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Office of Policy Analysis, Research & Innovation

Incorporation of Recycled Asphalt Shingles in Hot-Mixed Asphalt Pavement Mixtures

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Rises in construction and asphalt binder costs, as well as the growing pressures on landfills, have contributed to the increased use of tear-off scrap shingles (TOSS) and manufacturer waste scrap shingles (MWSS) into hot-mixed asphalt (HMA) pavement mixtures. This research project was undertaken to address the responsible incorporation of recycled asphalt shingles (RAS) into HMA pavement mixtures to ensure environmental benefits are realized and pavement durability is retained or improved.

The research consisted of a literature review, extensive laboratory testing and field evaluations of in service RAS/RAP HMA pavements. Binder testing established a strong correlation between the new asphalt binder to total asphalt binder ratio and the extracted high/low binder performance grade temperatures. Dynamic modulus testing on HMA mixtures proved to be an invaluable tool in comparing the effects of RAS and RAP on mixture properties across a wide range of temperatures. Field performance appeared to validate the laboratory findings in some instances.

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Final Report

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AASHTO	American Association of State Highway Transportation Officials
AC	Asphalt Cement
AFT	Asphalt Film Thickness – See Bituminous Specifications
ESAL (BESAL)	Equivalent Single Axel Loading (Bituminous ESAL)
HMA	Hot-Mixed Asphalt
Mn/DOT	Minnesota Department of Transportation
MPCA	Minnesota Pollution Control Agency
MWSS	Manufacturer Waste Scrap Shingles
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles (includes both TOSS and MWSS)
TOSS	Tear-off Scrap Shingles
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate

EXECUTIVE SUMMARY

Rises in construction and asphalt binder costs, as well as the growing pressures on landfills, have contributed to the increased use of tear-off scrap shingles (TOSS) and manufacturer waste scrap shingles (MWSS) into hot-mixed asphalt (HMA) pavement mixtures. Currently the 2009 Minnesota Department of Transportation (Mn/DOT) specifications allow a 5% MWSS replacement for the allowable recycled asphalt pavement (RAP) in HMA pavement mixtures. Although there have been pilot projects that have used TOSS with and without RAP, there is no provision for the use of TOSS in the current specifications.

This study investigated the effect of asphalt binder grade and content, RAP source and content and different shingle sources and proportions on HMA mixture properties with the goal of giving recommendations toward a comprehensive shingle specification, including the option of using TOSS.

A matrix of laboratory-produced mixtures that incorporated recycled asphalt shingles (RAS) which included both TOSS and MWSS, and RAP was tested for both asphalt binder and mixture properties. Recovered asphalt binder from HMA and RAS were tested for high and low temperature properties. Tests for stripping and thermal cracking characteristics were performed on laboratory and field HMA specimens incorporating RAS. A survey of the field performance of RAS/RAP mixtures used in Minnesota was conducted to help verify laboratory evaluation. An outcome of the project was to recommend changes to the asphalt shingle specifications including the use of TOSS.

The mixtures appeared to be more homogenous with the finer ground TOSS. TOSS tended to demand slightly more asphalt binder than MWSS. All mixtures met American Association of State Highway and Transportation Official's (AASHTO) HMA mix design requirements as well as Mn/DOT's voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) specifications. Binder extraction and performance grading (PG) of RAS/RAP HMA mixtures showed a strong correlation between the virgin binder content and the high and low PG temperatures. Mixture testing showed a correlation between virgin binder content and dynamic modulus values at a high test temperature. These results provide justification for the current 70% minimum virgin binder criterion. Note that the materials in this study met this criterion with 19% recycled materials content. All mixes in this study, except for those that had 25% RAP and 5% RAS, met Mn/DOT's adjusted asphalt film thickness (AFT) requirements. Mixture and binder testing indicated that increasing RAP in RAS mixtures increased the total stiffness of the mixture. The use of different RAP sources in the mix design didn't have a significant effect on the stiffness of the mixture.

The asphalt binder contained in TOSS is typically stiffer than that contained in MWSS; however, the age of the processed RAS needs to be considered. The differences in binder stiffness resulted in high mixture modulus for the TOSS mixes. Decreasing the shingle content to 3% minimized the observable differences between the MWSS and TOSS shingle sources.

It was shown that using a softer virgin binder in the mixture could reduce the mix stiffness dramatically without a corresponding increase in cost. An unmodified PG 51-34 binder would not be significantly more expensive than a conventional PG 58-28 binder.

Plant-produced mixtures were found to have lower modulus values than comparable lab-produced mixtures. This difference, most likely, is due to the heating of the recycled materials and the longer mixing dwell times of laboratory produced mixtures, which allowed for significantly more mixing of the RAP, RAS and virgin binders to occur. It was unclear if the coarseness of the MWSS gradation or the difference in binder stiffness resulted in the MWSS mixes having lower dynamic modulus (|E*|) measurements. It is well documented that a finer RAS grind and longer mixing dwell time will result in more blending of the RAS binder.

The research team recommends:

- Mn/DOT retain the AASHTO 70% new asphalt binder to total asphalt binder ratio requirement
- Both MWSS and TOSS can be used at the 3% level
- The current processed shingle gradation and deleterious material requirements should be incorporated for all shingles
- Binder grades used with TOSS and MWSS should be limited to PG 64-28, PG 58-28 and PG 51-34 until additional work can be done on the effect of shingles with modified binders.

Recommended future research should focus on the development of an easier and quicker mixture performance test. This may involve applying the Hirsh model to calculate |E*| from binder tests. A new mix design procedure that more closely simulates plant production of RAP/RAS mixtures needs to be developed, including investigation of using softer binder or softening agents to allow more recycled materials to be used in RAP/RAS mixes. Wet Hamburg tests could be used to evaluate moisture sensitivity, and Flow Number tests could be used to characterize mixture stability.

CHAPTER 1. INTRODUCTION

Introduction

For the past few decades' highway departments have been cooperating with the paving industry and local solid waste environmental groups to incorporate manufacturer waste scrap shingles (MWSS) and, more recently tear-off scrap shingles (TOSS) into asphalt pavement mixtures. Since the completion of a number of projects in Minnesota, several issues have arisen, which prompted the Minnesota Department of Transportation (Mn/DOT) Office of Materials and Road Research (MRR) to enter into an interagency agreement with the Minnesota Pollution Control Agency (MPCA) in order to conduct research that was motivated by the following:

1. Increasing disposal of MWSS and TOSS in landfills
2. Rising costs of construction and asphalt binder
3. Currently the Mn/DOT Bituminous Specifications only allow MWSS as a replacement for recycled asphalt pavement (RAP) in HMA mixtures
4. Premature failures of in place hot-mixed asphalt (HMA) shingle pavements have been attributed to too little new/virgin asphalt binder in the mixture
5. Insufficient research has been done on the effects of softening agents or on the optimal amount of soft binder content to maximize the use of asphalt shingles in HMA mixtures

Experimental Plan

Based on results from previous HMA asphalt shingle research, the researchers developed an experimental plan to investigate the effect of asphalt binder grade and content, RAP source and content, and MWSS and TOSS proportions on HMA mixture and binder properties. A testing matrix consisting of 17 different mixtures with variable amounts of RAS and RAP was developed. This testing matrix was oriented at addressing the following questions:

1. Verify the current AASHTO 70% new binder to total binder ratio requirement for RAS/RAP mixtures
2. Observe the effects of RAS/RAP on HMA mixture durability
3. Observe possible differences in performance between MWSS and TOSS mixtures
4. Observe the effects of "softer grade" asphalt binder in RAS/RAP mixtures
5. Observe the effects of different RAP sources
6. Observe the differences between lab produced and plant produced HMA mixtures

Mixture proportions and testing plans can be seen in Table 1.1 and Table 1.2 respectively. In an effort to limit the number of variables, the mixture design was based on a single gradation from one set of materials. The design was set at a SuperPave Traffic Level 3 (1 to 3 million design ESAL's) using either a performance grade (PG) 58-28 or an unmodified PG 51-34. The asphalt binders and mixtures were evaluated with an array of tests designed to characterize properties related to performance.

Asphalt binders were recovered from: virgin (no recycled material), RAP and RAS mixtures and tested for high temperature stiffness and low temperature creep stiffness and m-value. Continuous (actual) performance grades of the recovered binders were accomplished. Binder master curves were generated from dynamic shear rheometer testing.

Volumetric properties were measured on all mixtures. Dynamic modulus (AASHTO TP 62) testing was used to generate master curves, which gave stiffness values of the various mixtures across a wide range of temperatures and loading frequencies. This stiffness data was invaluable in comparing the effects of different concentrations, and types, of RAS and RAP on mixture performance. In addition, comparing asphalt binder and mixture master curves was used to ascertain the level of binder blending. Lottman analysis was done on selected mixtures to determine moisture sensitivity and asphalt pavement analyzer (APA) testing was run to ascertain susceptibility to permanent deformation.

Lastly, field evaluations were conducted on a number of existing asphalt shingles /RAP construction projects in order to verify the laboratory evaluation, determine the performance of the mixtures with respect to cracking, rutting, raveling and stripping.

Table 1.1. MPCA Material Study Matrix

Mix		**Recycled Material**			**Binder**	
Mix No	**Mix ID**	**RAP (%)**	**TOSS (%)**	**MWSS (%)**	**PG 58-28**	**PG 51-34**
1	PG 58-28 Control	0	0	0	x	
2	15% RAP	15	0	0	x	
3	25% RAP	25	0	0	x	
4	30% RAP	30	0	0	x	
5	15% RAP 5% MWSS	15	0	5	x	
6	15% RAP 5% TOSS	15	5	0	x	
7	25% RAP 5% TOSS	25	5	0	x	
8	25% RAP 5% MWSS	25	0	5	x	
9	25% RAP 5% TOSS 51-34	25	5	0		x
10	25% RAP 5% MWSS 51-34	25	0	5		x
11	25% RAP 3% TOSS	25	3	0	x	
12	25% RAP 3% MWSS	25	0	3	x	
13	15% RAP 3% TOSS	15	3	0	x	
14	15% RAP 3% MWSS	15	0	3	x	
15	10% RAP 5% TOSS	10	5	0	x	
16	15% RAP 5% TOSS	15*	5	0	x	
17	5% TOSS	0	5	0	x	

*Different RAP Source – millings containing 4.0% asphalt cement (AC)

Table 1.2. MPCA Testing Matrix

<table>
<tr><th rowspan="2">Mixture Testing</th><th colspan="2">Binder Testing</th></tr>
<tr><th>Recovered from Mixtures</th><th>Processed Shingles</th></tr>
<tr><td>• Gradation
• %AC
• Air Voids, G_{se}, SG_{agg}, TSR
• VMA, VFA
• Asphalt Film Thickness
• |E*| Master Curve-Mix
• Calculated G* Master Curve- Binder
• APA Rut Testing</td><td>• High temperature stiffness
• Low temperature creep stiffness and m-value
• G* Master Curve</td><td>• High temperature stiffness
• Low temperature creep stiffness and m-value
• Gradation
• Deleterious Materials</td></tr>
</table>

CHAPTER 2. LITERATURE REVIEW

Using recycled asphalt shingles in hot-mix asphalt (HMA) has been a developing technology for more than two decades with growing acceptance by both construction contractors and government agencies. The recent spike in asphalt and cement prices, has prompted the search for acceptable, in terms of performance, supplements to virgin materials. The state of Minnesota has sponsored several research studies on the use of recycled asphalt shingles in HMA mixtures over the past 15 years.

Newcomb, Stroup-Gardiner, Weikle and Drescher (1) investigated the influence of recycled asphalt shingles on HMA mixture properties. The researchers found that up to 5% MWSS could be used in HMA mixtures with a minimum impact on the mixture properties; however 7.5% asphalt shingle content yielded a noticeable softening of the mixture, which may be detrimental to pavement performance. Softening was also seen in the indirect tensile tests of the 10% shingle mixtures on the Hassan Township project, see Project No. 3: Hassan Township Park Drive. The mixture stiffness was adversely decreased when the shingle content exceeded 5% by weight of the aggregate, which led many agencies to limit the shingle content to 5%. The use of TOSS shingles resulted in the embrittlement or stiffening of the mixture which may be undesirable for low temperature cracking resistance properties. The use of MWSS and TOSS, to a lesser degree, resulted in a less temperature susceptible mixture. Increasing the asphalt shingles content reduced the HMA mixtures' demand for new/virgin asphalt binder. This was true more so for the fiberglass and TOSS mixtures than those containing felt-backed asphalt shingles.

Newcomb et al. (1) evaluated moisture sensitivity using a modified Lottman conditioning procedure. The resilient modulus and tensile strength of the mixtures were tested; then samples were subjected to partial saturation and freezing. After 24 hours the samples were thawed and tested again for resilient modulus and tensile strength. The reduction of either tensile strength or modulus was used as an indicator of moisture induced damage. It was found that the use of MWSS did not significantly change the moisture susceptibility of the mixture, but TOSS did.

Newcomb et al. (1) examined low temperature cracking using an indirect tensile test (IDT) performed at a low loading rate in order to simulate volumetric changes induced by daily temperature changes in the field. Tensile strengths at low temperatures were shown to decrease with increasing shingle content. The strain at peak stress increased for the mixtures containing felt-backed shingles with the harder asphalt cement. However, the mixtures made with the TOSS showed a decrease in strain capacity with increased shingle content, implying that this material will be more brittle at low temperatures than the control mixture. The field mixtures obtained from Wright County was subjected to the same testing sequence as the laboratory mixtures. Results showed that it behaved similarly to the laboratory mixture containing 5% felt-backed shingle waste from the manufacturing process.

In 1996 Janisch and Turgeon (2) documented the construction and performance of three test sections in Minnesota: Willard Munger Recreational Trail (1990), T.H. 25 in Mayer (1991) and County State Aid Highway (CSAH) 17 in Scott County (1991). The in-place field performance of these test sections was similar to the control sections, which justified the inclusion of MWSS as a salvage material in HMA under Mn/DOT specification 2331.E2e, Recycled Mixture

Requirements. There was little difference between the laboratory results of the shingle and non-shingle mixtures, and the in-place air voids were much higher than expected for all of the mixture types used on these projects which could lead to raveling/stripping. Generally, the extracted asphalt binder in the shingle mixtures was stiffer than the asphalt binder in the control sections. This was expected since the grade of asphalt used in shingle manufacturing is stiffer than the asphalt typically used in pavements. However, this slight increase in asphalt binder stiffness has not resulted in any additional cracking, with respect to the control section, at the time of the report, five-to-six years after construction.

Eight percent of shingles added to HMA contributed between 0.27% and 0.30% asphalt binder by weight to the wearing course mixtures (Mn/DOT 2331 Type 42). For each percent of shingle scrap that was added to the HMA there resulted in a contribution of 0.12% to 0.22% asphalt binder by weight to the binder/base course mixtures (Mn/DOT 2331 Type 32). Economic benefits occur from using waste shingle scrap in HMA when the cost of incorporating the shingle scrap into the mixture is less than the savings that results from the need for less asphalt binder.

Based on the performance of the test sections and the University of Minnesota's laboratory study, shingle scrap from shingle manufacturing was an allowable salvage material under Mn/DOT specification 2331.3E2e. Because of the limited data set on shingle mixtures in Minnesota the maximum amount of shingle scrap allowed is 5%, by weight of aggregate (2).

In 1991 Turgeon (3) authored a report on the construction and performance of a two mile section of the Willard Munger Recreational Trail which was constructed with asphalt paving mixtures containing varying percentages of recycled tire rubber and shingle scrap. The nine-percent shingle-only mixture met specifications and yielded an economic advantage of decreasing the asphalt binder demand of the mixture. Ground shingle scrap effectively reduced asphalt demand and increased Marshall Stability. Analysis of core samples removed after construction showed low density, low tensile strength and high air voids when compared to the control mix. Mixtures containing shingles had lower recovered asphalt penetrations when compared to the control mixture (3).

In 2006 McGraw (4) documented the HMA shingle construction and performance on Park Drive in Hassan Township, Hennepin County, Minnesota. MWSS were placed in the southbound lane and TOSS in the northbound lane. Five sections used a performance grade asphalt binder (PG) 58-28 and one section used a PG 52-34 binder. The mixture designs utilized no other recycled bituminous material (no RAP). Note that of the four inch thick pavement, the top two inches were considered a wear course mixture and the lower two inches were considered a non-wear course mixture. The non-wear course mixtures consisted of 5% shingles and had a 76.1% new AC ratio.

The following 200-ft, single-lane test sections were constructed:

- 5% MWSS wear (75.4% New AC)
- 10% MWSS wear (51.5% New AC)
- 5% TOSS wear (79.7% New AC)
- 10% TOSS wear (65% New AC)
- 10% TOSS wear (63.6% New AC) adjusted binder
- 0% shingles wear and non-wear

The binder content of the shingle materials were measured by chemical centrifuge extractions. Results indicate that MWSS has about 20% and the TOSS approximately 36% asphalt binder by weight. At 5% shingle addition the MWSS had 1% binder contribution to the total binder while the TOSS contributed 1.8%. The PG grading of the recovered binder shows that overall, there is not much impact on the PG grade at 5% with either shingle source. The high temperature grade increases about one-half of a PG grade and the low temperature grade remains about the same. The difference comes at 10% TOSS shingle addition. The 10% TOSS raises the high temperature grade two and one-half PG grades and the low temperature grade by one-half grade. The impact of the addition of the softer PG 52-34 binder is seen by decreasing both temperatures by one-half grade. The addition of the 52-34 binder to the 10% TOSS mixture almost makes the binder a -28 grade.

McGraw (4) described a significant difference in the sizing of the shingle product after processing. The coarseness of the Hassan shingles may have lead to the variability seen in the in-place voids. Mn/DOT Mix Design Lab personnel noted some large chunks of un-reacted shingles in the mixtures when preparing the gyratory specimens. The smaller the size of the processed shingles, the more shingle binder contributes to the total binder in the mix. The finer grind of shingles produced by the Dem-Con company was used in the Dakota County CSAH 26 project. This mixture seemed to be very uniform and homogeneous. Looking forward to the shingle specification, it would be beneficial to specify a finer ground shingle. The Texas DOT specifies 100% passing the #4 (4.75 mm) sieve and no more than 40% passing the #200 (0.075 mm) sieve. Gradation test results for the Dem-Con shingles showed about 85% passing the #4 (4.75 mm) sieve. Inspection of the processing of the Dem-Con shingles in fall 2008 showed a very uniform product and no deleterious material including, but not limited to: metals, nails, glass, paper, rubber, wood, plastic, soil, brick, tars, and other contaminating substances.

A 2007 AAPT paper by McGraw, Zofka, Krivit, Schroer, Olson, and Marasteanu (5) described research in which Mn/DOT, the MPCA and the University of Minnesota investigated the use of both TOSS and MWSS combined with traditional RAP materials. The same PG 58-28 binder was used to prepare three different mixtures: 20% RAP only, 15% RAP plus 5% TOSS, and 15% RAP plus 5% MWSS. The results indicated that the two types of shingles performed differently. The MWSS appeared to be beneficial, as it decreased the stiffness and did not affect the strength of both mixtures and extracted binders. The addition of TOSS appeared to affect the properties in a negative way, although it also decreased the stiffness of both binders and mixtures. However, it lowered the strength of the binder significantly at the higher test temperature and increased the binder's critical temperature. The addition of RAS lowered the temperature susceptibility of the binders making them stiffer than conventional and RAP modified binders at temperatures more characteristic of fatigue cracking distress. To validate the results of this study it becomes important to expand the analysis to more sources of materials and to build pavement sections that would offer critical field evaluation of these products.

The results from the previous shingle research showed a need to conduct mixture testing when evaluating RAP and RAP/RAS mixtures. The amount of mixing of the binder from new asphalt, RAP and RAS needs to be determined. Bonaquist (6) proposed a method using the Asphalt Mixture Performance Test to evaluate the effective stiffness of RAP and RAS mixtures and the amount of binder mixing taken place in those mixtures. Mixture master curve data is used to calculated binder properties which in turn is compared to recovered binder properties. The difference in the master curves gives an indication of the amount of binder mixing. Bonaquist commented that the grind of the processed shingles and the mixing dwell time can affect the amount of recycled binder that mix with the virgin binder. This method will be used on this study to compare effects of adding RAP and RAS to mixtures.

The economic incentive to using of recycled materials is to both reduce the demand for virgin asphalt binder and to reduce the amount of materials entering landfills. In summary, the results of laboratory and field evaluations have consistently indicated that HMA mixture properties are influenced by both the amount and type of recycled materials (MWSS and TOSS have different effects). RAP only mixes have different effects on the high and low temperature properties of HMA than RAP plus RAS and RAS only mixes. Generally, the addition of recycled materials stiffens the mixture, the amount of stiffening depends primarily upon the amount of mixing between the recycled and virgin binder, which is influenced by the mixing dwell time, the fineness of the grind of the processed shingle material (Bonaquist), which can also affect the uniformity of the mixture. The stiffness of the recycled binder also plays a role, with RAS typically much stiffer than RAP and TOSS stiffer than MWSS. The difference between master curves generated from the Hirsch model, and those generated from mixture testing can give an indication on the amount of binder mixing.

In general it has been found that greater than 5% shingle content (by weight of aggregate) adversely decreased the modulus (1). In addition to stiffness properties, the use of TOSS was found to increase the mixture susceptibility to moisture damage, while MWSS did not. The impact of the addition of the softer PG 52-34 binder is seen by decreasing both temperatures by one-half of a PG grade. This study will build on the previous studies by using a testing matrix to isolate the effects of each material (RAP, MWSS and TOSS) as well as the effects of softer asphalt binder. In addition this study will not examine shingle contents greater than 5% due to the already established negative effects on performance.

CHAPTER 3. MIXTURE DESIGN

Introduction

The design of HMA laboratory mixtures consisted of:

- Virgin binder and aggregates (No recycled materials)
- Virgin binder and aggregate plus a proportion of recycled binder and aggregate derived from RAP
- Virgin binder and aggregate plus a proportion of recycled binder and aggregate derived from MWSS and RAP
- Virgin binder and aggregate plus a proportion of recycled binder and aggregate derived from TOSS
- Virgin binder and aggregate plus a proportion of recycled binder and aggregate derived from TOSS and RAP

Aggregate Properties

Three virgin aggregate materials and two virgin asphalt binders were used in the laboratory designs. Four recycled materials were used: an asphalt-rich RAP, an asphalt-poor RAP, MWSS and TOSS. All of the recycled materials contributed both aggregate and binder to the overall mixture. Table 3.1 shows the characteristics of the aggregate materials, including the gradations, used in the mixtures. The aggregate materials used in the mixtures consisted of a pit-run-sand, a quarried ¾ in. (19 mm) dolostone, a quarried dolostone manufactured sand, a ¾ in RAP and RAS (either MWSS or TOSS). The minimum crushing requirement for this traffic level is 55% single-face crushed. All of the produced mixtures had a crushing content between 86 to 97%, which met the specifications.

Table 3.1. Characteristics of Aggregate Materials

% passing	**Mix Gradation Min-Max**	**Pit Sand**	**Crushed Rock**	**Manu. Sand**	**RAP#1**	**RAP#2**	**TOSS**	**MWSS**
3/4	100	100	100	100	100	100	100	100
1/2	85 - 89	100	60	100	94	96	100	100
3/8	76 - 82	99	37	100	87	90	100	100
#4	63 - 70	97	3	99	69	76	100	98
#8	52 - 60	90	1	75	55	64	99	97
#16	40 - 47	78	1	48	44	53	85	81
#30	28 - 33	54	1	33	32	38	65	61
#50	15 - 19	27	1	19	18	22	49	53
#100	5 - 8	7	1	6	10	12	35	40
#200	2 - 5	3	1	3	6.6	8	24.1	30.9
% AC		0	0	0	5.6	4.0	26.4	17.8
Gsb		2.662	2.707	2.709	2.626	2.618	2.650	2.650
-#4 Gsb		2.662	2.707	2.709	2.626	2.618	2.650	2.650

Figure 3.1 shows the MWSS and TOSS gradations. The two TOSS samples had consistent gradation results, and both satisfied Mn/DOT's gradation requirement for roofing shingles in hot mix asphalt (100% passing the 1/2-in. (12.5 mm) sieve and 90% passing the #4 (4.75 mm) sieve).

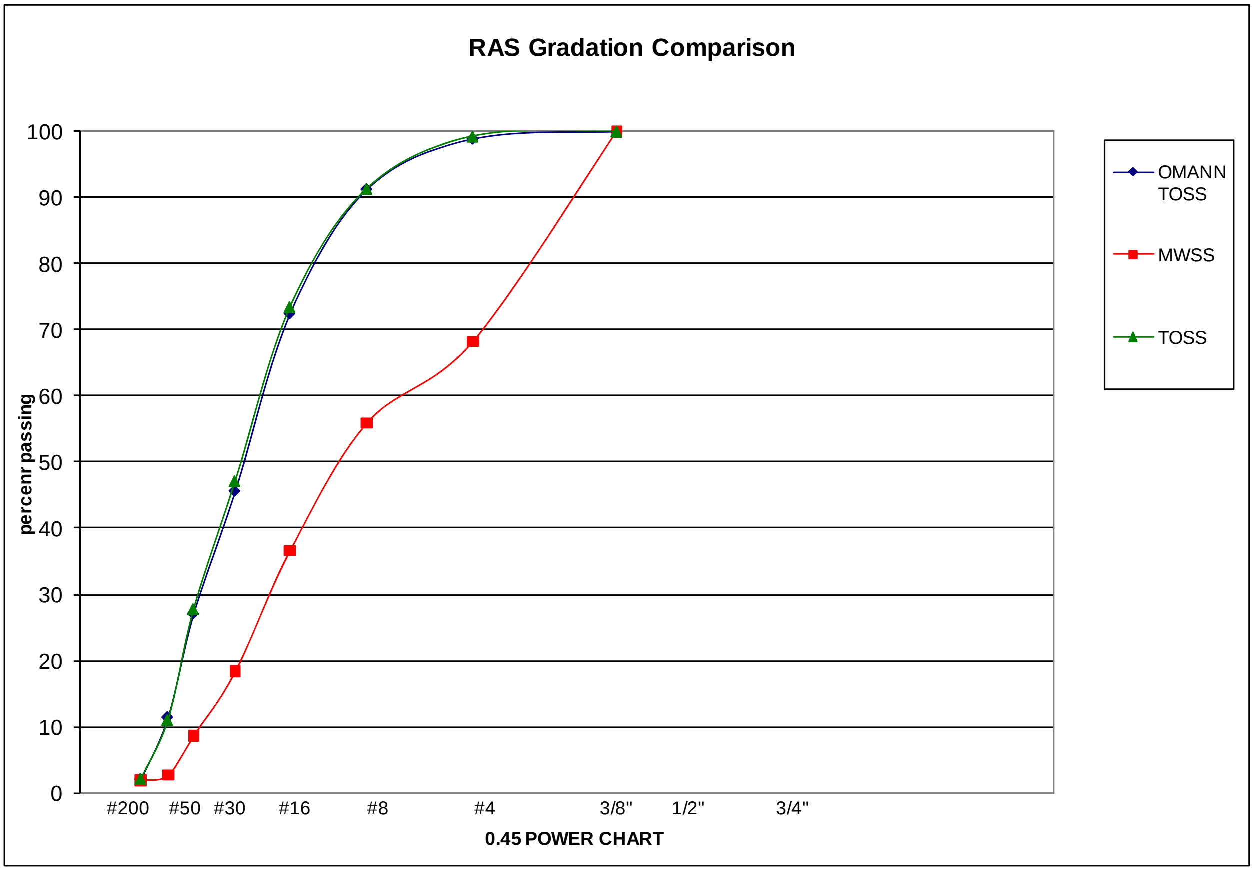

Figure 3.1. MWSS and TOSS Gradations

Figure 3.2. MWSS (Left) and TOSS (Right)

The MWSS material did not meet the Mn/DOT gradation, was much coarser and appeared less uniform than the TOSS, as shown in Figure 3.2. The Mn/DOT mix design staff cautioned that the coarse MWSS gradation and non-uniformity could potentially lead to moisture sensitivity problems.

The deleterious material (DM) specification for processed shingles states that scrap asphalt shingles shall not contain extraneous waste materials. Extraneous materials include, but are not limited to: asbestos, metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics and shall not exceed 0.5% by weight as determined on material retained on the 4.75-mm (No. 4) sieve. DM testing consists of sieving a 500-700 gram sample on the #4 sieve, then manually picking and weighing the deleterious material. Figure 3.3 shows the DM testing results of the MWSS and TOSS, the TOSS met the 0.5% DM specification, and the MWSS did not.

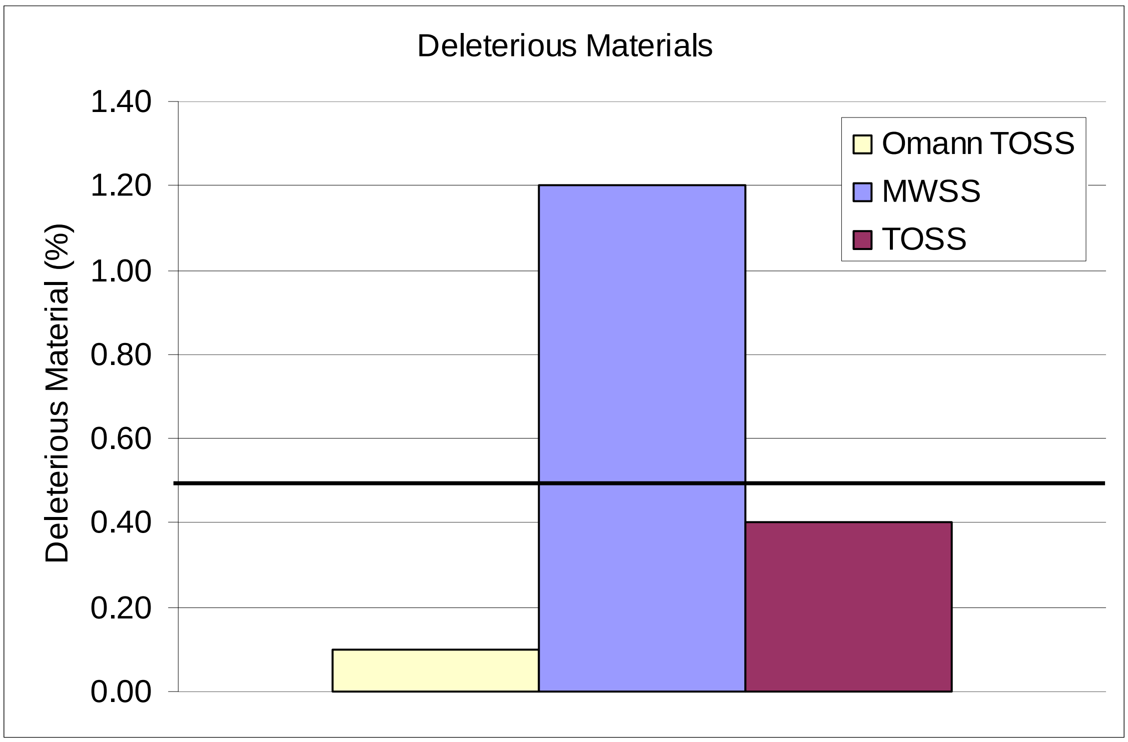

Figure 3.3. Deleterious Material Content of TOSS and MWSS

Sample Preparation

Prior to batching and mixing, the virgin aggregate products were split into coarse and fine fractions on the #8 (2.36 mm) sieve. The plus #8 material was processed further by separating it into individual size fractions ranging from the ¾ to the #8 sieves. The RAP was split on the #4 (4.75 mm) sieve and the plus #4 material was processed further by separating it into individual size fractions from the ¾-in. thru the #4. The RAS was not split. The aggregate fractions were then recombined into the proper proportions for each mixture blend. The batching weight of the RAP was adjusted for its binder content, which was 5.6 and 4.0% for RAP sources 1 and 2 respectively.

The aggregate and RAP were preheated for four to five hours at 315 °F (157 °C). The shingles were blended with the sand prior to preheating. The mixture batch weights were 25,000 grams each. The design blends were mixed in a Lancaster Batch Mixer. The aggregate blend was mixed for one to two minutes prior to adding the binder. The binder was added while the bowl and mixing blades were rotating. After the addition of asphalt binder, the blend was mixed for an additional two minutes to achieve coating. The mixture was then conditioned in an oven at a temperature of 275 °F (135 °C) for two hours. After short term curing the mixture was split into pre-weighed samples and tested for bulk and maximum specific gravities in accordance with AASHTO T209, T312 and TP62. A gyratory compactor (AFGC125X or "Big Pine") was used to compact all of the specimens to 60 gyrations.

A number of specimens were fabricated for each of the seventeen mixtures as each mixture design was successfully completed. The following 136 gyratory specimens were produced as part of the mix design process and to provide material in the binder and mixture testing phase of the project:

- Two gyratory specimens per mix (34 total) were fabricated during the design process to determine optimum mixture volumetric properties. The specimens were produced with dimensions of 150 mm (6 in.) diameter and 115 mm (4.5 in.) height. The data regarding the individual points is not attached to this report, but is available by request.
- One gyratory specimen per mix (17 total) that served as both a design verification point and as material for use in Task 4 (binder extraction, recovery, and binder property testing). The specimens were produced with dimensions of 150 mm (6 in.) diameter and 115 mm (4.5 in.) height.
- Three gyratory specimens per mix (51 total) for use in testing mixture dynamic modulus (|E*|). The specimens were produced with dimensions of 150 mm (6 in.) diameter and approximately 225 mm (9 in.) height.
- Two gyratory specimens per mix (34 total) for use in testing mixture rutting resistance (APA). The specimens were produced with dimensions of 150 mm (6 in.) diameter and 115 mm (4.5 in.) height.

Mixture Design

The basic mixture design in this study was based on an existing Job Mix Formula (JMF) that has been produced in Minnesota for the past five years. The mixture meets the requirements for a Mn/DOT SuperPave 12.5 mm nominal maximum aggregate size, traffic level 3 (1-3 million ESAL's). The designs were performed by the Bituminous Office Hot Mix Laboratory staff at the Mn/DOT Office of Materials and Road Research and followed the guidelines set forth in Mn/DOT standards for gyratory mixture design, which are available on the Bituminous Office Website http://www.dot.state.mn.us/materials/bituminous.html. Laboratory production enabled the formulation and design evaluation of multiple test points which optimized mixture volumetric requirements.

A PG 58-28, non-polymer modified, asphalt binder (specific gravity of 1.036), was used in all but two of the RAS/RAP mixtures. A comparably priced, PG 51-34, non-polymer modified, asphalt binder was used in the remaining two mixtures (9 and 10) in order to investigate the binder and mixture properties resulting from using a softer binder.

Each mixture was adjusted to meet the following mixture design requirements: 4.0% air voids, minimum 14.0% voids in the mineral aggregate (VMA), 65-78% voids filled with asphalt (VFA), and a Dust to Binder ratio of 0.6-1.2 (F/E). Table 3.2 shows the aggregate proportions that were used; all mixtures are considered to be fine graded with Fine Aggregate Angularities (FAA) of 42. The final aggregate designs are presented in Figure 3.4 along with the average gradation resulting from the study. Based on these gradations, the laboratory mixtures used an average of 78.7% virgin and 21.3% recycled materials. The breakdown by individual product useage was approximately 29.5% pit-run sand, 26.3% crushed rock, 22.9% manufactured sand, 17.9% RAP, 2.1% TOSS, and 1.2% MWSS.

Table 3.2. Mixture Formula Proportions

Product	**Pit Sand**	**Crushed Rock**	**Manufactured Sand**	**RAP#1**	**TOSS**	**MWSS**	**RAP#2**	**Total %**
Mix 1	30	37	33	0	0	0		100
Mix 2	24	32	29	15	0	0		100
Mix 3	30	25	20	25	0	0		100
Mix 4	27	23	20	30	0	0		100
Mix 5	30	26	24	15	0	5		100
Mix 6	30	26	24	15	5	0		100
Mix 7	27	23	20	25	5	0		100
Mix 8	27	23	20	25	0	5		100
Mix 9	27	23	20	25	5	0		100
Mix 10	27	23	20	25	0	5		100
Mix 11	28	23	21	25	3	0		100
Mix 12	28	23	21	25	0	3		100
Mix 13	35	26	21	15	3	0		100
Mix 14	35	26	21	15	0	3		100
Mix 15	32	27	26	10	5	0		100
Mix 16	30	26	24	0	5	0	15	100
Mix 17	35	35	25	0	5	0		100

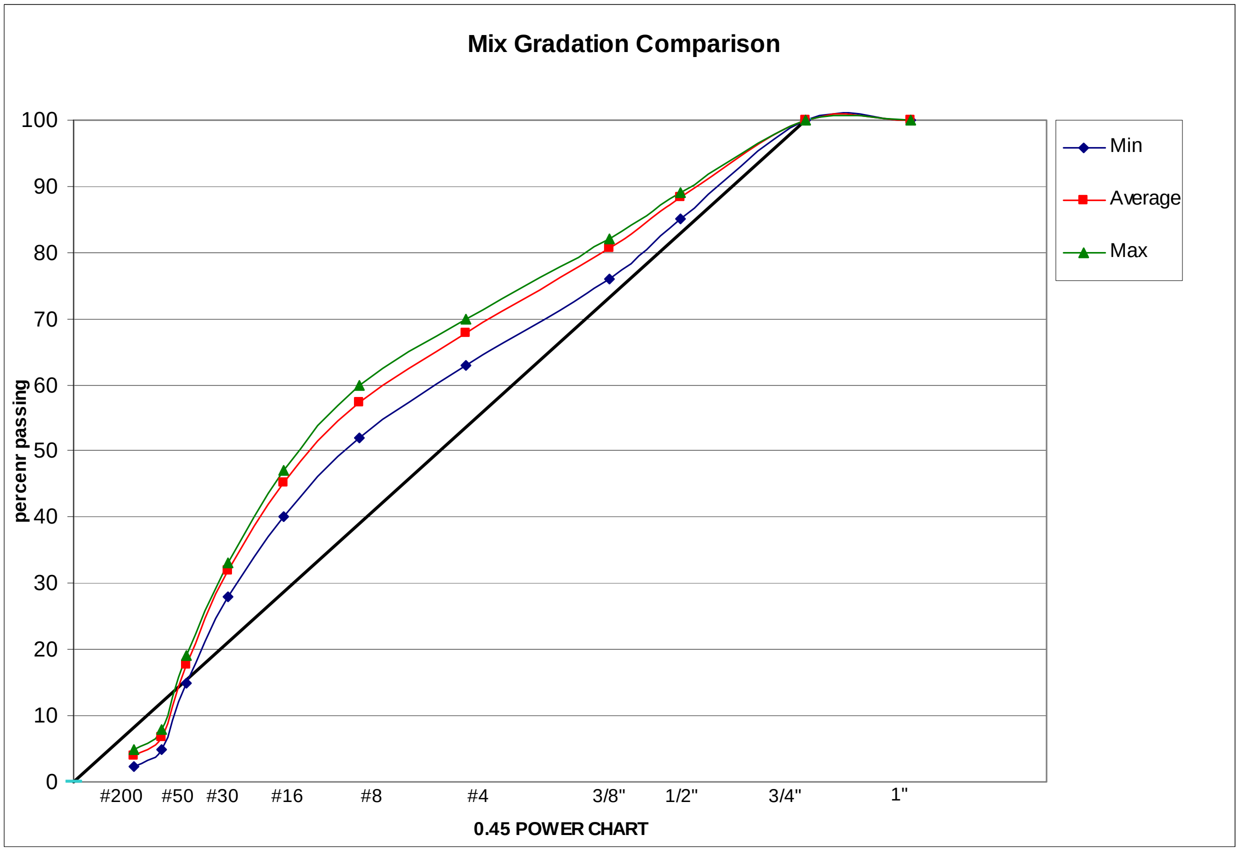

Figure 3.4. Mixture Design Gradations

Table 3.3 lists the asphalt content of the mixtures as a percentage of the total mixture weight. The term "Total AC" represents the recycled plus virgin asphalt binder in the mixture, while "Add AC" represents only the amount of virgin binder. The term "Pbe" is calculated from the mixture volumetric properties and refers to the amount of effective binder. Effective binder is the quantity of asphalt material that has not been absorbed into the aggregate particles. The TOSS generally provided more binder than MWSS, as shown by the lower amounts of virgin binder. This suggests that, in order to meet the 70% new binder criterion, less amount of RAP would be allowed in a TOSS mixture than a comparable MWSS mixture.

Several of the mixtures are identified as containing new-to-total asphalt ratios that are lower than the current Mn/DOT requirement of 70%. This deviation is acceptable in this instance since this study will evaluate the usefulness of the 70% criterion. As previously stated, the volumetric properties of the mixtures satisfied all Mn/DOT requirements. Mixture volumetric data is presented in Table 3.4. Note that the four mixes that fail to meet the Mn/DOT minimum Asphalt Film Thickness criterion of 8.5 microns also have the four lowest new-to-total asphalt ratios.

Table 3.3. Mixture Asphalt Demand Properties

Mix	% RAP	% TOSS	% MWSS	Total AC	Add AC	% New AC	Pbe
1	0	0	0	5.8	5.8	100.0	5.3
2	15	0	0	5.3	4.5	84.9	4.7
3	25	0	0	5.3	3.9	73.6	4.9
4	30	0	0	5.4	3.7	68.5	4.9
5	15	0	5	5.5	3.8	69.1 †	5.1
6	15	5	0	5.7	3.5	61.4 †	5.3
7	25	5	0	5.4	2.7	50.0 †	4.9
8	25	0	5	5.2	2.9	55.8 †	4.6
9	25	5	0	5.4	2.7	50.0 †	4.9
10	25	0	5	5.2	2.9	55.8 †	4.7
11	25	3	0	5.4	3.2	59.3 †	5.0
12	25	0	3	5.3	3.4	64.2 †	4.9
13	15	3	0	5.7	4.1	71.9	5.2
14	15	0	3	5.6	4.2	75.0	5.2
15	10	5	0	5.7	3.8	66.7 †	5.4
16	15*	5	0	6.1	4.2	68.9 †	5.6
17	0	5	0	6.0	4.7	78.3	5.5

(†) Value is below minimum recommended in Mn/DOT 2360 shingle provision.
*RAP is from RAP source #2

Table 3.4. Mixture Volumetric Properties

Mix	Air Voids	Gmm	Gmb	Gse	Gsb	VMA	VFA	F/E	adj AFT
1	3.7	2.495	2.402	2.732	2.691	15.9	76.6	0.5	11.2
2	4.1	2.507	2.404	2.723	2.684	15.2	72.9	0.6	9.8
3	4.1	2.493	2.390	2.706	2.673	15.3	73.0	0.7	9.1
4	3.7	2.491	2.399	2.708	2.670	15.0	75.4	0.7	9.0
5	3.9	2.490	2.393	2.711	2.679	15.6	75.0	0.9	8.7
6	3.6	2.478	2.388	2.706	2.679	15.9	77.2	0.8	9.2
7	4.0	2.489	2.389	2.706	2.672	15.4	73.9	0.9	8.2 †
8	4.1	2.503	2.410	2.714	2.672	14.8	72.5	1.0	7.6 †
9	4.5	2.489	2.378	2.707	2.672	15.8	71.8	0.9	8.2 †
10	4.0	2.496	2.397	2.707	2.672	15.0	73.5	1.0	7.8 †
11	3.8	2.482	2.387	2.698	2.672	15.5	75.3	0.8	8.9
12	4.0	2.491	2.391	2.703	2.672	15.3	73.7	0.9	8.5
13	4.0	2.483	2.383	2.712	2.677	16.1	74.9	0.7	9.4
14	4.2	2.483	2.378	2.707	2.677	16.1	73.8	0.8	9.0
15	4.2	2.474	2.371	2.701	2.682	16.6	75.0	0.7	9.4
16	3.8	2.469	2.375	2.713	2.677	16.7	77.2	0.8	9.6
17	4.0	2.480	2.382	2.717	2.689	16.6	76.3	0.6	10.4

(†) Value is below the minimum 8.5 microns listed in Mn/DOT Special Provisions.

Figure 3.5 shows the amount of new asphalt added to the mixtures relative to the total recycle content. The method of least-squares linear regression was used to show that, for this set of data, the total recycled material content of the mixture would be limited to approximately 20% in order to satisfy the 70% new binder criterion. Mixtures containing 5% RAS would, on average be limited to 14.8% RAP. There would be different allowable percentages of RAP based on the properties and proportions of the RAS.

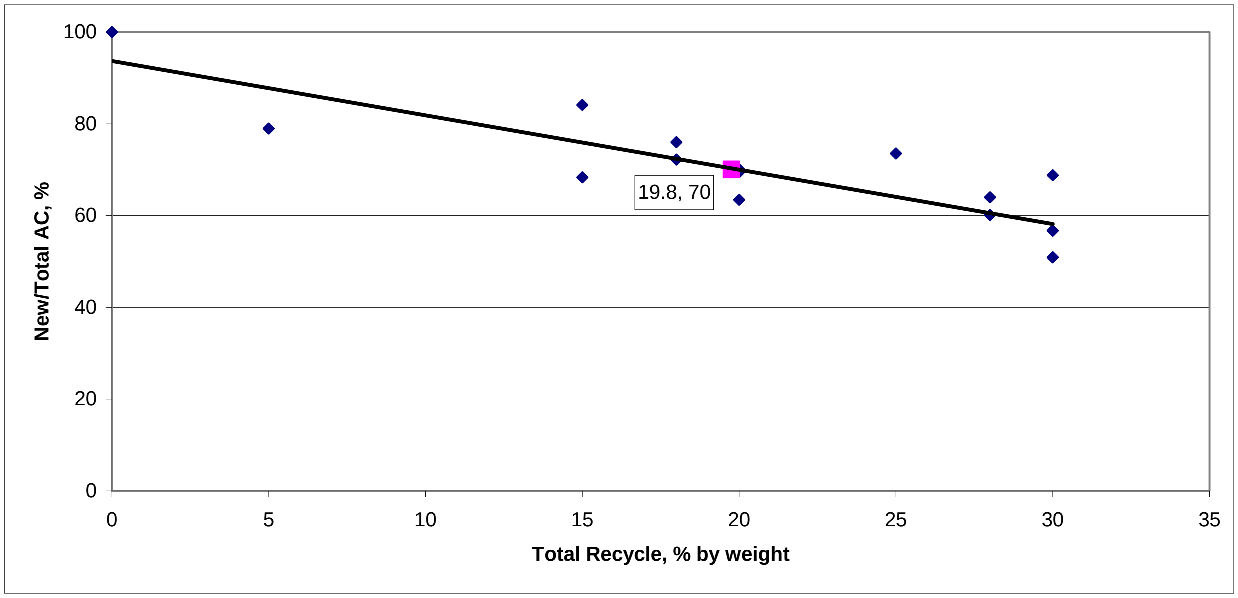

Figure 3.5. New Binder to Total Binder Ratio vs. Total Recycled Materials Content

Summary of Mixture Design

Several observations were made during the mixture design and specimen production phase, including:

- Mixture temperatures cooled quicker with the addition of shingles. This was apparent when designers noticed a loss in workability as the hot materials were mixed and as tools were scraped.
- Shingles made the mixtures appear dryer (less asphalt binder) than those produced with just RAP.
- Mixtures with the coarser ground (MWSS) shingles had a tendency to clump up during the mixing process.
- The mixtures appeared to be more homogenous with the finer ground (TOSS) shingles. Tear off shingles tended to demand slightly more asphalt binder than the manufactured product.
- Inconsistencies were noticed during the design of the 30% RAP mix (Mix 4). Subsequent inspection showed that RAP#1 was contaminated by the presence of crack filler material. The design of Mix 4 was completed after removing all visible traces of contaminant from RAP#1.

CHAPTER 4. LABORATORY TESTING

Asphalt Binder Testing
Asphalt binder was extracted, recovered and tested from the HMA mixtures. The recovered binder properties of the various mixtures were compared to each other to identify:

- Effect of RAP content
- Effect of different RAP sources
- Effect of RAS Content
- Effect of MWSS vs. TOSS
- Effect of using a soft virgin binder (PG 51 - 34)
- Differences between plant-produced and lab-produced mixtures
- Repeatability of binder master curve generation

Extraction/Recovery and Binder Grading
The asphalt binders were extracted from the prepared mixtures in Table 4.1. The process involves doing a solvent centrifuge extraction on the mixture using toluene. The extract is centrifuged at high speeds to remove the mixture fines from the binder. The solvent is removed using the ASTM D5404- Rotovap recovery process.

To address the controversy on whether the solvent recovery process affects binder properties, a search of the Mn/DOT Asphalt Binder Lab database was conducted on testing done to verify binder grades in cores and mixtures. A few examples from that search are listed below. This process has become so successful that it has become standard operating procedure in the Asphalt Binder Lab to verify PG Binder grades on cores and mixtures and is used to recover binder for other testing.

Cores taken from the PG 58-28 control sections on the Hassan Township Shingle Study were extracted and the binder recovered using the Mn/DOT process described above. The binder from those mixtures graded out to be PG 61.8-30.6 and PG 61.5-31.5. Typically PG 58-28 binder samples received from asphalt suppliers' grade out to be about PG 60-30. This indicated that the recovery process has little effect on straight run asphalt binder. To determine if polymer-modified binder is affected by the recovery process, binder from cores taken from Olmstead County CR 112 were tested. The PG 58-34 binder in the non-wear lift of the cores tested out to be PG 60.0-36.9 which is consistent with PG 58-34 tank sample results. The non-wear lift of the core was analyzed to eliminate any concern of surface aging. These results indicate that this process can be used to determine binder properties without much effect to the binder in the process. There are other peer-reviewed research papers verifying this (7, 8). It should be stated here that the extraction process does blend all the virgin, RAP and shingle binder. This is useful to determine a 100% blending scenario and for determining the degree of blending in the HMA mixtures.

Table 4.1 and Table 4.2 show the high and low temperature PG grades of the extracted binder for each mixture and the individual materials, respectively. It can be seen that the addition of RAP and/or RAS increases the high and low temperature PG grades. The softening effect can be seen when using PG 51-34 binder.

Table 4.1. Shingle Mixture Binder Performance Grade (PG) Binder Grading

Mix #	Mix Identification	High PG Temp	Low PG Temp	Continuous PG Grade	PG Grade
1	PG 58-28 Control	63.7	-31.0	63.7 -31.0	58-28
2	15% RAP	72.4	-20.9	72.4 -20.9	70-16
3	25% RAP	77.2	-19.7	77.2 -19.7	76-16
4	30% RAP	75.4	-25.6	75.4 -25.6	70-22
5	15% RAP 5% MWSS	78.7	-16.7	78.7 -16.7	76-16
6	15% RAP 5% TOSS	80.1	-16.3	80.1-16.3	76-16
7	25% RAP 5% TOSS	84.6	-14.1	84.6 -14.1	82-10
8	25% RAP 5% MWSS	79.3	-18.7	79.3 -18.7	76-16
9	25% RAP 5% TOSS 51-34	75.9	-21.9	75.9 -21.9	70-16
10	25% RAP 5% MWSS 51-34	75.1	-23.2	75.1 -23.2	70-22
11	25% RAP 3% TOSS	81.0	-17.5	81.0 -17.5	76-16
12	25% RAP 3% MWSS	79.5	-18.2	77.2 -18.2	76-16
13	15% RAP 3% TOSS	78.1	-18.6	78.1 -18.6	76-16
14	15% RAP 3% MWSS	78.5	-19.2	78.5 -19.2	76-16
15	10% RAP 5% TOSS	77.7	-17.1	77.7-17.1	76-16
16	15% RAP 5% TOSS	79.4	-20.3	79.4-20.3	76-16
17	5% TOSS	75.6	-24.2	75.6-24.2	70-22

Table 4.2. Recycled Material Binder Performance Grade (PG) Binder Grading

Material Identification	High PG Temp	Low PG Temp	Continuous PG Grade	PG Grade
RAP Source 1	79.9	-17.4	79.9 -17.4	76-16
RAP Source 2	74.3	-28.8	74.3 -28.8	70-28
Omann TOSS	112.7	-11.4	112.7-11.4	
Knife River MWSS	107.5	+6.0	107.5+6.0	

The source of shingles doesn't seem to have much of an effect on the low temperature PG grade of the 15% RAP/RAS mixtures. As we increased the RAP content to 25%, there is a bit of stiffening with the TOSS shingles and softening with the MWSS. This may either be variability of the testing or within the materials itself. Even with trying to control all aspects in the mixing process, the variability of the materials would enter some error in the testing. Different amount of intermixing could occur with the RAP, RAS and virgin binders.

Figure 4.1 and Figure 4.2 show the comparison of the high temperature and low temperature PG grades for the RAS/RAP mixtures, respectively. These plots show that the addition of RAP and/or RAS increases the high and low temperature PG grades. The softening effect of using the softer binder is significant with the MWSS experiencing an increase in low temperature PG grade from -19 to -23 and the TOSS experiencing an increase in low temperature PG grade from

-14 to -22 as shown in Figure 4.2. Future work of interest is to use the 51-34 binder with 10 or 15% RAP and 5% TOSS.

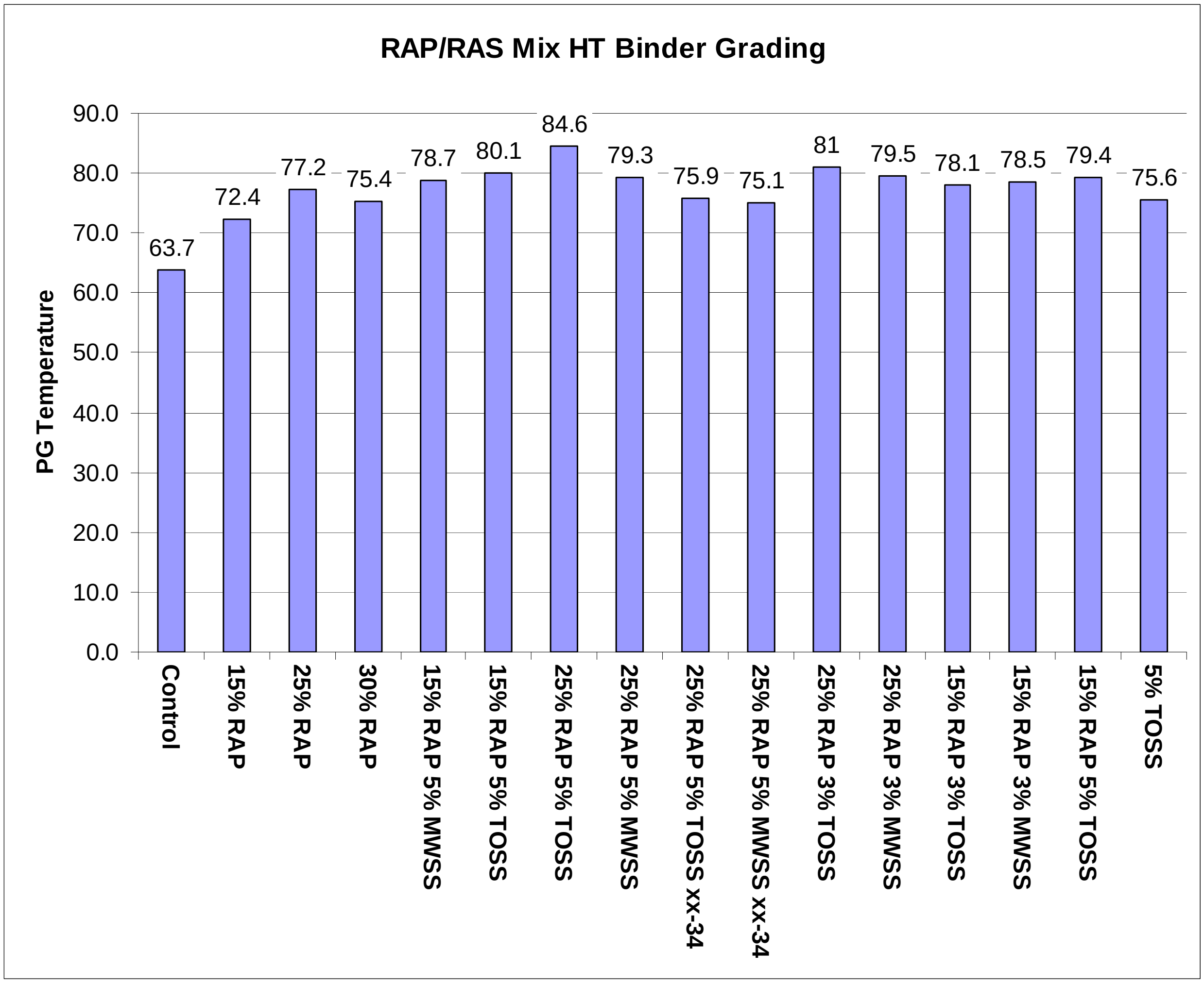

Figure 4.1. RAP/RAS Mixture High Temperature PG Binder Grading

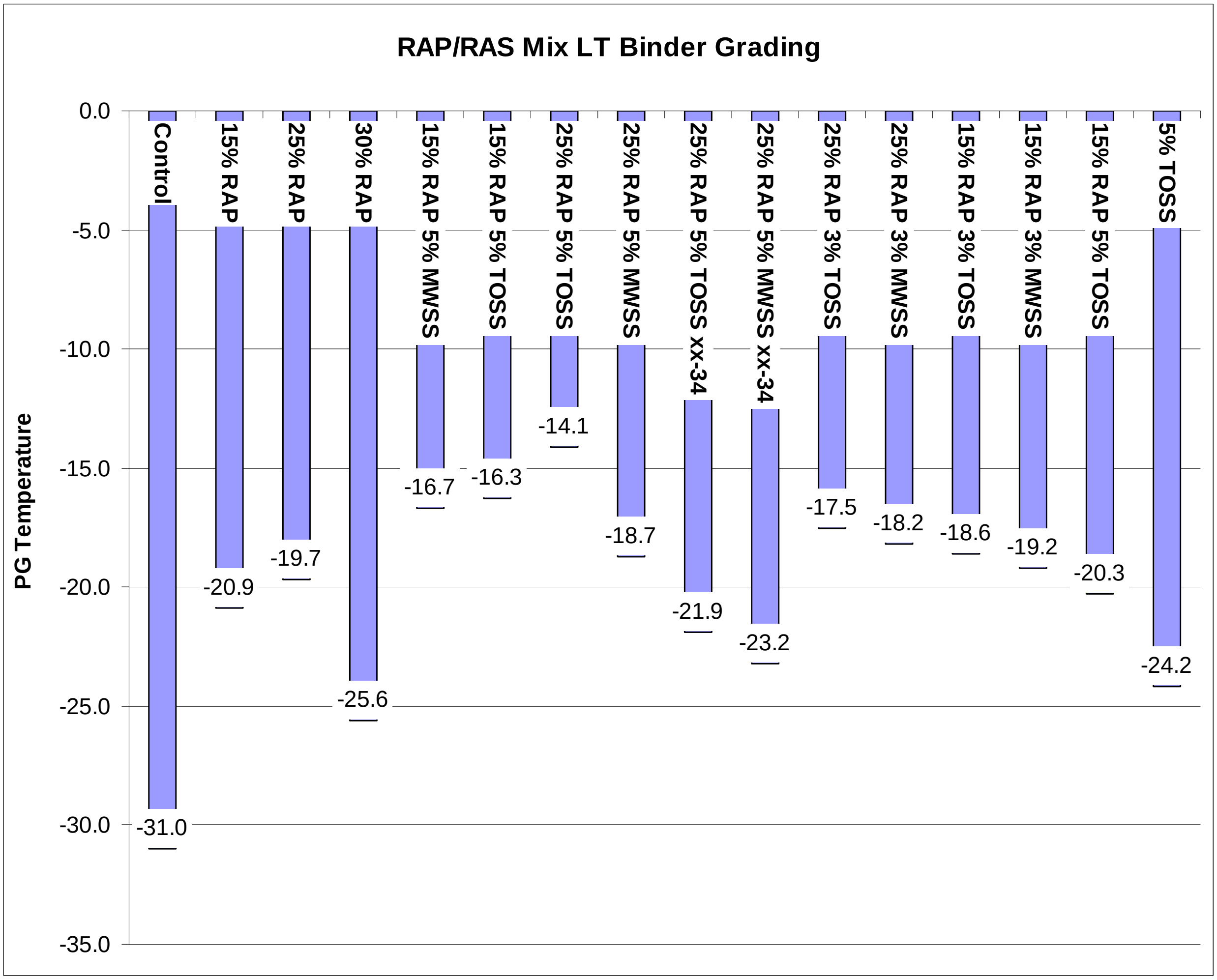

Figure 4.2. RAP/RAS Mixture Low Temperature PG Binder Grading

Closer examination of the RAS and RAP binder properties in Table 4.1, suggests that binder stiffness, as indicated by PG grade, appears to be related to the new asphalt binder to total asphalt binder ratio. This apparent relationship was investigated further by plotting new binder to total binder ratio against the low and high temperature PG grade of the asphalt binder as shown in Figure 4.3 and Figure 4.4 respectively. Both plots excluded mixtures 9 and 10, circled in red, from the linear regression, due to the different binder grade of these two mixtures. Least squares linear regression indicated a stronger relationship using the high PG grade than the low PG grade (R^2 of 0.89 vs. 0.77). Both plots show an inverse relationship between the new asphalt binder to total asphalt binder ratio and the mixture binder PG grade; decreasing the new binder ratio increases the binder low temperature grade, or raises the binder high temperature grade. The results suggest that decreasing the proportion of new binder in the mixture will have an adverse effect on the durability, if other changes are not made to counteract the stiffening effects such as using a softer binder. In fact, using a softer binder had a dramatic effect on both the low and high temperature properties as shown in both plots. The regression equation for binder low temperature properties predicts a low PG temp of -12.1°C for a mixture with 50% new binder ratio and a PG 58-28 binder; however mix 9, which had 50% new binder ratio and a PG 51-34 binder had a low PG temp of -21.9. The regression equation for binder high temperature properties predicts a high PG temp of 85.6°C for a mixture with 50% new binder ratio and a PG 58-28 binder; however mix 9, which had 50% new binder ratio and a PG 51-34 binder had a high PG temp of 75.9°C. The current AASHTO 70% new binder to total binder criterion appears justified. This 70% criterion could be met with approximately 15% RAP plus 5% TOSS.

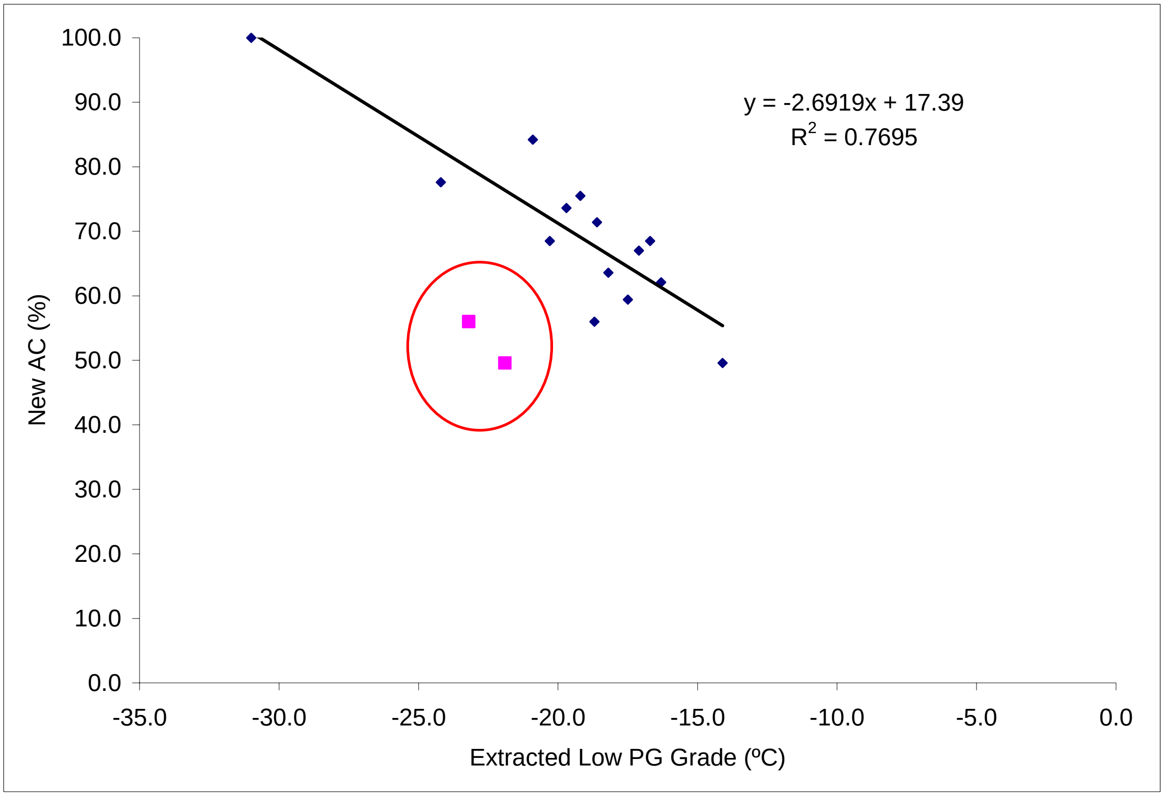

Figure 4.3. New Binder to Total Binder Ratio vs. Low Temperature PG Grade

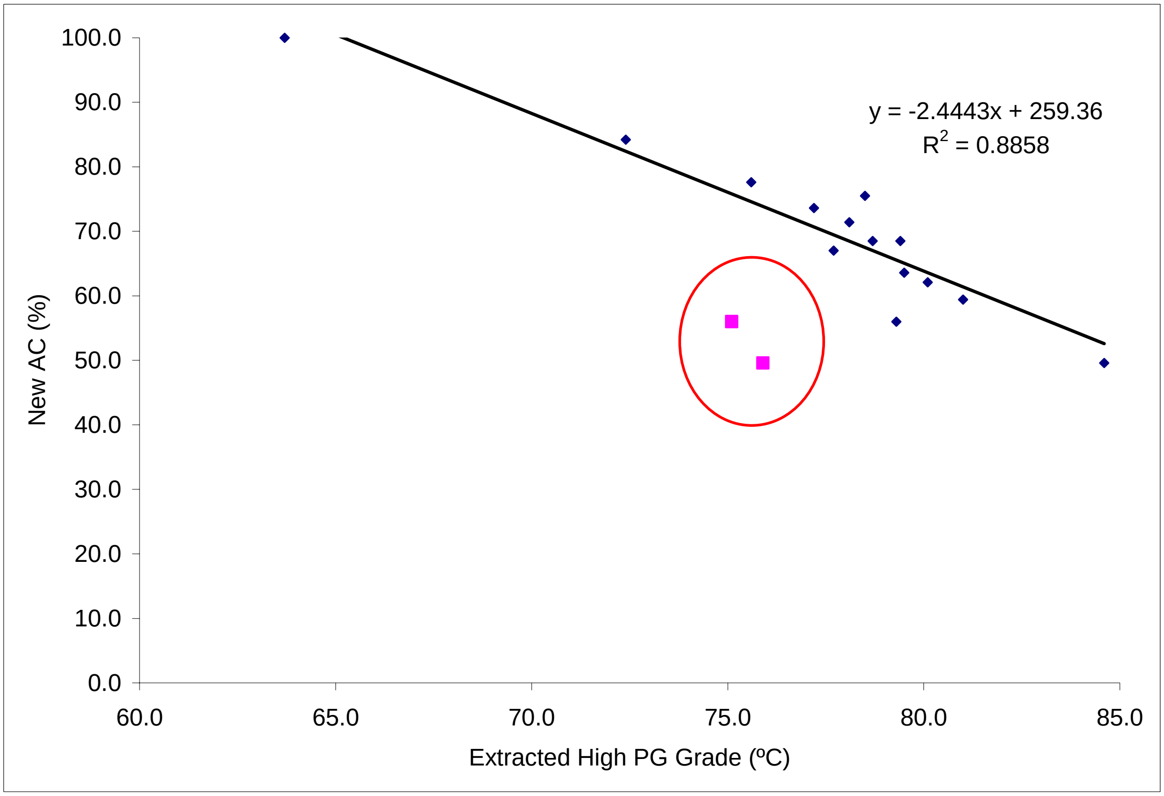

Figure 4.4. New Binder to Total Binder Ratio vs. High Temperature PG Grade

Dynamic Shear Rheometer Testing and Binder Master Curves

The dynamic shear rheometer (DSR), shown in Figure 4.5, is a SuperPave test used to characterize asphalt binders at intermediate and high temperatures. Binder properties at these temperatures are thought to be responsible for fatigue and rutting distresses. A balance needs to be struck when specifying binders; traffic and weather conditions also need to be considered. A binder should be stiff at higher temperatures to prevent rutting, flexible at intermediate temperatures to prevent excessive fatigue damage and soft at lower temperatures to reduce thermal cracking.

The DSR test consists of a thin asphalt binder specimen placed under an oscillating dynamic load. The ratio of the applied stress divided by the measured strain yields the complex modulus (G*). The absolute value of the complex modulus (|G*|) is a measure of the overall resistance to deformation under dynamic shear loading, and can be thought of as an indication of binder stiffness (9).

Complex Modulus master curves were generated by testing the binders at different temperatures and loading times (frequencies), these results were then combined, yielding a representation of binder properties over a wide range of temperatures and frequencies. Comparing the master curves of recovered binder from the various mixtures can give an indication of the effects of RAP, RAS and virgin binder (content and grade) on the properties of the mixtures. This process of generating master curves is very repeatable as shown in Figure 4.6. The master curves in this document were plotted on a set of logarithmic axes. This convention tends to graphically compress high numeric values and emphasize differences at low numeric values.

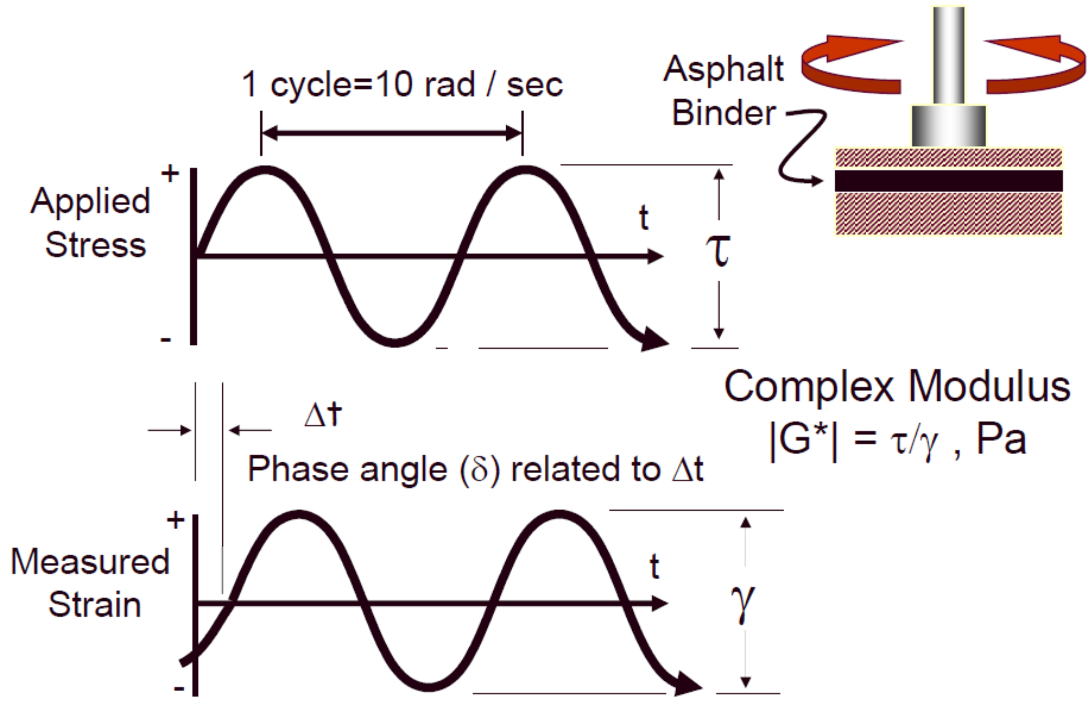

Figure 4.5. DSR Test Schematic (9)

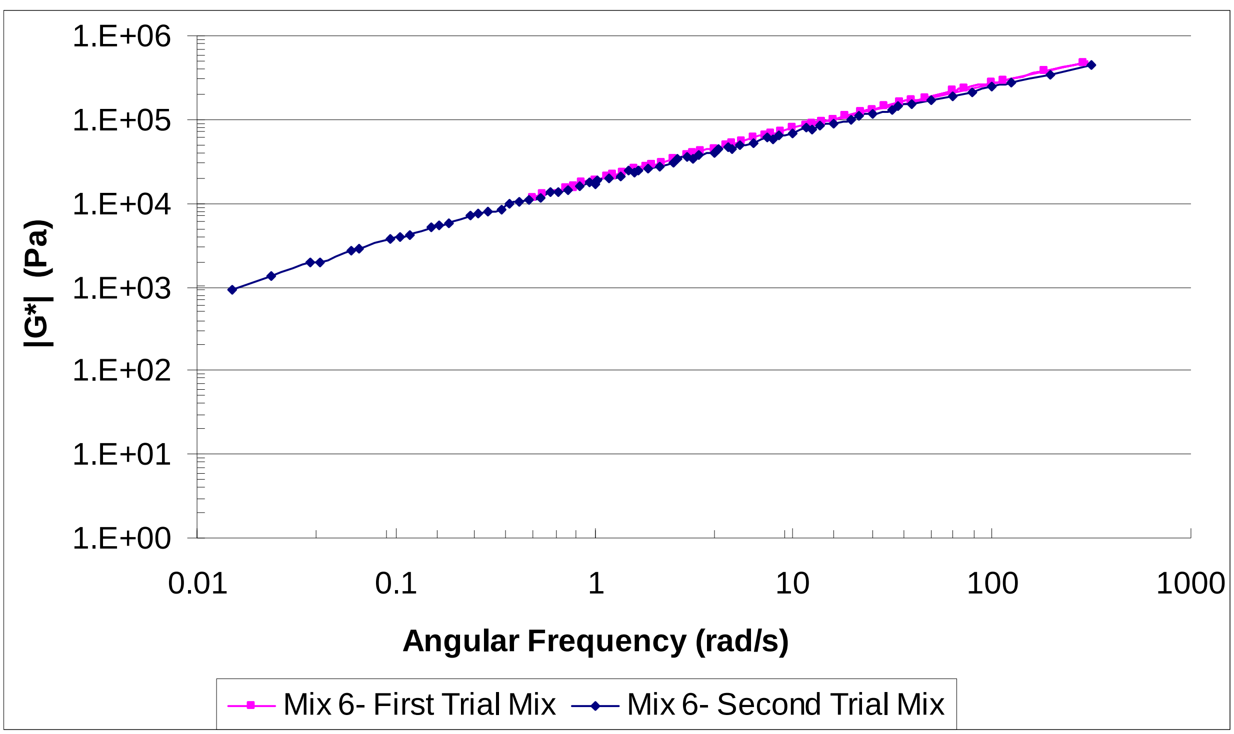

Figure 4.6. Repeatability of Binder Master Curve Determination

Figure 4.7 shows a comparison between a lab-produced and a plant produced mixture (sampled from the 2008 Ramsey County Recreational Trail project). The mixture designs are slightly different, but both contained 5% TOSS from the same source with the same gradation. The lab-produced mix binder is stiffer at all temperatures; however the ratio of complex modulus appears to be larger at the lower frequencies than the higher frequencies. For example, at a frequency of 0.11-0.12 radians/second Mix 17 is more than five times stiffer than the Ramsey County Trail Mix (648 vs. 119 Pa), however at a frequency of 100 radians/second Mix 17 is only twice as stiff (107,500 vs. 52540 Pa). This is most likely the result of differences in heating the RAS and RAP in the mixing process and indicates that the RAS binder in the plant-produced mixture didn't blend as much with the virgin binder as the lab produced mixture did. The relatively less mixing between the TOSS binder and the virgin binder can be attributed to the short mixing dwell time in the HMA plants, which has been documented in previous research (4).

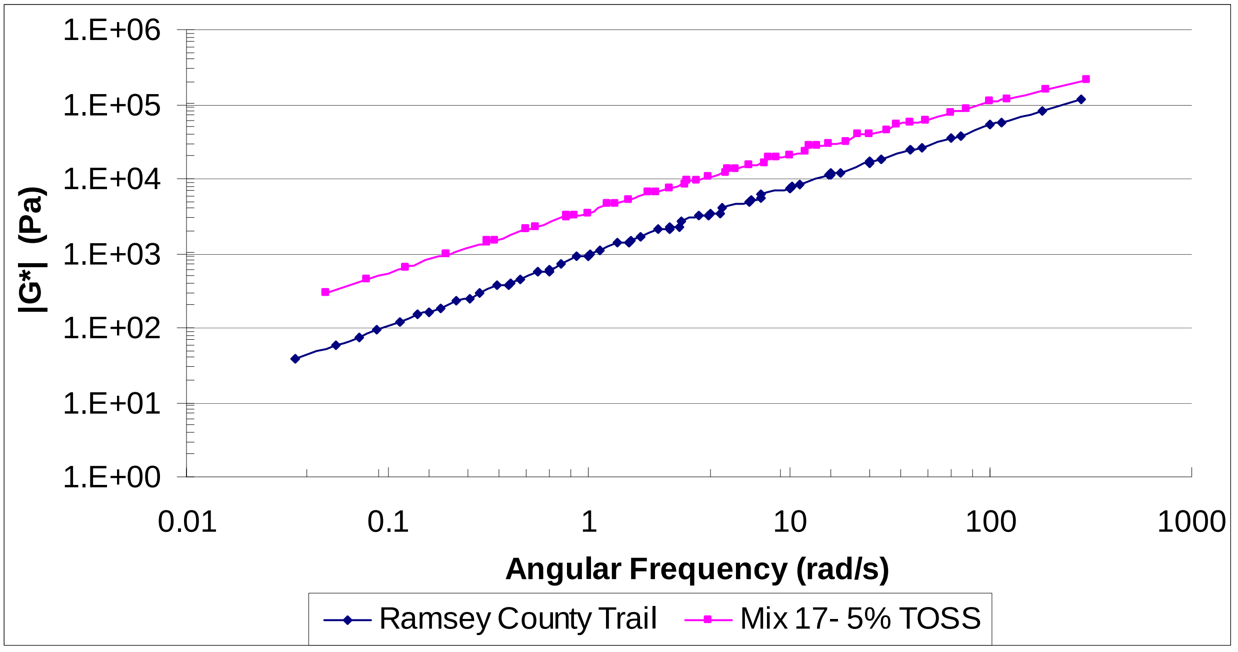

Figure 4.7. RAP/Shingles Mixture Low Temperature PG Binder Grading

In a similar manner the binder master curves from 25% RAP-plus-5% TOSS mixtures are compared in Figure 4.8. Note that the lab produced mixture is stiffer than the plant produced mixture, indicating a higher degree of blending between the TOSS binder and the virgin binder in the lab produced mix. The difference between the two curves (ratios of complex modulus) appears to be larger at the lower frequencies (high temperature) than the higher frequencies (low temperature).

Figure 4.9 shows the two plant-produced mixtures included in this study. The consistent increase in binder stiffness across all test temperatures can be primarily attributed to the 25% RAP content of the Hennepin County Road 10 mixture. Interestingly, the curves appear to be parallel indicating that the ratios of the stiffness values don't vary with temperature.

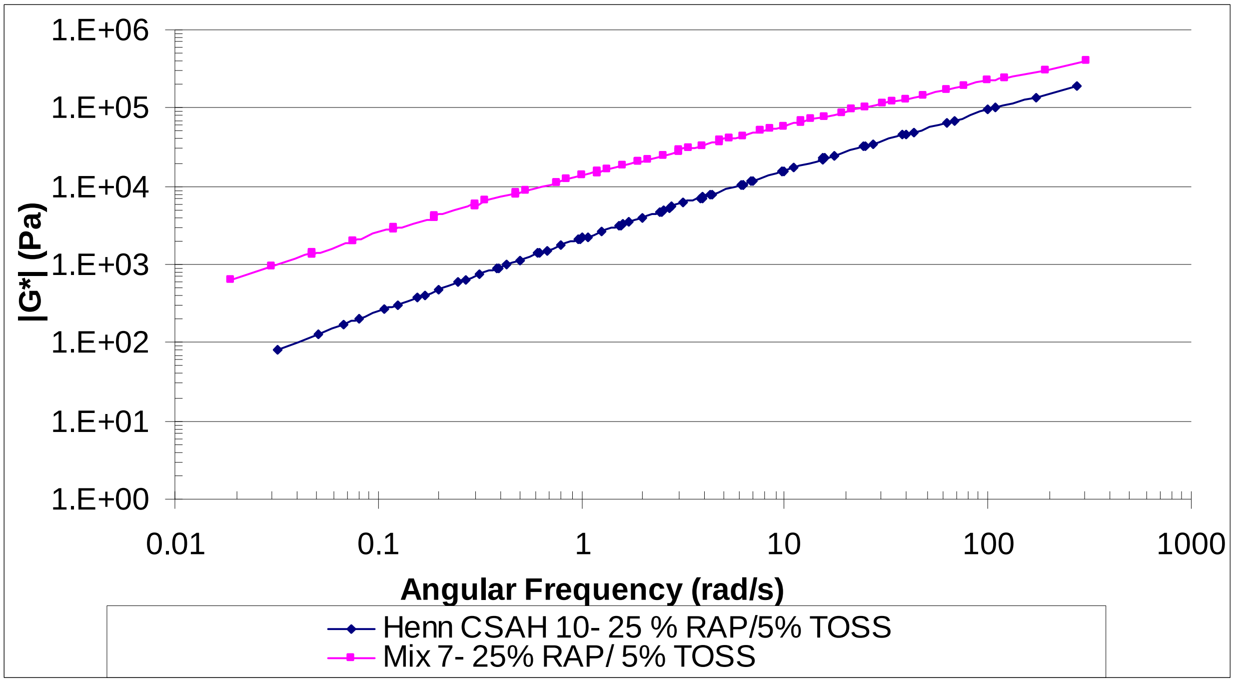

Figure 4.8. Master Curves on 25% RAP 5% TOSS Binders

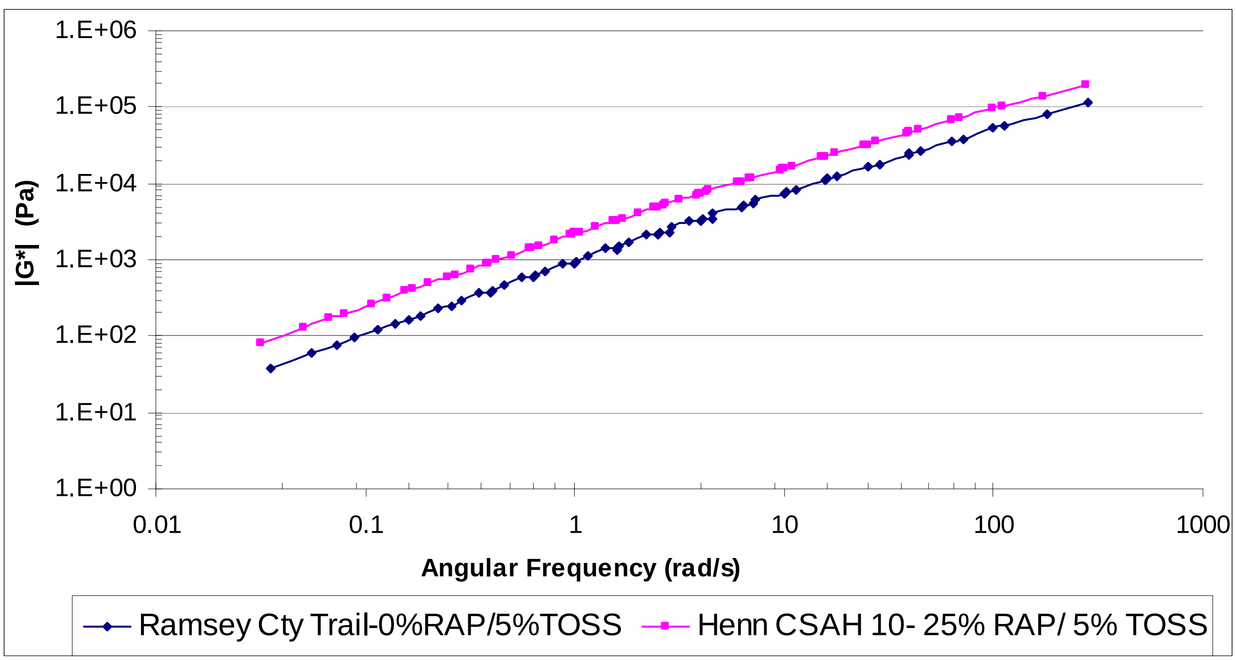

Figure 4.9. Master Curve on Plant Produced Mix Binders

Figure 4.10 depicts the stiffening effect of increasing RAP content in HMA mixtures. It can be seen that as the RAP content is reduced, the stiffness of the binder is also reduced. At the high temperature (low frequency) and intermediate temperatures there is little difference between the complex modulus curves of the 25 and 100% RAP binders. At the same time the 25% RAP mixture binder properties approaches the 15% RAP binder at lower temperatures, however there is still a visible separation. This lack of separation at intermediate temperatures may suggest that the 25% RAP mixture has low fatigue resistance, which would have to be confirmed by mixture fatigue testing. It is apparent that the 15% RAP mixture would perform better than the other tested mixtures at low temperatures due to its lower stiffness values at the lower frequencies. It is interesting to note that the 5% TOSS mixture has high temperature properties similar to the 25 and 100% RAP binders and at the lower temperatures (higher frequencies) it is very near the properties of the 15% RAP. Knowing the performance of RAP mixtures in Minnesota, we could deduce that the 5% TOSS mixture would perform similar to that of the RAP only mixtures, which would need to be verified by comparing the field performance of these types of mixtures.

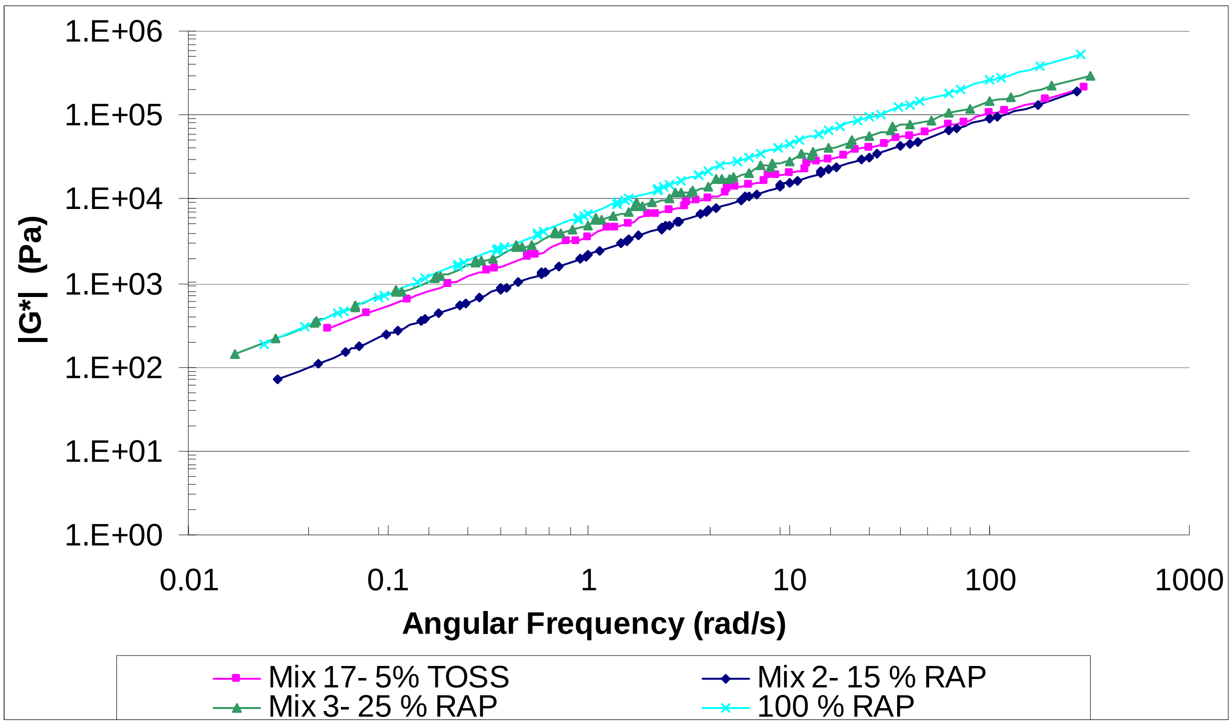

Figure 4.10. Effect of Increasing RAP

Figure 4.11 is a comparison of 5% TOSS shingle mixtures with increasing RAP contents. There is little difference between the master curves of the 10 and 15% RAP mixture binders, but a significant change is seen at the 25% RAP level. This separation might be related to percent new asphalt. The 25% RAP mixtures range from 50% to 64% new asphalt to total mixture asphalt. The 15% RAP with 5% TOSS mixture has 61% new asphalt binder to total asphalt binder ratio while the other 15% RAP mixtures are all near the 70% level and the 10% RAP with 5% TOSS mixture has 67%. This significant difference in new AC added to the mixtures appears to have a dramatic effect on the total stiffness of the mixture binder. It was established earlier that the new binder content was related to the binder high temperature PG grade.

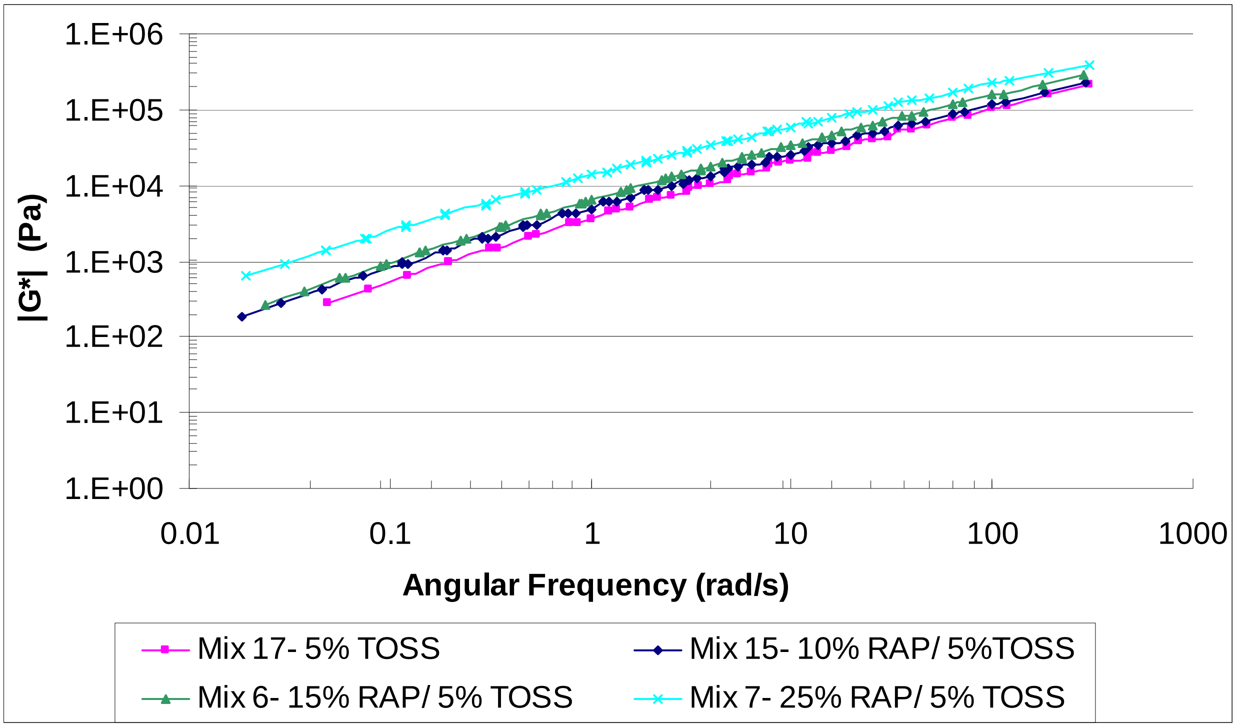

Figure 4.11. 5% TOSS Mixtures with Increasing RAP

Figure 4.12 shows that the 25% RAP mixture was stiffer when blended with 5% TOSS than with 5% MWSS binder. This would indicate that by using MWSS or by decreasing the RAS content, a mix designer could decrease the stiffness of the mixture. This might give the mix designer some latitude in determining how much RAP and RAS to add to a mix. Of course, mixture volumetric properties and other criteria must be met to produce a durable mixture. Note that there appears to be little difference between MWSS and TOSS at the 3% level.

Figure 4.13 shows that at a 15% RAP level, there is little difference between MWSS or TOSS, or the amount of RAS added up to 5%. This may be related to the amount of new asphalt binder added to these mixtures.

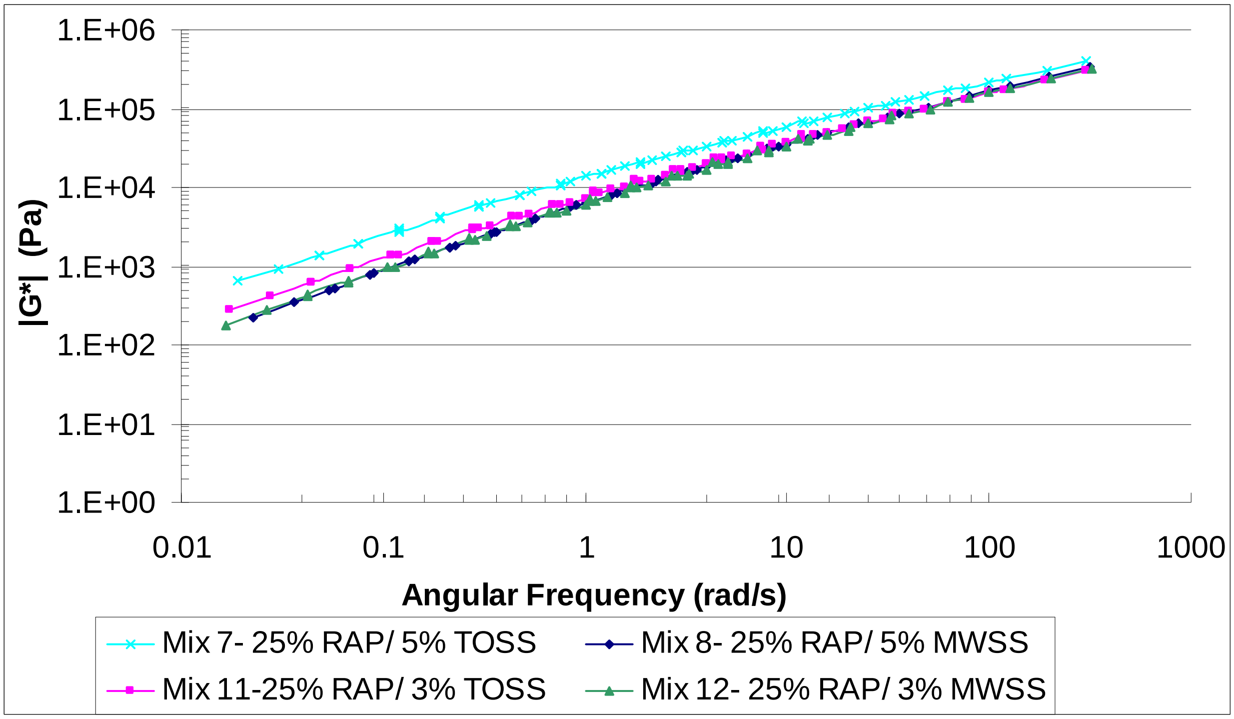

Figure 4.12. 25% RAP with 3 and 5% Shingles

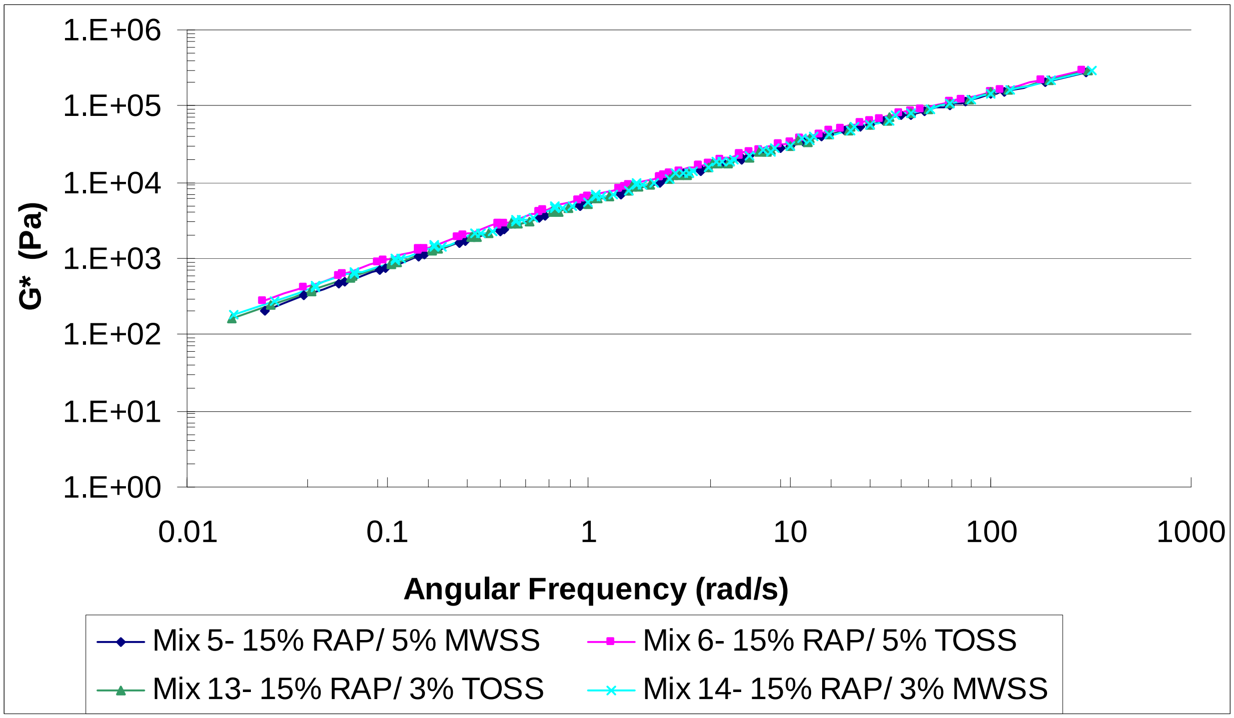

Figure 4.13. 15% RAP with 3 and 5% Shingles

As shown earlier, the binder stiffness could be decreased by using softer grade asphalt, or a softening agent. Figure 4.14 shows the dramatic effect of using a PG 51-34 binder as the virgin asphalt in mixtures. The -34 binder is consistently softer at all frequencies and the softening is much more significant for the mixtures using TOSS. Laboratory work shows MWSS and TOSS mixtures using the softer virgin binder have very similar properties. This was verified in the Hassan Township Shingle Study (4). In that study it was determined that the combination of 10% shingles along with PG 51-34 virgin binder would produce a mixture close to that of the control (PG 58-28).

It was hypothesized that changing the source of RAP, and consequently the amount of recycled asphalt binder content, would have an effect on the ratio of new to total asphalt binder in the mixture, which would affect the overall performance. Note that the binder properties of the two RAP sources are listed in Table 4.1. Figure 4.15 shows the master curves of two identical mix designs, except in RAP source (5.6% RAP AC content for Mix 6 vs. 4.0% RAP AC content for mix 16). There is virtually no observable difference between the binder master curves of the two mixtures, perhaps due to the dilution effect. The differences between master curves would most likely be more pronounced at higher RAP contents.

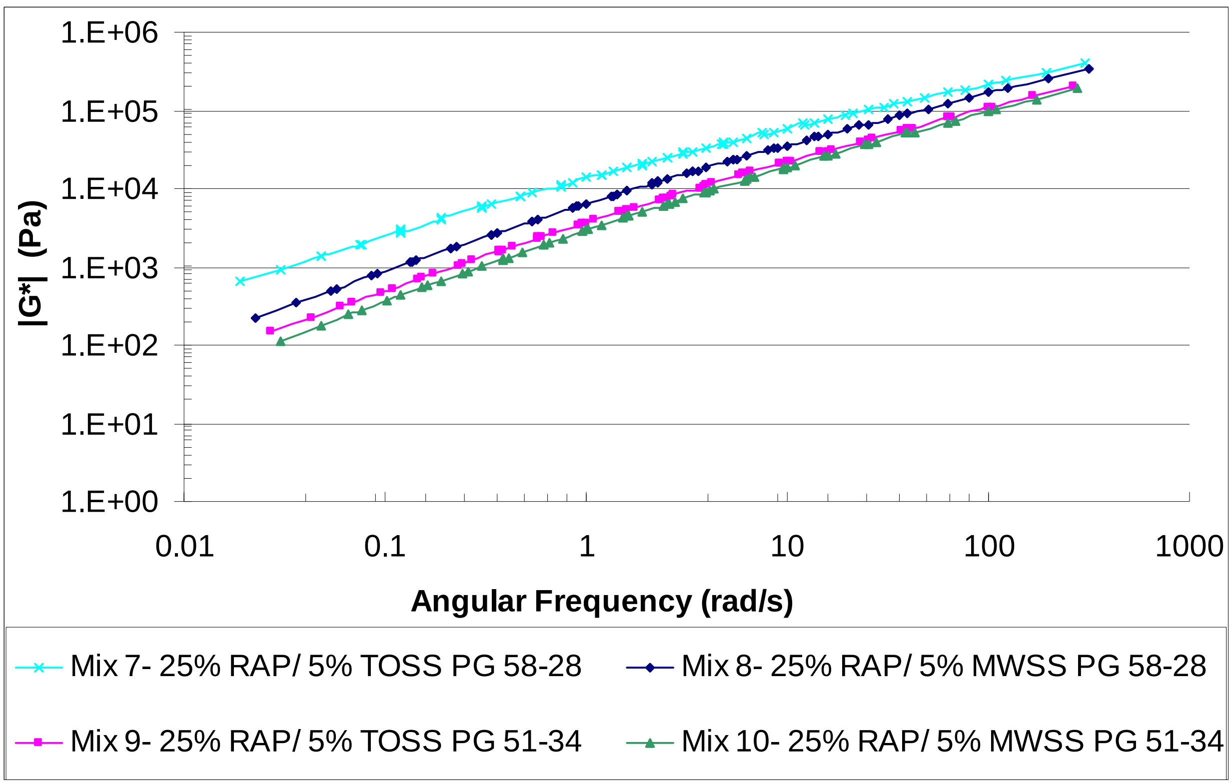

Figure 4.14. Effect of Softening with PG 51-34 Binder

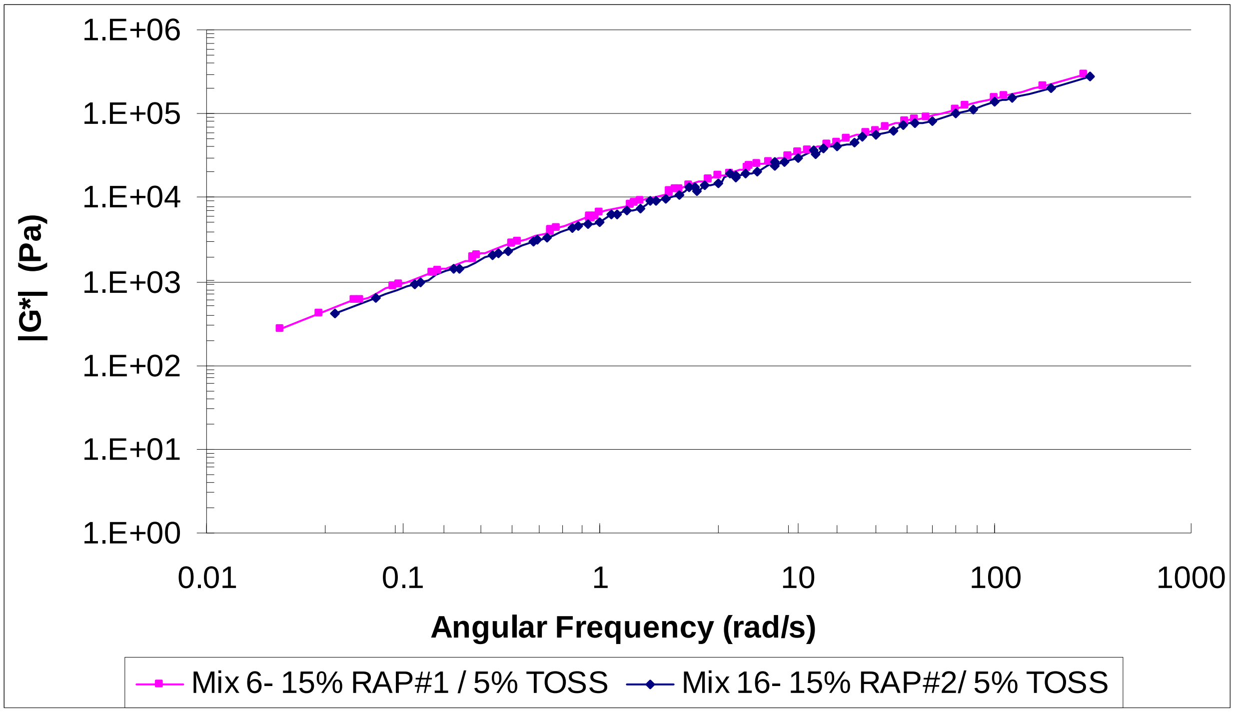

Figure 4.15. Effect of Different RAP Sources

Summary of Asphalt Binder Testing

The asphalt binder testing demonstrated that, according to binder extraction and PG grading results, TOSS binder material is stiffer than MWSS. The different effects of these two RAS binders, on the composite mix binder, are most pronounced at higher RAP concentrations (25 percent). The testing also demonstrated the stiffening effects of RAP on the composite binder properties and the softening effects of using a softer grade (PG 51-34) binder. The conclusions that can be drawn from these asphalt binder tests are limited because the RAS/RAP binders completely combine with the virgin asphalt binder, which is not representative of HMA mixtures incorporating RAS/RAP.

Asphalt Mixture Testing

Dynamic Modulus Testing and Mixture Master Curves

The dynamic modulus laboratory testing consisted of subjecting asphalt mixture specimens to sinusoidal loading in order to characterize the viscoelastic responses across a range of temperatures and loading frequencies. The dynamic modulus (E*) is a measure of the material stiffness, and is calculated by dividing the peak-to-peak stress by the peak-to-peak strain. The absolute value of the measured dynamic modulus (|E*|) can be used to compare mixture stiffness and assist in the characterization necessary for mechanistic-empirical pavement design.

The dynamic modulus of samples collected from this project was determined using an Interlaken Universal Material Testing machine in the Mn/DOT Maplewood Laboratory. The testing apparatus uses a servo-hydraulic, computer-controlled, closed-loop system, which also contains a tri-axial cell and environmental chamber as shown in Figure 4.16. Three Linear Variable Differential Transducers (LVDTs) were used to measure specimen deformation also shown in Figure 4.16.

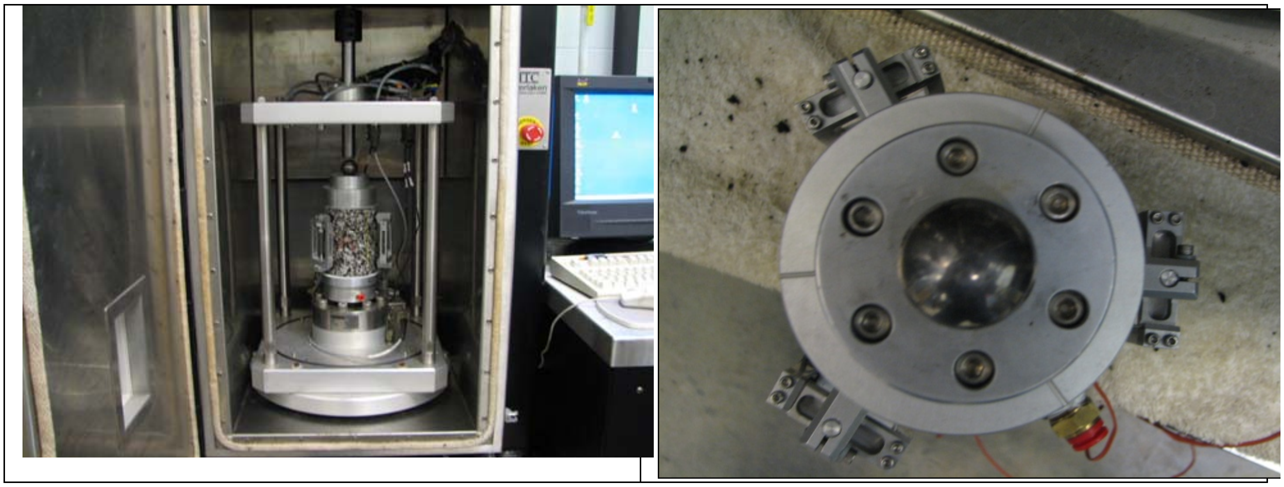

Figure 4.16. Dynamic Modulus Testing Apparatus and LVDT Setup

The dynamic modulus test was performed on a minimum of two samples representing each of the 17 mixtures containing various amounts of RAS and RAP as described earlier. The testing was performed in accordance with AASHTO TP62 which included six loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) and five temperatures (10, 40, 70,100 and 130 ºF). Mixtures containing the PG 51-34 binder could not be tested at the highest temperature (130 ºF), due to the softness of the mixture preventing a secure fit of the LVDTs.

Dynamic modulus mater curves were developed according to basic time-temperature superposition theory, which allows data to be shifted about a predetermined reference temperature. The test data was fitted with respect to a reference temperature of 70 ºF (21 ºC) and the |E*| data was imported to a spreadsheet program where the equation parameters were developed based on sigmoidal function given in equation 1, such that the sum of the least squares was minimized.

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta-\gamma\log(f\ +S_T)}} \qquad \text{Equation 1.}$$

Where:
δ is the minimum value of |E*|
$\delta + \alpha$ is the maximum value
f and S_T describe the frequency shifted at the reference temperature
β and γ are parameters describing the shape of the sigmoidal function

Figure 4.17 shows a typical mixture master curve, which represents the mixture's behavior over a range of temperatures and loading frequencies, and will be invaluable in comparing the mixture's performance. Note that the mixture master curves capture how well the RAS/RAP binder mixes with the new, or virgin, asphalt binder. Thus these master curves serve as a much better representation of actual mixture performance than the binder master curves, which completely blends RAS/RAP and virgin binders during the extraction/recovery process.

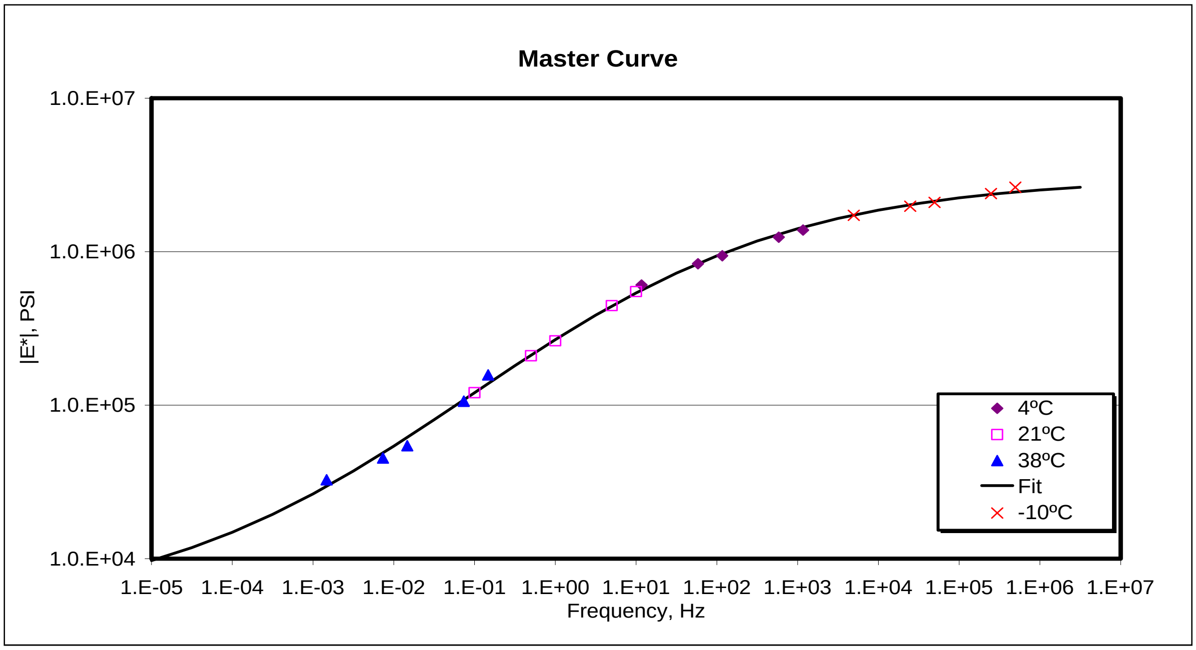

Figure 4.17. A Typical Dynamic Modulus Curve

Figure 4.18 shows comparison of RAP effects on dynamic modulus. In general, the modulus increases as RAP content increases and these differences appear to be more pronounced at the lower frequencies (higher temperatures) than the higher frequencies (lower test temperatures). However, as was the case with the binder complex modulus results presented earlier, the master curves were plotted on a set of logarithmic axes. This convention tends to graphically compress high numeric values and emphasize differences at low numeric values. The dynamic modulus curve of the 30% RAP mixture is noticeably higher than that of the control (Mix 1), which contains no RAP.

Figure 4.19 shows the master curves of mix 7 and 8, both of which contain 25% RAP and either 5% TOSS or 5% MWSS respectively to illustrate the difference between using MWSS and TOSS. Each mixture type was tested at least twice as shown by the dashed and solid lines; the similar results between replicates suggest that the testing procedure is very repeatable. This figure is important because it demonstrates that there is in fact a difference in mixture performance between TOSS and MWSS at the 5% level, they are not the same product. The TOSS stiffens the mix more than the MWSS; this could be due to more complete mixing of the TOSS, due to its finer gradation, or the fact that the TOSS binder is stiffer than the MWSS binder, or a combination of both.

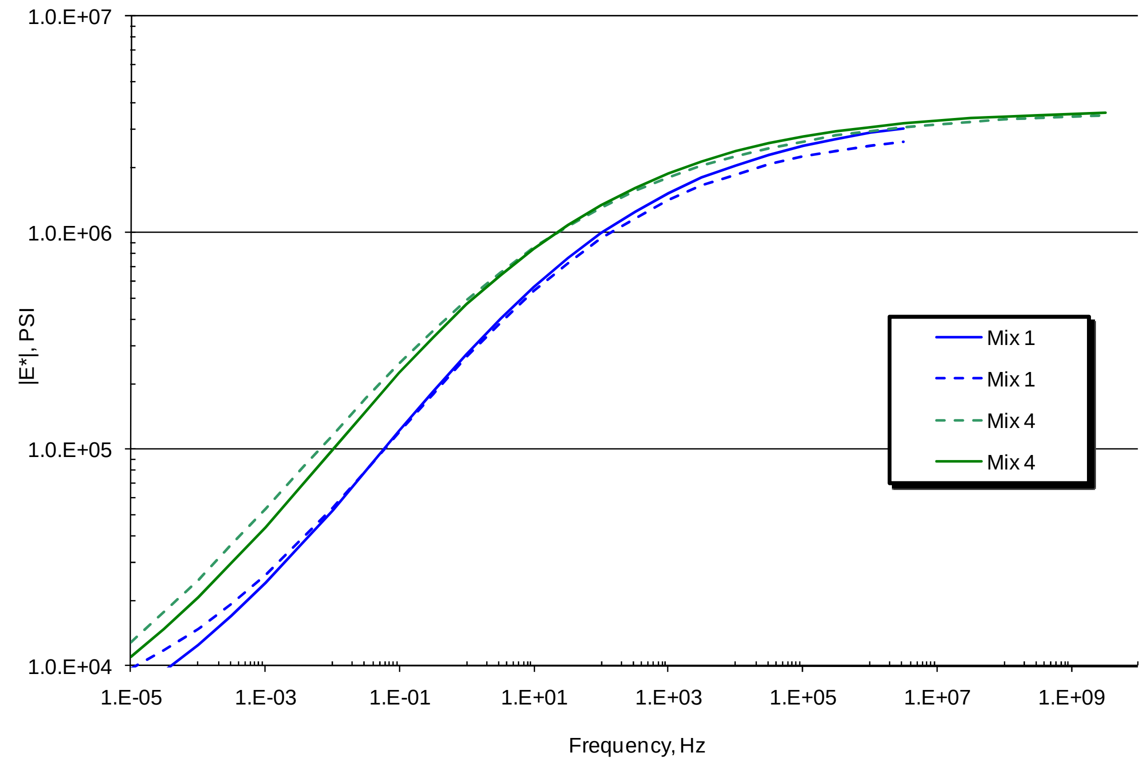

Figure 4.18. RAP Effects on |E*| Mix 1 (Control) and Mix 4 (30% RAP)

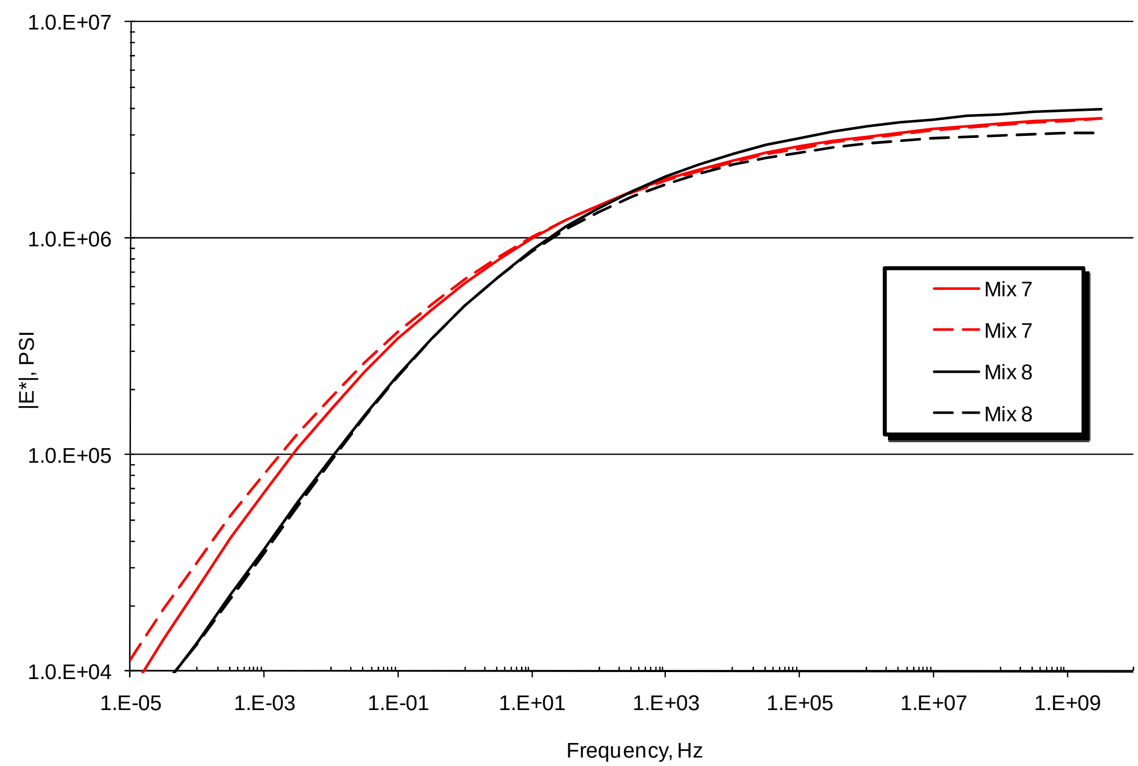

Figure 4.19. |E*| of Mix 7 (25% RAP/5% TOSS) and Mix 8 (25% RAP/5% MWSS)

Figure 4.20 shows mix 7 and 8, as well as the control mix, not surprisingly the addition of recycled materials stiffens the mixture. Mix 7 appears to be stiffer than Mix 8, suggesting that TOSS has a stiffer binder than the MWSS, which is expected due to the increased aging of TOSS through long term exposure to oxidation, solar radiation and high temperatures, which was confirmed earlier through binder extraction and gradation (Table 4.2). It is interesting to note the difference between the control (Mix 1) and Mix 8 appears to be similar as the difference between Mix 7 and Mix 8 at certain frequencies, which is a very significant difference. This large difference in performance between the MWSS and TOSS RAS sources was not expected to be as large as the difference between a virgin mix and a MWSS mix.

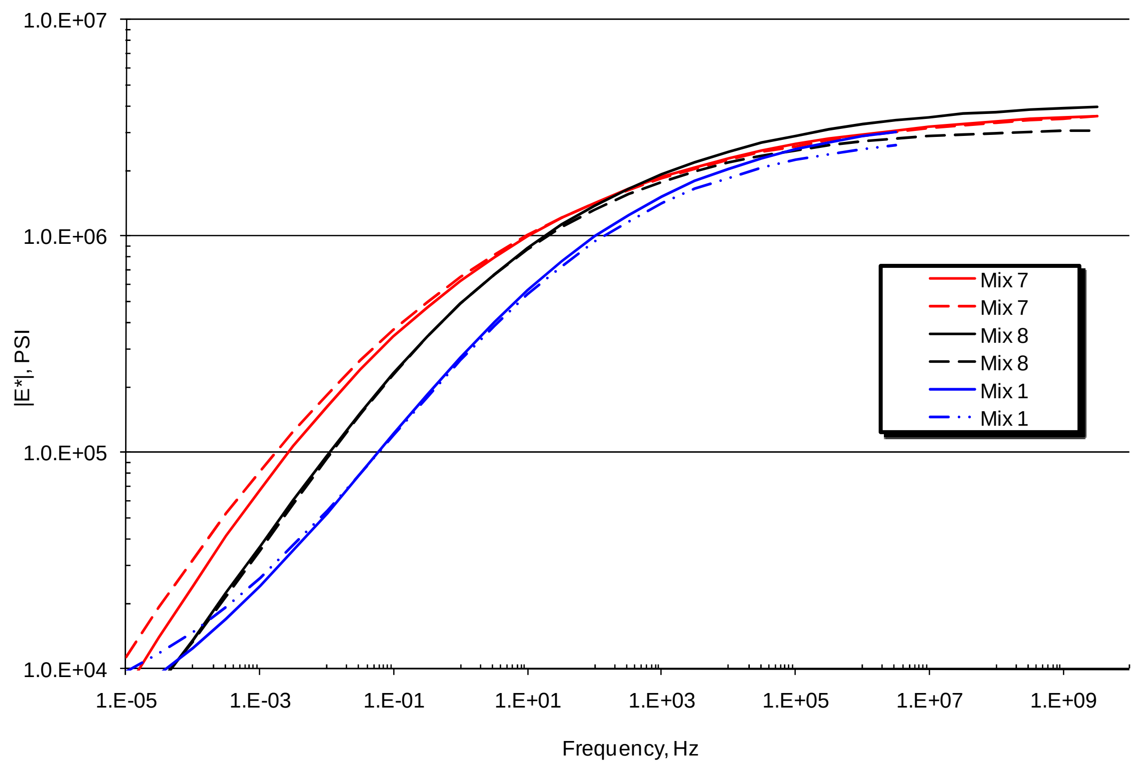

Figure 4.20. |E*| of Mix 1, Mix 7 (25% RAP/5% TOSS) and Mix 8 (25% RAP/5% MWSS)

Figure 4.21 shows mixtures 5 and 6, both of which contain 15% RAP and either 5% MWSS or 5% TOSS respectively. Again the mixture containing TOSS is stiffer than the mixture containing MWSS and the ratio of the modulus values are the greatest at the lowest frequencies (higher temperatures). Note that the mixes appear to be parallel in the low to mid frequencies.

Figure 4.22 shows mixtures 9 and 10 both of which contain 25% RAP and either 5% TOSS or 5% MWSS respectively; however these mixtures differ from mixes 7 and 8 in that they contain a softer binder (PG 51-34). The softer grade binder (PG 51-34) appears to make the mixture softer, and the master curve smoother and more gradual than the same mix with the stiffer (PG 58-28) binder.

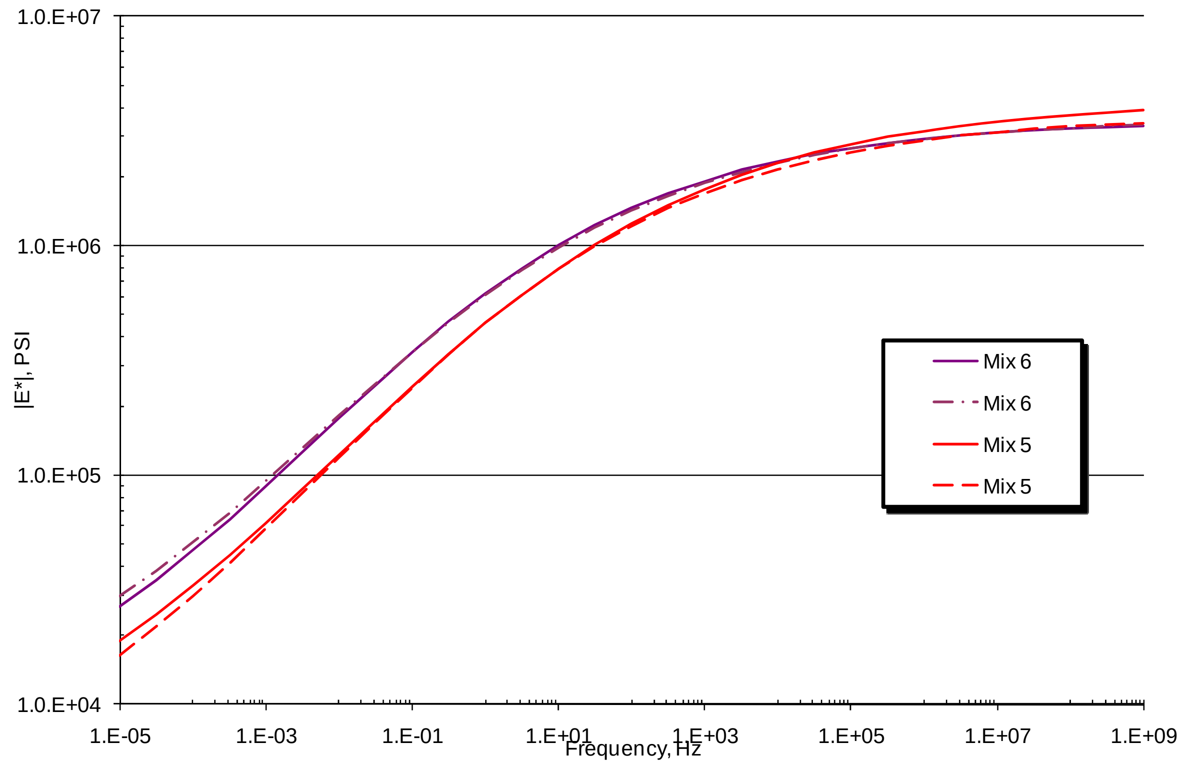

Figure 4.21. |E*| of Mix 5 (15% RAP/5% MWSS) and Mix 6 (15% RAP/5% TOSS)

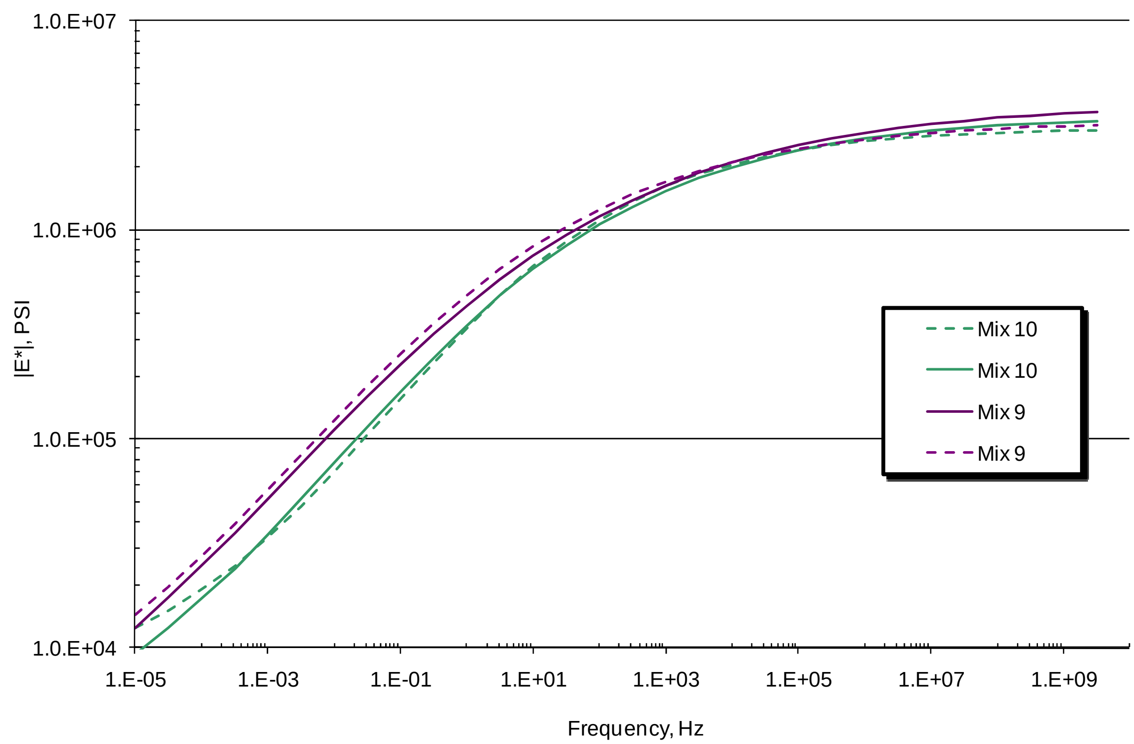

Figure 4.22. |E*| of Mix 9 (25% RAP/5% TOSS) and Mix 10 (25% RAP/5% MWSS)

Figure 4.23 shows the dynamic modulus results of mix 7 and a plant produced mixture collected from a production paving project in Hennepin County. Mix 7 and Hennepin County had 50% and 64% new asphalt binder to total binder ratios and target AC contents of 5.4% and 5.6%, respectively. Both mixtures contain the same binder grade, the same percentage of RAP (25%), as well as the same type and source of RAS (5% TOSS). The primary difference between the two mixtures is the production method: laboratory vs. plant. The lab produced mixture is stiffer than the plant produced mixture, suggesting that greater mixing is occurring in the laboratory. This underscores a research need to find laboratory mixing methods that more closely match plant production mixing results.

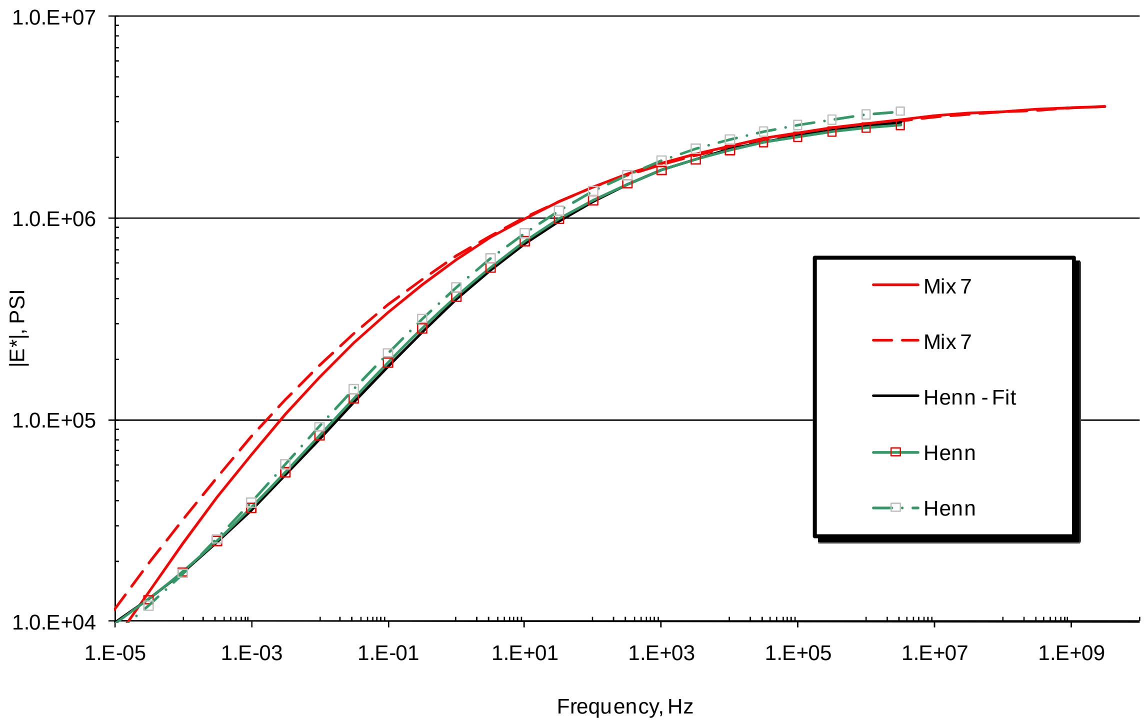

Figure 4.23. Comparison of Plant Produced Mix with Lab Produced Mix (25% RAP/5% TOSS)

Figure 4.24 shows the master curves of mixtures 11 and 12 both of which contain 25% RAP and either 3% TOSS or 3% MWSS respectively. Figure 4.25 shows the master curves of mixtures 13 and 14 both of which contain 15% RAP and either 3% TOSS or 3% MWSS respectively. From both figures, there is little observable difference between the MWSS and TOSS, suggesting that differences between TOSS and MWSS are minimized at the 3% level and when combined with either 15, or 25% RAP. This result is unexpected, as it was established earlier that TOSS and MWSS are in fact different products and both had very different effects on the mixture at the 5% level.

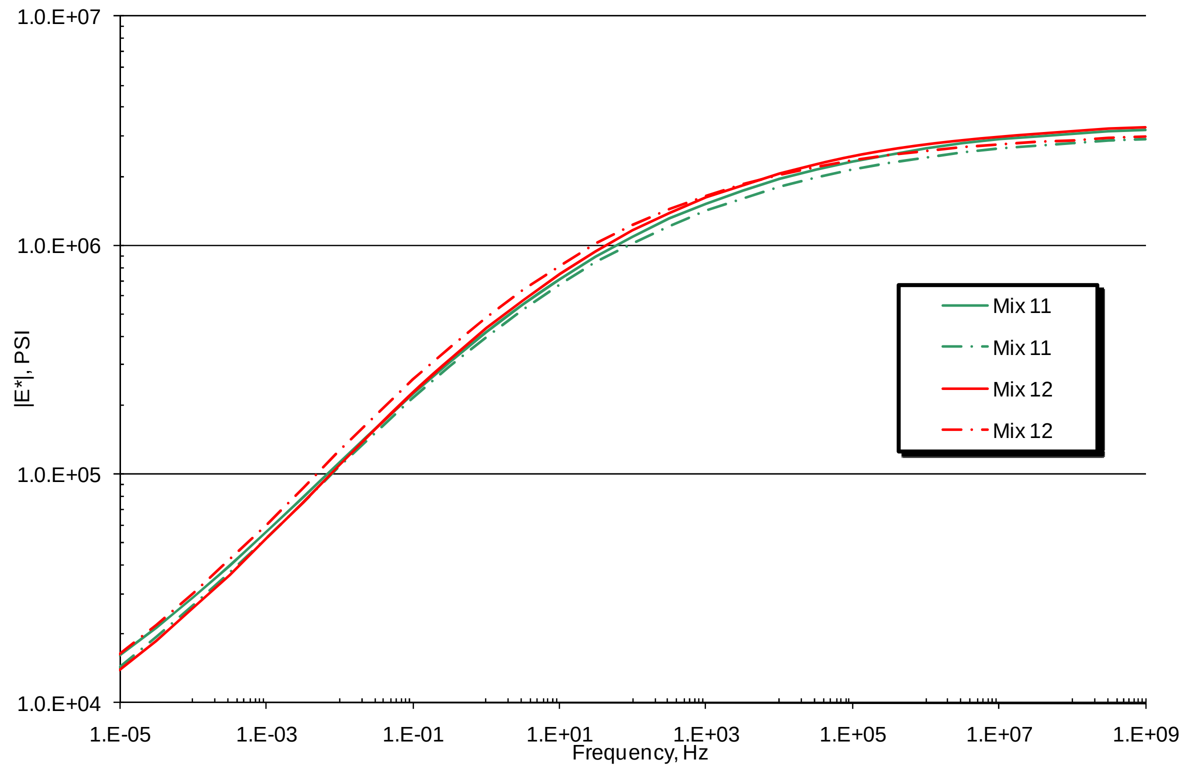

Figure 4.24. |E*| of Mix 11 (25% RAP/3% TOSS) and Mix 12 (25% RAP/3% MWSS)

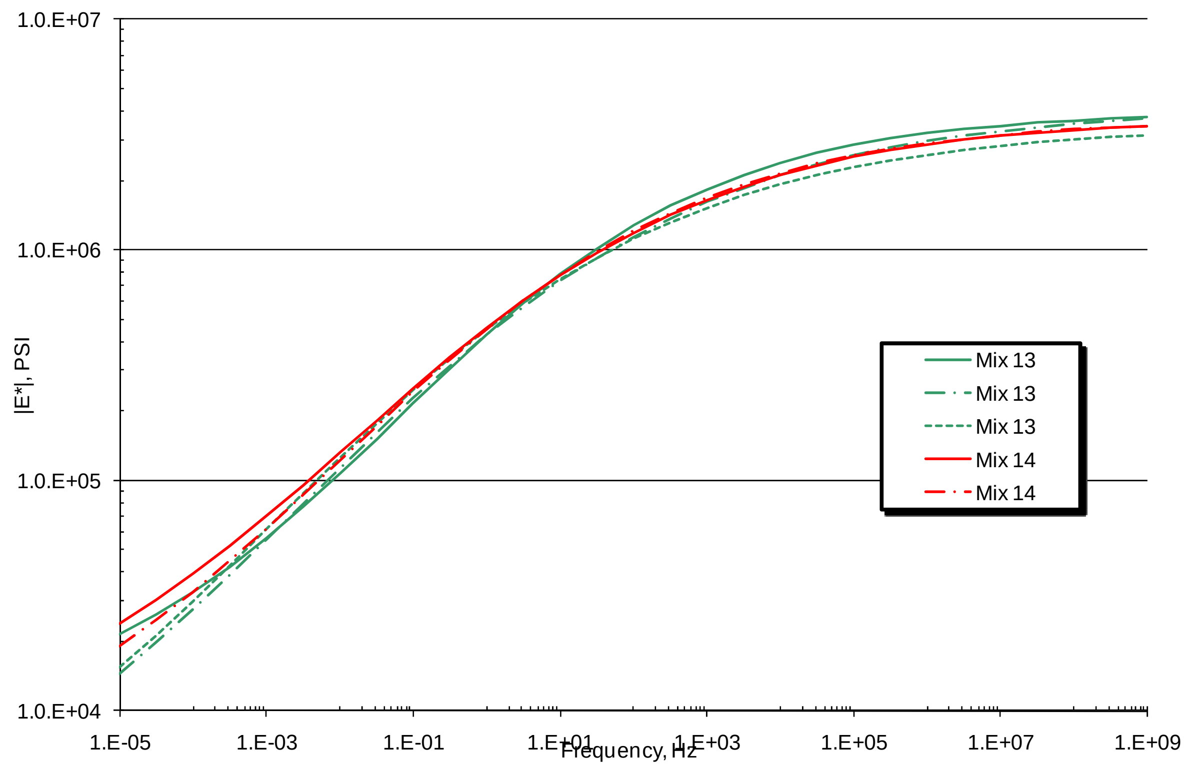

Figure 4.25. |E*| of Mix 13 (15% RAP/3% TOSS) and Mix 14 (15% RAP/3% MWSS)

Figure 4.26 to Figure 4.27 show comparative plots of |E*| for all 17 different mixture types for test temperatures of 10 and 100 ºF, respectively. The mixtures are arranged in order, from left to right, in increasing new binder to total binder ratio (% new AC) and the total recycled materials content in terms of RAP, RAS as well as the mix number are also designated. A vertical red line is drawn at the 70% mark (the current virgin binder to total binder ratio specified in the Mn/DOT shingle specifications, Appendix A). As expected, the stiffness decreases with increasing temperature and decreasing frequency. There appears to be little observable difference between mixtures on either side of the red line. At 100 ºF Mix 17 (5% TOSS) appears to behave similarly to Mix 2 (15% RAP), which demonstrates the dramatic stiffening effect of TOSS compared to RAP.

For each test temperature, dynamic modulus was plotted against the percent new AC content. Figure 4.28 shows the greatest correlation among the test temperatures, which occurred at 10 HZ and 100 ºF. If the PG 51-34 data points, circled in red, are removed, then the fit becomes much better with an R^2 value of 0.57 instead of 0.40. The data point circled in blue appears to be an outlier, and if removed, the R^2 value becomes 0.75. This trend indicates that, the mixture becomes less stiff with decreasing proportion of virgin binder. This inverse relationship between stiffness and new binder content (decreasing stiffness with increasing proportion of virgin binder) confirms the binder test results, which indicated that there are differences in performance between mixtures with differing proportions of virgin asphalt binder. These differences appear to be most evident at the higher test temperatures.

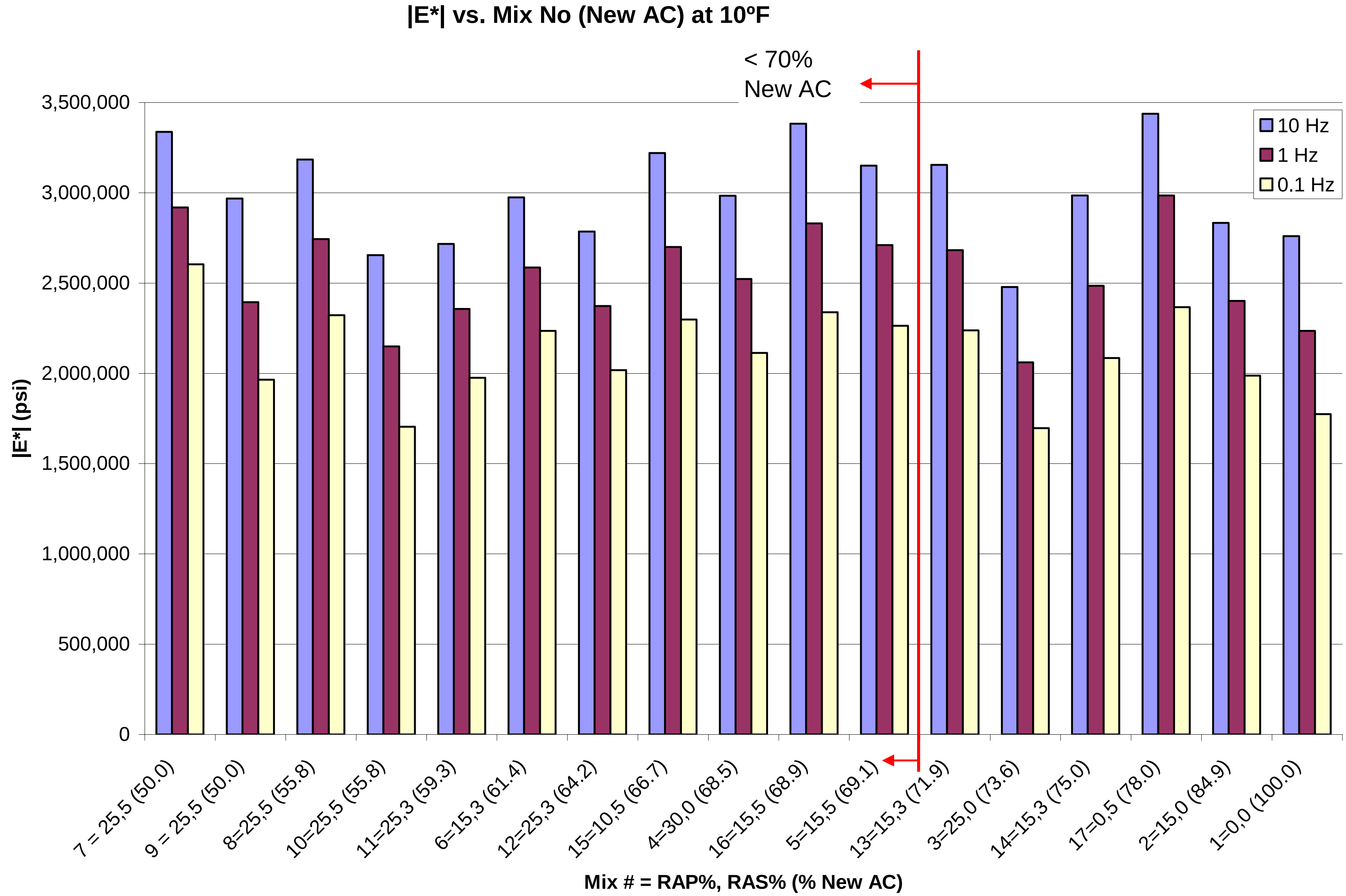

Figure 4.26. |E*| vs. Mix No. (New AC) at 10 ºF

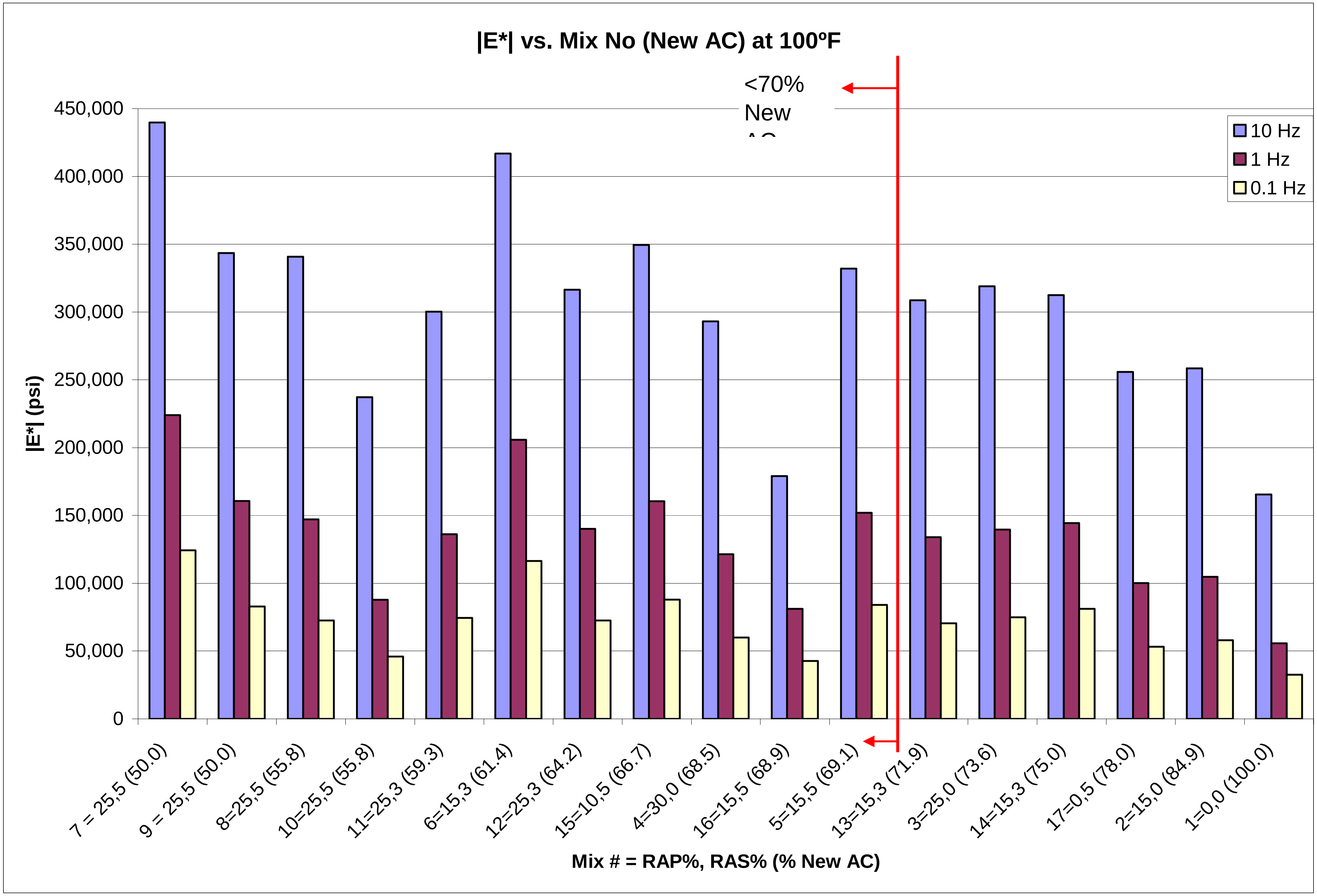

Figure 4.27. |E*| vs. Mix No. at 100 ºF

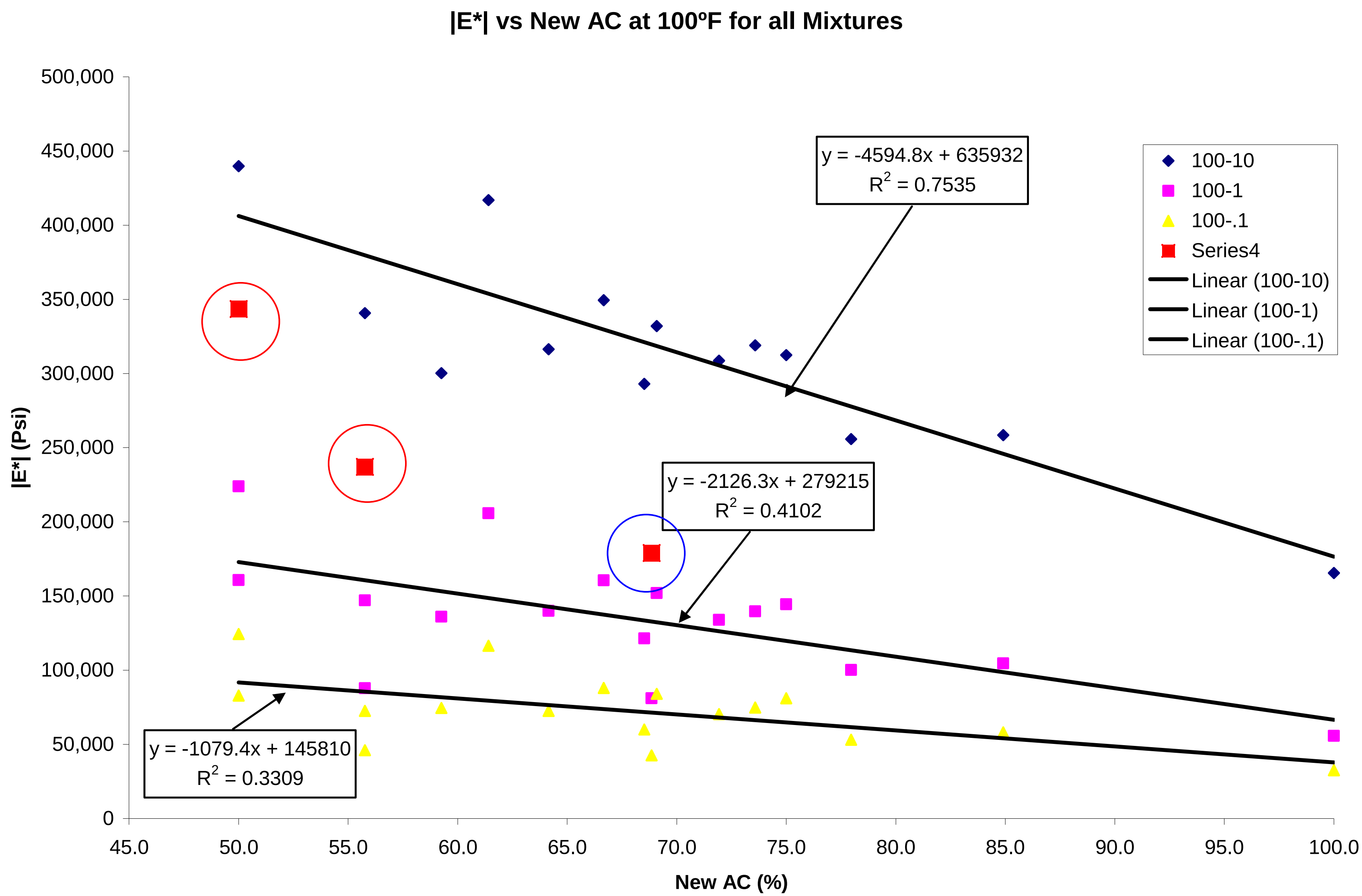

Figure 4.28. |E*| vs. % New AC at 100 ºF

Predicting |E*| with the Hirsch Model

The Hirsch model was first developed by T.J. Hirsch in the early 1960s and later refined by Christensen, Pellinen, and Bonaquist (10 - 12). The Hirsch concept models the behavior of HMA by combining volume fractions of the various material phases such as modulus values for aggregate and asphalt binder and also volumetric design parameters. The model presented in Equation 2 is used to predict the dynamic compressive (|E*|) modulus of HMA.

$$|E^*|_{mix} = Pc\left[4{,}200{,}000\left(1 - VMA/100\right) + 3|G^*|_{binder}\left(\frac{VFA \times VMA}{10{,}000}\right)\right] + \left(1 - Pc\right)\left[\frac{1 - VMA/100}{4{,}200{,}000} + \frac{VMA}{3VFA|G^*|_{binder}}\right]^{-1} \quad (2a)$$

where:

$$Pc = \frac{\left(20 + \frac{VFA \times 3|G^*|_{binder}}{VMA}\right)^{0.58}}{650 + \left(\frac{VFA \times 3|G^*|_{binder}}{VMA}\right)^{0.58}} \quad (2b)$$

$|E^*|_{mix}$ = predicted dynamic modulus of the mixture, psi
VMA = voids in mineral aggregate, %
VFA = voids filled with asphalt, %
$|G^*|_{binder}$ = measured complex modulus of the binder, psi

In order to effectively use the Hirsh model, the binder and mixture data must be represented in consistent units. In this case rheometer testing was performed with the objective of comparing modeled mixture master curves with those from actual tests. The Hirsch equation was applied to generate mixture modulus values at 0.1, 0.5, 1.0, 5.0, and 10.0 Hz at four temperatures (54.4, 37.8, 21.1, and 4.4 ºC). The resulting Hirsch |E*| data was used to generate mixture master curves at a temperature identical to the mixture test master curves (70 ºF, 21.1 ºC). Figure 4.29 compares the predicted |E*| (obtained from |G*| of PG 58-28) against |E*| obtained from performing dynamic modulus tests on mix 1 (control). The model predicts the actual performance reasonably well; however the model does over predict the stiffness at lower frequencies.

Figure 4.30 compares the predicted |E*| (obtained from |G*| of extracted binder from mix 6) against |E*| obtained from performing dynamic modulus tests on mix 6, which had 15% RAP and 5% TOSS. The model predicts the actual performance very well indicating that the mixture was well mixed.

Predicting |E*| using the Hirsch model needs to be conducted on plant produced HMA. It would be expected that the mixture |E*| would be lower than the calculated |E*|. Additional testing is necessary to verify this. However due to the apparent repeatability of this technique, it may be possible to use the Hirsch model to predict |E*| with binder testing.

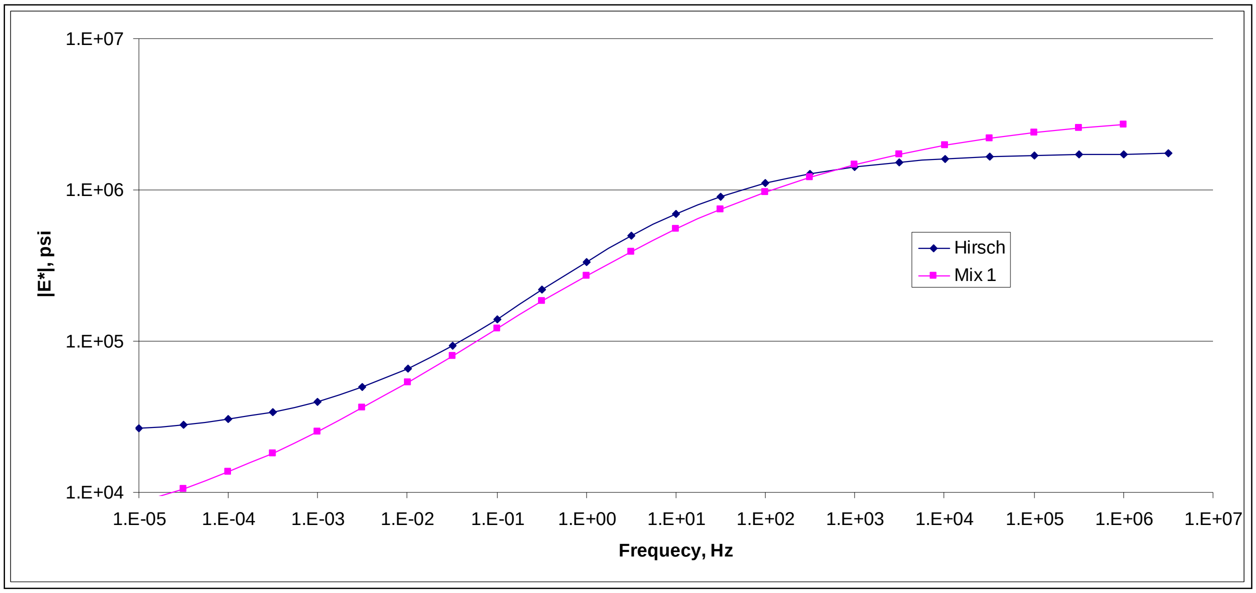

Figure 4.29. Comparison of Predicted |E*| (from G* of PG 58-28) vs. Measured |E*| (Mix 1)

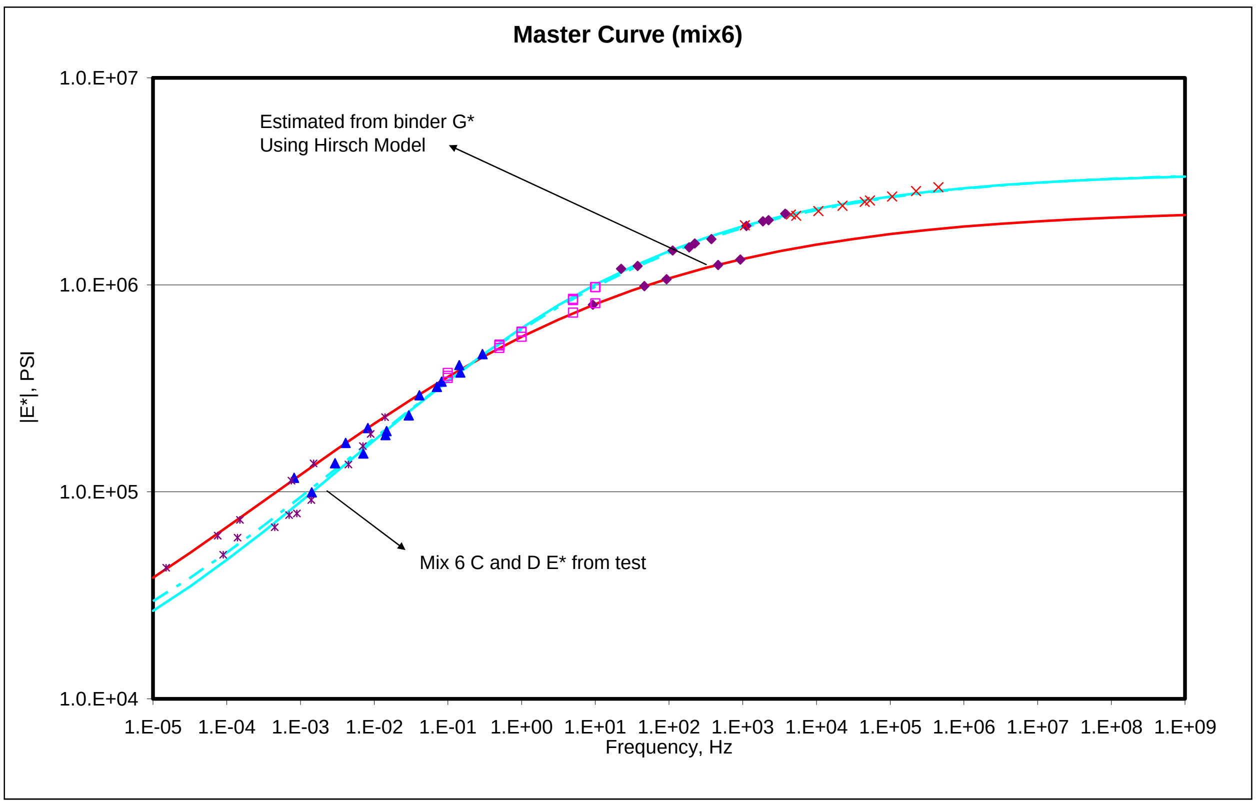

Figure 4.30. Comparison of Predicted |E*| (from Binder G*) vs. Measured |E*| (Mix 6)

Rutting Susceptibility – APA Testing

The asphalt pavement analyzer (APA) device, as shown in Figure 4.31, was used to experimentally evaluate the mixture's susceptibility to rutting. The test consisted of applying 8,000 cycles of 100 lbf strokes to the lab-produced gyratory specimens at 137 ºF (58ºC), which is approximately equivalent to 1,000,000 ESALS. A mixture's susceptibility to rutting is typically dependent upon the binder (content and stiffness) as well as the gradation of the mixture and air void content. Higher rut depths indicate a softer mixture where lower rut depths indicate a stiffer mixture; typical level three mixtures evaluated by Mn/DOT have rut depths between 6 – 10mm. The APA results were analyzed to isolate the effects of:

- RAP content
- Shingle Content
- Different shingle source
- Using a softer binder

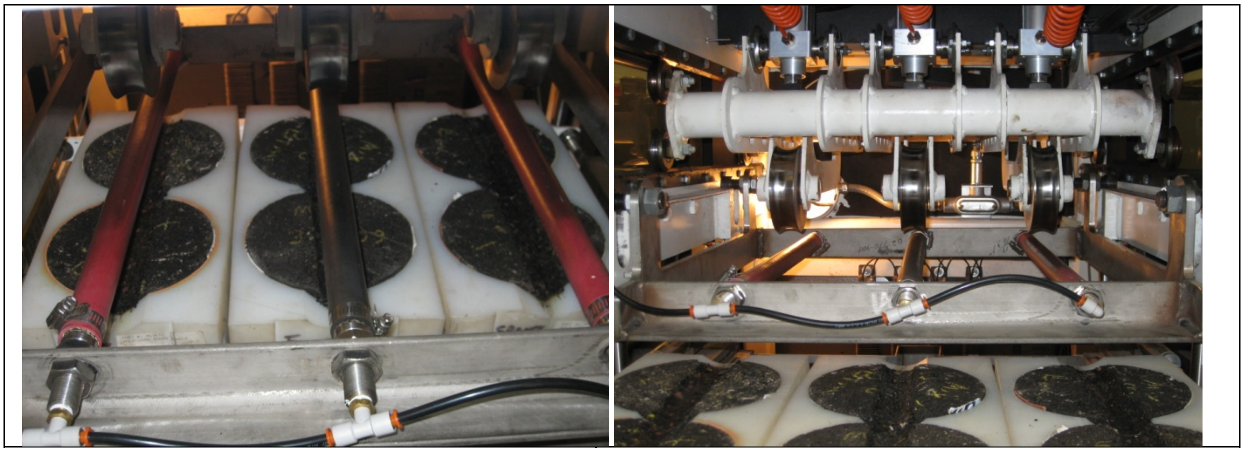

Figure 4.31. Asphalt Pavement Analyzer (APA) or Rut Tester

Figure 4.32 shows the rut depth after 8,000 strokes for all tested mixtures. Figure 4.33 and Figure 4.34 show the effect of the different type of shingles at 5% (MWSS and TOSS) at a given RAP content of 25 and 15% respectively. Note that the rut depth of the TOSS mixtures don’t change significantly with changes in RAP content, but the MWSS does change significantly, exhibiting more than a 3mm change in rut depth. Note also that the rut depth of MWSS mixtures is consistently higher than the TOSS mixtures in all instances, indicating that TOSS has a greater stiffening effect on the mixture than MWSS. Figure 4.35 shows the effect of the PG -34 binder, which increases the rut depth (as expected). Figure 4.36 shows the effect of shingle type (MWSS and TOSS) at 3% and 25% RAP, note that the differences are much less pronounced than at the 5% shingle level, but the MWSS still exhibits higher rutting than the TOSS.

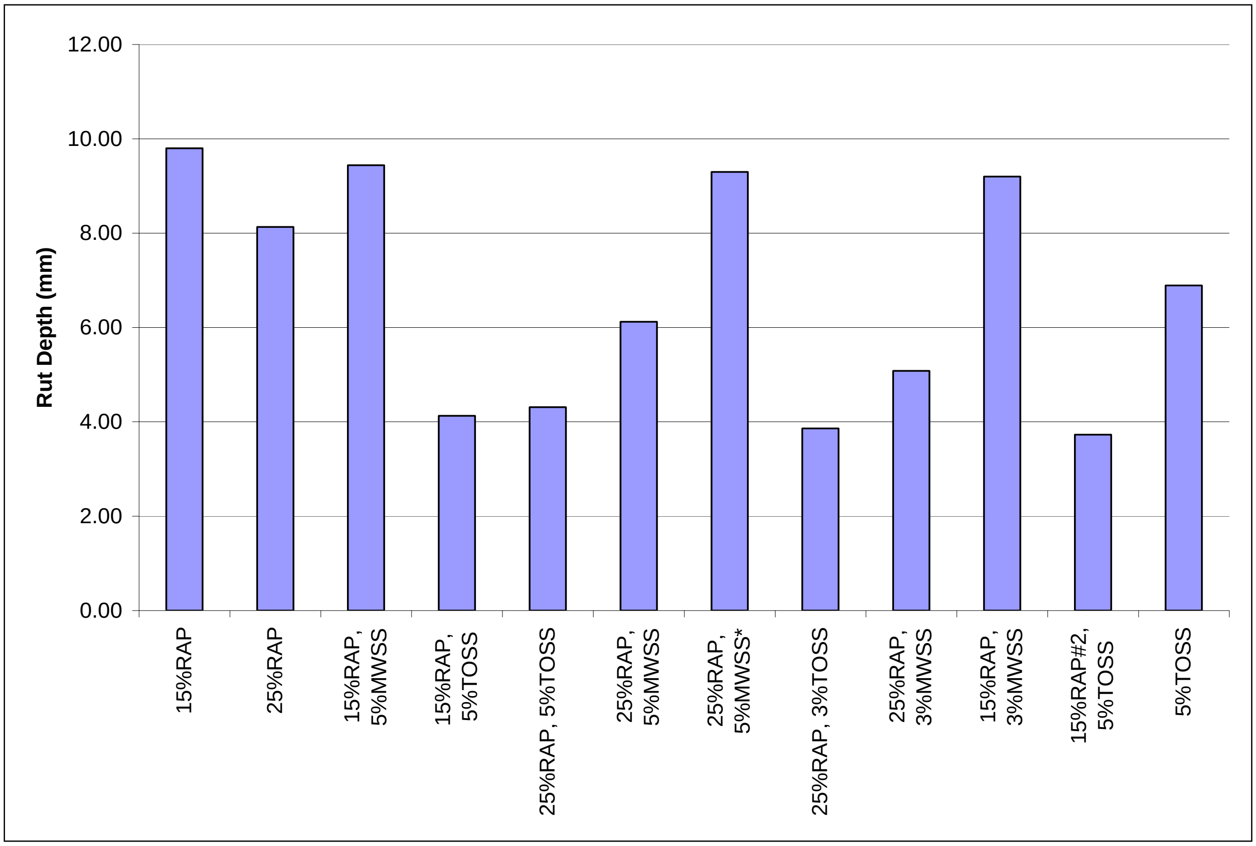

Figure 4.32. Rut Depth after 8,000 Strokes

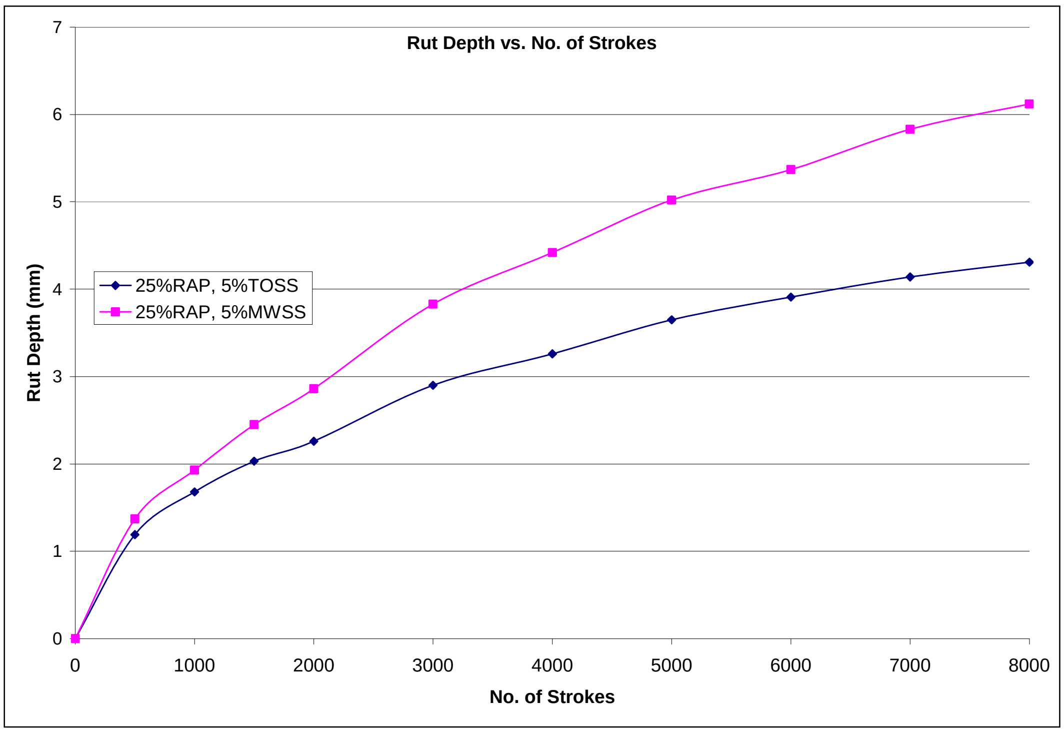

Figure 4.33. Rut Depth vs. No. of Strokes for Mixes 7 & 8 (Shingle Type @ 5 & 25% RAP)

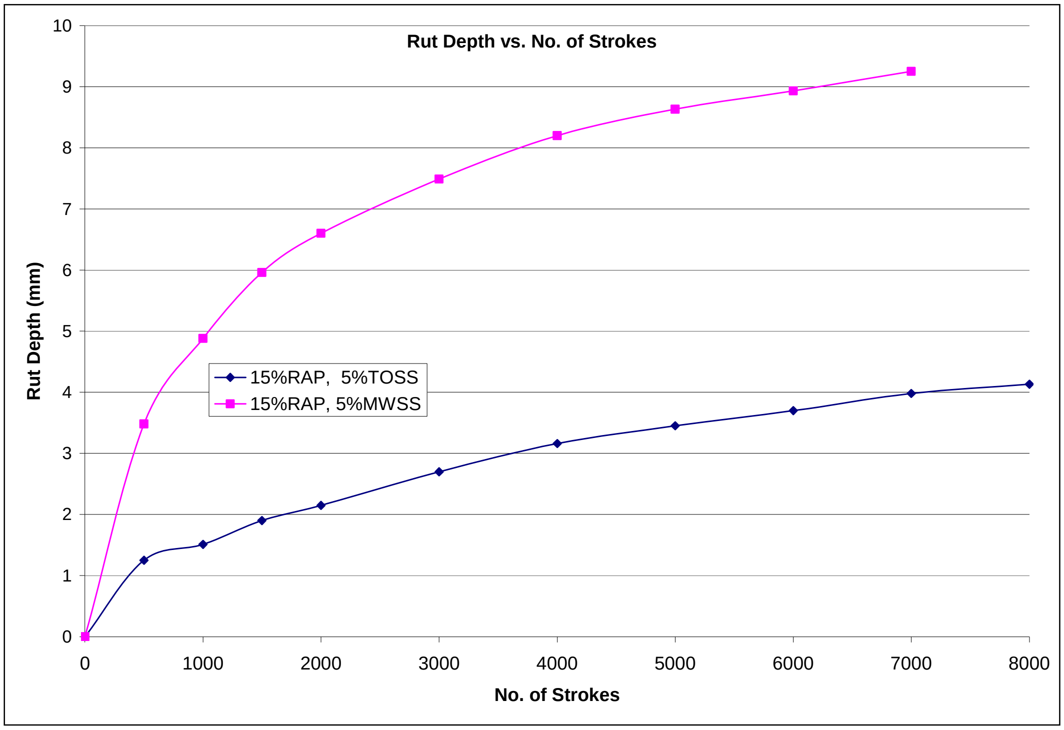

Figure 4.34. Rut Depth vs. No. of Strokes for Mixes 5 & 6 (Shingle Type @ 5 & 15% RAP)

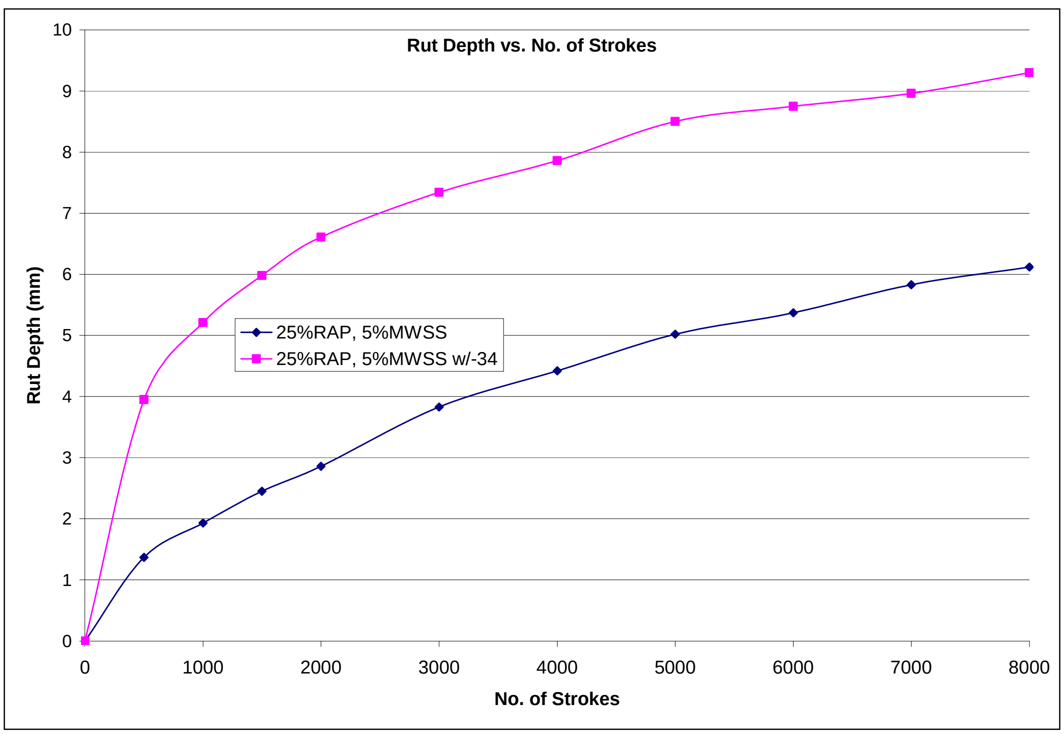

Figure 4.35. Rut Depth vs. No. of Strokes for Mixes 8 & 10 (Effect of -34 Binder)

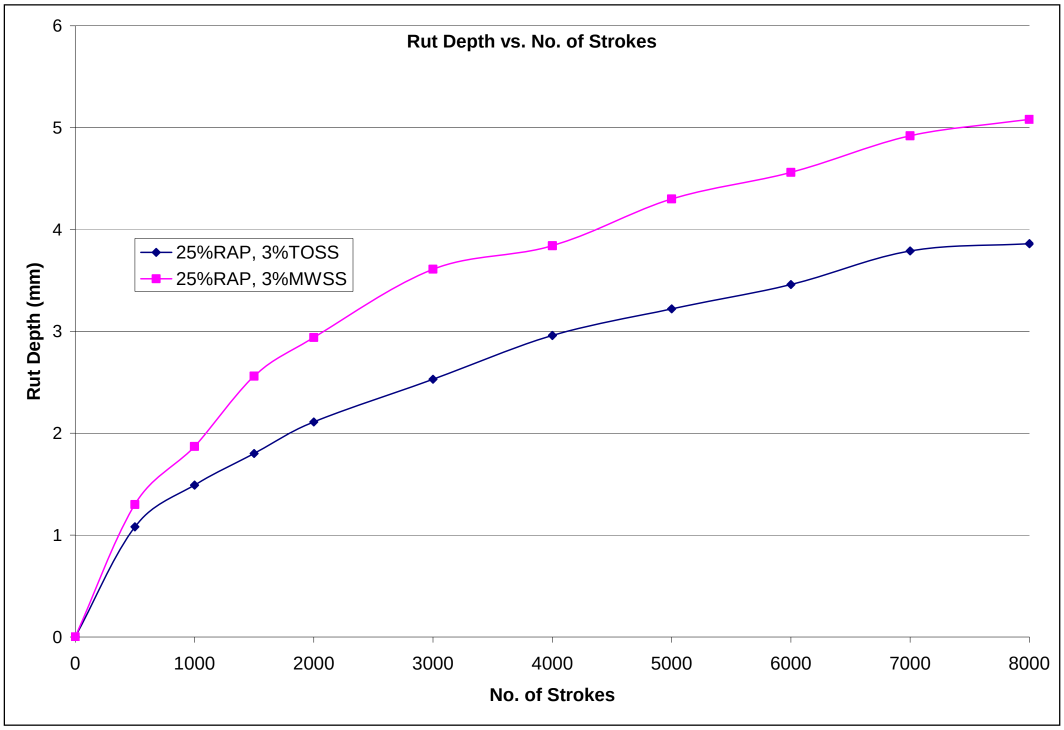

Figure 4.36. Rut Depth vs. No. of Strokes for Mixes 11 & 12 (Shingle Type @ 3 & 25% RAP)

Moisture Sensitivity – Lottman Test

The moisture sensitivity was ascertained by performing modified Lottman tests in accordance with ASTM D 4867. The moisture sensitivity was gauged by comparing splitting tensile test results of control, or non-moisture conditioned specimens (dry strength) against those of moisture conditioned specimens (wet strength). Figure 4.37 shows a splitting tensile test as well as several failed specimens; note the relatively dry appearance of the RAS mixture. The ratio of the wet strength to the dry strength represents the tensile strength ratio, or TSR.

The loose mixture that comprised the four test specimens was conditioned at 275 ºF for 2 hours prior to compaction. After compaction, the four specimens per mix type were allowed to sit overnight at room temperature before testing. The air voids of all individual TSR Specimens ranged from 7.2 to 7.7%. Each pair of moisture conditioned subset samples were partially saturated for five minutes by applying a vacuum of 20-in. mercury. The degree of partial saturation was between 62.3 to 67.9%. After the 24-hour moisture conditioning period the percent saturation was between 80.6 to 92.6% and the change in volume, or percent swell, ranged from 0.52% to 0.80%. Note that there was no freeze-thaw conditioning cycle used.

For the selected mixes, the difference in tensile strength between a pair of conditioned specimens ranged from 0.5 to 3.5 pounds per square inch (psi). The difference between a pair of dry (control) specimens ranged from 3.3 to 13.5 psi. The approximate visual stripping of all conditioned specimens was ten to 15%. All control specimens appeared “dry” when compared against typical RAP only production mixture specimens. Table 4.3 shows the testing results which appear to indicate that the percent new AC is inversely related to the strengths, and directly related to the tensile strength ratio (TSR). The MWSS appears to have a higher TSR than the TOSS, perhaps due to the higher new AC percent.

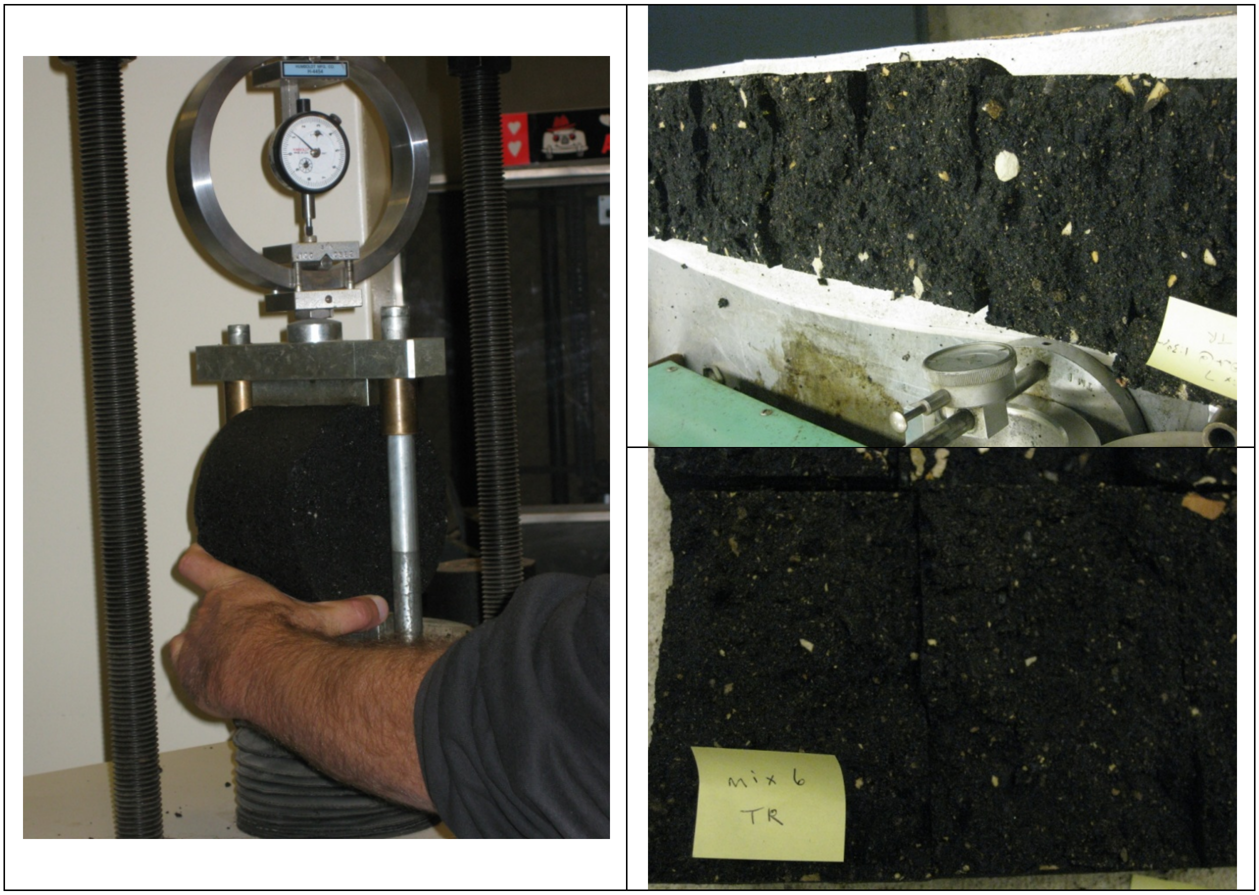

Figure 4.37. Lottman Testing Apparatus (Left) and Failed Specimens (Right)

Table 4.3. Lottman Testing Results

MIX No.	Recycled Material Content	Dry Strength (psi)	Wet Strength (psi)	TSR	New AC (%)
Mix 15	10%RAP 5%TOSS	152.3	103.1	67.4	66.7
Mix 6	15%RAP 5%TOSS	155.1	108.1	69.7	61.4
Mix 7	25%RAP 5%TOSS	181.7	113.0	62.2	50.0
Mix 5	25%RAP 5%MWSS	146.3	109.9	75.1	69.1

<u>Summary of Asphalt Mixture Testing</u>

The RAS/RAP HMA mixtures were tested to characterize: stiffness (dynamic modulus), rutting potential (APA), and moisture sensitivity (Lottman). These tests, especially the dynamic modulus tests (which included a variety of temperatures and loading frequencies) were more useful than the binder tests at characterizing RAS/RAP behavior in HMA mixtures because they didn't completely combine the RAS/RAP binders with the virgin binder. However, differences were observed between laboratory mixing techniques and plant mixing techniques which underscored the need for laboratory methods that more closely mirror plant production.

Dynamic modulus tests demonstrated that TOSS is stiffer than MWSS. The difference between the two RAS sources was most pronounced at the 5% level, and was apparent regardless of RAP concentrations. The largest ratios among modulus values were observed at the lower frequencies, which corresponded to the higher temperatures. The dynamic modulus testing did not test at temperatures low enough to effectively characterize low temperature cracking, so results from Dr. Marasteanu's work on the same materials will be valuable. Dynamic modulus testing also demonstrated that the stiffening effects TOSS alone appears to be much greater than RAP alone. The softening effects of using a softer grade (PG 51-34) binder were also apparent in the reduced stiffness and different (smoother) shape of the master curve. The differences between MWSS and TOSS, as well as the softening effects of the softer grade binder (PG 51-34) were confirmed with the APA rut testing. Moisture sensitivity tests (Lottman) suggested that the TOSS may be more susceptible to moisture damage than MWSS.

CHAPTER 5. FIELD EVALUATIONS

Since 2005 several experimental asphalt paving projects have been constructed using both MWSS and TOSS shingles. Special provisions have enabled the use of TOSS shingles for specific projects only.

Six projects were identified for field evaluations during 2008. The projects utilized either TOSS, separate sections of TOSS and MWSS, or had an important MWSS performance history. Most of the projects were constructed after 2005.

Evaluations consisted of establishing 500-foot long monitoring stations. The stations were visually rated for transverse, longitudinal and joint cracking. Rutting performance and surface characteristics were also noted. Results were reported in terms of cracked linear feet per section. Distresses are reported for 500-ft monitoring sections unless otherwise noted.

Project Details and Field Reviews

Project No. 1: Dakota County CSAH 26

Project No: CP 26-29, SAP 19-626-15

Contractor: Bituminous Roadways – mixture and construction

This reconstruction of CSAH 26 was performed in 2005 located on the eastbound and westbound sections of 70th Street in Inver Grove Heights. The typical section included concrete curb-and-gutter as well as center median. Width varied due to a number of left and right turn lanes.

Twenty-five percent RAP, 5% MWSS shingles, and PG 58-34 asphalt binder were included in the wear and binder course design, which had a virgin binder content of 56.9%. Three separate non-wear Marshall Mixture designs were used in the project:

1. Five % MWSS and 15% RAP with a PG 58-28 binder (new binder/total binder = 62.1%)
2. Five % TOSS and 15% RAP with a PG 58-28 binder (new binder/total binder = 60.0%)
3. Twenty % RAP with a PG 58-28 binder (new binder/total binder = 78.9%)

Three 500-ft monitoring stations, one for each non-wear mix design, were established in the westbound lane during the 2008 performance review. A number of transverse cracks were observed in each section, usually coinciding with locations of storm drains, manholes, or concrete median termini. Rutting was not apparent and not measured. A survey performed in 2006 by the Mn/DOT Pavement Management unit collected data showing that the portion of this project on CR 26 contained 60.8% low severity, 37.4% medium severity, and 0.1% high severity rutting. Transverse cracking was found infrequently in the 2006 record. Table 5.1 shows the number of cracks and the total linear feet of cracking after three years of service for each non-wear mix design. Note that the 15% RAP and 5% TOSS section appears to be performing the best, followed closely by the 20% RAP section. The 15% RAP and 5% MWSS has the greatest amount of transverse cracking and the lowest amount of longitudinal joint cracking. Any conclusions on performance related to new binder/total binder ratio must be tempered by the presence of utilities (curb and gutter, manholes, etc.) which appeared to significantly influence pavement performance.

Table 5.1. CSAH 26, 3rd-Year Performance Review

Section	Length	Longitudinal Joint		Transverse Cracking		Notes
		No.	Lin. Ft.	No.	Lin. Ft.	
20% RAP 0% RAS	500	5	89	3	15	7 LF shoulder cracking. Patches at manholes.
15% RAP 5% MWSS	500	2	56	8	48	31 LF shoulder cracking.
15% RAP 5% TOSS	500	5	59	2	15	20 LF shoulder cracking. Patches at manholes.

Project No. 2: US Highway 10
Project No: SP 0502-95
Contractor: Knife River – mixture and construction

This mill-and-overlay construction was performed in 2005 along the east and westbound side of US 10, beginning at the Morrison county line near Royalton, MN (milepost 156+00.909) and ending at the concrete surfaced pavement (milepost 168+00.920). A total of four inches of asphalt was placed in two lifts over a variable thickness bituminous pavement. The typical section was a four-lane rural divided highway with occasional left and right turn lanes.

The asphalt mix designs for the upper two inch lift used a PG 64-34 asphalt binder and included 25% RAP plus either three or 5% MWSS, which yielded 63 and 54% new binder to total binder ratios respectively (both well below the current AASHTO 70% criterion). Note that the lower two inch lift did not incorporate RAS.

District engineers reported that the shingle sections experienced substantial reflective cracking during the first winter of service. The pavement was very brittle in appearance, and cracks continued to deteriorate during the following year. A subsequent mixture design review prompted a statewide specification change that required asphalt-shingle mixtures to have a minimum of 70% new binder.

SP 4901-73, constructed in 2005, was selected as the control section due to its similarities to SP 0502-95. The asphalt mix designs for the upper two inch lift used a PG 64-28 asphalt binder and included 30% RAP (no RAS) which yielded a 70% new binder to total binder ratio.

Results from a field review of two 500-ft monitoring sections of the RAS mixture yielded mean values of 17 transverse cracks per lane and 146 linear feet of transverse cracking as shown in Table 5.2. A video-log review of the control section conducted between 2006 and 2008 revealed 16 transverse cracks per lane and 137 linear feet of transverse cracking. The video log also showed the cracks to be less severe, which agrees with field observations made by district personnel (Figure 5.1 and
Figure 5.2). The lower amount and severity of cracking provides additional evidence that higher new binder to total binder ratios increase the mixture's durability. Rutting was not apparent on any section, and Mn/DOT pavement management data showed that the shingles rutting stations had developed medium severity rutting over 19.4 and 6.6% of the stations, with low severity

rutting on the remainder. The control section had developed medium severity rutting over 16.4% of the section with low severity on the remainder.

Figure 5.1. T.H. 10 - 5% RAS: May 2008 (Left) and March 2007 (Right)

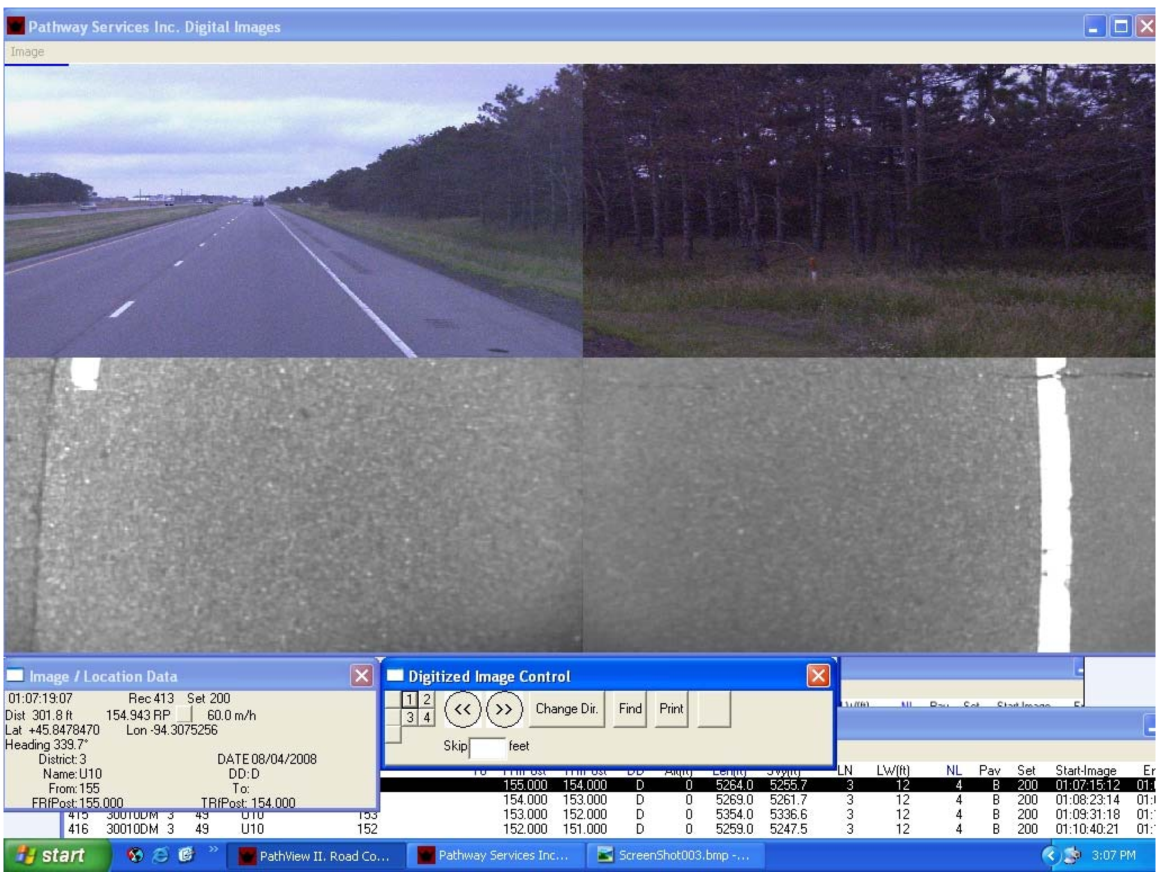

Figure 5.2. T.H. 10 - Control, 30% RAP, 0% RAS: May 2008

Table 5.2. US 10, 3rd-Year Performance Review

Section	Length (ft)	Longitudinal		Transverse		Shoulder		Notes
		No.	Lin. Ft.	No.	Lin. Ft.	No.	Lin. Ft.	
MWSS RP 166 WB Driving Ln.	500	10	238	16	118	41	308	Edge joint 457 LF. Unmelted crack sealant found in mat. Low to medium severity cracks. 6.6% medium severity rutting, 88.9% low severity.*
MWSS RP 166 WB Passing Ln.	500	12	497	15	125	13	39	Center joint 500 LF. 3-ft shoulder width. Low to medium severity cracks.
MWSS RP 160 WB Driving Ln.	500	6	52	23	190	45	349	Edge joint 424 LF. Unmelted crack sealant and shingle found in mat. Low to medium severity cracks. 16.4% medium severity rutting, 80.5% low severity.*
MWSS RP 160 WB Passing Ln.	500	4	75	14	150	14	42	Center joint 500 LF. 3-ft shoulder width. Low to medium severity cracks.
Control 30% RAP RP 155 WB Driving Ln.	500	*na	*na	16*	137*	*na	*na	Edge joint 149 LF*. Low severity cracks*. 19.4% medium severity rutting, 79.7% low severity.*
Control 30% RAP RP 155 WB Passing Ln.	500	*na	*na	*na	*na	*na	*na	Center joint 500 LF*. Low severity cracks*.
* Obtained from Mn/DOT Pavement Management video log and data								

Project No. 3: Hassan Township Park Drive
Project No: N/A
Contractor: Oman Brothers – mixture and construction

This project, constructed in 2006, is located on Park Drive beginning at the intersection with Tucker Road in Hassan Township (Hennepin County). The 600 foot project upgraded the intersection surface from gravel to bituminous. The final typical section was 22 to 24 ft wide with 1 to 2 ft gravel shoulders. A total of four inches of asphalt was placed in two 2-in. lifts. The lower two inches (non-wear course) used a PG 58-28 binder, included 5% shingles, and had a 76.1% new binder to total binder ratio. The top two inch (wear) course consisted of six mixture designs which incorporated TOSS and MWSS as well as two binder grades as described below:

1. 5% MWSS, PG 58-28 (new binder/total binder = 75.4%)
2. 10% MWSS, PG 58-28 (new binder/total binder = 51.5%)
3. 5% TOSS, PG 58-28 (new binder/total binder = 79.7%)
4. 10% TOSS, PG 58-28 (new binder/total binder = 65.0%)
5. 10% TOSS, PG 52-34 (new binder/total binder = 63.6%)
6. 0% RAS wear and non-wear (new binder/total binder = 100%)

Ten field cores were obtained at random locations for each section for testing at the University of Minnesota. Mn/DOT personnel established six monitoring sections shortly after construction, and performed performance reviews at six month intervals, see Table 5.3. Test section length was the entire available section, usually 200-ft per type. Limited transverse cracking was observed during the 2008 spring review and several core holes had developed multiple one ft long low-severity cracks (Figure 5.3). Transverse profile measurements obtained using a dipstick device, showed slight season-to-season variation, but little wheel path deformation (rutting). In January 2009 a mid-winter inspection of cracking was performed. Several newly developed cracks were visible although the roadway was partly obscured by snow.

Figure 5.3. Hassan Township: Coring (Left) and Transverse Cracking (Right), March 2008

Figure 5.4 shows cracking performance data obtained from the Hassan Township site, which shows that the control section has the least amount of cracking and is followed closely by the mixture with 10% TOSS and PG 51-34 binder. The 5% MWSS and TOSS mixtures appear to be performing similarly, as well as the 10% MWSS and TOSS mixtures. The 10% RAS sections, interestingly, appear to have developed cracking slower than the 5% RAS sections suggesting that the percent new AC may not be the best indicator of performance for this particular section. This could be partially explained by the very short length, and thus influence of each mix on the other. Note that the two mixtures that have similar transverse cracking patterns are directly across from each other in the transverse direction (Figure 5.5).

Table 5.3. Hassan Township, 2nd-Year Performance Review

Section	Wear Course (%)	Non-wear (%)	PG Grade	New AC (%)	10/3/2008 Transverse Cracking*		1/29/2009 Transverse Cracking*	
					No.	Linear Ft.	No.	Linear Ft.
MWSS	5	5	58-28	75.4	3	20	3	26
MWSS	10	5	58-28	51.5	0	0	2	24
Control	0	0	58-28	100.0	1	3	1	12
TOSS	5	5	58-28	79.7	2	18	2	24
TOSS	10	5	58-28	65.0	2	2	2	24
TOSS	10	5	51-34	63.6	0	0	1	12
* Results for 200-ft, single-lane, monitoring stations.								

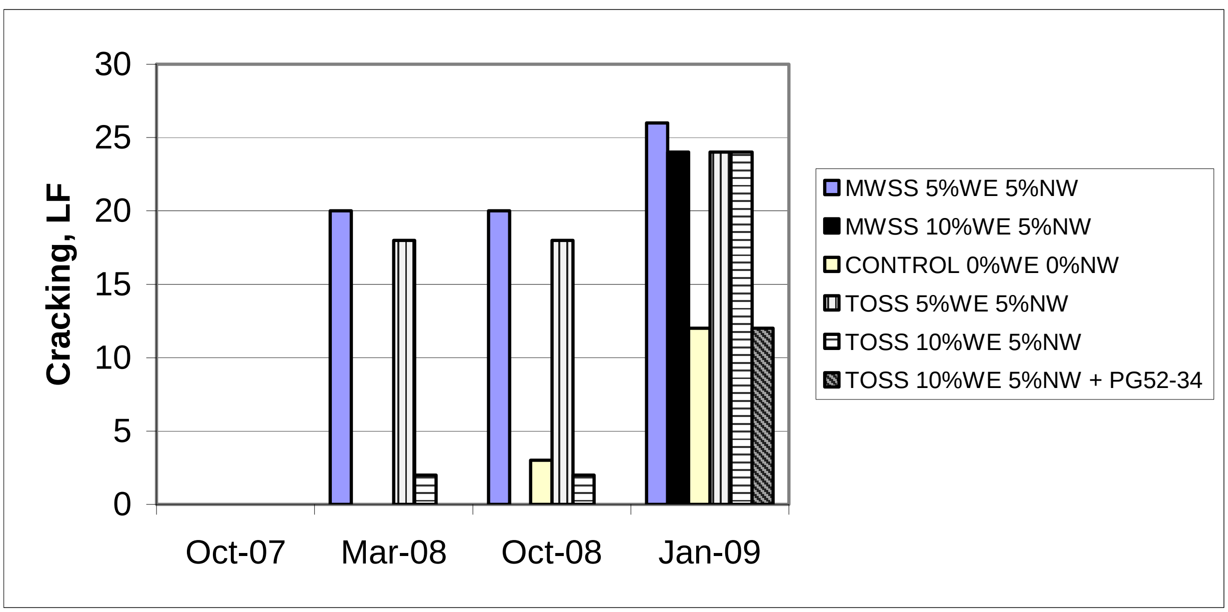

Figure 5.4. Test Section Performance in Hassan Township

Figure 5.5. Test Section Location in Hassan Township

<u>Project No. 4: Ramsey County Lower Afton Trail</u>
Project No: CP
Contractor: Midwest Asphalt – mixture and construction

This project was constructed in 2007 as part of a Ramsey County demonstration of recycled materials. The final typical section was a single-lane recreational trail. A total of four in. of HMA was placed over approximately a one mile length. The HMA mixture design used a PG 58-28 binder, incorporated 5% TOSS and had a new binder to total binder ratio of 77%.

Two crack monitoring sections were established during a 2008 field review, which found no cracking or rutting.

<u>Project No. 5: MnROAD Mainline (I-94)</u>
Project No: SP 8680-157
Contractor: Hardrives – mixture and construction

MWSS and TOSS test sections were included as part of the 2008 reconstruction of the MnROAD mainline test road on I-94. These sections are located in both shoulders of the westbound lanes.

Table 5.4 shows the various mixture types included in the MnROAD shingle study. During construction a single paving pass was used to place the passing lane wear course and shoulder for several cells. In these cases the shingle content was zero. Other shoulder construction used mixtures specifically intended for the shoulder, and were placed using separate paving machine passes. MnROAD cells are approximately 500 ft long. Shoulders on cells 15 – 23 used a PG 58-28 binder, 5% TOSS and had a new binder to total binder ratio of 74%. Shoulders on cells 5, 6, 13 and 14 used a PG 58-28 binder, 5% MWSS and had a new AC ratio of 81%.

Table 5.4. Description of 2008 MnROAD I-94 Shoulder Construction

MnROAD Cell	**Mn/DOT Mix Type**	**Description**	**PG Grade**	**RAP**	**Design Gyrations**
15-19, 23	SPWEB440C Special	Warm asphalt wear course and passing shoulder	58-34	20%	90
15-23	SPWEB440B (1)	5% TOSS driving shoulders	58-28	0%	90
5,6,13,14	SPWEB440B (1)	5% MWSS shoulders	58-28	0%	90
20	SPWEB440B	Wear course and passing shoulders	58-28	30%	90
21	SPWEB4430B Special	Wear course and passing shoulders	58-28	30% fractionated	90
22	SPWEB440C Special 1	Wear course and passing shoulders	58-34	30% fractionated	90

Cell 5 driving lane shoulders were a bituminous overlay above a granular interlayer placed above existing bituminous shoulders. Several sensor instrumentation conduits were cut through the existing shoulder prior to paving, and wick drains were run from the mainline through the granular interlayer. Cells 6 and 15-23 shoulders were newly constructed over granular material (Figure 5.6).

Figure 5.6. MnROAD MWSS Shoulder Construction

By November 2008 construction activities were completed and the sections were evaluated and found to be in new condition and free of cracks. Longitudinal profile measurements reflected differences due to the presence of sensor installations and construction methods. A subset was identified that varied merely by shingle type, binder grade, recycled percentage, and construction date.

Table 5.5. As-built IRI for 2008 MnROAD Shoulder Construction

MnROAD Cell	IRI (in/mi) [a]	TOSS	% MWSS	% RAP	Lane	Constructed
5	211.3	0	5	0	Driving	Oct-08
6	153.5	0	5	0	Driving	Oct-08
6 & 5	184.7	0	5	0	Driving	Oct-08
16	53.4	5	0	0	Driving	Sep-08
17	63.6	5	0	0	Driving	Sep-08
17 & 16	58.6	5	0	0	Driving	Sep-08
20 [c]	79.1	0	0	30	Passing	Sep-08
9 & 8	76.1	0	0	0	Passing	Sep-92
[a] Average of two measurements [c] Control						

<u>Project No. 6: Hennepin County CSAH 10</u>
Project No: CP 8727, SP 27-610-24
Contractor: Knife River – mixture, Hennepin County – construction

This bituminous overlay was constructed in 2008 on CSAH 10 (rural two-lane highway) from 0.1 miles west of Greenfield Road to the intersection of CSAH 123 (Pioneer Trail). A single lift of 1.5 inches of HMA was placed over the existing bituminous pavement. The asphalt mix design used a PG 58-28 asphalt binder and incorporated 25% RAP and 5% of either MWSS or TOSS which yielded 60 – 64% and 55 – 58% new binder to total binder ratios, respectively. One performance monitoring section was established for each mixture type during the 2008 review. No reflective cracking or rutting was observed during the initial review.

Figure 5.7. Hennepin County Rd. 10 RAS Construction

Summary of Field Project Observations

The new binder to total binder ratio of the mixtures was shown to be influenced by the amount and type of recycled material, agreeing with previously stated laboratory results of this study. For some projects, the relationship between the new binder to total binder ratio appeared to be validated, as in the case with TH 10 and in other cases, the percent the new binder to total binder ratio did not appear to influence the cracking as heavily as other factors, namely Dakota County 26 and Park Drive in Hassan Township. These projects also demonstrated performance benefits (Park Drive in Hassan Township) of using a softer grade binder confirmed the laboratory results of this study. Many of the projects had relatively short in place service lives which limits the conclusions that can be drawn. In some cases field personnel reported that the RAS mixtures visually appeared to be more brittle with more severe cracking. These observations were not easily quantified in field ratings, due to the nature of the rating process. As with all field experiments it is difficult to fully control all variables, however, there appears to be little difference in field performance between MWSS and TOSS mixtures.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This research project was motivated by both environmental concerns of rising landfill deposits of RAS and the financial concerns of rising construction and materials costs, especially asphalt binder. The incorporation of RAS into HMA mixtures must be done so in a prudent and cautious manner to avoid unnecessary and costly premature pavement failures. Initial incorporation of Manufacturers Waste Scrap Shingles (MWSS) into HMA pavements yielded encouraging results and prompted waste management organizations, industry and government to investigate incorporation of Tear-Off Scrap Shingles (TOSS) into HMA pavements.

This research project consisted of: a literature review, extensive laboratory testing of laboratory produced mixtures and field evaluations of in-place plant produced mixtures. This study was constructed in such a way as to address the following:

1. *Implement RAS/RAP provisional specification:*
   Based on the findings of this research project, a RAS/RAP provisional specification was developed to allow the use of TOSS with approval of the engineer, as shown in Appendix A (Note that this will become a permissive specification for the 2010 construction season).

2. *Verify the AASHTO 70% new asphalt binder to total asphalt binder criterion for RAS/RAP mixtures:*
   Extraction and gradation of asphalt binders from the matrix of laboratory produced RAS/RAP HMA mixtures showed a strong correlation between the virgin binder content and the high/low PG temperatures of that binder. Mixture Dynamic modulus testing showed a correlation between the dynamic modulus values and new binder content at high temperature, providing further evidence of the relationship between virgin binder content and mixture durability. Field evaluations of RAS/RAP mixtures showed that the relationship between the new binder to total binder ratio appeared to be validated, as in the case with TH 10 and in other cases, the percent the new binder to total binder ratio did not appear to influence the cracking as heavily as other factors, namely Dakota County 26 and Park Drive in Hassan Township.

3. *Observe the effects of RAS/RAP on HMA mixture durability:*
   There have been successful RAS/RAP projects that are performing adequately; however it only takes one failure to serve as a reminder of the potential negative effects of recycled materials on HMA durability. Evaluation of a failed hwy section revealed a low virgin binder to total binder ratio, which was shown to be related to the amount of recycled material. Dynamic modulus tests on laboratory produced mixtures for this study demonstrated that there is in fact, a significant difference in stiffness, especially at the lower frequencies (higher temperatures), between mixtures containing RAS/RAP and virgin mixtures. The APA rut testing results also showed a reduction in rut depth with increasing amounts of RAP/RAS indicating increased mixture stiffness. Moisture sensitivity tests (Lottman) conducted on RAP/TOSS mixtures failed to meet current Mn/DOT specifications, while tests on a RAP/MWSS mixture had higher values.

Increased moisture sensitivity could mean a potential decrease in durability. Thermal (low temperature) cracking heavily influences the durability of Minnesota HMA pavements. The low temperature binder PG grade was increased with the addition of RAP and RAS suggesting an increase in thermal cracking potential of the mixture. The University of Minnesota has a contract to further investigate the low temperature cracking properties of RAS/RAP mixtures using innovative techniques on the same materials as the current study.

4. *Observe possible differences in performance between MWSS and TOSS mixtures:* Generally, TOSS increased the mixture demand for new binder more than MWSS, which lowered the new binder to total binder ratio. Extraction/recovery of MWSS and TOSS showed TOSS to be stiffer. DSR tests on extracted binder showed increasing differences between mixtures containing TOSS or MWSS and RAP, as the RAP content increased. Dynamic modulus test results showed little difference between MWSS and TOSS at the 3% level, regardless of RAP content. When the RAS content was 5%, HMA mixtures containing TOSS were visually stiffer than similar mixtures containing MWSS, these differences were most apparent at the lower frequencies (higher temperatures).

5. *Observe the effects of "softer grade" asphalt binder in RAS/RAP mixtures:* The use of a softer grade (PG 51-34) binder was shown in both asphalt binder and mixture tests to dramatically affect the properties of RAS/RAP mixtures when compared to similar mixtures containing a stiffer grade binder (PG 58-28). Dynamic modulus results showed reduced stiffness and a smoother master curve shape. Field performance from Hasan Township confirmed these laboratory results. A control section comprised of PG 58-28 binder and no RAS/RAP performed similarly to a section comprised of PG 52-34 binder and 10% TOSS.

6. *Observe the effects of different RAP sources:* The laboratory evaluation of two different types of RAP, which had different RAP AC content and slightly different PG grades, showed little observable difference in performance.

7. *Observe the differences between lab produced and plant produced HMA mixtures:* Dynamic Modulus master curves were used to compare lab produced and plant produced mixtures. The results showed that laboratory preparation methods generally achieved greater mixing between the recycled and virgin binders which yielded stiffer mixtures than comparable plant produced mixtures.

Recommendations

1. Maintain the AASHTO 70% new asphalt binder to total asphalt binder requirement for RAS mixes.
2. The processed shingle gradation and deleterious material specification listed in the TOSS special provision should be used for both TOSS and MWSS.
3. Binder grades should be limited to PG 64-28, PG 58-28 and PG 51-34 until further research can determine the effects of shingles on modified binders.

4. Project monitoring efforts need to continue so that engineers can better understand performance with respect to time.
5. Evaluate the University of Minnesota’s work on low temperature cracking in the context of the current 70% new asphalt binder to total asphalt binder requirement.

Future Work

1. Investigate adding PG 51-34 binder to 10 and 15% RAP mixes with TOSS
2. Develop laboratory mixture design and production procedures that better simulate plant-produced material.
3. Further investigate the use of binder tests to estimate |E*| via the Hirsch Model and determine if approximation would be sufficient for inputs into the MEPDG.
4. Develop a mixture performance test to predict expected mix performance for mix design enhancements.
5. Test mixes with other processed shingle sources/binder grades and traffic levels.
6. Investigate the AASHTO 70% new asphalt binder to total asphalt binder ratio requirement for RAP only mixes.
7. Participate in the Performance of Recycled Asphalt Shingles in Hot-Mixed Asphalt pooled fund study.

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APPENDIX A. Mn/DOT RAS SPECIFICATIONS & SPECIAL PROVISIONS

Provision for Scrap Asphalt Shingles from Manufacture Waste (05/20/2009)

DESCRIPTION

Scrap asphalt shingles from a shingle manufacturing facility may be used in hot mixed asphalt mixtures produced under specification 2360.

MATERIALS

Scrap asphalt shingles may be included in both wear and non-wear courses to a maximum of 5 percent of the total weight of mixture. Only scrap asphalt shingles from manufacturing waste are suitable. The percentage of scrap shingles used will be considered part of the maximum allowable RAP percentage (see Table 2360.3-B2a). Refer to Section 2360.2 G1 to select a virgin asphalt binder grade. The ratio of added new asphalt binder to total asphalt binder shall be 70% or greater ((added binder/total binder) x 100 >= 70). A minimum of 1 spotcheck per day per mixture blend is required to determine new added binder.

All scrap shingle materials shall consist of organic felt, and/or fiberglass shingles, obtained from a shingle manufacturing facility.

All scrap shingle materials shall be processed to meet the following gradation requirements:

Gradation (% passing)

Sieve Size (mm [**inch**])	(% passing)
12.5 [**1/2 inch**]	100
4.75 [**#4**]	90

The final product shall have no particle exceeding the maximum aggregate size allowed under Specification 2360. To conduct the gradation testing, a 500-700 gram sample of processed shingle material is air dried and then dry sieved over the 1/2" and #4 sieves and weighed.

Shingle asphalt binder content is to be determined by chemical extraction, MnDOT Lab Procedure 1852.

An aggregate bulk specific gravity (Gsb) of 2.650 may be used in lieu of determining the shingle aggregate Gsb by Mn/DOT 1205 (AASHTO T84).

Before a Mixture Design Report for a particular mixture is authorized, the following shall be submitted, along with materials and paperwork required by 2360.3:

I. Certification by the processor of the shingle scrap, as to the shingle scrap content and source. Certification forms are located at the back of this provision and also available from the Bituminous Office.

Deleterious Materials

Scrap asphalt shingle shall not contain extraneous waste materials. Extraneous materials including, but not limited to, metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics shall not exceed 0.5 percent by weight as determined on material retained on the 4.75-mm (No. 4) sieve. To conduct deleterious material testing, a 500-700 gram sample of processed shingle material is sieved on the #4 sieve and any extraneous waste material is picked and weighed.

CONSTRUCTION REQUIREMENTS

Scrap shingles from manufacture waste shall be stockpiled separate from other salvage material. Blending of scrap shingle material in a stockpile with other salvage material is prohibited. Blending of a virgin sand material with the processed shingles, to minimize agglomeration of the shingle material, is allowed, but, the blended sand must be accounted for in the mixture design.

Scrap Shingle Certification Sheet
PROCESSOR

S.P. No:______________________ **Project:**______________________________________

Name:____

Address:____

____

Contact:____

Phone:____

We the undersigned, certify that all of the shingle scrap to be used on this project came from a shingle manufacturing facility or facilities and is not tear-off or re-roof material. We certify this shingle scrap material contains only shingles; no other material was added or introduced to this shingle scrap. We also certify the material consisted of only organic and/or fiberglass shingles and contains no asbestos greater than the NESHAP threshold or other hazardous material. Additionally, we certify the shingle scrap meets MnDOT gradation and deleterious material requirements for processed shingle scrap.

____

Processor of Shingle Scrap Material Date

____

Name of Contractor to Whom Processed Shingle Scrap Material Was Supplied

Manufacturer of Shingle Scrap:

Name: ____

Address: ____

____

Contact: ____

Phone: ____

Please be advised the "Provision for Tear-Off Scrap Asphalt Shingles" is not a Standard Provision and its use requires the approval of the Engineer. When approved by the Engineer, Tear-Off Scrap Shingles can be considered an approved equal under Specification 1605.

Provision for Tear-Off Scrap Asphalt Shingles (05/20/2009)

DESCRIPTION

Tear-Off Scrap shingles (TOSS), as an asphalt binder source, may be included in hot mixed asphalt mixtures produced under specification 2360 when approved by the Engineer.

MATERIALS

Tear-Off Scrap shingles (TOSS) may be included in both mainline wear and non-wear courses to a maximum of 5 percent of the total weight of mixture when approved by the Engineer. The percentage of TOSS used will be considered part of the maximum allowable RAP percentage (see Table 2360.3-B2a). Refer to Section 2360.2 G1 to select a virgin asphalt binder grade. The ratio of added new asphalt binder to total asphalt binder shall be 70% or greater ((added binder/total binder) x 100 >= 70). A minimum of 1 spotcheck per day per mixture blend is required to determine new added binder.

All TOSS materials shall be processed to meet with the following gradation requirements:

Gradation (% passing)

Sieve Size (mm [**inch**])	(% passing)
12.5 [**1/2 inch**]	100
4.75 [**#4**]	90

The final product shall have no particle exceeding the maximum aggregate size allowed under Specification 2360. To conduct the gradation testing, a 500-700 gram sample of processed shingle material is air dried and then dry sieved over the 1/2" and #4 sieves and weighed.

Shingle asphalt binder content is to be determined by chemical extraction, MnDOT Lab Procedure 1852.

An aggregate bulk specific gravity (Gsb) of 2.650 may be used in lieu of determining the shingle aggregate Gsb by Mn/DOT 1205 (AASHTO T84).

Before a Mixture Design Report for a particular mixture is authorized, the following shall be submitted, along with materials and paperwork required by 2360.3:

I. Certification by the processor of the shingle scrap, as to the shingle scrap content and source. Certification forms are located at the back of this provision and also available from the Bituminous Office.

Deleterious Materials

Scrap asphalt shingle shall not contain extraneous waste materials. Extraneous materials including, but not limited to, asbestos, metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics shall not exceed 0.5 percent by weight as determined on material retained on the 4.75-mm (No. 4) sieve. To conduct deleterious material testing, a 500-700 gram sample of processed shingle material is sieved on the #4 sieve and any extraneous waste material is picked and weighed.

Reclaimed asphalt shingle shall contain less than the maximum percentage of asbestos fibers based on testing procedures and frequencies established by Mn/DOT, state or federal environmental regulatory agencies.

CONSTRUCTION REQUIREMENTS

TOSS shall be stockpiled separate from other salvage material. Blending of TOSS material in a stockpile with other salvage material is prohibited. Blending of a virgin sand material with the processed shingles, to minimize agglomeration of the shingle material, is allowed, but, the blended sand must be accounted for in the mixture design.

Tear-Off Scrap Shingle Certification Sheet
TEAR-OFF PROCESSOR

S.P. No:______________________ **Project:**____

Name:____

Address:____

____

Contact:____

Phone:____

We the undersigned certify that all of the asphalt shingle tear-off scrap is derived from non-regulated facilities such as private, pitched roof, residential "single family" re-roofing projects (e.g., buildings with up to four units per structure).

We certify that this shingle scrap material contains only shingles; no other material was added or introduced to this shingle scrap. We also certify the material contains no asbestos greater than the NESHAP threshold or other hazardous material. Additionally, we certify the TOSS meets MnDOT gradation and deleterious material requirements for processed shingle scrap.

____

Processor of Tear-Off Shingle Scrap Material Date

____

Name of Contractor to Whom Processed Tear-Off Shingle Scrap Material Was Supplied

Supplier of Tear-Off Shingle Scrap:

Name: ____

Address: ____

____

Contact: ____

Phone: ____

APPENDIX B. HMA RAS/RAP PROJECTS

Project	Agency	Built	Recycle Component *	% in mix	Spec No. and Year	PG	Section	Review Date	Notes
CSAH 26	Dakota County	2005	MW	5	2360LV 2005	58-28	Wear, Nonwear, Granular base. Urban	12/12/08	Test sections in nonwear layer. Established sections with landmarks.
CSAH 26	Dakota County	2005	RAP	20	2360LV 2005	58-28	Wear, Nonwear, Granular base. Urban.	12/12/08	Test sections in nonwear layer. Established sections with landmarks.
CSAH 26	Dakota County	2005	TO	5	Modified 2360LV 2005	58-28	Wear, Nonwear, Granular base. Urban.	12/12/08	Test sections in nonwear layer Established sections with landmarks.
TH 10 Rice	Mn/DOT	2005	RAP + MW	25+5 and 27+3	2360 2005	64-34	Mill and overlay above existing Pavement and Granular base. 4 lane divided hwy.	10/6/08	Mileposts 166 and 169 westbound.
TH 10 W. of Royalton	Mn/DOT	2005	RAP	30	2360 2005	64-34	Mill and overlay above existing Pavement and Granular base. 4 lane divided hwy.		Milepost 155 westbound. Control for TH 10
Park Drive	Hassan Township	2006	MW	5, 10	Modified 2360LV 2006	58-28	Wear, Nonwear, Granular is prepared gravel road. Rural low volume road.	10/3/08 1/29/09	Established GPS & PK nails.
Park Drive	Hassan Township	2006	MW	10	2360LV 2006	52-34	Wear, Nonwear, Granular is prepared gravel road. Rural low volume road.	10/3/08 1/29/09	Established GPS & PK nails
Park Drive	Hassan Township	2006	No recycle	100	2360LV 2006	58-28	Wear, Nonwear, Granular is prepared gravel road. Rural low volume road.	10/3/08 1/29/09	Established with GPS & PK nails.

Continued Project	Agency	Built	Component *	% in mix	Spec No. and Year	PG	Section	Review Date	Notes
Park Drive	Hassan Township	2006	TO	5, 10	Modified 2360LV 2006	58-28	Wear, Nonwear, Granular is prepared gravel road. Rural low volume road.	10/3/08 1/29/09	Established with GPS & PK nails.
Lower Afton Trail	Ramsey County	2007	TO	5	Modified 2360LV 2007	58-28	Wear, Nonwear, Granular. Bike path.	11/21/08	Established GPS & PK nails.
CSAH 10	Hennepin County	2008	RAP+MW	25+5	2350MV 2008	58-28	Overlay on unmilled pavement	11/24/08	Established sections with GPS & PK nails.
CSAH 10	Hennepin County	2008	RAP+TO	25+5	2350MV 2008	58-28	Overlay on unmilled pavement.	11/24/08	Established sections with GPS & PK nails.
I-94 MnROAD	Mn/DOT	2008	MW	5	2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 5 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	MW	5	2360 2008	58-28	HMA shoulder overlay, granular, existing shoulders. Wick drains.	11/17/08	Cell 5 Driving lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	MW	5	2360 2008	58-28	Shoulder over granular	11/17/08	Cell 6 Driving and Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	MW	5	2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 13 Driving and Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	MW	5	2360 2008	58-28	Shoulder over granular	11/17/08	Cell 14 Driving and Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	20	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 15 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	20	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 16 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	20	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 17 Passing lane. 4-lane divided highway.

Continued Project	Agency	Built	Component *	% in mix	Spec No. and Year	PG	Section	Review Date	Notes
I-94 MnROAD	Mn/DOT	2008	RAP	20	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 18 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	20	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 19 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	30	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 20 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	30	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 21 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	30	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 22 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	RAP	20	Modified 2360 2008	58-34	Shoulder over granular.	11/17/08	Cell 23 Passing lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	TO	5	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 15 Driving lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	TO	5	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 16 Driving lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	TO	5	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 17 Driving lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	TO	5	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 18 Driving lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	TO	5	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 19 Driving lane. 4-lane divided highway.
I-94 MnROAD	Mn/DOT	2008	TO	5	Modified 2360 2008	58-28	Shoulder over granular.	11/17/08	Cell 23 Driving lane. 4-lane divided highway.

* TO = Tear Off Shingles, MW = Manufacturer Waste Shingles, RAP = Recycled Asphalt Pavement