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Best Practices for RAP Use Based on Field Performance

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16. Abstract (Limit: 250 words)

This study included a survey of practicing local engineers, field performance observations of new bituminous and bituminous overlay construction, and laboratory testing. The most common binder performance grades were identified along with the most common percentage of recycled asphalt in bituminous mixtures.

Local engineers regarded cracking, rutting, and construction as the most important issues when using recycled asphalt pavement. Roughly one-third of Minnesota agencies exclude RAP from wear course mixture.

Analysis of dynamic modulus curves from field cores showed that full-depth specimens were more useful for relating field and laboratory performance than were the wear or non-wear course specimens. Analysis showed stronger relationships existed to low temperature performance grade and to the percentage of new asphalt binder in the mixture than to the percentage of RAP in the mixture. Field performance related well to mixture master curves in the middle portion of the test frequency range.

Recommendations include using low-temperature grades of PG-34, including RAP in the wear course, and using material control to achieve good performance. Other consideration are specifying the source material origin, screening and separating by particle size (fractionated RAP), or specifying RAP asphalt content.

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Best Practices for RAP Use Based on Field Performance

Final Report

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Table of Contents

List of Tables

List of Figures

Executive Summary

This study included a survey of practicing local engineers, field performance observations of new bituminous and bituminous overlay construction, and laboratory testing. It was found that in Minnesota the most commonly used asphalt binders were performance grades PG 58-28 and PG 58-34. These were used with or without recycled asphalt pavement in the mixture design. It was also found that mixtures most commonly included recycled pavement at levels of 20 to 30 percent.

Local engineers regarded cracking, rutting, and construction issues as most important with respect to using recycled asphalt pavement in asphalt mixtures. Roughly one-third of the Minnesota agencies using RAP exclude it from the wear course mixture.

Analysis of dynamic modulus mixture master curves produced from field cores showed that full-depth specimens were more useful for relating field and laboratory performance than were the wear or non-wear course specimens.

Analysis of field performance showed stronger relationships existed to low-temperature performance grade and to the percentage of new asphalt binder in the mixture than to the percentage of RAP in the mixture. Field performance related well to mixture master curves in the middle portion of the test frequency range. The strength of the relationship decreased as frequency increased.

Recommendations include that agencies review their policy to including RAP in the wear course, low-temperature performance grade -34 binder may benefit early performance, and material control can be used to achieve a better performance history. Specifying the source material origin, screening and separating by particle size (fractionated RAP), or specifying asphalt content are several management options.

Chapter 1: Background

Literature Review

A literature review was completed to gain background for both the use of Recycled Asphalt Pavement (RAP) in asphalt mixtures and the evaluation of RAP in Minnesota and other states.

Paul [1] conducted a five-year laboratory and field evaluation of pre-Superpave recycled projects for Louisiana. Performance was examined from structural, serviceability and distress perspectives. The study focus was on five hot-mix recycled projects and five conventional control projects, constructed between 1978 and ‘81. Recycled projects were compared with a control section having similar design, traffic and geographic location.

Results showed no significant difference in performance, upper pavement strength, or recovered asphalt cement properties. Analysis of cores showed no degradation although extracted binder contents were lower than the construction values.

It was observed that recycled pavements exhibited slightly more longitudinal cracking than their conventional counterparts. The sections that exceeded the production mixture viscosity limit of 12,000 poises had more cracking than the paired control pavements. The study concluded that pavements containing 20 – 50 percent reclaimed asphalt concrete by weight performed similar to conventional pavements for a period of six to nine years after construction. These results included both binder and wearing course mixtures. The project recommended that Louisiana use up to 30 percent reclaimed material in nonwear courses and up to 15 percent in the wear course.

Kandhal [2] conducted a project for Georgia, evaluating the performance of five recycled projects in comparison to virgin (control) asphalt pavements. Up to that time most recycled pavements in Georgia used AC-20 asphalt cement and 10 to 25 percent RAP. Virgin HMA pavements generally used AC-30 asphalt.

In this study road sections were evaluated for in-situ mix properties, recovered asphalt binder properties, and laboratory re-compacted mix properties. Conclusions regarding statistical tests were based on t-tests at a 5 percent level of significance.

Kandhal identified projects that used both recycled and virgin mixes on the same project and then performed a comparative evaluation. Findings showed that both virgin and recycled sections performed satisfactorily after 1 – 2 ¼ years of service. There was no significant rutting, raveling and weathering, or fatigue cracking. There was no statistical difference between in-situ mixture, aged asphalt binder, and re-compacted mixture properties between virgin and recycled sections. There was a statistical difference between the Gyratory Elasto-Plastic Index (GEPI), roller pressure values, and indirect tensile strengths of virgin and recycled sections.

This study also evaluated 18 recycled and 15 virgin HMA pavements constructed independently throughout the state during a 2-3 year time frame. The properties of the binders recovered from the mixtures of these projects formed a database for comparative purposes. When treated as independent groups of unequal sizes, no statistically significant differences were found for percent air voids, penetration, and viscosity properties between the virgin and recycled pavements. There was also no significant overall difference in performance based on visual inspection.

Results indicated that recycled pavements performed as well as the virgin pavements at that time in Georgia. It was recommended that these virgin and recycled sections should be reevaluated after another 2-3 years service, focusing on pavement surface and aged asphalt properties.

The NCHRP 9-12 [3] report provides guidelines for incorporating RAP in Superpave mixtures and advocates stockpile testing as an important means of product assessment and quality control. The report has several detailed sections including the results from the Black Rock, Binder, and Mixture Effects studies.

The report says RAP use may be limited by shortcomings in RAP aggregate properties. RAP aggregates should be checked for Superpave criteria such as Angularity, Flat and Elongated, and Sand Equivalent.

Ingberg [4] described histories of pre-Superpave recycling projects from 1976-1980 in Minnesota. Topics covered include Sulfur Extended Asphalt and Sulfur Extended Asphalt-Recycled projects, as well as salvaged materials. For these projects, material quality and gradation was emphasized, not where the materials came from. It was noted that for projects in urban areas it was common to use RAP from stockpiles. Because of the relatively small size of urban projects there would likely be difficulty in returning RAP to the same structures. Rural projects would be more likely to contain RAP from the same project.

RAP stockpile condition can influence project economics. Keep deleterious material out of stockpile to reduce premature failure, and cover or construct the stockpile to keep out moisture. Unprotected stockpiles can have 5-15 percent moisture content. At 5 percent moisture and fuel prices at $1.00 per gallon, the cost is $1.00 per ton to dry. The author suggests that ownership of salvaged material should go to the party controlling the end use.

The development of Permissible Hot-Mix Recycling Specifications was described, including a summary of Mn/DOT Specification 2332, edition 1978.

Marti's [5] project included a literature review of Minnesota recycling specifications and a survey describing over ten years of Minnesota experience. Results showed the effectiveness of cold in-place and hot asphalt recycling in road maintenance and construction. The report literature review covered the Basic Asphalt Recycling Manual (BARM) and the current (2002) Mn/DOT specifications for recycling.

The survey effort concluded most agencies were pleased with their recycling experience and that Mn/DOT specifications were most often used. Although full depth reclamation was common (49 out of 83 responses), agencies inquired about cold in-place recycling (19 out of 83 responses). Several agencies reported that they would not use recycled asphalt in the wearing course. Visual inspection was the most common method of monitoring long-term performance.

The report states that project assessment and selection is one of the most important factors in achieving success in asphalt recycling. TAP meeting discussions noted that most perceived premature failures are due to incorrect selection of good candidate roadways. The main factors that should be considered in evaluating a project for recycling are:

- Existing pavement condition
- Availability of construction material
- Economics
- Time constraints compared to other rehabilitation alternatives

In the design and evaluation process, BARM recommends assessing the pavement for: surface distresses, maintenance activities, base or subgrade problems, and ride quality and safety features.

An economic analysis should be done to compare life-cycle costs of the different rehabilitation techniques and determine which is the most cost effective. The economic analysis provides a basis for selection of the rehabilitation technique, but other factors must also be considered, including good engineering judgement.

Sondag [6] described the material properties of RAP resulting from a laboratory study. The research uses resilient and complex modulus testing to compare virgin material mixtures to those with varying amounts of RAP. A dynamic shear rheometer (DSR) was used to determine the RAP binder Superpave performance grade after solvent extraction.

Mixtures were compacted with a gyratory compactor and contained: from 0 to 40 percent RAP, and either a PG 58-28, PG 52-34 or PG 46-40 virgin asphalt binder. RAP material and virgin aggregates were blended so that all samples had approximately the same gradation.
Recommendations were developed for complex modulus testing temperature and frequency due to problems experienced with test equipment.

The addition of RAP makes the mixture stiffer, as evidenced by an increase in resilient modulus and complex modulus measurements, according to the research. The addition of RAP also decreases the mixture phase angle, which corresponds to an increase in the elastic properties and a decrease in the viscous mixture properties.

Based upon resilient modulus and complex modulus test results, the RAP contents and respective asphalt binders shown in Table 1 [6] will result in RAP mixtures with stiffness similar to virgin mixtures:

Table 1 – Recommended RAP Contents and Asphalt Binders

Original Asphalt Grade	Asphalt Grade with RAP	RAP Content with District 6 RAP	RAP Content with District 8 RAP
PG 58-28	PG 52-34	20%	10%
PG 58-28	PG 46-40	50%	35%
PG 52-34	PF 46-40	25%	15%

Additional testing was recommended to verify field performance. The low-temperature cracking potential of these mixtures should be evaluated prior to use.

Li [7] studied the combined effects of RAP source, percentages, and asphalt cements, on dynamic modulus, IDT creep and strength, and moisture susceptibility testing. RAP material was blended with virgin aggregate such that all samples tested had approximately the same gradation. Moisture susceptibility tests showed all mixtures passed the minimum tensile strength ratio.

Dynamic modulus tests were performed at five temperatures (-20 to 40 ° C) and five frequencies (0.01 to 25 Hz). Master curves were constructed for each, showing the addition of RAP increased the complex modulus. Analysis showed that the asphalt binder and RAP source had a significant effect on the mixture modulus. It was also found that the mixtures containing

RAP became more variable as the percentage of RAP increased. Complex modulus test results were observed to have more variability at low temperatures.

Indirect tensile creep and strength tests were performed on the ten mixtures at -18 ° C and -24 ° C. The data showed stiffness increasing with percentage of recycled material. Mixtures with PG 58-34 binder were softer than the mixtures with PG 58-28 binder at -18 ° C. Asphalt binders extracted from the dynamic modulus samples were tested at high and low temperatures. Blending charts were constructed based on the test data. Test data showed that binder stiffness increased with the percentage of recycled material.

It was found that current specifications were adequate. Recommendations for further study include testing more mixtures and asphalt binders to encompass a wider range of materials used in Minnesota, comparing the laboratory test data to the field, and studying of the effects of the recycled materials on the performance of the mixtures at low temperature.

Zofka [8] investigated the usefulness of simple tests for obtaining binder properties required to develop RAP blending charts. The research focused on the use of the BBR, testing thin beams of asphalt mixtures to obtain mixture stiffness values then back-calculating binder stiffness using the Hirsch model. Conclusions include:

- BBR tests on thin beams of asphalt mixture show promise in measuring creep compliance (and stiffness) of asphalt mixtures.
- The BBR method has several advantages over IDT.
- The Hirsch model can be used, but under-predicts the binder stiffness compared to the measured stiffness. Currently the mixture stiffness is over-sensitive to the input binder stiffness.

The report proposes that since RAP is beneficial to mixture high temperature properties, virgin binder should be selected according to the PG limit required by the project location. The addition of RAP will increase that temperature limit.

Daniel's [9] laboratory research describes the effect of RAP on volumetric and mechanistic properties of asphalt mixtures. A Superpave 19-mm control mixture containing no RAP was compared to similar designs having 15, 25, and 40 percent RAP.

Two types of RAP were evaluated: processed and unprocessed (grindings). Testing included: dynamic modulus in tension and compression, creep compliance in compression, and creep flow in compression. Dynamic modulus and creep compliance master curves were constructed to describe the behavior of each mix over a range of temperatures.

- Results showed VMA and VFA increasing in the 25 and 40 percent RAP mixes.
  - Influenced by pre-heating time
- Dynamic modulus of the processed RAP mixtures:
  - Increased from the control to 15 percent RAP level.
  - 25 percent and 40 percent RAP mixtures exhibited dynamic modulus and creep compliance curves that were similar to the control mixture in both tension and compression.
- Creep compliance curves showed similar trends. Flow time increases with the addition of RAP, except for the 25 percent mixture.
- Results indicate that a mixture containing RAP will be more resistant to permanent deformation and less resistant to fatigue and thermal cracking. The addition of RAP to a mixture adds a proportion of aged binder and the effect of 15 percent RAP on the

rheological properties of the mixture is similar to that reported for aged mixtures. However, a combination of gradation, asphalt content, and volumetric properties is likely the cause of these trends.

- The study indicates that there is an optimal pre-heating time for RAP to allow the particles to soften, break down, and blend with the virgin materials. Further research in this area is needed to determine how best to simulate the plant operations in the lab, especially for mix design.

McDaniel [10] conducted experimental work with laboratory and plant produced mixtures containing RAP from three Midwestern states. Mixtures containing up to 50 percent RAP were evaluated using Superpave procedures. Findings show that:

- Superpave mixtures with 40 – 50 percent RAP can perform very well. However, the viability of obtaining a high percentage RAP mixture may be limited by the aggregate structure.
- Repeated shear testing showed that high percentage RAP mixtures were affected by aggregate structure.
- Addition of 20 to 25 percent RAP raised the high temperature grade one level for plant mixed material.

It was recommended that since the study was limited to three Midwestern states, each individual state should evaluate their own materials for RAP binder grades and gradations. States were also encouraged to monitor field performance with respect to rutting and cracking. "Based on past experience that shows recycled mixtures can perform well, no significant problems are expected, provided the mixtures are properly designed and constructed."

Chapter 2: Survey Results

A survey was sent to highway engineers to document the current climate of RAP use in municipal, county, and state agencies. Survey results are also used for the identification of local projects as candidates for additional analysis. The survey format was multiple choice and short answer, and contained 11 questions. The survey was distributed with the help of the Mn/DOT State Aid Office. Respondents had the option of submitting either an electronic or hard copy response.

Fifty-two agencies responded to the survey, including 10 cities, 37 counties, and 5 MnDOT districts. Results are presented graphically in Figures 1 through 9. A total of 10 agencies said they had projects suitable for the study. Of the 21 respondents electing to comment on premature failures, 15 said there had been none. However, in a question that asked what types of distresses and problems engineers have with RAP mixtures, 17 reported cracking, 16 construction, and 20 raveling problems.

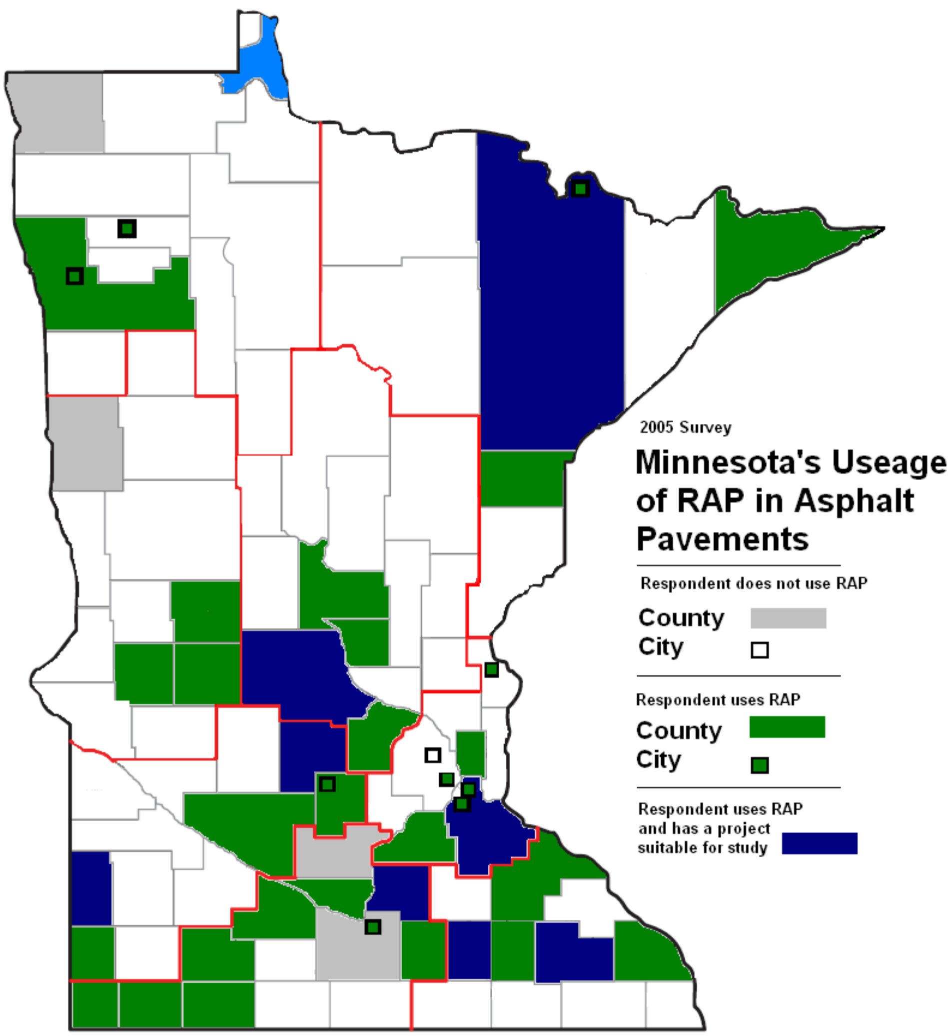

Figure 1 – Survey results from Minnesota cities and counties.

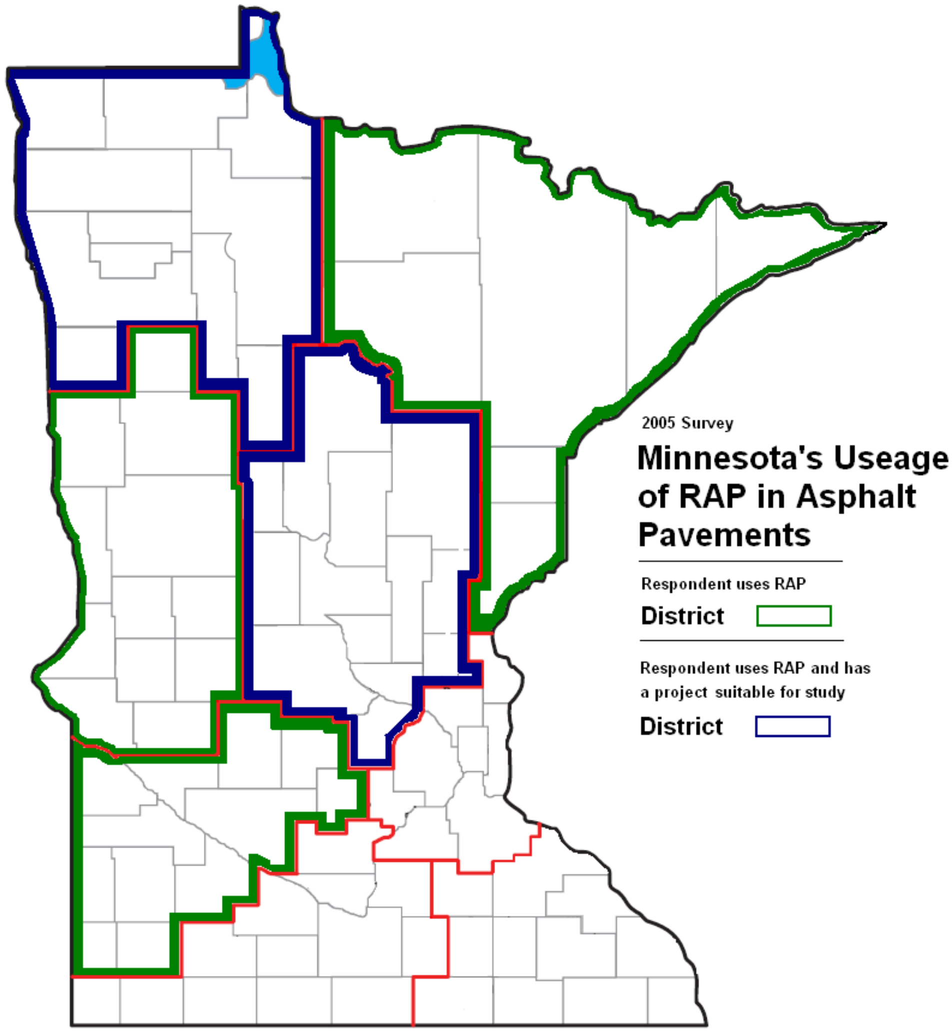

Figure 2 – Survey results from Mn/DOT districts.

<u>Question 1: Has your local agency ever included RAP in pavement design specifications?</u>

Yes (47 responses)
No (5)

<u>If no, for what reason?</u>

- The RAP is from non-verified sources and has been considered suspect. Also, we get about the same price for a non-RAP mix design.
- We have always "reclaimed" our asphalt with gravel base for use as class five. I assume the RAP would not have to come from our project.
- We have been using millings as aggregate base, up to 50 percent. Also, some older roads are made of road mix and not.
- Our RAP is productively used for shouldering, stabilizing aggregate base, and mixed with gravel for aggregate surfacing. None is available for RAP in pavements.

- It is my belief that virgin materials work better and blend together better, also, if doing a 2360 mix & you incorporate a 2340 RAP, the contractor is getting a better deal, also we use a PG 58-34 on the wear coarse so if you incorporate a PG 58-28, the contractor is receiving the 58-34 pmt. for a 58-28 AC content.

<u>If no, what change in specification is needed for you to consider using RAP in the Wear or Nonwear course?</u>
RAP stockpiling quality control, testing and quality assurance verification
Don't know. Maybe not a change in spec as much as education about product and its performance.
None (2 responses)

<u>Question 2: If yes, choose the allowable percentage of RAP in your specification.</u>

10 % (1)
20 % (15)
25 % (2)
30 % (20)
40 % (9)

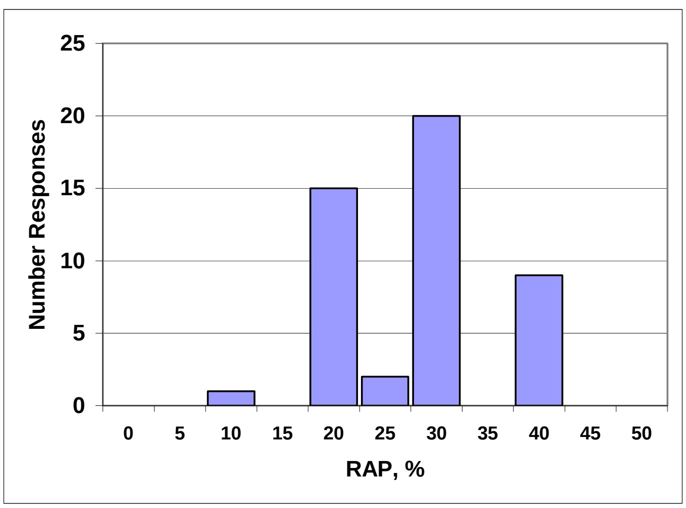

Figure 3 – Percentage RAP allowed in local Minnesota construction specifications.

<u>If yes, where is it allowed?</u>

Wear (29)
Non Wear (47)

Figure 4 – Minnesota's use of RAP in bound pavement construction.

Question 3: Does RAP in the Wear Course affect performance?

Yes (22)
No (30)

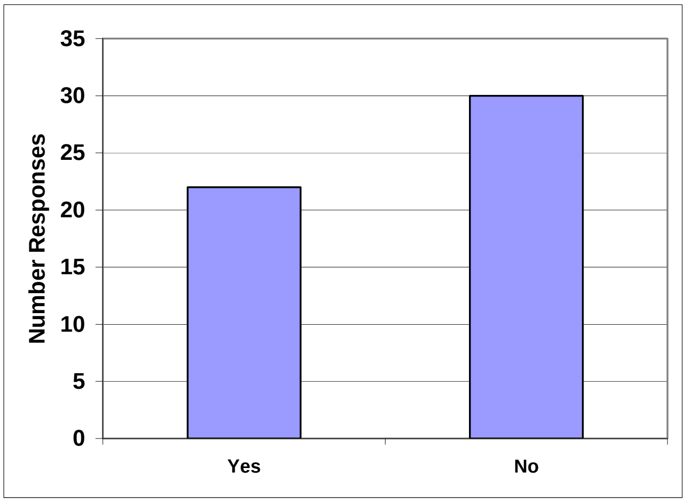

Figure 5 – Does RAP affect pavement performance?

Question 4: Check all applications that RAP is used for:

New Construction	(47)
Overlay Construction	(41)
Shoulders	(27)
Other Applications	(15)

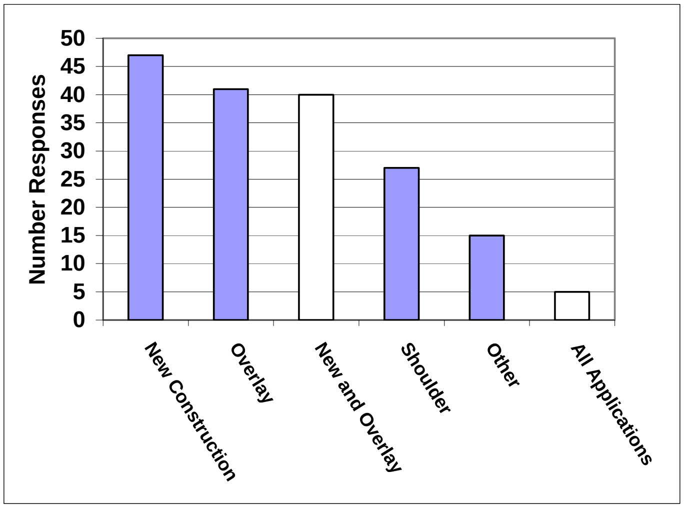

Figure 6 – Use of RAP in pavement construction.

Note: From this respondent pool, 40 used RAP in both new and overlay construction. Five respondents used RAP in all 4 of the construction choices.

Question 5: What PG graded asphalt binders do you commonly use?

Table 2 – Question 5, PG Binder Response

PG Grade	RAP Mixtures	Non-RAP Mixtures
52-34	6	5
58-28	41	45
58-34	21	23
58-40	1	2
64-28	5	5
64-34	5	5
70-28	1	1
70-34	1	1

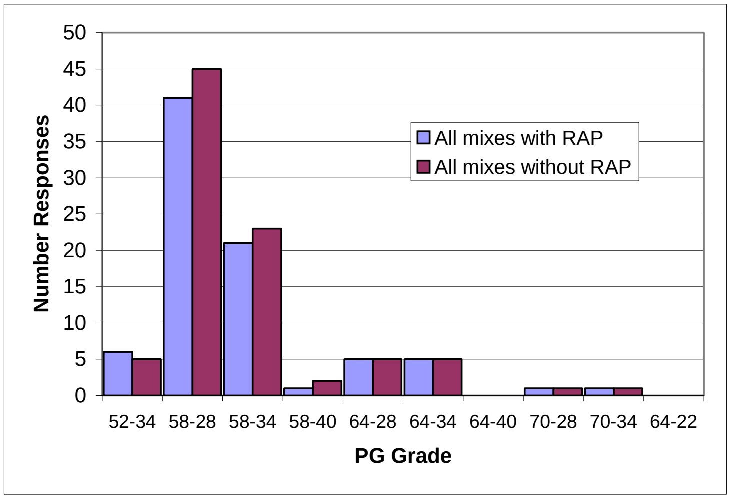

Figure 7 – PG grade frequency for Minnesota city, county, state agencies.

<u>Question 6: Distresses or problems you are concerned about with RAP mixtures:</u>

Cracking (17)
Rutting (8)
Raveling (20)
Construction (16)
None (9)
Other:

- Variability (of oil content, gradation) affects other mix properties (2)
- Not enough history to document (locally)
- Debris or Foreign Material in RAP (2)
- RAP effects uniformity of mixes
- Spalling from the shale and other "soft" aggregates used in the original production of the RAP material
- Balling up of crack fill material
- The mix tends to be more stiff
- Premature aging and oxidation
- Aesthetics. RAP mixes have chunks and sometimes balls of rubberized crack filler.

<u>Question 7: Please comment on any early failures/successes, or concerns associated with RAP mixtures:</u>

- None, no failures (15 responses)
- We have just begun using RAP mixtures. Therefore, we don't have enough of a track record to indicate failures or successes. (3 responses)
- Early RAP was not heated correctly, workability issues and large clumps present (2 responses)
- New hot mixes turn gray immediately. Not sure if this is RAP related though.

RAP material quality concerns:

- Debris or Foreign material in RAP (2 responses)
- Spalling from the shale and other "soft" aggregates used in the original production of the RAP material.
- Worry about the rap quality … is it off one road, or from a bunch of little projects combined in one stockpile …
- Oversize problems when used in the wear.
- Problems with raveling and cracking in past projects when used in the wear course.

Mixture properties concerns:

Properties and percentage of "old" AC versus "add" AC

On one project the mix did not pass specification, which was blamed on the RAP material and caused the need to remove a section of the newly laid product.

One problem with RAP is keeping the design specifications within the mix design parameters due to some variability in the RAP being introduced into the mix. Also can be mat issues when there are "globs" of oil and fines from the RAP material in the new mat.

Non-wear success:

Has worked well in the past in the non-wear (2)

Because we only allow rap in the non-wear we have not had any concerns.

Mixture performance observations:

- Less rutting problems are associated with rap mixtures. Late fall paving should be avoided with rap mixtures. More stability is associated with rap mixtures.
- RAP mixes are generally less expensive and are more stable.
- RAP mixes have held up well in northern Minnesota. Stability has been high on Marshall design mixes.
- Rubberized crack sealer that causes contractor problems and surface defects.
- Balling up of crack fill material in the wear course on thin overlays.
- Brittle mixes resulted in longitudinal crack spacing of less than 10 feet on pavement placed on new granular grade.
- May make the mixture dry and require a seal coat sooner.
- Concerned that wearing course mixtures with RAP could potentially become dry and/or brittle due to increased oxidation rates.
- Generally successful, however, we do have one project … which is causing us concern because of premature thermal cracking.

Recommendations:

- 20 years ago we had problems with a runway overlay … with RAP, and it was excluded from wear courses for several years thereafter.
- Used 50 percent RAP in the mid 1990's. 30 percent should be about the max RAP percent.
- RAP mixes have performed like virgin mix. Some of the old mix designs were too lean and ravel whether RAP or virgin material.
- If RAP percent is kept to 20 percent or less seems not to affect the mix properties.

Question 8: What method is used to recycle the asphalt pavement?

Reclaiming machine with pickup machine/scraper	(21)
Milling machine loading trucks	(49)
Removal in large blocks with crushing at stockpile	(22)

Other:

- Mill it off and use the RAP as a subbase in regrading. We also mill it and leave it as a base on resurfacing projects with great success. Very little is actually used in HMA.
- We don't specify RAP we just allow its use so the RAP is already on hand at the plant.
- Milling machine loading trucks is most common.

Question 9: Are RAP stockpiles managed?

Yes (23)
No (29)

Regardless of your response above, please indicate what the special considerations should be when managing RAP stockpiles.

- We have no spec or knowledge of how the contractor manages his pile.
- The City doesn't manage the pile. The contractor is in control of the material.
- Contractor responsibility (2).
- None.
- It needs to be recrushed when taken from the stock pile due to compaction during stockpile construction.
- Keep the material separate and clean.
- The RAP must be clean and sorted by source.
- Different roadways have different mixtures and if you do not keep these stockpiles separated it may be tough to keep your new mixtures consistent.
- Age and oil content of pavement taken from, future use of RAP
- Do not allow heavy equipment or truck onto the stockpiles. May have to recrush the stockpile.
- Do not push up a pile with dozers as it becomes too hard to load out later on.
- Quality control and quality assurance.
- Consideration to avoid contamination of RAP. Consideration for water drainage to avoid contamination of environment.
- Prevent segregation of pile.
- Drainage.
- Stockpiled in sites with planning and zoning approval and storm water discharge permit review.
- Blending to get better uniformity.
- Keep it uniform if possible.
- Run extraction tests for asphalt content during crushing.
- Determine the mix, PG grade and age of the asphalt.
- Making sure any oversized chunks are screened out.
- Particle size, so you are getting a consistent product.
- None.

- Not overly concerned with the origination of the RAP, as long as the ultimate bituminous mixture meets specifications.
- Keep foreign material segregated.
- Crushing and screening material for oversize. Drainage should be considered. Hard surfaced platform or stockpile pad is helpful. Separate stockpiles based on asphalt cement content. Uniformity, segregation, contamination and age of stockpile are also factors to consider.
- NA
- Pile uniformity is sometimes difficult to achieve, therefore mix uniformity becomes an issue.
- We do not stockpile - Material taken to commercial plant or used as a class 7 aggregate.
- All contained within pits.
- Stable foundation for stockpile, aggregate base not dirt or clay to prevent contamination.
- May have to do additional crushing if stockpile sits to long in certain weather conditions.
- The contractors manage them. Gradations and samples represent the pile.
- In order to manage oil content, keep separate stockpile for rap material coming from different locations.
- Testing the rap for oil content during the milling process and keeping rap with different oil percentages separated to help eliminate ups and downs in oil content of the bituminous mixture being produced.
- We have not typically dealt with RAP management, but rather let the contractor be responsible.
- Keep each source separate due to variations in asphalt content.
- Keeping them uniform.
- Good blending from a given source and do not add to existing pile from another source. Too hard to blend an existing large stockpile with new material added to it. Oil percentages change too much due to lack of managing.
- They need to be tested during the mix design process.
- RAP should be stockpiled according to project from which it is removed not combined with other piles.
- Under control of contractor-no management assumed.
- We currently have a contractor which placed a stockpile above a well hear protection area...we are concerned about leaching of bituminous.
- None
- They should be managed and used in conformance with MPCA rules and regs.
- We have not retained ownership of stockpiles. Contractors own the stockpiles and some manage them better than others, therefore we eliminate RAP in the wear to error on the safe side. Avoiding oversize material is the primary concern in managing piles and consistency of the oil content throughout the stockpile is another concern.
- Moisture absorption.
- Entire stockpile should be from a single source or have same material properties. Stockpiles should be sized prior to adding to new hot mix.

Question 10: As part of this field study, we are interested in examples of RAP mixtures with both good and poor performance. Does your agency have any candidate projects suitable for this study?

Yes (10)
No (42)

Question 11: Comments you would like to contribute to this study:

- We have allowed up to 20 percent RAP in the wear, but like to keep the total AC between 5.8 and 6.1 percent. The RAP has some material between 1/2" and 3/4", but when combined with 1/2" minus virgin aggregate, the composite is so close to a MV4 wear course mix that it is virtually the same.
- We follow Mn/DOT specs with nothing special.
- None, or N/A (3).
- We have not had failures with RAP to date.
- I would prefer to answer a survey that does not require me to enter all fields. I appreciate the pop-up to let me know I have not answered a question - I may have omitted the answer by mistake. However, I would like to be able to submit the survey, even if all questions are not answered.
- There are many variables in a bituminous mixture as well as roadway characteristics. Perceived mix problems due to RAP could be a combination of other issues such as total oil, i.e. film thickness, construction practices, density, etc.
- Results of this study will be helpful in promoting RAP. I guess a question I have is if the RAP does not come from your project, how does one know the condition of someone else's old asphalt (even with the testing done).
- We have had better experiences with rap mixtures than we have had with virgin mixtures.
- We have an SPS5 Research project West of Bemidji that has both rap and virgin mixes.
- We have used both rap and virgin material (contractor's choice) the last few years and do not notice any difference in the material used.
- We like to recycle RAP in our hot mix.
- We have used rap as a base material in addition to using it in a hot mix. By the way I don't know if rap affects a wear course, I had to answer the question to get out of this survey. You should allow for non-answers so as not to skew the survey with false information.
- We typically have RAP mixtures on our projects whenever it is available.
- We reclaim most of our pavements reducing amount of rap generated.
- We also use rap as aggregate base. Some feel this is not a good practice...but we like it.
- Real concerns about use as wear course – raveling because consistency is very touchy.

Chapter 3: Test Sections

The test matrix of HMA wear courses was developed from the agency survey results from Chapter 1 and from knowledge of available existing projects. The survey documented the current climate of RAP use in municipal, county, and state agencies. Out of 52 respondents a total of 10 said they had projects suitable for the study. Of the 21 respondents electing to comment on premature failures, 15 said there had been none. When asked what type of distresses and problems are associated with RAP mixtures the response was: 20 raveling, 17 cracking, and 16 construction related problems. These results suggest that premature cracking is either not observed, or is observed but not perceived to be a significant problem.

RAP percentage and binder grades were included in the test matrix based upon the survey results. Response showed the most frequently used percentages of RAP were 20 and 30, and the most frequent asphalt binder grades were PG 58-28 and 58-34. Both grades were used with equal frequency with or without RAP.

Description of Test Sections

Table 3 shows the highways that included binders and RAP percentages that were selected for testing.

Table 3 – Testing Matrix for LRRB 826

AGENCY	HIGHWAY	BINDER PG	RECYCLE TYPE	% RAP	DISTRESS
Mn/DOT D6	I-90	58-34 unmodified	None	0	Reflective cracking
		58-34 modified	None	0	
		58-28	None	0	
St. Louis County	County 4	58-28	County road millings	30	Transverse and wandering cracking
	County 16	58-34	County road millings	20	Occasional trans. crack.
Olmsted County	County 112	58-34		0	
		58-34	Plant RAP	20	
Mn/DOT D3	US-10	64-34	Plant RAP, shingles	30	Reflective cracking

I-90 (Mn/DOT District 6) south of Winona
Project Number: S.P. 8580-133 (paved in 1997)

Description:
This Superpave HMA overlay was a crown correction from a slope of 0.010 on the existing concrete panels to a slope 0.020 after paving. The BOC overlay was 4.0-in. at the outside edge and 5.3-in. on the centerline of 27-ft long concrete panels.

Pavement Sections for Research:
Three asphalt binders were used on this project. A PG 58-28 asphalt binder was used in the HMA on the west end of the project. A polymer modified (SBS) PG 58-34 asphalt binder was used in the left lane just west of the County Road 7 bridge. An unmodified PG 58-34 was used in the right lane just west of the County Road 7 bridge. The 27-ft long concrete panels were sawed and sealed at spacing of 27-ft, 54-ft and two sections had no sawed-and-sealed joints.

Summary:
2004 site visits showed that hairline cracking was pervasive. 2005 visits found that many of the new hairline cracks were still visible in April but were no longer visible in December. The fall 2005 visits indicate some crack healing had occurred throughout the year, most notably in the modified PG 58-34 test sections. Prior testing in 2002 of field cores showed that the modified asphalt binder was aging less than the unmodified binder.

Two 6-in. diameter cores of each section were obtained for potential binder testing.

Table 4 – I-90: Transverse Cracks – Linear Feet per 500-ft Station

YEAR	**WESTBOUND**			**COMMENTS**[a]
	Control Section PG 58-28[b]	**Unmodified PG 58-34**	**Modified PG 58-34**	
2000	156	72	108	No saw and seal
2002	160	96	96	No saw and seal
2003	195	136	196	No saw and seal
2004	199	142	196	No saw and seal
2005	218	136	175	No saw and seal
2000	12	0	0	54-ft saw & seal spacing
2002	39	0	12	54-ft saw & seal spacing
2003	92	12	108	54-ft saw & seal spacing
2004	102	12	108	54-ft saw & seal spacing
2005	102	12	65	54-ft saw & seal spacing

a Crack stations could not be duplicated between 2000 & 2002.
B Average of two 500-ft crack stations.

St. Louis County Road 4 south of Biwabik
Project Number: S.P. 69-604-57, C.P. 9247 (paved in 2004)

Description:
This HMA reconstruction consisted of two 12-ft driving lanes with 6-ft shoulders. Project length was 5.3 miles. Above the natural soil was 24 in. of select granular modified (less than 7 percent passing the #200 sieve), 6 in. of class 5 base material, and 5.5 in. of bituminous pavement. The bituminous pavement was constructed as 2.5 in. base lift, 1.5 in. binder lift, and 1.5 in. wear course lift. The maximum RAP content for this project was 30 percent, all coming from County Road 16 millings. The bituminous pavement was designed using Marshall MV criteria and was built using PG 58-28 asphalt binder.

The RAP stockpile was initially sampled for this project approximately one year after construction. Tests results for asphalt content of the stockpile were significantly lower than expected. Test results from a second sample obtained from the roadway showed expected levels of asphalt present in the pavement material.

Pavement Sections for Research:
The project staff obtained roadway and rap stockpile samples and continue to monitor this construction with respect to cracking.

Summary:
During the winter of 2004-05 this project developed transverse cracks at the rate of one per every 50 ft over the entire length of the project.

County staff provided eight 6-in. diameter cores at random locations for inclusion in the RAP testing matrix.

St. Louis County Road 16 east of TH 53
Project Number: S.P. 69-604-57, C.P. 9247 (paved in 2005)

Description:
This HMA reconstruction consisted of two 12-ft driving lanes with 6-ft shoulders. Above the natural soil was 24 in. of select granular modified (less than 7 percent passing the #200 sieve), 6 in. of class 5 base material, and 5.5 in. of bituminous pavement. The bituminous pavement was constructed as 2.5 in. base lift, 1.5 in. binder lift, and 1.5 in. wear course lift. The maximum RAP content for this project was 20 percent, all coming from County Road 16 millings. The bituminous pavement was designed using Marshall MV criteria and was built using PG 58-34 asphalt binder.

Pavement Sections for Research:
The project staff obtained roadway and rap stockpile samples and continue to monitor this construction with respect to cracking.

Summary:
During the winter of 2005-06 this project developed no transverse cracks. Occasional cracking was observed after two winters.

County staff provided three 6-in. diameter cores at random locations for inclusion in the RAP testing matrix.

Olmsted County Road 112 north of Rochester
Project Number: C.P. 06-01 (paved in 2006)

Description:
This HMA reclamation/reconstruction consisted of two 12-ft driving lanes with 6-ft shoulders. Above the natural soil was an existing 8 in. of aggregate base, 6 in. reclaimed bituminous surfacing, and 5.5 in. of new bituminous pavement. The bituminous pavement was constructed as 2 in. base lift, 2 in. binder lift, and 1.5 in. wear course lift. The maximum RAP content for this project was 20 percent, coming from plant stockpiles. The bituminous pavement was designed using Superpave criteria and was built using PG 58-34 asphalt binder.

Pavement Sections for Research:
This project was constructed with the assistance of Western Research Institute (WRI) to evaluate the performance of binders from a variety of crude oil sources. As part of the study one RAP and one Virgin section was included using a binder common to Minnesota. Project staff obtained plant mixed samples at the time of construction, and also roadway cores in 2008. They continue to monitor this construction with respect to performance.

Summary:
During the winter of 2006-07 this project developed no transverse cracks. Occasional cracking was observed after two winters.

County staff provided six 6-in. diameter cores of 20 percent and 0 percent RAP mixtures taken in the transition areas between WRI monitoring stations for inclusion in the RAP testing matrix.

US Highway 10 (Mn/DOT District 3)
Project Number: 0502-95 (paved in late season in 2005)

Description:
This HMA overlay consisted of four 12-ft driving lanes with 10-ft shoulders. Above the natural soil was 9 in. of aggregate base, 7.5 in. existing bituminous surfacing, and 4 in. of new bituminous pavement. The maximum RAP content for this project was 30 percent, coming from plant RAP and manufacture waste shingles stockpiles. The bituminous pavement was designed using Superpave traffic level 4 criteria and was built using PG 64-28 asphalt binder.

Pavement Sections for Research:
This bituminous mixtures for project were designed to include 30 percent recycled materials (RAP and shingles), and use either 3 or 5 percent shingles. Project staff obtained roadway cores during the winter of 2006 as part of an asphalt film thickness study. The cores will be shared

between the film thickness project and the RAP study. Staff continues to monitor this construction with respect to performance.

Summary:

During the winter of 2005-06 this project developed severe reflected transverse cracks. Increased cracking was observed during the second winter.

Chapter 4: Specimen Fabrication and Evaluation

A suite of laboratory tests were applied to pavement cores obtained from the candidate highways having non-overlay construction. The cores were initially prepared for dynamic modulus testing and bulk specific gravities were measured. After completion of modulus testing each wear and non-wear mixture was analyzed for asphalt binder content, performance grade, and aggregate gradation.

The standard methods for preparing dynamic modulus specimens refer to using cylinders of asphalt mixture that are adequately large to allow for 100 mm (4 in.) diameter by 150 mm (6 in.) to be produce from a coring and cutting process. The precut specimens may be either (gyratory) compactor-produced cylinders or field cores.

In this project the task of producing dynamic modulus specimens was challenging because the specimens originated from a limited amount of field cores, and single-core lift thicknesses were not adequate to provide the 150-mm height. As an alternative, the specimens were produced by first separating the wear and non-wear mixtures by sawing then recombining like courses using an epoxy. The recombined cores were then cored to 100 mm diameter and sawed to square the ends. The specimens produced in this manner were not all 100-mm in height, but were tall enough to accommodate attachment of 100-mm long linear variable differential transducers (LVDT's) that were used for data collection. Due to the existing construction conditions it was necessary to use four cores to produce a wear-course specimen and two cores to produce a non-wear specimen. Table 5 shows the set of specimens that were produced.

Table 5 – Dynamic Modulus Specimens from Field Cores

Road	% RAP	Cores	Nonwear Specimens	Wear Specimens	Full-Depth Specimens
St. Louis CR 4	20	3	0	0	3
St. Louis CR 16	30	8	2	1	2
Olmsted CR 112	20	6	2	1	2
Olmsted CR 112	0	6	2	1	2

After specimen production the dynamic modulus testing progressed according to standard protocol. The response of each specimen was tested at 0.1, 0.5, 1, 5, 10, and 25 Hz at temperatures of 14, 40, 70, 100, and 130ºF.

Figures 8 to 17 are photos of the specimens after completion of the dynamic modulus tests. LVDT attachment points are visible in the photos. Presence of the epoxy joint is apparent in the wear and non-wear photos.

Figure 8 – |E*| specimen set from St. Louis CR 4 cores.

Figure 9 – One wear and two non-wear |E*| specimens from St. Louis CR 4 cores.

Figure 10 – Wear course |E*| specimen from St. Louis CR 4 cores.

Figure 11 – Non-wear |E*| specimens from St. Louis CR 4 cores.

Figure 12 – Full-depth |E*| specimens from St. Louis CR 4 cores.

Figure 13 – Full-depth |E*| specimen set from St. Louis CR 16 cores.


Figure 14 – Full-depth |E*| specimen from St. Louis CR 16 core.


Figure 15 – |E*| specimen set from Olmsted CR 112 cores.

Figure 16 – Wear course |E*| specimen from Olmsted CR 112 cores.

Figure 17 – Full-depth |E*| specimen from Olmsted CR 112 core.

Asphalt binder content and aggregrate gradation were determined fom the wear and non-wear specimens. Additionally, asphalt binder recovery was performed to provide material for testing of binder performance grade. Performance grading tests followed the American Association of State Highway and Transportation Officials (AASHTO) standards: AASHTO T 313, *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer* (BBR), and AASHTO T 315, *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer* (DSR).

Chapter 5: Test Results

Aggregate and Asphalt Binder Test Results

Test results for the wear and non-wear courses of the subject highways are reported in Table 6. The tables shows measured aggregate gradations, asphalt binder content (AC), performance grade (PG), and average mixture bulk specific gravities (Gmb). Design binder content and maximum mixture specific gravity (Gmm) are additional elements of information that were added from project records. The values for dust-to-binder ratios, extracted-to-design binder contents, and average voids were calculated from the laboratory results.

Table 6 – Test Results

Sieve	CR 112 Wear 0%RAP	CR 112 NW 0%RAP	CR 112 Wear 20%RAP	CR 112 NW 20%RAP	CR 4 Wear	CR 4 NW	CR 16 Wear	CR 16 ++ NW
5/8	100	98	99	97	100	98	100	98
½	100	92	97	93	99	93	96	93
3/8	90	83	85	86	97	87	90	86
#4	46	65	41	70	81	72	73	72
#8	31	52	27	57	66	58	61	59
#10	29	49	25	54	62	54	58	56
#16	24	42	21	47	51	44	48	48
#40	19	26	15	29	29	24	27	30
#50	14	18	12	20	22	18	20	23
#100	8	7	8	8	12	11	10	12
#200	5.1	4.3	6	4.9	7.9	7.5	6.3	7.5
Parameter								
Extracted AC%	4.5	5.5	4.6	4.9	6.1	5.1	5.2	5.2
Design AC%	4.9	5.5	4.9	5.4	5.7	5.5	5.7	5.7
Extracted Ratio	0.918	1	0.939	0.907	1.070	0.927	0.912	0.912
Dust/binder	1.133	0.782	1.304	1	1.295	1.471	1.212	1.442
Design add AC%	0	0	NA	NA	4.9	4.4	4.9	4.9
High PG	66.1	60	68.2	63.9	66.1	65.9	63.4	63.1
Low PG	-36.4	-36.9	-32.1	-32.5	-30.6	-31.3	-34.5	-34.3
Design PG	58-34	58-34	58-34	58-34	58-28	58-28	58-34	58-34
2-yr Crack Spacing	500	500	310	310	50	50	500	500
% RAP	0	0	20	20	20	20	30	30
Average Gmb E* Specimen	2.284	2.378	2.24	2.347	2.334	2.328	2.367	2.367
Gmm	2.486	2.486	2.486	2.486	2.449	2.47	2.493	2.493
Average Voids E* Specimen	8.1	4.3	9.9	5.6	4.7	5.7	5.1	5.1
++ Same design for St. Louis CR 16 wear and non wear.								

According to the test results all of the asphalt binders met or exceeded their corresponding design for high temperature performance grade. However, the design low-temperature grade was not met by the material obtained from the CR 112 RAP section. In that case the low-temperature test was 1.5 to 1.9 degrees short of meeting the design requirement. The difference may be due to a combination of factors that include short term aging, RAP binder, or the presence of epoxy from the dynamic modulus specimens.

Figures 18 and 19 are plots of the extracted aggregate gradation results along with a reference line called 12.5 mm (0.5 in.) maximum density. From the plots it is apparent that the CR 112 wear mixtures are coarser than the rest of the mixtures in the study.

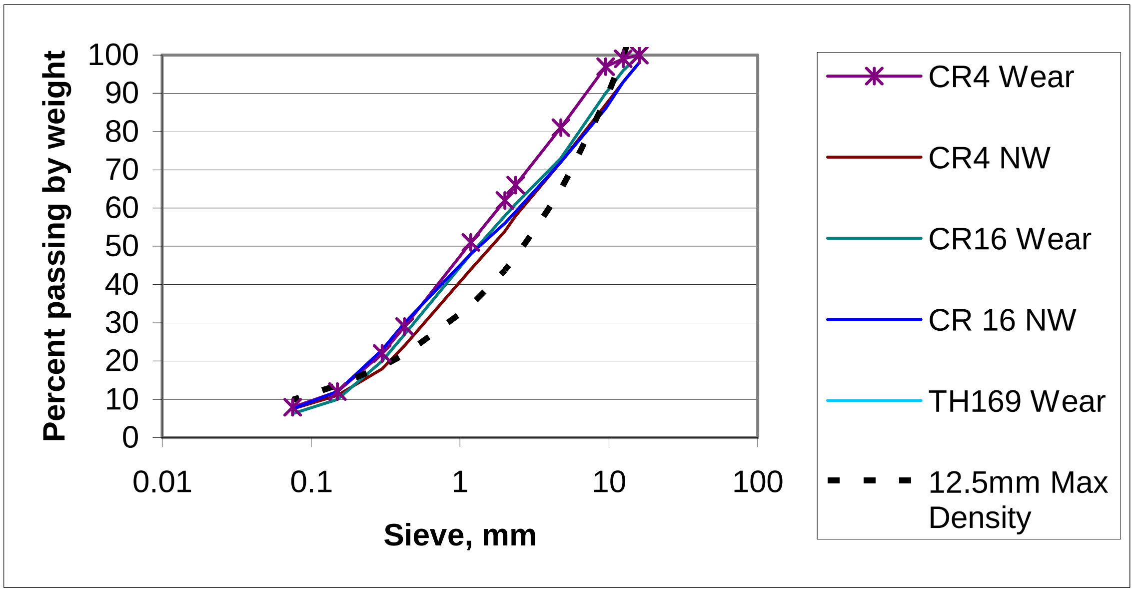

Figure 18 – St. Louis County extracted gradations.

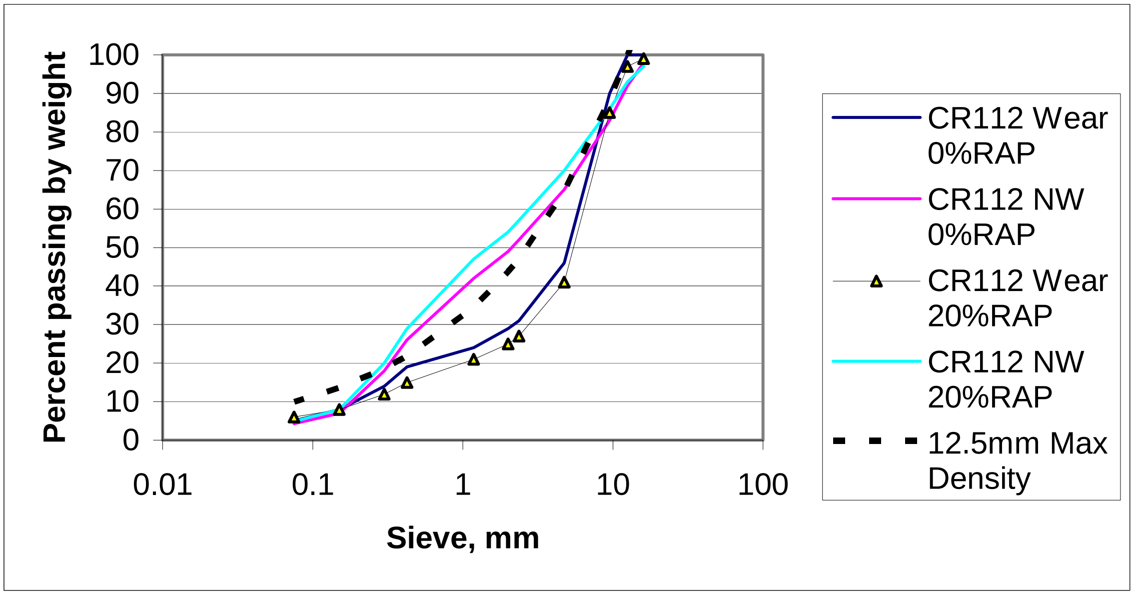

Figure 19 – Olmsted County extracted gradations.

Dynamic Modulus Results

Dynamic modulus testing was performed on full-depth as well as the wear and non-wear course specimens fabricated from field cores. Each specimen was tested at 6 frequencies and five temperatures, producing 6 x 5 x 17 = 510 specific measurements of dynamic modulus |E*|.

Figures 20 to 23 show the |E*| for the materials plotted at various temperatures and frequencies. The plots follow the expected trend of relatively lower |E*| values at higher temperatures. |E*| values tend to increase with test frequency.

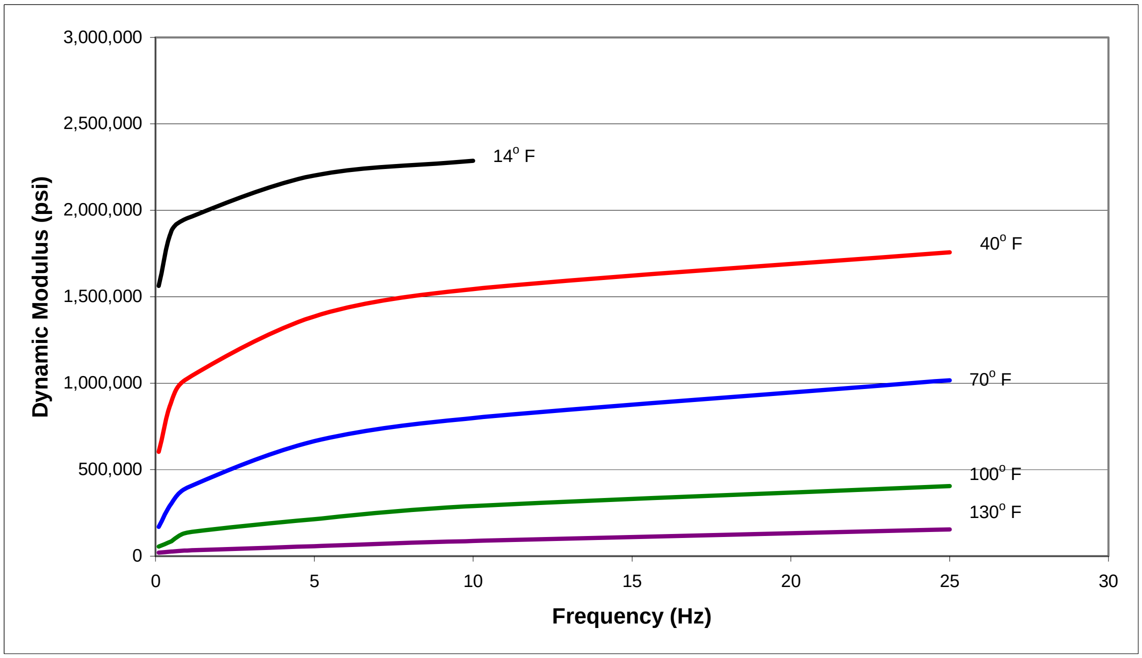

Figure 20 – St. Louis CR 4, 58-28 plus 30% RAP (Wear Course) 14ºF – 130ºF.

Note that the mixtures having the highest modulus were at 20 (CR 112) and 30 (CR 4) percent RAP, both occurred during testing at the highest frequency and lowest temperature. Note that the plots of high temperature data were relatively flat at all frequencies for all mixtures.

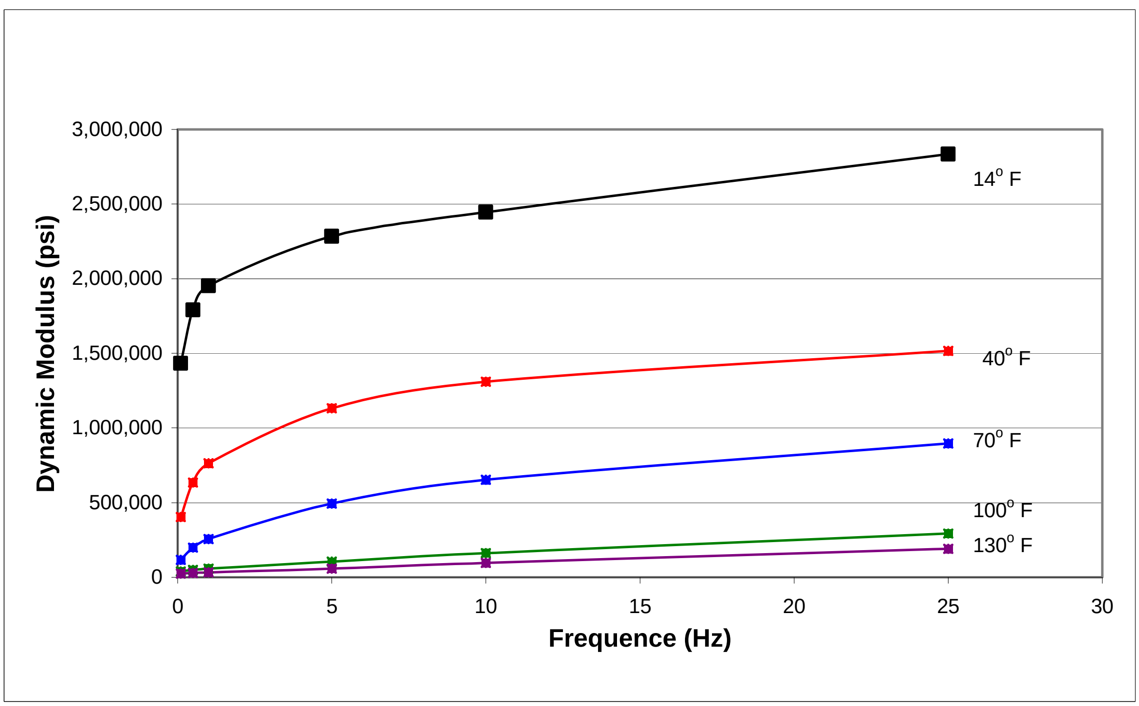

Figure 21 – St. Louis CR 16, 58-34 plus 20% RAP, (Full Depth) 14ºF – 130ºF.

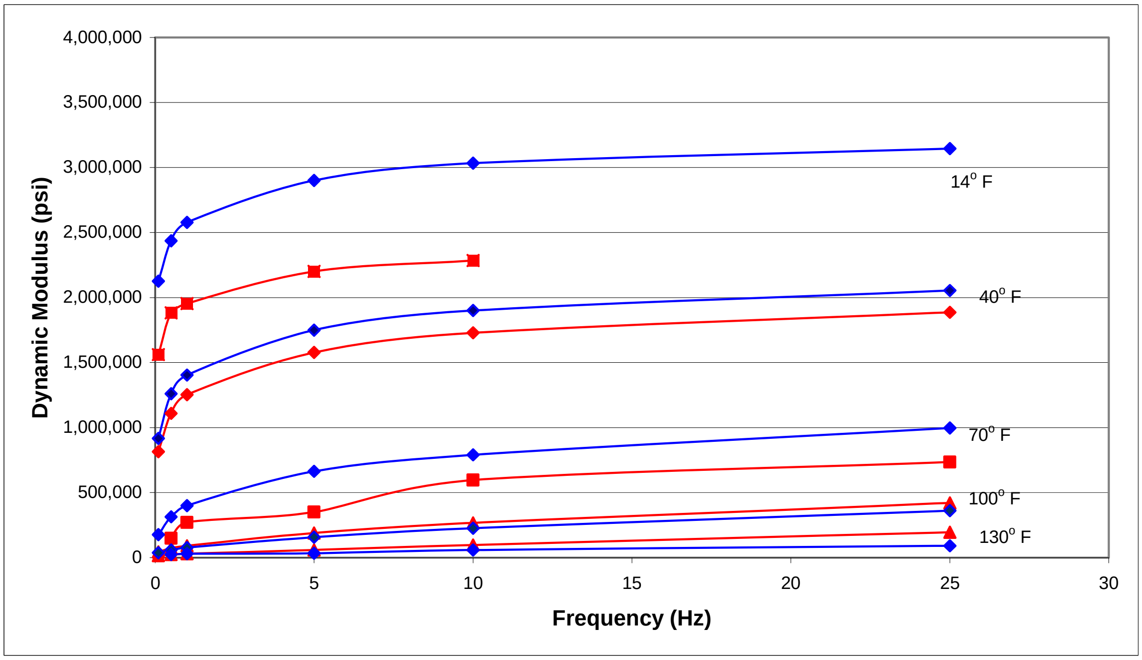

Figure 22 – St. Louis CR 4, 58-28 plus 30% RAP (Non Wear Course) 14ºF – 130ºF.

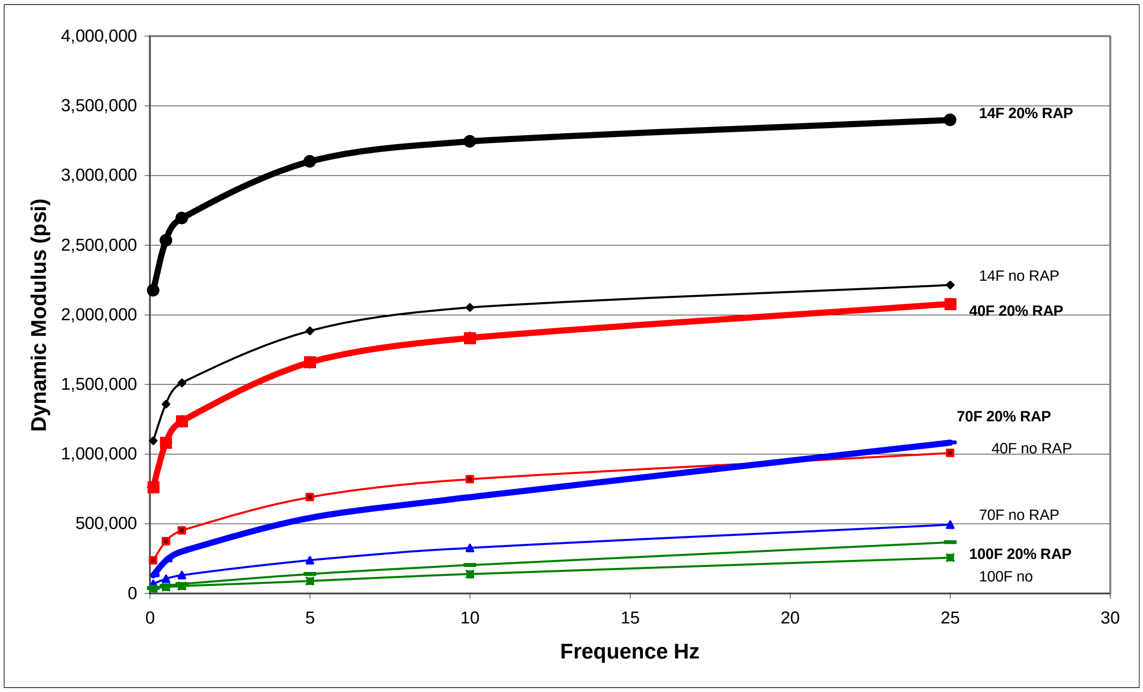

Figure 23 – Olmsted CR 112 Full Depth (58-34) and (58-34 plus 20% RAP) 14ºF – 130ºF.

Chapter 6: Analysis

Master curves were developed to compare the field and laboratory performance of all the mixtures. Curves were developed for the full-depth, non-wear, and wear course specimens. A statistical comparison was also performed to examine the relationship of field performance and mixture characteristics.

Master Curve Results

According to basic time-temperature superposition theory, master curves may be generated by shifting data about a predetermined reference temperature. For the purpose of comparing the mixture performance data was fitted with respect to a reference temperature of 70ºF. |E*| data was input to Microsoft Excel, and a "solver" routine was used to develop the equation parameters based on minimizing least squares. The datat was fitted to the sigmoidal function given in equation 1.

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

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, and β and γ are parameters describing the shape of the sigmoidal function.

Figure 24 shows a typical master curve developed from |E*| test results. In this figure the fitted curves are plotted together with shifted data. Portions of the curve located outside the data range, approximately 0.001 to 400,000 Hz, are extrapolated from the least squares fit. Figures 24 to 30 include all master curves developed from the |E*| results.

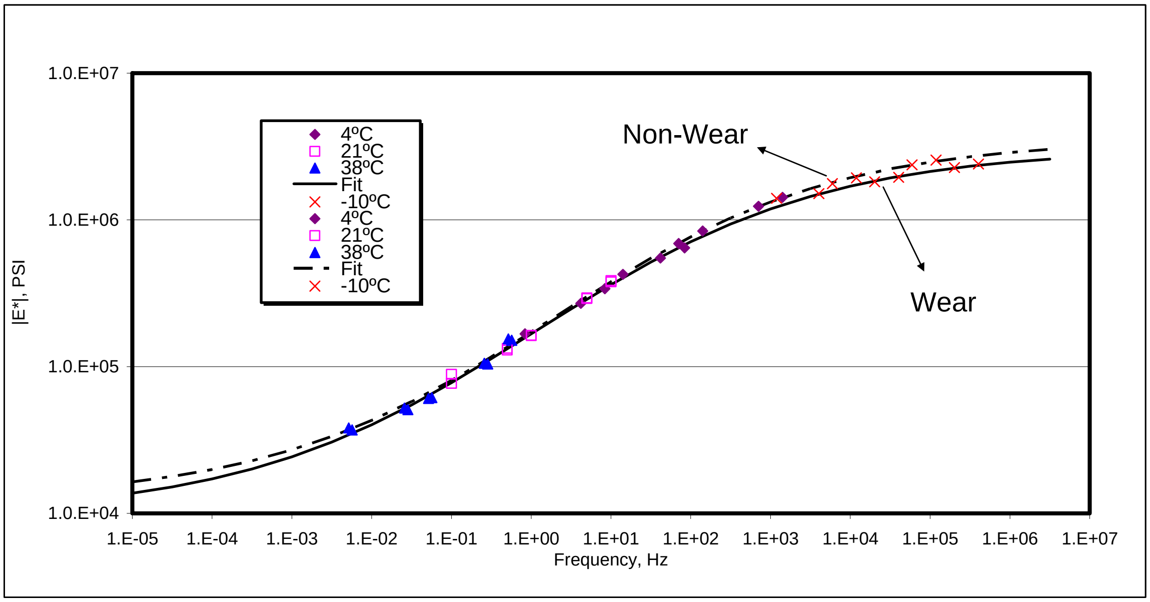

Figure 24 – |E*| master curve for Olmsted CR 112 wear and non-wear course specimens; 58-34 with no RAP.

Figure 24 shows the wear and non-wear course mixtures of CR 112 are essentially the same.

Differences are apparent in Figure 25, which shows a difference between the CR 112 RAP and no-RAP full-depth specimens. In this case the mixture design differed only in the proportion of RAP used. Note the results for the RAP mixture shows that stiffer response occurs through most of the curve. Stiffer response is associated with more brittle behavior, especially for high frequency (low-temperature) conditions. This behavior is also found when comparing the CR 112 wear and non-wear master curves in Figures 26 and 27. The difference is consistent with the observation of thermal crack development as noted in the field performance of the two mixtures

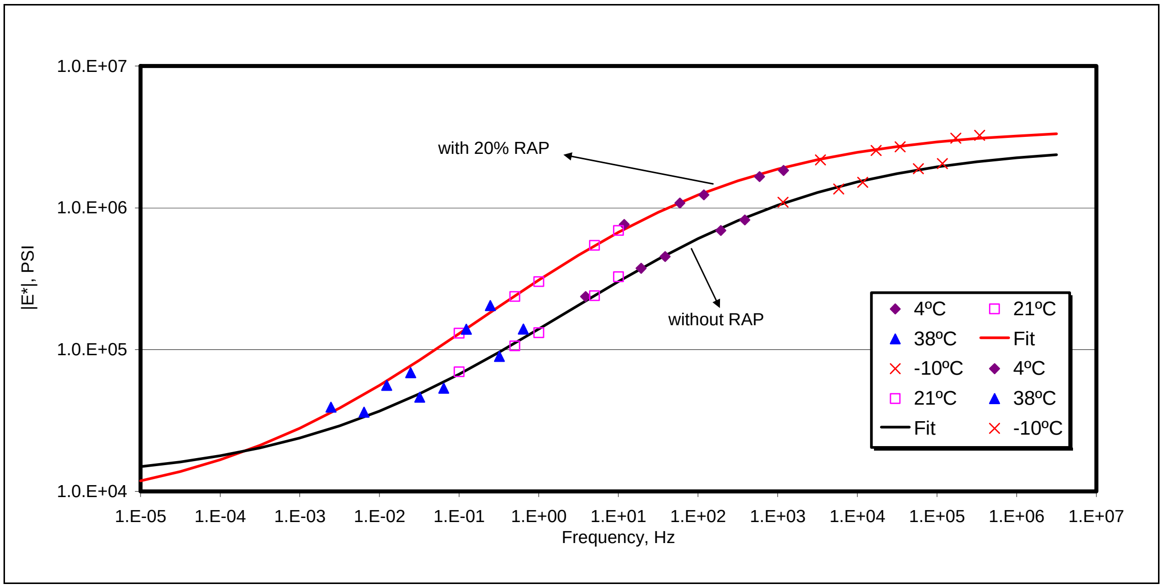

Figure 25 – |E*| master curve for Olmsted CR 112 full depth cores; 58-34.

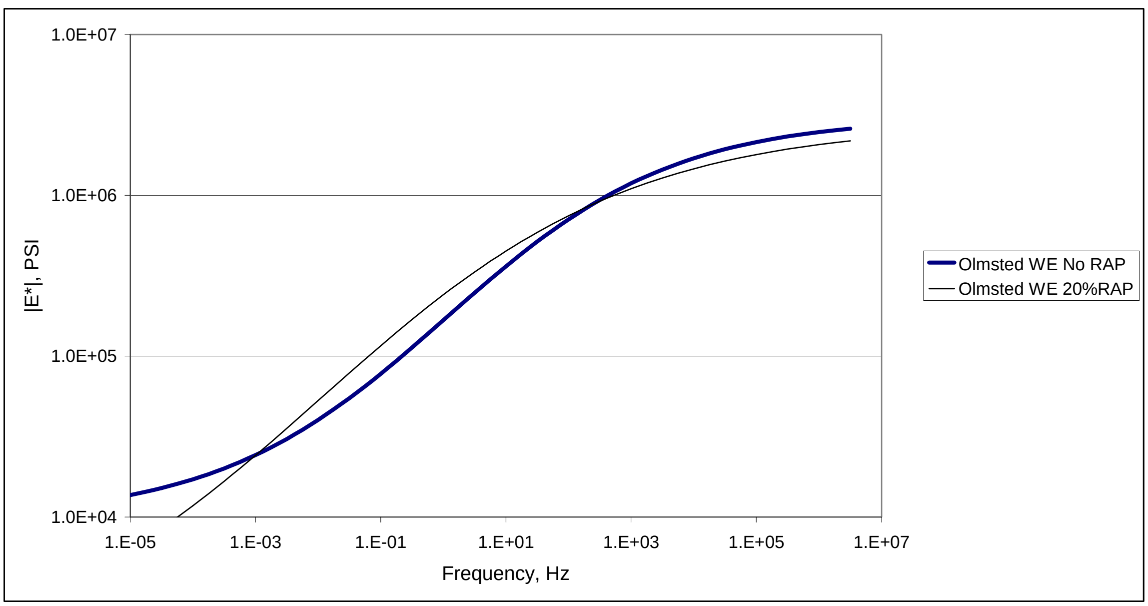

Figure 26 – |E*| master curve for Olmsted CR 112 wear course specimens; 58-34.

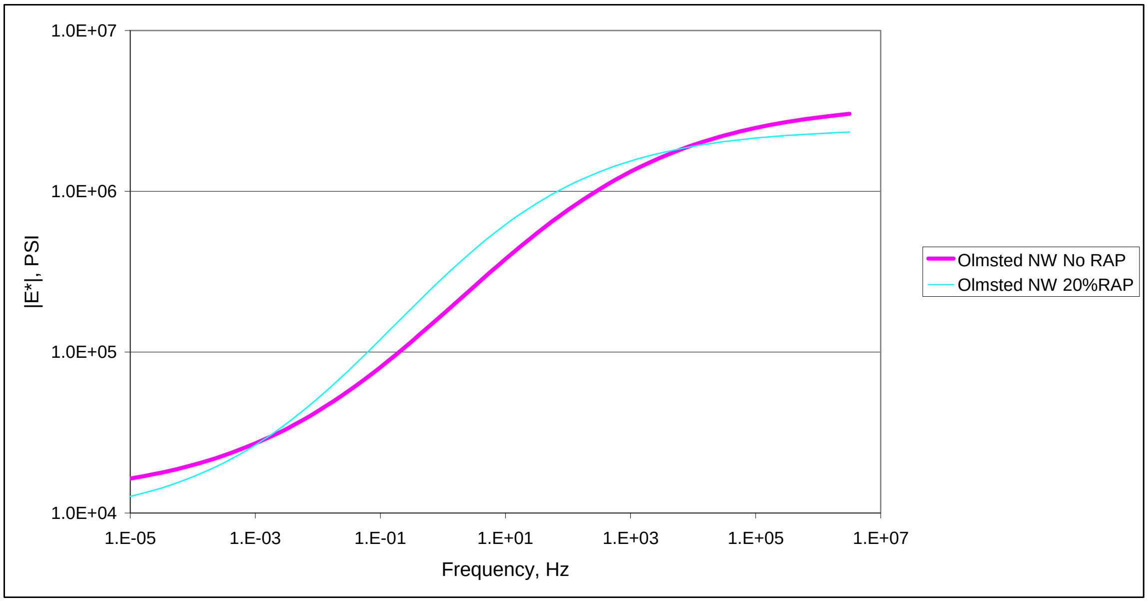

Figure 27 – |E*| master curve for Olmsted CR 112 non-wear course specimens; 58-34.

In the case of St. Louis CR 4 there was little difference between the full-depth, wear, and non-wear master curves shown in Figure 28.

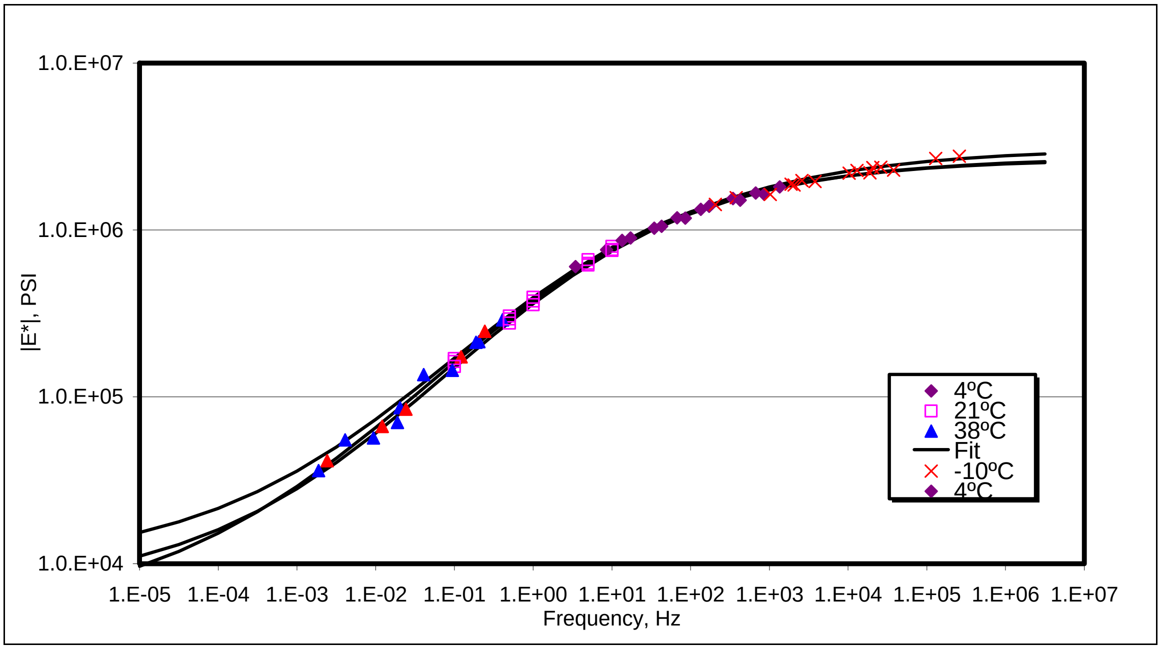

Figure 28 – |E*| master curve for St. Louis CR 4 wear, non-wear course and full depth; 58-28 with 30% RAP.

St. Louis CR 16 construction differed from CR 4 in that the wear design was also used for the non-wear course, the total amount of RAP was 10 percent less, and the asphalt binder low-temperature grade was -34. Some evidence of the mixture differences is apparent when comparing the full depth master curves in Figure 29. In this case the mixture having more RAP and a relatively stiffer binder shows a higher |E*| for portions of the curve within the shifted data.

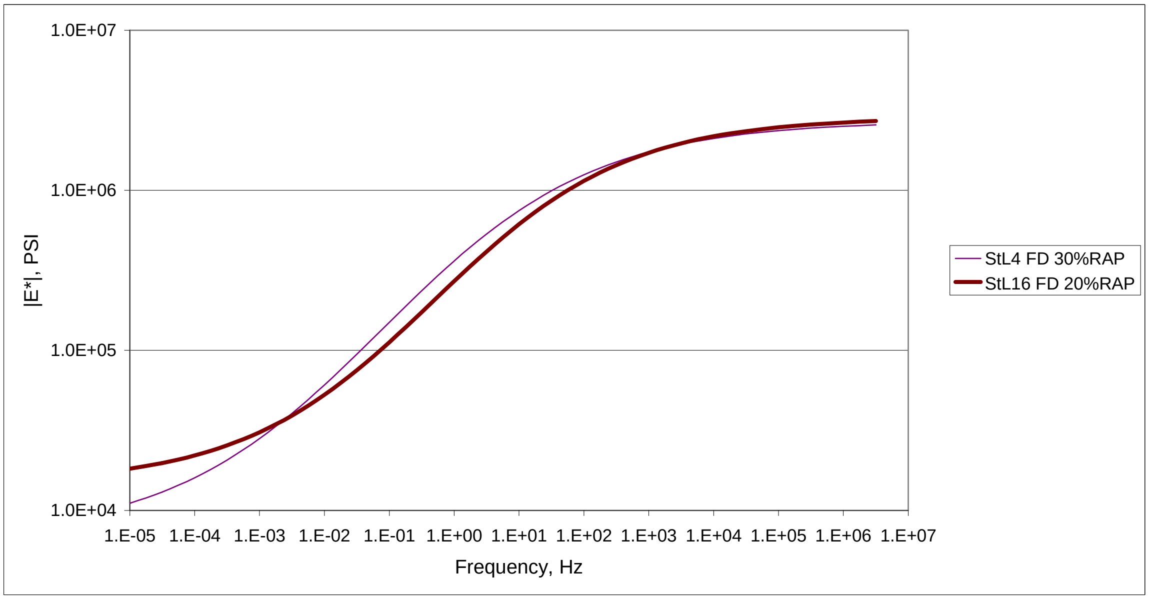

Figure 29 – |E*| master curve for St. Louis County; 20% and 30% RAP.

Figure 30 compares master curves of the 30 percent RAP (CR 4) section to the other mixtures for specimens fabricated from full-depth cores. The figure shows that CR 4 behaves in a stiffer manner through most of the interpolated portion of the curve. Also in Figure 30, the 0 percent RAP (CR 112) section shows the lowest |E*| values with the exception of the low frequency portion of the curve. These trends correspond to the field performance of the 30% RAP (CR 4) section, which showed significantly greater early distress than the other mixtures.

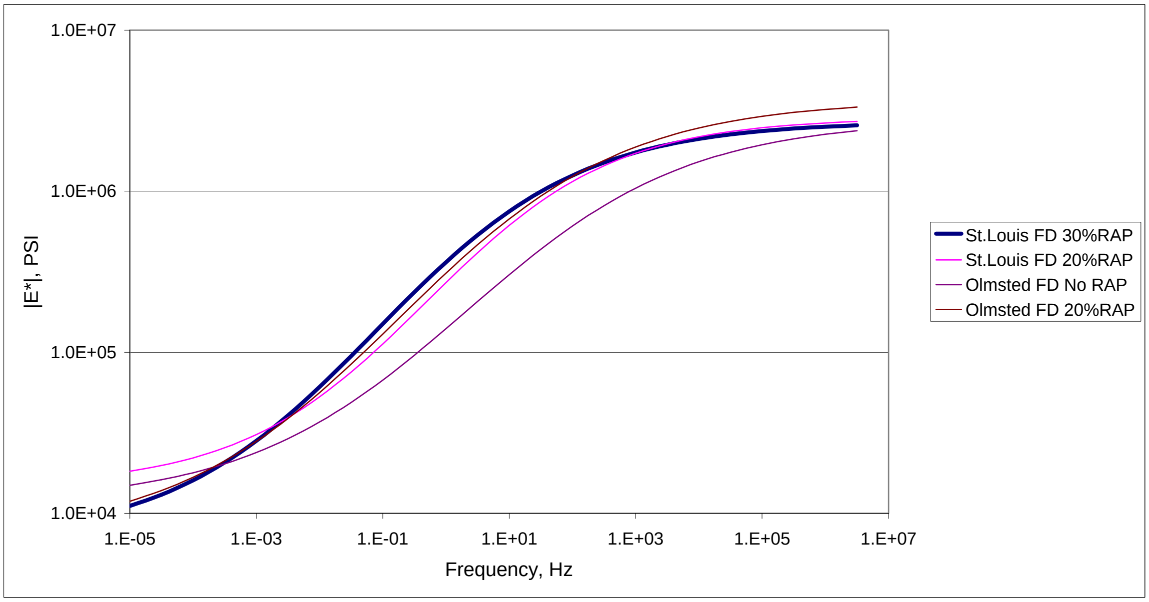

Figure 30 – |E*| master curve comparison for St. Louis CR 4 and Olmsted CR 112.

Statistical Comparison of Mixture Parameters

Mixture performance was compared by assigning a performance ranking to the roadway data shown in Table 6, and performing correlations on the resulting data set. Rankings are shown in Table 7. Although CR's 16 and 112 (0 RAP) showed similar early thermal cracking performance they were assigned this particular order 2 and 1 because of early differences in surface quality and seasonal ride characteristics.

Table 7 – Roadway Performance Rankings

Road	Crack Interval, ft	Performance Rank
CR 112 Wear 0% RAP	500	1
CR 112 NW 0%RAP	500	1
CR 112 Wear 20% RAP	310	3
CR 112 NW 20% RAP	310	3
CR 4 Wear 30% RAP	50	4
CR 4 NW 30% RAP	50	4
CR 16 20% RAP	500	2
CR 16 NW 20% RAP	500	2

Correlation coefficients were developed based on observed field performance and the mixture test results in Tables 6 and 7. The results are presented in Table 8, and show a very strong relationship between field performance and low-temperature performance grade and also percentage of new asphalt binder.

Relationships were moderate for percent RAP, percent passing the #100 (0.15 mm) sieve, high temperature performance grade, dust-to-binder ratio, and percent passing the #200 (0.075 mm) sieve.

In addition to these results there was a strong correlation with Gmm (R = -0.699). Gmm is a parameter that is not expected to affect performance.

Table 8 – Statistical Performance Relationships

Parameter	Correlation
%RAP	0.513
#100	0.538
HIPG	0.552
Dust/binder	0.572
#200	0.667
New AC	0.724
LOPG	0.988

According to the plots in Figures 24 to 30, field performance is best represented by dynamic modulus master curves from full-depth specimens. Statistical relationships between the field performance ranking, observed cracking, and |E*| were developed along the entire frequency range for all full-depth master curves.

As expected, it was found that observed cracking and performance rank were well correlated with R = -0.933. Figure 31 shows that the correlation between performance and |E*| was strongest in the middle portion of the frequency range, with the strength of relationship decreasing as frequency increases.

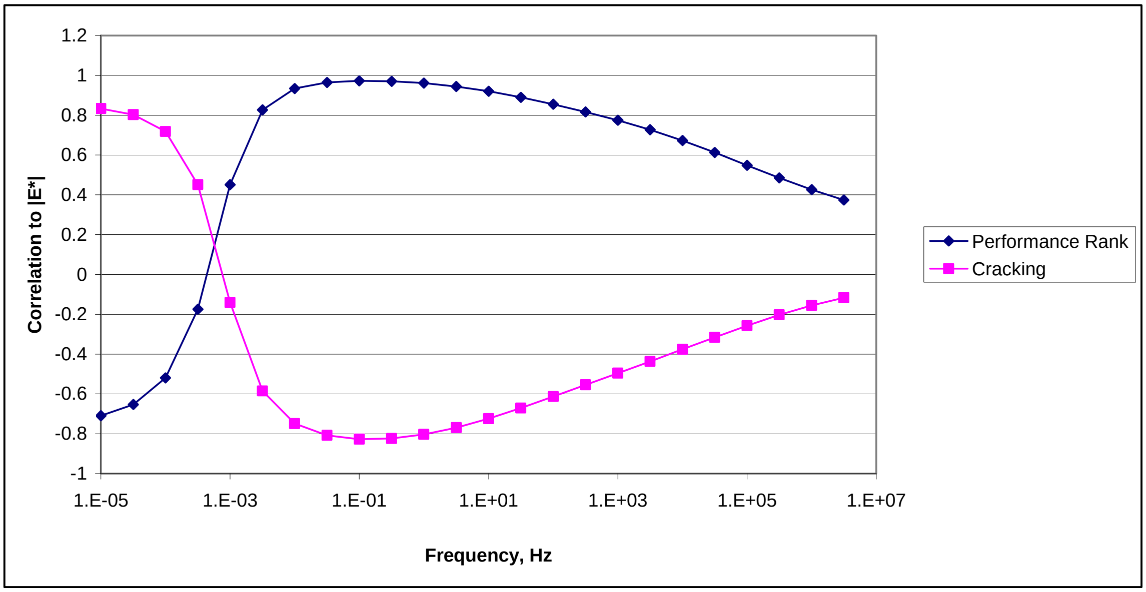

Figure 31 – Relationship of field performance and |E*| master curves.

Chapter 7: Summary and Recommendations

Summary

The main parts of this study included:

- A survey of practicing engineers and review of literature.
- Selection and documentation of actual construction projects representing current Minnesota practice and exhibiting a range of field performance.
- Obtain specimens from the construction projects after a period of service.
- Laboratory testing and analysis of specimens fabricated based on constraints resulting from available typical sections.

A survey of practicing local engineers found that in Minnesota the most commonly used asphalt binders were performance grades PG 58-28 and PG 58-34. These binders were used frequently in highway-type asphalt mixtures that contained from zero to 40 percent recycled asphalt pavement. The survey also found that Minnesota mixtures most commonly included recycled pavement at levels of 20 to 30 percent by weight.

Local engineer responses regarding the most important issues regarding the use of recycled asphalt included cracking, rutting, and construction issues. Roughly one-third of the Minnesota agencies using RAP exclude it from the wear course mixture. Respondent comments focused on RAP material characteristics as well as handling and construction issues, and did not discuss the economic component of this topic.

Several construction projects were identified for early performance monitoring. The projects included two bituminous overlay and four new pavement constructions.

Early performance issues were apparent on one of the overlay projects, where a design combining PG 64-34 asphalt binder and 30 percent RAP could not prevent 100 percent reflective cracking during the first winter of service. Another overlay project included a design using PG 58-28 and PG 58-34 binders and no recycled material. Reflective cracking also occurred on that project, but at a gradual rate over a period of years. Monitoring results showed that PG 58-34 performed better than the PG 58-28 during the early period of service.

The four new pavement constructions were placed over reclaimed base and reconstructed base courses. RAP percentages were maintained between wear and non-wear courses.

One pair of reconstructed projects was located in St. Louis County, and used RAP from the same source but varied mixture design by RAP percentage and asphalt binder grade. That pair showed significantly different early performance as the 30 percent RAP plus PG 58-28 design developed extensive transverse cracking during the first winter of service, and the 20 percent RAP plus PG 58-34 did not develop early transverse cracks. Observations of the surface performance of this pair found popouts and spalling, especially the road with early cracking.

The second pair of reconstructions were placed on an Olmsted County highway and used a design with PG 58-34 binder plus either zero or 30 percent RAP. In this case the contractor RAP stockpile was the source of recycled material. This pair showed good performance during the first year, and only several cracks in the RAP section during the second winter of service.

Field cores were obtained from the field monitoring sites, and the new constructions were selected for laboratory evaluations. Laboratory testing included aggregate gradation, asphalt content and grade, specific gravity, and dynamic modulus. Laboratory personnel developed a method for fabricating dynamic modulus specimens from wear and non-wear components of the field cores.

Aggregate gradations of all mixtures except the Olmsted County wear courses were generally finer than a theoretical 12.5 mm (0.5 in.) maximum density function. Test results showed that the asphalt binders met high and low-temperature performance grade design standards. One exception was the RAP section located in Olmsted County, whose low-temperature binder test results were did not meet the -34 grade criteria.

Modulus data obtained at 14 ° F showed that the stiffest performance occurred in the Olmsted County 20 percent RAP and St. Louis County 30 percent RAP mixtures. Analysis using mixture master curves showed that wear and non-wear course mixtures performed essentially the same. Curves from full-depth specimens were more useful for relating field performance to dynamic modulus. This finding was both logical and convenient since the field performance of the wear course is arguably influenced by the entire roadway structure.

A statistical analysis of field performance was performed with respect to the test results and mixture characteristics. The results showed stronger relationships existed for low-temperature performance grade and the percentage of new asphalt binder in the mixture than to the percentage of RAP in the mixture. Field performance related well to mixture master curves in the middle portion of the test frequency range. The strength of the relationship decreased as frequency increased.

Recommendations

The project survey shows that some practitioners have concerns regarding use of RAP in the wear course, and some agencies restrict use to the non-wear course. It is strongly recommended that agencies review their policy to include RAP in the wear course for the following reasons:

- Based on the laboratory test results and field observations, all of the mixtures performed acceptably in terms of rutting resistance.
- Asphalt high temperature performance grades (PG's) indicate the contribution of rut resistance provided by the binder. This particular data set possessed similar high temperature PG's, and no strong relationship resulted between high temperature PG and percent RAP. However, RAP material can often have elevated high temperature PG's that could beneficially contribute stiffness during conditions when mixtures are prone to rutting.
- Results from this study found only a moderate relationship between the percent of RAP in the mix and the onset of early thermal cracking.
- The low-temperature grade of the binders and percentage of new binders used in this study were strongly related to early performance. This reinforces the concept that it is possible to address concerns about low-temperature performance during the mixture design phase, whether or not the design includes RAP.

Field performance results showed that the use of low-temperature performance grade -34 (PG-34) binder benefitted early performance. The use of PG-34 is recommended. Refer to binder selection guidelines developed by the Minnesota Department of Transportion for high temperature PG selection.

Material control can be used to achieve a better performance history. It is recommended that contractors employ progressive RAP stockpile management techniques to increase recycling, attain high quality designs, and achieve optimum field performance. Agencies may consider specifying the source material origin, screening and separating by particle size (fractionated RAP), or asphalt content.

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Appendix A – Mixture Testing Files

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	**CO-BC08-0103**	Sampled By:	
Project Number:	TLRR826A	Submitted By:	Ed Johnson
Engineer:	Ed Johnson	Sampled From:	Nonwear
Grade:		Date Sampled:	
Refinery:		Date Received:	10/22/2008
Manifest Number:	Rochester Sand Gravel/Mathy	Report Approved:	**11/25/2008 9:07**
Field ID:	OLM RN (Dist. 6)		
Remarks:	HMA Cores 0% RAP grad/PG sampled 2008		

		Test Results	**Specificatio**	
Tests on Recovered Asphalt Binder			**Minimum**	**Maximum**
DSR, G*/SIN δ (kPa),			1.98	
BBR, Stiffness (MPa),		190		324
BBR, m-Value,		0.348	0.285	
PG Grade of Recovered Binder		60.0-36.9		
% AC		5.5		
% Volatiles				
IR On Volatiles				
Recovered Aggregate Gradation (%Passing)				
Sieve Size:	5/8"	98		
	1/2"	92		
	3/8"	83		
	#4	65		
	#8	52		
	#10	49		
	#16	42		
	#20			
	#40	26		
	#50	18		
	#100	7		
	#200	4.3		

Disposition:

Comments: BBR Value @ -24C.

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = Mn/DOT Modified

If you have any questions, please call: (651) 366-5549

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Jason Szondy

CO-BC08-0103 Ver. 2 Page 1 of 1 11/25/2008 9:07

Figure A.1 – Olmsted CR 112 non-RAP, non-wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	CO-BC08-0105	Sampled By:	
Project Number:	TLRR826A	Submitted By:	Ed Johnson
Engineer:	Ed Johnson	Sampled From:	Wear
Grade:		Date Sampled:	
Refinery:		Date Received:	10/22/2008
Manifest Number:	Rochester Sand Gravel/Mathy	Report Approved:	11/25/2008 9:10
Field ID:	OLM RW (Dist. 6) CR112		
Remarks:	HMA Cores 0% RAP grad/PG sampled 2008		

		Test Results	Specificatio Minimum	Maximum
Tests on Recovered Asphalt Binder				
DSR, G*/SIN δ (kPa),			1.98	
BBR, Stiffness (MPa),		252		324
BBR, m-Value,		0.325	0.285	
PG Grade of Recovered Binder		66.1-36.4		
% AC		4.5		
% Volatiles				
IR On Volatiles				
Recovered Aggregate Gradation (%Passing)				
Sieve Size:	5/8"	100		
	1/2"	100		
	3/8"	90		
	#4	46		
	#8	31		
	#10	29		
	#16	24		
	#20			
	#40	17		
	#50	14		
	#100	8		
	#200	5.1		

Disposition:

Comments: BBR Value @ -24C.

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = MnDOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0105 Ver: 2 Page 1 of 1 11/25/2008 9:10

Figure A.2 – Olmsted CR 112 non-RAP, wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	CO-BC08-0110	Sampled By:	
Project Number:	LRRB626 CR112	Submitted By:	
Engineer:	Ed Johnson	Sampled From:	Olmstead CR112 Rochester Sa
Grade:		Date Sampled:	
Refinery:		Date Received:	12/05/2008
Manifest Number:		Report Approved:	1/6/2009 10:26
Field ID:	F,G 20% RAP NON-WEARCOURSE HMA CORE		
Remarks:	PG TESTING		

Tests on Recovered Asphalt Binder	Test Results	Specificatio Minimum	Specificatio Maximum
DSR, G*/SIN δ (kPa),		1.98	
BBR, Stiffness (MPa),	131		324
BBR, m-Value,	0.315	0.285	
PG Grade of Recovered Binder	63.9-32.5		
% AC	4.9		
% Volatiles			
IR On Volatiles			

Recovered Aggregate Gradation (%Passing)

Sieve Size:	
5/8"	97
1/2"	93
3/8"	86
#4	70
#8	57
#10	54
#16	47
#20	
#40	29
#50	20
#100	8
#200	4.9

Disposition:

Comments: BBR results @ -18C.

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = Mn/DOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0110 Ver: 1 Page 1 of 1 1/6/2009 10:26

Figure A.3 – Olmsted CR 112 RAP, non-wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	CO-BC08-0109	Sampled By:	
Project Number:	LRRB826 CR112	Submitted By:	
Engineer:	Ed Johnson	Sampled From:	Olmstead CR112 Rochester Sa
Grade:		Date Sampled:	
Refinery:		Date Received:	12/05/2008
Manifest Number:		Report Approved:	1/6/2009 10:25
Field ID:	A 20% RAP WEARCOURSE HMA CORE		
Remarks:	PG TESTING		

Tests on Recovered Asphalt Binder	Test Results	Specificatio Minimum	Specificatio Maximum
DSR, G*/SIN δ (kPa),		1.98	
BBR, Stiffness (MPa),	175		324
BBR, m-Value,	0.322	0.285	
PG Grade of Recovered Binder	68.2-32.1		
% AC	4.6		
% Volatiles			
IR On Volatiles			

Recovered Aggregate Gradation (%Passing)

Sieve Size:	Test Results
5/8"	99
1/2"	97
3/8"	85
#4	41
#8	27
#10	25
#16	21
#20	
#40	15
#50	12
#100	8
#200	6.0

Disposition:

Comments: BBR results @ -18C.

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = Mn/DOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0109 Ver. 1 Page 1 of 1 1/6/2009 10:25

Figure A.4 – Olmsted CR 112 RAP, wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	CO-BC08-0111	Sampled By:	
Project Number:	LRRB826 CR4	Submitted By:	
Engineer:	Ed Johnson	Sampled From:	St. Louis Cty CR4
Grade:		Date Sampled:	
Refinery:		Date Received:	12/05/2008
Manifest Number:		Report Approved:	1/6/2009 10:27
Field ID:	A 30% RAP WEARCOURSE HMA CORE		
Remarks:	PG TESTING		

	Test Results	Specificatio Minimum	Maximum
Tests on Recovered Asphalt Binder			
DSR, G*/SIN δ (kPa)		1.98	
BBR, Stiffness (MPa),	206		324
BBR, m-Value,	0.328	0.285	
PG Grade of Recovered Binder	66.1-30.6		
% AC	6.1		
% Volatiles			
IR On Volatiles			

Recovered Aggregate Gradation (%Passing)

Sieve Size:	
5/8"	100
1/2"	99
3/8"	97
#4	81
#8	66
#10	62
#16	51
#20	
#40	29
#50	22
#100	12
#200	7.9

Disposition:

Comments: BBR results @ -18C.

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = MnDOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0111 Ver: 1 Page 1 of 1 1/6/2009 10:27

Figure A.5 – St. Louis CR 4 RAP, wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	CO-BC08-0112	Sampled By:	
Project Number:	LRRB826 CR4	Submitted By:	
Engineer:	Ed Johnson	Sampled From:	St. Louis Cty. CR4
Grade:		Date Sampled:	
Refinery:		Date Received:	12/05/2008
Manifest Number:		Report Approved:	1/6/2009 10:28
Field ID:	B,C 30% RAP NON-WEAR HMA CORE		
Remarks:	PG TESTING		

Tests on Recovered Asphalt Binder	Test Results	Specificatio Minimum	Maximum
DSR, G*/SIN δ (kPa),		1.98	
BBR, Stiffness (MPa),	174		324
BBR, m-Value,	0.344	0.285	
PG Grade of Recovered Binder	65.9-31.3		
% AC	5.1		
% Volatiles			
IR On Volatiles			

Recovered Aggregate Gradation (%Passing)

Sieve Size:	
5/8"	98
1/2"	93
3/8"	87
#4	72
#8	58
#10	54
#16	44
#20	
#40	24
#50	18
#100	11
#200	7.5

Disposition:

Comments: BBR results @ -18C.

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = Mn/DOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0112 Ver. 1 Page 1 of 1 1/6/2009 10:28

Figure A.6 – St. Louis CR 4 RAP, non-wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	**CO-BC08-0130**	Sampled By:	
Project Number:	LRRB826 CR16	Submitted By:	Ed Johnson
Engineer:	Ed Johnson	Sampled From:	St. Louis Cty. CR16
Grade:		Date Sampled:	
Refinery:		Date Received:	12/31/2008
Manifest Number:		Report Approved:	**1/21/2009 14:16**
Field ID:	G,H,I NON-WEAR		
Remarks:	20% RAP PG X-34 Full depth cores		

	Test Results	Specificatio Minimum	Specificatio Maximum
Tests on Recovered Asphalt Binder			
DSR, G*/SIN δ (kPa),		1.98	
BBR, Stiffness (MPa),	317		324
BBR, m-Value,	0.303	0.285	
PG Grade of Recovered Binder	63.1-34.3		
% AC	5.2		
% Volatiles			
IR On Volatiles			

Recovered Aggregate Gradation (%Passing)

Sieve Size:	
5/8"	98
1/2"	93
3/8"	86
#4	72
#8	59
#10	56
#16	48
#20	
#40	30
#50	23
#100	12
#200	7.5

Disposition:
Comments:

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = Mn/DOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0130 Ver. 1 Page 1 of 1 1/21/2009 14:16

Figure A.7 – St. Louis CR 16 RAP, non-wear course test results.

Minnesota Department of Transportation
Recovered Asphalt Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	**CO-BC08-0129**	Sampled By:	
Project Number:	LRRB826 CR16	Submitted By:	Ed Johnson
Engineer:	Ed Johnson	Sampled From:	St. Louis Cty. CR16
Grade:		Date Sampled:	
Refinery:		Date Received:	12/31/2008
Manifest Number:		Report Approved:	**1/21/2009 14:15**
Field ID:	G,H,I WEAR		
Remarks:	20% RAP PG X-34 Full depth cores		

Tests on Recovered Asphalt Binder	**Test Results**	**Specificatio** Minimum	Maximum
DSR, G*/SIN δ (kPa),		1.98	
BBR, Stiffness (MPa),	**278**		324
BBR, m-Value,	**0.306**	0.285	
PG Grade of Recovered Binder	**63.4-34.5**		
% AC	**5.2**		
% Volatiles			
IR On Volatiles			

Recovered Aggregate Gradation (%Passing)

Sieve Size:	
5/8"	**100**
1/2"	**96**
3/8"	**90**
#4	**73**
#8	**61**
#10	**58**
#16	**48**
#20	
#40	**27**
#50	**20**
#100	**10**
#200	**6.3**

Disposition:

Comments:

Test Procedures: ASSHTO T-44, T48, T240, TP1, TP3, TP5, PP1, ASTM D4402 M = MnDOT Modified

If you have any questions, please call: (651) 366-5549

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CO-BC08-0129 Ver: 1 Page 1 of 1 1/21/2009 14:15

Figure A.8 – St. Louis CR 16 RAP, wear course test results.