USE OF RECLAIMED ASPHALT PAVEMENTS (RAP) IN AIRFIELDS HMA PAVEMENTS

AIRFIELD ASPHALT PAVEMENT TECHNOLOGY PROGRAM
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DISCLAIMER

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USE OF RECLAIMED ASPHALT PAVEMENTS (RAP) IN AIRFIELDS HMA PAVEMENTS

Final Report

for

AAPTP Project 05-06

Submitted to

Airfield Asphalt Pavement Technology Program

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ABSTRACT

This report documents the results and findings of the AAPTP *Project No. 05-06*: Use of Reclaimed Asphalt Pavements (RAP) in Airfields HMA Pavements. The report includes a review of current technology in RAP pavements and its application in highway and airfield pavements. Additionally, the report includes the current highway specifications on the use of RAP and a mechanistically based method to transfer the RAP technology that has been successfully used on highway pavements into the design and specification systems for RAP on airport pavements. Review of in-service airfield pavements was conducted as part of this study. Furthermore, the report includes an evaluation of the impact of RAP on the performance life of HMA airfield pavements under three actual airport traffic mixes of a large hub, small hub, and general aviation. The Life cycle cost analysis used the characteristics and mechanical properties of HMA mixtures in the LEDFAA1.3 airfield pavement design software to compare the estimated performance life of HMA pavements with and without RAP materials. Finally, sections 401-3.3 and 403-3.3 of FAA's P-401 and P-403 specifications, respectively, on RAP were reviewed and recommendations were made based on the findings of the research effort conducted in this project.

CHAPTER 1 INTRODUCTION

Reclaimed asphalt pavement (RAP) is formed by cold milling, heating/softening and removal of the existing aged asphalt pavement, full depth removal, or plant waste HMA materials. Recycling of the RAP has become more popular since the mid 1970's although it had been practiced as early as 1915. The first sustained efforts to recover and reuse old asphalt paving materials were conducted during 1974 in Nevada and Texas. The escalating increases in crude oil prices as well as cost of energy in general, are expected to result in increased prices of asphalt binders and a resulting interest in the use of RAP in pavements. Furthermore, several studies showed that asphalt mixtures containing RAP can have equivalent performance to virgin mixtures. Different agencies and contractors have made extensive use of RAP in constructing highway pavements while the use of RAP on airfield pavements has been somewhat limited.

The overall goal of the mix design process of hot mixed asphalt (HMA) is to recommend a mix that can withstand the combined actions of traffic and environment. Therefore, it is critical to assess the impact of the various mix components on the performance of the constructed pavement (i.e. resistance to rutting, fatigue, and thermal cracking). The existence of RAP in the mix presents a challenge to the design engineer due to the complex interaction among the new and recycled components of the mix. The inclusion of RAP materials in the HMA mix can improve its resistance to rutting while it may jeopardize its resistance to fatigue and thermal cracking. The key to successfully include RAP in the HMA mix is to be able to assess its impact on pavement's performance while recognizing the uniqueness of each project with respect to both materials and loading conditions.

The properties of RAP are largely dependent on the properties of the constituent materials (i.e. aggregate type, quality and size, extracted binder properties, etc.). The RAP composition is affected by the previous maintenance and preservation activities that were applied to the existing pavement. For example, in many airfield pavement a coal tar sealer is often applied in parking, maintenance and refueling areas, to protect the asphalt concrete pavement from possible damage due to fuel spillage. Additionally, sometimes RAP from several projects are mixed in a single stockpile. Deleterious materials or lower quality materials may be present in one of the stockpiles. Consequently, a high variability may be introduced in the RAP materials affecting the RAP properties and most likely, depending on the RAP content in the mix, may result in a variable RAP containing HMA mixture. Using a low quality and/or highly variable RAP materials can lead to premature failure of the HMA pavement. The badly deteriorated pavement will lead to both, foreign object damage (FOD) and rough surface creating a safety hazard for aircraft traffic on taxiways and runways. All these issues may limit the use of RAP in the various types of airport pavements (taxiways, runways, aprons, or cross roads) and require the implementation of an effective quality control program.

PROBLEM STATEMENT

The successful use of reclaimed asphalt pavement materials is well known and has been used throughout the highway pavement industry. The use of RAP on airfield pavement has been somewhat limited. Procedures and tests for binder and mix characterization and HMA mixture design have changed significantly over recent years. A review of current state of practice and appropriate application of RAP materials to airport pavements is needed. The AAPTP Project 05-06 will provide a comprehensive document that identifies the benefits, successful use, and criteria for use on airfields to encourage further consideration and wider use of RAP on airfield pavements.

The specifications and procedures for use of RAP on Federal Aviation Administration (FAA) pavement projects are contained in items P-401 and P-403 of Advisory Circular 150/5370-10C and a similar specification, UFGS-32 12 15, is used for military airfields.

RESEARCH OBJECTIVE

The objective of this study is to establish updated technical guidance on the use and benefits of reclaimed asphalt pavement in airfield hot mix asphalt materials and to document existing use on airport pavements. This guidance will be developed based upon a literature review as well as documented use and performance of airfield pavements that utilized RAP in HMA. The final product for this effort will include a final report, revisions to sections 401-3.3 and 403-3.3 of FAA's P-401 and P-403 specifications, respectively, and presentation material for a 4-hour of training/workshop covering the feasibility, mix design, quality control, construction and performance of airfield pavements using reclaimed asphalt materials.

The AAPTP Project 05-06 includes both a literature review and a field performance element. The literature review consists of gathering information on performance of airfield and highway pavements using RAP. The emphasis of this project is directed towards information on HMA airport pavements. Although laboratory testing requirements is to be addressed in the guidance, no direct laboratory testing was envisioned in this project. The overall objective will be accomplished by completing the following seven tasks.

- Task 1.0 – Review of existing literature.
- Task 2.0 – Collect and document field performance of mixture containing RAP and original properties.
- Task 3.0 – Identify and provide recommended laboratory tests.
- Task 4.0 – Evaluate the existing FAA specification on RAP.
- Task 5.0 – Develop preliminary report.
- Task 6.0 – Develop fully documented training materials.
- Task 7.0 – Develop final draft project report.

CHAPTER 2 BENEFITS OF RAP USAGE

Asphalt pavement is the most recycled product in the U.S. According to Mike Acott *(1)*, president of the National Asphalt Pavement Association (NAPA), "… every year, approximately 73 million tons of reclaimed asphalt pavement is reused, or nearly twice as much as the combined total of 40 million tons of recycled paper, glass, aluminum, and plastics."

This Chapter summarizes the review of the benefits and costs of using RAP materials in HMA.

BENEFITS OF RECYCLING

RAP is a very valuable resource to both public and private consumers. The use of RAP in new HMA reduces production cost and conserves diminishing resources of aggregates and petroleum products. The following benefits justify the use of RAP.

- Reduction in construction costs.
- Less disposal materials.
- Reduced transportation cost.
- Conservation of aggregates and binders.
- Conservation of energy.
- Preservation of environment (reduction in toxic and greenhouse gas emissions).
- Preservation of existing pavement geometrics.
- Reduction in user delay.
- Reduction in road wears due to less transport of materials.

Economic Aspects

In 1997, Kandhal and Mallick showed that the savings in using 1 ton of RAP material instead of 1 ton of virgin mix was of a magnitude of $8.20 (this figure takes into account milling and transportation costs for RAP) *(2)*. Additionally, they showed that using RAP will results in savings between 14% and 34% per ton for 20% and 50% RAP in the mix, respectively. In 1999, Brown showed typical average cost savings for various government agencies and regions (Table 1) *(3, 4)*.

Table 1 Typical Cost Savings by Agencies and Regions *(4)*.

Agency	**Average Savings (%)**
Florida	24-26
Georgia	4-8
New York	20
Wisconsin	10-13
FHWA	1-30
U.S. Corps of Engineers	16
Region	**Average Savings (%)**
Northwest	24-26
Southwest	4-18
North Central	20
South Central	10-13

In 2007, the NAPA information series 123 publication on *Recycling Hot-Mix Asphalt Pavements (5)* included a discussion on the cost associated with using RAP. First the value of RAP as the value of the equivalent amount of virgin asphalt and aggregate materials are determined as follows (costs used are for illustration purposes only).

Assume: RAP asphalt content of 4%
Cost of virgin asphalt = $350/ton
Cost of virgin aggregate = $10/ton

Value of the RAP: Asphalt cement in RAP = $350 × 0.04 = $14/ton
Aggregate in RAP = $10/ton × 0.96 = $9.60/ton
Total value of RAP = $14/ton + $9.60/ton = $23.60/ton

The cost associated with using RAP may change depending on the amount of RAP used in the mix. The typical costs are associated with obtaining the RAP. However, there may be other costs to consider, especially when plant modification is necessary as well as processing and additional quality control/assurance tests and mix design development. Higher percentages of RAP (over 25%) may also require additional testing and processing and a more expensive asphalt binder than the one used with the virgin mixture *(5)*.

Table 2 shows two examples for the cost associated with obtaining and processing RAP *(5)*. The first example in the table is for RAP obtained from millings on the project where the cost of milling is included in the contract and the second example is for RAP purchased and requires processing.

Table 2 Typical Savings Examples by Using RAP.

Costs	**Example 1 RAP obtained from millings***	**Example 2 RAP purchased**
Value of RAP	$23.60/ton	$23.60/ton
RAP cost		- $ 2.00/ton
Plant cost for extra equipment	- $ 0.75/ton	- $ 0.75/ton
Trucking cost	- $ 3.00/ton	
Processing and handling cost	- $ 5.00/ton	- $ 5.00/ton
Extra quality control cost	- $ 0.25/ton	- $ 0.25/ton
Total Savings	$14.60/ton	$15.60/ton
Savings per 10%RAP in mix	$ 1.46/ton (6%)	$ 1.56/ton (7%)
Savings per 20%RAP in mix	$ 2.92/ton (12%)	$ 3.12/ton (13%)
Savings per 30%RAP in mix	$ 4.38/ton (19%)	$ 4.68/ton (20%)
Savings per 40%RAP in mix	$ 5.84/ton (25%)	$ 6.24/ton (26%)

*Cost of milling included in the contract

Table 2 shows that the use of RAP obtained from millings in the HMA mix may result in savings between 9% and 34% per ton for 10% and 40% RAP in the mix, respectively. On the other hand, the purchase and use of RAP in the HMA mix may result in savings between 8% and 31% per ton for 10% and 40% RAP in the mix, respectively.

Horvath *(4)* reported the costs in 2003 for in-plant hot mix recycling of 1,000 kg of RAP in Belgium. The data in Table 3 showed that pavement material costs are reduced by approximately 26% if 40% RAP is used. Additionally, Table 4 shows, based on the following assumptions, the production costs other than those of materials *(4)*:

- Asphalt mixing plant with a yearly production of 200,000 ton HMA, equipped for recycling with a parallel drum.
- Recycling rate (mass RAP on total mass HMA) of 40% for 100,000 ton/yr of binder/base courses, no recycling for wearing courses (also 100,000 ton/yr).
- RAP available on stock at plant, suitable for recycling, worth 5 dollars/ton.
- Investment cost for asphalt mixing plant: $3,700,000 per year versus $89,000.
- Extra costs for quality controls on RAP and on RAP containing HMA mixes (laboratory equipment + half-time personnel): $22,000.

Adding the costs listed in Tables 3 and 4 gives $18.40 per metric ton without recycling and $16.00 per metric ton if 40% RAP is used in Belgium *(4)*. These figures lead, for the above mentioned assumptions, to a $2.40 saving when 40% RAP is used.

Table 3 Calculation of the Materials Cost in 1,000 kg Batch of HMA – Belgium *(4)*.

Material	Percent in HMA	Unit Price ($/ton)	HMA without Recycling	HMA with 40% Recycling
Stones	58	10	5.8	3.5
Sand	30	8	2.4	1.5
Filler	7	20	1.4	0.84
Asphalt	5	100	5.0	3.0
RAP	0-40	5	0	2.0
Subtotal			14.6 $/ton	10.8 $/ton

Table 4 Calculation of the Materials Cost in 1,000 kg Batch of HMA – Belgium *(4)*.

Cost Element ($/ton HMA)	Plant with no Recycling	Plant with Recycling
Investment in equipment + financing costs	1.48	2.04
Maintenance of equipment	0.45	0.78
Quality control	0.22	0.44
Energy use	1.55	1.94
Subtotal	3.80	5.20

Potential Energy Savings

During the 2006 national workshop for Materials and Energy Conservation for Hot-Mix Asphalt in Indianapolis, Charles F. Potts, CEO of Heritage Construction & Materials, illustrated the total potential energy savings with the use of RAP and other activities. Table 5 shows a total potential savings of $5.15 per ton for an HMA plant with annual production of 200,000 tons/year with a fuel cost of $1.50/gallon and $2.00/gallon for the dryer and heater, respectively.

Table 5 Example of Various Energy Savings (After C. F. Potts).

Activity	Savings in dollars/year	Cumulative Potential savings
1. Aggregate drying costs: - Paving and sloping under stockpile storage - reduce fuel 0.6 gal./ton - Savings: (0.6 gal./ton) × ($1.50/gal.) × (2000,000 ton/yr.)	$180,000/yr.	$180,000/yr.
2. Asphalt storage system - Insulate all lines, a.c. piping, add stack heat exchanger	$ 70,000/yr.	$250,000/yr.
3. Electricity (add VFD drives to exhaust fan, burner blower)	$ 60,000/yr.	$310,000/yr.
4. Recycle (increase amount of recycle by 10%) - Savings: Oil (25-5) $ 2.00/ton	$400,000/yr.	$710,000/yr.
Total Savings per ton: ($710,000/yr) ÷ (2000,000 ton/year)		$3.55/ton
5. Switch to Coal burner…$60.00 / ton coal - gals./ton = $1.76 - burn 20% oil; 80% coal - Fuel cost = 0.2 × ($1.50) + 0.8 × ($0.36) = $0.59 / gal. - Savings = ($1.50 – $0.59) × ($1.76) × (2000,000 ton/yr)	$320,320/yr.	$1,030,320/yr.
Total Potential Savings per ton		$5.15/ton

CHAPTER 3 LITERATURE REVIEW

This chapter provides the findings of the literature review on the materials properties, specifications, test procedures, design methods, and performance of airfield and highway pavements using RAP. This chapter only presents the major findings of the various studies and performance evaluation and Appendix A presents expanded summaries of some of the reviewed studies. It should be noted that not all studies presented in this report are coupled with expanded information in the appendix.

REVIEW OF RESEARCH EFFORTS

Minnesota Department of Transportation

In 2004, Li et al. conducted a study for the Minnesota DOT to investigate the effect of RAP type and percentage on the final asphalt mixture properties *(6)*. Ten mixtures consisting of three RAP percentages (0, 20% and 40%), two virgin asphalt binders (PG58-28 and PG58-34), and two RAP sources (RAP and millings), were studied. The RAP sources were provided by a local contractor and were identified as follows:

- Millings – RAP from a single source, milled up from I-494 in Maple Grove. The RAP has a binder content of 4.3% and an extracted binder grade of PG76-22.
- RAP – RAP combined from a number of sources and crushed at the HMA plant. The RAP has a binder content of 5.4% and an extracted binder grade of PG70-22.

The RAP material was blended with virgin aggregate such that all samples tested had approximately the same gradation. The Superpave mix design process was used to determine the optimum asphalt content of the mixtures. The AASHTO T283 test results indicated an increase in both dry and wet tensile strength and a decrease in the tensile strength ratio as the percentage of RAP or millings increases. However all ten mixtures passed the minimum tensile strength ratio of 75%.

The limited data obtained in this project showed that the addition of RAP increased the dynamic modulus and that the asphalt binder grade and RAP source had a significant effect on the mixture modulus. However, this effect was not found to be significant enough at low temperatures and high frequencies.

Additionally, the mixtures containing RAP exhibited higher variability than virgin mixtures (i.e., 0% RAP). The variability increased with the increase in RAP content. Dynamic modulus test results were observed to have more variability at low temperatures.

In 2008, Li et al. *(7)* evaluated the resistance to low temperature cracking of the same ten mixtures by measuring the fracture energy of the mixes at three temperatures (-18, -24, and -36°C) using the Semi Circular Bending (SCB) fracture test. Higher fracture energy in the SCB test reflects a higher resistance to low temperature cracking. The researchers found that the percentage of RAP in the mixtures significantly affect the fracture resistance. It was found that the control mixtures (0% RAP) have relatively the best resistance to low temperature cracking with a similar resistance to the 20% RAP mixtures. The addition of 40% RAP significantly decreased the low temperature fracture resistance when compared to the 0% RAP mixtures. Additionally, the experimental data showed no significant effect of the RAP source on the fracture resistance of HMA mixtures at low temperatures. Additional information on both studies of Li et al. can be found in *Appendix A*.

National Cooperative Highway Research Program

In 1997, in an effort to incorporate the usage of RAP in Superpave HMA mixtures, the National Cooperative Highway Research Program (NCHRP) funded a three years research study to evaluate the effects of RAP on Superpave mixtures *(8)*.

In this study (i.e., NCHRP 9-12), three possible levels of interaction between aged and virgin binders were compared experimentally: black rock (no blending), actual practice (blending as it usually occurs in practice), and total blending (100% blending). Two RAP contents (10% and 40%) were used, and in all cases, the overall gradation and total asphalt binder content were kept constant. Three sources of RAP (Florida, Connecticut, and Arizona), two virgin binders (PG52-34 and PG64-22), and one virgin aggregate were used. All mixtures were produced following the Superpave specification for the 12.5 mm nominal maximum size mix.

The produced blended mixtures were evaluated for resistance to rutting, fatigue, and thermal cracking. The repeated shear constant height (RSCH) test was used to measure the mixtures resistance to rutting. The frequency sweep (FS) test was used to measure the mixtures resistance to fatigue cracking. The indirect tension (IDT) test was used to evaluate the mixtures resistance to thermal cracking.

The results of the performance tests showed no significant differences among the three blending methods at a RAP content of 10% while a significant difference existed at the 40% RAP content. The black rock case was statistically different from the actual practice and total blending cases.

The actual practice technique was recommended for the other parts of the study. The results of this part of the study supported the common belief that each RAP mix should be individually designed to fully assess the interaction between the RAP materials and the virgin materials in the blended mix.

Additionally, the impact of the RAP binder properties on the virgin binder properties was evaluated. The study evaluated the impact of RAP at 10%, 20%, and 40% on the critical temperatures of the blended binder. The critical temperatures are the temperatures at which a binder just meets the specified Superpave criteria, for example, a $G^*/\sin\delta$ of 1.00 kPa for the unaged (original) binder. The results of this part of the research supported the following recommendations: a) at the 10% RAP, the effects of the RAP binder are negligible, b) at the 20% RAP content, the effects of the RAP binder can be compensated for by using a virgin binder that is one grade softer on both the high and low temperature grades, and c) at the 40% RAP content, a blending chart should be used to either determine the appropriate virgin binder grade or to determine the maximum amount of RAP that can be used with a given virgin binder.

This experiment also evaluated the possibility of analytically evaluating the impact of the RAP binder on the critical temperatures of the blended binder (i.e. RAP binder plus the virgin binder). The Asphalt Institute (AI) equation shown below was used to analytically determine the critical temperatures of the blended binder.

$$T_c = T_{virgin} + (\%RAP)(T_{RAP} - T_{virgin}) \qquad \text{(Equation 1)}$$

where, T_c = the critical high, intermediate, or low temperature of the blended binder
T_{virgin} = the critical high, intermediate, or low temperature of the virgin binder
T_{RAP} = the critical high, intermediate, or low temperature of the RAP binder
$\%RAP$ = percentage of RAP in decimal

The results of the AI equation were compared to the actual measured critical temperatures of the blended binder with and without RTFO aging of the RAP binder. The NCHRP 9-12 data indicated that the AI equation can be used to get reasonable estimates of the impact of the RAP binder on the critical temperatures of the blended binder. However, the estimated critical temperatures should only be used at the RAP source approval stage and actual testing of the blended binder should be conducted during the mix design process.

An additional study was performed to investigate the impacts of adding 0%, 10%, 20%, and 40% RAP on the properties of the final mix. All combinations of the three RAP sources and two virgin binders were evaluated. The virgin binder grades were not changed according to blending chart calculations. The RSCH test was used to assess the mixtures resistance to rutting, the flexural beam fatigue test was used to assess the mixtures resistance to fatigue cracking, and the IDT test was used to assess the mixtures resistance to thermal cracking.

Overall, the NCHRP 9-12 data showed that permanent shear strains decreased as RAP content increased. The IDT data showed no effects on creep stiffness with RAP contents up to 10%, but over 10% the stiffness increases. The flexural beam fatigue results showed that the fatigue life of the mix decreases with the addition of the RAP if the grade of the virgin binder is not adjusted to account for the inclusion of the RAP. In general, the researchers concluded that a softer binder is needed to compensate for the increased mixtures stiffness due to the inclusion of the RAP materials and to help improve the fatigue and low temperature cracking resistance of the mixtures.

Overall, this research revealed that the impact of RAP on the properties of the mix depends on the stiffness of the RAP materials. The stiffer the RAP materials, the more adversely the properties of the final mix are affected. Additional supporting data can be found in *Appendix A* of this report.

Recommendations of the NCHRP Study

The recommended NCHRP 9-12 process for selecting the virgin asphalt binder grade based on the percentage of the RAP materials and the properties of the RAP binder is summarized in Table 6. The process recommends actions for combinations of the RAP contents and RAP binder grade. The NCHRP recommendations presented in Table 6 were interpolated from the research data that were generated at 0%, 10%, 20%, and 40% RAP. The first row represents the maximum amount of RAP that can be used without changing the specified virgin binder grade. The second row represents the percentage of RAP that can be used when the virgin binder grade is decreased by one grade (i.e. decreasing 6 degrees on both high and low temperatures grades). The third row is for high RAP contents and when it is necessary to extract, recover, and test the RAP binder and to construct a blending chart.

The process of developing and using a blending chart is summarized in the NCHRP 9-12 report and is based on the following equation.

$$T_{virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \qquad \text{(Equation 2)}$$

where: T_{Blend} = the critical temperature of the blended asphalt binder
T_{virgin} = the critical temperature of the virgin asphalt binder
T_{RAP} = the critical temperature of the recovered RAP binder
%RAP = percentage of RAP expressed as a decimal

Table 6 NCHRP Project 9-12 Binder Selection Guidelines for RAP Mixtures.

Recommended Virgin Asphalt Binder Grade	RAP Percentage Recovered RAP Grade		
	PGXX-22 or lower	**PGXX-16**	**PGXX-10 or higher**
No change in binder selection	< 20%	< 15%	< 10%
Select virgin binder one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used)	20 – 30%	15 – 25%	10 – 15%
Follow recommendations from blending charts	> 30%	> 25%	> 15%

For example, if a RAP binder is graded as PG64-16, it fits under the category of PGxx-16, therefore, the RAP can be used at 15% without any change in the specified virgin binder grade, or it can be used at 15-25% with lowering the specified virgin binder grade by a full grade at the high and low temperatures. However, if this RAP material is to be used at a content higher than 25%, then the blending chart process should be used to define the necessary grade of the virgin binder.

According to NCHRP 9-12, the critical high temperature of the RAP binder needs to be determined by testing the recovered unaged RAP binder in the DSR at high temperature. The critical intermediate temperature needs to be determined by testing the RTFO-aged RAP binder in the DSR and the critical low temperature by testing the RTFO-aged RAP binder in the BBR. The NCHRP recommended process differs from the Superpave PG system by not subjecting the recovered RAP binder to the long-term aging through the PAV.

When RAP is used in HMA mixes the bulk specific gravity of the RAP aggregate needs to be determined. According to NCHRP 9-12, the bulk specific gravity of the RAP aggregate may be estimated by determining the maximum theoretical specific gravity of the RAP mixture and using assumed asphalt absorption for the RAP aggregate to calculate the RAP aggregate bulk specific gravity, if the absorption can be estimated with confidence. The RAP aggregate effective specific gravity may be used in lieu of the bulk specific gravity at the discretion of the agency. The use of the effective specific gravity may introduce an error into the combined aggregate bulk specific gravity and subsequent VMA calculations. Therefore, the agency may need to specify adjustments to the VMA requirements to account for this error based on experience with their local aggregates.

The NCHRP recommendations are now part of the AASHTO M323 standard specification for Superpave Volumetric Mix Design.

North Central Superpave Center

In 2002, a regional pooled fund study conducted by the North Central Superpave Center looked at typical materials from the north central United States to determine if the findings of NCHRP 9-12 were valid for Midwestern materials and to expand the NCHRP findings to include higher RAP contents *(9)*. Three RAP materials from Indiana, Michigan, and Missouri were evaluated. Mixtures were designed and tested in the laboratory with each RAP, virgin binder and virgin aggregate at RAP contents up to 50%. The laboratory mixtures were compared to plant produced mixtures with the same materials at the medium RAP content of 15-25%. The results showed that mixtures with up to 50% RAP could be designed under Superpave, provided the RAP gradation and aggregate quality were sufficient. In some cases, the RAP aggregates limited the amount of RAP that could be included in a mix design to meet the Superpave volumetric and compaction requirements. Linear binder blending charts to determine the virgin binder grade were found to be appropriate in most cases. Additionally, the laboratory tests indicated an increase in rutting resistance with the increase of RAP content if the virgin binder grade was unchanged. Provided the RAP properties are properly accounted for in the material selection and mix design process, the researchers found that superpave mixtures with RAP can perform very well *(9)*.

In 2006, McDaniel et al. evaluated the influence of RAP content on the mixture and recovered binder properties of plant-produced HMA mixes by studying the dynamic moduli of RAP mixtures and binders *(10)*. RAP was added at 15, 25 and 40% levels to HMA with PG64-22 and at 25% and 40% levels to HMA with a PG58-28 binder. In addition, control mixture samples with PG64-22 and no RAP were also collected and tested for comparison. Researchers showed that there is no statistically significant differences in low temperature mean strength and dynamic modulus of the control mixture and the mixtures with 15% and 25% RAP. Some differences between the control and the 40% RAP mixtures were found only at the higher test temperatures *(10)*.

In summary, this study showed that adding small amounts of RAP may not change the mix properties greatly. As the percentage increases, some effect on the mixture properties is noted, but not in proportion to the amount of RAP being added. When the percentage is high enough, the RAP binder would create a significant change in the mixtures properties. In a similar manner, the influence of RAP on the final HMA property also varies with the RAP amount. It was also recommended that the percent of binder in the RAP material should be considered in addition to the percent of RAP being used *(10)*. Additional supporting data for both studies can be found in *Appendix A* of this report.

Saskatchewan Highways and Transportation, Canada

In 1996, Puttaguanta et al. *(11)* compared the predicted fatigue performance and moisture damage of HMA mixtures containing 0, 25, and 50 % RAP materials. The data for the predicted numbers of load repetitions to fatigue failure of the various mixtures at three temperatures showed that the virgin mix (i.e., 0% RAP) can sustain a higher number of load repetitions than the HMA mixtures containing 25 and 50% RAP at 5°C, whereas at higher temperatures all the mixtures had an equal number of load repetitions to failure. Additionally, a negligible difference was found between the 25 and 50% RAP mixes. The data for the AASHTO T283 moisture damage evaluation showed that the virgin mix (i.e., 0% RAP) had tensile strength and resilient modulus ratios less than 80% while the RAP containing mixes had ratios greater than 80%. Additional supporting data can be found in *Appendix A* of this report.

Western Regional Superpave Center (WRSC)

In 2007, Hajj et al. *(12)* evaluated the laboratory performance of HMA mixes with 0, 15, and 30% RAP from three different sources in terms of their resistance to:

- Moisture damage: AASHTO T283.
- Rutting: asphalt pavement analyzer (APA).
- Fatigue: flexural beam fatigue test.
- Thermal cracking: thermal stress restrained specimen test (TSRST).

This study covered one source of virgin aggregates, and one source of virgin asphalt binders to design HMA mixtures with two target asphalt binder grades: PG64-22 and PG64-28. The PG64-22 is a neat asphalt binder mostly used in the bottom and middle lifts of the HMA layer. The PG64-28 is a polymer-modified binder mostly used in the top lift of the HMA layer. The three RAPs used in this study were selected from three different local sources.

- Source I: plant waste from a contractor plant in Reno, Nevada (4.6% binder content by weight of RAP).
- Source II: reclaimed asphalt from a 15-year old HMA pavement in Reno, Nevada (5.4% binder content by weight of RAP).
- Source III: reclaimed asphalt from a 20-year old HMA pavement in Reno, Nevada (5.8% binder content by weight of RAP).

The testing matrix consisted of six Marshall designed RAP containing HMA mixes and one control mix (0% RAP) for each of the target virgin binders of PG64-22 and PG64-28.

Based on the data generated from this experiment, the following conclusions were made. While reviewing the findings and conclusions, it should be well recognized that in most cases the addition of RAP materials necessitated a change in the virgin binder grade from the target binder grade as shown in Table 7. This change in the virgin binder grade had impact on the measured performance properties of the final mix.

Table 7 Required Virgin Binders Grades for the Various RAP Sources and Contents.

RAP	Recovered RAP Binder Grade	Required Virgin Binder Grade (Based on Blending Chart)			
		Target Binder: PG64-22		Target Binder: PG64-28NV	
		15% RAP	30% RAP	15% RAP	30% RAP
Source I	PG82-16	PG64-22	PG58-28	PG64-34	PG58-34
Source II	PG82-16	PG64-28	PG58-28	PG64-34	PG58-34
Source III	PG82-16	PG64-28	PG58-28	PG64-34	PG58-34

- The Marshall Mix Design method as outlined in the Asphalt Institute's Mix Design Manual MS-2 can be used to design HMA mixes with 15 and 30% RAP.

- The blending chart method was found to be conservative and not highly reliable in identifying the appropriate grade of the virgin binder for the various RAP sources and RAP contents.

- Impact of RAP on moisture damage resistance:
  PG64-22 mixtures:
  - The addition of 15 or 30% RAP to a mix resulted in an acceptable resistance to moisture damage regardless of the source of the RAP with a reduction in the unconditioned and conditioned tensile strengths.
  - The 15% RAP mixes had higher resistance to moisture damage than the 30% RAP mixes.

  PG64-28 mixtures (polymer modified asphalt binder):
  - The addition of 15 or 30% RAP to a mix resulted in an acceptable resistance to moisture damage regardless of the source of the RAP with a reduction in the unconditioned and conditioned tensile strengths.
  - The 15% RAP mixtures had lower resistance to moisture damage than the 30% RAP mixtures.

- Impact of RAP on rutting resistance:
  PG64-22 mixtures:
  - The addition of 15% RAP to a mix resulted in a better rutting resistance than the virgin mix when RAP from a 15 to 20-year old HMA pavement (Sources II and III) is used.
  - The addition of 30% RAP to a mix resulted in a better rutting resistance than the virgin mix only when RAP from a 20-year old HMA pavement (source III) is used.
  - The addition of 15 or 30% RAP from the plant waste to a mix resulted in a lower resistance to rutting than the virgin mix.

  PG64-28 mixtures (polymer modified asphalt binder):
  - The addition of 15% and 30% RAP to a mix resulted in a rutting resistance equivalent to the virgin mix with a rut depth significantly lower than the APA failure criteria regardless of the source of the RAP.

- Impact of RAP on fatigue resistance:
  PG64-22 mixtures:
  - The addition of 15% RAP to a mix resulted in either better or equivalent resistance to fatigue than the virgin mix regardless of the RAP source.
  - The addition of 30% RAP to a mix resulted in a better resistance to fatigue than the virgin mix only in the case of RAP from a 20-year old HMA pavement (source III).

  PG64-28 mixtures (polymer modified asphalt binder):
  - The addition of 15 or 30% RAP to a mix resulted in a significant reduction in fatigue resistance regardless of the RAP source.
- Impact of RAP on thermal cracking resistance:
  PG64-22 mixtures:
  - The addition of 15 or 30% RAP to a mix resulted in either a better or equivalent resistance to thermal cracking regardless of the RAP source.

  PG64-28 mixtures (polymer modified asphalt binder):
  - The addition of 15 or 30% RAP to a mix resulted in a significantly better resistance to thermal cracking regardless of the RAP source.

Table 8 compares the properties of the RAP containing mixtures to the properties of the control mix (i.e., 0% RAP).

Table 8 Overall Summary of the Laboratory Evaluation of RAP Containing Mixtures.

Target Binder Grade	**RAP Source[#]**	**RAP %**	**Impact of RAP on Resistance to[+]**							
			Moisture		**Rutting**		**Fatigue**		**Thermal Cracking**	
PG64-22	I	15	Pass	--	--	Worse	Better	--	Same	--
		30	Pass	--	--	Worse	--	Worse	Better	--
	II	15	Pass	--	Better	--	Same	--	Better	--
		30	Pass	--	--	NA	--	Worse	Better	--
	III	15	Pass	--	Better	--	Better	--	Same	--
		30	Pass	--	Better	--	Better	--	Better	--
PG64-28 (polymer modified)	I	15	--	Fail	Same	--	--	Worse	Better	--
		30	Pass	--	Same	--	--	Worse	Better	--
	II	15	Pass	--	Same	--	--	Worse	Better	--
		30	Pass	--	Same	--	--	Worse	Better	--
	III	15	Pass	--	Same	--	--	Worse	Better	--
		30	Pass	--	Same	--	--	Worse	Better	--

[+] *Statistically compared to control mixture (0% RAP).*

In addition to the above laboratory evaluation, two field HMA mixtures containing 15% RAP from a pavement in Sparks, Nevada were sampled during construction and evaluated in the laboratory in terms of their resistance to moisture damage (AASHTO T283), rutting (APA at 140°F), fatigue (flexural beam tests at 72°F), and thermal cracking (TSRST) *(12)*. The constructed HMA layer consisted of 3 lifts of 2.5 inch each. The bottom lift consisted of a dense graded HMA with 15% RAP material manufactured with a PG64-22 neat asphalt binder (F-22-15). The middle and the top lifts consisted of a dense graded HMA with 15% RAP material manufactured with a PG64-28 polymer modified asphalt binder (F-28-15). Based on the data generated from this experiment, the following conclusions were made:

- The PG64-22 neat asphalt mix (F-22-15) failed to meet the minimum tensile strength ratio (TSR) of 70% required by owner agency indicating a poor resistance to moisture damage. The PG64-28 polymer modified mix (F-28-15) barely passed the minimum required TSR indicating a marginal resistance to moisture damage.

- In the case of rutting resistance, both field mixes met the Nevada DOT APA criterion of 8 mm under 8,000 cycles at 140°F. The use of polymer modified binder reduced the APA rut depth by about 42% compared to the neat asphalt binder.

- The use of RAP in a polymer modified mixture (F-28-15) increased the mixture's laboratory resistance to fatigue cracking when compared to the mix with neat asphalt binder (i.e., F-22-15).

- In the case of resistance to thermal cracking, the field mixtures exhibited a fracture temperature within 1°C of the low performance temperature of the corresponding target binder grades (i.e. -22°C and -28°C).

- In a summary, the evaluated pavement section is expected to have acceptable performance in rutting, fatigue, and thermal cracking, but might show signs of failure due to moisture sensitivity problems.

It should be noted that all mixtures were treated with 1.5% hydrated lime by dry weight of aggregate without any marination and fulfilled the agency requirement for TSR at the mix design stage. Therefore, attention should be given to the durability property of the field produced mixtures. Previous studies on field mixtures sampled from behind the paver showed higher percentage of TSR failures for mixes treated with lime without marination when compared to mixes treated with lime followed by 48 hours marination. Additional supporting data can be found in *Appendix A* of this report.

Other Research Studies

In 2005, Daniel and Lachance evaluated the effect of RAP and its content (0, 15, 25, and 40%) on the volumetric and mechanistic properties of Superpave designed HMA mixes manufactured with an unmodified PG58-28 asphalt binder *(13)*. Two types of RAP were evaluated:

- Processed RAP: consisted of a mix of recycled asphalt pavement, Portland cement concrete and sometime slight amount of organic material and had 3.6% of a PG94-14 asphalt binder.
- Unprocessed RAP (grindings): consisted of recycled asphalt pavement that was milled from a pavement surface and had 4.9% of a PG82-22 asphalt binder.

At the mix design stage, the researchers found that the VMA and VFA of RAP containing mixtures are higher than that of the control mixture and the VMA of unprocessed RAP containing mixes increases with the increase in RAP content.

As part of this study, the researchers evaluated the heating time effect on the volumetrics of the 40% processed RAP mixture by heating the RAP before mixing for three different times:

- 2 hours heating time: standard procedure used by the New Hampshire DOT to simulate plant conditions.
- 3.5 hours heating time: time required for the RAP to reach mixing temperature.
- 8 hours heating time: equivalent to the time the aggregate is heated (usually overnight) in the oven.

When the same compaction effort was used in fabricating the specimens, the test results (Table 9) showed a decrease in the VMA by 0.5% when the heating time increases from 2 to 3.5 hours, and then an increase by almost 3% with the longer heating time. The researchers' claimed that: a) at the shorter heating time, the RAP is not heated enough to allow the RAP particles to break up into smaller pieces and blend with the virgin materials, and b) at the longer heating time, the RAP was likely aged further and the RAP particles have hardened and even fewer of them were able to break down and blend with the virgin material. This indicated that there is an optimum heating time for the RAP material to allow for the greatest extent of blending between the virgin and RAP materials. To determine the optimum heating time a detailed research is required.

Table 9 Effect of RAP Pre-heating Time on 40% Processed RAP Mixture Volumetrics.

Compaction method	**Property**	**Preheating duration**		
		2 Hrs	**3. 5 hrs**	**8 hrs**
	G_{mm}	2.484	2.480	2.479
Same compaction effort	Air void (%)	4.0	4.4	7.6
	VMA (%)	15.1	14.6	17.5
	VFA (%)	73.6	70.1	56.3
Same air void content	Air void (%)	4.0	4.0	4.0
	VMA (%)	15.1	14.2	14.4
	VFA (%)	73.6	71.2	72.2

When the same design air void content of 4% was used in fabricating the specimens, the test results (Table 9) showed that longer heating times decrease the VMA values, and may affect the mixture design and design asphalt content. Therefore, designing a RAP containing mixture using the Superpave design method depends heavily on the heating time of the RAP materials. Therefore, it is very important that laboratory procedures for designing RAP containing mixtures simulate the plant operations as close as possible *(13)*.

When samples produced according to the mix designs were tested for dynamic modulus under compression the variability of the results increased with increasing RAP content, but when the samples were tested in tension the variability of all RAP mixes were lower than that of the control mix. Additionally, the data showed that the 15% RAP mix has a higher stiffness than the control mix at both tension and compression tests. The 25 and 40% RAP mixes showed similar stiffness as the control mix in both tension and compression, though these were expected to have higher stiffness than the 15% RAP mix. The stiffness reduction of the 25 and 40% RAP mixtures was attributed to the finer gradations and higher VMA and VFA values.

When samples were tested for creep compliance, the 15% RAP mixture had higher stiffness and lower compliance when compared to the control mixture. But the 25% and 40% RAP mixtures did not follow the same trend set by the 15% RAP mix. This behavior was again attributed by the researchers to the finer gradations and higher VMA and VFA values. Additional supporting data for this study can be found in *Appendix A* of this report.

In 2007, Xiao et al. investigated the impact of using both RAP and crumb rubber on the rutting resistance characteristics of the rubberized asphalt mixtures containing RAP *(14)*. The experimental design was divided into two parts. For the first phase of the research work, two rubber types (Ambient and Cryogenic), four rubber contents (0, 5, 10, and 15% by weight of virgin binder), and three crumb rubber sizes (−14 mesh, −30 mesh, and −40 mesh) were used to make various mixtures. To avoid the influence of blending, one aggregate source (designated as L) and one binder source and grade (PG64-22) were used for preparing the samples. A total of 13 mix designs were conducted in this phase. The second part of the work included the validation of the findings from the first phase by using another aggregate source (designated as C) and another binder grade (PG52-28). A total of three mix designs were conducted for the second phase. The RAPs were taken from the same geographical area as the virgin aggregates. Both RAP sources (L and C) were approved by the South Carolina DOT and mixed with an original binder equivalent to a PG64-22. Four RAP percentages (0, 15, 25, and 30%) were used in the mixtures made with aggregate L and three RAP percentages (0, 15 and 38%) with aggregate C.

Experiments were carried out to evaluate the indirect tensile strength (ITS) and rutting susceptibility of the various mixtures using the asphalt pavement analyzer (APA). Tests were also performed to determine the rutting properties of various mixtures with respect to rubber production type, content, and size in the mixture. Based on the test results the following conclusions were made *(14)*. Additional supporting data can be found in *Appendix A* of this report.

- Increasing the RAP percentages in the mixtures containing crumb rubber resulted in higher stiffness and ITS values, indicating higher stability. This increase was also very effective in improving rutting resistance over the conventional mixtures.
- Increasing the rubber content resulted in a decrease in the ITS value and creep stiffness. However, adding crumb rubber into the HMA effectively increased the rutting resistance. Increasing the percentage of rubber considerably improved the ability of the mixtures to resist deformation as measured by the APA test. In general, the mixtures containing rubberized binder produced samples that exhibited lower rut depths than the mixes using the virgin binder.

- The results of the ITS tests suggested that the ambient rubber has produced results similar to those of the cryogenic rubber when the same rubber content is used. However, the rut depth of the two types of rubber mixtures suggested that the ambient rubber has higher rutting resistance when mixed with 25% RAP.
- The results of the ITS and rutting tests of mixtures made with 10% ambient rubber and 25% RAP showed that the effect of rubber size is rather small; the ITS values and the rut depths of these mixtures using various rubber sizes were similar.
- The results of the study showed that as air voids in the modified mixtures decrease, the rut depth from the APA test decreases, exhibiting a similar trend as in the conventional asphalt mixtures.

Summary of the Reviewed Research Studies

Table 10 summarizes the findings of the literature review on the use of RAP in HMA mixes. It was found that RAP can be used in both Superpave and Marshall mix design methods.

In general, most studies on laboratory produced mixtures concluded that the effect of RAP on mixtures' properties is negligible at low RAP contents of 15% to 20% *(7, 8, 9, 10)*. The low RAP content did not significantly affect the stiffness and strength of the mix at low and high temperature. However the increase in RAP content beyond 20% increased the mixture stiffness and strength resulting in an increase in rutting resistance *(6, 7, 9, 10, 14)*. When no change to the virgin binder grade was made, the higher RAP contents (>40%) resulted in a significant increase in the stiffness of the mix at high, intermediate, and low temperatures *(8, 9)*. Some studies indicated an increase in the variability of the measured mechanical properties of the mix with the increase in RAP content *(7, 13)*.

A study conducted on plant produced mixtures with up to 40% RAP and two virgin binder grades revealed that the RAP did not have as much impact as expected *(10)*.

The HMA mixtures with higher RAP contents were, in general, not significantly stiffer than the virgin mix. The binder did not stiffen linearly with increasing RAP content. In this case, dropping the virgin grade from a PG64-22 to a PG58-28 was not necessary. The test results suggest that the current NCHRP binder recommendations are restrictive and more investigations are needed to fully understand the behavior of RAP containing mixtures and plant operations keeping in mind that this study was conducted for only one plant, one RAP source, and one set of virgin materials.

A recent study conducted at the university of Nevada showed that the addition of 15% and 30% RAP to a mix designed with the Marshal method resulted in an acceptable resistance to moisture damage but with a reduction in the unconditioned and conditioned tensile strengths *(12)*. In general, the study showed that the 15% RAP mix with a neat target asphalt binder grade had a laboratory performance similar to that of the virgin mix (0% RAP) in terms of rutting, fatigue, and thermal cracking. On the other hand, the addition of RAP to polymer modified mixtures resulted in a significant reduction in the fatigue properties of the mix. The blending chart method was found to be conservative and unreliable in most of the cases.

Table 10 Overall Summary of Reviewed Research Studies.

Research	Objective	Description	Findings
Minnesota DOT *(6, 7)*.	Effect of RAP type and percentage on asphalt mixture properties.	Total of 10 mixes: - %RAP: 0, 20, 40. - Millings binder content 4.3%. - RAP binder content 5.4%. - PG58-28 & PG58-34. - Superpave mix design.	- Mixes TSR at 77°F > 75%. - |E*| increased with RAP. - |E*| affected by RAP source & asphalt binder. - RAP induced higher variability in measured properties & variability increased with RAP content. - Creep stiffness increases with %RAP or millings. - Mixes with PG58-34 binder softer than mixtures with PG58-28 binder at -18°C. - Extracted binder stiffness increased with %RAP or millings. - SCB fracture energy decreased with RAP content - RAP source does not affect the SCB fracture energy
NCHRP *(8)*.	Incorporate use of RAP in superpave HMA mixtures.	- 3 RAP sources: low stiffness RAP (PG82-22 and 5.9% binder), medium stiffness RAP (PG82-22 and 4.9% binder), high stiffness RAP (PG82-10 and 5.3% binder). - Virgin binder: PG52-34 & PG64-22. - %RAP: 0, 10, 20, & 40.	- RAP does not act like a black rock. - Linear blending equations appropriate with some non-linearity above 40% RAP. - Negligible effect of RAP at low RAP content. - At intermediate RAP content, effect of RAP compensated by using virgin binder 1 grade softer on both high & low temperature grades. - At high RAP content: use blending chart. - Properties of low RAP content mix similar to that of no RAP mix. - High RAP content stiffens the mix at high, intermediate, and low temperature. - Higher RAP content exhibits more rutting resistance and lower beam fatigue life when no change made in virgin binder grade.
North Central Superpave Center (9).	Laboratory performance of superpave asphalt mixtures incorporating RAP.	- 3 RAP sources: Indiana (4.7% binder), Michigan (3.8% binder), Missouri. (4.4% binder) - RAP content: up to 50%. - Plant produced mix at 15-25% RAP.	- Mixes with up to 50% can be designed under Superpave if RAP gradation and aggregate quality sufficient. - Linear blending charts appropriate in most cases. - Plant mixes showed similar performance as lab mixes except for Indiana mixes. - Increase in RAP content increases rutting resistance when virgin binder unchanged. - Small amount of RAP has low impact on performance - Consider RAP aggregate gradation and quality in mix design.
North Central Superpave Center (10).	Influence of RAP on mix & recovered binder of plant-produced HMA.	- 15, 25, 40% RAP + PG64-22 virgin binder. - 25% & 40% RAP + PG58-28 virgin binder. - Control mix: PG64-22 & 0% RAP.	- At 15% & 25% RAP, no difference in mean strength at low temperature and |E*|. - Some differences between control & 40% RAP mix at higher test temperature. - adding small amount of RAP may not change mix properties greatly.
Saskatchewan Highways & Transportation (11).	Compare lab fatigue performance & moisture damage of virgin & mixes containing RAP.	- One RAP source with 6.4% binder - 50% RAP core samples from Hwy 11, Canada. - RAP & virgin aggregate were used to prepare 25 & 50% RAP mixes in lab.	- At low temperature virgin mix perform well in fatigue - At high temperature all mixes perform equally in fatigue - RAP mixes perform much better in moisture susceptibility test than virgin mixes

Table 10 Overall Summary of Reviewed Research Studies (cont'd).

Research	Objective	Description	Findings
Western Regional Superpave Center *(12)*.	Laboratory evaluation on the use of RAP in laboratory produced HMA mixes.	- 3 RAP sources: 1 plant waste (4.6% binder) and 15 (5.4% binder) and 20 (5.8% binder) years-old reclaimed pavements. - 3 RAP contents: 0%, 15%, & 30%. - 2 target binder grades: PG64-22 and PG64-28 (polymer modified). - Virgin binder grades: selected based on blending charts. - RAP mixes are compared to no RAP mixes	- Marshall Mix Design method can be used to design mixes with 15 and 30% RAP. - Blending chart method conservative & not reliable. - Mixes had Acceptable resistance to moisture damage. - Reduction in the unconditioned & conditioned TS of the 15 & 30% RAP mixes. - PG64-22 mixes: 15% RAP mixes showed higher resistance to moisture damage than 30% RAP mixes. - PG64-28 mixes: 15% RAP mixes had lower resistance to moisture damage than 30% RAP mixes. - RAP increased rutting resistance of PG64-22 mixes except for RAP from plant waste. - PG64-28 RAP mixes showed good rutting resistance and similar to that of no RAP mix. - In general, PG64-22 RAP mixes showed better or equivalent fatigue resistance to the no RAP mix. -RAP in PG64-28 mixes significantly reduced fatigue resistance. - RAP mixes showed better or equivalent thermal cracking resistance to the no RAP mix.
Western Regional Superpave Center *(12)*.	Laboratory evaluation on the use of RAP in filed sampled HMA mixes.	- Two field mixes with 15%RAP - Two binders: PG64-22 & polymer modified PG64-28	- PG64-22 mix failed to meet minimum TSR of 70%. - PG64-28 mix barely passed minimum required TSR. - Mixes met the NDOT APA criterion of 8mm. - Polymer modified binder reduced APA rut depth by about 42% compared to neat asphalt binder. - Use of RAP in a polymer modified mix increased mix resistance to fatigue cracking in laboratory test when compared to the neat binder (PG64-22) mix. - Use of RAP in a polymer modified mix reduced the resistance to fatigue cracking in mechanistic analysis when compared to neat binder -Fracture temperature was within 1°C of low performance temperature of corresponding target binder grades (i.e. -22°C & -28°C). - Mixes might show signs of failure in the field due to moisture sensitivity problems. - Attention should be given to moisture resistance of field mixtures.
Daniel and Lachance *(13)*.	Evaluation of volumetric and mechanistic properties of RAP mixtures	-2 RAP sources; processed (3.6% binder of PG94-14) and unprocessed (4.95% binder of PG82-22) - One virgin binder; PG58-28 - 0%, 15%, 25% & 40% RAP contents	- VMA & VFA increase with RAP - RAP preheating time affect the VMA - 15% RAP increased stiffness|, 25% & 40% show similar stiffness as control mix - 15 RAP decreased creep compliance, 25% & 40% showed similar creep compliance as control mix - RAP mixtures show higher variability in compression - Finer gradation, Increased VMA & increased binder content reduce the effects of aged stiffer binder
Xiao et al. *(14)*.	Investigation of the use of both RAP and crumb rubber (CR) in HMA mixes.	- Evaluate indirect tensile strength (ITS). - Rutting resistance under APA.	- Higher RAP% in mixes containing CR resulted in higher stiffness & ITS, indicating higher stability. - Increase in rubber content decreased ITS & creep stiffness. - CR effectively increased rutting resistance of mix. - Increasing % of rubber considerably improved ability of mixes to resist deformation.

PERFORMANCE OF RAP CONTAINING MIXES IN HIGHWAY PAVEMENTS

Performance of Pavements Containing RAP in California

The California Department of Transportation (Caltrans) initiated a study to evaluate the performance of in-service recycled asphalt pavements in California. As part of this study, sixty 15% RAP test sections located in three of California's environmental zones – Desert (DS), Mountain (MT) and North Coast (NC) – along four routes (one in each of Caltrans' Districts 1, 7, 9 and 11) were considered. Five of these sections have a Cement Treated Base (CTB), while the rest of the sections have an aggregate base course. Deflection, roughness, distress and cores/bores were among the data attributes collected from the test sections. Laboratory tests were performed on the cores recovered from the field. Also, analysis was performed on the data collected from these sections to evaluate the actual field performance of RAP in different environmental zones.

In 2007, Zaghloul et al. *(15)* reported the observed field performance of the RAP containing sections, as well as the results of the evaluation analysis, and compared the performance of the RAP containing sections by environmental zone. The sections had been in service for 5 to 9 years.

The following three performance indices were used to evaluate the structural and functional performance of the sections as well as the construction consistency.

- Structural adequacy index (SAI): developed by normalizing the effective Gravel Equivalent (GEeff), which is backcalculated from FWD testing and evaluates the in-situ structural capacity of the pavement section in its current condition, with respect to the gravel equivalent calculated based on the as-built pavement structure (GEas-built). The GEas-built is calculated from core/bore results by summing the product of each layer thickness and its corresponding equivalent gravel factors (Gf).

- Distress index (DI): is a re-scaled version of the PCI used in the Micro-Paver.
- Roughness index (RI): is a re-scaled version of the IRI.

Table 11 summarizes the findings based on the analysis of the performance data from all sixty sections *(15)*. Additional supporting data can be found in *Appendix A* of this report.

Table 11 Expected Service Lives for the RAP Containing Sections in California

Environmental Zone	**Expected Service Lives (years) Based on**			**Triggering Failure Mode**
	Structural Performance	**Distress Performance**	**Roughness Performance**	
North Coast	18	21	17	Ride quality
Desert	15	9	15	Distress*
Mountain	11	13	15	Structural

* Distress service life can be significantly increased if appropriate maintenance activities, such as crack sealing, are applied in a timely fashion.

In 2008, Zaghloul and Holland *(16)* compared the performance of 47 RAP sections located in the same three California environmental zones to the performance of other treatments, located within a reasonable distance on the same route, such as AC overlay, Mill & AC overlay and Rubber Asphalt Concrete overlay (RAC). Although the sections were on the same route, some sections were as far as 60 miles apart and were considered as having same environmental and traffic conditions. In total, 131 sections covering 7 different treatments were considered in the analysis. The performance comparisons were made using deterioration models that were developed to estimate the in-situ structural capacity, distress condition, and roughness condition for all sections at the same age (5 years) to allow fair comparisons. Also, the expected structural, distress, and roughness service lives were estimated for all treatments based on the field-observed conditions. The results of the analyses suggested that in all three environmental zones (i.e., North Coast, Desert, and Mountain), the long-term RAP performance of RAP containing mixtures is likely to be comparable to other treatments located within a reasonable distance on the same route.

Performance of Pavements Containing RAP in Louisiana

In 1996, Paul compared the relative performance of mixes containing 20 to 50% RAP on five different projects to conventional HMA mixes on four different projects in Louisiana *(17)*. The conventional and RAP containing projects were selected using the following criteria: same contractor, similar mix designs, similar design traffic, same geological region, and constructed during the same time frame.

The functional (roughness, surface conditions, and rutting) and structural performance (structural number (SN) using the Dynaflect device) of the various projects were measured and compared. Ten evaluation locations within each project were monitored annually for five years. The major forms of distresses recorded were longitudinal and transverse cracking and rutting. Recycled pavements showed moderate transverse cracking where as control sections showed slight transverse cracking. Rutting was less than 0.25 inch on all projects.

Field samples were collected and tested for specific gravity, asphalt content, gradation, viscosity, penetration, and ductility. All pavements showed increased densification from traffic beyond the initial construction compaction. The aggregate gradation results showed no significant changes after 5 years. When tested immediately after production, the two plant produced mixtures from the RAP sections with cracking higher than the control sections had recovered viscosity binders higher than the maximum allowable viscosity of 12,000 poises. Check *Appendix A* of this report for additional supporting data.

Overall, the researchers found that the pavements containing 20-50% RAP performed similarly to the conventional pavements for a period of 6 to 9 years after construction.

Performance of Pavements Containing RAP in Georgia

In 1995 a research project was undertaken to evaluate the performance of a RAP containing pavement section and a control (virgin) section on five different projects in Georgia *(18)*. In situ mixture properties (such as air voids, resilient modulus, and indirect tensile strength), recovered asphalt binder properties (such as penetration, viscosity, $G^*/\sin\delta$, and $G^*\sin\delta$), and laboratory re-compacted mix properties (such as gyratory stability index and confined dynamic creep modulus) were measured. The RAP material proportion in the mixtures from all five projects varied between 10 and 25%.

After 1.5 to 2.25 years in-service, both virgin and RAP containing sections of the five projects were performing satisfactory with no significant rutting, raveling and weathering, fatigue cracking, and no significant differences between their measured properties. Even though the virgin sections showed a slightly higher indirect tensile strength, no visual distress was found in RAP containing sections as a result of this difference. Check *Appendix A* of this report for additional data.

It should be noted that the recovered binders exhibited a G*/sinδ value well above the 1 kPa criterion for original binders and a G*sinδ value well below 5,000 kPa at the PAV aged condition; hence, indicating higher resistance to rutting and fatigue, respectively (Table 12).

Table 12 Recovered Binder Test Results from Georgia Test Sections

Recovered binder Property	Average of 5 Projects		Are differences Significant at 5% Level
	Control	RAP	
Penetration @ 25°C (0.1 mm)	20	20	No
Viscosity @ 60°C (Pas)	5,466	4,688	No
G*/sinδ kPa @ 64°C	17.9	15.4	No
G*sinδ kPa @ 22°C	1,356	1,288	No

Accordingly, ten additional virgin mix wearing courses projects and thirteen additional RAP containing wearing courses projects constructed during the same period throughout the state of Georgia were also evaluated. No statistically significant differences were found between the recovered asphalt properties (penetration and viscosity) from the virgin and RAP containing pavements. Additionally, based on visual inspection there was no significant overall difference in the performance of virgin and RAP containing pavements.

Based on the findings of this study, it was concluded that the RAP containing pavements are generally performing as well as the virgin pavements. Therefore, it was implied that the Georgia Department of Transportation (GDOT) recycling specifications, recycled mix design procedures, and quality control are satisfactory. Additionally, the evaluation showed that the specification to achieve a viscosity between 6,000 and 16,000 poises for the blended binder (RAP binder + virgin binder) is reasonable.

Performance of RAP Containing SPS-9A Sections in Connecticut

In efforts to validate the Superpave mix design and binder selection procedures, several sections were built throughout North America and their performances were monitored under the long-term pavement performance program (LTPP). Initially, under the LTPP special pavement sections pilot phase (SPS-9P) nine projects were constructed and their performances were used for refining the Superpave procedures. In the second phase (SPS-9A) twenty four projects were built throughout North America to monitor the long-term performance of Superpave procedures and compare them with conventional methods used by local agencies. Every project had at least 3 sections. One section constructed with the state agency conventional mix design procedure, another section with the Superpave mix design procedure, and the last section with the Superpave mix design procedure and a change in the binder grade at either the high or low performance temperature. The pavement structures were maintained uniform within each project. The long-term performance of these sections was monitored for rutting, fatigue, non wheel path longitudinal (NWP) cracking, and transverse cracking *(19)*.

Among those SPS-9A projects, the Connecticut B (CT-B) project was constructed with 20% RAP containing sections. The three sections within the CT-B project included a section with the conventional Connecticut DOT mix (Marshal Mix with AC-20 binder), a section with a Superpave designed mix and a PG64-28 asphalt binder, and a section with a Superpave designed mix and a PG64-22 asphalt binder. It should be noted that the PG grade recommended for this location by the LTPP is a PG58-28.

After 8 years of service, the average rut depth of the CT-B project for all three sections that included 20% RAP was around 2.0 mm while the overall average for the rest of the national projects (SPS-9A) was 4.4 mm with most of them having a rut depth greater than 2.0 mm. No fatigue cracking was found in the CT-B project while the average fatigue cracked area for the rest of the SPS-9A national projects was around 27 m^2. No transverse cracking were observed in the CT-B project on all three sections while the overall average was 8.3 m^2. The average NWP cracking (100 m^2) for the CT-B project containing 20% RAP was higher than the overall average of the rest of the SPS-9A projects (83 m^2). In summary, the CT-B RAP sections showed a good field performance with no fatigue and transverse cracking on all three sections after 8 years in-service.

Summary of Performance of Pavements containing RAP in Highway

Table 13 summarizes the findings of the review of the performance of RAP containing mixtures on highway pavements.

In general, highway pavements with 15 to 20% RAP are performing well and similar to pavements without RAP. Additionally, it was found that the GDOT requirement on the TFOT aged viscosity between 6,000 and 16,000 poises on the blended asphalt binder (RAP binder + virgin binder) is a reasonable specification. Louisiana had good experience with the performance of mixes with 50% RAP when compared to the conventional pavements for a period of six to nine years after construction. Additionally, no significant differences existed in the recovered asphalt binder properties from Louisiana pavements containing RAP and pavements without RAP. The Connecticut SPS-9A sections with 20% RAP showed good field performance with some non wheel path cracking and no fatigue and transverse cracking on all three sections (one Marshall and two Superpave designed mixes) after 8 years in-service.

Table 13 Overall Summary of RAP Performance on Highway Pavements.

Research	Objective	Description	Findings
California *(15)*.	Evaluation of performance of in service RAP in California.	- 60 sections with 15% RAP. -5 Sections with CTB. - Collected Deflection, roughness & distress measurements.	-Life expectancy of RAP sections in North Coast zone are 18, 21 and 17 years respectively for Structural adequacy, Distress and Roughness - Life expectancy of RAP sections in desert zone are 15, 9 and 15 years respectively. -Life expectancy of RAP sections in mountain zone are 11, 13 and 15 years respectively. -RAP sections in North Coast zone perform better than the other 2 zones (may be attributed to the CTB).
California *(16)*.	Comparison of in service RAP pavements with virgin pavements	- 47 sections with 15% RAP - Total of 131 sections with 7 types of treatments -Collected Deflection, roughness & distress measurements.	- Life expectancy of all RAP sections ranged from 9 to 20 years in terms of Structural adequacy, Distress and Roughness -Long term performances of RAP sections comparable with virgin sections with same environmental and loading condition
Louisiana *(17)*.	Evaluation of recycled projects for performance.	- 5 projects used 20 - 50% RAP+4 conventional HMA mixtures - Conventional & RAP projects had: same contractor, similar mix designs, similar design traffic, and same geological region. - Measured functional & structural performance.	- Major distresses were longitudinal and transverse cracking and rutting - Overall, pavements containing 20-50% RAP performed similarly to the conventional pavements for a period of 6 to 9 years after construction. - No significant differences existed in the recovered asphalt binder properties from pavements containing RAP and pavements without RAP.
Georgia *(18)*.	Compare in-service performance of recycled and virgin HMA pavements and review the GDOT`s specifications for recycling.	-5 projects with a control (virgin) section and a recycled section (RAP 10-25%). - Additional 10 virgin mix projects and 13 recycled wearing course projects constructed throughout GA were evaluated (RAP 10-25%).	- Results from the 5 projects: No difference found between virgin & recycled surface after 1.5 to 2.25 years of service. Both virgin and recycled sections performed well with no significant rutting, raveling & weathering, & fatigue cracking. - Recovered binder tests from the 5 projects showed good resistance to fatigue and rutting - Results from additional projects: No difference found between extracted binder properties of recycled & virgin pavements. Recycled pavements are performing as well as virgin pavements. - Current GDOT`s recycling specs are satisfactory. - Specification to achieve a viscosity of 6,000 & 16,000 poises for the blend binder is reasonable.
Connecticut *(19)*.	Long-term performance of recycled HMA.	- 20% RAP - 3 sections: AC-20, PG64-28, PG64-22	- RAP sections showed a good field performance with no fatigue and transverse cracking on all three sections after 8 years in-service.

PERFORMANCE OF RAP CONTAINING MIXES IN AIRFIELD PAVEMENTS

US Army Research and Development Center

In 2005, Shoenberger and Demoss *(20)* reported on the performance of 8 to 12 years old HMA airfield pavements containing RAP at four air force bases (AFB):

- Columbus AFB: located in Columbus, Mississippi, U.S., which has hot and humid summers and mild and wet winters.
- Lajes Field: located on Terceira Island in the Azores, Portugal, which has mild climate with warm summers and no freezing winter temperatures.
- MacDill AFB: located in Tampa, FL, U.S., which has hot and humid summers and mild winters.
- McGuire AFB: located near Wrightstown in central New Jersey, U.S., and has warm summers and moderate winter temperatures.

The RAP was cold milled from the existing pavement at all four bases and was combined at a rate between 35 and 60% with new aggregate, neat asphalt binder, and possibly either rejuvenators or hot mix recycling agent to produce the final RAP containing HMA mix at each location. None of the pavements required repairs for structural deficiencies during construction.

A combination of several factors limited the effectiveness of this performance evaluation, including: the limited number of RAP containing pavements evaluated, differing times of service, differing climatic conditions, variations in the amounts of RAP material used, and variations in virgin aggregates, asphalts, and recycling agents used in the blended mixtures. Therefore, only general trends were feasible due to the multiple variations of the various properties of the pavements investigated in this study.

The researchers reported that the pavement condition index (PCI) values varied from 37 (poor) to 80 (very good) with block cracking at low severity levels being the major distress noted on all pavements and at all locations except for Lajes Field where the block cracking was at high severity level. The Lajes Field had the only RAP mix that contained a recycling agent. A laboratory study conducted by Brown *(21)* with this type of recycling agent and others showed a decrease in durability in the RAP containing mixtures versus only using asphalt cement without a recycling agent. The pavement at the MacDill AFB had low to medium severity patching and raveling distresses in addition to low severity block cracking.

Pavement samples were obtained from each section. Properties such as field density, maximum theoretical density, asphalt content, and aggregate gradation were obtained. The recovered asphalt cements were evaluated for penetration, viscosity, and specific gravity. Table 14 shows some of the research findings. The results of these tests were then compared with test data obtained during construction to verify that the field mixture met specification requirements. More information on this study is reported in *Appendix A* of this report.

Table 14 Evaluation of RAP Containing HMA Mixes Properties.

Material	Property	Trend since construction	Comments
Recovered Asphalt	Penetration	Decreased	Related to aging or hardening of asphalt binder.
	Specific gravity	Increased	
Mixture	Asphalt content	Increased	Should have made the RAP mixes susceptible to load related distresses. However, pavements generally had only climatic or durability related distresses.
	Densities	Below minimum	Adversely affected pavements durability.

Based on the performance and materials evaluations of the various pavements the researchers were able to make the following conclusions *(20)*.

- HMA pavements containing RAP have been successfully used by the Air Force. These airfield pavements have provided good performance. The pavements investigated have performed satisfactorily for 8 to 12 years (except for a high speed taxiway at McGuire AFB). The majority of distresses found in the evaluated RAP containing pavements, as with virgin mixtures, were from environmental or climatic causes with very few load related distresses even in the parking and taxiway areas.
- PCI values, obtained for the RAP containing pavements, showed that the rates of deterioration appear to be similar for all sections. Condition surveys showed that the investigated RAP containing pavements performed similar to virgin HMA mixtures under similar circumstances.
- The use of RAP in HMA pavements on airfield can be an economical solution while being beneficial to the environmentally conscious society.

Massachusetts Port Authority

In 2003, the Massachusetts Port Authority (Massport) evaluated the performance of four mix designs that are in service at the Logan International Airport pavement in Boston, MA, by testing field cores for rutting and moisture damage.

- PG76-28 modified P-401 mix.
- Reclaimed asphalt pavement (RAP)/latex modified P-401 mix: 18.5% RAP + 4% SBR latex modified PG64-28 asphalt binder.
- Latex modified stone matrix asphalt (SMA) mix
- Rosphalt 50™ modified P-401 mix: trademark of the Royston Laboratories Division of Chase Corporation and is described as a concentrated thermoplastic virgin polymeric material which is added to an HMA to improve its rut resistance.

The APA rut depths at 140°F (60ºC) under dry condition indicated a statistically significant difference in rutting of the various mixtures with the RAP P-401 and Rosphalt 50™ P-401 mixtures ranking better than the PG76-28 P-401 and SMA mixtures *(22)*.

Under wet condition in the APA test, all mixtures exhibited a wet rut depth equivalent to the dry rut depth except for the RAP P-401 which indicated aggravation in rutting in the presence of moisture. However, none of the wet rut depths were above the

4.5-5.0 mm range and none of the mixtures showed evidence of visual stripping. From a purely ranking point of view, the results indicated that the Rosphalt 50™ P-401 mix had the lowest wet rutting, and the PG76-28 P-401 had the highest wet rutting while no statistically significant differences in the wet rut depths were identified.

As of 2003, the RAP P-401 mix has performed very well in the field through two summers and tested well in the laboratory. The PG76-28 and SMA mixtures have shown slight indications of rutting in the field *(22)*.

In view of the unsuccessful past attempts by Massport to prevent moisture damage problems, Mallick et al. *(23)* started recently investigating the stripping potential of the locally available aggregates typically used to manufacture HMA mixes for the Logan International Airport and the type of additives that would be required to improve the mixtures' ability to resist moisture and stress induced pavement damages.

This project was broken into multiple phases, each one building on the results of the previous ones. During the different phases, a number of different types of aggregates, asphalt, accelerated loading testing and laboratory tests were used. Tests were conducted on laboratory mixed and compacted samples, plant mixed and laboratory compacted samples, as well as cores from field compacted mixes. The results were analyzed and used for drawing conclusions and making recommendations to be implemented and applied for HMA paving jobs at Logan airport only. In addition to the evaluated mixtures, the study also included several mixtures with 18% RAP and a 4% latex PG64-28 binder.

As a result of the study, it was found that the TSR test alone is not a good indicator of performance for local mixes. It has been recommended that hydrated lime be used in paving mixes because of its proven effectiveness in this study to reduce moisture damage. Mixes containing about 18% RAP were found to perform adequately but quality control was a concern due to varying sources of RAP. Six freeze-thaw cycles were found necessary to identify moisture susceptible mixes supplemented with an accelerated loading test to be conducted for paving mixes before accepted for placement *(23)*. More information on both studies are reported in *Appendix A* of this report.

National Institute for Land and Infrastructure Management, Japan

In 2006, a study was conducted by Hashiya et al. to examine the use of RAP in airport pavement surface courses through laboratory tests and field experiments *(24)*. Two key points were initially subjected to extensive study in the laboratory: the effect of rejuvenating agents on performance of RAP containing mixtures and the possibility of increasing the proportion of RAP materials in the total mix. RAP was then experimentally included in in-service airport pavement surface courses. Almost no difference was found between the performance of pavements containing RAP and those without RAP. In addition, the applicability of 100% RAP mixes to airport pavements, the possibility of re-recycling asphalt concrete, and the influence of RAP aggregate quality on performance were investigated in an effort to further promote the recycling of asphalt concrete. Based on the findings of this study the researchers made the following conclusions.

- The properties of HMA Mixtures with RAP made with different rejuvenating agents were similar, although the properties of the RAP binders varied.
- HMA mixes with and without RAP had nearly equivalent performance. This was also true for 100% RAP pavements.

- The performance of pavements containing RAP obtained from airport pavements at RAP content up to 70% satisfies the specifications for use as a surface course in airport pavements.
- Re-recycled asphalt concrete has similar properties to recycled asphalt concrete.
- Recycled asphalt concrete containing low-quality old aggregate compares well with that containing higher-quality aggregate.

Based on these findings, it was concluded that RAP content up to 70% using old aggregate obtained from airport pavements is very suitable for the surface course of airport pavements. Moreover, investigation of certain additional measures shows that further promotion of asphalt concrete recycling is possible.

Naval Civil Engineering Laboratory, Port Hueneme, California

In 1986, Cline and Hironaka *(25)* documented the relative performance of both the Needles airport in California with 50% RAP material in the surface course and the Barnes county municipal airport at Valley City in North Dakota with 70% RAP material in surface course versus virgin asphalt concrete pavement surfaces at the same locations. Both of these airports had general aviation traffic of low volume.

In 1986, after 5 years of construction, the PCI of the Runway 2-20 with 50% RAP mix at the Needles airport averaged 85 with an overall rating classified as very good according to the FAA specifications. Longitudinal and transverse cracking and raveling of low severity were the major distresses observed at the runway with the climatic effect on material durability as the primary distress mechanism. The laboratory tests on conventional HMA mixes obtained from field cores from the Runway 2-20 showed higher resilient modulus values, Marshall stability, and flow values than the RAP containing mixes obtained from the highway projects indicating a stiffer mix. The dry tensile strength of the field cores was higher than previously built projects with RAP. The RAP mixes exhibited a retained tensile strength ratio of 87% indicating no stripping problems due to moisture. The extracted/recovered asphalt binder from cores exhibited high viscosity and low penetration values indicating an aged binder *(25)*.

In 1985, after 5 years of construction, the PCI of the taxiway with a full depth HMA with 70% RAP at the Valley City, North Dakota airport averaged 75 with an overall rating classified as very good in accordance with the FAA specifications. The primary pavement distresses at the Valley City airport were longitudinal and transverse cracking and raveling at low severity in the 3/8-inch chip seal that was placed on top of the RAP HMA surface with the climate and material durability being as the primary distress mechanism. The laboratory tests on field cores from the Valley City airport showed lower Marshall stability value and generally high resilient modulus values than the other RAP containing highway projects covered in this study. The dry tensile strength of the field cores was similar to previously constructed RAP mixtures; however the retained tensile strength ratio was 25 to 35% indicating potential stripping and loss of strength in the presence of water. The extracted/recovered asphalt binder from cores exhibited typical values of viscosity and penetration for asphalt surfaces *(25)*. More information on this study is reported in *Appendix A* of this report.

Summary of Pavements Containing RAP Performance in Airfield Pavements

Table 15 summarizes the findings of the review of the performance of RAP containing mixtures on airfield pavements. In general, RAP mixes showed good resistance to rutting in the field as well as in the laboratory. Environmental distresses like block cracking and raveling were the primary type of distresses encountered in pavements containing RAP. In general, the use of higher RAP percentage (35% to 65%) with a recycling agent decreased the durability properties of mixtures containing RAP.

Table 15 Overall Summary of RAP Performance on Airfield Pavements.

Research	Objective	Description	Findings
US army research and development center *(20).*	Evaluation of in- service performance of pavements containing RAP in air force airfields (8-12 years old).	- 3 airports from US & 1 from Terceira Island in Portugal. - 35% to 60% RAP with rejuvenators or recycling agents. - No pre-overlay structural deficiency. - Extracted asphalt & aggregate tested for physical properties.	- PCI values ranged from 37 (poor) to 80 (very good) - Lower severity block cracking at all airports with high severity block cracking at the Portugal airport which was the only mixture containing RAP with recycling agent. - Laboratory study *(21)* with same type of recycling agent and others showed a decrease in durability in the mixtures containing RAP. - 1 airport also had low to medium severity patching and raveling distresses. - Under same environment pavements containing RAP performed similarly to virgin pavements. - Design of mixes with RAP should be adjusted to resist environment than to resist load.
Massachusetts Port Authority *(22, 23)*.	- Identify a rut & a moisture resisting mix. - Identifying moisture resistance test method.	- 7 mixes evaluated for rutting. - 1 mix: 18.5% RAP with 4% SBR latex PG64-28 binder. - 3 mixtures evaluated for moisture resistance: PG76-28 mix, SMA, & 18%RAP with 4% latex PG64-28 mix. - Mixes are placed in the field & field cores, plant mixes, & lab mixes were tested.	- mix containing RAP showed highest rutting resistant under dry APA & aggravation in rutting resistance under wet APA but not statistically different from other mixes. -Visual observation showed no indication of striping. - TSR alone is not a good indication of moisture resistance. - Hydrated lime improved moisture resistance. -Tensile strength after 6 cycles and accelerated loading test are good to identify moisture resistant mixtures. -18% RAP mix performed well for moisture resistance in the lab and field.
National Institute for Land and Infrastructure Management, Japan *(24)*.	- Possibility of using RAP in airport surfaces. - Effect of rejuvenators on performance of mixes containing RAP.	- Intensive lab testes performed with various RAP contents & rejuvenators - Evaluate field performance of an airfield test sections.	- Properties of mixes with RAP were similar with various rejuvenators. - 100% RAP pavements performed nearly as virgin pavements. -70% RAP pavements satisfied specifications for field performance. -Re-recycled pavement performed equal to recycled pavements. - 70% RAP pavement is suitable for airport surfaces.
Naval Civil Engineering Laboratory, Port Hueneme, California *(25)*.	Comparing performance of pavements containing RAP in airfields with virgin airfield pavements & highway pavements containing RAP.	- Two 5-year old airport pavements from Cal. and N. Dakota with 50% & 70% RAP. -Field cores tested for Marshal stability, Mr,, moisture sensitivity. - Extracted binder tested for viscosity & penetration.	- Both pavements rated as very good condition according to FAA specifications on PCI. - Environmental distresses were the primary distress in both pavements. -Binder tests, Mr values and marshal stability showed a higher stiffness for California airport & typical values for N. Dakota airport. - RAP mixes from California airport exhibited a TSR of 87% and those from N. Dakota airport a TSR of 25-35%.

VARIABILITY OF RAP MATERIALS

The variability of the material is one of the major concerns agencies have about the use of RAP in HMA mixes. Since variability of virgin aggregates can change based on source and producer, it should be reasonable to expect that RAP variability will change according to its source and methods of removal and processing. Additionally, since RAP is removed from an old pavement, its composition will be affected by the previous maintenance and preservation activities that were applied to the existing pavement. For example, in many airfield pavement applications like parking areas, maintenance and refueling areas, a fuel-resistant sealer is often applied to protect the asphalt concrete pavement from possible damage due to fuel spillage. Additionally, base, intermediate, and surface courses from the old pavement may all be mixed together in the final RAP.

If the RAP varies widely in properties such as gradation or asphalt content, the resulting HMA may also be variable. For example, a significant variation in the passing No. 200 material will affect mixtures properties such as VMA and air voids. When evaluating the dynamic modulus of laboratory produced HMA mixtures containing RAP, Li et al. *(6)* found that such mixtures showed variability in the tested replicates and that variability increased with the addition of RAP. Furthermore, the dynamic modulus test results were observed to have more variability between replicates at low temperatures.

In 1984, Kallas *(26, 27)* illustrated the difference in RAP composition and variability by evaluating the gradation and the asphalt binder content of RAP materials from core samples and after milling from four different projects. Table 16 summarizes the average and the standard deviation of the percent passing No. 8 and No. 200 sieves along with the RAP asphalt binder content for the various projects. The data in Table 16 shows a higher variability in the percent passing values of the RAP materials from core samples when compared to the values for the RAP materials after millings. Additionally the aggregate gradations become finer after removal, processing, and stockpiling. Therefore, RAP source variability can be reduced by screening and crushing to separate stockpiles containing different sizes of RAP *(27)*.

Table 17 shows additional data on the variability of RAP materials in terms of the percent passing No. 8 and No. 200 sieves along with the asphalt binder content *(27)*.

Tables 16 and 17 include the average standard deviations reported by Granley *(28)* on the variations of typical HMA surface mixes during HMA production of 26 different projects. Additionally Tables 16 and 17 include the process standard deviations that are inherent in section 401-6.5 of the FAA's P-401 specification for control charts. The action and suspension limits that are presented in P-401-6.5 for the passing No. 200 and the asphalt content are 2 times and 3 times the corresponding process standard deviation, respectively. In other words, the action and suspension limits for the passing No. 200 are ±2.0% and ±3.0%, respectively. Similarly, the action and suspension limits for the asphalt content are ±0.45% and ±0.70%, respectively. The process standard deviations for the action and suspension limits in Section 401-6.5 were obtained from a review of data based on 200,000 tons of HMA produced in FAA's Eastern Region in 1977 *(29)*.

By comparing the RAP standard deviations to the typical HMA surface standard deviations and the FAA P-401 standard deviations, the data reveals that some sources of RAP have more variability in composition than average HMA surface course production.

Using these sources, the RAP content would have to be limited to produce RAP containing HMA mixtures that comply the uniformity requirements in most specifications. Additionally Tables 16 and 17 show that some sources of RAP have less composition variability than average HMA surface course production; hence, the RAP content in HMA would not be restricted based on its compositional variability *(27)*.

Table 16 RAP composition of core samples and stockpiles

Sample	**Number of samples tested**	**% Passing**				**Asphalt binder content**	
		No. 8 sieve		**No. 200 sieve**			
		Ave.	**σ_{n-1}**	**Ave.**	**σ_{n-1}**	**Ave.**	**σ_{n-1}**
California Road cores	12	54	8.3	9.9	2.01	5.4	0.71
California stockpile after milling	5	69	6.5	11.8	0.34	5.2	0.04
North Carolina Road cores	12	69	3.2	6.1	0.66	5.7	0.11
North Carolina stockpile after milling	5	72	0.9	8.0	0.11	5.7	0.11
Utah Road cores	12	52	3.8	8.7	2.60	6.5	0.28
Utah stockpile after milling	10	58	2.8	9.9	1.15	6.2	0.44
Virginia Road cores	12	41	2.1	9.7	0.79	5.3	0.20
Virginia stockpile after milling	6	52	1.1	13.0	0.30	5.2	0.12
Typical HMA surface variability *(28)*	-	-	2.81	-	0.94	-	0.28
HMA surface variability on Airport Pavements (P-401-6.5) *(29)*	-	-	-	-	1.00	-	0.23*

* %AC from solvent extraction

Table 17 RAP composition from various sources

Sample	**Number of samples tested**	**% Passing**				**Asphalt cement content**	
		No. 8 sieve		**No. 200 sieve**			
		Ave.	**σ_{n-1}**	**Ave.**	**σ_{n-1}**	**Ave.**	**σ_{n-1}**
Newton county stockpile	10	47.5	4.95	7.14	0.74	5.52	0.23
Forest Park stockpile millings	5	3.6	3.41	7.02	1.08	5.46	0.31
Forest Park stockpile of chunks	5	39.0	2.81	6.87	0.39	4.61	0.55
Resaca plant stockpile	10	36.4	2.20	8.72	1.36	5.08	0.21
Bryan county stockpile	10	42.9	4.63	4.75	0.71	4.83	0.42
Lowndes county	10	49.3	4.82	7.36	0.75	5.60	0.48
New Jersey cores	23	50.5	3.20	7.00	1.11	5.91	0.48
Spartan Asphalt 1994 stockpile	70	58.1	3.50	9.00	0.82	3.80	0.30
Typical HMA surface variability *(28)*	-	-	2.81	-	0.94	-	0.28
HMA surface variability on Airport Pavements (P-401-6.5) *(29)*	-	-	-	-	1.00	-	0.23*

* %AC from solvent extraction

In 1996, a research project was undertaken by Solaimanian and Tahmoressi to evaluate the production and construction variability of HMA mixtures containing large quantities of RAP material *(30)*. Four construction projects were selected where two of the projects used 35 percent RAP material, while the other two used 40 and 50 percent RAP. Table 18 shows the projects information.

The researchers categorized the objectives of this study as follows:

- To determine the variability that exists in stockpiles of RAP material. The variability may be due to stockpiling methods or may be inherent in the materials.
- To determine the variability in the plant-produced HMA containing between 20 and 50 percent RAP.
- To provide statistical information on RAP variability and its influence on HMA through data analysis. These data will be used to determine the allowable maximum amount of RAP and its effect on the mixture uniformity. The data will be useful in improving Texas DOT QC/QA HMA specifications and test procedures.

Table 18 Projects Information

Project	Highway	Aggregate Source	Asphalt Source	Mix Type	Tonnage	%RAP
1	IH20	Vulcan Material	Coastal AC-10	C Surface	12,000	35
2	IH20	G-H Perch & CXI	Lion AC-10	C Base	15,000	35
3	IH20	Transit Matrial	Fina AC-10	D Surface	20,000	50
4	SH 100	Parker La Farge and Fordyce	Coastal AC-5	B Base	30,000	40

In all cases, dedicated RAP stockpiles were used. A series of tests were performed at both the hot-mix plant laboratory and the University of Texas (UT) asphalt laboratory. The tests at the plant included extraction, gradation, and asphalt content using nuclear gauge. A number of specimens were also compacted and shipped to the Texas Department of Transportation Materials and Tests Division for Hveem stability testing. Additionally, asphalt recovery, penetration, and viscosity tests for both HMA and RAP were conducted at the UT laboratory. Each day, four sublots were sampled. The results obtained from the tests were analyzed for gradation and asphalt content deviations, air voids, penetrations and viscosities, and stabilities. Pay adjustment factors were determined for gradation and asphalt content deviation, as well as for air voids.

The testing data showed that the aggregate gradation of the RAP sources varied within a wide range and in most of the cases the RAP material gradation exhibited higher variation than that of conventional HMA. On the other hand, the aggregate gradations of the plant mixes were, in most of the cases, finer than the targeted JMF gradation. Figure 1 shows the mean deviations of the gradations for the No. 10 sieve from JMF. The analyzed data showed that as the RAP content increases the mean deviation increases with the mean deviations of all 4 projects higher than that of a conventional HMA mix.

Additionally, the asphalt content of RAP materials and plant mixtures was analyzed and the mean deviations from JMF were calculated and are shown in Figure 2. The data shows that the asphalt content mean deviations of RAP containing mixtures are higher than that of conventional HMA mix. Figure 3 shows the variation of the air voids standard deviation with the RAP content in the mix indicating that the variability in air voids increases as the RAP content increases. Additionally, the standard deviation of the stability values in Figure 4 shows that the RAP containing mixtures have higher variability than conventional HMA mix.

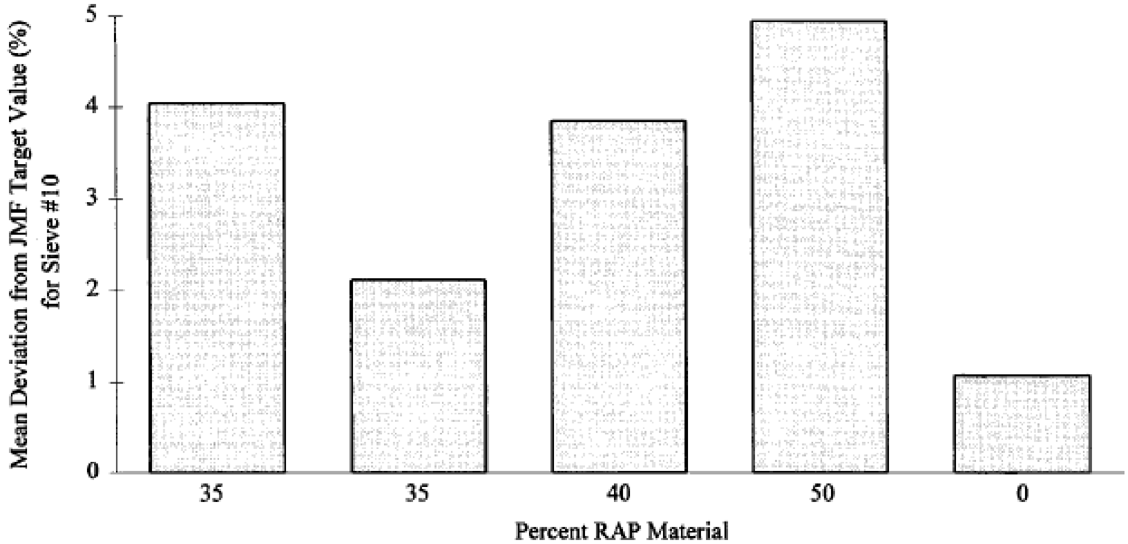

Figure 1 Mean deviations from job mix formula target gradation for sieve No. 10

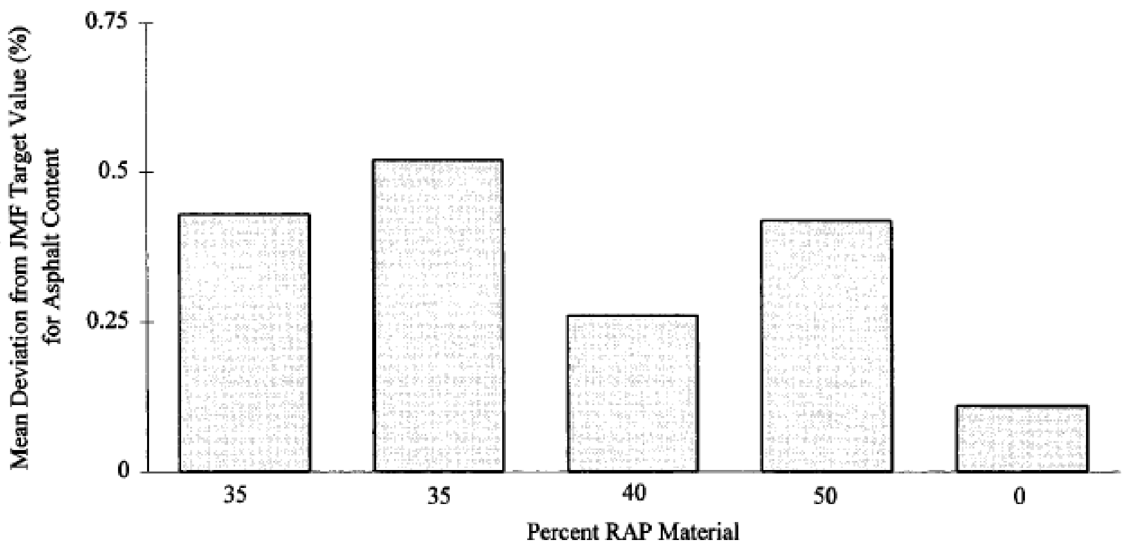

Figure 2 Mean deviations from target job mix formula asphalt content

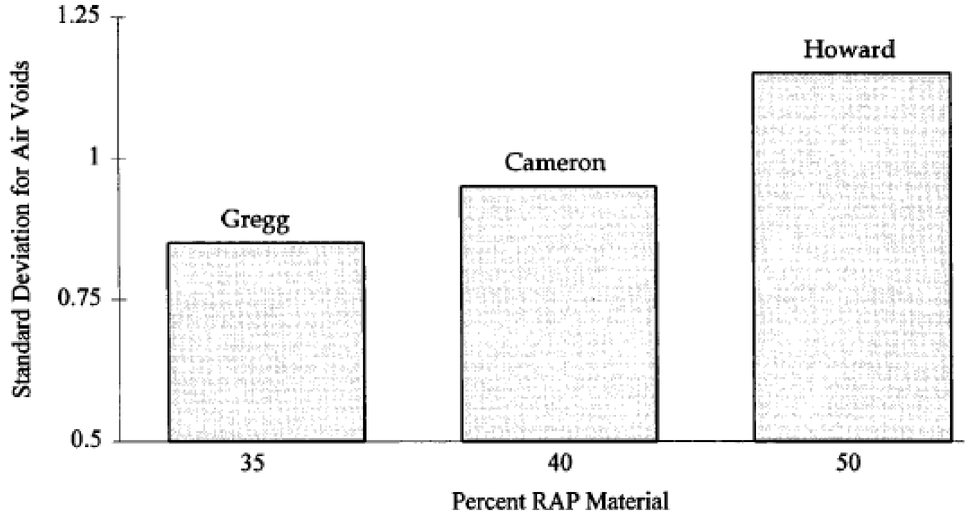

Figure 3 Standard deviations for air voids as a function of RAP content in the mix

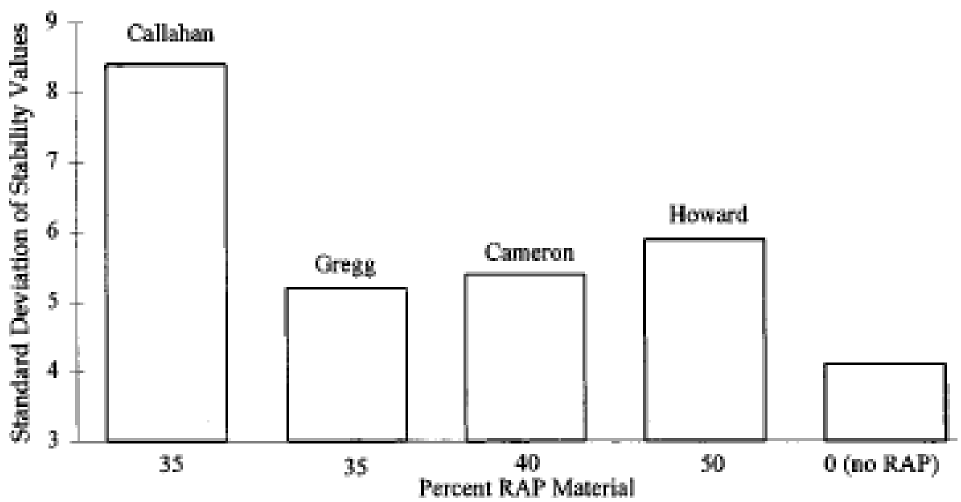

Figure 4 Standard deviations for stability values as a function of RAP content in the mix

Figures 5 and 6 show the penetration and viscosity of the binders recovered from RAP material and plant mixtures, respectively. The RAP binders were stiffer than plant mixture binders and the variation in RAP binders properties resulted in variation in plant mix binder properties.

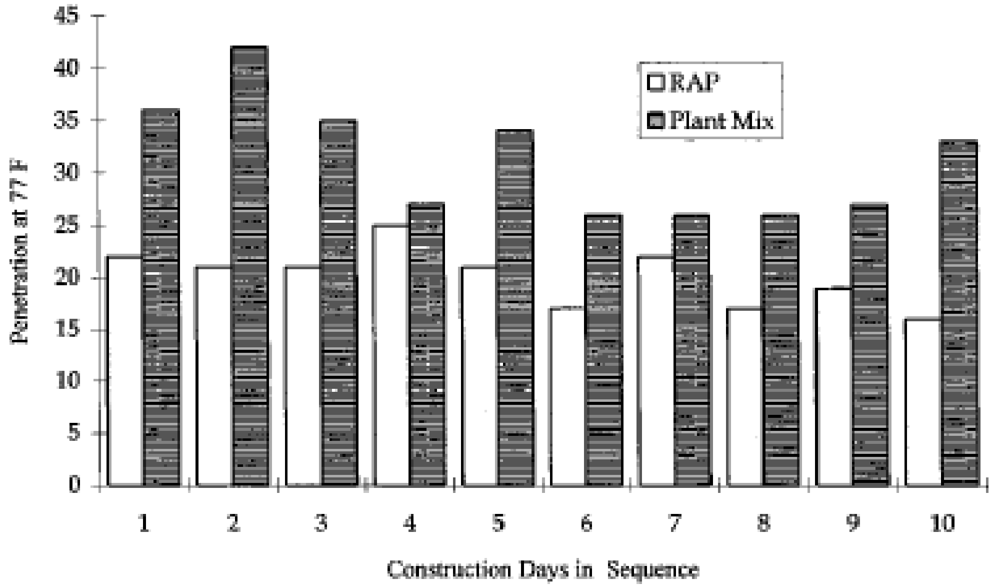

Figure 5 Sample daily penetrations

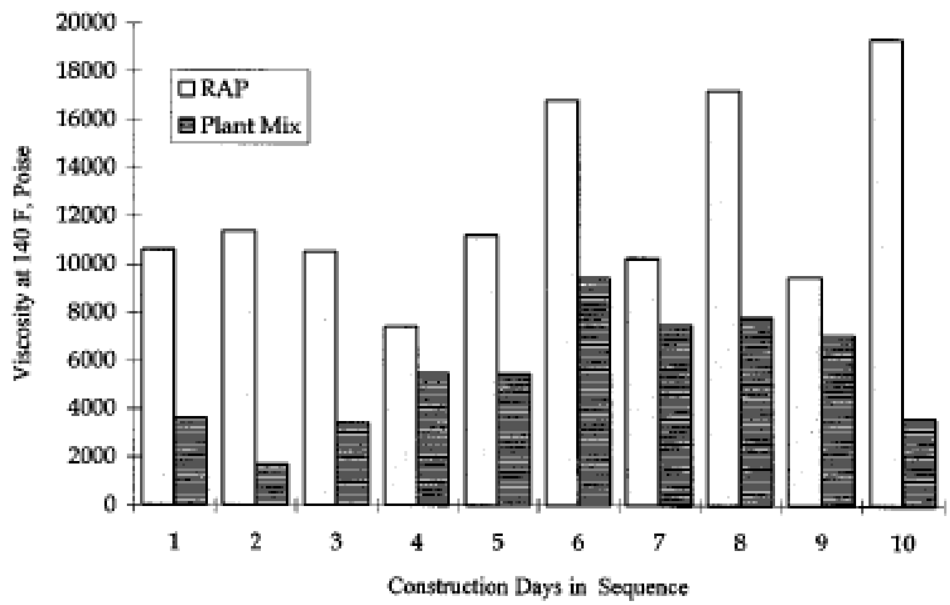

Figure 6 Sample daily viscosities

In general, these high-percentage RAP projects indicated higher variability than a typical HMA project without RAP. The gradations of plant-produced mixtures were finer than the job mix formula target gradations, possibly because of aggregate crushing during the milling operation *(30)*.

The following conclusions were made by the researchers based on the results of this study *(30)*.

- The HMA projects with a high percentage of RAP exhibited a larger variation in asphalt content, gradation, air voids, and stabilities compared with typical HMA projects without RAP material.
- The average pay factors for gradation deviations on No. 10 and No. 200 sieves are about 0.9 to 0.95, values that are considerably lower than typical average values of about 1.02 for mixes without RAP.
- The average pay factor for asphalt content material deviation is about 0.9, which is considerably lower than the typical average value of about 1.02 for mixes without RAP.
- The average pay factor for air voids is around 1.00, which is just about what is obtained for typical mixtures.
- In general, use of a high percentage of RAP material did not influence densities as much as it influenced the asphalt content and gradation.
- The projects with higher variations in the asphalt content of the RAP material also had higher variation in the asphalt content of the plant mix.
- The projects with higher variability in the properties of the RAP binder also had higher variability in the properties of the plant mix binder. The RAP binder with higher coefficient of variation in the penetration also resulted in a higher coefficient of variation in penetration of the plant mix binder.
- In general, for all projects, the production gradation was finer than the job mix formula target gradation.
- As expected, the extracted binder from the RAP material was considerably stiffer than the binder extracted from the plant mix.
- Significantly higher viscosities and lower penetrations were obtained for the binder from the RAP material than for the binder from the plant mix.

Sometimes RAP from several pavements are mixed in a single stockpile where deleterious materials or lower quality materials are also present. Mixed stockpiles may also include materials from private properties that may not have been built to the same original standards as highway or airfield projects. Consequently, a high variability may be introduced in the RAP materials that may affect the RAP properties and most likely resulting in a variable HMA mixture. Using a low quality and/or highly variable RAP materials can definitely lead to premature failure of the HMA pavement. The badly deteriorated pavement will lead to both, foreign object damage (FOD) and rough surface creating a safety hazard for aircraft traffic on taxiways and runways. Statistically based limits on the variability of the final mixture properties can encourage proper RAP processing and stockpiling by contractors to help them meet these mixture properties *(31)*. All these issues may limit the use of RAP in the various types of airport pavements (taxiways, runways, aprons, or cross roads) and require the implementation of an effective quality control program.

Good stockpile management practices should be followed to keep material variability in check. A research conducted by Nady has shown that the variability of RAP can be controlled and may not be as high as normally anticipated *(32)*. Different sources of RAP from various locations in Iowa were tested by Nady and were found to be remarkably consistent. The researcher related the consistency in the tested IDOT milled RAP and the random RAP products to three main factors:

- IDOT is the single largest consumer of construction materials and local aggregate producers must meet all IDOT requirements and specifications.
- The IDOT gradation for the nominal 12.5mm (0.5 inch) mixture is a standard which has not deviated much in the past 40 years.
- Uniformity of the RAP tested has to do with the milling methods used to process the mix.

In 1998, Estakhri et al. *(33)* conducted a study to examine the variability of RAP and its effect on the variability of HMA for the Florida Department of Transportation (FDOT) mixtures. Data were analyzed for 33 hot-mix designs, which incorporated a total of 19 different RAP stockpiles from 13 HMA contractors located throughout the state.

These data included standard deviations from the mean on Marshall stability, air voids, extracted aggregate gradation, and extracted asphalt content. In general, the researchers found that the variability of the recycled FDOT mixtures was comparable to the variabilities reported by other agencies for HMA.

Two types of statistical parameters were used in the variability analysis: coefficient of variation and chi-squared measure of spread. The performed analysis addressed the following two questions:

- Does the amount of RAP in a mix cause an increase in the variability of that mix?
- What is the variability of RAP compared to the variability of virgin aggregates? How do these variabilities compare with the variability of HMA?

The results of this analysis generally indicated the following findings. Even though there are multiple important material properties that could also be used to characterize variability, the only measure of variability that was used in the analysis was aggregate gradation. Therefore, conclusions regarding variability are based on gradation only *(33)*.

- The variability of RAP is not statistically different from that of the stockpiled virgin aggregates at the asphalt plant site.
- When looking at 75 percent of the data, RAP and virgin aggregate (based on data from quarry or pit) are not statistically different, but when including all of the data (the maximum absolute deviation), RAP is significantly more variable than virgin aggregate.
- The variability of virgin aggregate at the point of production is generally lower than that of the stockpiled virgin aggregate at the asphalt plant site.
- RAP (as analyzed under the restrictions of this study) does not show an adverse effect on the variability of HMA.

Recently, a West Coast Contractor has been working on evaluating the various properties of two RAP stockpiles from two different locations: California and Arizona.

Both RAP stockpiles consisted of mainly milling materials. The standard deviations and averages of the RAP asphalt binder content and physical properties, and the RAP aggregate gradation were determined from a number of sampled materials. Samples from 8 different locations around the perimeter of the already existing California RAP stockpile were taken. Samples from the Arizona RAP were taken during the production of the RAP stockpile. Tables 19 and 20 show preliminary results for the standard deviations (SD) and averages of the various properties of the RAP stockpiles.

Table 19 Extracted RAP Gradation and Asphalt Binder Content

SIEVE (AASHTO T30)	California RAP						Arizona RAP					
	Solvent Extraction+ (ASTM D2172 and D5404)			Ignition (CTM 382)#			Solvent Extraction+ (ASTM D2172 and D5404)			Ignition (CTM 382)#		
	No.!	Ave.	SD*	No.!	Ave.	SD*	No.!	Ave.	SD*	No.!	Ave.	SD*
1-in.	8	100.0	0.00	--	--	--	4	100.0	0.00	2	100.0	0.00
3/4-in.	8	100.0	0.00	--	--	--	4	98.8	0.50	2	98.0	0.00
1/2-in.	8	98.3	0.89	--	--	--	4	89.3	2.50	2	88.5	1.06
3/8-in.	8	91.5	2.07	--	--	--	4	77.5	1.73	2	77.0	1.41
No. 4	8	70.4	3.38	--	--	--	4	53.0	2.31	2	51.5	1.06
No. 8	8	54.3	2.82	--	--	--	4	39.0	2.31	2	37.5	1.06
No. 16	8	43.8	2.92	--	--	--	4	29.0	1.83	2	27.5	1.06
No. 30	8	34.6	3.11	--	--	--	4	21.8	1.26	2	20.0	0.71
No. 50	8	24.0	1.85	--	--	--	4	14.0	1.15	2	13.0	0.71
No. 100	8	16.1	1.46	--	--	--	4	9.3	0.96	2	8.5	0.35
No. 200	8	11.1	1.15	--	--	--	4	6.8	0.90	2	5.6	0.39
AC Content, % DWA$	8	3.52	0.31	3	5.30	0.31	4	4.04	0.22	2	4.66	0.19

+ Reflux extraction method using 85% Toluene + 15% Alcohol. Rotary evaporator method for recovery.
# California Test Method 382: "Determination of Asphalt Content of Bituminous Mixtures by the Ignition Method."
! Number of samples tested.
* Denotes Standard Deviation.
$ Denotes Dry Weight of Aggregates.

The following conclusions can be made when the data in Table 19 are compared to both, the average standard deviations reported by Granley *(28)* on the variations in typical HMA surface mixture during HMA production of 26 different projects, and the standard deviations reported by Burati and Willenbrock on the variation in HMA surface mixtures on civil airport pavements *(29)*.

- California RAP:
    - The percent passing No. 8 sieve of the extracted RAP aggregates using the reflux had an SD of 2.82 and was equal to the SD of 2.81 reported by Granley for a typical HMA surface mixture.
    - The percent passing No. 200 sieve of the extracted RAP aggregates using the reflux had an SD of 1.15 and was higher than the SD of 0.94 and 1.0 reported by Granley and Burati, respectively, for HMA surface mixtures.
    - The RAP asphalt binder content from both the reflux and ignition methods had an SD of 0.31 and were higher than the SD of 0.28 and 0.23 reported by Granley and Burati, respectively, for HMA surface mixtures.

- Arizona RAP:
    - The percent passing No. 8 sieve of the extracted RAP aggregates using the reflux and ignition methods had an SD of 2.31 and 1.06, respectively, and were lower than the SD of 2.81 reported by Granley for a typical HMA surface mixture.
    - The percent passing No. 200 sieve of the extracted RAP aggregates using the reflux and ignition methods had an SD of 0.90 and 0.39, respectively, and were lower than the SD of 0.94 and 1.0 reported by Granley and Burati, respectively, for HMA surface mixtures.
    - The RAP asphalt binder content from both the reflux extraction and ignition methods had an SD of 0.22 and 0.19, respectively, and were lower than the SD of 0.28 and 0.23 reported by Granley and Burati, respectively, for HMA surface mixtures.

It should be noted that the asphalt binder content for the California RAP measured using the reflux extraction was on average lower than the one measured by the ignition method by 1.78%. This difference in binder content might be attributed to a breakdown in the aggregate particles caused by the ignition oven which can lead to erroneous estimates of the binder content.

By comparing the RAP standard deviations to the standard deviations of typical HMA surface during HMA production, the data reveals that the California RAP source have in general equivalent variability in composition to the HMA surface mixtures during production, whereas the Arizona RAP source have lower variability in composition than the HMA surface mixes during production. However attention should be made to the test methods used for extracting the aggregates. In general, a higher variability in gradation and asphalt binder content was found with the reflux extraction when compared to the ignition method.

Table 20 Extracted RAP Binder Physical Properties

Property	Test Method	Test Temp, °C	California RAP			Arizona RAP		
			No.	Ave.	SD*	No.	Ave.	SD*
Absolute Viscosity, Poises	ASTM D2171	60	2	1,020,651	279,868	2	279,224	4,885
DSR, G*/sinδ, kPa	AASHTO T315	60	8	436.0	143.94	4	158.6	25.56
		64	8	216.9	73.73	4	88.2	17.25
		70	8	78.9	27.82	4	35.2	6.08
		76	8	29.3	9.97	4	14.4	2.26
		82	8	11.7	3.95	4	6.3	0.86
		88	8	5.0	1.68	4	2.8	0.41
		Critical Temp	8	93.3	2.6	4	89.9	1.10
BBR, Stiffness, MPa	AASHTO T313	6	2	258.0	50.9	--	--	--
		0	2	471.0	7.1	2	98.5	0.7
		-6	--	--	--	2	174.0	1.4
BBR, m-value	AASHTO T313	6	2	0.316	0.0212	--	--	--
		0	2	0.258	0.0014	2	0.318	0.0014
		-6	--	--	--	2	0.243	0.0014
BBR Critical Temp	AASHTO T313	Critical Temp	2	4.7	1.8	2	-1.5	0.1

* Denotes Standard Deviation.

The DSR test results presented in Table 20 was conducted on the original recovered asphalt binder (i.e., no aging). The DSR data indicate that the properties of the recycled asphalt binder vary by source and within a stockpile of RAP. The magnitude of the variability is likely the result of the following:

- Original stiffness of the asphalt binder.
- Source of the original asphalt binder.
- Age of recycled pavement.
- Consistency of pavement millings.
- Local climatic conditions.
- In-place volumetric properties of the pavement.

The recovered asphalt binder was aged in the PAV at 110°C and the residual asphalt binder was tested in the Bending Beam Rheometer (BBR). The BBR data in Table 20 indicate that the low temperature stiffness of the recovered asphalt binders from the two sources are different. The variability of the stiffness was greater with the California RAP source as compared to the Arizona RAP. The m-value variability for each source was similar.

Based on the testing performed, the California RAP asphalt binder would straight (Superpave) grade out as a PG 93-5 (PG 88-4) and the Arizona as a PG 89-11 (PG 88-10).

The same West Coast contractor is continuing to evaluate the variability of RAP (asphalt binder and gradation) at a number of other locations.

Currently, the on-going NCHRP 9-33 "*A Mix Design Manual for Hot Mix Asphalt*" research project proposes a method for estimating feasible RAP contents for a mixture based on the variability of the RAP and the desired production variability. The amount of RAP that can be added without exceeding an agency's specification limits depends on the specification limits, the variability of the RAP, the variability of similar mixtures produced without RAP, and the consistency of the equipment adding the RAP.

The following summarizes the preliminary results of the proposed method by the on-going NCHRP 9-33 project. It should be noted that readers should refer to the final NCHRP 9-33 report for the correct and final details. The proposed method requires first the determination of the standard deviations and averages of the various properties of the RAP stockpiles to be used in the HMA production (i.e., RAP binder content, aggregate gradation). Each RAP stockpile should be sampled at 8 to 10 locations distributed throughout the pile. At each sampling location, a total of 22 lb of RAP for each mix design that will be prepared as well as 11 lb for the characterization of the RAP needs to be obtained. For example, if two mixtures, a base and a surface mix are to be designed using the same RAP, then obtain 55 lb of RAP at each sampling location. The 11 lb sub-sample is used to determine the average and variability of the binder content and aggregate gradation in the RAP in the stockpile. Either ignition oven or solvent recovery method can be used. If ignition oven is to be used there should be local experience on the ignition oven procedure and correction factors should be established. Once the binder content and aggregate gradations are determined for all the samples the average and the standard deviations of each property can be determined using the following equations.

$$\overline{X} = \sum_{i=1}^{n} \frac{X_i}{n} \qquad \text{(Equation 3)}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$ (Equation 4)

where, $\overline{X}$ = stockpile average
X_i = result of location *i*
n = total number of locations tested
s = standard deviation

The RAP properties average values are used to determine the required virgin aggregate percentages from each stockpile to get the required blend gradation of the final HMA mix. Then the values of the percent passing through each sieve and the binder content are calculated considering as if the mixture is produced only from virgin materials of same proportions determined in the previous step. The typical standard deviations of the various properties of the virgin mixtures are obtained from local experiences. From these values the standard deviations of various properties of the HMA mixtures with RAP can be calculated using the Equation 5.

$$\sigma_m = \sqrt{\alpha^2 \sigma_R{}^2 + (1-\alpha)^2 \sigma_V^2 + (\overline{X_V} - \overline{X_R})^2 \sigma_\alpha^2}$$ (Equation 5)

where, σ_m = standard deviation of final mixture
$\overline{X_V}$ = average of virgin mix (properties calculated as if only virgin material used)
$\overline{X_R}$ = average of RAP stockpile
σ_V = standard deviation of virgin mixture
σ_R = standard deviation of RAP stockpile
α = percent RAP included in RAP
σ_α = standard deviation of RAP proportion in total mix (error due to proportioning equipment)

When the RAP stockpile is fractionated into different sizes, each size stockpile average and standard deviations should be determined and used in the calculation of the standard deviations of various properties of the HMA mixtures with RAP. In summary, first the standard deviation due to inclusion of the first size stockpile is determined. Then, this value is used in place of virgin mixture standard deviation to calculate the standard deviation due to the inclusion of the second stockpile. Likewise the standard deviation of the final mixture can be calculated due to the inclusion of all stockpiles.

This method helps to find the standard deviations of various properties of the final HMA mixture containing RAP. Comparing these standard deviations with the allowable standard deviations specified by the agencies will help to decide whether the produced mixture would satisfy the specifications or not. This method will help the HMA producers to adjust the RAP content or to reduce the RAP variability to satisfy the specifications set by the agencies.

Processing the RAP by crushing or screening, or both, can also help to reduce the variability in RAP material. The National Asphalt Pavement Association (NAPA) has an excellent publication entitled Recycling Hot Mix Asphalt Pavements *(5)* that discusses processing and handling RAP at the plant and during construction. This publication provides a new and updated document on how to recycle and it summarizes for producers and agencies the equipment and methods that others are successfully using to reclaim, size, store, and process RAP in various types of HMA facilities throughout the country. The following summarizes some of the key elements of RAP processing and storing. For further details and more information check the referred NAPA publication *(5)*.

RAP Processing and Storing *(5)*

The millings from a single source have typically consistent quality, gradation and composition (i.e., aggregate gradation and properties, and asphalt content and characteristics). Practically, all facilities use the RAP materials below 2 inches in size without further processing. However, the use of high percentages of RAP may necessitate crushing and screening of the RAP into separate stockpiles of large and small fractions such as 1” x ½”, ½” x ¼”, and less than ¼”. Fractionating the RAP will permit a greater control in producing mixes to meet volumetric properties.

Scalping screens are often installed between the RAP cold feed bin and the transfer belt conveyor in the HMA facility since RAP may pack together in stockpiles creating larger particles. Many producers use a “RAP breaker” or “lump breaker” which resembles a small crusher, positioned between the bin and the belt.

Full-depth RAP, or RAP that arrives at the facility in large sizes, must be crushed prior to recycling into a new pavement. The most used types of crushers and crushing configurations by most contractors are:

- Horizontal impact crushers: typically used as both the primary and as a secondary crusher by re-circulating the oversize material back through the crusher.
- Jaw/roll combination: proven effective for downsizing slabs of RAP material. In both the jaw and roll crushers, especially on warm humid days, the RAP can stick together or agglomerate forming a flat, dense mass of RAP material between the crusher surfaces. This can slow production, as the crusher must be stopped and cleaned, however this does not affect the quality of the processed RAP material.

Field experience has shown that careful blending and crushing operations will result in a remarkably consistent RAP product (aggregate gradation and asphalt content and characteristics). The production of a homogenous RAP product from a composite pile requires first to blend the RAP thoroughly with a front-end loader or bulldozer and then to down-size the top stone size in the RAP in the crushing operation to one size smaller than the top size in the HMA being produced (e.g., 5/8 inch for a ¾ inch top-size mix). This will ensure that the asphalt-aggregate bond in the RAP material is broken as much as possible and no oversize stone appears in the mix.

RAP Stockpiling *(5)*

Experience has proven that large, conical RAP stockpiles are preferred. Practical experience has shown that RAP does not have a tendency to recompact in large piles. Additionally, since RAP has a tendency to hold water and not drain over time like an aggregate stockpile, low, horizontal, and flat stockpiles are subject to greater moisture accumulation than tall, conical stockpiles. Consequently, covering RAP stockpiles is even more economical than covering virgin aggregate stockpiles. However, RAP should never be covered with a tarp or plastic especially in humid climates as covering causes condensation under the tarp. Therefore, most RAP stockpiles are either left uncovered, or RAP is stored under the roof of an open sided building.

Many producers pave under the RAP stockpiles hoping that this contributes to both drainage from the RAP pile and reduces possible moisture absorption from the ground. An added benefit to paving is that possible contamination is eliminated as the front-end loader collects material close to the grade on which the stockpile is resting.

RAP Fractionating *(5)*

Crushing and screening the RAP into different sizes may be necessary to maximize the percentage of RAP used in a mix and still meet the gradation and volumetric requirements. Fractionating the RAP into different sizes such as 1” x ½”, ½” x ¼”, and less than ¼” will result a better control over the gradation, asphalt content, and volumetric properties of the produced mix. Whether the recycled materials are all from the same project or different projects, constructing separate coarse and fine RAP stockpiles will minimize segregation of RAP particles, and allow greater flexibility in adjusting RAP content for the final aggregate gradation. Table 21 shows the typical gradations from a contractor who produces mixes with up to 50 percent RAP by fractionating their RAP into two stockpiles.

Table 21 Fine and Coarse RAP Stockpile Gradations

Screen Size	**3/4”**	**1/2”**	**3/8”**	**#4**	**#8**	**#30**	**#100**	**#200**	**%AC**
Fine RAP Stockpile									
Average % passing	100	100	99.4	91.9	76.8	50.0	18.2	10.1	5.76
Standard Deviation	0.0	0.0	0.8	2.1	3.1	3.2	1.7	1.0	0.4
Coarse RAP Stockpile									
Average % passing	100	92.7	70.2	27.2	19.6	13.8	7.8	5.6	4.20
Standard Deviation	0.0	3.4	5.0	2.1	1.8	2.6	1.8	1.4	0.2

HIGHWAY AGENCIES SPECIFICATIONS

A large number of highway agencies allow RAP in HMA pavements. Several agencies have their own specifications on RAP usage in HMA mixtures. Table A.35 in *Appendix A* summarizes the various highway agencies specifications for the use of RAP materials in HMA mixtures along with the mix design method used *(34, 35)*. Additionally, Figures A.19 through A.24 in *Appendix A* show the responses from a survey conducted by the North Carolina Department of Transportation for the specified and average use of RAP in 38 different U.S. states. Based on the review of the data presented in *Appendix A*, the following observations can be made.

- Most highway agencies allowed the use of RAP in HMA Mixes.
- Most specifications limit practical use of higher percentages of RAP in HMA mixes.
- Most highway agencies specifications change with the mix type (i.e., dense graded mix, SMA, open graded mix…) and production method (batch plant versus drum mix plant).
- Most highway agencies allow maximum 10-25% of RAP in surface mixes and a higher percentage of RAP in base mixes. However, some agencies restrict the use of RAP in the surface course for pavements with high applied number of equivalent single axle load (ESAL).
- Some highway agencies require the sources of the RAP materials to be approved prior to their usage in the HMA mix.
- Some highway agencies specify maximum size for the RAP material that is greater than the maximum size of the regular HMA mix.
- Some highway agencies restrict or limit the use of RAP to 10% with polymer modified HMA mixtures.
- Most highway agencies require an adjustment to the binder grade when more than 15-20% RAP is used.
- RAP is used with Marshall, Hveem, and Superpave mix design methods.

Since moisture damage and durability of RAP mixtures has been a concern for highway agencies, a review of the State DOTs specifications for moisture sensitivity and durability tests was conducted. It was found that no particular test or specification for moisture resistance other than what is specified for regular HMA mixtures is implemented for mixtures with RAP. The state DOTs specifications for moisture resistance and other laboratory performances tests for HMA mixtures were reviewed and are summarized in Table 22.

Table 22 shows that the AASHTO T283 test is the most widely adopted test for evaluating HMA mixtures resistance to moisture damage. The minimum required tensile strength ratio (TSR) varied among the state agencies and ranged from 70 to 85%. Some highway agencies required in addition to the minimum TSR, a minimum value for the unconditioned tensile strength (TS).

Additionally, Table 22 shows the asphalt pavement analyzer and the Hamburg wheel tests as the most commonly used tests by some state highway agencies for determining rutting resistance of HMA mixtures. The criteria for both tests varied with the traffic level.

Table 22 Summary of States Specifications for Moisture Sensitivity.

State	Moisture Sensitivity Requirement	Other Required Mixture Test
Alabama	80% TSR (AASHTO T283)	NA
Alaska	NA	NA
Arizona	--	--
Arkansas	80% TSR (AASHTO T283)	NA
California	Min Hveem stability of 30 for mix A and 25 for Mix B after moisture vapor susceptibility (Cal Test 307)	
Colorado	70% TSR, CP L-5109 Method B	NA
Connecticut	NA	NA
Delaware	80% TSR (AASHTO T283)	NA
Florida	80% TSR (AASHTO T283) Minimum unconditioned tensile strength of 100psi	
Georgia	80% TSR Min uncond. strength of 60 psi at 55°F (GCT 66) (A tensile splitting ratio >70% may be acceptable so long as all individual test values >100 psi (690 kPa).	rutting on APA after 8000 cycles (49°C) of max 7, 6 & 5mm for level A, level B, level C&D mix designs respectively (GD115)
Hawaii	NA	NA
Idaho	85% Immersion - Compression (AASHTO T 165)	NA
Illinois	75% TSR for 4 inch and 85% TSR for 6 inch (AASHTO T283)	NA
Indiana	80% TSR (AASHTO T283)	NA
Iowa	80% TSR (AASHTO T283)	NA
Kansas	80% TSR (AASHTO T283)	NA
Kentucky	80% TSR according to ASTM D4867 using 150mm samples with 65±5 % saturation	NA
Louisiana	80% TSR for modified asphalt and 75% for unmodified asphalt (AASHTO T283)	NA
Maine	NA	NA
Maryland	85% TSR according to ASTM D4867	NA
Massachusetts	--	--
Michigan	80% TSR (AASHTO T283)	NA
Minnesota	75% TSR (AASHTO T283)	NA
Mississippi	85% TSR - MT-63	NA
Missouri	80% TSR (AASHTO T283)	NA
Montana	--	--
Nebraska	80% TSR (AASHTO T283)	NA

Table 22 Summary of States Specifications for Moisture Sensitivity (cont'd).

State	Moisture Sensitivity Requirement	Other Required Mixture Test
Nevada	70% TSR at 77°F Unconditioned tensile strength min 65psi for PG64-28 NV binder and 100 psi for PG76-22NV binder	Max of 8 mm rut depth after 8,000 cycles at 60°C in APA
New Hampshire	80% TSR (AASHTO T283)	NA
New Jersey	NA	NA
New Mexico	85% Minimum retained strength according to AASHTO 165	NA
New York	80% TSR (AASHTO T283)	NA
North Carolina	85% TSR (AASHTO T283)	Max. rut depth of 11.5 to 4.5 mm respectively for 0.3 to 30 million ESALs at 60°C after 8,000 cycles in APA
North Dakota	NA	NA
Ohio	80% TSR (AASHTO T283)	NA
Oklahoma	Permeability should be less than 12.5×10-5 cm/s	Max of 3-8 mm rut depth depending on traffic level at 64°C after 8,000 cycles in APA
Oregon	80% TSR (AASHTO T283)	Max of 4-6 mm rut depth depending on traffic level at 64°C after 8,000 cycles in APA
Pennsylvania	80% TSR (AASHTO T283)	NA
Rhode Island	NA	NA
South Carolina	80% TSR (SC-T-70) with 60 psi minimum wet strength	Max rut depth of 3mm for Type A and 5 mm for Type B and Type CM at 64°C after 8000 cycles in APA
South Dakota	NA	NA
Tennessee	TSR of 80% and a minimum tensile strength of 100 psi for polymer modified binder and 80psi for non polymer binder	Max. of 0.35 and 0.40 inch rut depths for 10,000 & 5,000 ADT respectively at 147°F after 8,000 cycles in APA
Texas	NA	Max. rut depth of 12.5 mm at 50°C after 20,000, 15,000, and 10,000 cycles respectively for PG76-xx, PG70-xx, PG64-xx under Hamburg wheel test
Utah	--	Max. rut depth of 10 mm after 20,000 cycles in Hamburg wheel test
Vermont	80% TSR (AASHTO T283)	NA
Virginia	80% TSR (AASHTO T283)	Max. rut depth of 3.5, 5.0, and 7.0 mm respectively for more than 10, 3-10, 0-3 million ESALs at 49°C after 8,000 cycles in APA
Washington	NA	NA
West Virginia	NA	NA
Wisconsin	75% TSR (ASTM D4867)	NA
Wyoming	75% TSR (ASTM D4867)	NA

CHAPTER 4 REVIEW OF IN-SERVICE AIRFIELD PAVEMENTS

Three civilian airports and one military airport were identified as using HMA pavements with RAP. The four airports are Logan International Airport (BOS), Griffin-Spalding County Airport (6A2), Pekin Municipal Airport (C15), and Oceana Naval Air Station (NTU). Three of those airports (BOS, 6A2, NTU) had RAP in the HMA surface course. The C15 airport had a base course with a 100% RAP material. This chapter only presents information on the performance of pavements containing RAP at the four airports. More detailed information can be found in *Appendix B* of this report.

BOSTON-LOGAN INTERNATIONAL AIRPORT, BOSTON, MASSACHUSETTS

Boston-Logan International Airport (BOS) is located 3 miles east of Boston, Massachusetts, and is publicly owned by the Massachusetts Port Authority (Massport). As of October of 2006, Logan Airport has an average of 1120 flights per day, or about 409,000 flights per year, among which 60% are commercial aviation, 32% are air taxi aviation, and 8% are transient general aviation.

The airport is located in the FAA New England Region. The airport has an elevation of 20 feet above sea level. According to the LTPPBind Software the average yearly highest and lowest air temperatures for the airport are 90 and 1°F, respectively. For the airport location, the LTPPBind Software calls for a PG64-28 asphalt binder grade for less than 10 million ESALs application and 98% reliability.

At Logan Airport, the runways, taxiways, and terminal area taxilanes (referred to as alleyways) are constructed of HMA pavements supplemented with portland cement concrete aprons for aircraft parking at the terminal. The pavements at Logan must support loads up to 873,000 lb for Boeing 747 at the maximum takeoff weight. Tire pressures can be in excess of 200 psi and the traffic is highly channelized.

In 2001, Aggregate Industries of Saugus, MA, developed an HMA mix containing RAP for repairs on Taxiway November to combat rutting and stripping. A 1,000 feet section was inlaid with 4" of the RAP containing mix. This portion of Taxiway November handles l00,000 operations annually (14,000 equivalent A330 operations), particularly for hot weather departures from Runways 22R and 22L *(36)*. The original RAP mix used 1" maximum aggregate size gradation, PG64-28 binder, 18% RAP, 4% latex, and 0.5% liquid antistrip and is still performing well today.

This RAP containing mix was used for repairs only from 2001 to 2003. Based on its success for local repairs, the same 15-20% RAP containing mix became Logan's "everyday" mix in 2004 to the present. The current RAP containing mix uses a 0.75" maximum aggregate size gradation, PG64-28 binder, 4% latex, and 1% lime for antistripping and is performing well. Accelerated loading tests in the laboratory for rutting and moisture induced damage have confirmed that this mix is equivalent to a virgin HMA with a PG76-28 binder. The Massport P-401 specification requires the RAP to be of a consistent gradation and do not allow the use of RAP obtained from the project site.

In 2000, the overall condition of the northern portion of the Runway 4R-22L at Logan Airport was good to very good with PCI values between 64 and 81. The runway had mostly longitudinal, transverse cracking, raveling and weathering distresses. On average, the runway had around 60% of materials related distresses and 25% of load related distresses. The PCI values for 2006 were estimated between 47 and 72. Following this evaluation in 2006, the center 75 feet of the northern portion of the Runway 4R-22L was reconstructed according to the new specifications. The last time any major pavement rehabilitation work was performed on the runway was in 1990, when a 5 inch AC20 P-401 overlay with a stress membrane was constructed. Routine crack sealing has been performed on the pavement.

The reconstruction consisted of milling down 12 inches from the center 75 feet of the runway and then placing 12 inches of new pavement. The HMA mix consisted of a 0.75 inch maximum size, 18.5% RAP with a PG64-28 binder modified with 4% latex and 1% lime. No specific problems related to the use of RAP were encountered during construction. The majority of the pavement sections met the in-place density specification.

On September 18, 2007 Dr. Hajj, a member of the UNR research team visited the Logan Airport and conducted a windshield visual inspection of the Runway 4R-22L. It was determined that the runway is in excellent condition with no visible rutting observed. Figure 7 shows the center 75 feet of the runway along with the existing crack-sealed HMA old pavement on both sides of the center part. No signs or potential of foreign object damage (FOD) was observed because of the use of RAP in the mix.

Figure 7 Runway 4R-22L at Logan International Airport (taken on 09-18-07)

GRIFFIN-SPALDING COUNTY AIRPORT, GRIFFIN, GEORGIA

The Griffin-Spalding County Airport (6A2) is located in Griffin approximately 40 miles southwest of Atlanta, Georgia. The Griffin-Spalding Airport is open to public use and is jointly owned by the City of Griffin and Spalding County, GA. As of March 2006, the Griffin-Spalding Airport has an average of 55 flights per day, or about 20,000 flights per year, among which half of them are transient general aviation and the rest are local general aviation.

The airport is located in the FAA Southern Region. The airport has an elevation of 958 feet above sea level. According to the LTPPBind Software the average yearly highest and lowest air temperatures for the airport are 94 and 9°F, respectively.

The Runway 14-32 and the Taxiway A at the Griffin-Spalding Airport were rehabilitated in 1999 and 2000, respectively. Runway 14-32 is 75 feet wide by 3701 feet long and has a weight bearing capacity of 26,000 lbs for single wheel aircraft and 30,000 lbs for double wheel aircrafts.

In 1999, a Superpave mix design was conducted using 17% of recycled material from highway pavements in Georgia and a typical PG67-22 asphalt binder for the Griffin area. The RAP material was tested for gradation and binder content (4.5% by total weight of mix). The Georgia department of transportation (GDOT) requires that the blend of the virgin asphalt binder with the recovered RAP binder after aging in the thin film oven test meets a viscosity of 6,000 to 16,000 poises (600 to 1600 Pa). The mix was treated with 0.9% hydrated lime by total weight of aggregates (virgin + RAP aggregates). The mix had an optimum binder content of 4.8% by total weight of mix and exhibited a dry tensile strength (TS) of 123 psi at 55°F and a tensile strength ratio (TSR) of 82.6%. The mix met the minimum TS of 60 psi and TSR of 80% required by GDOT. This mix was used to rehabilitate the Runway 14-32 in 1999 and the Taxiway A in 2000.

During construction the typical GDOT requirements for regular HMA mixtures were followed and no specific problems due to the use of RAP were reported. Some pavement sections failed to meet the in-place density specifications imposed by FAA.

In 2001, one year after rehabilitation, the airport Taxiway A was in very good condition with isolated distresses and a calculated PCI value of 97 *(37)*. The distresses include unsealed, low-severity longitudinal and transverse (L&T) cracks, oil spillage, and a low-severity patch.

Two years after rehabilitation (2001), the Runway 14-32 was in very good condition with very little distress and a calculated PCI value of 98. The only distress type noted on the runway was low-severity patching in several areas along the length. The patched areas were relatively large and scattered along the length of the runway. It should be noted that in 1998 (i.e., one year before rehabilitation) the runway had a PCI value of about 70.

Both, the runway and the taxiway did not show any type of load related distresses that are attributed to a structural deficiency in the pavement such as fatigue cracking and rutting. However the distresses that were observed were more of climate or durability type of distresses.

On September 17, 2007 the Griffin-Spalding County airport was visited by Dr. Hajj and visual inspections of the Runway 14-32 and the taxiway A were performed. Overall, it was determined that the runway exhibits moderate cracking at the longitudinal construction joints and moderate transverse cracking over the entire runway (Figure 8). The transverse cracks were approximately 20 to 30 feet apart and did not extend across the entire runway width. Additionally, moderate raveling was observed especially along the longitudinal joints. However, no visible rutting was observed.

Figure 8 Transverse cracking along Runway 14-32 at Griffin-Spalding Airport

On the other hand, Taxiway A overall is exhibiting low severity transverse cracking that are 20 to 30 feet apart (Figure 9). The transverse cracks did not extend across the entire taxiway width. Additionally, low raveling was observed especially along the longitudinal joints. However, no visible rutting was observed.

No signs or potential of foreign object damage (FOD) was observed at both the Runaway 14-32 and Taxiway A because of the use of RAP in the mix.

Figure 9 Transverse cracking along Taxiway A at Griffin-Spalding Airport

PEKIN MUNICIPAL AIRPORT, PEKIN, ILLINOIS

The Pekin Municipal Airport (C15) is located approximately 15 miles south of Peoria, Illinois. The Pekin Municipal Airport is open to public use and owned by the City of Pekin, IL. As of December 2006, the Pekin Municipal Airport has an average of 25 flights per day, or about 10,000 flights per year, among which 44% are transient general aviation, 33% local general aviation, and 22% are air taxi aviation.

The airport is located in the FAA Great Lakes Region. The airport has an elevation of 530 feet above sea level. According to the LTPPBind Software the average yearly highest and lowest air temperatures for the airport are 92 and -13°F, respectively.

The only Runway 9-27 at the Pekin Municipal Airport is 75 feet wide and 5000 feet long and has a weight bearing capacity of 15,000 lbs for single wheel aircraft. The runway consists of three sections. The first pavement section was constructed in 1963 and had a PCI of 59 in August 1999. The second pavement section was constructed in 1967 and had a PCI of 58 in August 1999. The third pavement section was constructed in 1988 as part of the runway extension and had a PCI of 53 in August 1999.

In September of 2000, a crack survey was performed to determine the extent and severity of the cracking. The total length of the east portion of the runway is 3,775 feet with a total of 107 cracks with about one crack every 36 feet. There was a total of 49 high and medium severity full width cracks or one full width crack every 77 feet. Additionally, there was a total of 31 high severity full width cracks or one high severity crack every 122 feet. It was also noted that the severity of the crack was worse in the outside edges of the runway, where moisture accumulates. The excessive moisture also helped in leaching of the cement from the soil cement base course.

In 2002, the HMA pavement at the runway was reconstructed by milling off the entire existing HMA surface, pulverizing and re-compacting the existing cement treated base (CTB) course, placing and compacting 4-inch of the RAP millings, and then overlaying with a 6 inch of new HMA. The 100% RAP layer was used as an interlayer and a base course between the pulverized CTB course and the new HMA overlay. The RAP millings were crushed and sieved during the design process.

During construction, the contractor was concerned that his current equipment would not be supported by the pulverized cement treated base course. After pulverization this was not an issue. At one location (about 100 feet long) the pulverized soil cement was very unstable and was replaced with the RAP millings. The RAP millings fulfilled the Pekin Municipal Airport special provision Item AR800237 for bituminous milling base course.

On August 28, 2007 Dr, Hajj visited the Pekin Municipal Airport and conducted a visual inspection of the Runway 9-27. Overall, it was determined that the runway is in good condition with low severity transverse cracking over the entire runway (Figure 10a). Low to moderate severity cracks on the longitudinal construction joints were observed (Figure 10b). No visible rutting was observed.

(a) (b)

Figure 10 a) Transverse cracking along runway 9-27 at Pekin Municipal Airport
b) Longitudinal construction joint along runway 9-27 at Pekin Municipal Airport

There have been no maintenance activities since construction (i.e., 5 years ago). In summer of 2003 the runway had a PCI value of 100 with no distresses observed on the pavement surface. In summer of 2007, the runway had a PCI value of 89 with longitudinal and transverse cracking observed. The present condition of the eastern 3,800 feet of Runway 9-27 is mainly due to the cracks at the longitudinal construction joints whereas the cracking in the old pavement was mainly related to cracking in the cement treated base (prior reconstruction, in 1988).

Figure 11 shows the excess RAP millings at the job site. The City of Pekin used some of the excess RAP millings to pave alleyways in the city and the rest was sold out to the local Township Highway Department. The Township Highway Department used the RAP millings on low volume roads, such as alleyways, as a low cost surfacing.

Figure 11 Excess RAP millings at Pekin Municipal Airport

OCEANA NAVAL AIR STATION, VIRGINIA BEACH, VIRGINIA

The Oceana Naval Air Station (NTU), owned and managed by the U.S. Navy, is located in Virginia Beach, Virginia. The airport is located in the FAA Eastern Region.

The airport has an elevation of 23 feet above sea level with respectively average yearly highest and lowest air temperatures of 92 and 6°F according to the LTPPBind Software.

The HMA pavement at the Taxiway Alpha has been resurfaced approximately every 8 to 10 years. The last resurfacing job was in 2000 where the middle 32 feet of the taxiway were milled and replaced with a 2.5-inch Navy airfield mix (almost identical to a P-401 HMA surface course) containing 20% RAP. The RAP containing mix consisted of a 1.0 inch maximum aggregate size with a PG70-22 asphalt binder.

The pavement's daily traffic is equivalent to approximately 200 repetitions of tactical aircraft (F-14 and F-18) and 1 repetition of cargo (C-141 or C-17) aircraft. The tactical aircraft have single tricycle gear geometry with a tire pressure of 240 psi. The C-141 has a dual tandem tricycle gear with a tire pressure of 120 psi.

Before reconstruction in 2000, the pavement consisted of an HMA overlay on top of a PCC pavement with fabric between the PCC and the HMA layer. The pavement exhibited rutting in the wheelpaths at approximate distances of 8 to 14 feet left and right of the centerline. The rutting was generally described as being up to 1.0" over the 6 feet wide travel path of the wheel gear. Other major distresses in the pavement were reflective cracking from the underlying Portland cement concrete pavement. The majority of the cracks exceeding 1/4" width had been sealed as a part of routine maintenance.

In September 2007, Darrell G. Bryan of the Naval Facilities Engineering Command, Atlantic was contacted for the current condition of the HMA pavement with 20% RAP. According to Darrell, after 7 years in-service, the mix at Taxiway Alpha is again exhibiting rutting in the wheel paths (from 0.25 to 0.75 inch depth) and minor reflective cracking from the underlying PCC pavement. He associated the rutting to the constant aircraft traffic with high tire pressures and the asphalt binder grade used, and not specifically to the use of RAP in the mix. No difficulties or issues were encountered during design or construction because of the use of RAP in the HMA mix. Additionally, no signs or potential of foreign object damage (FOD) was observed at the locations where HMA mixtures with RAP were used. During construction, the RAP materials were sampled every 500 tons and tested for aggregate gradation and asphalt binder content.

In general, over the last 10 years, HMA mixtures containing 20-25% RAP have performed well for the Navy in the Mid-Atlantic and Northeast United States, except possibly for taxiway and runway pavements subjected to constant traffic having relatively high tire pressures (according to D. G. Bryan). However, the current Navy policy is to not allow the use of RAP in surface mixes of pavement trafficked by aircraft, as in recent years the consistency of the RAP material has raised some concerns. Consistency concerns include possible contamination with paving fabrics, relatively poor aggregates, and gradation control.

CHAPTER 5 OVERALL RECOMMENDATIONS FOR AIRFIELD PAVEMENTS

This chapter summarizes the findings from the literature and field reviews that were performed as part of this research effort and include an evaluation of the impact of RAP on the performance life of HMA pavements. Finally recommendations on the use of RAP in airfield HMA pavements are provided.

OVERALL SUMMARY OF FINDINGS

Findings of the Literature Review

The following summarizes the findings of the literature review performed in Chapter 3.

- RAP can be used with both Superpave and Marshall mix design methods. In either case the blend materials has to meet the typical required properties for the mix design method.
- Effect of RAP on properties of the laboratory produced mixtures with neat asphalt binders is negligible at low RAP contents (< 15-20%).
- When no change to the neat virgin binder grade is made, the high percentage of RAP (>40%) significantly increases the stiffness of the mix at high, intermediate, and low temperatures resulting in an improved rutting resistance and a reduction in fatigue and thermal cracking resistance.
- Current NCHRP 9-12 binder recommendations were developed for neat asphalt binders. Therefore, care should be exercised when using RAP with modified binders. Additionally, these binder recommendations need to be further investigated for plant produced RAP mixtures.
- The bulk specific gravity of RAP aggregates can be either estimated from the determined maximum theoretical specific gravity of the RAP mixture and assumed asphalt absorption for the RAP aggregate, or the RAP aggregate effective specific gravity is used in lieu of the bulk specific gravity.
- The moisture sensitivity criterion based on AASHTO T283 at the mix design stage can be achieved on RAP containing mixtures. However failure to achieve the criterion might be observed in field produced mixtures. In general, a

reduction in the unconditioned and conditioned tensile strengths of field produced mixtures might be observed.

- In general, highway pavements with 15 to 20% RAP material are performing well and similar to pavements without RAP material.
- In general, the review of literature on the use of RAP in the surface course of airfield pavements showed a good resistance to rutting while environmental distresses like block cracking and raveling were the primary type of distresses encountered.
- The quality of RAP material is affected by the previous maintenance and preservation activities that were applied to the pavement where the RAP was obtained. RAP variability may affect mixtures volumetric and physical properties. Processing RAP by crushing or screening, or both, can help to reduce the variability in RAP material.
- Good stockpile management practices should be followed to keep material variability in check. The National Asphalt Pavement Association has an excellent publication entitled Recycling Hot Mix Asphalt Pavements *(5)* that discusses processing and handling RAP at the plant and during construction.
- Most highway agencies allow the use of maximum 10-25% RAP in surface mixes and a higher percentage in base mixes. Specifications were also related to the mix type (i.e., dense graded HMA, SMA, open graded friction course, etc.) and production method (i.e., batch plant versus drum mix plant). Some highway agencies restrict or limit the use of RAP in the surface course of pavements subjected to high ESALs.
- Some highway agencies restrict or limit the use of RAP to 10% with polymer modified HMA mixtures.
- Most highway agencies require an adjustment to the binder grade when more than 15-20% RAP is used.
- Most highway agencies limit the maximum size of the RAP.

Findings of the Field Performance Review

The following summarizes the findings from the field performance of airfield pavements containing RAP that was accomplished in Chapter 4.

- In 2001, at the Logan International Airport (BOS) in Massachusetts, a Marshall designed HMA mix with 17% RAP and a latex modified PG64-22 was used in the surface course of a section of the Taxiway November. After 6 years of construction, the pavement is still performing well with no signs of rutting. The pavement doesn’t show any signs or potential of foreign object damage (FOD). In 2006, the center 25 feet of the northern portion of Runway 4R-22L was reconstructed with an HMA mix with 0.75 inch nominal maximum size (NMS), 18.5% RAP, and a PG64-28 binder modified with 4% latex. No specific problems were encountered during construction due to the use of RAP in the mix. The majority of the pavement sections met the in-place density specification. After 1 year of service, the runway is in excellent condition with no visible rutting observed.

- In 1999, at the Griffin-Spalding County Airport (6A2) in Georgia, a Superpave designed HMA mix containing 17% RAP was used in the surface layer of the runway and taxiway pavements. During construction the typical GDOT requirements for conventional HMA were followed and no problems were encountered due to the use of RAP in the HMA mix. Some pavement sections failed to meet the in-place density specifications imposed by FAA. After 8 years of service, the HMA mix with 17% RAP is still in good condition with moderate severity transverse cracking and cracks at the longitudinal construction joints. The pavement has moderate raveling specifically along the longitudinal joints. However, no visible rutting is observed. The pavement doesn't show any signs or potential of foreign object damage (FOD).
- In 2002, at the Pekin Municipal Airport (C15) in Illinois, a 100% RAP layer was used as an interlayer and a base course between the pulverized existing CTB course and the new HMA overlay at the airport unique runway. After 5 years of service, the pavement is in good condition with low severity transverse cracking over the entire runway, and low to moderate severity cracking of the longitudinal construction joints, and no visible rutting.
- In 2000, at the Oceana Naval Air Station (NTU) in Virginia, a Marshall designed HMA mix with 20% RAP was used in the surface layer of the middle 32 feet of the Taxiway Alpha asphalt pavement. After 7 years of service, the HMA mix with 20% RAP at the taxiway is again exhibiting rutting in the wheel paths mainly associated with the constant aircraft traffic with high tire pressures and not specifically to the use of RAP in the mix. No difficulties or issues were reported during design or construction due to the use of RAP in the HMA mix. Additionally, the pavement doesn't show any signs or potential of foreign object damage (FOD).

IMPACT OF RAP ON PERFORMANCE LIFE OF HMA PAVEMENTS

The impact of RAP on the performance life of HMA pavements is evaluated using the airfield pavement design software LEDFAA1.3. The analysis is conducted using measured characteristics and mechanical properties of HMA mixtures to compare the estimated performance life of HMA pavements with and without RAP materials. Several LEDFAA1.3 runs were performed with varying the asphalt layer properties for the RAP material. The analysis is conducted using the characteristics and properties of the 0% and 20% RAP mixtures that were evaluated by Li et al. as part of their research study for the Minnesota Department of Transportation *(6)*.

The evaluated mixes included RAP at the contents of 0 and 20% and two sources of virgin asphalt binders (PG58-28 and PG58-34). The RAP was obtained from a number of different sources that were crushed and combined together at the HMA plant. The following labeling applies to the evaluated mixes.

- R028 and R2028: represent the 0% and 20% RAP mixtures produced with the virgin asphalt binder of PG58-28, respectively.
- R034 and R2034: represent the 0% and 20% RAP mixtures produced with the virgin asphalt binder of PG58-34, respectively.

Pavements under three different airport traffic mixes were considered for this analysis: J. F. Kennedy International airport (NY), Sarasota-Bradenton airport (FL), and Smith Reynolds airport (VA), representing large hub, small hub, and general aviation, respectively. Table 23 show the traffic data used in these analyses which were taken from the DOT/FAA/AR-06/56 *(39)* final report entitled: “Comparative Design Study for Airport Pavement.” Since the modulus of the HMA layer varies with temperature, the analyses were performed at three different temperatures for each traffic mix.

In all cases, the analyzed pavements consisted of a 5 inch HMA layer on top of an asphalt stabilized base layer of 150 ksi, on top of a base layer of 30 ksi, and on top of a subgrade of 12 ksi, except in the case of general aviation airports where the stabilized base layer was not used. The “Undefined Layer” type in the LEDFAA1.3 design software was used for the HMA layer which allowed for the use of the measured dynamic moduli of all four HMA mixtures at the analysis temperatures. The dynamic modulus values at a loading frequency of 14 Hz were selected in the analysis corresponding to an average taxiway speed of 17.2 mph.

Table 23 Traffic Mix for Large Hub, Small Hub, and General Aviation Airports.

Category	Air plane	Weight (lb)	Annual departures
Wide body traffic mix (large hub) J. F. Kennedy International airport (NY)	A300-600	375,900	3,838
	A320	162,000	15,101
	A330	507,000	1,015
	B-757	270,000	7,544
	B-737-800	174,200	1,561
	B-747-200	833,000	2,207
	B-747-400	873,000	8,519
	B-767-200	335,000	6,178
	B-767-300ER	409,000	9,635
	B-777-200ER	632,500	3,111
	Concorde	410,000	406
	Fokker F100	100,000	12,117
	DC-9-32	121,000	569
	DC-9-51	121,000	488
	A340-500/600	750,000	2,441
	40-500/600 Belly	750,000	2,441
	A380-800	1,340,000	5,475
	B-747-SP	696,000	3
	DC-8	358,000	504
	MD-11	621,000	3,315
	MD-11 Belly	621,000	3,315
Narrow body traffic mix (small hub) Sarasota-Bradenton airport (FL)	DC-9-32	90,700	24
	B-737-200	115,000	979
	DC-9-51	121,000	282
	B-737-300	140,000	304
	B-727	169,000	319
	B-727	209,000	1,572
	B-757	255,000	72
	DC-8	276,000	10
	BAe 146	70,000	51
General aviation traffic mix Smith Reynolds airport (VA)	Dual Whl-10	10,000	72
	Sngl Whl-15	14,000	344
	Dual Whl-30	30,000	12
	Dual Whl-50	55,000	6
	Skyhawk-172	2,258	3,650
	Gulfstream-G-IV	75,000	72
	Gulfstream-G-V	90,900	36

Figures 12 and 13 show the dynamic modulus curves at 70°F for the various mixtures evaluated by Li et al. *(6)*. The extracted binders from the laboratory-produced R028 and R2028 mixes were both graded as PG64-28. On the other hand the extracted binders from the laboratory-produced R034 and R2034 mixes were both graded as PG64-34. Both extracted binders were one grade higher than the corresponding high performance temperature of the virgin binder grade used in the mix. Table 24 shows the dynamic modulus values of the various mixtures used in the analyses.

Table 24 Mixtures Dynamic Modulus at Analysis Temperatures

Mix	**Dynamic Modulus at 14 Hz (psi)**		
	25°C	**46°C**	**52°C**
R034	298,675	72,665	50,280
R2034	382,670	75,540	51,240
R028	453,255	93,220	64,855
R2028	569,935	100,630	60,300

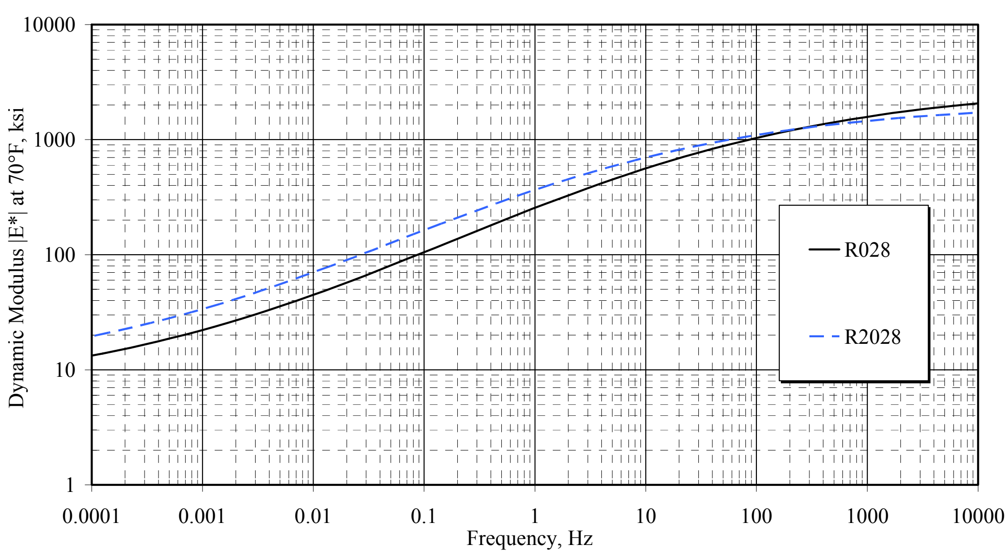

Figure 12 HMA dynamic modulus curves of R028 and R2028 at 70°F

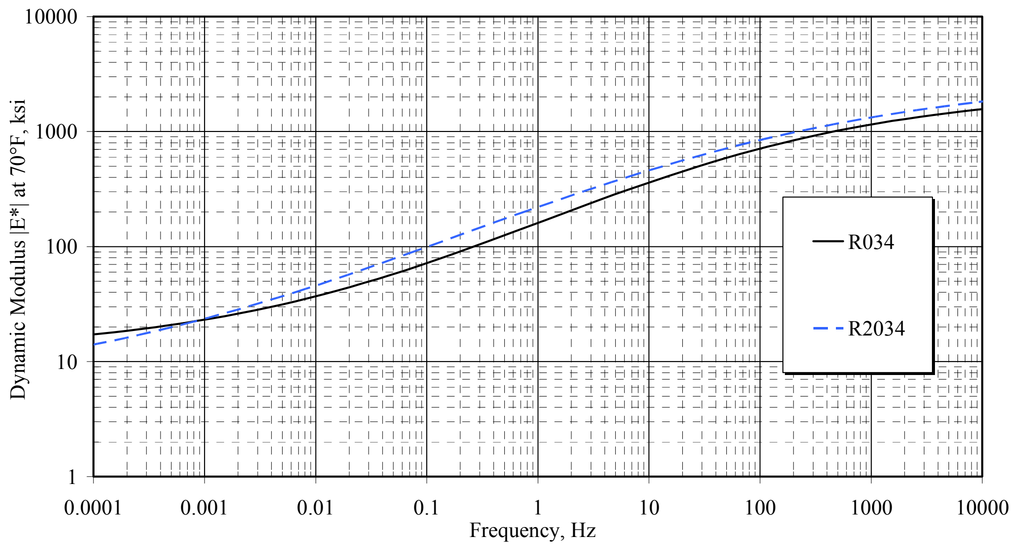

Figure 13 HMA dynamic modulus curves of R034 and R2034 at 70°F

The pavement sections for each traffic mix and each temperature were first designed for 20 years using the dynamic modulus of the 0% RAP mixture and then the performance life of the designed pavement section is evaluated using the modulus of the corresponding 20% RAP mixture. Table 25 shows the designed pavement sections for the various mixtures and at different temperatures along with the corresponding pavement life and the cumulative damage factor (CDF) values for subgrade and asphalt layer.

The analysis of the data at 25°C shows a 26 to 52 percent increase in the pavement life (i.e., 5.2 to 10.4 years) when the 0% RAP mix is substituted with the 20% RAP mix. When the analysis is conducted at 46°C, an increase in pavement life between 2.5 and 12 percent was observed (i.e., 0.5 to 2.4 years). On the other hand, the analysis at 52°C showed a slight increase in the pavement life between 0.5 and 2 percent (i.e., 0.1 to

0.4 years) when the R2034 RAP mix is used while a reduction between 4.5 and 8.5 percent (i.e., 0.9 to 1.7 years) was observed when the R2028 RAP mix was used.

In general, the addition of 20 percent RAP to a mix increased the life of a pavement under a traffic mix of a small hub, large hub, and general aviation.

Table 25 LEDFAA1.3 Pavement Analyses Results

Traffic Mix	Temp. (°C)	Mix	Thickness (inches)				Life (years)	Percent Difference in Life (years)	Subgrade CDF for 20 years	Asphalt CDF
			HMA	Stabilized Base	Subbase	Total				
Large hub- J. F. Kennedy Intl airport (NY)	52	R034	5.00	13.00	14.80	32.80	20.0	2.0	1.00	0.00
		R2034	5.00	13.00	14.80	32.80	20.4	(0.4)	0.98	0.00
	46	R034	5.00	13.00	13.76	31.76	20.0	5.0	1.00	0.00
		R2034	5.00	13.00	13.76	31.76	21.0	(1.0)	0.95	0.00
	25	R034	5.00	11.00	12.09	28.09	20.0	52.0	1.00	0.01
		R2034	5.00	11.00	12.09	28.09	30.4	(10.4)	0.66	0.02
	52	R028	5.00	13.00	14.10	32.10	20.0	-8.5	1.00	0.00
		R2028	5.00	13.00	14.10	32.10	18.3	(-1.7)	1.09	0.00
	46	R028	5.00	13.00	12.96	30.96	20.0	12	1.00	0.00
		R2028	5.00	13.00	12.96	30.96	22.4	(2.4)	0.89	0.00
	25	R028	5.00	10.00	12.35	27.35	20.0	44.0	1.00	0.02
		R2028	5.00	10.00	12.35	27.35	28.8	(8.8)	0.69	0.04
Small hub- Sarasota- Bradenton airport (FL)	52	R034	5.00	18.00	19.05	42.05	20.0	0.5	1.00	0.03
		R2034	5.00	18.00	19.05	42.05	20.1	(0.1)	0.99	0.03
	46	R034	5.00	17.00	19.79	41.79	20.0	3.0	1.00	0.06
		R2034	5.00	17.00	19.79	41.79	20.6	(0.6)	0.97	0.07
	25	R034	5.00	15.00	18.04	38.04	20.0	30.0	1.00	0.61
		R2034	5.00	15.00	18.04	38.04	26.0	(6.0)	0.77	0.77
	52	R028	5.00	18.00	18.46	41.46	20.0	-5.0	1.00	0.05
		R2028	5.00	18.00	18.46	41.46	19.0	(-1.0)	1.05	0.04
	46	R028	5.00	17.00	19.06	41.06	20.0	6.5	1.00	0.10
		R2028	5.00	17.00	19.06	41.06	21.3	(1.3)	0.94	0.12
	25	R028	5.00	15.00	16.51	36.51	20.0	26.0	1.00	0.89
		R2028	5.00	15.00	16.51	36.51	25.2	(5.2)	0.79	1.21
General aviation - Smith Reynolds (VA)	52	R034	5.00	0.00	16.65	21.65	20.0	1.0	1.00	0.11
		R2034	5.00	0.00	16.65	21.65	20.2	(0.2)	0.99	0.12
	46	R034	5.00	0.00	16.07	21.07	20.0	2.5	1.00	0.21
		R2034	5.00	0.00	16.07	21.07	20.5	(0.5)	0.97	0.22
	25	R034	5.00	0.00	13.25	18.25	20.0	38.5	1.00	0.74
		R2034	5.00	0.00	13.25	18.25	27.7	(7.7)	0.72	0.80
	52	R028	5.00	0.00	16.25	21.25	20.0	-4.5	1.00	0.18
		R2028	5.00	0.00	16.25	21.25	19.1	(-0.9)	1.05	0.16
	46	R028	5.00	0.00	15.66	20.66	20.0	6.0	1.00	0.29
		R2028	5.00	0.00	15.66	20.66	21.2	(1.2)	0.94	0.32
	25	R028	5.00	0.00	11.90	16.90	20.0	46.5	1.00	0.87
		R2028	5.00	0.00	11.90	16.90	29.3	(9.3)	0.68	0.89

GENERAL RECOMMENDATIONS FOR AIRFIELD PAVEMENTS

After a thorough review of the various efforts on the use of RAP and applicability along with its long-term field performance on highway and airfields pavements the following recommendations can be made for the use of RAP on airfield pavements (Tables 26 and 27).

- Allow a maximum of 20% RAP in either the base or surface HMA mixes if the recovered RAP binder is PGXX-22 without changing the grade of the virgin target asphalt binder. The review showed a good performance of the 15 to 20% RAP containing HMA mixes on airfield pavements.
- Allow a maximum of 15% RAP in either the base or surface HMA mixes if the recovered RAP binder is PGXX-16 without changing the grade of the virgin target asphalt binder.
- Allow 20% to 25% of RAP in the base HMA mixes if the recovered RAP binder is PGXX-22 by changing the virgin binder grade one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used).
- Allow 15% to 25% of RAP in the base HMA mixes if the recovered RAP binder is PGXX-16 by changing the virgin binder grade one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used).
- Allow a maximum of 10% RAP in either the base or surface mixes for recovered RAP binder of PGXX-10 or higher with the virgin binder grade determined using the blending chart method.
- Consider using anti-strip additive to improve the long term durability of HMA mixtures containing RAP.
- The RAP shall be free of contaminants that are potentially detrimental to the mixture performance. Such contaminants may be, but not limited to, coal-tar sealer, rejuvenator, material containing coal-tar, and paving fabrics. Therefore, precautions are needed specifically when using RAP from airfield aprons that might have been contaminated with fuel spillage and/or contained a fuel resistant sealer or mix. When similar situations are encountered it is recommended to strip the pavement surface before recycling the existing asphalt layer(s).
- Recommend a minimum TSR of 80% and a minimum unconditioned TS of 90 psi at 77°F for PG64-XX or higher and a TS at 77°F of 70 psi for PG58-XX or lower. In severe climatic conditions, testing under multiple freeze thaw cycles is recommended.
- RAP shall be of a consistent gradation and asphalt content.
- Limit maximum aggregate size in RAP and the processed RAP size to 2 inch.
- Follow the National Asphalt Pavement Association (NAPA) publication entitled Recycling Hot Mix Asphalt Pavements *(5)* for processing and handling RAP at the plant and during construction.

Table 26 Recommendations on the Use of RAP in HMA Mixes of Airfield Pavements.

Type of Mix	Recommended Virgin Asphalt Binder Grade	RAP Percentage Recovered RAP Grade		
		PGXX-22 or lower	PGXX-16	PGXX-10 or higher
Surface and Base Mix	No change in binder selection	< 20%	< 15%	--
Base Mix	Select virgin binder one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used)	20% – 25%	15% – 25%	--
Surface and Base Mix	Follow recommendations from blending charts	--	--	< 10%

Table 27 AASHTO T283 Recommendations for RAP Containing Mixes.

Virgin target binder	Dry Tensile Strength at 77°F	Tensile Strength Ratio at 77°F	Notes
PG64-XX or higher	Minimum 90 psi	Minimum 80%	• Severe climatic conditions might require multiple freeze-thaw cycles. • Consider anti-strip additive to improve long-term durability.
PG58-XX or lower	Minimum 70 psi	Minimum 80%	

If for some reasons, it was decided to use a RAP at a rate higher than the recommended in Table 26, then the blending chart method needs to be followed in selecting the grade of the virgin binder. Furthermore, the final mix needs to be evaluated for fatigue and thermal cracking to ensure the good performance of the mix at intermediate and low pavement temperatures.

CHAPTER 6 RECOMMENDATIONS FOR LABORATORY TESTS

This chapter presents recommendations on the laboratory tests required for designing HMA mixtures containing RAP for airfield projects. The proposed tests are based on the recommendations in Chapter 5 and the review of literature on RAP research and the long-term performance histories of HMA pavements containing RAP that were collected in the previous chapters.

RAP MATERIALS EVALUATION

Evaluating the RAP materials consists of measuring the properties of the binder and aggregates of the reclaimed mix. Several research studies have been conducted to identify the best methods for separating and testing the binder and aggregates of the RAP materials but there have not been any standard procedures that agencies can use on a routine basis. Based on this review study and the guidelines provided by NCHRP Research Results Digest No. 253 *(31)* the following laboratory tests were recommended.

It should be noted that the Research Results Digest No. 253 is the recommended guidelines of using RAP in Superpave mixtures. The researchers believe that such guidelines can also be used with the Marshall method to design HMA mixtures containing RAP.

Determining RAP Binder Properties

In the case of the binder in the RAP, the two critical properties are: binder content and binder properties. The extraction and recovery of RAP asphalt binder is necessary to determine the RAP binder content and PG grade. The recommended procedures are AASHTO T164 or ASTM D2172 for the centrifuge (method A) or reflux (method B) extraction. The aggregate should be saved for later evaluation.

The recommended procedures for the recovery of the extracted RAP binder are AASHTO T170 or ASTM D1856 for the Abson method or the ASTM D5404 for the rotary evaporator method. The physical properties and critical temperatures of the recovered RAP binder should be determined in accordance with AASHTO M323. Those properties will be used for either blending at a known RAP percentage or for blending with a known virgin binder grade.

Determining RAP Aggregate Properties

In the case of the aggregates in the RAP, the two critical properties that need to be evaluated are gradation and specific gravity. Additionally, certain physical properties of the RAP aggregates may need to be determined depending on the amount of RAP to be used in the mix.

Gradation

The gradation of the aggregates in the RAP materials can be evaluated through the solvent extraction or the ignition oven. If a solvent extraction was used, the extracted RAP aggregate gradation should be determined in accordance with AASHTO T30 or ASTM D5444. The ash content from the solvent extraction must be accounted for in the RAP aggregate. If an ignition oven was used, the RAP aggregate gradation should be determined in accordance with AASHTO T27 or ASTM C136 and the amount passing No. 200 (0.075 mm) sieve should be quantified using AASHTO T11 or ASTM C117

However, it should be noted that an ignition oven can change the gradation and properties of some aggregates because of aggregate particles breakdown; therefore, local experience with typical aggregate types in ignition ovens should be considered. These breakdowns can also lead to erroneous estimates of the binder content with some aggregates, especially for RAP sources with unknown correction factors. Experience with local aggregates can indicate if an ignition oven is an appropriate method to use in a given area. Ignition oven should be allowed only if it is calibrated against the solvent extraction method. Many states are now evaluating the effects of ignition ovens on typical aggregate properties. These evaluations also can be valuable when assessing RAP aggregate properties.

Specific Gravity/Absorption

The specific gravity of the combined gradation of RAP and stockpiles aggregates is required for the volumetric calculations of a mix design. Therefore, the bulk specific gravity of each aggregate stockpile, including the RAP aggregate needs to be determined for the calculation of the bulk specific gravity of the combined aggregates. Measuring the RAP aggregate specific gravity would require extracting the RAP, sieving it into coarse and fine fractions, and determining the specific gravity of each fraction. However, it can be difficult to accurately measure the bulk specific gravity of the RAP aggregate since the extraction process can change the aggregate properties and may result in a change in the amount of fine material.

According to NCHRP Research Results Digest No. 253, some states in the past have used the effective specific gravity (G_{se}) of the RAP aggregate instead of its bulk specific gravity (G_{sb}). The effective specific gravity can be calculated from the RAP mixture maximum specific gravity (G_{mm}), which can easily be determined by conducting ASTM D2041. When the asphalt content of the RAP is determined by extraction or ignition oven and the binder specific gravity is assumed, the effective specific gravity is then calculated from Equation 6. This estimate of the RAP aggregate effective specific gravity can be used to calculate the combined aggregate specific gravity, which is then used to calculate the VMA.

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \qquad \text{(Equation 6)}$$

where, G_{se} = effective specific gravity of aggregate
G_{mm} = theoretical maximum specific gravity of the paving mixture from the ASTM D2041 test
P_b = RAP binder content at which the ASTM D2041 test was performed, percent by total mass of mixture
G_b = specific gravity of RAP binder

However, substituting the G_{se} for the G_{sb} of RAP aggregates will result in overestimating both the combined aggregate bulk specific gravity and the VMA since for a given aggregate, G_{sb} is always smaller than G_{se}. For instance, when the G_{se} of RAP is used in lieu of G_{sb}, the calculated VMA value will often change by 0.3% per 10% of RAP used or one-tenth reduction in the optimum asphalt binder content leading to dry mixes when designing to minimum VMA (After *Murphy Pavement Technology*). This introduced error will be greater when higher percentages of RAP are used. For this reason, some states that allow the use of G_{se} for the RAP aggregate also increase their minimum VMA requirements to account for this error.

An alternative approach used by some states was also discussed in the NCHRP Research Results Digest No. 253, and it consists of assuming a value for the absorption of the RAP aggregate. On the basis of past experience with the same aggregates, some states can estimate this value quite accurately. The G_{sb} of the RAP aggregate can be calculated based on this assumed absorption using Equations 7 and 8. This G_{sb} value can then be used to estimate the combined aggregate bulk specific gravity and to calculate VMA.

$$P_{ba} = 100 \times \frac{G_{se} - G_{sb}}{G_{sb} G_{se}} \times G_b \qquad \text{(Equation 7)}$$

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba} G_{se}}{100 \times G_b} \right) + 1} \qquad \text{(Equation 8)}$$

where, P_{ba} = absorbed asphalt binder, percent by weight G_{sb} of aggregates
G_{se} = effective specific gravity of aggregate
G_{sb} = bulk specific gravity of aggregate
G_b = specific gravity of RAP binder

Recently, Murphy Pavement Technology introduced a new test method for the measurement of the bulk specific gravity of RAP aggregates. The test method is briefly summarized as follows.

First the asphalt binder content of the RAP material (P_b) is determined according to AASHTO T164: "Quantitative Extraction of Bitumen from Bituminous Paving Materials." Additionally, the maximum theoretical specific gravity (G_{mm}) of a RAP sample is determined after mixing with a 1% virgin asphalt binder (PG64-22 or PG58-22) by dry weight of RAP. The 1% asphalt binder is added to the RAP mixture to ensure a uniform coating of all particles. Then, the adjusted P_b of the RAP mixture is calculated to account for the 1% virgin asphalt binder added. Next, the effective specific gravity (G_{se}) of the RAP aggregate is calculated using Equation 9.

$$G_{se} = \frac{100 - Adjusted\ P_b}{\frac{100}{G_{mm}} - \frac{Adjusted\ P_b}{1.040}} \qquad \text{(Equation 9)}$$

Finally, the aggregate bulk specific gravity (G_{sb}) of the RAP aggregate is calculated using Equation 10.

$$G_{sb}(RAP) = G_{se}(RAP) - 0.100 \qquad \text{(Equation 10)}$$

Each engineering consultant or agency should evaluate materials typically used in their area and determine which approach gives the consultant the most confidence. If historical records are available that can indicate the source of the predominant aggregates in the RAP, it may be possible to accurately estimate aggregate properties, such as asphalt absorption. If it was decided to substitute the effective specific gravity for the bulk specific gravity of RAP aggregates, then the error introduced in VMA calculations by this substitution should also be examined in attempt to minimize it. Adjusting the minimum VMA requirements to compensate for the error introduced by the substitution may help to minimize the error. If it was decided to use the test method proposed by Murphy Pavement Technology then the proposed equation that correlates G_{sb} to G_{se}

(Equation 10) needs to be first validated since it will be influenced most likely by aggregate absorption and geological formations within each region/state.

Hardness/Wear

The RAP aggregate should also be tested to determine its physical properties as is done with virgin aggregates. Knowledge of how locally available aggregates are changed by ignition ovens may help to determine if an ignition oven is a viable technique for obtaining bare RAP aggregate for testing.

Traditionally, the Los Angeles Abrasion Test (AASHTO T96 or ASTM C131) has been used as a measure for the resistance of aggregate to the degradation that may occur during production, placement, or even during its in-service life. Since RAP aggregates were most likely been tested for hardness and wear before their initial use and been subjected to most of the breakdown during production, construction, and performance, the use of the abrasion test in characterizing RAP aggregate is questionable.

Cleanliness

The sand equivalent test (ASTM D2419) determines the percentage of fine clay particles contained in the fine aggregate compared with the amount of sand in the aggregate. The percentage is an indication of how clean the fine aggregate is and how well the binder can coat the fine aggregate. This test is not required for the RAP aggregate because the fine aggregate was already used in HMA and is already coated with asphalt. Also, the test is probably not meaningful for extracted aggregate because fines may be washed away during solvent extraction or additional fines may be created by aggregate degradation during extraction.

Particle Shape and Angularity

Particle shape is usually characterized as the number of flat and elongated particles and is determined according to ASTM D4791 procedure. The aspect ratio of the coarse aggregate particles (greatest dimension to smallest) is measured and the percent mass of flat and elongated coarse aggregate is calculated. Because of the way RAP is processed, it is most likely that the coarse aggregate fraction will not contain a large amount of flat and elongated particles. However some aggregates tend to crush into flat and elongated particles as well as some types of crushers also tend to produce more particles with this undesirable shape. Therefore, the ASTM D4791 test should be considered for RAP aggregate.

The coarse aggregate angularity is quantified in terms of the amount of material having one or two or more fractured faces. The RAP aggregate should be sieved and separated into coarse and fine fractions. The coarse aggregate (retained on No. 4 [4.75 mm] sieve) should be analyzed for coarse aggregate angularity using ASTM D5821. The fine aggregate angularity (AASHTO T304 or ASTM C1252) should be determined on the RAP aggregate that passes a 2.36-mm (No. 8) sieve. The fine aggregate angularity of the RAP aggregate may be changed (usually decreased) by the extraction process.

Soundness

Aggregates are subjected to multiple freeze-thaw cycles using a sodium or magnesium sulfate solution in accordance with AASHTO T104 or ASTM C88. Since RAP has already been exposed to field environmental conditions during its performance life then the usefulness of the soundness test to evaluate RAP aggregates is questionable.

MIX DESIGN

The mix is composed of mineral aggregate, RAP material, and asphalt binder. The design procedure for the HMA mixes containing RAP is similar to regular HMA mixtures by treating RAP aggregate as another stockpile. The amount of RAP in the mix is limited to the numbers shown in Table 28.

Table 28 RAP Content in HMA Mixes of Airfield Pavements.

Type of Mix	Recommended Virgin Asphalt Binder Grade	RAP Percentage Recovered RAP Grade		
		PGXX-22 or lower	PGXX-16	PGXX-10 or higher
Surface and Base Mix	No change in binder selection	< 20%	< 15%	--
Base Mix	Select virgin binder one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used)	20% – 25%	15% – 25%	--
Surface and Base Mix	Follow recommendations from blending charts	--	--	< 10%

The NCHRP Report No. 452 describes a step-by-step Superpave mix design process with RAP which can easily be adapted for a Marshall mix design. The changes to standard mix design procedures are described below *(8)*:

- The RAP aggregate must be heated gently and to a lower temperature than aggregates are normally heated to avoid changing the RAP binder properties.
- The RAP aggregate specific gravity must be estimated.
- The weight of the RAP binder must be accounted for when batching aggregates.
- The total asphalt content is reduced to compensate for the binder provided by the RAP.
- A change in virgin binder grade may be needed depending on the amount of RAP, desired final binder grade, and RAP binder stiffness.

When batching out the RAP aggregates, it is important to remember that part of the weight of the RAP is binder. It is necessary to increase the weight of RAP and decrease the amount of new binder added to take the presence of this RAP binder into account. The weight of dry RAP that would provide a given weight of RAP aggregate is calculated using Equation 11:

$$\text{Mass of dry RAP} = \frac{Mass\ of\ RAP\ aggregate}{\left(100 - \%RAP\ Binder\right)} \times 100 \qquad \text{(Equation 11)}$$

The RAP asphalt binder content (*%RAP binder*) and grade should be determined according to the recommended methods described earlier for the evaluation of RAP materials.

The final mix has to meet the mixture's volumetric requirements for the mix design procedure at the optimum binder content. The minimum required VMA might be adjusted if the effective specific gravity of the RAP aggregate is used in lieu of its bulk specific gravity. The required asphalt binder content at the design air voids needs to be reduced by the amount of asphalt binder in the RAP stockpile. The recovered binder from the final blended mix should meet the requirements for the target binder grade.

The moisture sensitivity of the designed mix is determined in accordance with the AASHTO T283 test "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage." The designed mix shall meet a minimum tensile strength ratio of 80% and a minimum dry tensile strength of 90 psi at 77°F for virgin binders of PG64-XX or higher and a minimum unconditioned TS at 77°F of 70 psi for virgin binders of PG58-XX or lower. In severe climatic conditions, testing under multiple freeze thaw cycling is recommended. Antistrip additives need to be considered in every mix design at a rate determined by the appropriate testing and engineering judgment.

Because of the variability incorporated by the AASHTO T283 test itself, Sebaaly et al. evaluated the current AASHTO T283 moisture sensitivity test and the following recommendations were made in order to improve the repeatability of the test within a single laboratory: *(38)*

- Use 5 replicates in measuring the unconditioned and conditioned tensile strength (TS).
- Keep the coefficient of variation (CV) of the 5 replicates to 10% or less. Replace samples if necessary to achieve a CV of 10% or less.
- Keep the saturation level as close to 75% as possible but in no case it should be less than 70% or greater than 80%.
- Keep the samples air-voids at 7+/-0.5%.
- Keep the loading rate at 2 in/min (25 mm/min). This can be achieved by using a mechanical loading machine.
- If the above recommendations were followed, the expected range of TSR within a single laboratory is 4 percentage points.

Any change in the characteristics of RAP materials (i.e., change in RAP source, RAP aggregate gradation, RAP binder content, etc.) will necessitate an entirely new mix design. Care should be taken to the depth of millings when RAP is obtained from the pavement of the project being constructed, since typically different mixes are used in different pavement layers which may change the RAP gradation and binder content.

Mechanical Property Testing

The review of the state highway agencies specifications showed, whenever available, that the same laboratory performance tests and criteria are used for both regular and RAP mixtures. Some agencies implemented either the asphalt pavement analyzer test (APA) or the Hamburg wheel test as part of their mix design method with different performance criteria for different traffic levels.

The performance criteria and the pass/fail values are used to distinguish between a good and a poor HMA mix. Since airport pavements are typically subjected to more severe loading conditions with a lower number of repetitions than highway pavements, then the transfer of the performance criteria from highway pavements into airport pavements is a delicate step requiring special analyses.

The significantly higher aircraft tire loads and tire inflation pressures along with different tire configurations impose more complex stress conditions within the structure of airport pavements that are significantly different than those encountered on highway pavements. Hence, pavements response differently to aircraft loading than to highway traffic loading.

In an attempt to study the impact of aircraft loading on the response of HMA pavements a mechanistic analysis was conducted. Several factors affect the prediction of the pavement responses to traffic loading and its long-term performance. The pavement is a layered system and the HMA surface layer exhibits viscoelastic behavior. The loading time and temperature are some of the most important factors that affect the stiffness of the HMA layer. During the past several years, the University of Nevada has developed an advanced pavement response model (3D-Move) which incorporates the effects of viscoelastic properties of asphalt layers and the speed of the moving loads in evaluating pavement responses to traffic loads *(40)*. The model can handle complex surface loadings such as multiple loads and non-uniform and non-circular stress distributions (normal and shear) at the tire-pavement interface. The 3D-Move has undergone field verifications in which responses of two full-scale road tests were used to validate the application of the model *(41)*.

In an effort to establish an equivalency between highway and airport pavements, first the 3D-Move model is used to estimate the responses of typical airport pavements under aircraft loadings and typical highway pavements under truck loading. Then, the estimated responses of the two pavements are used to transfer the technology from highway pavements to airport pavements through adjustments of the applicable specifications. For example, if a RAP specification for highway pavements includes a criterion on the maximum rut depth under the asphalt pavement analyzer (APA), such a specification will be modified to account for the stress conditions encountered in airport pavements relative to those encountered in highway pavements.

A detailed analysis for both typical airfield and highway pavements under a fully loaded Boeing 727 airplane and a fully loaded 18-wheel tractor-semitrailer, respectively is shown in *Appendix C* of the report. Predicted asphalt layer rut depths were used to identify the performance criteria for HMA mixes on airfield pavements under the third scale Model Mobile Load Simulator (MMLS3) and the asphalt pavement analyzer (APA) laboratory tests.

Third scale Model Mobile Load Simulator (MMLS3)

The MMLS3 test allows for a rapid assessment of the permanent deformation and moisture sensitivity of cylindrical laboratory specimens compacted to specific densities or asphalt cores retrieved from the field. Studies are underway to formalize criteria to assess the rutting and moisture susceptibility of mixes tested using the MMLS3 in the laboratory. Interim criteria were established by South African researchers for acceptable rutting performance at critical temperature (>50°C) and after 7200 load applications per hour.

- For roads and highways: maximum 3.0 mm after MMLS3 load applications
- For airfields: maximum 1.8 mm after MMLS3 load applications.

The following calculations show how the South Africa Criteria for MMLS3 compare to the criteria developed by the approach proposed in this research. The following relationship is proposed in this research to convert highway criterion to airfield criterion using the estimated rut depths of 0.18 and 0.46 mm under normal highway and taxiing loads, respectively.

$$\text{Airfield criterion} = \text{Highway criterion} \times \left(1 - \frac{\text{Highway Rut Depth}}{\text{Airfield Rut Depth}}\right)$$

$$= 3.0 \times \left(1 - \frac{0.18}{0.46}\right) = 1.83 \text{ mm.}$$

The 1.83 mm criterion developed in this research is very close to the 1.8 mm criterion recommended by the South Africa research, thus proving the validity of the proposed conversion technique.

If the estimated rut depths during braking were to be used then the criterion for the MMLS3 at the slow moving braking areas would be:

$$\text{Airfield criterion} = \text{Highway criterion} \times \left(1 - \frac{\text{Highway Rut Depth}}{\text{Airfield Rut Depth}}\right)$$

$$= 3.0 \times \left(1 - \frac{0.44}{0.76}\right) = 1.26 \text{ mm.}$$

Asphalt Pavement Analyzer (APA)

Depending on traffic level, the Oregon DOT specifies a maximum APA rut depth at 64°C of 4 to 6 mm after 8,000. Applying the relationship proposed in this research, the criterion at the airfield will have to be dropped from 4.0 mm to 2.5 mm at 64°C:

$$\text{Airfield criterion} = \text{Highway criterion} \times \left(1 - \frac{\text{Highway Rut Depth}}{\text{Airfield Rut Depth}}\right)$$

$$= 4.0 \times \left(1 - \frac{0.18}{0.46}\right) = 2.5 \text{ mm}$$

Briefly, the mechanistic analysis for the airport and highway pavements showed promising results in converting highway performance criteria to airport applications. It should be noted that the mechanistic analysis results are highly dependent on the pavement structure, material properties, temperature of analysis, and the applied loads. For example Georgia DOT has different APA criteria at 49°C for their various standard mix levels. Therefore, adjusting the GDOT criteria to airfield pavements requires the mechanistic analysis to be run at 49°C for the GDOT different materials characteristics. Additionally the recommended performance criteria from the mechanistic analysis need to be validated in the field before full implementation.

QUALITY CONTROL/ASSURANCE

Good quality control (QC) practices are essential to produce consistently high-quality recycled HMA mixes. Quality control of recycled mixtures is not significantly different than those of conventional HMA except that some additional tests need to be performed when producing HMA mixes with RAP. The process should be monitored for processed RAP moisture content, asphalt binder content, and aggregate gradation. Changes in these properties would reflect variations in the RAP material. The additional procedures needed for HMA containing RAP are discussed below.

RAP Material

It is important to measure the asphalt content and gradation at several locations on each of the RAP stockpiles before beginning production. Table 29 gives ranges for sampling and testing RAP materials during production *(42)*. The testing frequency should be adjusted based on the variability of materials in RAP and the type of mix being produced.

Table 29 Suggested Quality Control Schedule for RAP (after NAPA Series 124).

Test Description	Sampling Location	Frequency[1,2] (samples/lot)	Priority
Asphalt content	Stockpile or combined RAP feed	1 – 5	High
Gradation	Stockpile or combined	1 – 5	High
Binder extraction and recovery	Stockpile or combined RAP feed	1	Low
Binder properties	Post extraction and recovery	1	Low
Aggregate properties	Post extraction	1	Medium – Low

[1] Frequency and types of testing will depend upon variability of source materials and the intended end-use of the HMA. Historical records and materials evaluation should be consulted before determining testing frequency.
[2] If the RAP stockpile is built ahead of production and additions are not being made to the pile, it may be possible to dramatically reduce the sampling frequency.

RAP Moisture Content

The moisture content in the RAP is determined in much the same way as the moisture content of a sample of stockpiled aggregates is checked. The moisture content of the RAP mixture must be determined by test method ASTM D2216.

RAP Binder Content

Asphalt binder content must be determined from the extraction process in accordance with AASHTO T164 or ASTM D2172 for the centrifuge (method A) or reflux (method B) extraction. Ignition oven can be used if calibrated against the solvent extraction methods.

RAP Aggregate Gradation

The gradation of the aggregates in the RAP materials must be evaluated through the solvent extraction or the ignition oven. If a solvent extraction was used, the extracted RAP aggregate gradation should be determined in accordance with AASHTO T30 or ASTM D5444. The ash content from the solvent extraction must be accounted for in the RAP aggregate. If an ignition oven was used, the RAP aggregate gradation should be determined in accordance with AASHTO T27 or ASTM C136 and the amount passing No. 200 (0.075 mm) sieve should be quantified using AASHTO T11 or ASTM C117. The material passing No. 200 (0.075 mm) sieve must be monitored closely since RAP may have a significant amount of material passing No.200 sieve.

Final Mix

In addition to the tests conducted for conventional mixtures the produced final mixtures must be tested for moisture sensitivity in accordance with AASHTO T283 test method since the moisture resistance of HMA mixtures containing RAP is a concern for most highway agencies.

CHAPTER 7 EVALUATION OF FAA SPECIFICATION ON RAP

The specifications and procedures for use of RAP on Federal Aviation Administration (FAA) pavement projects are contained in sections 401 and 403 of Advisory Circular 150/5370-10C and a similar specification, UFGS-32 12 15, is used for military airfields. This Chapter evaluates and presents suggested modifications to the existing FAA P401-3.3 and FAA P403-3.3 specifications on RAP.

REVIEW OF FAA P-401-3.3/P-403-3.3 SPECIFICATIONS DATED 9/29/2007

The Review of the FAA P-401 and P-403 Specifications for Recycled Asphalt Concrete in view of the review of RAP related studies is as follows.

Sections P-401-3.3 and P-403-3.3 specify that RAP shall be of a consistent gradation and asphalt content and properties. The specification does not define what a RAP material with consistent properties is.

A research study conducted by Kallas *(26, 27)* showed the variation in terms of average and standard deviation of properties of RAP material collected from cores and after milling from different projects. By comparing the RAP standard deviations for the percent passing No. 8 sieve, percent passing No. 200 sieve, and asphalt binder content to the typical HMA surface standard deviations (2.81, 0.94, and 0.28, respectively *(28)*, the data revealed that some sources of RAP have more variability in composition than average new HMA surface course production. The RAP content from these sources would have to be limited to produce RAP containing HMA mixes that meet the uniformity requirements in specifications. Additionally the data showed that some sources of RAP have less composition variability than average new HMA surface course production; hence, the RAP content in recycled HMA would not be restricted based on its compositional variability. It should be noted that the average standard deviations of 2.81, 0.94, and 0.28 for the percent passing No. 8 sieve, percent passing No. 200 sieve, and asphalt binder content, respectively, were reported by Granley *(28)* based on the variations in asphalt construction for 26 projects producing HMA surface mixtures without RAP.

Therefore, when RAP is used in HMA, the first step in the mixture design process is to determine the average and standard deviation of the RAP binder content and gradation using samples taken from 8 to 10 random locations distributed throughout the RAP pile. This information is used to estimate feasible RAP contents that will satisfy gradation and variability requirements. It is recommended to follow the method proposed by NCHRP 9-33 to determine the amount of RAP that can be added without exceeding the specification limits.

A review conducted by the National Asphalt Pavement Association (NAPA) *(5)* on recycling HMA pavements showed that processing the RAP by crushing or screening, or both, can also help to reduce the variability in RAP material. Additionally, fractionating the RAP into different sizes may be necessary to maximize the percentage of RAP used in a mix and still meet the gradation and volumetric requirements. The NAPA publication *(5)* provides a new and updated document on how to recycle and summarizes for producers and agencies the equipment and methods that others are successfully using to reclaim, size, store, and process RAP in various types of HMA facilities throughout the country.

Sections P-401-3.3 and P-403-3.3 specify that the contractor may obtain the RAP from the job site or an existing source. However, RAP containing coal tars may require additional precautions during production and may be excluded.

It should be recognized that RAP from airfield aprons may be contaminated with fuel spillage and may contain coal-tar sealer, rejuvenator, or material that contains coal-tar which may impact the properties of the final mix. Therefore, and since no actual study was conducted to evaluate the impact of contaminant type and amount on the final mixture's properties, it is recommended that RAP materials shall be free of contaminants that are potentially detrimental to the mixture performance.

When RAP from existing sources is used it should be collected from pavements that were built to highway or airport standards and specifications and shall be free of contaminant such as, but not limited to, coal-tar sealer, rejuvenator, material that contains coal-tar, and paving fabrics.

Sections P-401-3.3 and P-403-3.3 specify that (RAP) should not be used for surface mixes, except on shoulders. It can be used very effectively in lower layers or for shoulders. Engineer is to specify the maximum percentage of reclaimed asphalt allowed in the mix. The amount of RAP shall be limited to 30 percent, as long as the resulting recycled mix meets all requirements that are specified for virgin mixtures.

The process described by NCHRP Project 9-12 *(8)* for selecting RAP content in HMA mixes recommends actions for combinations of the RAP contents and RAP binder grade. The process specifies the maximum amount of RAP that can be used without changing the specified virgin binder grade, the percentage of RAP that can be used when the virgin binder grade is decreased by one grade (i.e. decreasing 6 degrees on both high and low temperatures grades), and the blending chart method to be used for high RAP contents.

In general, most studies on laboratory produced mixtures concluded that the effect of RAP on mixtures' properties is negligible at low RAP contents of 15% to 20% *(7, 8, 9, 10)*. The low RAP content did not significantly affect the stiffness and strength of the mix at low and high temperatures. However the increase in RAP content beyond 20% increased the mixture stiffness and strength resulting in an increase in rutting resistance *(6, 7, 9, 10, 14)*. When no change to the virgin binder grade was made, the higher RAP contents (>40%) resulted in a significant increase in the stiffness of the mix at high, intermediate, and low temperatures *(8, 9)* and a reduction in the low temperature cracking resistance *(7, 13)*.

In general, the review of the performance of RAP containing HMA mixes on highway pavements showed that mixes with 15 to 20% RAP are performing well and similar to pavements without RAP. Louisiana had good experience with the performance of mixes with 50% RAP when compared to the conventional pavements for a period of six to nine years after construction *(17)*. The Connecticut SPS-9A sections with 20% RAP showed good field performance with some non wheel path cracking and no fatigue and transverse cracking on all three sections (one Marshall and two Superpave designed mixes) after 8 years in-service *(19)*.

In general, the review of the performance of RAP containing HMA mixes on airfield pavements showed a good resistance to rutting in the field as well as in the laboratory. Environmental distresses like block cracking and raveling were the primary type of distresses encountered in the pavements containing RAP.

The Logan International Airport (BOS) in Massachusetts experienced HMA mixes containing 15 to 20% RAP in the surface layers. The pavements with the RAP containing HMA mixes are performing well with no signs of distresses or foreign object damage (FOD). The use of RAP at a rate of 15 to 20% is now mandatory for all constructed surface layers of Logan airport asphalt pavements. At the Griffin-Spalding County Airport (6A2) in Georgia, the 8 year old pavement at the runway and taxiway designed with a Superpave HMA surface mix containing 17% RAP is still in good condition with moderate severity transverse cracking and cracks at the longitudinal construction joints. The pavement has moderate raveling specifically along the longitudinal joints. However, no visible rutting is observed. The pavement doesn't show any signs or potential of foreign object damage (FOD). At the Oceana Naval Air Station (NTU) in Virginia, the Marshall designed HMA mix with 20% RAP in the surface layer of the middle 32 feet of the Taxiway Alpha asphalt pavement is again exhibiting rutting in the wheel paths after 7 years of service. This is mainly associated with the constant aircraft traffic with high tire pressures and not specifically to the use of RAP in the mix.

Therefore, based on the review of the various efforts on the use of RAP and applicability along with its long-term field performance on highway and airfields pavements the recommendations on the use of RAP in HMA surface and base mixes are shown in Table 30.

If for some reasons, it was decided to use a RAP at a rate higher than the recommended in Table 30, then the blending chart method needs to be followed in selecting the grade of the virgin binder. Furthermore, the final mix needs to be evaluated for fatigue and thermal cracking to ensure the good performance of the mix at intermediate and low pavement temperatures.

Table 30 Recommendations on the Use of RAP in HMA Mixes of Airfield Pavements.

Type of Mix	Recommended Virgin Asphalt Binder Grade	RAP Percentage		
		Recovered RAP Grade		
		PGXX-22 or lower	**PGXX-16**	**PGXX-10 or higher**
Surface and Base Mix	No change in binder selection	< 20%	< 15%	--
Base Mix	Select virgin binder one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used)	20% – 25%	15% – 25%	--
Surface and Base Mix	Follow recommendations from blending charts	--	--	< 10%

Sections P-401-3.3 and P-403-3.3 specify the percentage of asphalt in the RAP shall be established for the mixture design according to ASTM D2172 using the appropriate dust correction procedure.

In the case of the binder in the RAP, the two critical properties are: binder content and binder properties. The recommended procedures are AASHTO T164 or ASTM D2172 for the centrifuge (method A) or reflux (method B) extraction. The recommended procedures for the recovery of the extracted RAP binder are AASHTO T170 or ASTM D1856 for the Abson method or the ASTM D5404 for the rotary evaporator method. The physical properties and critical temperatures of the recovered RAP binder should be determined in accordance with section X1.2 in Appendix X of AASHTO M323. Using Table 30 with the determined RAP binder grade, the maximum allowable RAP content in the mix will be determined.

It should be noted that the ignition oven shall not be used for determining the RAP binder content. An ignition oven can change the gradation and properties of some aggregates because of aggregate particles breakdown. These breakdowns can lead to erroneous estimates of the binder content with some aggregates, especially for RAP sources with unknown correction factors.

Sections P-401-3.3 and P-403-3.3 does not specify or require the measurements of the physical properties of the RAP aggregate.

The gradation of the aggregates in the RAP materials shall be evaluated through the solvent extraction. The extracted RAP aggregate gradation shall be determined in accordance with AASHTO T30 or ASTM D5444. The bulk specific gravity of the extracted RAP aggregate should be determined and included in the calculation of the bulk specific gravity of the combined aggregates. The bulk specific gravity of the RAP aggregate may be estimated by determining the theoretical maximum specific gravity (G_{mm}) of the RAP mixture and using an assumed asphalt absorption for the RAP aggregate to back-calculate the RAP aggregate bulk specific gravity, if the absorption can be estimated with confidence. The RAP aggregate effective specific gravity may be used in lieu of the bulk specific gravity at the discretion of the engineering consultant or agency. The use of the effective specific gravity may introduce an error into the combined aggregate bulk specific gravity and subsequent VMA calculations. The engineering consultant or agency may choose to specify adjustments to the VMA requirements to account for this error based on experience with local aggregates. An increase of 0.3% in minimum VMA may be required for a 10% RAP content (After *Murphy Pavement Technology*).

Sections P-401-3.3 and P-403-3.3 requires the RAP containing HMA mix be designed using procedures contained in the Asphalt Institute's Manual Series Number 2 (MS-2). The job mix shall meet the requirements of paragraph 401-3.2. Additionally, the tensile Strength Ratio (TSR) of the composite mixture, as determined by ASTM D4867, shall not be less than 75%, nor shall the dry strength be less than 200 psi as determined by ASTM D1074. Anti-stripping agent shall be added to the asphalt, as necessary, to produce a TSR of not less than 75% while maintaining a minimum dry strength of 200 psi. Engineer may specify a TSR of not less than 80% in areas that are prone to stripping *instead of a TSR of 75%. Engineer may specify one or more freeze-thaw conditioning cycles in areas that are prone to stripping at a TSR of 75%.*

Because of moisture sensitivity concerns, the RAP containing mixes should, in addition to the minimum dry compressive strength of 200 psi (ASTM D1074), satisfy the recommendations of Table 31. The mix design shall demonstrate that the RAP containing mix can attain a minimum dry tensile strength as determined by ASTM D4867 of at least 90 psi for mixes with a PG64-XX or higher and of at least 70 psi for mixes with a PG58-XX or lower. Additionally, the Tensile Strength Ratio (TSR) of the final mixture, as determined by ASTM D4867, shall not be less than 80%. In severe climatic conditions multiple freeze-thaw conditioning are required at a TSR of 75%. Anti-strip additives need to be considered in every mix design at a rate determined by the appropriate testing and engineering judgment.

The engineer might decide on running the ASTM D4867 with 5 replicates in a subset instead of 3 to minimize the variability inhibited in the test. Any change in the characteristics of RAP materials (i.e., change in RAP source, RAP aggregate gradation, RAP binder content, etc.) will necessitate an entirely new mix design.

Table 31 ASTM D4867 Requirements for RAP Containing Mixes.

Virgin target binder	Dry Tensile Strength at 77°F	Tensile Strength Ratio at 77°F	Notes
PG64-XX or higher	Minimum 90 psi	Minimum 80%	• Severe climatic conditions might require multiple freeze-thaw cycles. • Consider anti-strip additive to improve long-term durability.
PG58-XX or lower	Minimum 70 psi	Minimum 80%	

Sections P-401-3.3 and P-403-3.3 specify the appropriate test should be selected to conform to the grade of new asphalt specified. If a penetration grade is specified, use *penetration test. If a viscosity grade is specified, use a viscosity test. If a PG asphalt binder is specified, use the dynamic shear rheometer and bending beam tests.*

When RAP is used in HMA mixes, the PG grade system shall be used for characterizing RAP binder grade as well as the grade of the blended binder recovered from the final mix.

Sections P-401-3.3 and P-403-3.3 specify that the blend of new asphalt cement and the RAP asphalt binder shall meet the requirements in paragraph 401-2.3. The virgin asphalt cement shall not be more than two standard asphalt material grades different than that specified in paragraph 401-2.3

Follow the recommendations of Table 30 for the virgin asphalt binder grades.

Sections P-401-3.3 and P-403-3.3 does not specify any additional quality control testing other than the one used for regular HMA mixes.

The quality control testing program specified by FAA P-401-6.3/P-403-6.3 requirements for regular HMA mixes should also be followed for the RAP containing HMA mixes besides the tests described in Chapter 6 for QC/QA that are necessary to control the RAP material during production.

For the surface mixes with RAP material the same acceptance criteria specified in FAA P-401-5.2 for regular HMA surface mixes will be followed. Acceptance is based on the stability, flow, and air voids of the HMA mix and mat density, joint density, thickness, smoothness, and grade of the constructed pavement.

For the base mixes with RAP material the same acceptance criteria specified in FAA P-403-5.2 for regular HMA base mixes will be followed. However, the acceptance criteria specified in FAA P-403-5.2 includes only mat density, joint density, thickness, smoothness, and grade of the constructed pavement. Therefore when RAP is used in the

HMA base mixes the stability, flow, and air voids of the HMA mix according to P-401-5.2 shall be included.

PROPOSED REVISION FOR THE FAA P-401-3.3/P-403-3.3 SPECIFICATIONS

401-3.3/403-3.3 RECYCLED ASPHALT CONCRETE. Recycled HMA shall consist of a mixture of reclaimed asphalt pavement (RAP), coarse aggregate, fine aggregate, mineral filler, and PG asphalt cement. The RAP is recommended to be used in surface or base mixes at the maximum proportions shown in Table 1.

Table 1 Maximum Allowable RAP Content in HMA Mixes.

Type of Mix	Recommended Virgin Asphalt Cement PG Grade	RAP Percentage Recovered RAP Binder PG Grade		
		PGXX-22 or lower	PGXX-16	PGXX-10 or higher
Surface/ Base Mix	No change in binder selection	< 20%	< 15%	0%
Base Mix	Select virgin binder one grade softer than normal (i.e. select a PG58-28 if a PG64-22 would normally be used)	20% – 25%	15% – 25%	0%
Surface/ Base Mix	Follow recommendations from blending charts	0%	0%	< 10%

NOTES:
1. The blend of virgin asphalt cement and the RAP asphalt binder shall meet the requirements in paragraph 401-2.3.
2. The virgin asphalt cement shall not be more than two standard asphalt material grades different than that specified in paragraph 401-2.3.

RAP should not be used at a percentage higher than the maximum specified in Table 1 unless if the recycled asphalt concrete mix is proven to have acceptable moisture resistance according to Table 2 and a good performance in fatigue (AASHTO T321) and thermal cracking under the thermal stress retrained specimen test.

The RAP shall be free of contaminants that are potentially detrimental to the mixture performance. Such contaminants may be, but not limited to, coal-tar sealer, rejuvenator, material containing coal-tar, and paving fabrics. The RAP shall be of a consistent gradation and asphalt content. When RAP is fed into the plant, the maximum RAP chunk size shall not exceed 2 inches.

RAP samples should be taken from 8 to 10 random locations distributed throughout the RAP pile and evaluated for RAP binder content and gradation. The average and standard deviation of the RAP binder content and aggregate gradation within the RAP stockpile should be determined and used to estimate the amount of RAP that can be added without exceeding the mixtures specification limits.

* *

The National Asphalt Pavement Association Series No. 123 on recycling HMA pavements showed that processing the RAP by crushing or screening, or both, can also help to reduce the variability in RAP material. Additionally, fractionating the RAP into different sizes may be necessary to maximize the percentage of RAP used in a mix and still meet the gradation and volumetric requirements. The NAPA publication provides a new and updated document on how to recycle and summarizes for producers and agencies the equipment and methods that others are successfully using to reclaim, size, store, and process RAP in various types of HMA facilities throughout the country.

* *

The recycled asphalt concrete mix shall be designed using procedures contained in the Asphalt Institute's Manual Series Number 2 (MS-2). The percentage of asphalt in the RAP shall be established according to ASTM D 2172 using the centrifuge (method A) or the reflux (method B) extraction. The extracted RAP binder shall be recovered for the mixture design according to ASTM D1856 for the Abson method or the ASTM D5404 for the rotary evaporator method. The PG grade of the recovered RAP binder shall be determined according to section X1.2 in Appendix X of AASHTO M323.

* *

The percentage of asphalt in the RAP can be established according to ASTM D6307 using the ignition oven only if the ignition oven is calibrated against the centrifuge or the reflux extraction methods.

It should be noted that an ignition oven can change the gradation and properties of some aggregates because of aggregate particles breakdown; therefore, local experience with typical aggregate types in ignition ovens should be considered. These breakdowns can also lead to erroneous estimates of the binder content with some aggregates, especially for RAP sources with unknown correction factors. Experience with local aggregates can indicate if an ignition oven is an appropriate method to use in a given area.

* *

The extracted RAP aggregate gradation should be determined according to ASTM D5444. The ash content from the solvent extraction must be accounted for in the RAP aggregate. The material passing No. 200 (0.075 mm) sieve must be monitored closely since RAP may have a significant amount of material passing No.200 sieve. The bulk specific gravity of extracted RAP aggregate should be determined and included in the calculation of the bulk specific gravity of the combined aggregates. The extracted RAP aggregate should be sieved into coarse and fine fractions with the specific gravity of each

fraction determined according to ASTM C127 and ASTM C128, respectively. Other methods for determining the bulk specific gravity of extracted RAP aggregate may only be accepted upon the approval of the Engineer. The recycled asphalt concrete mix shall meet the requirements of paragraph 401-2.1/403-2.1 for aggregate properties.
The job mix shall meet the requirements of paragraph 401-3.2/403-3.2. In addition to those requirements, the job mix formula shall indicate the percent of reclaimed asphalt pavement and the percent and PG grade of new asphalt binder. The Contractor shall submit documentation to the Engineer, indicating that the mixing equipment proposed for use is adequate to mix the percent of RAP shown in the job mix formula and meet all local and national environmental regulations.

Tensile Strength Ratio (TSR) and unconditioned tensile strength (TS) of the recycled asphalt concrete mix, as determined by ASTM D4867, shall conform to the requirements of **Table 2**.

Table 2 ASTM D4867 Requirements for RAP Containing Mixes.

Virgin target binder	Unconditioned Tensile Strength (TS) at 77°F	Tensile Strength Ratio (TSR) at 77°F
PG64-XX or higher	Minimum 90 psi	Minimum 80%
PG58-XX or lower	Minimum 70 psi	Minimum 80%
NOTES: 1. Engineer may specify multiple freeze-thaw conditioning cycles in severe climatic conditions or in areas that are prone to stripping at a TSR of 75%. 2. Engineer may specify the use of anti-strip additive to improve long-term durability. 3. Engineer may require running the test with 5 replicates in a subset instead of 3 to minimize the variability inhibited in the test.		

The acceptance criteria specified in paragraph P-401-5.2 shall be followed for all recycled asphalt concrete mixes.

The quality control testing program specified in paragraph P-401-6.3 shall be followed for all recycled asphalt concrete mixes.

* *

Table 3 gives ranges for sampling and testing RAP materials during production. The testing frequency should be adjusted based on the variability of materials in RAP and the type of mix being produced.

Table 3 Suggested Quality Control Schedule for RAP (after NAPA Series 124).

Test Description	Sampling Location	Frequency[1,2] (samples/lot)	Priority
Asphalt content	Stockpile or combined RAP feed	1 – 5	High
Gradation	Stockpile or combined	1 – 5	High
Binder extraction and recovery	Stockpile or combined RAP feed	1	Low
Binder properties	Post extraction and recovery	1	Low
Aggregate properties	Post extraction	1	Medium – Low

NOTES:
1. Frequency and types of testing will depend upon variability of source materials and the intended end-use of the HMA. Historical records and materials evaluation should be consulted before determining testing frequency.
2. If the RAP stockpile is built ahead of production and additions are not being made to the pile, it may be possible to dramatically reduce the sampling frequency.

* *

CHAPTER 8 OUTLINE FOR THE TRAINING PRESENTATION

This Chapter illustrates the anticipated outline for the 4-hour training course on the use of RAP in HMA mixture on airfield pavements.

- Review of FAA current specifications on the use of RAP in airfield pavements.

- Benefits of RAP in HMA mixtures.
    - Economic aspect.
    - Impact of RAP on performance life.

- Review of impact of RAP content on mixtures properties and field performance.
    - Review of research study.
    - Performance of HMA mixes containing RAP in highway pavements.
    - Performance of HMA mixes containing RAP in airfield pavements.
    - State highway agencies use of RAP.
    - Recommendations on the maximum allowable RAP content in airfield pavements.

- RAP characteristics
    - RAP source.
    - RAP variability.

- Mix design
    - RAP materials evaluation.
    - Mix design.
    - Job mix.

- Acceptance criteria and quality control testing program.

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