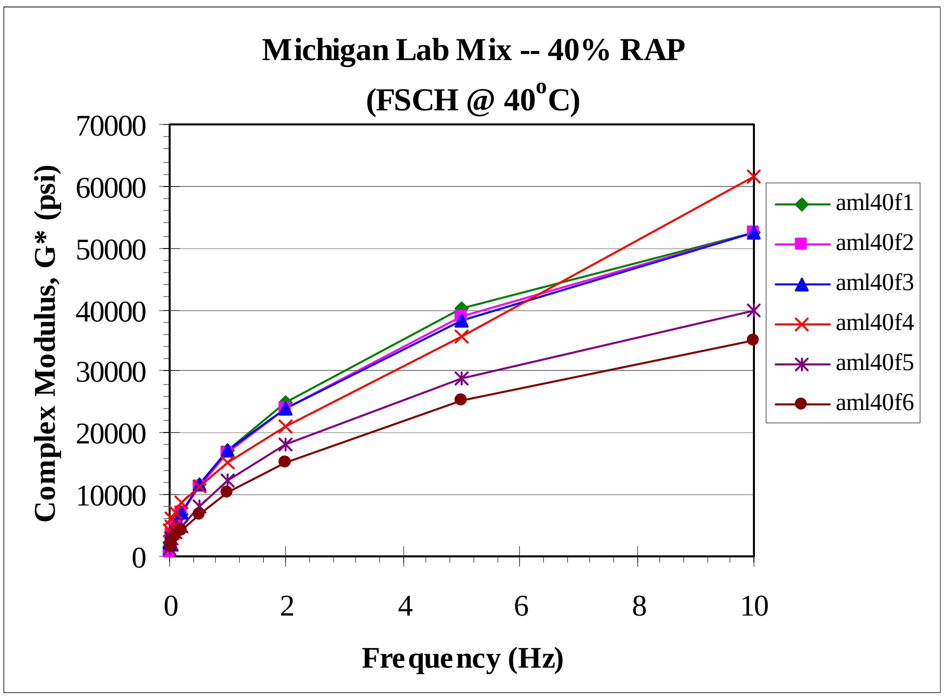

Michigan Lab Mix -- 40% RAP
(FSCH @ 20°C)
Complex Modulus, G* (psi)
350000
300000
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
Frequency (Hz)
aml40f1
aml40f2
aml40f3
aml40f4
aml40f5
aml40f6


Michigan Plant Mix
(FSCH @ 40°C)
Complex Modulus, G* (psi)
40000
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
Frequency (Hz)
40mpf1
40mpf2
40mpf3
40mpf4
40mpf5
40mpf6

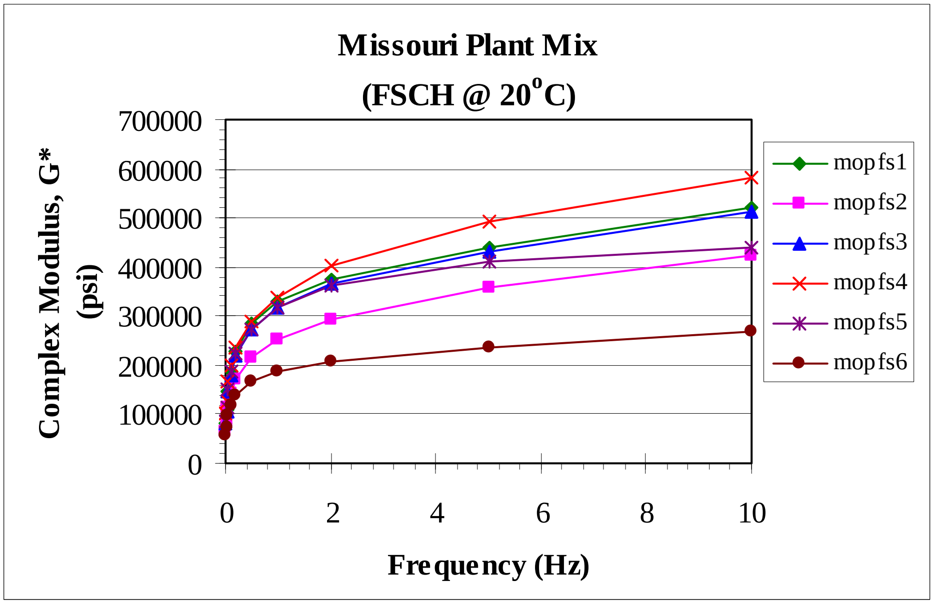

Michigan Lab Mix -- 0% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
Frequency (Hz)
40ml0f1
40ml0f2
40ml0f3
40ml0f4
40ml0f5
40ml0f6



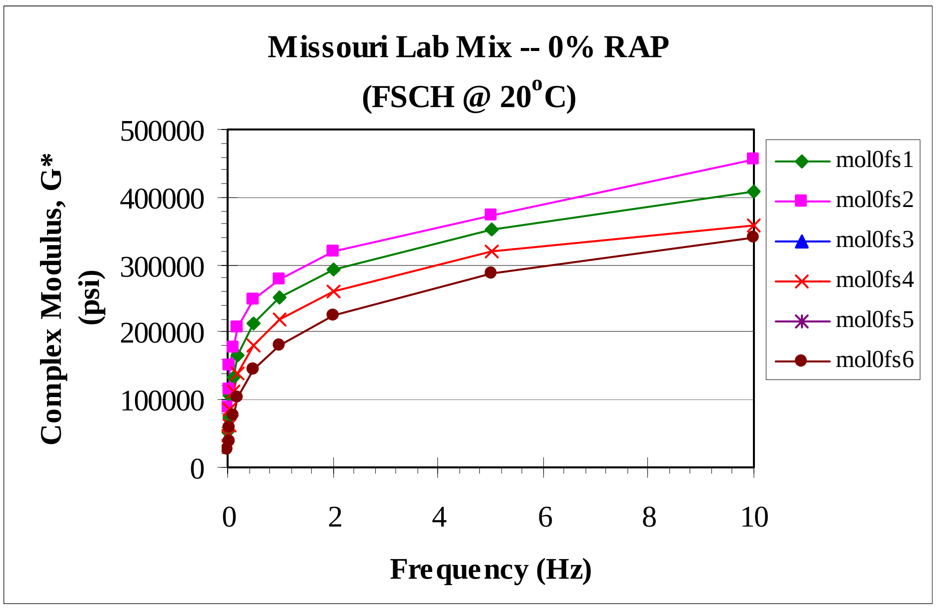
Michigan Lab Mix -- 25% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
60000
50000
40000
30000
20000
10000
0
0
2
4
6
8
10
Frequency (Hz)
40ml25f1
40ml25f2
40ml25f3
40ml25f4
40ml25f5
40ml25f6



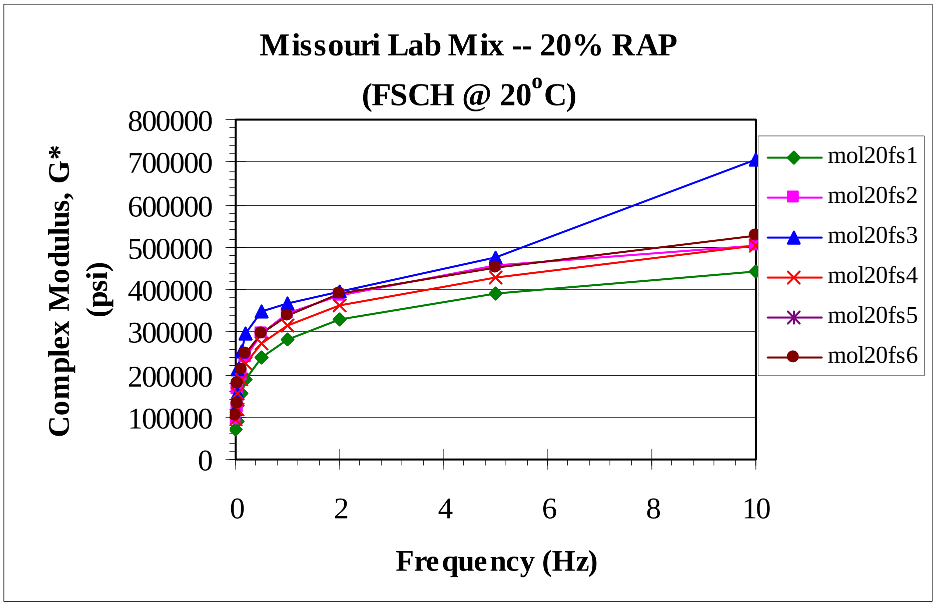
Michigan Lab Mix -- 40% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
70000
60000
50000
40000
30000
20000
10000
0
0
2
4
6
8
10
Frequency (Hz)
aml40f1
aml40f2
aml40f3
aml40f4
aml40f5
aml40f6

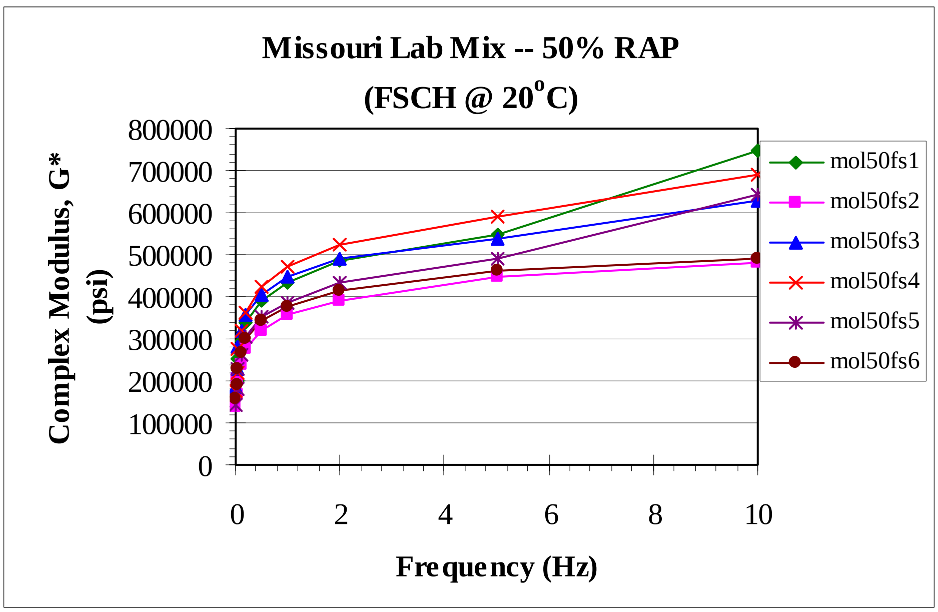


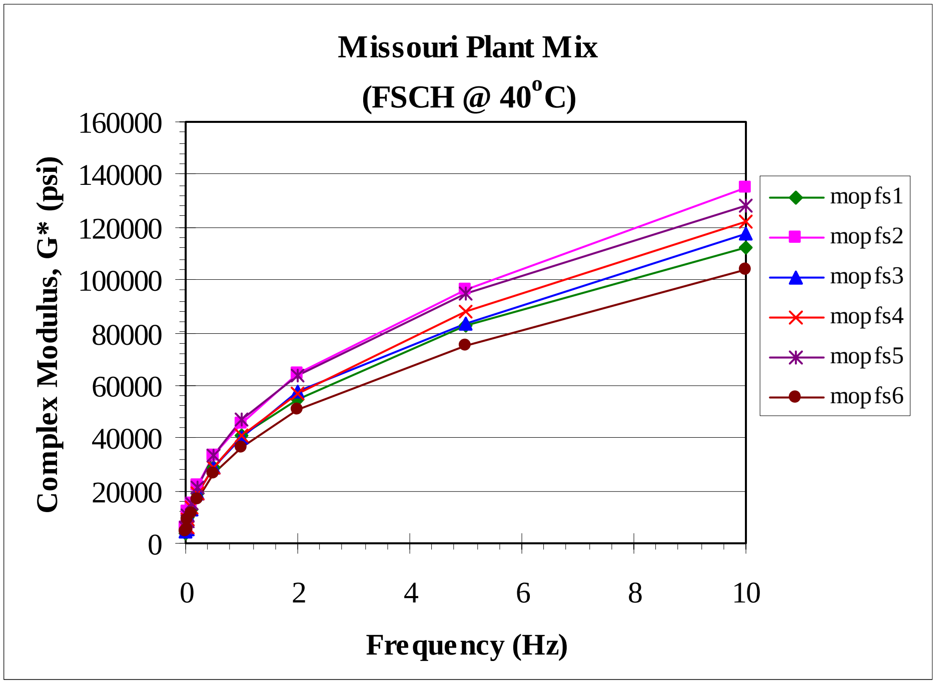
Missouri Plant Mix
(FSCH @ 20°C)
Complex Modulus, G*
(psi)
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
mopfs1
mopfs2
mopfs3
mopfs4
mopfs5
mopfs6

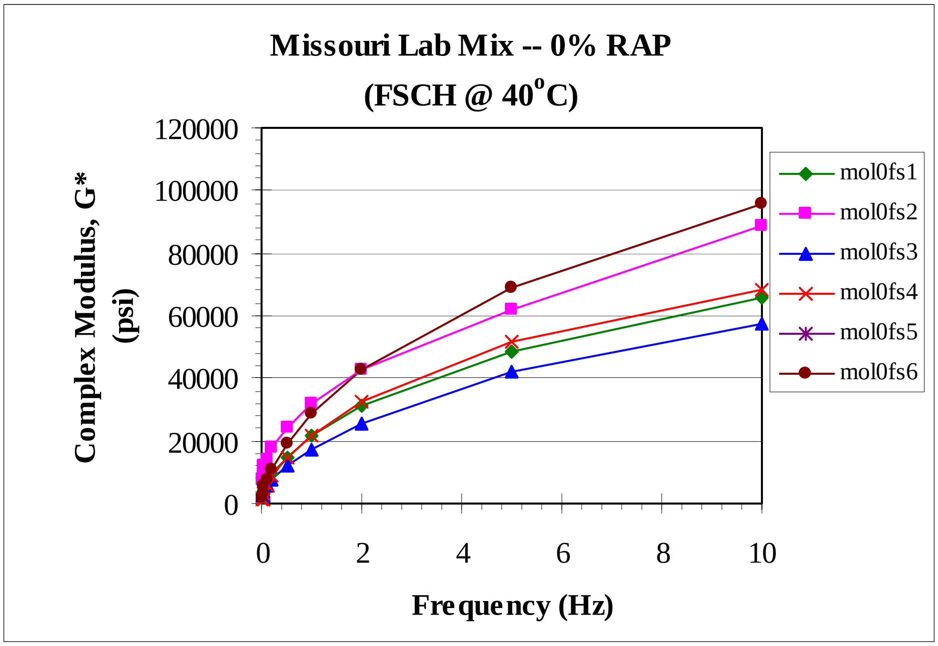


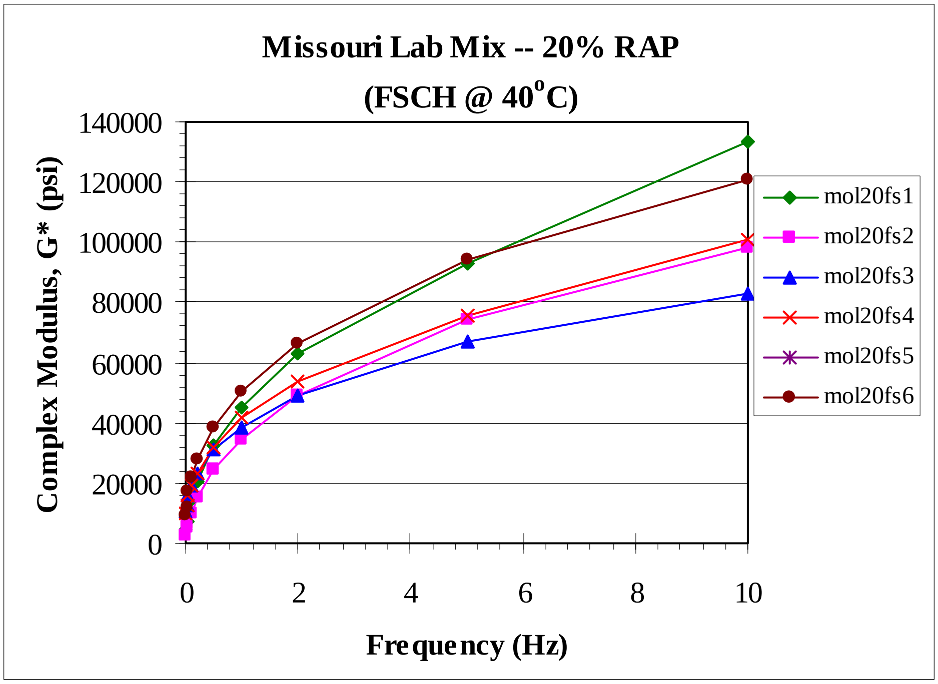
Missouri Lab Mix -- 0% RAP
(FSCH @ 20°C)
Complex Modulus, G*
(psi)
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
mol0fs1
mol0fs2
mol0fs3
mol0fs4
mol0fs5
mol0fs6


Missouri Lab Mix -- 20% RAP
(FSCH @ 20°C)
Complex Modulus, G*
(psi)
800000
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
mol20fs1
mol20fs2
mol20fs3
mol20fs4
mol20fs5
mol20fs6

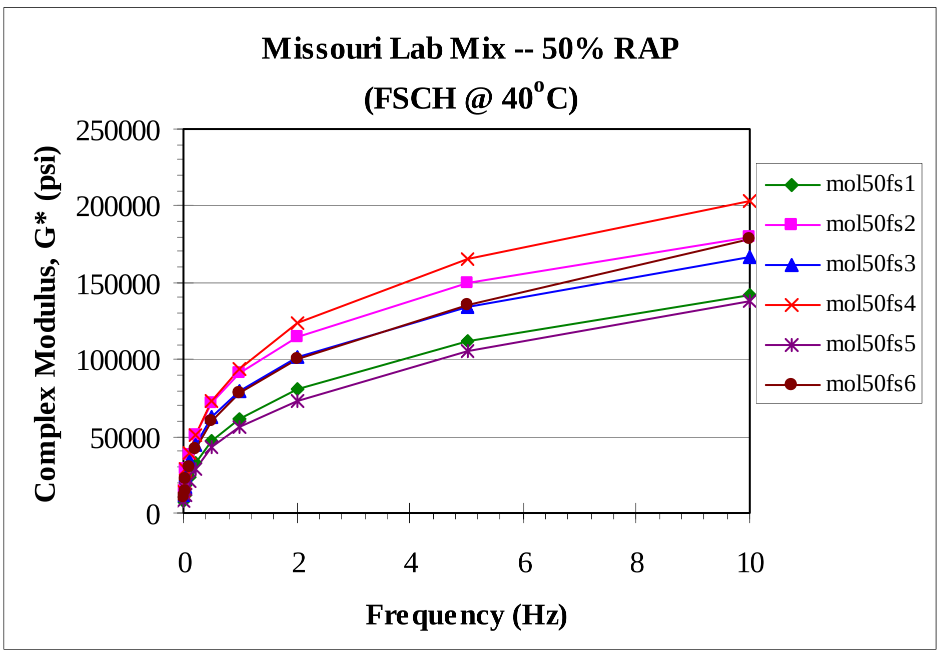

Missouri Lab Mix -- 50% RAP
(FSCH @ 20°C)
Complex Modulus, G*
(psi)
800000
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
Frequency (Hz)
mol50fs1
mol50fs2
mol50fs3
mol50fs4
mol50fs5
mol50fs6


Missouri Plant Mix
(FSCH @ 40°C)
Complex Modulus, G* (psi)
160000
140000
120000
100000
80000
60000
40000
20000
0
0
2
4
6
8
10
Frequency (Hz)
mopfs1
mopfs2
mopfs3
mopfs4
mopfs5
mopfs6


Missouri Lab Mix -- 0% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
120000
100000
80000
60000
40000
20000
0
0
2
4
6
8
10
Frequency (Hz)
mol0fs1
mol0fs2
mol0fs3
mol0fs4
mol0fs5
mol0fs6

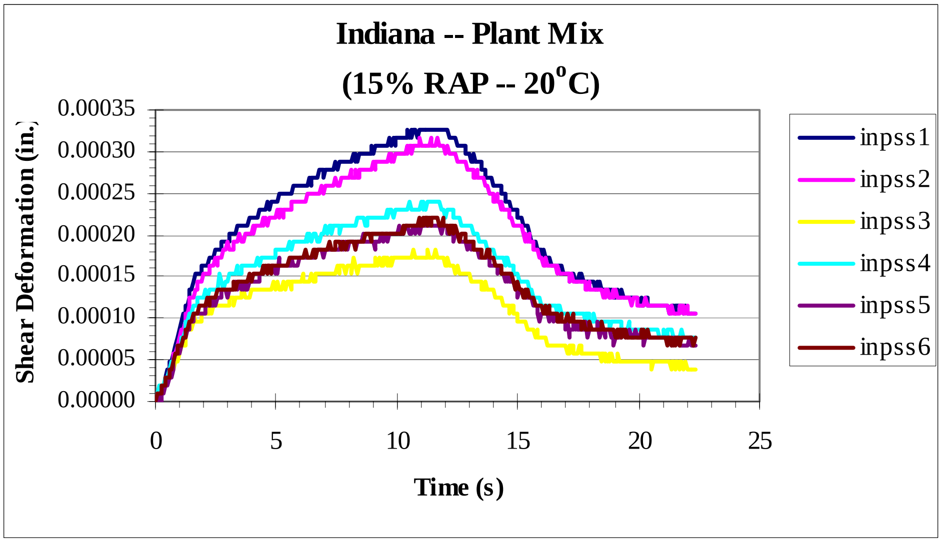


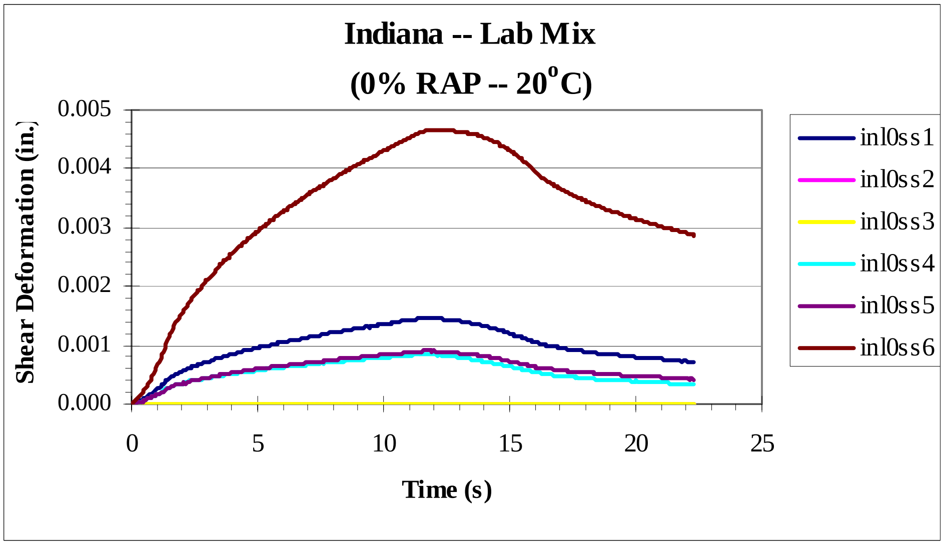
Missouri Lab Mix -- 20% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
140000
120000
100000
80000
60000
40000
20000
0
0
2
4
6
8
10
Frequency (Hz)
mol20fs1
mol20fs2
mol20fs3
mol20fs4
mol20fs5
mol20fs6

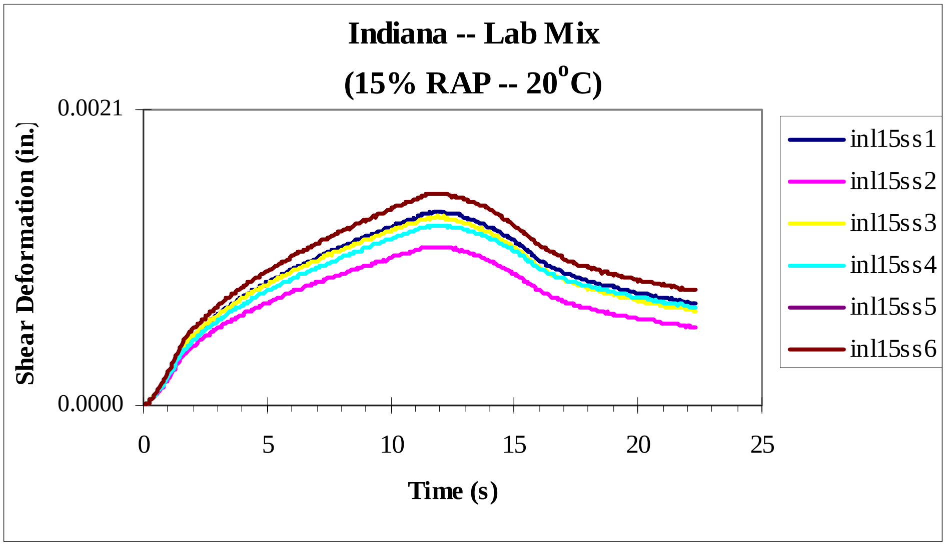


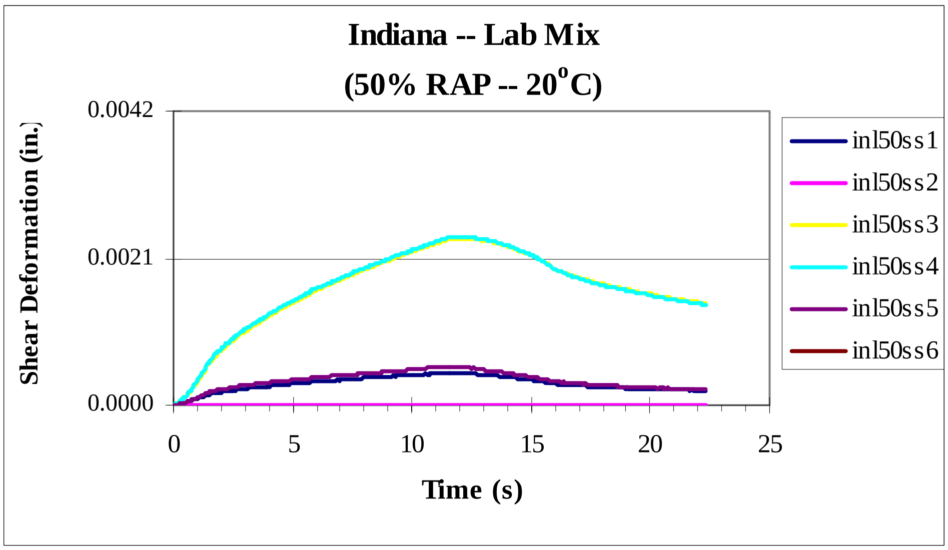
Missouri Lab Mix -- 50% RAP
(FSCH @ 40°C)
Complex Modulus, G* (psi)
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
Frequency (Hz)
mol50fs1
mol50fs2
mol50fs3
mol50fs4
mol50fs5
mol50fs6

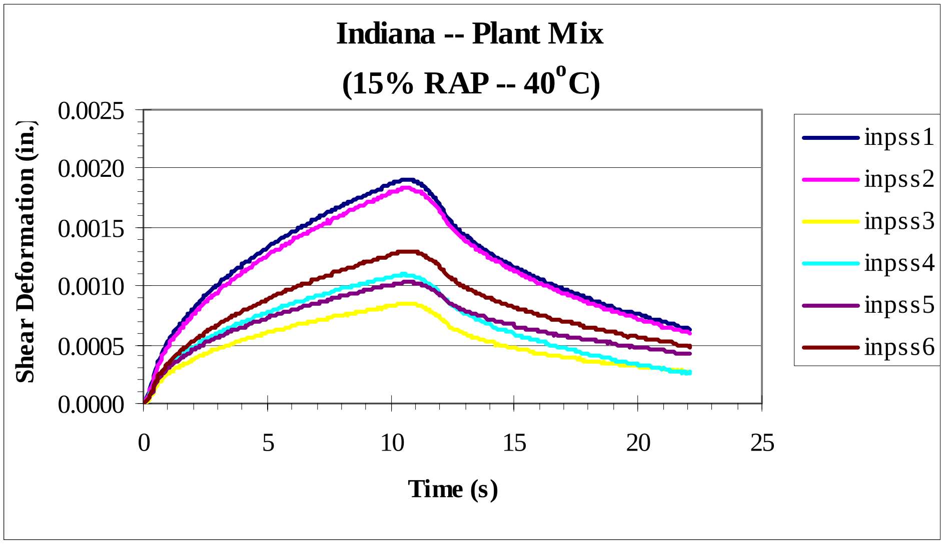
APPENDIX B – Simple Shear Results at 20 and 40°C

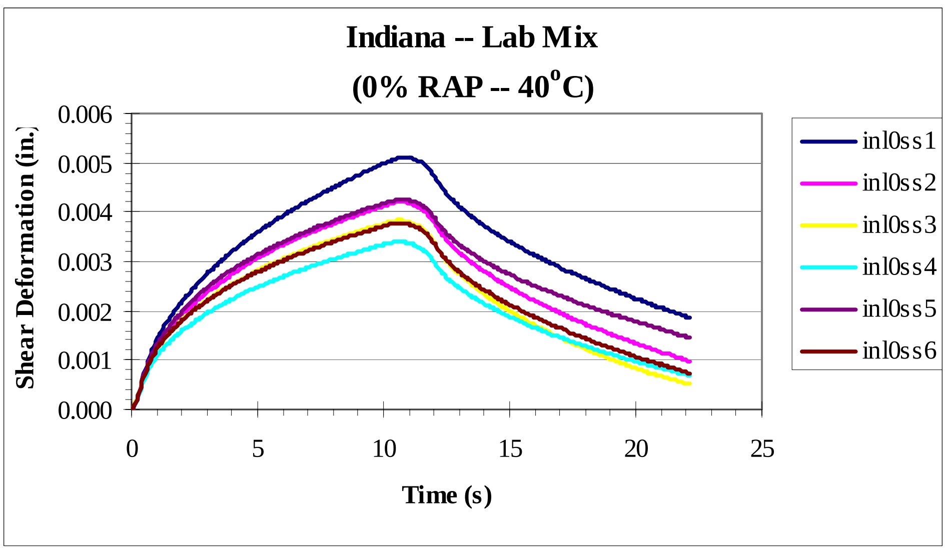


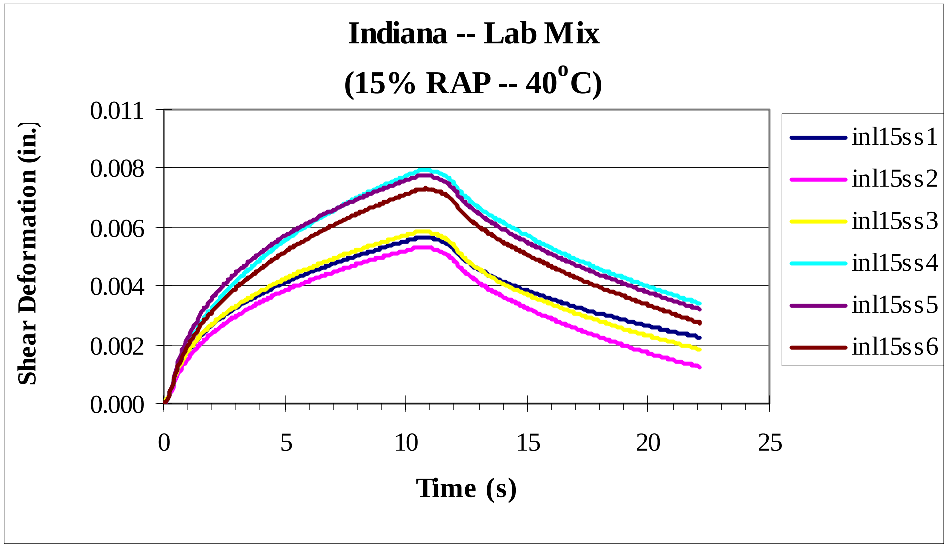


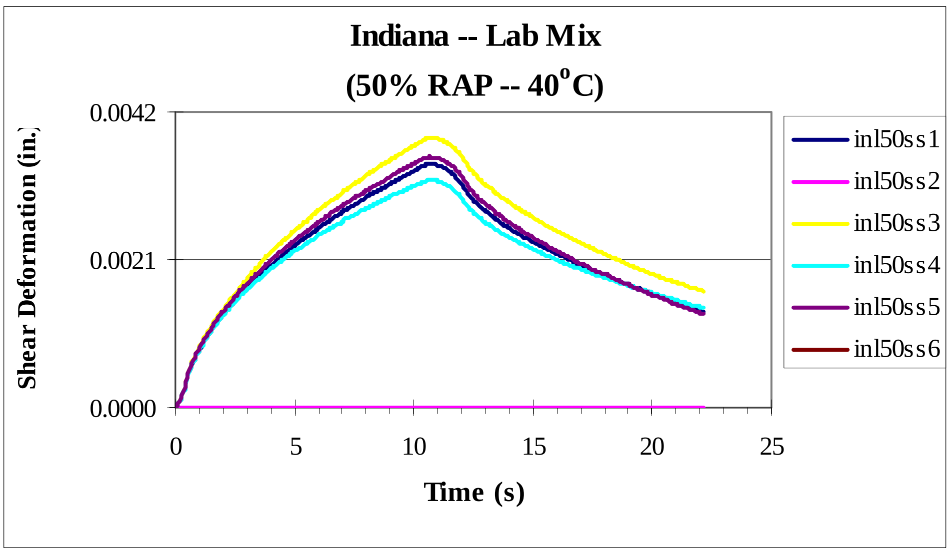

Indiana -- Lab Mix
(15% RAP -- 20°C)
Shear Deformation (in.)
0.0021
0.0000
0
5
10
15
20
25
Time (s)
inl15ss1
inl15ss2
inl15ss3
inl15ss4
inl15ss5
inl15ss6

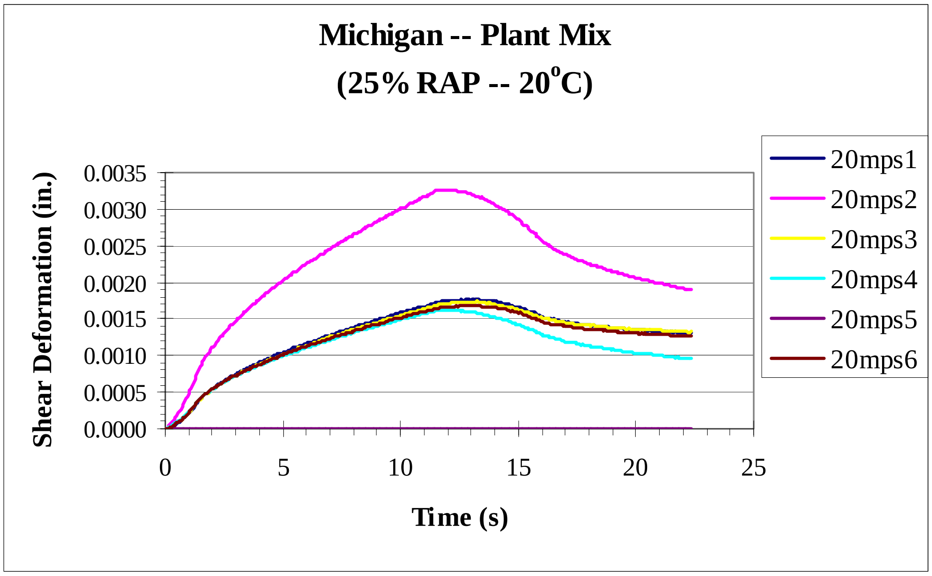

Indiana -- Lab Mix
(50% RAP -- 20°C)
Shear Deformation (in.)
0.0042
0.0021
0.0000
0
5
10
15
20
25
Time (s)
inl50ss1
inl50ss2
inl50ss3
inl50ss4
inl50ss5
inl50ss6

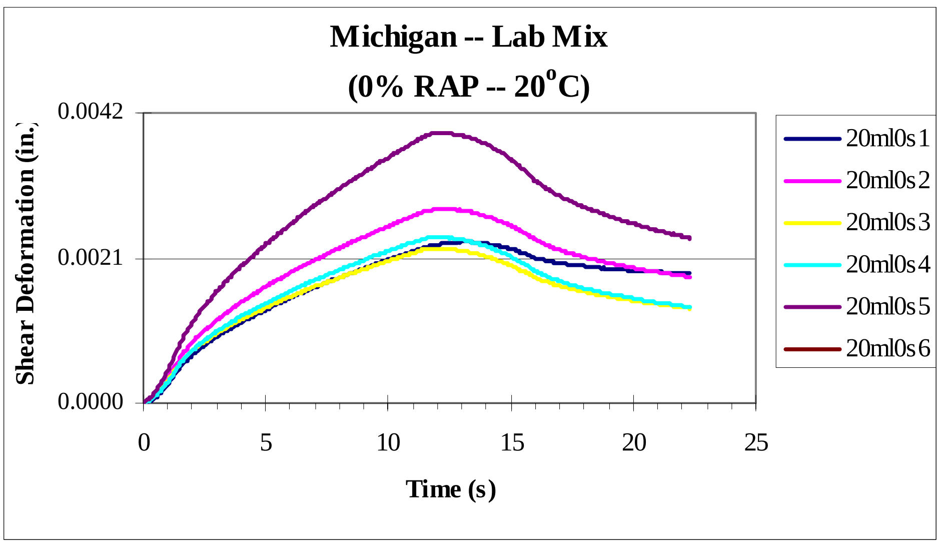

Indiana -- Plant Mix
(15% RAP -- 40°C)
Shear Deformation (in.)
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0
5
10
15
20
25
Time (s)
inpss1
inpss2
inpss3
inpss4
inpss5
inpss6

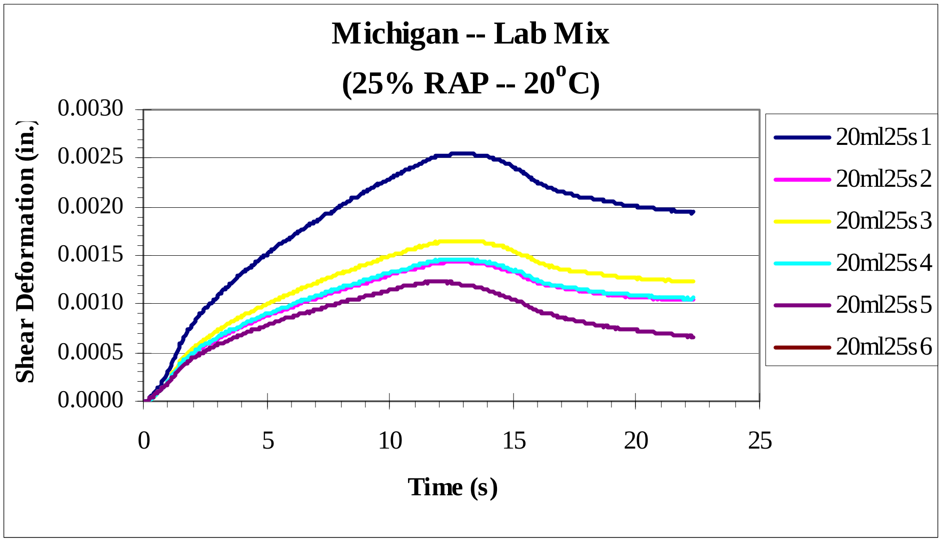

Indiana -- Lab Mix
(0% RAP -- 40°C)
Shear Deformation (in.)
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
5
10
15
20
25
Time (s)
inl0ss1
inl0ss2
inl0ss3
inl0ss4
inl0ss5
inl0ss6


Indiana -- Lab Mix
(15% RAP -- 40°C)
Shear Deformation (in.)
0.011
0.008
0.006
0.004
0.002
0.000
0
5
10
15
20
25
Time (s)
inl15ss1
inl15ss2
inl15ss3
inl15ss4
inl15ss5
inl15ss6

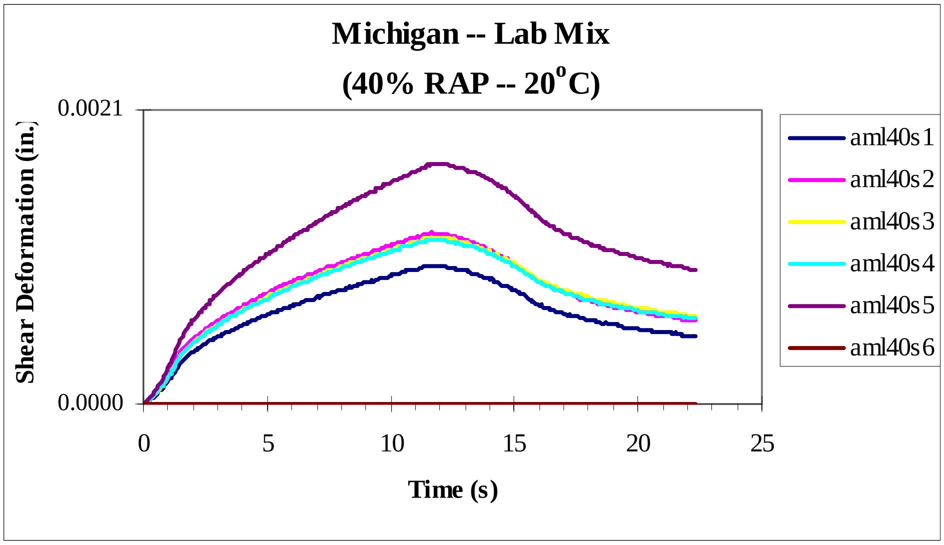

Indiana -- Lab Mix
(50% RAP -- 40°C)
Shear Deformation (in.)
0.0042
0.0021
0.0000
0
5
10
15
20
25
Time (s)
inl50ss1
inl50ss2
inl50ss3
inl50ss4
inl50ss5
inl50ss6


Michigan -- Plant Mix
(25% RAP -- 20°C)
Shear Deformation (in.)
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0
5
10
15
20
25
Time (s)
20mps1
20mps2
20mps3
20mps4
20mps5
20mps6

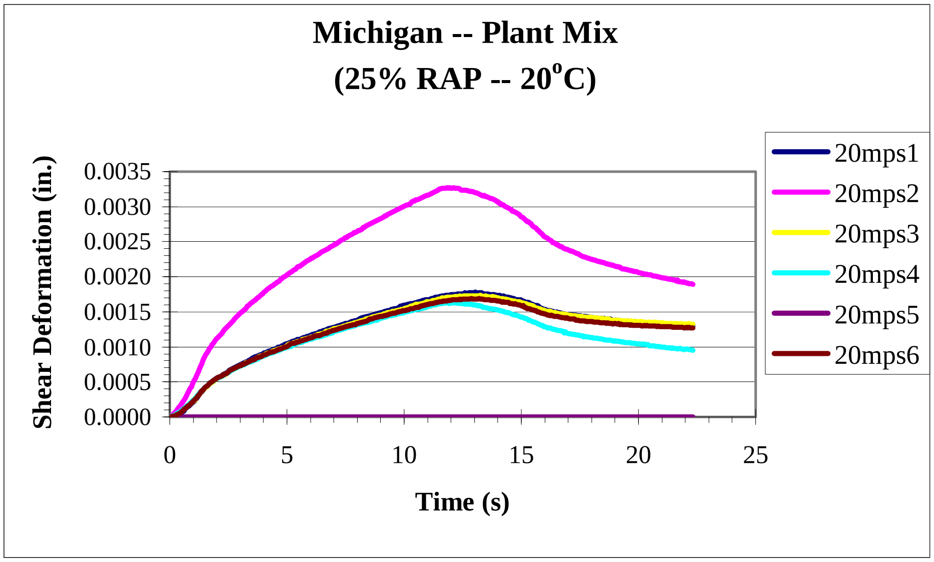

Michigan -- Lab Mix
(0% RAP -- 20°C)
Shear Deformation (in.)
0.0042
0.0021
0.0000
0
5
10
15
20
25
Time (s)
20ml0s1
20ml0s2
20ml0s3
20ml0s4
20ml0s5
20ml0s6



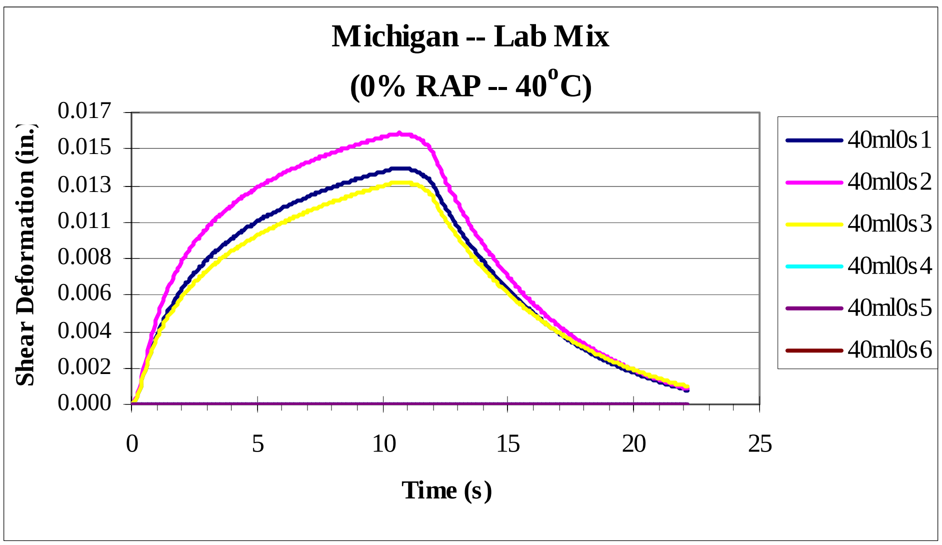
Michigan -- Lab Mix
(25% RAP -- 20°C)
Shear Deformation (in.)
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0
5
10
15
20
25
Time (s)
20ml25s1
20ml25s2
20ml25s3
20ml25s4
20ml25s5
20ml25s6



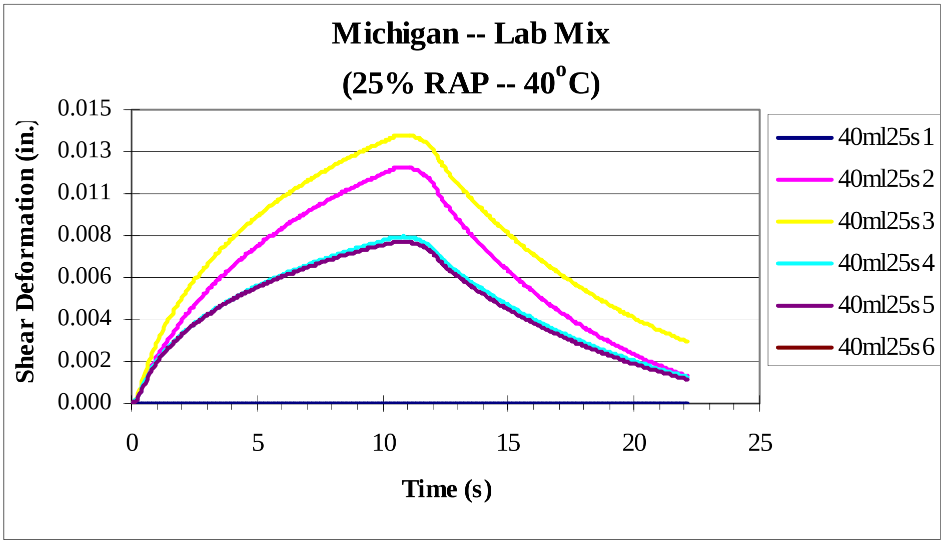
Michigan -- Lab Mix
(40% RAP -- 20°C)
Shear Deformation (in.)
0.0021
0.0000
0
5
10
15
20
25
Time (s)
aml40s1
aml40s2
aml40s3
aml40s4
aml40s5
aml40s6

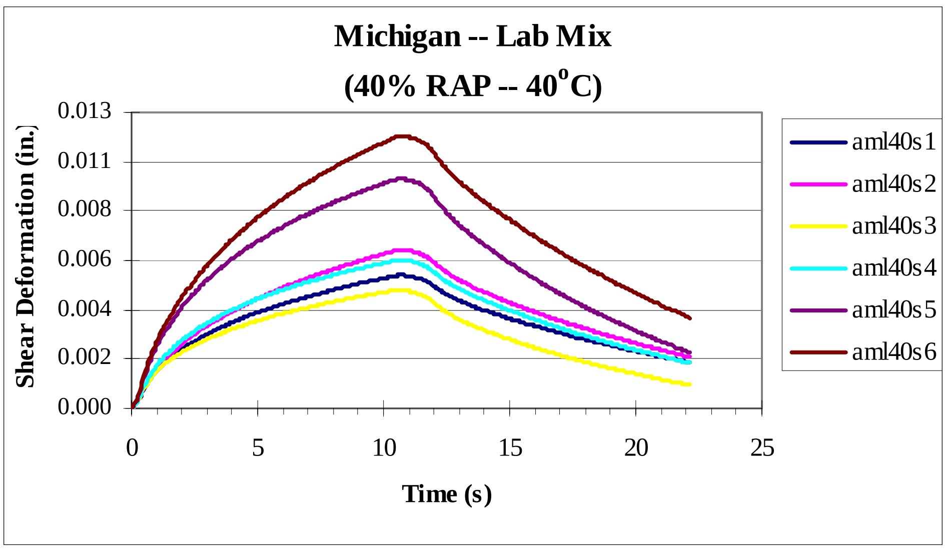


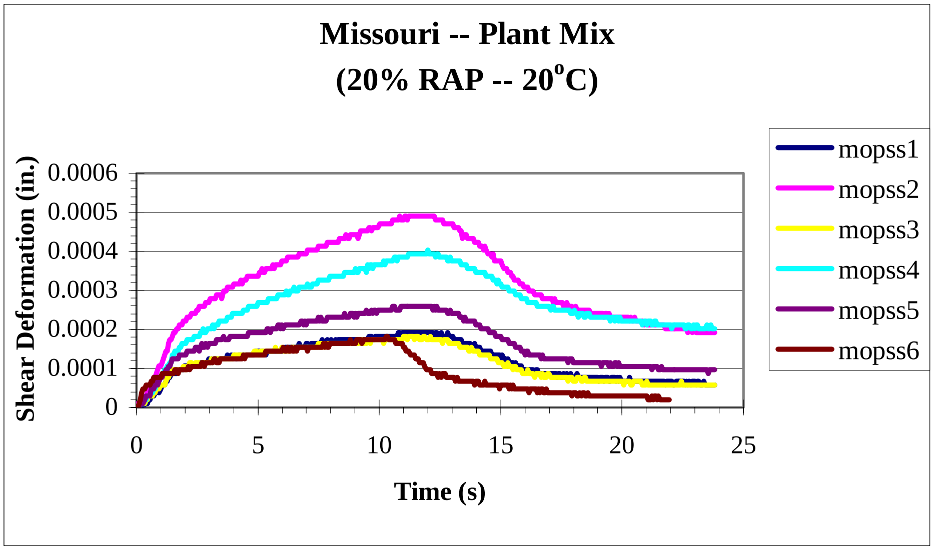
Michigan -- Plant Mix
(25% RAP -- 20°C)
Shear Deformation (in.)
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0
5
10
15
20
25
Time (s)
20mps1
20mps2
20mps3
20mps4
20mps5
20mps6



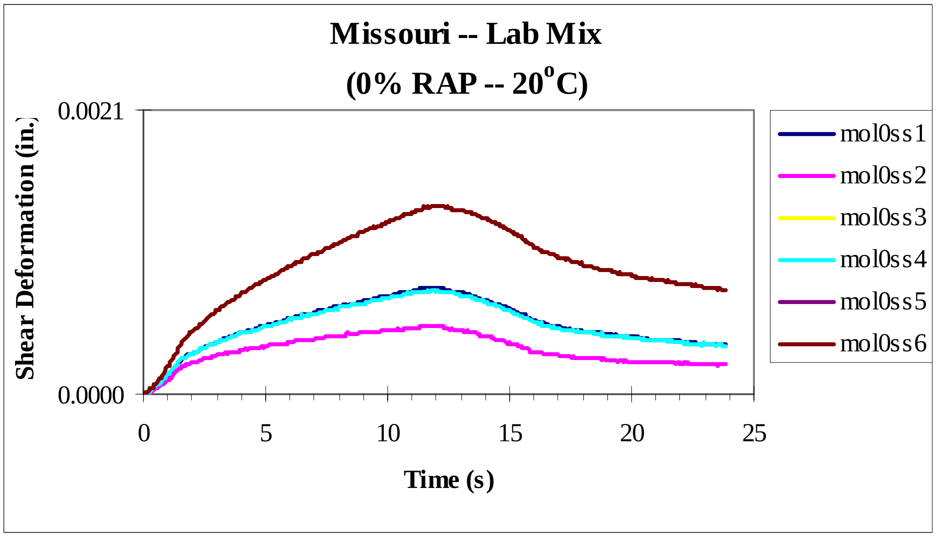
Michigan -- Lab Mix
(0% RAP -- 40°C)
Shear Deformation (in.)
0.017
0.015
0.013
0.011
0.008
0.006
0.004
0.002
0.000
0
5
10
15
20
25
Time (s)
40ml0s1
40ml0s2
40ml0s3
40ml0s4
40ml0s5
40ml0s6


Michigan -- Lab Mix
(25% RAP -- 40°C)
Shear Deformation (in.)
0.015
0.013
0.011
0.008
0.006
0.004
0.002
0.000
0
5
10
15
20
25
Time (s)
40ml25s1
40ml25s2
40ml25s3
40ml25s4
40ml25s5
40ml25s6

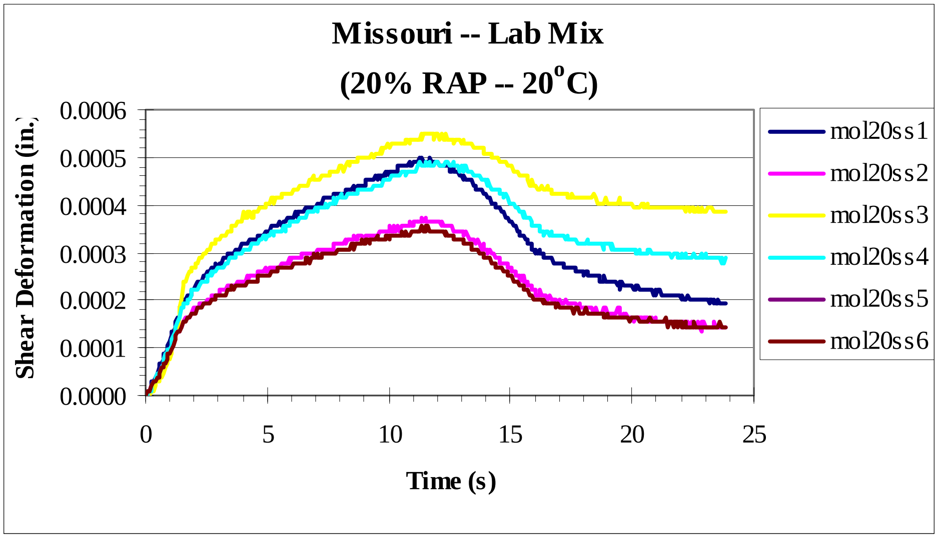

Michigan -- Lab Mix
(40% RAP -- 40°C)
Shear Deformation (in.)
0.013
0.011
0.008
0.006
0.004
0.002
0.000
0
5
10
15
20
25
Time (s)
aml40s1
aml40s2
aml40s3
aml40s4
aml40s5
aml40s6

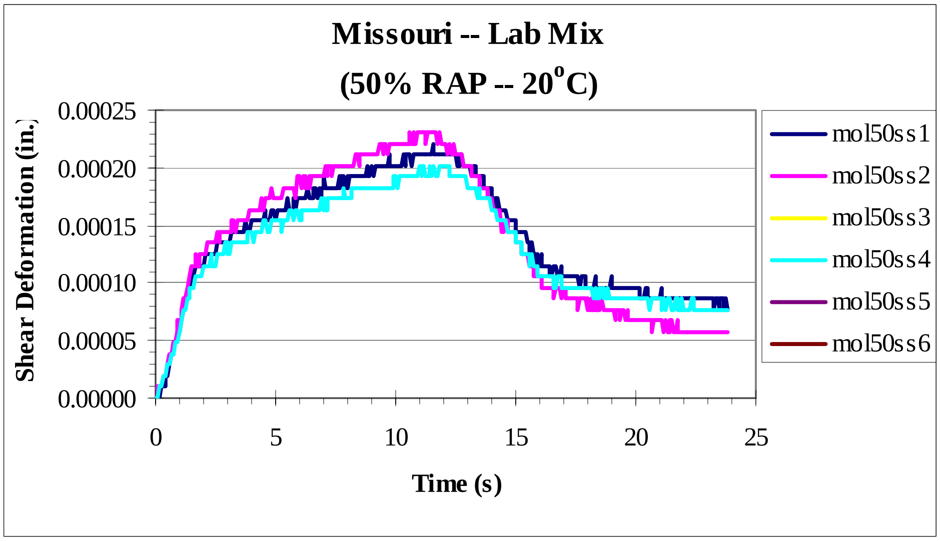


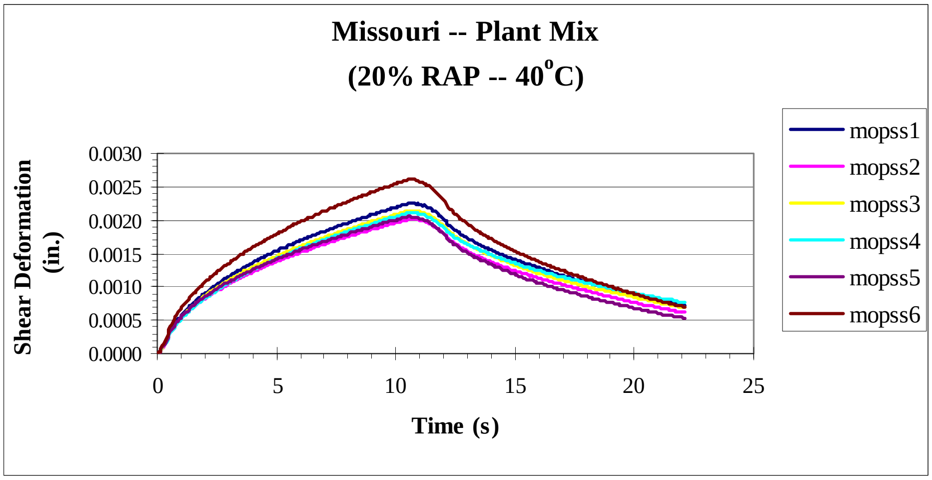
Missouri -- Plant Mix
(20% RAP -- 20°C)
Shear Deformation (in.)
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
5
10
15
20
25
Time (s)
mopss1
mopss2
mopss3
mopss4
mopss5
mopss6

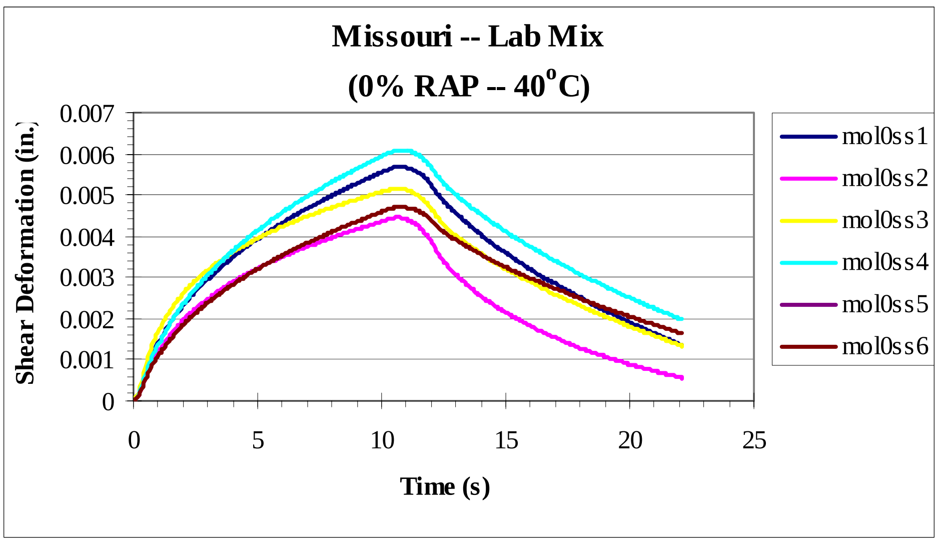


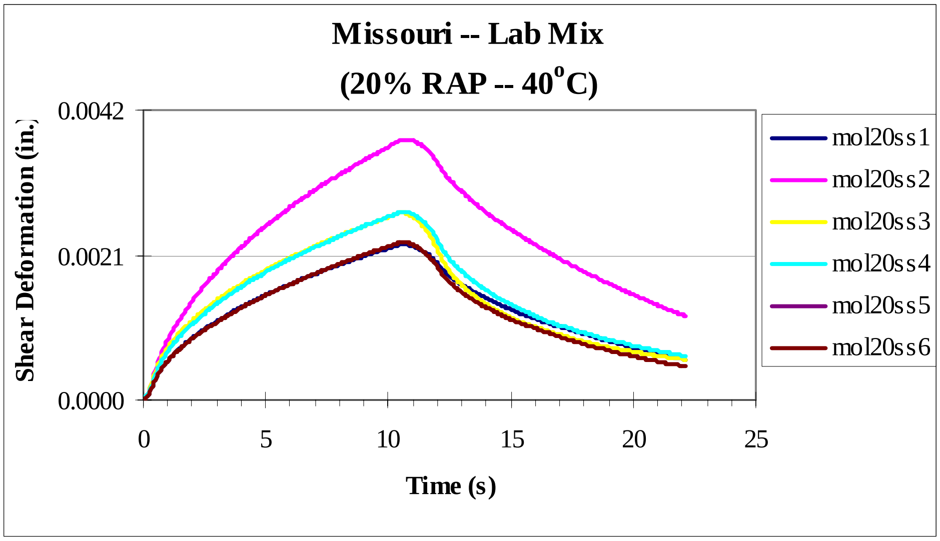
Missouri -- Lab Mix
(0% RAP -- 20°C)
Shear Deformation (in.)
0.0021
0.0000
0
5
10
15
20
25
Time (s)
mol0ss1
mol0ss2
mol0ss3
mol0ss4
mol0ss5
mol0ss6

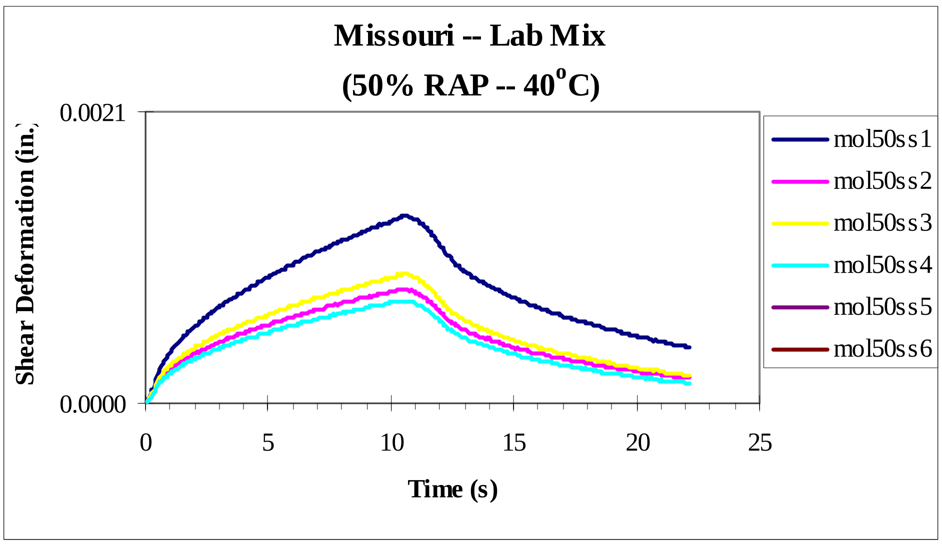

Missouri -- Lab Mix
(20% RAP -- 20°C)
Shear Deformation (in.)
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
0
5
10
15
20
25
Time (s)
mol20ss1
mol20ss2
mol20ss3
mol20ss4
mol20ss5
mol20ss6


Missouri -- Lab Mix
(50% RAP -- 20°C)
Shear Deformation (in.)
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
0
5
10
15
20
25
Time (s)
mol50ss1
mol50ss2
mol50ss3
mol50ss4
mol50ss5
mol50ss6

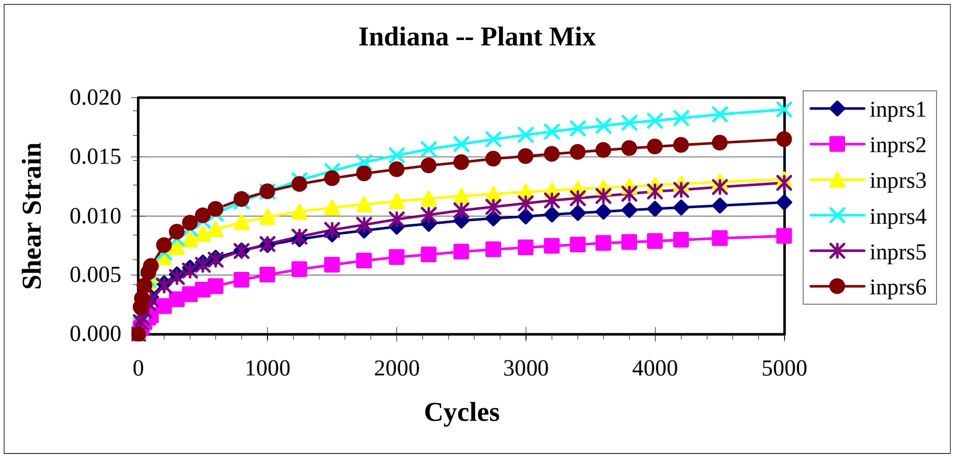

Missouri -- Plant Mix
(20% RAP -- 40°C)
Shear Deformation (in.)
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0
5
10
15
20
25
Time (s)
mopss1
mopss2
mopss3
mopss4
mopss5
mopss6

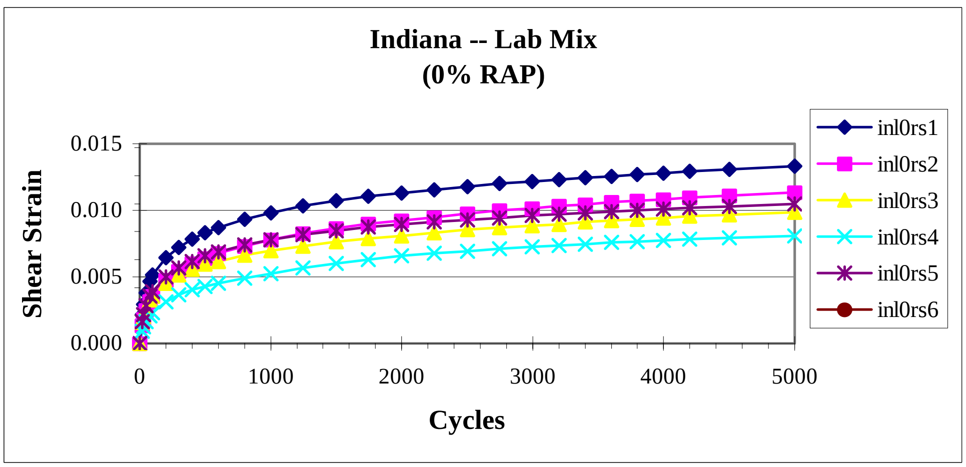

Missouri -- Lab Mix
(0% RAP -- 40°C)
Shear Deformation (in.)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
5
10
15
20
25
Time (s)
mol0ss1
mol0ss2
mol0ss3
mol0ss4
mol0ss5
mol0ss6

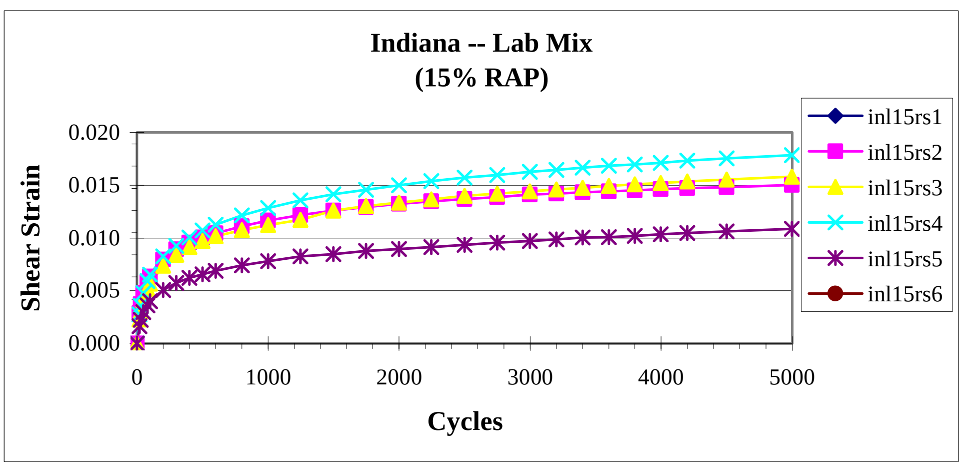

Missouri -- Lab Mix
(20% RAP -- 40°C)
Shear Deformation (in.)
0.0042
0.0021
0.0000
0
5
10
15
20
25
Time (s)
mol20ss1
mol20ss2
mol20ss3
mol20ss4
mol20ss5
mol20ss6

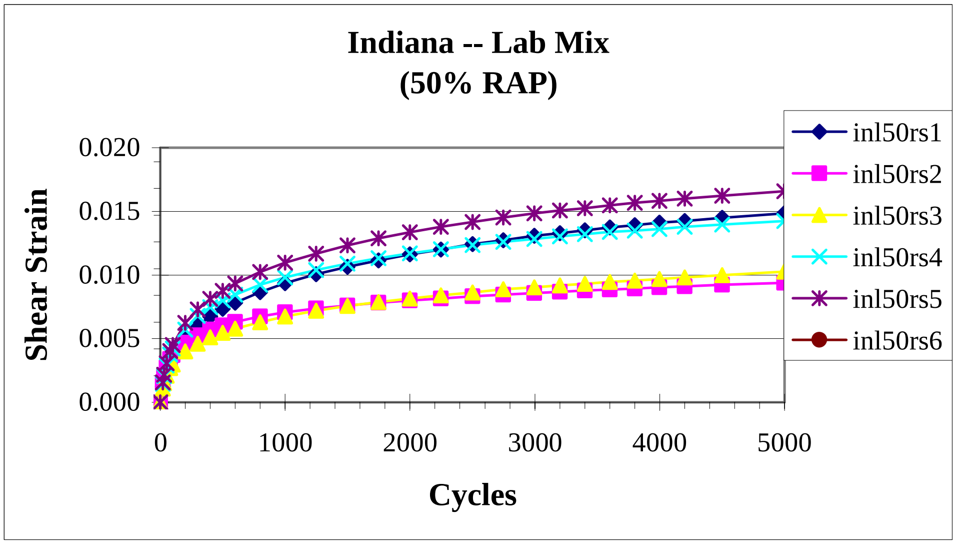

Missouri -- Lab Mix
(50% RAP -- 40°C)
Shear Deformation (in.)
0.0021
0.0000
0
5
10
15
20
25
Time (s)
mol50ss1
mol50ss2
mol50ss3
mol50ss4
mol50ss5
mol50ss6

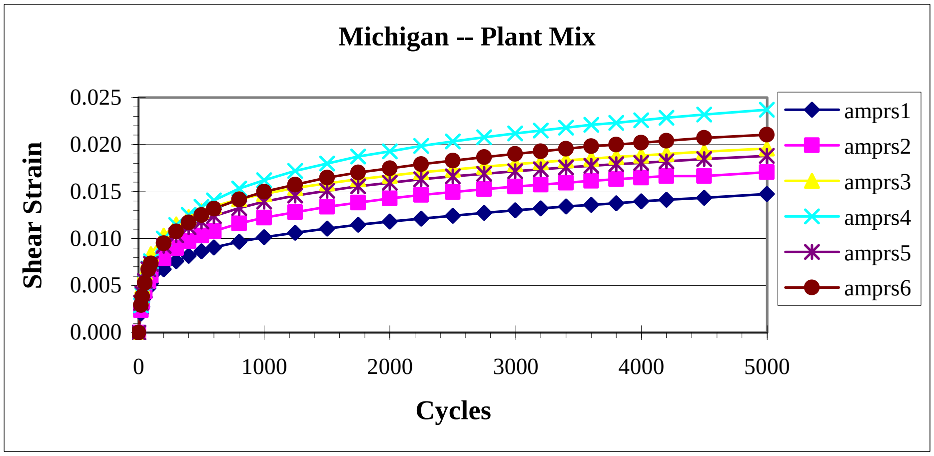
APPENDIX C – Repeated Shear Results at 58°C

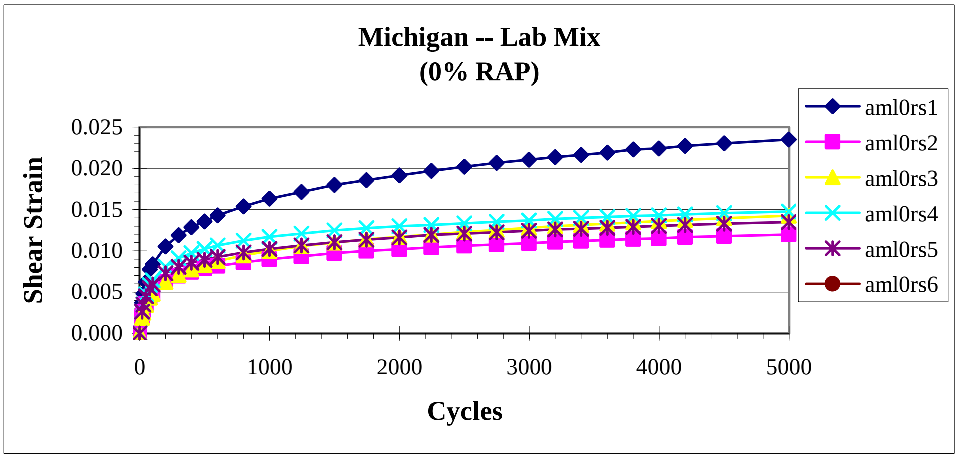


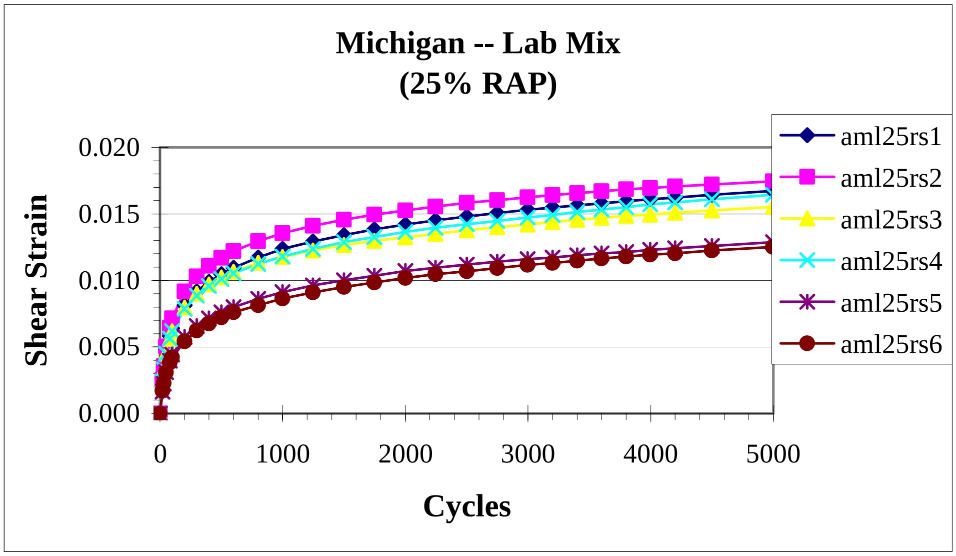




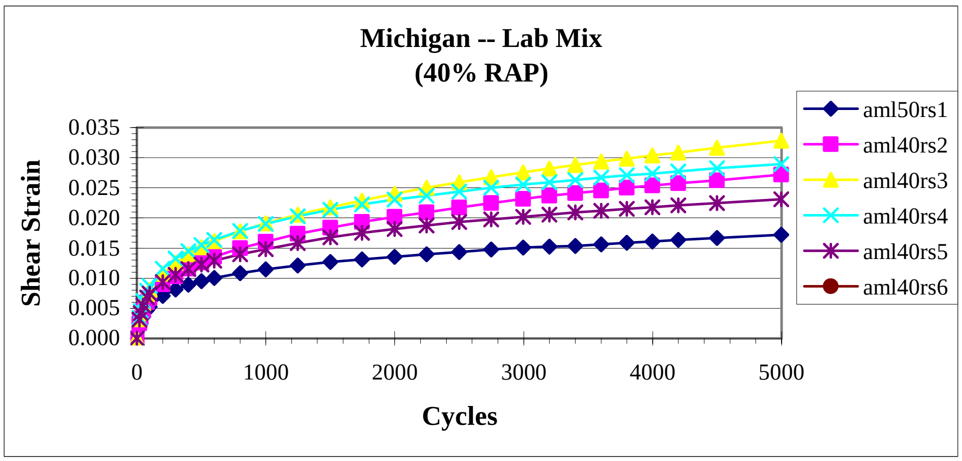

Indiana -- Lab Mix
(50% RAP)
Shear Strain
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
Cycles
inl50rs1
inl50rs2
inl50rs3
inl50rs4
inl50rs5
inl50rs6


Michigan -- Plant Mix
Shear Strain
0.025
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
Cycles
amprs1
amprs2
amprs3
amprs4
amprs5
amprs6

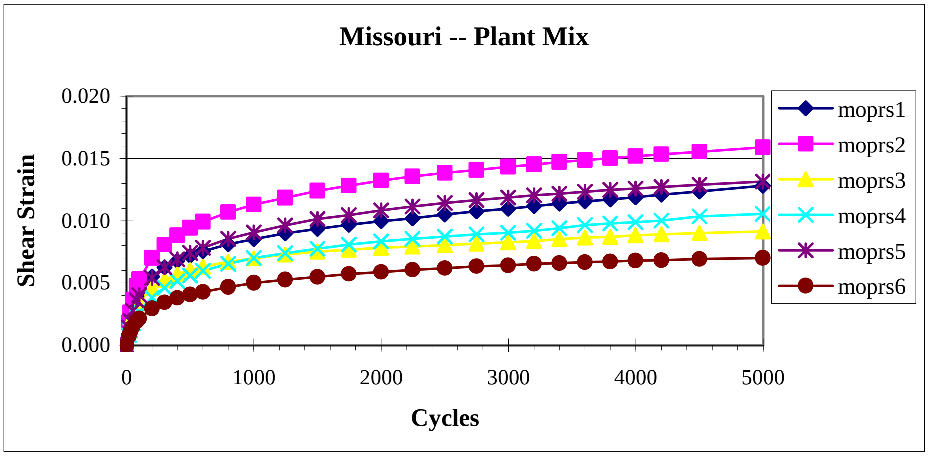

Michigan -- Lab Mix
(0% RAP)
Shear Strain
0.025
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
Cycles
aml0rs1
aml0rs2
aml0rs3
aml0rs4
aml0rs5
aml0rs6

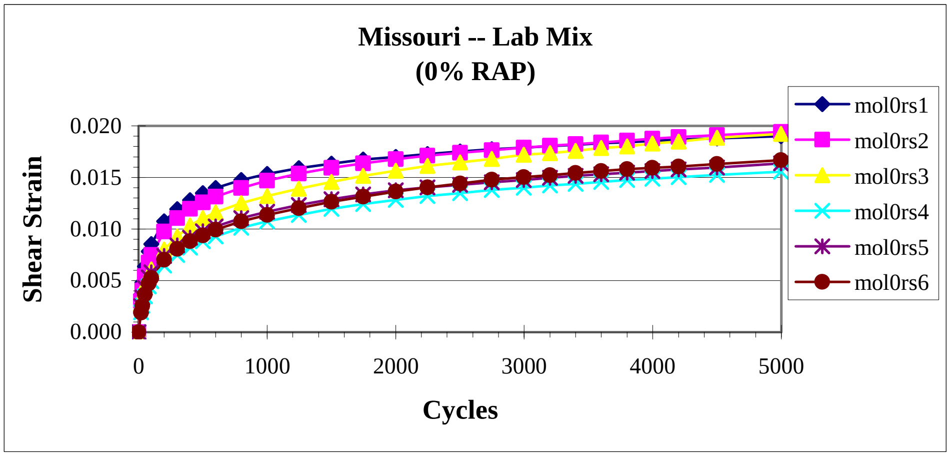


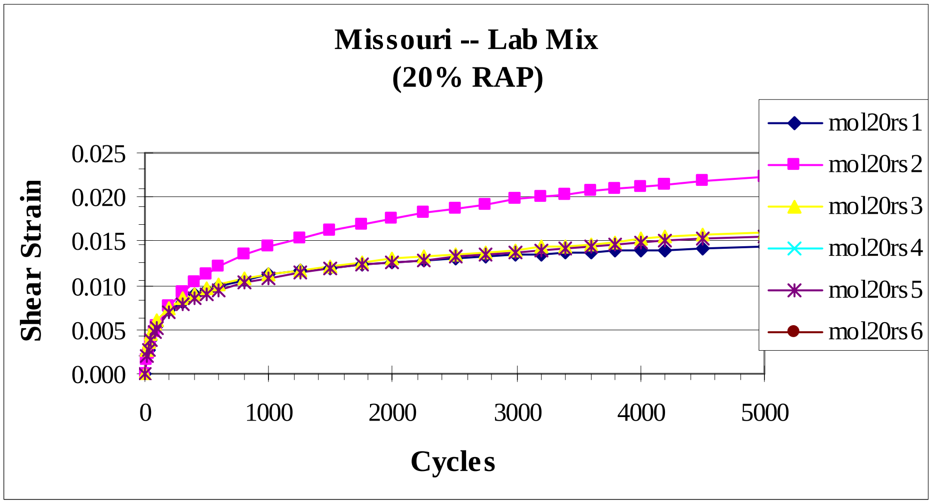
Michigan -- Lab Mix
(25% RAP)
Shear Strain
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
Cycles
aml25rs1
aml25rs2
aml25rs3
aml25rs4
aml25rs5
aml25rs6

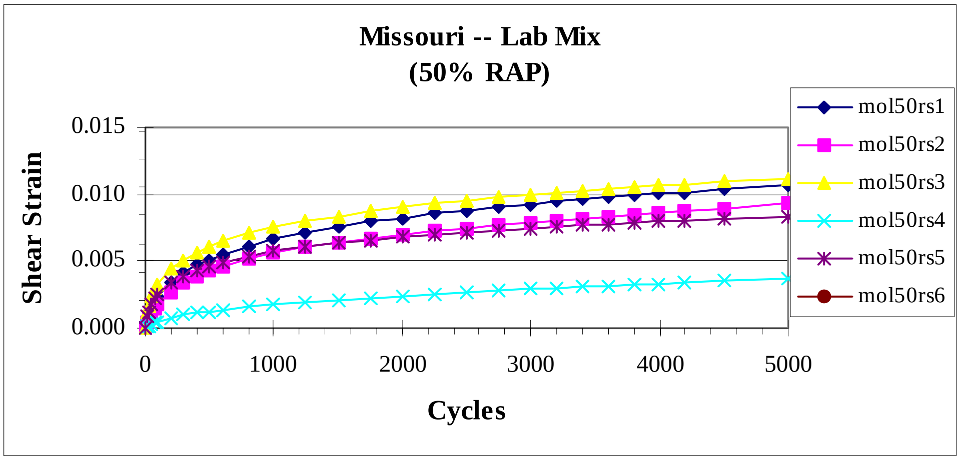


Michigan -- Lab Mix
(40% RAP)
Shear Strain
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
Cycles
aml50rs1
aml40rs2
aml40rs3
aml40rs4
aml40rs5
aml40rs6


Missouri -- Plant Mix
Shear Strain
Cycles
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
moprs1
moprs2
moprs3
moprs4
moprs5
moprs6


Missouri -- Lab Mix
(0% RAP)
Shear Strain
Cycles
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
mol0rs1
mol0rs2
mol0rs3
mol0rs4
mol0rs5
mol0rs6


Missouri -- Lab Mix
(20% RAP)
Shear Strain
Cycles
0.025
0.020
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
mol20rs1
mol20rs2
mol20rs3
mol20rs4
mol20rs5
mol20rs6


Missouri -- Lab Mix
(50% RAP)
Shear Strain
0.015
0.010
0.005
0.000
0
1000
2000
3000
4000
5000
Cycles
mol50rs1
mol50rs2
mol50rs3
mol50rs4
mol50rs5
mol50rs6