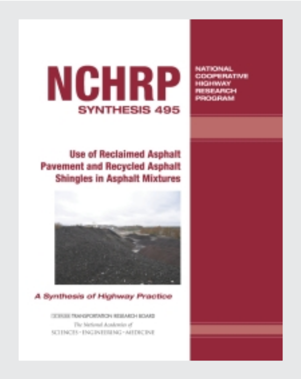

Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 495

Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments and by committees of AASHTO. Topics of the highest merit are selected by the AASHTO Standing Committee on Research (SCOR), and each year SCOR's recommendations are proposed to the AASHTO Board of Directors and the Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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Cover figure: RAP stockpiles. *Credit*: Mary Stroup-Gardiner

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Donna L. Vlasak
Senior Program Officer
Transportation Research Board

This synthesis summarizes current practices for the use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in the design, production, and construction of asphalt mixtures. It focuses on collecting information about the use, rather than just what is allowed, of high RAP, RAS, and/or a combination of RAP and RAS.

A literature review, a survey of state agencies, and case examples were used to document current knowledge and practices.

Mary Stroup-Gardiner, Gardiner Technical Service, Monterey, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

USE OF RECLAIMED ASPHALT PAVEMENT AND RECYCLED ASPHALT SHINGLES IN ASPHALT MIXTURES

SUMMARY

The practice of utilizing reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in new asphalt mixtures has increased in recent years because of its economic and environmental benefits. RAP has already become one of the most widely used materials in the United States, and RAS is emerging as a material of interest to the paving community. With increased demand and limited supplies of aggregate and binder, recycled materials with usable asphalt binders and aggregates can be valuable sources of these materials. Although the potential benefits associated with using these recycled materials are high, only a few state agencies currently use more than 25% RAP (designated as high RAP in this synthesis), RAS, or a combination of both in their roadway asphalt mixtures. The objective of this synthesis is to summarize current practices for the use of high RAP and RAS in the design, production, and construction of asphalt mixtures.

The scope of this synthesis focuses on collecting information about the *use*, rather than just what is allowed, of high RAP, RAS, and/or a combination of RAP and RAS. A literature review, a survey of state agencies, and case examples were used to document current knowledge and practice. The literature review collected information about designing, producing and placing, testing, actual performance, and potential economic benefits when using high RAP, RAS, or a combination of both in asphalt mixtures.

State materials engineers were surveyed to collect information about current practices for determining recycled material properties, developing mix designs, and using laboratory testing for assessing pavement performance. State construction engineers were surveyed about how to produce and place mixtures with recycled materials. Responses were received from 45 of the 51 agencies (50 states and the District of Columbia), an 88% response rate.

Case examples were developed for five key topics. The first example shows how the Georgia Department of Transportation (DOT) developed and revised its specifications to encourage contractors to consistently submit mix designs using from 30% to 40% RAP in all pavement layers. The second example documents contractor practices and procedures used to produce and place high RAP mixtures for Georgia and five other surrounding states (Alabama, Florida, North Carolina, South Carolina, and Tennessee). The third case example provides guidance from a Missouri contractor for processing RAS for use in asphalt mixtures. The fourth case example shows how the Minnesota DOT collected performance data from non-state agency project roadway databases (i.e., county roadways) used in surface mixtures. The fifth example documents four recent research projects (three RAP, one RAS) designed to estimate the percentage of recycled asphalt binder that can be transferred to the virgin aggregate in the asphalt plant before the virgin asphalt is added (i.e., dry mixing).

Information obtained from the literature and from the surveys show that recycled material asphalt influences the upper and lower critical performance grade (PG) temperatures with the upper critical temperatures changing about twice as fast as the lower critical temperatures. The asphalt in tear-off RAS, also referred to as postconsumer RAS, is stiffer than that from manufacturing waste (preconsumer) RAS. Either source of RAS has asphalt properties that are significantly stiffer than RAP asphalt.

Gradations of the recycled material aggregate are routinely directly measured. The aggregate specific gravity is estimated from measurements of the theoretical maximum specific gravity of the recycled material (prior to removing the asphalt), although a few agencies directly measure the fine and coarse aggregate specific gravity after either ignition oven removal or solvent extraction of the asphalt.

Laboratory practices for drying recycled materials, batching materials for sample preparation material, preheating times and temperatures, and the order of the addition of materials to the mixing bowl vary considerably. Each state agency or group of researchers uses different test methods and criteria for the laboratory assessment of performance characteristics. At this time, there are no consistent practices for preparing, testing, and evaluating asphalt mixtures with recycled material content.

RAP material can be obtained from the demolition of old pavement that produces chunks that have to be broken up or crushed, milling of existing pavement surfaces, and fresh mixtures remaining from plant start-up, shutdown, or rejected out-of-specification mixtures. RAP aggregate gradations, dust content (i.e., percent passing 0.075-mm sieve), and asphalt content vary because of the types of equipment used to crush and/or mill the old pavement, processing practices, milling depths, and the types of mixtures in each layer milled. Fractionating the RAP into two, or at most three, sizes can help minimize material variability when higher percentages of RAP are used. Finer RAP fractions tend to have higher asphalt contents than coarser fractions, but can also have high percentages of minus 0.075-mm material that can limit the percentage of RAP that can be used (i.e., specification limits on dust-to-asphalt ratio).

Several agencies use specific terms to designate RAP materials based on common aggregate characteristics, asphalt content and properties, how the RAP is processed (e.g., "extended RAP"), and how the stockpile is built, tested, and maintained (e.g., "captive" and "continuous"). However, this terminology is agency-specific; there is no consistency in terms.

Separate stockpiles are required for manufacturer because the asphalt content and properties are significantly different for manufacturer (pre-consumer) and tear-off (post-consumer) waster RAS. The aged tear-off shingle asphalt is significantly stiffer than the asphalt in manufacturing waste RAS. Regardless of the type, RAS ground to a maximum particle size of 3/8 in. is more easily distributed throughout the asphalt mixture during production.

The age, type, and equipment options (e.g., flighting, double drums, and separate drying drums for recycled materials) of the plant control the ability of the plant to remove any moisture in the recycled materials. The percentage and/or type of recycled material that can be added to the mixture is directly related to the ability of the plant to remove the moisture. Although covering the recycled material stockpiles help minimize moisture content, only a limited number of agencies indicated that this practice is either used by contractors in their state or is required by their agency.

Contractor costs increase significantly because higher plant temperatures (i.e., increased energy consumption) are required to superheat the virgin aggregate for heat transfer to the recycled materials. Increased wear on plant equipment and baghouse damage resulting from the high heat and increased down time for maintenance also increase costs. High plant temperatures can also damage asphalt properties and increase the likelihood of penalties (disincentives) for out-of-specification mixture temperatures. These additional production costs can offset savings from lower material costs, which is one of the potential benefits attributed to the increased use of recycled materials.

The pavement performance reported in the literature found that performance is related to construction difficulties, the percentage of virgin asphalt in the mixture, and changes in the upper virgin asphalt PG temperature. Early signs of pavement distress(es) in RAP mixtures corresponded to documented construction difficulties such as visible deleterious materials (oversized RAP), dry looking mixtures (low asphalt contents), and mixture segregation. Reductions in load-related longitudinal cracking can be achieved by using a virgin asphalt with a reduced upper PG temperature. More than 5 years of service life is the minimum time needed for differences between virgin (control) mixtures and mixtures with recycled materials to emerge. Mixtures placed next to or over jointed or cracked portland cement concrete pavements show signs of reflective cracking, regardless of whether or not recycled materials are used in the mixtures.

Suggestions for future research that may help increase the use of recycled materials in asphalt pavements included

- Improve laboratory procedures for drying, preparing, preheating, mixing, and compacting mixtures that more closely replicate what happens during production at the asphalt plant.
- Study of existing pavements with high RAP content (more than 25%), RAS, and combinations of RAP and RAS in surface mixtures for more direct correlation between the type and percentage of recycled materials and individual pavement distresses.
- Establish the expected service life of mixtures with recycled materials. This information is necessary for life-cycle cost calculations.
- Study recyclability of high RAP, RAS, and RAP/RAS combination mixtures.
- Investigate the impact of minimum and maximum silo storage times on recycled material asphalt mixtures.

CHAPTER ONE

INTRODUCTION

According to FHWA, there are approximately 2.8 million miles of paved public roadways in the United States, which have used approximately 18 billion tons of asphalt mixtures. These mixtures are typically comprised of approximately 95% quarried rock products and/or sand and gravel pit extracted materials, and 5% asphalt obtained from the processing of crude oil. Preserving, maintaining, and expanding the highway infrastructure requires a continual supply of the natural resources that are used in pavements. In recent years, roofing shingle byproducts from the manufacturing process and from construction and demolition projects have been identified as an additional source of asphalt and aggregate materials that can have economic and environmental advantages when used as a partial replacement for asphalt mixture material components.

Although approximately 99% of asphalt pavement material that is removed from any roadway is recycled back into infrastructure-related materials and products, there are a number of factors that limit the most economically and environmentally beneficial uses of the reclaimed asphalt pavement (RAP) materials. Barriers to increased RAP use in higher quality asphalt mixtures include higher RAP variability because of different RAP sources, demolition and milling processes, and aged asphalt with significantly different properties than required for fresh asphalt mixtures.

Major barriers to the acceptance and/or increased use of recycled asphalt shingles (RAS) in asphalt mixtures are the result of significantly different asphalt properties of roofing shingle asphalt compared with the properties of paving grade asphalts needed for acceptable pavement service life. Additional barriers to the use of RAS include contaminates from the waste recovery processes (e.g., non-RAS materials from construction and demolition waste), potentially hazardous materials in older products (e.g., asbestos and coal tar), and uniform processing practices that provide materials that can be handled with current asphalt plant technology.

Information needed to increase the use of RAP or encourage the general acceptance of RAS by state agencies includes McGraw et al. 2010; Scholz 2010; Copeland 2011; and Willis et al. 2012:

- Measuring the recycled material properties and material variability.
- Guidance for asphalt mix design practices and procedures that include different or a higher percentage of recycled materials.
- Understanding how the age and type of asphalt plant equipment impacts the addition of recycled materials during production.
- Documented pavement performance (service life) of roadways constructed with asphalt mixtures containing higher percentages of RAP, RAS, or with combinations of the two.

The accurate measurement of recycled material properties can be difficult because traditional test methods were developed using virgin aggregates and asphalts. Determining the properties of the individual recycled materials requires separating the materials by removing and recovering the asphalt, as well as collecting the remaining mineral materials. It is important to make appropriate selections of and modifications to test methods used to characterize recycled material asphalt and aggregate properties. It is important that the selected test methods and any modifications be documented, as well as information about any additional asphalt testing requirements so that increase testing time and costs can be anticipated.

Asphalt mix designs are used to determine the optimum asphalt content and the combinations of aggregate sizes (i.e., gradation) needed to achieve key performance-related mixture properties. When recycled materials are added to the mixture, the calculation or estimation of the contribution of recycled material asphalt to total asphalt content is required. The virgin asphalt grade needs to be selected to offset for changes in the asphalt properties owing to the inclusion of the recycled material asphalt. It is important that the existence of standardized laboratory practices and procedures, and performance-related laboratory tests and criteria to estimate pavement performance be identified.

Asphalt plant type, age, and characteristics influence the uniformity of asphalt mixtures with different or higher percentages of recycled materials. Useful processing and stockpiling practices for recycled materials, additional testing for quality control (QC) recycled material property variability, and any asphalt plant modifications that can be made to increase the percentage and/or type of recycled materials needs to be identified.

Any documented pavement performance of asphalt mixtures with high RAP, RAS, or a combination thereof is also necessary.

Information related to these topics was collected through a literature review and two agency surveys. The state materials engineers were surveyed to collect information about determining recycled material properties, procedures, and practices for preparing mix design samples, volumetric and performance testing, and their perceptions of the impact of different types and percentages of recycled materials on performance. State construction engineers were surveyed to collect information about processing and stockpiling recycled materials, asphalt mixture production, transport, and placement of asphalt mixtures with recycled materials. Responses were received from 45 of the 51 agencies (50 states and the District of Columbia), which is an 88% response rate (Figure 1).

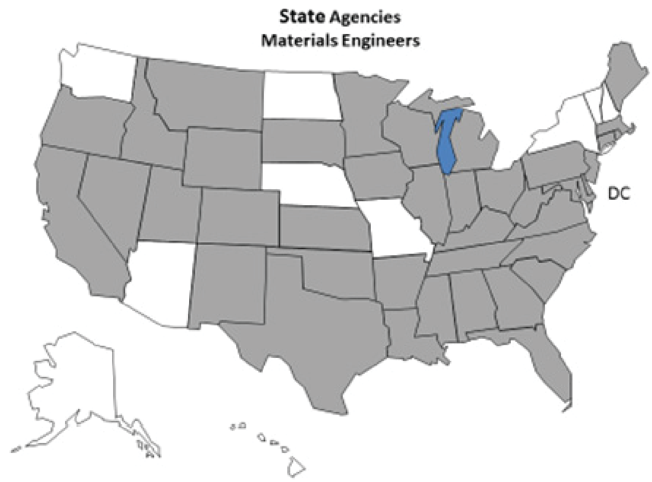


FIGURE 1 Agencies participating in surveys (shaded states are responding agencies). (*Source*: Stroup-Gardiner.)

This synthesis is organized by the follows topics:

- Chapter two—Literature Review
- Chapter three—State Material Engineer Survey
  - Topics covered in this survey included recycled material properties, mix design practices and procedures, and volumetric and performance testing.
- Chapter four—State Construction Engineer Survey
  - Topics covered in this survey included producing and placing high RAP, RAS, and combination RAP and RAS mixtures.
- Chapter five—Case Examples
  - Topics include revising state specifications to encourage routine high RAP usage (state agency and contractor perspectives), locating and using nonstate agency databases for evaluating pavement performance, contractor's perspective for using RAS, and recent research studies to evaluate transfer of recycle material asphalt to virgin aggregate.
- Chapter six—Conclusions
- Abbreviations and Acronyms
- References
- Appendix A—State Materials Engineer Survey
- Appendix B—State Construction Engineer Survey
- Appendix C—Responding Agencies

CHAPTER TWO

LITERATURE REVIEW

Since 2009, the National Asphalt Pavement Association (NAPA) has tracked the use of RAP and RAS in the United States through annual industry surveys, and has determined that the use of both has increased in the United States (Hansen and Copeland 2013). In 2009, contractors in 23 states reported producing less than 15% of their total amount of asphalt mixtures with RAP (Figure 2). By 2012, contractors in only 12 states used RAP in less than 15% of their total tonnage (i.e., more states using at least 15% RAP). These changes represent an increase in the total tonnage of asphalt mixtures with RAP by 22% from 2009 to 2012 (from 56 to 68.3 million tons). RAP is used in all states and is typically available throughout each state, although the majority of the RAP stockpiles are usually concentrated along major highways (transportation logistics) and near urban areas (more miles of roadways) (Figure 3).

RAS was used in almost 1.9 million tons of asphalt mixtures in 2012. As of 2012, contractors in 17 states reported using RAS in all four of the annual NAPA surveys (Figure 4). However, contractors in 10 states failed to report using RAS in any of the NAPA annual surveys. Contractors in four states (Florida, Georgia, West Virginia, and Massachusetts) reported using RAS prior to 2012, but did not report any usage in 2012 (i.e., fewer states using RAS).

Information about RAP and RAS topics that influence the use of these materials in asphalt mixtures are presented in this chapter. This information is organized into the following topics:

- Recycled material properties
- Asphalt mix designs with recycled materials
- Mixture testing
- Asphalt plant practices and equipment
- Pavement performance
- Economics
- Research in progress.

RECYCLED MATERIAL PROPERTIES

The recycled material asphalt content, asphalt properties (after extraction and recovery), aggregate gradation, and aggregate specific gravity are most often determined by testing. Aggregate consensus properties (i.e., various particle shape characteristics) and source properties (toughness, durability, clay-sized particulates, and polish value) are only occasionally determined, if at all, at this time. Any requirements are agency-specific and can require the testing of individual recycled materials or the properties of the total asphalt mixture after removing the asphalt from the particulates.

Asphalt Content

Either the ignition oven (AASHTO T308) or solvent extraction (AASHTO T164) test methods can be used to measure the asphalt content of recycled materials. The ignition oven burns the asphalt off of the aggregate at high temperatures and the percentage of mass loss is measured as the asphalt content. In some cases, a correction factor may be needed for nonasphalt components that burn off along with the asphalt (e.g., some limestones and shingle backing materials). These factors can be established by calculating the difference in the asphalt content between solvent extraction and ignition oven results. Alternatively, historical laboratory results can be used to estimate aggregate correction factors. When testing RAS, AASHTO PP78-14 recommends using 400 grams of RAS so that the ignition oven ventilation system is not overloaded (i.e., clogged). If necessary, the RAS sample can be split and run and tested in two parts. One report noted the ignition oven RAS asphalt content was higher than obtained with solvent extraction (Roque et al. 2015).

Centrifuge or reflux solvent extraction methods to determine the asphalt content use one of several solvents [trichloroethylene (TCE), *n*-propyl bromide (nPB), toluene, methylene chloride, or a toluene and ethanol blend]. When the asphalt does not have to be recovered from the solvent for asphalt testing, a vacuum extraction method or simply soaking the recycled materials in solvent can be used to estimate the amount of asphalt in recycled material. Alternatively, an organic solvent such as Bioact™ can be used with all of the solvent extraction methods when the asphalt does not need to be recovered. Any solvent extraction method can have difficulties with removing all of the asphalt from both porous (absorptive) virgin aggregates and from RAP because of the strong bonds of the harder asphalt with the aggregate surface. The hard RAS asphalt can be difficult to dissolve and remove from the other shingle materials with solvents (NCAT 2012).

In general, the asphalt content determined with the ignition oven method is slightly higher than determined using solvent extraction methods (Michael 2011). This is attributed to a small percentage of the asphalt being strongly bound to the aggregate, which is not removed by the solvent.

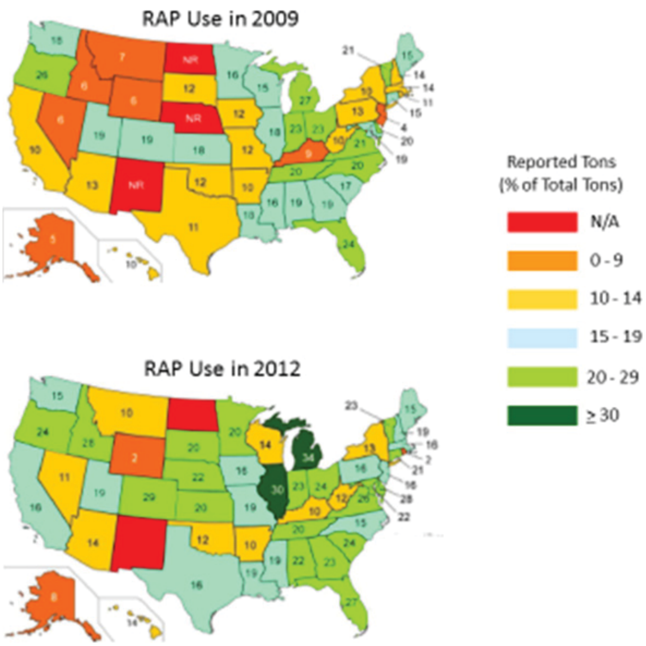


FIGURE 2 Use of RAP in the United States in 2009 and 2012 as reported by contractors (*Source*: Hansen and Copeland 2013).

Advantages associated with using the ignition oven method for determining the asphalt content are that test results can be obtained quickly for QC testing and aggregate properties can be determined after the asphalt is removed. Disadvantages include the need for correction factors to account for the mass loss of materials other than asphalt, which may be burned off during testing.

Advantages for using solvent extraction are that the asphalt can be recovered for testing and the aggregate properties can be determined after the asphalt is removed. The disadvantages are the length of test time, the need to use solvents that are costly to purchase and to dispose of after testing, and worker safety concerns.

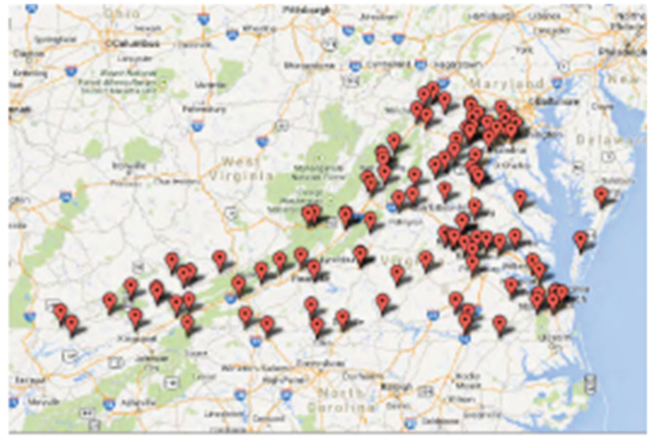


FIGURE 3 Example of locations of RAP stockpiles along transportation routes and around urban areas in Virginia (*Source*: Hoppe et al. 2015).

Measuring Asphalt Content—Section Summary

- The ignition oven method is used more frequently to determine the asphalt content; however, correction factors may be necessary to account for any aggregate mineralogy or other nonasphalt material that also burns off. Adjustments to the oven temperatures and sample size for testing RAS may be necessary.
- Solvent extractions are used to remove the asphalt from recycled materials when the recycled material asphalt is to be recovered for testing. However, fewer agencies use solvent extraction methods because of the difficulties with obtaining and disposing of the solvents (i.e., safety and environmental hazards).

RECYCLED MATERIAL ASPHALT PROPERTIES

Both the centrifuge or reflux solvent extraction methods generate a solution of solvent and asphalt from which the asphalt can be recovered using either the Abson (AASHTO T170) or

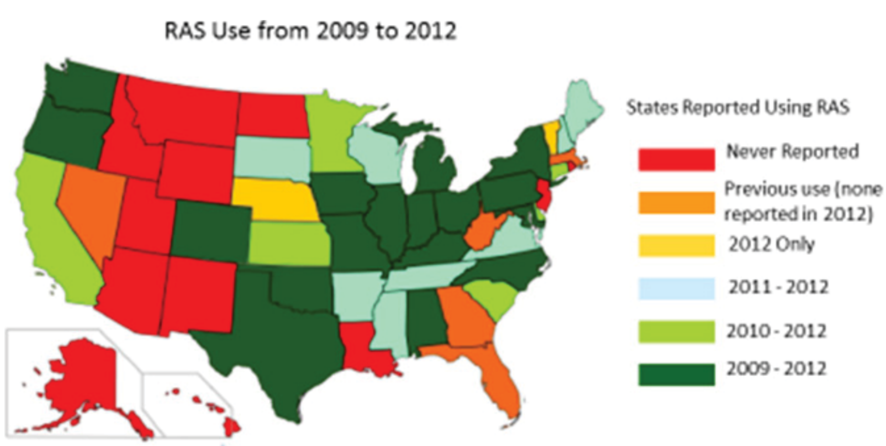


FIGURE 4 Use of RAS in the United States as reported by contractors (*Source*: Hansen and Copeland 2013).

Rotavapor (ASTM D5404) recovery methods. A range of solvents (TCE, nPB, and methylene chloride) can be used with either method. Zhou et al. (2013) compared different extraction and recovery methods for RAS asphalt for testing and found that neither the choice of extraction or recovery method influenced RAS asphalt properties.

An alternative method for extraction and recovery is detailed in the AASHTO T319 Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binders from Asphalt Mixtures. This test method uses a combined solvent extraction–Rotavapor recovery process. However, significant difficulties with extracting and recovering when using the AASHTO T319 method were noted by Scholz (2010) when testing RAS samples that included:

- RAS asphalt clogged screens and the outlet of the extraction vessel.
- Material was described by lab staff as very thick and viscous.
- Removing tear-off shingle asphalt with solvent extraction was difficult.
- Recovering sufficient RAS asphalt for low temperature binder testing was difficult.

The recovered asphalt is used to determine the upper and lower critical PG temperatures using:

- A rotational viscometer (Brookfield) at high temperatures;
- A dynamic shear rheometer (DSR) at high, intermediate, and low temperatures; and
- A bending beam rheometer (BBR) at low temperatures.

DSR testing is used to determine the critical high PG temperature and evaluate properties at intermediate and low in-service temperatures. Test results for both the virgin and recycled material asphalt are used to estimate changes in the upper critical PG temperature based on the percentage of each asphalt in the anticipated total asphalt blend. Roque et al. (2015) used DSR testing to evaluate recycled RAP and virgin asphalt and found the shear modulus (G^*) as well as the $G^*/\sin\delta$ parameter increased with the increasing percentage of RAP at both the high and intermediate test temperatures. Different RAP sources had different shear moduli and other DSR parameters. Maupin et al. (2008) found that RAP asphalt changed the high and low temperature asphalt grading, with the low temperature grading changing from a PG xx-22 to a PG xx-16 for the recovered asphalts from RAP mixtures and increased the high PG temperature by one to two grades.

Scholz (2010) reported difficulties in determining the low temperature DSR properties for RAS asphalt because the stiffness of the asphalt exceeded the DSR equipment limitations. Similar difficulties were reported by NCAT (2012) and Zhou et al. (2013).

BBR results use measurements of the asphalt stiffness, *s*, and a rate of change in stiffness with time parameter, m-value, at low temperatures to determine the critical low PG temperature. Roque et al. (2015) found the low temperature BBR stiffness increased with increasing RAP, m-value decreased with the increasing percentage of RAP, and the magnitude of the changes were dependent on the RAP source. Several other researchers reported that the critical low PG temperature increased with increased recycled material asphalt (Maupin et al. 2008; Schroer 2009; McGraw 2010; Booshehrian et al. 2013; Scholz 2010; Zhou et al, 2013).

Scholz (2010) used the correlation between changes in the critical upper PG and changes in the critical lower PG temperatures to estimate the critical low temperature for RAS asphalt. Scholz found this approach useful because DSR equipment limitations precluded testing the stiff RAS asphalt at low test temperatures.

Limited information about changes in the viscosities of blends of virgin and recycled asphalts were found in the literature, most likely the result of the large sample size that has to be extracted and recovered for this test. Roque et al. (2015) showed that rotational viscosity increased with a combination of RAP and polymer-modified virgin asphalt, but the magnitude of the changes was dependent on the RAP source. When between 20% and 40% RAP asphalt was blended with crumb rubber modified asphalt the stiffness of the crumb rubber asphalt masked the impact of one source of RAP asphalt (little change).

This concept of a linear relationship between changes in the upper and lower critical temperatures was used in this synthesis to compare DSR data from multiple studies. Data generated from six different research projects with different types, percentages, and combinations of recycled materials, as well as different virgin asphalt grades and various rejuvenators were used to develop a regression equation (Figure 5) that

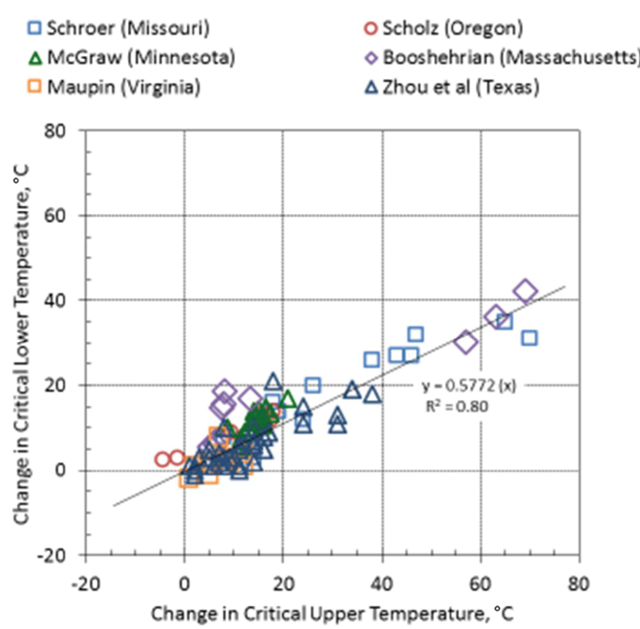


FIGURE 5 Correlation of changes in upper critical PG temperatures to changes in the lower critical PG temperatures.

shows that Scholz' conclusion of a generally linear relationship between changes in critical upper and lower PG temperatures can be replicated with data from other researchers. The upper critical temperature changes almost twice as much as the lower critical temperature.

Two additional test methods, the multiple stress creep recovery and the binder fracture energy tests, were used by various researchers to evaluate the impact of recycled material asphalt on performance-related asphalt properties. The multiple stress creep recovery test (AASHTO TP70) uses the data to calculate the nonrecoverable creep compliance and the average percent recovery information that is used to indicate asphalt-related rutting characteristics. Roque et al. (2015) found that the nonrecovery creep compliance decreased with the increasing percentage of RAP (i.e., rut resistance increased). The results were dependent on the RAP source and the percent recovery parameter was more dependent on the type of polymer modifier in the asphalt than on the percentage of RAP. Other researchers found the nonrecoverable creep strain, J_{nr}, also had a good correlation with rut resistance (Anderson and Bukowski 2012; Booshehrian et al. 2013), with lower J_{nr} values indicating improved rutting resistance. The higher percentage strain recovery, ε, values also indicate increased resistance to rutting.

The binder fracture energy test was developed to predict the cracking potential of the asphalt at intermediate temperatures (Roque et al. 2015). The geometry is designed to focus the failure location at the center of the specimen (Figure 6) and the area under the stress and strain plot is used to calculate the fracture energy density, which is the area under the stress strain curve up to stress peak. The fracture energy density decreased with increasing RAP and was sensitive to the different RAP (i.e., cracking potential increased) sources used in the study.

New Approach to Binder Modification with RAS

Recent research explored a different approach to incorporating RAS asphalt into virgin asphalt (Salari 2012). This study adapted a concept for using finely ground tire rubber as an asphalt modifier, which is referred to as the wet process, for incorporating ultra-finely ground RAS. Grinding of the RAS was accomplished using a Pulva-Sizer with a rotor assembly and hammer mill, and operated at 9,600 rpm. A Coulter Particle Size Analyzer, operated in wet mode, showed that the mean RAS particle sizes were 85.5 µm for tear-off RAS and 201.9 µm for manufacturer waste RAS. Asphalt and RAS blends were prepared using a mechanical shear mixer operated at 1,500 rpm for 30 minutes using 0%, 10%, 20%, 30%, and 40% RAS.

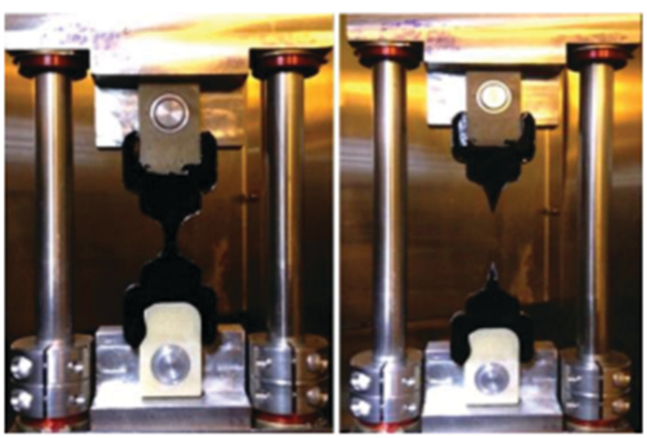


FIGURE 6 Binder fracture energy test (*Source*: Roque et al. 2015).

An HP-GPC analysis was used to evaluate changes in the high and low molecular weight components in the blended asphalts. Results showed the high molecular weight content (3,000 or greater) increased slightly for the RAS blends and there was more of a shift toward the higher molecular weights when blending the RAS with the softer PG 52-28 asphalt, which indicates an increased potential to crack at warmer critical low PG temperatures.

Confocal laser scanning microscopy used to detect the formation of wax crystals can be responsible for asphalt hardening at low temperatures (i.e., increase critical low PG temperature). The results showed that waxy crystals in the virgin asphalt were not evident once RAS was added. The microscopy also showed that ground minerals were uniformly dispersed in the asphalt.

Brookfield rotational viscosity testing of the finely ground RAS increased the viscosities from 3% to 130% over a range of temperatures (95°C to 135°C). The viscosity increase was proportional with the increasing percentage of RAS and the viscosities were higher, as expected, when the blends were produced with the tear-off shingles. The Brookfield viscosity measurements were designed to estimate the viscosity temperature susceptibility (VTS) using the following equation:

$$VTS = \frac{(\log\log(n_1) - \log\log(n_2))}{\log(T_2 + 273.15) - \log(T_1 + 273.15)}$$

Where:

n_1 and T_1 = viscosity in Pa.s at $T_1 = 95°C$
n_2 and T_2 = viscosity in Pa.s at $T_2 = 135°C$.

Increases in VTS indicate increases in the temperature susceptibility of the asphalt. In general, VTS changes were small and the trends showed that the value of VTS decreased with the increasing percentage of RAS.

Superpave asphalt testing revealed that the RAS increased both the critical upper and lower PG temperatures. DSR frequency sweeps showed that the only significant differences in the shear modulus and phase angle were seen at 5°C. Blends of virgin asphalt and 10% RAS were less stiff and more elastic (higher phase angle) than the 20% RAS blend. The thixotropy (i.e., non-Newtonian behavior) of the blends increased with the percentage of RAS at the intermediate temperatures, but not at the upper or lower temperatures. The shear stress increased with increasing RAS and the samples tended to fail during testing at 6°C.

Separation of the RAS and particulate materials during storage was evaluated using the "cigar tube" test (ASTM D7173-05). At 20% or lower percentages of RAS, some blends showed evidence of separation and high levels of separation at the 40% RAS level, possibly the result of the mineral fillers settling to the bottom over 48 hours and suggested that a digestion tank with an agitator and heater can be implemented if the wet process is used to produce these types of blends in the field.

Recycled Material Asphalt Properties— Section Summary

- DSR shear modulus and rotational viscosities increase with increasing recycled asphalt content. Changes in the critical PG temperatures can be dependent on RAP sources.
- Recycled materials appear to have more influence on the upper and intermediate critical asphalt temperatures than on the low critical temperatures. Upper critical temperatures increase about twice as quickly as the lower critical temperatures.

RECYCLED MATERIAL AGGREGATE PROPERTIES

Gradations are typically evaluated after the asphalt is removed from the recycled materials using either the ignition oven or solvent extraction methods. Roque et al. (2015) found that gradation analysis of aggregates after using the ignition oven were finer than for the same aggregates recovered from solvent extraction.

Consensus properties (i.e., particle shape characteristics), other than gradation, are less frequently determined for recycled material particulates. Particle shape characteristics include the measurement of flat and elongated particles (ASTM D4791), percent fractured faces of coarse aggregates (AASHTO T61 and ASTM D5811), and the fine aggregate angularity (AASHTO TP56). Fine aggregate angularity (AASHTO TP56) is only necessary when there is more than about 30% fine RAP aggregate (Newcomb et al. 2007).

Source aggregate properties are rarely determined for RAP aggregate because the testing was used to accept the original aggregate source when the asphalt mixtures were originally produced. Source properties include sand equivalent (AASHTO T76 and ASTM D2419), organic impurities (AASHTO T21 and ASTM C40), clay lumps and friable particles (AASHTO T112 and ASTM C142), toughness with the Los Angeles abrasion test (AASHTO T96), and soundness (AASHTO T104 and ASTM C88). If toughness is to be evaluated, the micro-Deval method (AASHTO T58) can be used (Newcomb et al. 2007; Copeland 2011).

The sand equivalent may be waived because of changes in aggregate properties after either ignition oven or solvent extraction methods can influence the test results.

Aggregate Bulk Specific Gravity

The bulk specific gravity (G_{sb}) of the virgin and recycled material aggregate is required to calculate the voids in mineral aggregate (VMA), a key mix design volumetric property. Aggregate-specific gravity can be measured for the aggregate remaining after either the ignition oven or solvent extraction. However, measured bulk specific gravities tend to be higher for aggregates obtained from the ignition oven than from solvent extraction (Table 1).

Alternatively, the recycled material theoretical maximum specific gravity, G_{mm}, can be measured and the value is used to estimate the effective specific gravity, G_{se}:

$$G_{se} = \frac{(100 - P_b)}{\left(\frac{100}{G_{mm}}\right) - \left(\frac{P_b}{G_b}\right)}$$

The recycled material asphalt content, P_b, is obtained using either the ignition oven or solvent extraction method and the recycled material asphalt-specific gravity, G_b, can be obtained from historical records or assumed based on

TABLE 1
EXAMPLE OF THE PERCENTAGE OF ASPHALT CONTENT OBTAINED BY IGNITION OVEN AND SOLVENT EXTRACTION* AS WELL AS THE BULK SPECIFIC GRAVITIES OF THE AGGREGATES AFTER THE ASPHALT IS REMOVED

Property		RAP 1	RAP 2	RAP 3	RAP 4	RAP 5	RAP 6
P_b	After Ignition Oven	5.43	5.04	5.81	6.27	5.3	5.62
	After Solvent Extraction	5.64	4.98	5.11	5.28	4.69	5.18
G_{sb}	After Ignition Oven	2.765	2.689	2.682	2.525	2.632	2.643
	After Solvent Extraction	2.719	2.647	2.650	2.481	2.610	2.573

Source: Michael (2011).
*Centrifuge extraction with TCE solvent was used.

experience. The calculated effective specific gravity is then used to calculate the bulk specific gravity of the aggregate, G_{sb}, using:

$$G_{sb,estimated} = \frac{G_{se}}{\left(\frac{G_{se}\ P_{ba}}{(100)(G_b)}\right)+1}$$

The percentage of asphalt absorbed, P_{ba}, by the recycled aggregate is generally assumed based on typical values for local aggregate sources or previous experience when using RAP. The asphalt absorption by the RAS particles is considered to be negligible (AASHTO PP78-14).

Adjustments to the theoretical maximum specific gravity test (AASHTO T209, ASTM D2041) may be necessary to keep the RAS particles from floating on top of the water during testing. Misting alcohol onto the surface helps reduce the surface tension and allows the RAS particles to settle (AASHTO PP78-14).

It is important that the effective specific gravity not be used as a direct replacement for the bulk specific gravity value of the RAP; however, because of the low absorption of the RAS aggregate, G_{se}, the RAS effective specific gravity can be used until a better method is available (AASHTO PP78-14).

Recycled Material Aggregate Properties—Section Summary

- Gradations of recycled material aggregates are determined after either ignition oven or solvent extraction to remove the asphalt. The ignition oven may damage the aggregate and gradations tend to be finer than after solvent extraction.
- Aggregate specific gravity measured after ignition oven testing is typically higher than values obtained after solvent extraction.
- Aggregate specific gravities can be calculated by measuring the theoretical maximum specific gravity, calculating the effective aggregate specific gravity, and, finally, the bulk specific gravity of the aggregate.
- Using the effective specific gravity of the recycled material aggregates as a direct replacement for the bulk specific gravity is *not recommended for RAP*, but can be acceptable for RAS because of the negligible absorption of asphalt by the RAS particles.
- Consensus and source aggregate properties are not typically measured for individual recycled material aggregates at this time, although these properties may need to be determined when the percentage of recycled material increases.

ASPHALT MIX DESIGNS WITH RECYCLED MATERIALS

Total Asphalt Content

The total asphalt content (TAC) in the asphalt mixture is a function of the virgin asphalt and the available asphalt from the recycled materials. There are three approaches that can be used to establish the asphalt content available from the recycled materials. The first is to assume the entire asphalt content in the recycled material contributes to the total asphalt content. The second approach is to consider that none of the recycled asphalt is useful (i.e., "black rock"). The third approach acknowledges that the reality is somewhere in between, but that the actual percentage is difficult to determine. Regardless of which approach is used, the general equation for calculating the total asphalt content of the asphalt mixture is:

$$\text{TAC} = \begin{bmatrix} F_{\text{RAP}}(\text{RAP AC})(\text{RAP\%}) \\ +\ F_{\text{RAS}}(\text{RAS AC})(\text{RAS\%}) \\ +\ \text{Virgin AC\%} \end{bmatrix}$$

Where:

$F_{\text{RAP}}, F_{\text{RAS}}$ = Asphalt availability factors for RAP and/or RAS asphalt content;
RAP AC = Asphalt content of RAP, decimal form;
RAP% = Percentage of RAP in mixture, %;
RAS AC = Asphalt content of RAS, decimal form; and
RAS% = Percentage of RAS in mixture, %.

When 100% of the recycled material asphalt is considered to contribute to the total asphalt content the asphalt availability factors, F_{RAP} and F_{RAS}, are 1. If none of the recycled material asphalt is useful, then the asphalt availability factors are 0. AASHTO PP78-14 considers that only a portion of the RAS asphalt is available and recommends using a RAS asphalt availability factor between 0.70 and 0.85. This same standard assumes 100% of the RAP asphalt contributes to the total asphalt content by using a value of 1 for F_{RAP}. The availability factors for both RAS and RAP can vary depending on each agency's experiences. For example, Georgia uses an asphalt availability factor of 0.75 for RAP (Hines 2015).

A Louisiana laboratory study used a volumetric method to estimate the RAS asphalt availability factor for 12.5-mm mixtures with either 5% manufacturer waste RAS or 5% tear-off RAS, and a stone matrix asphalt (SMA) mixture with 5% tear-off RAS and 3% hydrated lime that was used to meet the passing 0.075-mm sieve size SMA requirement (Cooper et al. 2014). The asphalt availability factor measured using this approach ranged from 35% to 50% (0.35 and 0.50 in decimal form).

Other information related to asphalt availability factors found in the literature included:

- Virgin asphalt content can be reduced by approximately 0.2% for every 1% by weight of RAS (manufacturer's waste) used in a mixture (Mallick and Mogawer 2000).
- Five percent (5%) of RAS in the asphalt mixture contributes approximately 1% asphalt to the total binder content (AsphaltPro.com 2012; Jackson 2012).
- Mixtures with tear-off shingles require slightly more virgin asphalt than similar mixtures using manufacturer shingle waste (McGraw et al. 2010).

Recent research shows that the percentage of the virgin asphalt in mixture is more important to good pavement performance than the PG grade of the virgin asphalt (Johnson et al. 2013). The minimum amount of virgin asphalt can be defined by using a ratio of virgin asphalt to the total asphalt content asphalt binder ratio (ABR), which is calculated as:

$$\text{ABR} = \left[\frac{\text{Virgin asphalt, \%}}{\text{Total asphalt content, \%}}\right]$$

Alternatively, the maximum percent of recycled asphalt that can contribute to the total asphalt content can be defined as a ratio of the maximum percentage of recycled material asphalt to the total asphalt content (i.e., recycled binder ratio, RBR), which is calculated as:

$$\text{RBR} = \left[\frac{\left(\begin{array}{c}(\text{RAP AC})(\text{RAP\%})\\ +(\text{RAS AC})(\text{RAS\%})\end{array}\right)}{\text{Total asphalt content}}\right]100$$

The Minnesota Department of Transportation (MnDOT) established a minimum criterion of 70% for the ABR for its specifications in 2012. A revised version in 2013 defines the ABR based on the type of recycled materials, location in the pavement structure, and the specified virgin asphalt grade (Table 2) (Johnson et al. 2013).

The Texas DOT (TxDOT) specification requires a maximum RBR based on the originally specified PG asphalt, the allowable substitution of another PG asphalt, and the location of the mixture in the pavement structure (Table 3) (TxDOT 2014, Item 341).

TABLE 2
CRITERIA FOR MNDOT MINIMUM RATIO VIRGIN ASPHALT TO TOTAL ASPHALT BINDER (ABR)

Specified Asphalt Grade	Lift	Minimum ABR for Recycled Material Asphalt Mixtures		
		RAP only	RAS only	RAP and RAS
PG XX-28 PG 52-34 PG 49-34 PG 64-22	Wear	70	70	70
	Non-Wear	70	70	65
PG 58-34 PG 64-34 PG 70-34	Wear	80	80	80
	Non-Wear			

Source: MnDOT (2013; Table 2360-8).

The Bonaquist methodology is used by a number of researchers to evaluate if the recycled material asphalt fully contributes to the total asphalt content of the mixture. This method requires dynamic modulus, E^*, data for the compacted recycled material asphalt mixture be measured for a range of test temperatures and loading frequencies (Bonaquist 2007). The recycled material asphalt is extracted, recovered, and blended with virgin asphalt at the same percentages used for the mixture. The determined blended asphalt DSR shear modulus, G^*, using a range of test temperatures and loading frequencies and the G^* obtained data is mathematically converted to E^* values using the Hirsch model. The recycled asphalt fully contributes to the total asphalt content of the mixture when the dynamic modulus from the mixture testing and the E^* values calculated using the Hirsch model overlap. Mixed reports of the usefulness for this approach found in the literature are briefly described here.

McDaniel et al. (2012) used the Bonaquist method to evaluate if RAP asphalt fully blended with the virgin asphalt using 24 plant-produced RAP mixtures obtained from five different contractors. Twenty of the mixtures show that most RAP asphalt contributed to the total asphalt. However, one mixture showed that the RAP asphalt only partially contributed, and three other mixtures showed little contribution from the RAP asphalt. This study showed that RAP asphalt provided a significant contribution about 80% of the time, but only partial to little contribution 20% of the time.

Turner (2013) found that the Hirsch model did not accurately estimate asphalt properties of plant or laboratory produced mixtures used in this study. The model was also not sensitive to changes in the asphalt properties resulting from increases in the RAP content.

Total Asphalt Content—Section Summary

- The TAC of the asphalt mixture is calculated using the sum of the percentage of virgin asphalt and the asphalt contained in the percentage of the recycled materials added to the mixture. The percentage of useful recycled asphalt included in the calculation of the total asphalt content can be considered as 100% useful, 0% useful, or some percentage in between. The asphalt availability factor is used to define the percentage of useful recycled material asphalt.
- Recent research shows that the performance of recycled material asphalt mixtures is a function of the percentage of the virgin asphalt in the mixture and either the ABR or the RBR can be used to control the amount of virgin asphalt in the mixture.

TABLE 3
ALLOWABLE SUBSTITUTE PG BINDERS AND MAXIMUM RECYCLED BINDER RATIOS

Originally Specified PG Binder	Allowable Substitute PG Binder	Maximum RBR[1] for Recycled Material Asphalt Mixtures, %		
		Surface	Intermediate	Base
HMA				
76-22[2]	70-22 or 64-22	20.0	20.0	20.0
	70-28 or 64-28	30.0	35.0	40.0
70-22[2]	64-22	20.0	20.0	20.0
	64-28 or 58-28	30.0	35.0	40.0
64-22[2]	58-28	30.0	35.0	40.0
76-28[2]	70-28 or 64-28	20.0	20.0	20.0
	64-34	30.0	35.0	40.0
70-28[2]	64-28 or 64-28	20.0	20.0	20.0
	64-34 or 58-34	30.0	35.0	40.0
64-28[2]	58-28	20.0	20.0	20.0
	58-34	30.0	35.0	40.0
WMA[3]				
76-22[2]	70-22 or 64-22	30.0	35.0	40.0
70-22[2]	6-22 or 58-28	30.0	35.0	40.0
64-22[4]	58-28	30.0	35.0	40.0
76-28[2]	70-28 or 64-28	30.0	35.0	40.0
70-28[2]	64-28 or 58-28	30.0	35.0	40.0
64-28[4]	58-28	30.0	35.0	40.0

Texas Section 341, Table 5.
[1]Combined recycled binder from RAP and RAS.
[2]Use no more than 20.0% recycled binder when using this originally specified PG binder.
[3]WMA as defined in Section 341.2.6.2 "Warm Mix Asphalt (WMA)."
[4]When used with WMA, this originally specified PG binder is allowed for use at the maximum recycled binder ratios shown in this table.

- The Bonaquist method can be used to estimate if most or all of the recycled material asphalt contributes to the total asphalt content. At this time, this method is primarily a research tool.

SELECTING THE VIRGIN ASPHALT GRADE FOR RECYCLED MATERIAL MIXTURES

It is important that the virgin asphalt grade be selected so that combined the virgin and recycled asphalt properties meet the specified requirements. When lower percentages of recycled materials are used, usually less than 15%, no change in the typical virgin asphalt grade is required. When the recycled material content is between 15% and 25%, one grade softer is typically selected for the virgin asphalt. FHWA recommends extracting, recovering, and testing the recycled material content when using content of more than 25%. The test results are used to develop blending charts for selecting the required upper and lower PG temperatures used to specify the virgin asphalt.

One approach for using blending charts is to select the percentage of recycled material to be used in the mixture, determine the critical temperature determined for the recycled material asphalt and the critical temperature for the blend of virgin and recycled asphalt, then calculate the critical temperature for the virgin asphalt, T_{virgin}. For example, using the percent RAP (RAP%) as the recycled material, the equation for calculating the virgin asphalt critical temperature is:

$$T_{\text{virgin}} = \left(\frac{T_{\text{blend}} - (\text{RAP\%})(T_{\text{RAP}})}{(1 - \text{RAP\%})} \right)$$

The required time and cost associated with determining all of the different asphalt properties required for this approach can deter agencies from using more than 24% RAP. Other agencies have used research studies and local experience to identify specific virgin asphalt grades to be used for any percentage of recycled materials in asphalt mixtures.

For example, recent changes in the Florida specifications still use the three-tiered approach for adjusting the selection of the virgin asphalt, but identify the specific grade for each level of recycled material content (Table 4).

TABLE 4
VIRGIN ASPHALT GRADE FOR RAP MIXTURES

RAP Content, %	PG Grade
0–15	PG 67-22
16–30	PG 58-22
>30	PG 52-28

Source: Florida Department of Transportation Specifications (2015, Table 334-2).

SAMPLE PREPARATION FOR MIX DESIGNS

Laboratory procedures for material preparation, batching, preheating, mixing, and compacting asphalt mixtures for mix designs were originally developed using virgin aggregates and asphalts. Batching of materials has to consider what portions of the recycled material mass are included in the solid particulate measurements and what part of the mass is included in the determination of the total asphalt content.

Temperatures, mixing times, and order of addition of materials are based on typical asphalt plant operations. However, when recycled material is included in the mixtures, adjustments to conventional procedures may be necessary to account for how, when, where, and at what temperatures these materials are added during the asphalt plant production.

Calculating Batch Weights

The mass of any nonusable recycled asphalt is to be included as a part of the recycled material aggregate mass (AASHTO R-35). Various agencies have developed their own equations for determining material batch weights (masses) for mix design samples. Generic equations, modified from the Oregon DOT Section 2327-CB (calibration batch sheet) spreadsheet example to include asphalt availability factors for both RAP and RAS are shown here (ODOT 2013).

Batching calculations start with determining the total mass of the asphalt mixture sample, $\text{Mass}_{\text{sample}}$, needed to produce the desired sample height after compaction. The total mass of asphalt for one of the mix design asphalt contents, P_b, to be used in the design is calculated as:

$$\text{Mass}_{\text{total asphalt}} = \frac{((\text{Mass}_{\text{sample}})(P_b))}{100}$$

Typical mix designs use from three to five different total asphalt contents to determine the optimum asphalt content to be used with the selected aggregate gradation. Once the total mass of asphalt is determined, the total mass of aggregate, $\text{Mass}_{\text{total aggregate}}$, is calculated:

$$\text{Mass}_{\text{total aggregate}} = (\text{Mass}_{\text{sample}}) - (\text{Mass}_{\text{total asphalt}})$$

The mass of RAP asphalt that will be used in calculations of ABR and RBR is calculated using the target total asphalt content, P_b; the percentage of RAP to be used, RAP%; the percentage of recycled asphalt in the RAP, P_{br}; and the RAP asphalt availability factor, F_{RAP}. All percentages are expressed in whole numbers (i.e., *not* in decimal form):

$$\text{Mass}_{\text{RAP asphalt}} = F_{\text{RAP}}(\text{Mass}_{\text{sample}})\left[\frac{\left(1-\frac{P_b}{100}\right)}{\left(\frac{100}{\text{RAP\%}}-1\right)\left(\frac{100}{P_{br,\text{RAP}}}\right)+\left(\frac{100}{P_{br,\text{RAP}}}-1\right)}\right]$$

The mass of RAP aggregate is calculated as:

$$\text{Mass}_{\text{RAP aggregate}} = \text{Mass}_{\text{RAP asphalt}}\left(\frac{100}{P_{br,\text{RAP}}}-1\right)$$

The sum of both the calculated RAP asphalt and RAP aggregate is the mass of RAP that is to be batched:

$$\text{Mass}_{\text{RAP}} = \text{Mass}_{\text{RAP asphalt}} + \text{Mass}_{\text{RAP aggregate}}$$

If RAS is also included in the asphalt mixture, the same series of calculations are required to calculate the mass of RAS material to be batched. First, calculate the mass of RAS asphalt:

$$\text{Mass}_{\text{RAP asphalt}} = F_{\text{RAS}}(\text{Mass}_{\text{sample}})\left[\frac{(1-P_b)}{\left(\frac{100}{\text{RAS\%}}-1\right)\left(\frac{100}{P_{br,\text{RAS}}}\right)+\left(\frac{100}{P_{br,\text{RAS}}}-1\right)}\right]$$

Next calculate the mass of RAS aggregate:

$$\text{Mass}_{\text{RAP aggregate}} = \text{Mass}_{\text{RAS asphalt}}\left(\frac{100}{P_{br,\text{RAS}}}-1\right)$$

And then calculate the mass of RAS material to be batched:

$$\text{Mass}_{\text{RAS}} = \text{Mass}_{\text{RAS asphalt}} + \text{Mass}_{\text{RAS aggregate}}$$

Two additional calculations are used to determine the mass of virgin aggregate to be batched:

$$\text{Mass}_{\text{virgin aggregate}} = \text{Mass}_{\text{total aggregate}} - \text{Mass}_{\text{RAP aggregate}} - \text{Mass}_{\text{RAS aggregate}}$$

And the mass of virgin asphalt to add during mixing:

$$\text{Mass}_{\text{virgin asphalt}} = \text{Mass}_{\text{total asphalt}} - \text{Mass}_{\text{RAP asphalt}} - \text{Mass}_{\text{RAS asphalt}}$$

Material Preparation, Mixing, and Compacting

Each research study found in the literature uses defined, but laboratory-specific, steps to prepare materials for batching, combine materials for heating, and determine the order of addition of materials into the mixing bowl, short-term aging times and temperatures, and levels of compaction. Two examples of

TABLE 5
COMPARISON OF DIFFERENT LABORATORY PROCEDURES FOR BATCHING, PREHEATING, AND MIXING

Step	Minnesota Study (RAP Study) (*Source*: McGraw 2010)	Oregon Study (RAP and RAS Study) (*Source*: Scholz 2010)
Aggregates	Fractionate coarse and fines on 2.36-mm (No. 8) sieve; further fractionate coarse on individual sieve sizes	Fractionate into individual sizes (full range of sieve sizes)
RAP	Fractionate on 4.75-mm (No. 4) sieve; further fractionate coarse on individual sieve sizes	Fractionate into individual sizes from 9.5-mm (3/8-in.) to passing 0.15-mm (No. 100) sieve sizes
RAS	Not applicable	Fractionate into two sizes: ½-in. to 0.30-mm (No. 30), and passing 0.30-mm (No. 30)
Preheating	Aggregate: Preheat for 4 to 5 h at 315°F (157°C)	Aggregates: Preheat to mixing temperature
	RAP: Preheat for 4 to 5 h at 315°F (157°C)	RAP: Preheat to mixing temperature
	RAS: Not applicable	RAS: Keep at room temperature
Mixing	Aggregates and RAP dry mixed for 1 to 2 min	Dry-mix aggregates, RAP, and RAS
	Virgin asphalt added	Virgin asphalt added
	Mixed for an additional 2 min	Mixed (no time indicated)
Short-Term Aging	2 h at 275°F (135°C)	At compaction temperature
Compaction	N_{design} = 60	Not noted

variations in the steps used to prepare mix design samples are shown in Table 5.

Molenaar et al. (2011) compared laboratory mixing procedures to those used for two different asphalt plants (parallel flow plant and Astec Double Barrel drum plant) (Table 6). Standard laboratory practices as used by these researchers call for preheating both the virgin aggregate and RAP to 170°C (338°F). The parallel drum mix plant evaluated for comparison superheated the virgin aggregate to above 170°C (338°F) and preheated the RAP to 130°C (266°F). Both the virgin aggregate and RAP were dry mixed before adding the liquid asphalt. The second plant used for comparison was an Astec Double Barrel plant that superheated the virgin aggregate well above the standard laboratory temperature of 170°C (338°F). Higher temperatures were necessary because the RAP was added as stockpiled (at ambient temperatures, moisture contents between 1% and 4%) and the conductive heat transfer from the hot aggregate to the RAP is needed to both dry and preheat the RAP before adding the hot liquid virgin asphalt. Researchers tried to approximate the parallel plant temperatures in the laboratory but failed to come close to replicating heating conditions in the Astec Double Barrel drum.

Sample Preparation for Mix Designs—Section Summary

- Batch weights (masses) of the recycled materials are to be adjusted by the mass of the recycled material asphalt that is not considered in the calculation of the total asphalt content.
  - No standard procedure for batching, preparing, and mixing materials for samples with recycled materials was found in the literature. Laboratory temperatures and procedures for drying and preheating varied widely and do not appear to replicate temperatures and conditions used in typical asphalt plants.

TABLE 6
VARIABLES USED IN STUDY TO SIMULATE PLANT CONDITIONS IN THE LABORATORY MIXING PROCEDURES

Production Facility	Temperature Variables		
	Virgin Aggregate Preheating Temperature, °C (°F)		RAP Preheating Temperature
	30% RAP	60% RAP	
Typical Laboratory Procedure	170 (338)	170 (338)	170 (338)
Parallel Flow Plant	240 (464)	330 (626)	130 (266)
Astec Double Barrel Plant	290 (554)	430 (806)	25 (77)
	345 (653)	515 (959)	25 (77)

Source: Molenaar et al. (2011).

MIXTURE TESTING

The volumetric properties of the compacted samples are used as parameters for determining the optimum total asphalt content using the selected aggregate gradation. Performance-based testing of the compacted mixtures is used to evaluate that the likelihood the mixture, as designed, will achieve the design service life.

Volumetrics

Examples of recent research that report changes in mix design volumetrics resulting from the percentage and type of recycled materials are summarized in Table 7. There is general agreement that the asphalt film thickness decreases and the dust content increases with increasing percentages and/or different types of recycled materials. Some studies report decreases in air voids, VMA, and voids filled with asphalt (VFA) with increasing percentages of recycled materials or when using different types of recycled materials, whereas other studies have reported opposite trends. Differences in the reported volumetric trends are most likely a function of other factors such as gradations, effective volume of asphalt, and additives, rather than simply the use or increasing percentage of recycled materials.

AASHTO PP78-14 notes that although the percentage of RAS typically used in asphalt mixtures is small, the non-asphalt components that include the aggregate particles and backing materials can increase the VMA. At the same time, the dust content can decrease the VMA; however, the net change is usually a net increase in VMA. The dust-to-asphalt ratio can also increase. The AASHTO standard recommends limiting the percentage of RAS to 5% until more is known about the impact of RAS on mixture volumetrics.

MnDOT uses the adjusted asphalt film thickness (AFT) in its specification to ensure a minimum effective asphalt volume coverage that is a function of the aggregate surface area.

$$\text{AFT} = \frac{4870(P_{be})}{SA(P_s)}$$

And the AFT is:

$$\text{Adj. AFT} = \text{AFT} + [0.06(SA - 28)]$$

AFT = asphalt film thickness, μm;
SA = surface area, ft²/lb;
P_{be} = percentage effective binder;
P_s = percentage solids; and
Adj. AFT = adjusted asphalt film thickness, μm.

The surface area of the aggregate is calculated as:

$$SA = 2 + 0.02a + 0.04b + 0.08c + 0.14d + 0.30e + 0.60f + 1.60g$$

SA = surface area, ft²/lb;
a = 4.75-mm (No. 4);
b = 2.36-mm (No. 8);

TABLE 7
EXAMPLE OF VOLUMETRIC CHANGES WITH INCREASING RECYCLED MATERIAL PERCENTAGES*

Testing	Influence on Results for Mixtures with Recycled Materials				References
Volumetrics					
Air voids		↓	↑		Roque et al. (2015); Booshehrian et al. (2012)
VMA		↓	↑		Roque et al. (2015); Lee et al. (2015); Daniel and Lachance (2005); West and Willis (2014); Booshehrian et al. (2012); AASHTO PP78-14
VFA	S	↓	↑		Roque et al. (2015); Lee et al. (2015); Daniel and Lachance (2005); Booshehrian et al. (2012); Shannon (2012)
Film thickness		↓			Shannon (2012); AAT (2011)
Dust content	S		↑		Lee et al. (2015); Newcomb et al. (2007); Booshehrian et al. (2012); Shannon (2012)
Mixture Properties Needed to Calculate Volumetrics					
Theoretical maximum gravity			↑		Lee et al. (2015)
Percent binder absorbed		↓			Lee et al. (2015)

*Includes both RAP and RAS studies.
S = similar results in given research study; M = mixed results in given research study.
↓ Indicates a given property or test result *decreases* with *increasing percentage* of recycled material in given study.
↑ Indicates a given property or test result *increases* with *increasing percentage* of recycled material in given study.

c = 1.18-mm (No. 16);
d = 0.6-mm (No. 30);
e = 0.3-mm (No. 50);
f = 0.15-mm (No. 100); and
g = 0.075-mm (No. 200).

An alternative equation found in the literature for calculating the AFT is (AAT 2011):

$$\text{AFT} = \left(\frac{1{,}000\ V_{be}}{S_S\ P_S\ G_{mb}}\right)$$

Where:

AFT = apparent film thickness, μm;
V_{be} = effective binder content, % by total weight of mixture;
P_s = aggregate content, % by total weight of mixture; and
G_{mb} = bulk specific gravity, compacted sample.

A simplified equation for calculating the aggregate surface, S_S, area is:

$$S_S = \left(\frac{P_{0.30} + P_{0.15} + P_{0.075}}{5}\right)$$

Performance Testing

Performance testing used to evaluate key mixture properties related to key pavement distress(es) includes:

- Dynamic modulus to evaluate mixture stiffness.
- Loaded wheel rut testing.
- Cracking (bottom down and/or top-down traffic-related cracking, thermal cracking, reflective cracking) test methods:
  - Bending beam fatigue
  - Disk-shaped compact tension (DSC)
  - Indirect tension (IDT)
  - Overlay tester (Texas)
  - Repeated direct tension
  - Semi-circular bend (SCB)
  - Simplified viscoelastic continuum damage (S-VECD)
  - Thermal stress restrained stress test (TSRST) and uniaxial thermal stress and strain (UTSST).

Dynamic Modulus (AASHTO TP79)

The Asphalt Mixture Performance Tester (AMPT) can be used to determine the dynamic modulus (stiffness), referred to as the complex modulus, E^*, over a range of temperatures and/or loading frequencies (Figure 7). Stiffer mixtures are more resistant to rutting and, when located in the lower lifts, provide support to minimize longitudinal cracking in the wheel paths.

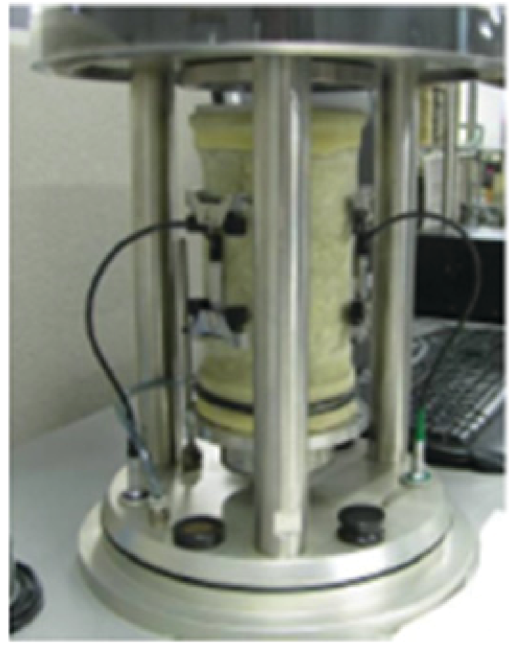


FIGURE 7 Set up for AMPT (*Source*: Michael 2011).

Cylindrical samples are loaded by applying a uniaxial sinusoidal in compression to the sample in an unconfined or confined condition. Test temperatures of 14°F, 39°F, 68°F, 102°F, and 123°F (−10°C, 4°C, 20°C, 38.8°C, and 54.4°C) have been used by some researchers (Michael 2011; Cooper et al. 2014).

Loaded Wheel Tracking Device (AASHTO TP63)

Loaded wheel devices [Hamburg, Asphalt Pavement Analyzer (APA)] simulate mixture deformation resulting from multiple passes of traffic loads (Figure 8). Mixtures that can sustain a preset number of passes without exceeding a maximum rut depth are considered resistant to rutting. When the loading passes are conducted under water, a discernible change (inflection point) in the depth versus number of passes is identified as the stripping inflection point (SIP). A higher number of passes associated with the inflection point indicates a more moisture-resistant mixture.

Test Methods for Evaluating Cracking Potential

There are eight test methods that can be used to evaluate traffic-related (fatigue, top-down, bottom-up) cracking, thermal cracking, and reflective cracking. Each test method is briefly described here and includes a description of the type(s) of cracking evaluated for the testing condition(s).

Bending Beam Fatigue Testing (AASHTO T321)

The bending beam fatigue test evaluates the potential for traditional fatigue cracking (i.e., bottom-up cracking). Testing is

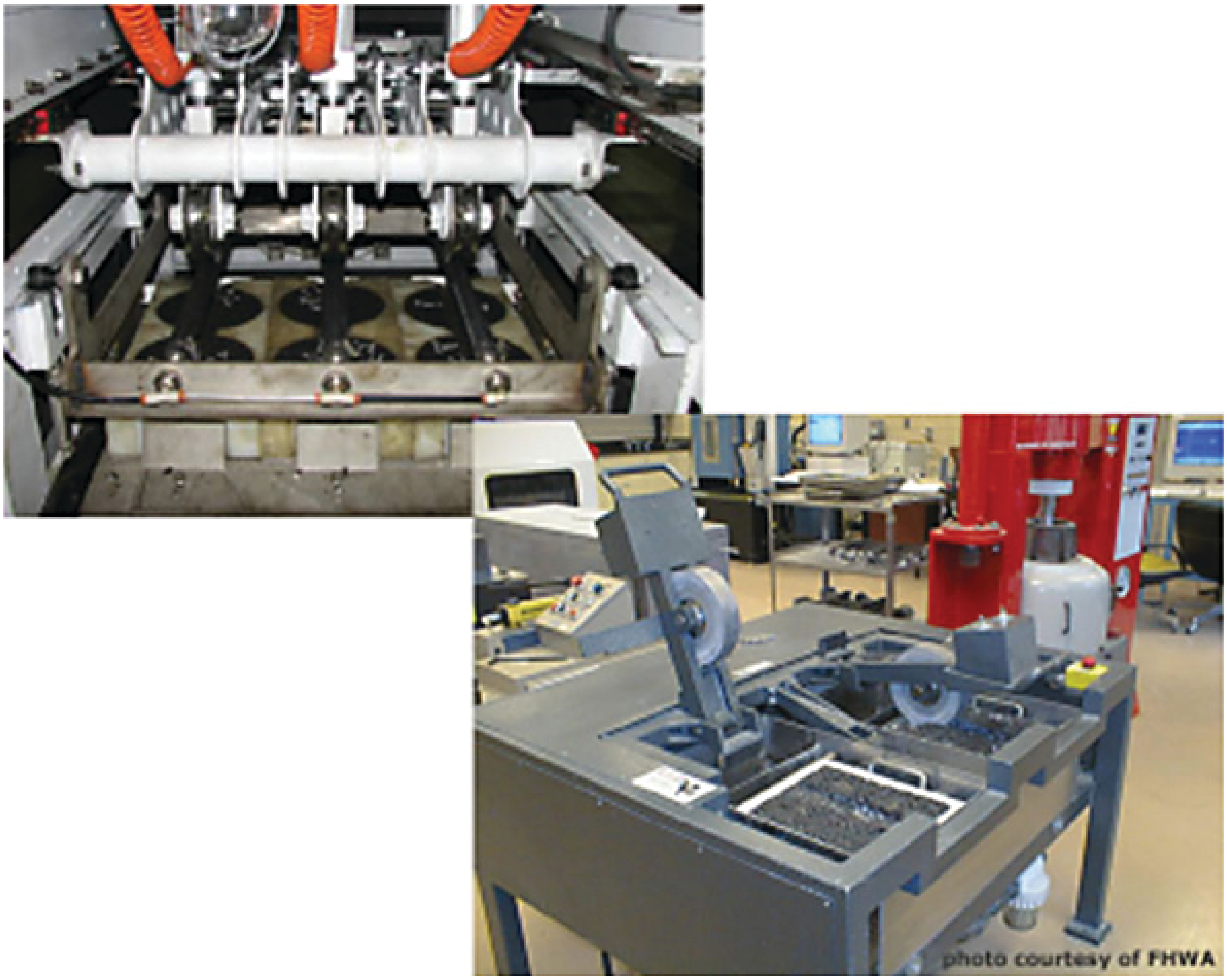


FIGURE 8 Types of loaded wheel testers used to evaluate asphalt mixture rutting potential APA (*upper left*) and Hamburg (*lower right*) (*Source*: Willis et al. 2012; Pavement Interactive website 2015).

usually conducted using at least two different stress or strain levels and the data are analyzed to determine the slope of the stress (or strain) versus the number of cycled to failure relationships (log-log relationships).

A rectangular beam is cut from a slab of compacted asphalt mixture, clamped into an apparatus, and a sine wave loading generates tensile stresses over the bottom center third of the beam (Figure 9). Loading frequencies can vary from 5 to 10 Hz and failure is typically defined as a 50% reduction of the initial stiffness. The resistance of the mixture to traffic-related flexural stresses and strains increases with the increasing number of cycles to failure. Alternatively, the data can be used in mathematical models to estimate the fatigue life of the mixture.

Disc-Shaped Compact Tension (ASTM D7313)

The disc-shaped compact tension test determines the fracture energy of an asphalt mixture at low temperatures. The low temperature cracking potential decreases as the fracture energy increases. Variations of this test method conducted at intermediate test temperatures can be used to evaluate potential reflective cracking characteristics.

Testing is conducted on a 2-in.-thick disc-shaped sample that has been cut from a gyratory compacted cylinder or a core (Figure 10). Two holes are drilled into either side of a thin notch cut into the edge of the sample and pins are inserted into the holes. A constant strain is applied to the notch (i.e., crack) so that it opens at a rate of 1 mm/minute. Failure typically occurs between 1 mm and 6 mm of crack opening. The standard test temperature is 10°C warmer than the lower PG temperature.

Indirect Tension (AASHTO T322)

The indirect tension test is used to determine the creep compliance and tensile strength of the mixture at low temperatures (Figure 11). An increase in the creep compliance indicates a mixture that can better resist low temperature cracking owing

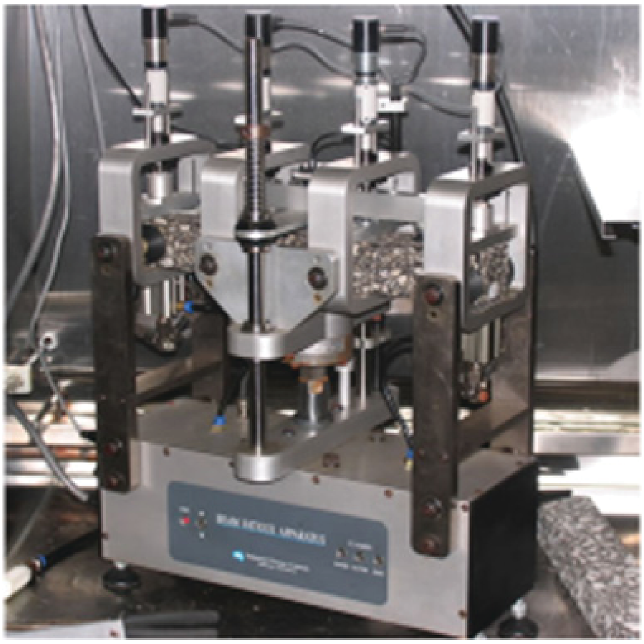


FIGURE 9 Beam fatigue apparatus (*Source*: Pavementinteractive [Online]. http://www.pavementinteractive.org/article/flexural-fatigue/).

to increased strains as temperatures drop. The tensile strength decreases with increases in creep compliance (i.e., inverse relationship).

Testing is conducted on a disc-shaped sample that has been cut from a gyratory compacted cylinder or core and is about 1.5-in. to 2.0-in. thick. Typically, the creep compliance is determined by applying a static load for 100 seconds. Because this portion of the testing is not destructive as long as the strain, ε, is kept below 500-με, several tests can be conducted at different temperatures. Once the creep com-

FIGURE 10 Disc-shaped tension test (*Source*: NCHRP 9-57 Workshop 2015).

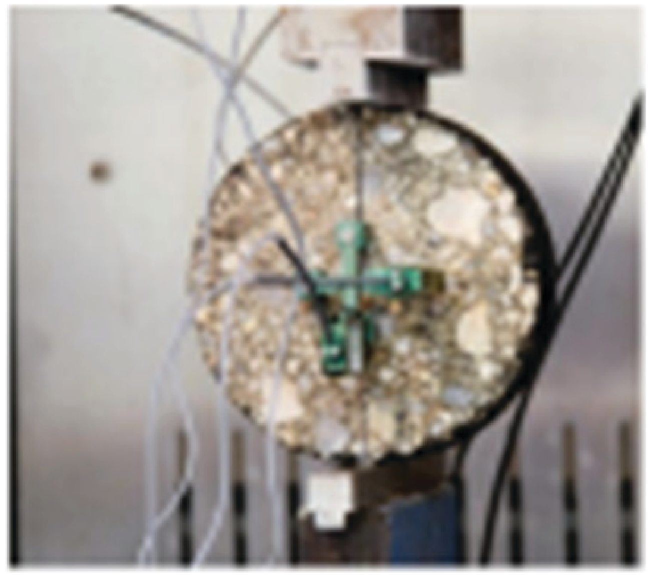


FIGURE 11 Indirect tension test (*Source*: NCHRP 9-57 Workshop 2015).

pliance testing is completed, the indirect tensile strength is determined (destructive portion of the test). The sample is loaded at a strain rate of 12.5 mm per minute until failure and the tensile strength is determined when the maximum load is reached.

The traffic-related top-down cracking potential can be estimated by using a variation of this test conducted at intermediate temperatures and calculations of the energy ratio, ER (Willis et al. 2012). Recommended energy ratio criteria are a minimum of 1.0 for less than 250,000 equivalent single-axle loads (ESALs)/year, a minimum of 1.3 when the traffic is below 500,000 ESALs/year, and a minimum of 1.95 for traffic levels up to 1 million ESALs.

Resilient modulus is obtained from stress and strain measurements by applying a repeated haversine load for 0.1 second followed by a 0.9 second rest period and measuring the stress and strain. Next, the creep compliance is performed using AASHTO T322-07 at a test temperature of 50°F (10°C) and a test duration of 1,000 seconds (creep compliance). The indirect tensile strength dissipated creep strain energy, which is a portion of the area under the stress-strain curve. The energy ratio:

$$ER = \frac{DSCE_f\left[7.294\left(10^{-5}\right)\right]\sigma^{-3.1}\left(6.36 - S_t\right) + 2.46\left(10^{-8}\right)}{m^{2.98} D_1}$$

Where:

σ = tensile stress at the bottom of the asphalt layer, 150 psi;
D_1, m = power function parameters;

$DSCE_f$ = dissipated stress creep energy at failure (portion of area under stress–strain curve from indirect tensile test); and
ER = energy ratio.

Overlay Tester (TEX-249-F)

The Overlay Tester is used to estimate the potential resistance of a mixture to reflective cracking and/or traffic-related top-down cracking. Resistance to cracking increases with the number of cycles needed to fail the sample.

The Overlay Tester uses a specimen cut from a gyratory compacted sample, adhered to horizontal steel plates separated by a narrow gap, which are moved back and forth using a saw tooth waveform (Figure 12). The force required to move the plates is recorded and failure is defined as a 93% reduction in the load magnitude recorded for the first cycle.

Texas DOT (TxDOT) uses a maximum displacement of 0.025 in. (0.635 mm); however, some research studies indicate that this displacement may be too high to evaluate stiff mixtures, such as those containing recycled materials. One study used displacement openings of 0.01, 0.013, and 0.015 in. (0.254, 0.330, and 0.381 mm). Results using the higher displacement were more variable and the lowest displacement level extended the number of cycles to failure for stiff mixtures to more than 2,000. A displacement of 0.013 in. was considered the most effective compromise between lowering the variability and keeping the testing time to a reasonable level.

Repeated Direct Tension (Texas A&M Test Method)

Information obtained from the repeated direct tension test are used to develop estimates of load-related bottom-up and top-down traffic-related cracking. The test uses a cylindrical sample (heights more than diameter) and applies cyclic tensile loads to obtain stress and strain data. The results are used to calculate Paris' law parameters, endurance limits, healing properties, and average crack size (Figure 13).

FIGURE 12 Overlay tester for evaluating reflective cracking resistance (*Source*: Klutzz and Mogawer 2012).

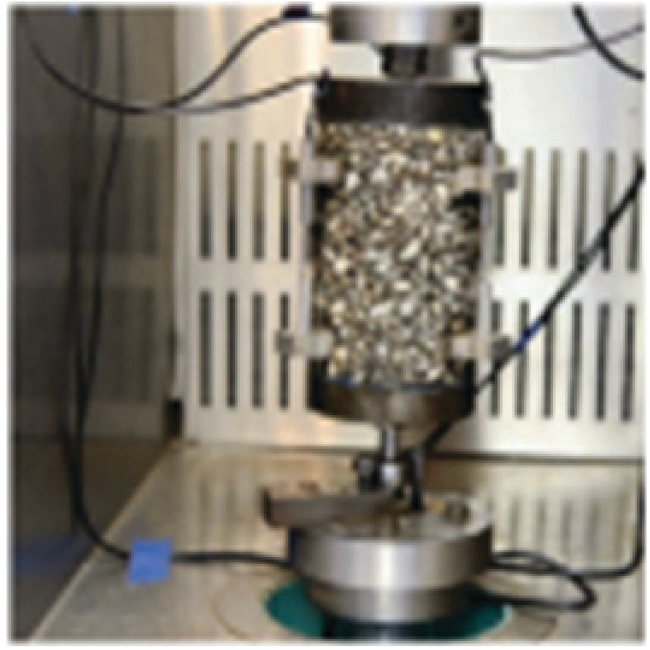


FIGURE 13 Repeated direct tension test (*Source*: NCHRP 9-57 Workshop 2015).

Semi-Circular Bend (AASHTO TP105)

The SCB critical fracture release energy, determined using multiple-notch depths and intermediate test temperatures [e.g., 77°F (25°C)], can be used as an indication for top-down, fatigue, and reflective cracking potential. When a single low temperature and a single notch depth is used, increases in fracture energy, G_f, and fracture toughness, K_{1C}, indicate increases in low temperature cracking resistance.

A thin circular disc is cut out of a gyratory compacted sample, or core, then cut in half to produce the semi-circular test specimen (Figure 14). The flat edge of the half circle is notched to the desired notch depth (a) to the specimen radius (r_d), typically from 0.5 to 0.75 (for intermediate temperature testing). The specimen is supported at either end of the flat side of the semi-circle (notched side facing down) and a constant load is applied to the top of the sample at a rate of 0.20 in./minute (0.5 mm/minute). The load and deformation with time is recorded and used to calculate the critical energy release rate, J_c value:

$$J_c = \left(\frac{1}{b}\right)\frac{dU}{da}$$

Where:

J_c = critical strain energy release rate, kJ/m^2;
b = specimen thickness, m;

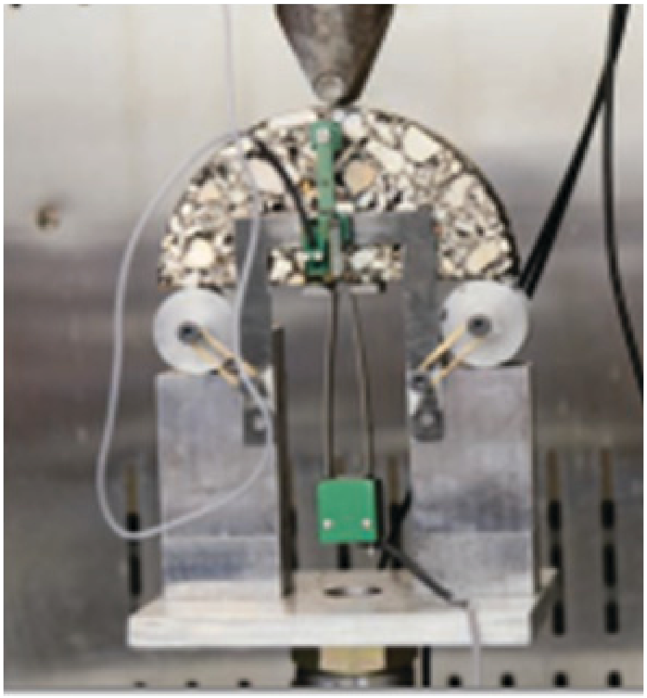


FIGURE 14 SCB testing set up and data plots needed for calculations of the energy ratio (*Source*: NCHRP 9-57 Workshop 2015).

U = strain energy to failure (i.e., area under deformation-stress curve up to maximum stress), kJ;
a = notch depth, m; and
dU/da = change of strain energy with notch depth, kJ.

Test results using different notch depths are used to calculate the strain energy that is plotted versus the notch depth, and the slope of the line is the value used for dU/da in the previous equation.

Simplified Viscoelastic Continuum Damage (AASHTO TP107)

The S-VECD test uses stress and strain measurements acquired under different loading conditions to estimate bottom-up and top-down traffic-related cracking (Figure 15). First, the dynamic modulus or frequency/temperature sweep testing is used to measure the mixture stiffness followed by the application of a constant strain until failure. The data from these tests are used as input into advanced mathematical models (e.g., linear viscoelastic continuum damage and viscoelastic continuum damage models with a public domain finite element program, FEP++).

Thermal Stress Restrained Specimen Test and Uniaxial Thermal Stress and Strain (AASHTO TP105)

The TSRST is used to measure the critical low cracking temperature and the tensile stress at failure (Figure 16).

FIGURE 15 Simplified viscoelastic continuum damage set up (*Source*: NCHRP 9-57 Workshop 2015).

A rectangular beam cut from a compacted asphalt mixture slab, or pavement section, is confined at either end so that it cannot contract as the temperature is lowered at 18°F (10°C) per hour. As the temperature drops, the stress essential to maintain the fixed specimen length increases. When the stress level exceeds the tensile strength of the material, the sample fractures (fails). The temperature at which the specimen fails is the critical cracking temperature.

FIGURE 16 Thermal stress restrained specimen test set up (*Source*: Western Regional Superpave Center [Online]. http://www.unr.edu/wrsc/research/facilities/asphalt).

Another use for this test configuration is measuring the coefficient of thermal contraction (UTSST).

Examples of Performance Test Results

Examples of recent results for a range of performance tests for RAP asphalt mixtures are summarized in Table 8. In general, increasing percentages of RAP decreases rutting potential and increases stiffness. Increasing percentages of recycled materials increases low temperature cracking potential (i.e., raises the critical low temperature). Mixed results, both within and between studies, can be found for cracking potential at intermediate temperatures and moisture sensitivity.

Fewer test methods (Table 9) have been used to evaluate the performance characteristics of RAS asphalt mixtures and findings tend to show limited significant differences between control and RAS mixture properties, which may be because of the small amount of RAS that is added (typically 3% to 5% typical).

A number of recent studies have investigated the use of rejuvenators added to the asphalt to help soften the stiffer recycled asphalt. A variety of materials used in the studies included those defined as rejuvenator or recycling additives in AASHTO R14 or ASTM D4552 standards, as well as waste vegetable oil, waste vegetable grease, organic oil (Hydrogreen S™), distilled tall oil, aromatic extract, waste engine oil (Zaumanis et al. 2014), flux oil, lube stock, slurry oil, lubricating oils, extender oils, Cyclogen-L (Cooper et al. 2014), and other specialty products (Al-Qadi et al. 2009).

TABLE 8
SUMMARY OF CHANGES IN RAP MIXTURE PROPERTIES

Testing		Influence of Increasing RAP				References
Rutting						
Rutting (loaded wheel units)		S	↓			Maupin (2008); Zaumanis et al. (2014); Willis et al. (2012); Watson et al. (2008)
Creep flow time					M	Daniel and Lachance (2005)
Creep stiffness				↑		Abdulshafi et al. (2002)
Cracking (Intermediate Temperatures)						
Fatigue		S	↓	↑	M	Maupin et al. (2008); Abdulshafi et al. (2002); Zaumanis et al. (2014); Vukosavlievic (2006); Watson et al. (2008); McDaniel et al. (2012)
Reflective cracking (Overlay Tester)				↑		Willis et al. (2012)
Dissipated energy				↑		Vukosavlievic (2006)
Fracture energy			↓			Vukosavlievic (2006)
SBC	**Fracture energy**		↓	↑		Lee et al. (2016); Willis et al. (2012); Johnson et al. (2013)
	Tensile strength			↑		Vukosavlievic (2006); Johnson et al. (2013)
	Fracture work				M	Lee et al. (2015)
Moisture Sensitivity						
Moisture sensitivity		S		↑		Olard (2010)
Toughness index			↓			Vukosavlievic (2006)
Differences over Range of Temperatures						
Stiffness (dynamic modulus)				↑	M	Daniel and Lachance (2005); Abdulshafi et al. (2002); Roque et al. (2015); Lee et al. (2015); Olard (2010); McDaniel et al. (2012)
Phase angle, mix			↓			Abdulshafi et al. (2003); Vukosavlievic (2006)
Fracture toughness		S			M	Lee et al. (2015); Johnson et al. (2013)
Low Temperature Testing						
Indirect tensile strength					M	Roque et al. (2015)
Indirect tensile creep compliance		S	↓	↑		Zaumanis et al. (2014); Roque et al. (2015); Johnson et al. (2013); Watson et al. (2008)
Thermal cracking				↑		Zaumanis et al. (2014)
Critical cracking temperature				↑		Vukosavlievic (2006); McDaniel et al. (2012)
Notched fracture energy			↓			Swiertz et al. (2011)
Failure strain			↓			Roque et al. (2015)
Energy Ratio			↓			Roque et al. (2015); Willis et al. (2012)

S = similar results in given research study; M = mixed results in given research study.

↓ Indicates a given property or test result *decreases* with *increasing percentage* of recycled material in given study.

↑ Indicates a given property or test result *increases* with *increasing percentage* of recycled material in given study.

TABLE 9
SUMMARY OF CHANGES IN RAS MIXTURE PROPERTIES

Testing	Influence of Increasing RAS				References
Rutting					
Rutting	S			M	Foo et al. (1999); Cooper et al. (2014)
Creep flow time	S				Maupin et al. (2008)
Cracking					
Fatigue	S	↓			Foo et al. (1999); Boyle and Bonaquist (2005); Maupin et al. (2008)
Thermal cracking	S				Foo et al. (1999)
Moisture Sensitivity					
Moisture sensitivity	S			M	Boyle and Bonaquist (2005); Maupin et al. (2008)
Stiffness	S				McGraw et al. (2010)

S = similar results in given research study; M = mixed results in given research study.
↓ Indicates a given property or test result *decreases* with *increasing percentage* of recycled material in given study.
↑ Indicates a given property or test result *increases* with *increasing percentage* of recycled material in given study.

Results for a range of performance testing for RAS mixtures with rejuvenators were found in the literature and are summarized in Table 10. Changes in the mixture properties depend on the percentage and type of rejuvenators used in the studies. Rejuvenators can reduce mixture stiffness and lower the critical low temperature when used in sufficient amounts; however, this can also increase the rutting potential. Care is required to select an optimum percentage of rejuvenators to achieve the desired results.

Mixture Testing—Section Summary

- RAP can either increase or decrease mixture volumetrics depending on variables such as gradation, effective volume of asphalt, and other additives.
- The nonasphalt components in RAS can increase VMA, and the dust content can decrease the VMA; however, the net change is usually a net increase in VMA. AASHTO PP78-14 recommends limiting RAS to 5%

TABLE 10
SUMMARY OF RECYCLED MATERIAL (RAP AND/OR RAS) MIXTURE PROPERTIES
WHEN USING REJUVENATORS

Testing	Influence of Using Rejuvenators in Mixtures with Recycled Materials				References
Rutting					
Rutting	S	↓	↑		Booshehrian et al. (2012); Shen et al. (2007); Tran et al. (2012); Green Asphalt Technologies (2012)
Cracking					
Reflective cracking	S		↑		Booshehrian et al. (2013)
Moisture Sensitivity					
Moisture sensitivity	S				Tran et al. (2012); Green Asphalt Technologies (2012)
Indirect tensile strength		↓	↑		Shen et al. (2007); Green Asphalt Technologies (2012)
Stiffness over Range of Temperature					
Stiffness	S	↓			Booshehrian et al. (2013); Sullivan (2011)
Phase angle, mix	S				Booshehrian et al. (2013)
Low Temperature Cracking					
TSRST				M	Booshehrian et al. (2013)
Critical cracking temperature		↓			Zaumanis et al. (2013); Tran et al. (2012)

S = similar results in given research study; M = mixed results in given research study.
↓ Indicates a given property or test result *decreases* with *increasing percentage* of recycled material in given study.
↑ Indicates a given property or test result *increases* with *increasing percentage* of recycled material in given study.

until more is known about the impact of RAS on mixture volumetrics.

- Increasing percentages of RAP may:
  - Increase stiffness and tensile strength, and decrease rutting potential.
  - Increase the thermal cracking potential (i.e., raise the cracking temperature).
  - Show mixed results for cracking potential at intermediate temperatures.
- Asphalt mixtures with or without RAS tend to show similar or mixed results.
  - Most rejuvenators increase rutting potential, decrease stiffness, and lower the critical low temperatures. *Care is required to select the optimum amount of rejuvenator used.*

ASPHALT PLANT PRACTICES AND EQUIPMENT

When higher percentages of RAP are used in asphalt mixtures, more attention to the RAP processing, stockpiling, and how RAP is added to the plant as needed (Udelhofen 2007). The age, type, and characteristics of the asphalt plant can limit the percentage and type of recycled materials that can be used. RAS material properties and sources of contaminates vary significantly among manufacture waste and tear-off shingles; therefore, it is required that they be processed and stockpiled separately. This section summarizes the key factors that can influence the use of recycled materials in asphalt mixtures.

Stockpiling and Processing Recycled Materials

Both RAP and RAS recycled material properties vary by source. RAP aggregate gradations and asphalt contents vary by the type of mixture (e.g., large stone base asphalt mixtures, dense-graded mixtures, and open-graded friction course), depth of pavement layer milled, type of milling equipment, and depth of milling. RAS aggregate and asphalt properties vary significantly between manufacturing waste shingles and old roofing materials (tear-off shingles). The variability of either recycled material can be minimized by keeping different types and sources in separate stockpiles. Incoming recycled materials are to be documented (e.g., by source, mix type, aggregate properties, asphalt content, and shingle type), materials tracked (process auditing), and equipment and asphalt plant or facility operators trained on how to appropriately manage recycled material stockpiles.

Storage Areas

A major factor influencing asphalt plant production rates and drying costs is the moisture content of the recycled materials. Sources of moisture in the recycled material stockpiles include rain, water used during processing, water sprayed on conveyor belts to prevent sticking, or water misted on stockpiles for fugitive dust control.

Moisture from rain can be minimized by covering the stockpiles (Figure 17). When the recycled material stockpiles are covered, an open-sided shed or building works most efficiently for access for loaders (Ontario Hot Mix Producers Association 2007). An opening at either end of the cover allows the loader operator to use the material stored in the shed to be the first used when producing the mix.

The next most effective option is to use a conical-shaped stockpile to help naturally protect it from rain or snow, place stockpiles on a paved slope surface to drain any excess water, limit the stockpile height to reduce potential for self-consolidation, and limit use of heavy equipment on top of the stockpiles to avoid compaction (West 2010; Garrett 2012; Jackson 2012; Cleaver 2013).

General estimates of typical RAP moisture contents by contractors are from 0.8% to 2% (Howard et al. 2009). Determining RAP stockpile moisture prior to asphalt mixture production is a function of the sampling depth into stockpile, the size of the stockpile, whether the RAP stockpile has been fractionated or unfractionated (finer RAP holds more water), time since milling, and recent rainfall. Moisture and dust in the recycled materials can contribute to clogging screens if in-line processing is used to size RAP as it is fed into the asphalt plant.

Besides moisture, a major challenge noted by Texas contractors when stockpiling RAS is workability. Hot weather and heating from solar radiation tends to stick RAS particles together, which makes it difficult to feed through cold feed bins and to obtain a uniform distribution in the mix. Covering RAS stockpiles not only limits additional moisture but helps with workability by limiting heating from solar gain.

FIGURE 17 Covering stockpiles helps control the moisture content (*Source*: Jackson 2012).

RAS clumping in the stockpile can also be minimized by blending with an acceptable source of fine aggregate or with RAP. A ratio of RAP to RAS of either 75:25 or 80:20 can minimize clumping; however, the RAP/RAS blend must be consistent throughout the stockpile to prevent variations in the material properties of the total mixture (Carolina Asphalt Pavement Association 2011; NCAT 2012).

RAP Stockpiles

RAP is obtained from pavement demolition, milling, and asphalt plant waste. Demolition is done with bulldozers or backhoes, is usually limited to small areas, and produces large blocks of old asphalt pavement that are to be crushed. Milling (grinding) removes one or more layers of an existing pavement surface. Milled materials tend to be finer and contain appreciable amounts of minus 0.075 mm than the gradation determined from cores and, typically, between 10% and 20% (Christman and Dunn 2013). Aggregate breakdown during milling is a function of the hardness and brittleness (impact resistance) of the aggregate, stiffness of asphalt that depends on the pavement temperature at the time of milling, milling machine speed, and depth of cut. Materials obtained from paved shoulders or lane widening projects, either by demolition or milling, may have different asphalt contents, aggregate gradations, and qualities of aggregates than those obtained from removing the main line roadways.

Plant waste is what is left over at the asphalt plant when the plant starts up, shuts down, or mixtures are rejected by the agency. When fresh asphalt mixtures are added to RAP stockpiles, the fresh, unaged asphalt and the gradations with significantly fewer fines can increase the variability of the RAP stockpile asphalt content, asphalt properties, and gradation. These are all reasons why unused fresh mixtures, RAP from different sources, and RAP from different processes should be stockpiled separately to minimize RAP variability (Figure 18).

FIGURE 18 Example of RAP from variations in RAP materials from various sources [demolition (*top, center*) and millings from different projects (*bottom*)] (*Source*: West 2010).

Agency terminology used to identify RAP stockpile characteristics varies substantially among agencies (Table 11). Examples of terms used to indicate that no new material can be added to a RAP stockpile once the QC testing is completed include “designated,” “captive,” “non-continuous,” and “certified.” Terms such as “active” and “continuous” are used to indicate RAP stockpiles that can be continuously replenished as the RAP is used. The continuous process of adding new material as the RAP is used can work well, but requires an established RAP QC plan that includes frequent, regular testing and analysis of the stockpile variability. This method is particularly helpful when the asphalt plant has limited space for multiple stockpiles.

The consistency of the RAP stockpiles can be evaluated by monitoring the coefficient of variability (COV) for multiple test results by taking samples from at least 10 different locations throughout the stockpile (AAT 2011). Alternatively, samples may be taken from haul trucks as the stockpile is built. Each sample is split so that one sample from each location can be used to determine the variability of the material properties stockpile (i.e., average, standard deviation) (Table 12). It is important that higher variability (higher COV) suggests stockpiles be reblended or the maximum percentage of RAP in mixture has to be reduced. The second set of split samples can be combined and split so that one “representative” sample is tested for use in mix design calculations.

Deleterious materials can be incorporated into the RAP when multiple lifts are milled (i.e., deep milling). This is because other materials such as crack fillers, soil from the underlying unbound layers, base materials, and paving geotextiles used between layers to reduce reflective cracking are removed along with the old pavement (Cleaver 2013). Geotextiles are a problem in RAP crushing operations because they tend to build up in crusher, wrap around moving parts, and lock up the crushing equipment. Geotextiles and crack fillers, which tend to be “ropes” of rubbery material, would be removed as the RAP is stockpiled. It is important that contamination of existing stockpiles be controlled, which means keeping out dirt, rubbish, vegetation, and trash. These contaminates are to be removed as soon as they are noticed so they are not covered up as the stockpile is built. Usually the plant QC personnel and loader operators are responsible for continuously monitoring unprocessed and processed RAP (West 2010).

Processing RAP

RAP stockpiles are most often built by using a vibrating grizzly with a single screen to control the top size of the RAP in the stockpile. The 12.5-mm or 9.5-mm (½-in. or ⅜-in.) screen is a typical size used for scalping as about 75% of as-milled RAP passes through ½-in. sieve. Any material not passing through the top screen is fed into a crusher or lump breaker before being fed back in the grizzly (McDaniel and Anderson

TABLE 11
EXAMPLES OF AGENCY TERMINOLOGY USED TO IDENTIFY TYPES OF RAP STOCKPILES

State	Specification Section (Source)	Terminology	Characteristics
Iowa	SS-0139, 2006	Classified	Documented source, defined quality of materials
Iowa	2303	Unclassified	Unknown source; visual inspection for uniformity; tested for gradation and asphalt content
		Designated RAP	Obtained from project; used on same project
		Active stockpiles	Term used but not defined
		Certified RAP	Sources known and no more than two sources in the same stockpile; stockpiles separated by aggregate quality and gradation, asphalt type, and content; no additional RAP added once tested
Ohio	401.04	Standard RAP	100% passing 2-in. screen (nonsurface mixtures) 100% passing ¾-in. screen (surface mixtures)
		Extended RAP	Fractionated or additional in-line processing of already approved stockpile; quality control plan. *In-line processing*: Double deck screen between cold feed bin and mixer with 9/16-in. screen for surface mixtures; 1.5-in. screen for base mixtures.
Florida	334-2.3.3	Continuous	RAP from one or more sources; processed, blended, or fractionated and stockpiled in a continuous manner; QC plan for monitoring gradation and asphalt content; visual inspection and review of data for suitability assessment
		Noncontinuous	Individual (single) stockpile with known gradation and asphalt content; QC plan; no additional material added once approved
		Homogenous	Material from Class I mixtures; requirements for aggregate quality, level of crushing, aggregate type (e.g., type of slag), and gradation; quality of RAP defined by lowest coarse aggregate quality; RAP from sources with similar asphalt content
		Conglomerate	Class I mixtures; 100% passing 5/8-in. screen (or smaller) crushed coarse aggregate, but more than one aggregate type or quality; inconsistent gradation and asphalt content prior to processing; no steel slag or expansive materials
		Conglomerate "D" Quality	Inconsistent gradation and asphalt content; no steel slag or expansive materials; coarse aggregate "D" quality or better

2001; West 2010). This results in a single stockpile with a wide range of particle sizes that are, like virgin aggregate stockpiles, prone to segregation. When lower percentages of RAP are used, variations in the RAP gradations generally have a low impact on the gradation and asphalt content of the final mixture. As the percentage of RAP increases, it becomes more difficult to maintain consistent gradation and asphalt content.

Better control of the RAP gradation and asphalt content in the stockpile can be accomplished by using two screens, such as a slotted ⅝ in. by 6 in. screen and a ¼ in. by 6 in. screen

TABLE 12
SUGGESTED PRELIMINARY VALUES FOR CONTROLLING RAP STOCKPILE VARIABILITY

RAP Material Property	Test Methods	Frequency	Minimum Number of Tests per Stockpile	Maximum Standard Deviation
Asphalt Content	AASHTO T164 or AASHTO 308	1 per 1,000 tons	10	0.5%
Recovered Aggregate Gradation	AASHTO T30	1 per 1,000 tons	10	5.0%, 0.014 mm or larger and 1.5%, 0.075-mm sieve
Recovered Aggregate Bulk Specific Gravity	AASHTO T84 and AASHTO T85	1 per 3,000 tons	3	0.030*
Consensus, source, or other aggregate properties		Samples may be obtained by retaining and combining aggregates used for gradation analysis		
Binder Recovery and PG Grading	AASHTO T319 or ASTM D5404 and AASHTO R29	1 per 5,000 tons	1	Not applicable

Source: After West and Willis (2014).
*Value recommended based on limited data and potential impact to mixture volumetrics (e.g., VMA).

to fractionate the RAP into coarse and fine RAP stockpiles. Because the asphalt content of finer RAP particles is generally higher than for the coarse RAP, fractionating the RAP also helps control the RAP asphalt content. The sizes used for fractionating will depend on mix designs being produced by the asphalt plant. Examples of commonly used sizes include:

- Passing the ½ in. (12.5 mm) and retained on ¼ in. (6.35 mm) (coarse RAP).
- Passing the ¼ in. (6.35 mm) screen (fine RAP).

Fine RAP fractions are most useful when producing smaller maximum size aggregate mixtures typically used in wear courses or thin lifts (Brock and Richmond 2007; Cleaver 2013). Processing the RAP just in time for a full day's production prevents the stockpiles from crusting in hot climate.

The RAP can be screened and stockpiled for future use or processing can be completed during asphalt mixture production using in-line sizing and crushing operations. In-line RAP crushers or crusher circuits use roller crushers (lump breakers) or reduced speed impact crushers to break up agglomerations (clumps) of RAP and/or RAS. These crushers typically have a minimal influence on gradations and samples obtained during production can be tested to monitor gradations before and after the in-line processing (Ontario Hot Mix Producers Association 2007). In-line processing is most useful when using lower percentages of recycled material.

Fractionating RAP stockpiles can also help manage the total dust content in the final asphalt mixture. A recent Iowa research study evaluated options for fractionating RAP to control and/or minimize dust content (Shannon 2012). The contractor participating in the study used an Astec ProSizer with a high frequency vibration screen to scalp the RAP on various screens to determine which size reduced the dust to useful levels so that higher percentages of RAP could be used and still meet dust to asphalt specification limits. Fractionating on the 4.75-mm screen was selected as a useful size for managing the total dust content (Table 13). The dust content as well as the percentage of coarse and fine RAP fractions varied between the RAP sources. The percentage of fine fractions in the RAP stockpiles ranged from approximately 35% to 56% and the dust content of the fine RAP fractions from 13% to 19%.

RAS Stockpiles

AASHTO MP23 requires that separate stockpiles be maintained for manufacturer waste shingles and tear-off shingles, because the RAS asphalt, particulates, and backing materials are significantly different between the two sources of RAS. The asphalt availability factors are also expected to be different for the different types of RAS.

Because manufacturing waste and tear-offs come obtained from very different points in the product life cycle, the types and quantities of deleterious materials will also be very different. Deleterious materials in manufacturing waste include packaging materials, scraps of unused or partially coated backing materials, and miscellaneous trash. Tear-off RAS can contain roofing underlayment materials, plywood from roof sheathing, roofing nails, scraps of flashing (aluminum scraps), and other construction demolition-related debris. AASHTO MP23-15 identifies deleterious materials as glass, rubber, soil, brick, paper, wood, and plastics, and is limited to no more than 1.5% of the material retained on and above the 4.75-mm (No. 4) sieve. The nonmetallic deleterious materials cannot exceed 0.5% of the total. Cleaning tear-off shingles before grinding helps limit deleterious materials (Figure 19) (Carolina Asphalt Pavement Association 2011; Jackson 2012).

TxDOT requires less than 1.5% deleterious materials using the Tex-217-F that utilizes:

- 1,000 g of RAS poured over a specially designed pan fitted with a magnet across the middle that removes most metals (Figure 20).
- Metal contaminates are weighed and the percentage of metal in the RAS is calculated.
- Remaining RAS material is sieved over the ⅜ in., No. 4, No. 8, and No. 30 sieves. The minus No. 30 material is discarded.

TABLE 13
EXAMPLE OF DUST CONTENT IN FRACTIONATED RAP

Iowa RAP Source	Passing 0.075-mm Sieve for Each RAP Fraction, %			
	Coarse (12.5 mm to 4.75 mm)		Fine (Minus 4.75 mm)	
	Percent in total RAP stockpile, %	Passing 0.075-mm sieve, %	Percent in total RAP stockpile, %	Passing 0.075-mm sieve, %
RAP A	44.0	9.1	56.0	18.4
RAP B	50.6	11.1	49.4	19.1
RAP C	64.2	7.2	34.8	13.1

Source: After Shannon (2012).

FIGURE 19 RAS stockpiles need to be free of debris prior to grinding (*Source*: Jackson 2012).

- Deleterious material retained on each sieve is visually determined and the total percentage of deleterious material is calculated.

AASHTO MP23 requires that RAS be certified as conforming to local requirements concerning asbestos when using tear-off shingles. If testing for asbestos is required, either polarized light microscopy (PLM) and transmission electron microscopy (TEM) test methods can be used. The TEM method is the most sophisticated for quantifying asbestos fibers in RAS. A list of accredited laboratories for asbestos testing can be found at: http://ts.nlst.gov/standards/scopes/programs.htm. Once the RAS has been tested, no more RAS can be removed to the stockpile (i.e., captive stockpile).

A Missouri DOT report noted that in 2008 its Department of Natural Resources allowed RAS to be processed under the National Emission Standards for Hazardous Air Pollutants guidelines that do not require testing for asbestos when the tear-off shingles come from small residential buildings (Schroer 2009).

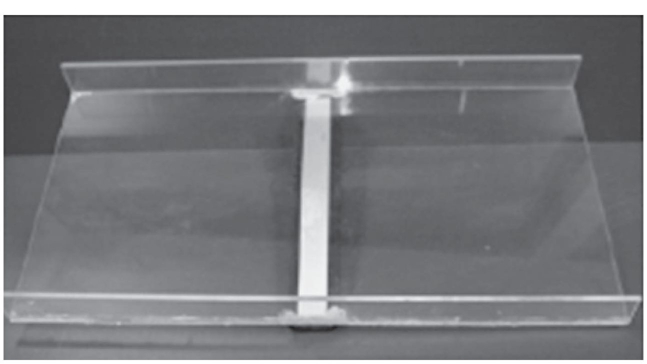


FIGURE 20 TxDOT tray for removing metal from RAS during testing for the percentage of deleterious materials (*Source*: TxDOT test procedure designation Tex-217-F).

Processing RAS

AASHTO MP23-15 requires that RAS be ground so that 100% of the particles pass the 9.5-mm (⅜-in.) sieve before the RAS asphalt extraction. The finer grinding size helps the uniformity of the RAS in the asphalt mixture, which reduces the occurrence of shingle clumps or pop-ups on the roadway (ForPros.com 2013). TxDOT grinds RAS so that it passes a ¼-in. sieve for better heat transfer and verifies the RAS gradations on a daily basis. Ground RAS can be uniformly blended with fine aggregate, powdered zeolites, or RAP to prevent the clumping (agglomeration) of the RAS (AASHTO MP23-14). Any of these materials that blended with the RAS would be included in the RAS aggregate calculations for mix design batch weights.

Asphalt Mixture Production

Various considerations and/or modifications are required to the asphalt plant when more than approximately 25% RAP is added to the mixture. Design changes to the cold feed bins and the conveyors can improve the uniformity of the amount of material that is fed into the plant. The plant type and characteristics can also limit the percentage of recycled materials that can be used. Batch plant characteristics are often more restrictive than drum mix plants.

Feeding Recycled Materials into Asphalt Plants

Wet RAP or hot summer temperatures make the recycled materials stickier and more likely to clump in the cold feed bins, stick to conveyor belts, and accumulate under conveyors (West 2010; Jackson 2012). Cold feed bin features that are useful allow the moisture content to be monitored for plant control, prevent recycled materials from sticking to the sides of the bins, aid in the flow of material out of the bottom of the bin, and provide easy access for plant personnel to maintain and clean the bins (Garrett 2012). Newer feed bin features that are also useful include heat recovery bins that help dry material and reduce emissions by reducing the need for higher temperatures for drying.

Cold feed bins with steep side walls also generally help prevent materials from sticking to the inside of the bin (Ontario Hot Mix Producers Association 2007). Increasing the RAS cold feed bin side slope by 70% improves the flow of the RAS, but decreases bin capacity. Because the RAS percentage is approximately 5%, the reduced bin capacity is still acceptable for typical production rates (AsphaltPro.com 2012). Adding small amounts of material such as RAS can be more easily controlled by adding the RAS with RAP through a cold fed bin. It is important that RAS cold feed bins be cleaned out nightly to prevent clumping.

A conveyor belt should have the proper slope, support, and optimum belt tension to keep the belt from sagging. Covering the conveyors to protect materials from the environment, vulcanized belts, and the addition of good belt scrapers minimize the amount of recycled materials that stick to the belts. When the conveyors are weigh belt scales, metering difficulties through cold feed bins can lead to nonuniform amounts of recycled material being fed into the plant (West and Willis 2014). Adding RAS on top of the RAP on the conveyor helps prevent the RAS from sticking to the conveyor belt.

Types of Asphalt Plants

The percentage of RAP that can be added during production depends on the age, type, and characteristics of the asphalt plant (Brock and Richmond 2007; AAT 2011). Plant differences directly impact the ability of the plant to add, dry, heat, and effectively mix materials. An Ohio survey in 2013 found that three states limited the percentage of RAP to 25% or less when producing asphalt mixtures with a batch plant and another three states limited the percentage of RAP to 40% when using a drum mix plant (ODOT 2013). Ohio DOT recently revised their specifications to allow a 5% higher percentage of RAP when either a counterflow drum mix plant or “mini-drum” batch plant (i.e., batch plant converted to continuous production) than when using a standard batch or parallel flow plant.

Regardless of the plant age or type, when higher percentages of recycled materials are used it is critical to have sufficient amounts of the processed material on hand to provide a continuous supply to the plant. Stopping the flow of RAP can cause the virgin asphalt to come into direct contact with the superheated virgin aggregate, which is not only a fire hazard and causes smoking, but can damage the asphalt. Higher temperatures needed for superheating high RAP contents also increase the wear and tear on plant equipment. Additional equipment inspections and maintenance for drum shells, flights, and any other area exposed to higher temperatures are required.

Higher RAP contents often require a softer asphalt, which means the plant has to have a second asphalt tank available. This can be a problem if the plant normally produces mixtures with a single grade of asphalt.

Batch Plants

Batch plants use conductive heat transfer from the heated virgin aggregate to preheat the recycled materials in the weigh bucket and pugmill throughout the dry-mix cycle (Banasik 2000). When the moisture content recycled material is too high the water flashes off as steam, which leads to potential emission problems. Plant operations or modifications are often necessary to facilitate drying and preheating higher percentages of recycled materials or recycled materials with elevated moisture contents (Table 14).

Drum Mix Plants

Older drums and newer single drum (either parallel or counterflow) mix plant operations or characteristics can be modi-

TABLE 14
SUGGESTIONS FOR USING BATCH PLANTS FOR PRODUCING MIXTURES WITH INCREASING PERCENTAGES OF RECYCLED MATERIALS

General Percentages of Recycled Materials	Options	Benefits
Under 25%	• Use separate belt scale • Add scalping screen for oversized materials (RAP)	• Improves uniformity of mixture
	• Slow down how fast RAP is fed into pugmill	• Allows more time for steam to vent
	• Keep recycled materials dry • Add additional venting capacity • Increase size of baghouse • Add separate baghouse unit for venting extra steam	• Minimizes emission problems • Keeps oily steam from clogging baghouse
	• Convert to combination or continuous batch plant facility	• Diverts superheated aggregate from bucket elevator directly into pugmill • Allows steam to be continuously vented into baghouse
25% to 40%	• Combine aggregate and RAP in bucket elevator, bypass main vibrating screen and discharge into No. 1 bin. • Add additional scale adjacent to tower	• Minimizes blinding screens • Better control of percent added
	• Preheat RAP prior to entering tower	• Helps manage venting of steam
40% or more	• Additional feed bins • Add parallel flow drum for recycled material drying • Increase mixing times	• Improves gradation control • Provides separate system for drying and venting • Improves uniformity of mixtures

Source: After Brock and Richmond (2007); AspahltPro.com (2012).

TABLE 15
GENERAL PLANT CHARACTERISTICS THAT HELP OR LIMIT THE PERCENTAGE OF RECYCLED MATERIALS THAT CAN BE ADDED TO THE MIXTURE DURING PRODUCTION

Type of Plant	Characteristics/Options	Benefits
Older drum plants	• Enlarge opening from RAP chute into drum	• Helps keep recycled materials from clogging opening
	• Slow production rate to compensate for shorter drum lengths in older plants	• Allows more time for drying and for recycled asphalt transfer to virgin aggregate
	• Avoid returning the dust from the baghouse near where the recycled material enters the drum	• Keeps dust from adhering to damp recycled material
Parallel flow drum plants	• Longer drum lengths in newer plants allows for more drying and mixing time	• Helps with conductive heat transfer from superheated virgin aggregate to recycled material • Helps remove moisture • Allows more time for steam to vent
	• Change flighting (plant staff needs training and experience for selecting proper flighting)	• Improves uniform mixing and drying of virgin aggregate and recycled materials
	• Relocate RAP collar further down the drum toward the discharge point and shorten the liquid asphalt pipe lines	• Lengthens the time for superheating the virgin aggregate
	• Add second dryer drum to replace RAP collar feed	• Improves ability to dry recycled materials by extending the dwell time (i.e., time in dryer drum)
Counterflow drum plant	• Heats virgin aggregates and recycled materials in different areas of the drum • Tend to have longer drum lengths	• Helps minimize emission problems • Allows more time for drying and heat transfer
Double drum plant	• Virgin aggregate superheated in inner drum • Outer drum dries and preheats RAP before it enters the inner drum; asphalt is added in the inner drum	• Moisture flashes off in outer drum; keeps steam and asphalt separated that minimizes emissions • Design allows higher RAP percentages (>40%) to be added to the mixture

Sources: Banasik (2000); After ForConstructionPros.com (2005); Olard (2010); Garrett (2012); Astec (2014).

fied to increase the percentage of recycled materials added to the mixtures. Counterflow and double drum mix plants are newer designs that accommodate a wider range and higher percentages of recycled materials (Table 15).

Moisture Content and Higher Plant Temperatures

Unless the plant design provides a separate system for drying and preheating the recycled materials, the temperature required for superheating the virgin aggregate is dependent on the amount of moisture in the RAP and the desired final mixture temperature. The most common equipment problem resulting from higher plant temperatures is caused by the elevated temperatures going from drum mixer to baghouse, which can increase from 10°F to 100°F higher than temperatures at the discharge point of the drum (Garrett 2012). This can damage the baghouse or carry liquid asphalt and fines into the baghouse and leads to increased maintenance and increased wear on drum shells, tires, and trunnions (Cleaver 2013).

Elevated temperatures require significantly more energy. For example, when 20% RAP is added, a change in moisture content from 0% to 5% only requires an increase in the aggregate temperature of less than approximately 45°F (Figure 21; temperatures measured at the stack). However, at 50% RAP,

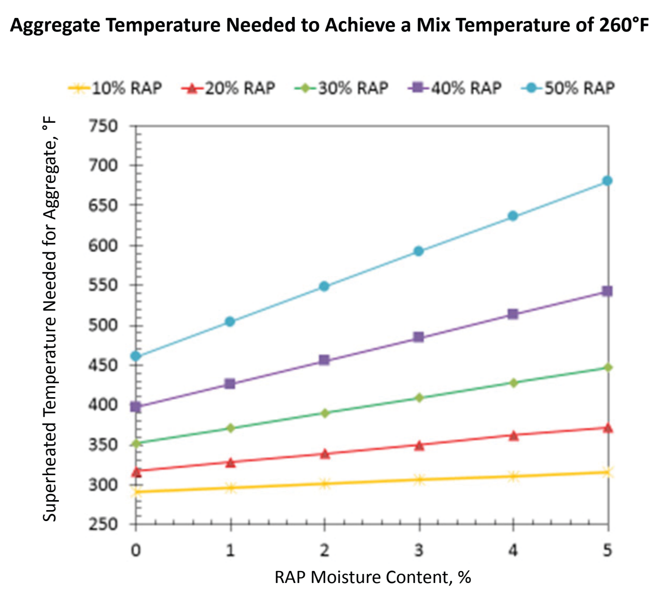


FIGURE 21 Impact of RAP moisture content and the percent of RAP on temperature (*Source*: After Brock and Richmond 2007).

the aggregate temperature needs to be increased from about 460°F (no moisture) to almost 700°F if the RAP contains 5% moisture (Brock and Richmond 2007). Separating drying and preheating the recycled materials process from the aggregate drying and heating can help keep temperatures to a reasonable level and limit damage to the plant.

Storage Times

Storage time in silos, particularly large silos, likely facilitates diffusion of the virgin asphalt into the layer of aged and/or stiff recycled material asphalt. Longer times at elevated temperatures accelerate the rate of diffusion (D'Angelo et al. 2014; Rowe 2014). Although diffusion occurs, information on the impact of silo storage times and temperatures on the blending (diffusion) of virgin and recycled material asphalt was not found in the literature.

Warm Mix Asphalt Used with Recycled Materials

Warm mix additives have been used by some agencies and contractors to keep mixture temperatures down to acceptable levels when producing mixtures with recycled materials. Warm mix asphalt (WMA) helps lower temperatures necessary to superheat aggregate, minimizes heat hardening of virgin binders, and limits overheating of RAP (Jackson 2012). The use of WMA in the production of asphalt mixtures increased approximately 26% from 2011 to 2012 (Hansen and Copeland 2013).

A 2009 survey conducted by South Carolina DOT (24 respondents) showed that two states (8%) used WMA as a way to increase the percentage of RAP used in mixtures, eight states (33%) did not specify WMA at that time, 12 states (50%) used WMA technology in conjunction with RAP mixtures, and 14 states (58%) had adopted specifications to allow for the use of WMA in general (Copeland 2011). West and Willis (2014) noted that no change in binder grade is needed if the percentage of RAP is kept between 26% and 40% and a foamed warm mix technology is used to keep the mixture temperature below 275°F.

Although WMA technologies can be useful in keeping mixture temperatures at acceptable levels, no information was found in the literature about how reducing temperatures with WMA addresses the reason for the higher temperatures, which is to dry moist (or wet) recycled materials.

Asphalt Plant Practices and Production—Section Summary

Stockpiling Recycled Material

- Covering recycled material stockpiles minimizes additional moisture from rain events and heating from solar gain.
  - Damp, sticky, recycled material clumps adheres to belts, blinds screens, and clogs crushers, all of which make it difficult to uniformly process and feed materials into the asphalt plant.
- Plant quality control (QC) personnel and loader operators are critical for keeping contaminates such as dirt, rubbish, vegetation, etc., out of the stockpiles. Contaminates should be removed as soon as they are noticed.
- RAP stockpiles:
  - Some agencies use agency-specific terms to designate RAP materials from designated sources, have similar material properties, use documented QC testing plans, and indicate how the stockpile is built and/or maintained.
  - Fractionating RAP helps control RAP stockpile gradations and ranges of RAP asphalt content.
- RAS stockpiles:
  - AASHTO MP78-14 requires a maximum RAS size of ⅜-in. (9.5-mm) sieve size.
    - △ Some agencies specify a finer grind maximum RAS size of passing ¼-in. (6.35-mm) sieve.
  - Ground RAS can be uniformly blended with fine aggregates, zeolites, or RAP to help minimize clumping.
    - △ Any material added to the ground RAS has to be accounted for in the mix design batch weights.

Asphalt Plants

- Additional cold feed bins or bins with improvements such as steeper side slopes, self-relieving bottoms, and moisture sensors help uniformly feed recycled materials into the asphalt mixture.
- Conveyor belts with appropriate slopes, covered, equipped with good belt scrapers, and supported so as not to sag help keep the recycled materials from clumping, sticking, and rolling backwards or off the conveyors.
- Batch plants can add higher percentages of RAP when the aggregate and RAP are combined in the bucket elevator and bypass the screens, preheat RAP prior to entering the tower, or converting to a continuous batch plant facility.
- Parallel flow drum mix plants can handle higher RAP percentages with proper flighting inside the drum, moving the RAP collar farther down the drum toward the discharge point, or adding a second drum for drying and preheating the recycled materials.
- Counterflow and double-barrel drum designs are newer designs that can handle higher percentages of recycled materials.
- Higher plant temperatures are required to superheat the virgin aggregate so that the conductive heat transfer is sufficient to dry and preheat the recycled materials when there is no separate system added to the plant for drying and preheating recycled materials.

- Higher moisture contents and percentages of RAP require significantly higher temperatures, which can damage both the plant and the asphalt material properties.
- Higher plant temperatures use significantly more fuel (energy), which increases the cost of the asphalt mixture.

PAVEMENT PERFORMANCE

Six RAP studies, eight RAS demonstration projects, and two combination RAP/RAS studies that reported pavement performance findings, were found in the literature. These studies are briefly summarized here.

RAP Pavement Performance

This section summarizes performance information reported for high RAP mixtures placed in Florida, Ohio, Minnesota, Alabama (NCAT test track), Manitoba (Canada), and Long Term Pavement Performance (LTPP) sections around the country.

Florida DOT

Projects using Marshall mix designs with 30% to 50% RAP were constructed from 1991 to 1999 (Nash et al. 2011). Information for evaluating the pavement performance of these mixtures was collected from construction reports (mix design, type of friction courses, structural layer with RAP), financial project management databases (project location, dates for start and completion), pavement management office (mix designs, tonnage), and pavement condition survey data (distress data, previous work on sections of interest, percent trucks, average annual daily traffic). Cracking is the top major distress in Florida and is measured based on the visual evaluation of the pavement surface.

The pavement life span was defined as the first year a deficient crack rating was documented. Similar mixtures without RAP were identified and used to establish a baseline for comparisons (i.e., control sections). RAP was typically used in a lower structural layer and a non-RAP friction course upper layer section placed on the surface. The performance of the RAP mixtures was inferred based on an evaluation of the distresses and the ride quality of the surface. The final data set was separated by 30%, 35%, 40%, and 45% RAP for the initial analysis.

The results showed that the performance of RAP mixtures generally decreased with the increasing percentage RAP when using the unfiltered database. When the analysis accounted for traffic volumes and only evaluated projects constructed with more than 5,000 tons of mixture with between 30% and 50% RAP, the RAP mixtures tended to perform better than the roadways without RAP mixtures. The same conclusion was reached for the projects, regardless of the type of non-RAP friction course placed over the RAP mixture.

Ohio DOT

In 1981, an experimental project with 25% RAP in the base course and 45% RAP in the intermediate course was built in Ohio, and after 24 years of service (2005) the RAP section compares favorably with the control section (West and Willis 2014).

Minnesota DOT

MnDOT performance evaluation was conducted using pavements with RAP in the wear courses and found that rutting was reduced when RAP mixtures were used (Johnson and Olson 2009). Approximately 32% of the projects had early cracking and 39% raveling. Most of these projects also noted construction problems that included:

- Problems with RAP chunks, debris, foreign materials, crack filling materials, and spalling from shale and other soft aggregate.
- "Globs" of oil and fines in the new mat.
- Evidence of stiffer mixtures causing workability issues.
- Asphalt content and gradation that were too variable.
- Oversized material problems when mixture was used in the wear course.
- Mixtures that looked grey, dry, and may require a seal coat sooner (i.e., signs of too low asphalt contents).

Performance and laboratory testing of cores from eight projects showed moderate correlations between the performance ranking for the project and:

- % RAP
- % passing 0.15-mm sieve
- % passing 0.075 mm
- Dust-to-binder ratio
- PG high temperature.

Correlations were obtained between cracking and both the dynamic modulus master curve (middle of the frequency range) and the percentage of RAP. However, stronger correlations were obtained between performance and both the percentage of virgin asphalt and the PG low temperature.

Alabama (NCAT Test Track)

The National Center for Asphalt Technology (NCAT), located in Opelika, Alabama, operates a 1.7-mile oval track as an accelerated loading testing facility. In Alabama, PG 67-22 is the standard grade of virgin asphalt for traffic levels of less than 10 million ESALs, and PG 76-22 for higher traffic levels is specified. Two of the 2006 NCAT test track sections evaluated

TABLE 16
LOAD-RELATED CRACKING OF RAP MIXTURES PLACED AT THE NCAT TEST TRACK IN 2006

Test Section	RAP Content*	RAP Asphalt, %	Virgin Asphalt Grade	Date of First Crack	ESALs at First Crack	Total Length of Cracking
Impact of Reducing Critical PG High Temperature (< 25% RAP)						
W4	20%	17.6	PG 67-22	No Cracking		
W3	20%	18.2	PG 76-22	4/7/2008	6,522,440	34.0
Impact of Reducing Critical PG High Temperature (>25% RAP)						
W5	45%	42.7	PG 58-28	8/22/2011	19,677,699	3.5
E5	45%	41.0	PG 67-22	5/17/2010	13,360,016	13.9
E6	45%	41.9	PG 76-22	2/15/2010	12,182,331	53.9
E7	45%	42.7	PG 76-22S	1/28/2008	5,587,906	145.5

Source: West et al. (2011).
*RAP asphalt content as a percentage of total aggregate.
**Percentage of RAP asphalt as a percentage of the total asphalt content.
S = 1.5% Sasobit in virgin asphalt.

pavement performance differences when using a PG 76-22 and a PG 67-22 virgin asphalt in mixtures with 20% RAP. Four test sections were also constructed in 2006, each with a different PG virgin asphalt grade and 45% RAP. After more than 20 million ESALs, none of the sections had more than 5 mm of rutting; however, some traffic-related cracking was documented (Willis et al. 2009; West et al. 2011). The total length of cracking decreased with each drop in the upper PG temperature grade (Table 16 and Figure 22).

Manitoba, Canada

In 2009, pavement sections with 0%, 15%, and 50% RAP, with and without changing the virgin asphalt grade (Pen 150–200; Pen 200–300), were placed in two 2-in. (50-mm) lifts on a Provincial Trunk Highway 8 miles from Gimi to Hnausa in Manitoba, Canada (Hajj et al. 2011). The distresses of concern for these sections were thermal cracking and moisture damage. Pavement condition surveys were conducted in October 2010 and, after 13 months of service, no distresses were seen in any of the sections. Researchers believed more time was needed to determine the impact of the variables on pavement performance.

LTPP SPS-5 Sections

LTPP special pavement sections (SPS)-5 have 18 sites, each consisting of nine overlay test sections to compare virgin

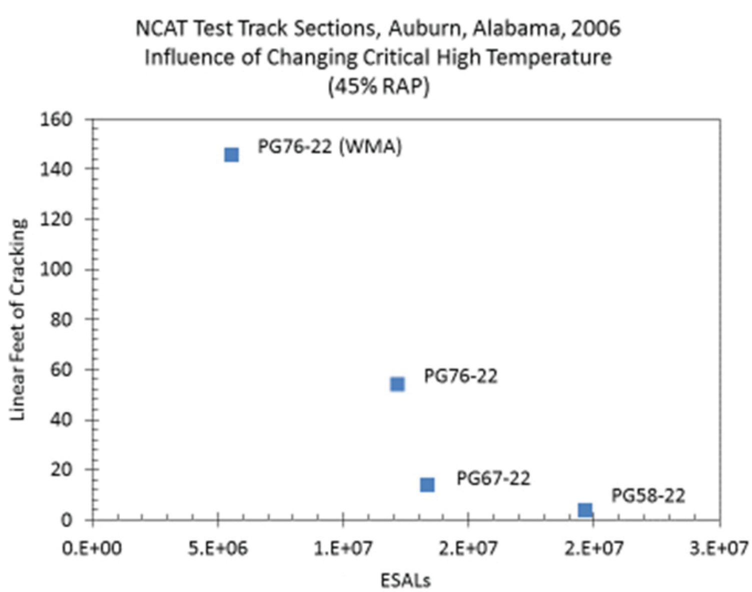


FIGURE 22 Influence of changes in virgin asphalt PG grade on traffic-related cracking (*Source*: After West et al. 2011).

asphalt mixtures with mixtures with up to 30% RAP. Overlays were either less than 2-in. (50-mm) thick or at least 5-in. (125-mm) thick. Pavement condition survey results for ride quality, rutting, and fatigue cracking were grouped into short-term performance (0 to 5 years in service) and long-term performance (more than 5 to 10 years) for statistical analyses (Wiser 2011). Over the short term (≤5 years), there were no statistical differences between virgin and RAP mixtures for 61% to 72% of the sections (Figure 23). LTPP (5 to 10 years) shows an increase in the statistical differences between the virgin and RAP mixtures. The percentage of sites with no statistical differences decreased from between 61% and 72% to between 33% and 44%. The virgin mixtures performed better than the RAP mixtures for between 33% and 50% of the sections. However, over time, 17% to 22% of the RAP mixtures showed better performance than the virgin mixtures.

There were only limited statistical differences for the thin overlays compared with thick overlays (Figure 24).

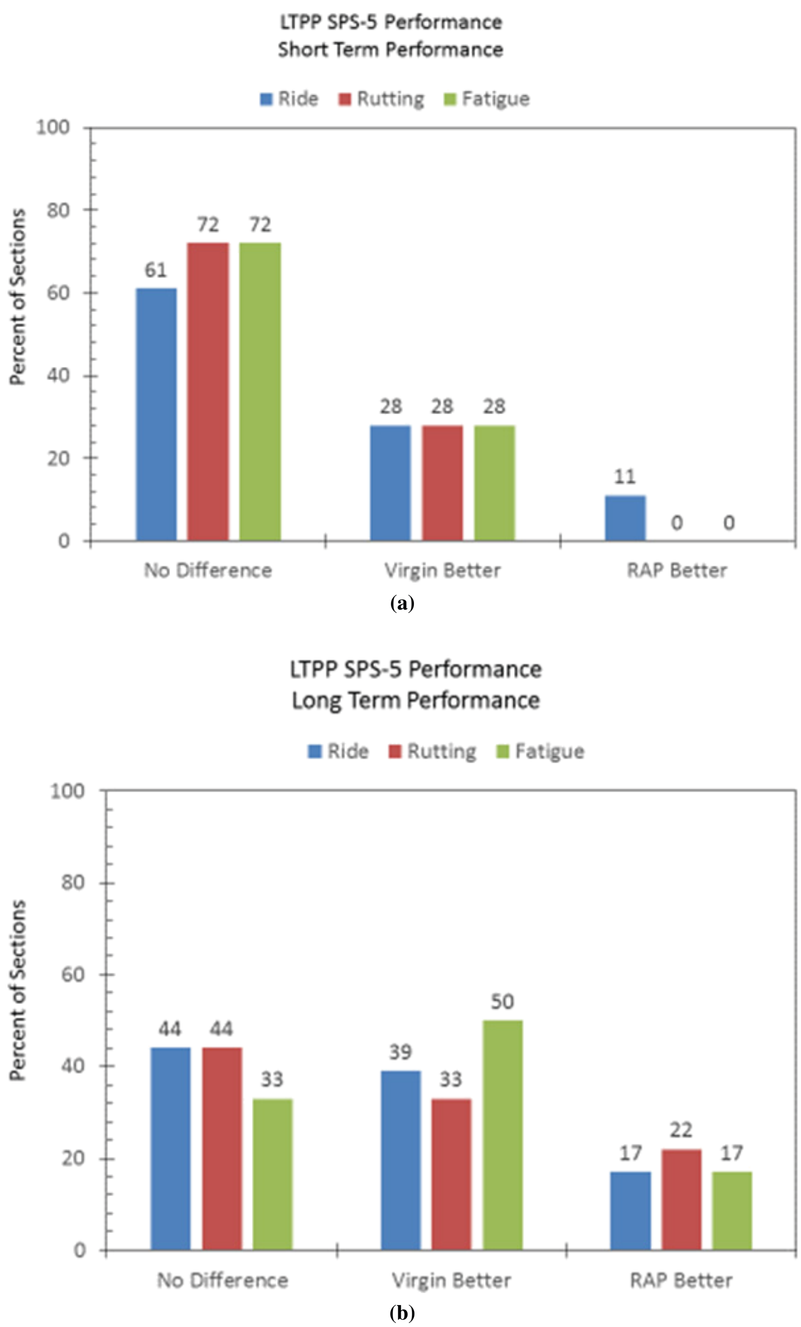
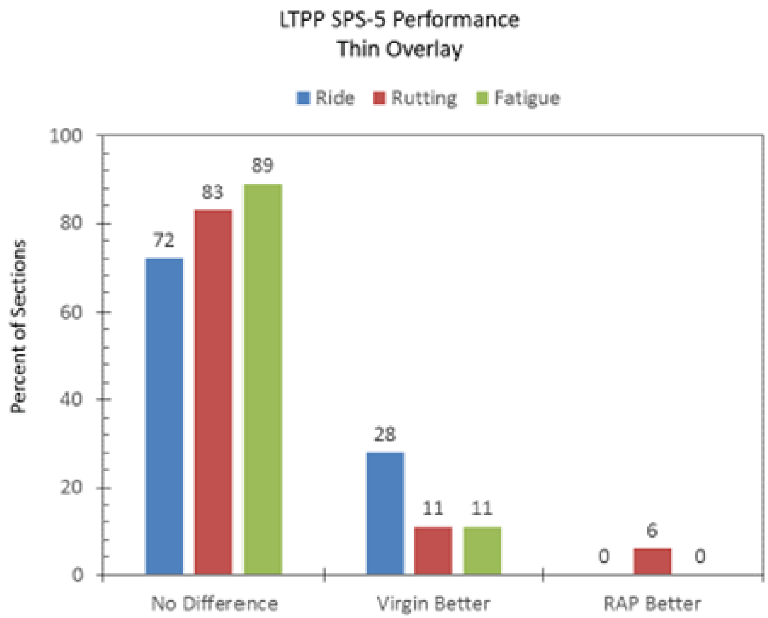
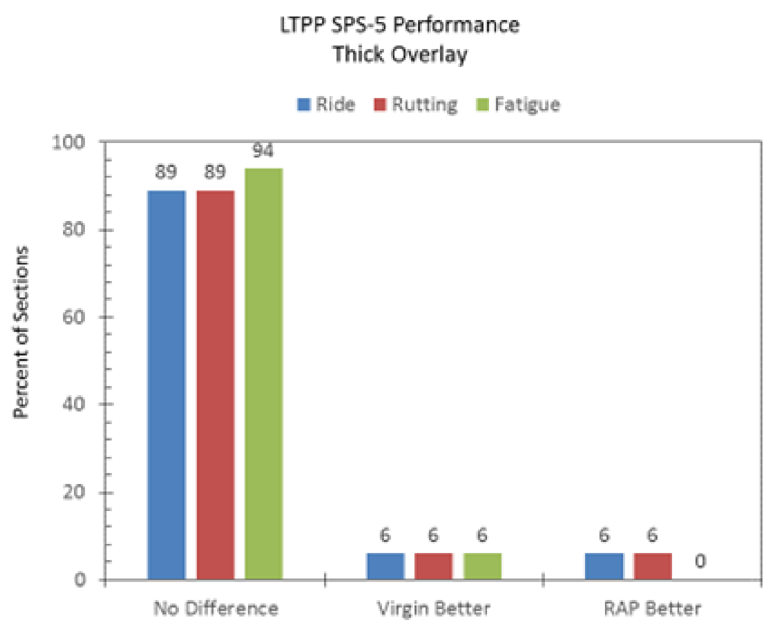


FIGURE 23 Statistical evaluation of LTPP SPS-5 sections of performance: (a) short term and (b) long term (*Source*: Wiser 2011).



(a)



(b)

FIGURE 24 Statistical evaluation of LTPP SPS-5 sections based on overlay thickness of mixtures with and without RAP (*Source*: Wiser 2011).

RAS Pavement Performance

The performance of RAS and combinations of RAP and RAS demonstration project test sections placed in eight states was recently evaluated. Information about the general performance of RAS mixtures across the country was discussed in a 2015 FHWA memorandum. This information about the performance of RAS mixtures is briefly summarized here.

Pooled Fund Study

The goal of the Transportation Pooled Fund (TPF) study program TPF 5(213) was to evaluate RAS grind size, percentage of RAS, RAS source (manufacturer waste, tear-offs), RAS with WMA, RAS as a fiber replacement in SMA, and RAS with ground tire rubber as an asphalt modifier on pavement performance (Williams et al. 2013). Demonstration projects were placed in Missouri (lead state), California, Colorado, Illinois, Indiana, Iowa, Minnesota, and Wisconsin. Each demonstration project evaluated variables of importance to each state agency and the pavement condition survey results are summarized in Table 17.

Pavement performance results 3 years after placement can be summarized as:

- *Missouri*: Fine grind RAS had less transverse cracking than coarse grind RAS. Missouri DOT routinely uses asphalts modified with ground tire rubber and transpolyoctenamer polymer to raise upper PG temperature.
- *Iowa*: The 0% to 5% RAS sections showed similar reflective (transverse) cracking.
- *Minnesota*: Slightly more transverse cracking in manufacturer waste RAS than in tear-off RAS sections; other test sections (all on shoulders) showed transverse cracking next to portland cement concrete (PCC) joints.
- *Indiana*: RAS asphalt mixtures had somewhat less transverse cracking than either RAP or WMA–RAS mixtures.

TABLE 17
SUMMARY OF PAVEMENT PERFORMANCE OF TEST SECTIONS PLACED FOR TRANSPORTATION POOLED FUND (TPF) PROGRAM TPF-5-(213)

State	Variable	Transverse (thermal) Cracking (low)	Transverse (thermal) Cracking (moderate to severe)	Transverse Cracking (reflective)	Longitudinal Cracking	Raveling	Comments
Missouri 3 years	15% RAP	28 ln ft	15 ln ft	—	—	—	PG 64-22 blended with 10% ground tire rubber and 4.5% transpolyoctenamer rubber (TOR)
	10% RAP/5% Fine RAS Post-Consumer	94 ln ft	4 ln ft	—	—	Some	
	10% RAP/5% Coarse RAS Post-Consumer	123 ln ft	16 ln ft	—	Some	—	
Iowa 3 years	0% RAS	—	—	155 ln ft*	165 ln ft	—	Reflective cracking at PCC joints and edge of driving lane
	4% RAS	—	—	142 ln ft*	—	Some	
	5% RAS	—	—	153 ln ft*	—	Some	
	6% RAS	—	—	147 ln ft*	—	Some	
Minnesota 3 years	5% Post-Manufacture RAS	199 ln ft			—	—	Transition section at MnROAD
	5% Post-Manufacture RAS	—	—	28 ln ft*	—	—	Shoulder, next to PCC; cracking at joint
	5% Post-Manufacture RAS	—	—	0 ln ft	—	—	Shoulder, next to PCC; cracking at joint
	5% Post-Consumer RAS	173 ln ft			—	Low to High	Transition at MnROAD
	5% Post-Consumer RAS	—	—	141 ln ft	—	Low to High	Shoulder, next to PCC; cracking at joint
	5% Post-Consumer RAS	—	—	4 ln ft	—	Low to High	Shoulder, next to PCC; cracking at joint
	30% RAP	0 ln ft			—	—	Shoulder
Indiana 3 years	HMA–RAP	112 ln ft*	78 ln ft*	—	4%*	Some	Overlay over thick HMA over PCC
	HMA–RAS	85 ln ft*	55 ln ft*	—	29%*	Some	Overlay over thick HMA over PCC
	WMA–RAS	198 ln ft*	77 ln ft*	—	43%*	Some	Overlay over thick HMA over PCC
Wisconsin 1 year	13% RAP/3% RAS Post-Consumer, WMA	No Distresses					Overlay over 4-in. HMA over PCC
	13% RAP/3% RAS Post-Consumer	No Distresses					
Colorado 1.5 years	20% RAP	—	—	0	—	Some	—
	15% RAP/3% RAS Post-Manufacture	—	—	25 ln ft	—	—	—
Illinois 1 year	PG 70-28, Polymer, 5% Post-Consumer RAS	No Distresses					—
	PG 70-28L 5% Post-Consumer RAS,SMA	No Distresses					—
	PG 58-28 Ground Tire Rubber (12%), 5% Post-Consumer RAS, SMA	No Distresses					—
	PG 70-28, Polymer, 11% RAP/3% Post-Consumer RAS, SMA	No Distresses					—
	PG 70-28L, 11% RAP/3% Post-Consumer RAS, SMA	No Distresses					—
	PG 58-28 Ground Tire Rubber (12%), 11% RAP/3% Post-Consumer RAS, SMA	No Distresses					—

Source: After Williams et al. (2013).
*Indicates values estimated from graphs in report.

Pavement performance results 1 and 1.5 years after placement can be summarized as:

- *Wisconsin*: No distresses seen in test sections (13% RAP/3% RAS).
- *Colorado*: Limited reflective cracking in the 15% RAP with 3% RAS section.
- *Illinois*: No distresses seen in test sections.

FHWA Memorandum

A memorandum was issued by the FHWA Administrator for Infrastructure on December 11, 2014, about the use of RAS in new asphalt pavements (FHWA 2014). The results from the November 2014 survey of the AASHTO Subcommittee on Materials showed that at least 14 states have maximum limit for RAS of 5% by total weight of the asphalt mixtures. Most states have various other limitations based on the location of the mixture in the pavement structure, traffic levels, binder availability factors, and the type of RAS used (manufacturer waste RAS preferred). The survey results also indicated that there were only a few states with a limited number of projects that can be used for pavement performance surveys.

This memorandum notes previous communications that reported increases in the number of agencies that were seeing premature cracking in relatively new asphalt pavements using 5% RAS mixtures and requests that each division office ensure that the AASHTO PP78-14 recommendations for binder availability factors of 0.70 to 0.85 be used when there are concerns about premature cracking. The lower vulnerability to cracking from brittleness in warmer climates was acknowledged.

Combination of RAP and RAS

Texas DOT

In 2009, 2-inch-thick overlay test sections were placed in Houston and Austin, Texas, using mixtures with 15% RAP and 3% RAS and a PG 64-22 virgin asphalt, and the performance of the test sections is currently being monitored every 6 months (Zhou et al. 2013). To date, the combination RAP and RAS test sections show no signs of distress as do the control sections.

Missouri DOT

Field projects, each with a control and two test sections, were constructed by Missouri DOT using mixtures with a (Schroer 2009):

- PG 58-22 virgin asphalt (required softer, but more expensive PG grade) with 20% RAP, and a combination of 5% RAS and 15% RAP.
- PG 65-22 (typical grade, lower cost) with 20% RAP, and a combination of 5% RAS and 15% RAP.

A wear course was placed over all of the mixtures and after 2 years of service no rutting or cracking was observed in any of the sections. After 3 years of service there was still no rutting, but cracking was starting to occur in the control section. Two cracks were seen in the 15% RAP and 5% RAS section and the standard PG 64-22. The cracking was attributed to an area where pavement geometry changed because of lane widening and was at the end of the concrete shoulder. Transverse cracking was seen in the center and passing lanes, but stopped at the joint adjacent to the driving lane, which contained the 15% RAP and 5% RAS layer.

Pavement Performance—Section Summary

High RAP asphalt pavement performance studies show the following:

- Minnesota DOT study:
  - Performance of Minnesota roadways is related to the PG critical low temperature and the percentage of virgin asphalt in the mixture.
  - Projects that showed early cracking also had construction problems associated with the nonuniformity of the mixture (i.e., visible deleterious materials, asphalt-fine balls, dry-looking mixtures, too-variable asphalt content, and gradation).
- NCAT test track:
  - Decreasing the upper PG temperature reduced the impact of high percentages of RAP on traffic-related cracking without a detrimental impact on rutting.
- Manitoba, Canada:
  - After 13 months (one winter), no thermal cracking was seen in any of the sections (0%, 15%, and 50% RAP); however, the researcher believed more time was needed for the assessment of pavement performance.
- LTPP SPS-5 sections:
  - There were only limited differences in ride quality, rutting, and fatigue cracking between virgin and RAP mixtures (30% or less RAP) within the first 5 years of performance.
  - Time periods of more than 5 years are required to see statistical differences in specific pavement distresses or quality.
  - After between 5 and 10 years of performance, mixtures with up to 30% RAP had similar performances compared with control sections almost half of the time (LTPP SPS-5 sections).
    - △ When there was a difference in the pavement performance the control sections (no RAP) performed better than the RAP sections approximately 30% of the time.
    - △ RAP sections performed better than the control sections approximately 20% of the time.

TABLE 18
EXAMPLE OF POTENTIAL MATERIAL COST SAVINGS

Materials		*Source*: Howard et al. (2009) Low	*Source*: Howard et al. (2009) High	*Source*: Willis et al. (2012)
Aggregates	Gravel	$14	$26	$15
	Limestone	$15	$38	
	Coarse sand	$3	$14	
	RAP aggregate:	—	—	$9
Asphalt (2009 costs)		$400	$500	$500 to $550
RAP Value	Processed and stockpiled	$15	$40	—

RAS pavement performance studies show:

- Pavement condition surveys conducted fewer than about 1.5 years after construction typically show no or very limited distresses.
- Most of the significant distresses witnessed in the limited RAS test sections reported in the literature at this time are related to PCC joints (reflective cracking).

ECONOMICS

The cost of asphalt mixtures is a function of materials, plant production, transportation, and placement. Of these four categories, the cost of materials accounts for approximately 70% of the asphalt mixture cost, and the most expensive single material is the asphalt cement (Copeland 2011; data from pre-2000 time period). Cost savings can potentially be achieved by using the asphalt in the recycled materials as a portion of the total asphalt content, because the asphalt is the single most expensive component.

Material cost savings are calculated by evaluating the amount of virgin material that is saved by replacing it with recycled materials. Examples of reported material costs are shown in Table 18. Some of the cost findings found in the literature are shown in Table 19.

Zhou et al. (2013) noted that the economics associated with the recycling of tear-off shingles are driven by landfill tipping fees, cost of RAS production, and the differences between virgin and recycled materials. Tipping fees can range from less than $10/ton to approximately $45/ton (Krivit 2007). The cost of processing RAS includes the manual labor costs for sorting and cleaning the raw construction debris, capital costs for processing equipment, and shingle transportation costs. Material costs and potential savings can be calculated using the following equations (Willis et al. 2012):

$$\text{Cost}_{\text{mix}} = \text{Cost}_{\text{virgin asphalt}} + \text{Cost}_{\text{virgin aggregate}} + \text{Cost}_{\text{RAP}}$$

$$\text{Cost}_{\text{virgin asphalt}} = \text{Price}_{\text{virgin asphalt}}\left[\text{AC\%}_{\text{mix}} - (\text{AC}_{\text{RAP}})(\text{RAP\%})\right]$$

$$\text{Cost}_{\text{virgin aggregate}} = \text{Price}_{\text{virgin aggregate}}\begin{bmatrix}\text{Agg\%}_{\text{virgin}} \\ -\text{RAP\%}(1-\text{AC}_{\text{RAP}})\end{bmatrix}$$

$$\text{Cost}_{\text{RAP}} = \text{Price}_{\text{RAP}}(\text{RAP\%})$$

Where:

Cost_{mix} = Material cost for total asphalt mixture, $/ton;

TABLE 19
EXAMPLE OF REPORTED COST SAVINGS WHEN USING RECYCLED MATERIALS

Time Period of Study	Findings	Source
Pre-2000	Using 20% to 50% RAP may provide cost savings of 20% to 50% when materials and construction costs were considered. This is a potential savings of 1% of mixture cost for every 1% of RAP used.	Kandhal and Mallick (1997)
2004 and 2006	Savings of about 7% to 8% with 10% RAP, 15% with 20% RAP, and 20% to 22% with 30% RAP.	Vukosavlievic (2006)
2006	Using 20% RAP had the potential to save about $42 million worth of asphalt cement a year.	Ontario Hot Mix Producers Association (2007)
2007	Evaluated bid costs for three projects, but found mixed results and noted more data were needed.	Maupin et al. (2008)
2010	Reported Florida DOT estimates recycling program saved over $38 million in materials costs in 2010. About 78% of all Florida mixtures contained RAP (average about 20%).	West and Willis (2014)
2011	Estimated savings to state of $3 to $5 a ton of mix when using between 5% and 7% of RAS (Missouri).	
2012	About 5% RAS can reduce mix cost by about 13% (Texas). Combination of RAS/RAP may reduce cost by up to 20%.	
2012	Material cost savings calculated as between 15% and 20% when using 30% RAP, and between 31% and 35% with 50% RAP.	Willis et al. (2012)

$Cost_{virgin\ asphalt}$ = Cost of virgin asphalt in mixture, \$/ton;
$Cost_{RAP}$ = Cost of virgin aggregate in mixture, \$/ton;
$Price_{virgin\ asphalt}$ = Price of virgin asphalt, \$/ton of asphalt;
$Price_{virgin\ aggregate}$ = Price of virgin aggregate, \$/ton of aggregate;
$Price_{RAP}$ = Price of RAP, \$/ton of RAP;
$AC\%_{mix}$ = Total asphalt content of mix, %;
$AC\%_{RAP}$ = Asphalt content of RAP, %;
RAP% = Percentage of RAP in mixture, %; and
Agg% = Percentage of aggregate, %.

Wet materials can increase production costs because higher temperatures are needed to dry recycled materials. One source estimates that the cost increases 13% for every 1% of moisture in the total mix (IBuildRoads™ 2012). Howard et al. (2009) documented that moisture content has a significant impact on the asphalt plant energy consumption (Table 20). Higher RAP moisture contents combined with higher percentages of RAP in the mixture are likely to increase plant energy usage in order to meet maximum mixture moisture content limits.

The costs associated with milling asphalt pavement, as reported by Christman and Dunn (2013), were calculated by a North Dakota district that typically uses 20% to 24% RAP in its asphalt mixtures. Between 2008 and 2012, the milling costs were about $1,458,865. A total of 530,857 tons of asphalt mixtures with RAP were placed, with an average additional virgin asphalt content of 4.31%. Non-RAP asphalt mixtures had an average virgin asphalt content of 6.1% for the same time period. An estimated reduction of 9,521 tons of virgin asphalt saved was estimated, providing a net savings of $2,778,630 (net savings = cost virgin asphalt saved – milling costs). The average cost of the virgin asphalt for this time period was $445 per ton.

The value engineering project option was used by three contractors in Virginia (Maupin et al. 2008). The cost savings were divided between the contractor and the Virginia DOT. Cost savings were obtained by increasing RAP from 20% to 21% (one project), and from 20% to 25% (two projects). The cost savings came from replacing virgin aggregate with RAP and from using a less costly asphalt because of an increased percentage of RAP (i.e., PG grade bump).

Maupin et al. (2008) used a database with 120 projects to conduct a statistical analysis using various economic models. These models showed significant relationships between the number of tons in a plant mix line item and the number of bids received; that is, more competition results in lower bid prices.

Most of the information on expected savings to the agencies by using recycled materials is based on simple calculations for material costs. Different PG grades have different costs and using a percentage of RAP and/or RAS that requires a change of the asphalt grade can impact the material costs. For example, an increase of only 2% of RAP, from 23% RAP to 25% RAP, can change the PG grade to a lower cost asphalt and help with the mixture cost (Willis et al. 2012). Although material costs were found to be the primary contributor to the asphalt mixture costs for information collected before 2000, the impact of the other three factors (plant production, transportation, and placement) on cost need to be re-evaluated (Copeland 2011). Factors such as increased costs associated with additional QC/quality assurance (QA) testing when using higher RAP contents, additional RAP processing, higher plant energy costs for superheating virgin aggregate, longer drying times (slower production rates), increased plant maintenance and equipment wear resulting from higher plant temperatures, and baghouse clogging, wear, and tear may shift the

TABLE 20
ESTIMATED ENERGY SAVINGS BECAUSE OF A REDUCTION IN MIXTURE MOISTURE CONTENT AND/OR PLANT TEMPERATURE

Moisture, %	Total Energy BTU/ton			Savings, %
	310°F (154°C)	240°F (116°C)	Change	
1.0	123,769	92,874	30,895	25.0
2.0	145,991	114,708	31,283	21.4
3.0	168,212	136,541	31,671	18.8
4.0	190,433	158,375	32,058	16.8
5.0	212,655	180,209	32,446	15.3
6.0	234,876	202,043	32,833	14.0
7.0	257,098	223,877	33,221	12.9
8.0	279,319	245,711	33,608	12.0
9.0	301,540	267,545	33,995	11.3

Source: Howard et al. (2009).

impact on costs from materials to production (Brock and Richmond 2007).

RESEARCH IN PROGRESS

There is currently one set of FHWA test sections and three NCHRP studies (NCHRP 9-55, NCHRP 9-57, NCHRP 9-58) under way with research topics related to the types and percentages of RAP and/or RAS in asphalt mixtures. The Turner–Fairbank Highway Research Center is currently evaluating several test sections placed at the Accelerated Loading Facilities (ALF) to establish realistic boundaries for high RAP mixtures using WMA technologies and RAS based on the percentage of asphalt replacement and virgin asphalt grade changes (TFHRC 2014). Testing at the ALF facility should be completed by 2016.

The objectives of NCHRP Project 9-55, Recycled Asphalt Shingles in Asphalt Mixtures with Warm Mix Asphalt Technologies, are to, at a minimum, address:

- Minimizing the risk of designing and producing mixtures containing WMA technologies and RAS with poor constructability and durability.
- Minimizing the risk of designing and producing mixtures containing WMA technologies and RAS that are susceptible to premature failure.
- Evaluating type, source, quality, and characteristics of RAS with and without RAP.
- Investigating binder design and selection, including evaluation of the composite binder.
- Exploring the current range of asphalt mixture production temperatures.

The objectives of NCHRP Project 9-57, Experimental Design for Field Validation of Laboratory Tests to Assess Cracking Resistance of Asphalt Mixtures (2015), are to select candidate laboratory tests for load- and environment-associated cracking applicable for routine use through a literature review and workshop, and to develop an experimental design for field experiments to establish, verify, and validate the laboratory tests. Test methods to evaluate top-down and/or bottom-up load-related cracking, thermal cracking, and reflective cracking that are being considered include (Table 21):

- Bending beam fatigue,
- DSC,
- IDT,
- Texas overlay tester,
- Repeated direct tension,
- SCB at low and intermediate temperatures,
- S-VECD,
- TSRST, and
- UTSST.

TABLE 21
SUMMARY OF POSSIBLE TEST METHODS THAT WILL BE EVALUATED UNDER NCHRP 9-57 CONTRACT

Name	Standard	Cracking Type	Specimen Geometry	Cracking Parameter	Criteria	COV
Bending Beam	AASHTO T321	Bottom-up fatigue	Rectangle, 15-in. length, 2.5-in. width, 2-in. thickness	Number of cycles to failure; fatigue equation	Pass/Fail	>50%
DSC	ASTM D7313	Low temperature and reflective	Disc, 6-in. diameter, 2-in. thickness, 2 holes (diameter 1 in.), notch depth of 2.45 in.	Fracture energy	Pass/Fail	10% to 15%
IDT	AASHTO T322	Low temperature	Disc, 6-in. diameter, 1.5-in. to 2.0-in. thickness	Creep compliance, tensile strength	—	<11%
	AASHTO T322	Top-down fatigue		Energy ratio	Pass/Fail	Not reported
Repeated Direct Tension	Texas A&M	Bottom-up and top-down fatigue	Cylinder, 4-in. diameter, 6 in. tall	Paris law parameters, endurance limit, healing properties, average crack size	Models	Low, but more work needed
SCB	AASHTO TP105	Low temperature	Semi-circle, 6-in. diameter, 1-in. thickness, 0.6-in. notch depth	Fracture energy	Pass/Fail	20%
SBC at Intermediate Temperatures	LTRC	Top-down fatigue cracking; reflective	Semi-circle, 6-in. diameter, 2.5-in. thickness, 1-in., 1.25-in., and 1.5-in. notch depth	Critical energy release rate	Pass/Fail	20%
S-VECD	AASHTO TP107	Bottom-up and top-down fatigue	Cylinder, 4-in. diameter, 5.1-in. tall	Number of cycled; predicted number of cycles	—	Low, but more work needed
			For *E**: 4-in. diameter, 6-in. tall			
TSRST/UTSST	AASHTO TP105 (Monotonic)	Low temperature	Rectangle, 10-in. length, 2-in. width, 2-in. thickness	Fracture temperature; coefficient of thermal contraction	Pass/Fail	About 10%
Texas Overlay Tester	Tex-249-F	Reflection cracking; bottom-up fatigue	Rectangle cut from gyratory; 6-in. maximum length, 3-in. width, 1.5-in. thickness	Number of cycled to failure; fracture parameters A and n	Pass/Fail	30% to 50%

Source: NCHRP 9-58 (2015).
— No information provided.

The objectives of NCHRP Project 9-58, Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios, are to:

- Evaluate the effectiveness of recycling agents in HMA and WMA mixtures with high RAS, RAP, or combined RAS and RAP binder ratios through a coordinated program of laboratory and field experiments.
- Propose revisions to several relevant AASHTO specifications and test methods.
- Develop training and workshop materials and deliver one workshop.

The scope covers the investigation of asphalt mixtures prepared with recycling agents and RAS, RAP, or combined RAS and RAP at recycled asphalt binder ratios of between 0.3 and 0.5, and the performance of the binders and mixtures will be evaluated. This research will be conducted on plant-mixed, laboratory-compacted specimens obtained from trial batches or production runs prepared in asphalt mix plants. Consistent laboratory conditioning procedures will be applied to all specimens and changes in mixture properties with aging in the field will be quantified.

CHAPTER THREE

STATE MATERIALS ENGINEERS SURVEY

The State Materials Engineer survey (Appendix A) focused on specific practices used when working with recycled materials in the laboratory, test methods, and any modifications needed when designing mixtures with recycled materials. Forty-five responses were received, including agencies that indicated they do not currently use at least 25% RAP or RAS in their mixtures. The main survey topics and the organization of this chapter are as follows:

- Total asphalt content
- Measuring recycled material asphalt content
- Selecting the virgin asphalt grade
- Material properties required for volumetric calculations
- Sample preparation
- Mixture testing.

TOTAL ASPHALT CONTENT

Accounting for Recycled Asphalt in Mixture

The contribution of the recycled asphalt to the total asphalt content can be considered as fully contributing (100% useful), partially useful, or not useful (0%; "black rock"). More than 78% of the responding agencies consider that 100% of the RAP asphalt is useful and fewer than 8% that none of the RAP asphalt is useful. Approximately 16% attribute only a portion of the RAP asphalt to the total asphalt content (Table 22).

Agencies view the contribution of the RAS asphalt differently than the RAP asphalt. Agencies are about evenly split between considering RAS asphalt as 100% useful and only partially useful (asphalt availability factor). Fewer than 15% of the respondents believe RAS does not provide any contribution.

When mixtures contain a combination of both RAP and RAS, 14 agencies consider the combined RAP and RAS asphalt as 100% available and only three believe none of the recycled asphalt contributes to the total asphalt content.

Twenty-seven respondents use the total asphalt content equation to calculate the asphalt content of the mixture (Table 23). Two agencies noted that they determine the asphalt content of 10 RAP samples and then use the average RAP asphalt content in the equation.

Specific asphalt availability factors were reported by eight agencies:

- 0.85 for RAS asphalt (four agencies).
- 0.75 for RAS asphalt (two agencies).
- 0.70 for RAS asphalt (one agency).
- 0.75 for RAP *and* RAS (one agency).

Additional information provided by the respondents about asphalt availability factors included:

- Use a percentage asphalt requirement, although there appears to be very little reactivation of recycled asphalt when using WMA, especially with RAS.
- Specification requires adding 0.2% virgin asphalt when RAS is used.
- Use effective binder content.
- Credit a 75% contribution of the RAP binder. The remaining 25% is added to the mix design/determined asphalt content, which is referred to as the "corrected optimum asphalt content (COAC)." We changed from 100% to 75% in 2012 and adjusted again 2014.
- Limit the percentage of RAP based on where it is in the pavement structure (i.e., lift-dependent) (three agencies):
  - 25% in lower lifts; 15% by weight in mixtures in the top 0.2 ft (2.5 in.).
  - 30% in base lift, 20% in binder lifts, 15% in wear course, but planning on changing to ABR.
  - Only allow RAS in maintenance mixtures and not in designed mixtures.
- Several states indicated that they were interested in using a reduction factor, but had not yet applied one.

Five agencies use the ABR equation to establish a minimum percentage of virgin asphalt in the total asphalt content (Table 24). One agency noted it set a minimum ABR value based on the lower PG temperature: 70% for PG xx-28 and 80% for PG xx-34. Another agency defines the minimum ABR based on the mixture type: 80% for surface mixtures and 65% for base and binder mixtures.

Six agencies use the RAP binder ratio to limit the percentage of recycled material asphalt that can be used to replace the virgin asphalt (Table 25). Two agencies limit recycled material asphalt from all of the recycled materials in the mixture to 23% of the total asphalt content. One agency uses

TABLE 22
GENERAL APPROACH FOR CONSIDERING CONTRIBUTION OF RECYCLED MATERIAL ASPHALT CONTENT TO TOTAL ASPHALT CONTENT

Survey Question: For the purposes of mix designs, indicate which "philosophy" is used to establish the contribution of the recycled material asphalt.							
Materials	**100% Available for Mix**		**0% ("Black Rock")**		**Agency-Assumed Percentage of the Total Recycled Asphalt Content**		**Responses per Row**
	%	*n*	*%*	*n*	*%*	*n*	*n*
RAP							
25% or Less RAP	83	29	3	1	14	5	35
More Than 25% RAP	77	23	7	2	17	5	30
RAS							
RAS, Manufacturer Waste	46	12	8	2	46	11	26
RAS, Tear-Offs	39	9	13	3	48	10	23
RAS, any Combination	42	12	7	2	48	9	27
Combination							
RAP and RAS Combination	42	14	9	3	48	8	33

Not all survey respondents answered all questions.

TABLE 23
USE OF TOTAL ASPHALT CONTENT (TAC) EQUATION

Survey Question: We use the sum of the new asphalt and recycled asphalt material content: Total asphalt content = (RAP asphalt content) (% of RAP in mix) + (RAS asphalt content) (% of RAS in mix) + (new asphalt content %)		
Use TAC Equation?	*%*	*n*
Yes	84	27
No	16	5

Not all survey respondents answered all questions.
n = 32.

TABLE 24
USE OF ASPHALT BINDER RATIO EQUATION

Survey Question: We use the asphalt binder ratio (ABR) equation: ABR = (virgin asphalt %)/(Total asphalt content %)		
Use ABR Equation?	*%*	*n*
Yes	21	5
No	78	18

Not all survey respondents answered all questions.
n = 23.

TABLE 25
USE OF RECYCLED BINDER RATIO EQUATION

Survey Question: We use the recycled binder ratio (RBR) RBR = (recycled binder content %)/(Total asphalt content %)		
Use RBR Equation?	*%*	*n*
Yes	26	6
No	74	17

Not all survey respondents answered all questions.
n = 23.

an ABR limit of 25%. Three agencies define the maximum limit based on where the mixture is located in the pavement structure:

- 20% for surface mixture and 35% for base and binder mixtures (one agency).
- 40% for surface mixtures and 45% for intermediate and base mixtures (one agency).
- 45%, but it varies (no specifics given) (one agency).

Total Asphalt Content Section Summary

- Agencies use the total asphalt content equation, but vary substantially in the values used for asphalt availability factors.
  - Eighteen agencies use a value of 1.0 (i.e., 100% availability for both RAP and RAS).
    - △ Eleven agencies use asphalt availability factors < 1.0, but the values used vary. Two of these agencies apply an asphalt availability factor to RAP as well as RAS.
  - Eleven agencies set limits on the percentage of the recycled material asphalt that can contribute to the total asphalt content (i.e., use either ABR or RBR).
- One agency noted that RAS does not appear to contribute to the total asphalt content when combined with WMA used to lower temperatures.

MEASURING RECYCLED MATERIAL ASPHALT CONTENT

How an agency prepares the RAP material before testing can impact the measured asphalt content. One question was included in the survey to determine which RAP fractions

TABLE 26
TESTING RECYCLED MATERIALS TO DETERMINE ASPHALT CONTENT

Survey Question: The asphalt content of the recycled materials is determined for each material. (Check all that apply.)		
Value	**%**	***n***
RAP (not fractionated)	88	29
Coarse RAP fraction	64	21
Fine RAP fraction	64	21
RAS	58	19
RAP and RAS combined prior to testing	39	13

Not all survey respondents answered all questions.
n = 33.

TABLE 27
PREPARATION OF RECYCLED MATERIALS PRIOR TO TESTING

Survey Question: If you separate RAP into coarse and fine fractions for testing, please indicate which sieve size is used for "retained on"/"percent passing."		
Value	**%**	***n***
4.75-mm (No. 4)	100	11
2.36-m (No. 8)	0	0

Not all survey respondents answered all questions.
n = 11.

are tested and if RAP and RAS are combined prior to determining the asphalt content. A second question was included to determine which sieve size(s) was (were) used to define coarse and fine fractions when the laboratory separates the RAP sample before testing.

Sizing Recycled Materials for Testing

Twenty-nine agencies routinely determine the RAP asphalt content for unfractionated RAP. Twenty-one of these agencies also determine the asphalt content for both coarse and fine fractions (Table 26). Thirteen agencies combine RAP and RAS before testing when the combination of recycled materials is used in the mixture.

Although 21 agencies measure the asphalt content of coarse and fine RAP fractions, only 11 fractionate the RAP in their laboratory (Table 27). These 11 agencies use the 4.75-mm (No. 4) sieve size to fractionate coarse and fine RAP. The differences between the number of agencies testing the individual coarse and fine fractions and those agencies fractionating the RAP in their laboratories before testing reflect the variations in the RAP samples submitted for mix designs by the contractors. That is, some contractors separated their RAP supplies into coarse and fine fractions, whereas others maintain RAP gradations with the full range of sieve sizes.

Test Methods to Determine Asphalt Content

There are two test methods that can be used to determine the asphalt content of mixtures as well as asphalt-containing recycled materials. These are the traditional solvent extraction methods (AASHTO T164) and the newer method using an ignition oven (AASHTO T308).

Twenty agencies use the ignition oven method for determining the asphalt content of the recycled materials (Table 28). The same 20 agencies also indicated that they conduct solvent extractions; therefore, these agencies have the ability to determine correction factors based on the differences in the mass lost during solvent extraction and the mass lost during ignition oven testing. This method of establishing an ignition oven correction factor is applicable to both aggregates prone to mass loss resulting from burning as well as to asphalt-containing recycled materials such as shingles with material content that also burns off (e.g., paper backing and roofing felt). Because eight agencies noted they no longer use any solvent extraction method in their laboratories, these agencies are not able to determine an ignition oven correction factor using this approach.

Comments about determining the ignition oven correction factor for mixtures include:

- Not used (four agencies).
- Differences in results from solvent extraction (AASHTO T164) and ignition oven (AASHTO T308) are used to

TABLE 28
IGNITION OVEN USAGE

Survey Question: Do you use the ignition oven to determine the recycled material asphalt content? (Check all that apply.)							
Materials	**Yes**		**No**		**Sometimes, Depending on Aggregate Type**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	***N***
RAP, unfractionated	69	20	28	8	3	1	29
Coarse RAP fraction	61	14	30	7	9	2	23
Fine RAP fraction	61	14	30	7	9	2	23
RAS	50	9	44	8	6	1	18
RAP and RAS combination	50	8	50	8	0	0	16

Not all survey respondents answered all questions.

TABLE 29
SOLVENT EXTRACTION TEST METHODS

Survey Question: If you use solvent extraction to determine the recycled binder content, indicate which method(s) is (are) used. (Check all that apply.)											
Materials	**Centrifuge**		**Reflux**		**Vacuum**		**Extraction Vessel, AASHTO T319**		**Soaking (nonstandard option)**		**Responses per Row**
	%	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*N*
RAP, unfractionated	77	17	14	3	9	2	0	0	0	0	22
Coarse RAP fraction	73	11	13	2	13	2	0	0	0	0	15
Fine RAP fraction	73	11	13	2	13	2	0	0	0	0	15
RAS	100	14	14	2	7	1	0	0	0	0	14
RAP and RAS combination	100	10	20	2	20	2	0	0	0	0	10

Not all survey respondents answered all questions.

determine a correction factor (four agencies for RAP, two for RAS).
- Varies or depends (no specifics) (two agencies).
- Use 0.5% (two agencies).
- Based on aggregate type.
- As described in the ignition oven test method (AASHTO T308).
- Applied only to the total mixture.
- Require the contractor to determine the ignition oven correction factor for RAS.

Solvent Extraction Methods

Twenty-two agencies use one or more solvent extraction methods, with the centrifuge methods being used most frequently (Table 29). Most agencies use the centrifuge extraction method with TCE solvent, although some agencies also use *n*-propyl bromide (Table 30). Similar responses were given, regardless of the material being tested. Eight agencies commented that they *do not use any* solvent extraction in their laboratories

Measuring Recycled Material Asphalt Content—Section Summary

- Most agencies use the ignition oven method for determining asphalt content.
- About half of these agencies also use a solvent extraction method for determining asphalt content and ignition oven correction factors (when needed).
- Nearly 20% of the states noted they are not using any solvent extraction method in their laboratories; therefore, they do not have the ability to determine correction factors for nonasphalt but burnable materials contained in the recycled materials using this method.

RECYCLED MATERIAL ASPHALT PROPERTIES

Twenty-two agencies also recover asphalt from the solvent after extraction (Table 31), but use a range of methods. Abson (eight agencies) and Rotavapor (eight agencies) are the most commonly used methods. Four agencies use the AASHTO T319 combination extraction and recovery method and two agencies state-specific methods.

TABLE 30
SOLVENTS USED WITH EXTRACTION METHODS

Survey Question: … And indicate which solvent(s) is (are) used. (Check all that apply.)									
Materials	**Trichloroethylene (TCE)**		***n*-Propyl Bromide (nPB)**		**Toluene**		**Toluene and Ethanol Blend**		**Responses per Row**
	%	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*n*
RAP	61	11	28	5	6	1	6	1	18
Coarse RAP fraction	79	11	21	3	0	0	0	0	14
Fine RAP fraction	79	11	21	3	0	0	0	0	14
RAS	62	8	38	5	0	0	0	0	13
RAP and RAS combination	75	9	25	3	0	0	0	0	12

Not all survey respondents answered all questions.

TABLE 31
METHODS USED FOR ASPHALT RECOVERY

Survey Question: Which recovery methods(s) do you use? (Check all that apply.)		
Value	**%**	***n***
Abson (AASHTO T170)	44	8
Rotavapor (ASTM D5404)	44	8
Combination Extraction/Recovery (AASHTO T319)	22	4
Agency-Specific Method	11	2

Not all survey respondents answered all questions.
n = 18; more agencies have recovery methods than indicated they recover recycled materials.

Not only do agencies use a range of methods for asphalt recovery, they also evaluate a range of different recycled material asphalt properties (Table 32). The high temperature DSR shear modulus, *G**, is determined as-is after recovery by eight agencies, and four agencies determine the high temperature *G** after rolling thin film oven (RTFO) conditioning of the recovered asphalt. Another two agencies determine the high temperature *G** after both RTFO and pressure aging vessel (PAV) conditioning.

Additional respondent comments included:

- Recovered asphalts are considered as already aged; we only use PAV aging to determine the low temperature grade.
- BBR is used to determine the stiffness and m-value for low temperature assessment; no RTFO aging is used before testing.
- Only dynamic shear rheometer testing is used to determine failure temperature for recovered asphalt.
- Use the Bonaquist method (see chapter two: Literature Review).

Recycled Material Asphalt Property—Section Summary

- The majority of agencies recovers extracted recycled material asphalt, but uses a range of recovery methods.
- No consistent approach is used when determining the high temperature DSR shear modulus, *G**, and low temperature BBR stiffness and m-value.
  - Some agencies determine this value for the as-recovered, and other agencies determine the high temperature *G** after RTFO conditioning, or after RTFO and PAV conditioning.
- One agency uses the Bonaquist method to evaluate if the recycled material asphalt fully contributes to the total asphalt content properties.

RECYCLED MATERIAL AGGREGATE PROPERTIES

Twenty agencies determine recycled material aggregate properties (Table 33). Six other agencies commented that they do not evaluate the individual recycled material aggregate properties because:

- Source and quality of RAP is known (two agencies).
- All RAP that is required comes from state roads.
- RAS aggregate is considered better quality than most of roadway fine aggregate.
- RAP and RAS aggregate properties are too variable to classify other than gradation.
- Only the mix design blend is tested.

Aggregate Test Methods

Consensus properties are those that experts consider important to the final pavement properties and include gradation; presence of clay-sized particles; that is, sand equivalent; and coarse and fine aggregate shape (Table 34). Twenty-four agencies

TABLE 32
RECYCLED MATERIAL ASPHALT PROPERTIES EVALUATED AFTER EXTRACTION AND RECOVERY

Survey Question: Indicate which binder tests you use to determine the true (continuous) recycled binder grade. (Check all that apply.)		
Testing	**%**	***n***
DSR, *G**, as-recovered high asphalt temperature	53	8
After Rolling Thin Film Oven (RTFO) Conditioning		
DSR, *G**, high asphalt temperature	33	5
DSR, *G**, intermediate asphalt temperature	40	6
BBR, Stiffness, low asphalt temperature	33	5
BBR, m-value, low asphalt temperature	27	4
Testing After RTFO and Pressure Aging Vessel (PAV) Conditioning		
DSR, *G**, intermediate binder temperature	13	2
Stiffness, low binder temperature for stiffness	20	3
m-value, low binder temperature	7	1

Not all survey respondents answered all questions.
n = 15.

TABLE 33
WHEN ARE AGGREGATE PROPERTIES DETERMINED FOR RECYCLED MATERIALS

Survey Question: Indicate when the aggregate properties of the individual recycled materials need to be determined.		
Materials	*%*	*n*
15% or less RAP	50	10
25% or less RAP	50	10
More than 25% RAP	40	8
RAS, manufactured waste	20	4
RAS, tear-offs	15	3
RAS, combination	15	3
RAP and RAS combination	30	6
We test aggregates for the mixture (after solvent extraction or ignition oven) rather than individual recycled aggregate properties	30	6

Not all survey respondents answered all questions.
n = 20.

determine RAP gradations (15 agencies after ignition oven and nine after solvent extraction). Slightly fewer agencies determine the percentage passing the 0.075-mm (No. 200).

Although the ignition oven method may alter aggregate properties to some degree, nine agencies determine various aggregate shape parameters after ignition oven testing. At most, five agencies evaluate RAP particle shape after solvent extraction, and five determine the sand equivalent for RAP after ignition oven testing.

RAS aggregate gradations are the only aggregate property evaluated. Eleven agencies determine the RAS aggregate gradations (six after ignition oven and five after solvent).

Respondents provided the following additional comments about recycled material aggregate properties:

- Consensus properties are determined for the blended aggregates.
- Only the sand equivalent on the composite of virgin aggregates is determined.
- Only test RAP aggregate when the source is unknown.
- Use AASHTO T335 instead of ASTM D5821 for determining the percentage of fractured faces.
- Check properties day to day; reserve the right to check RAP individually if needed.
- RAS aggregates considered to have better properties than other aggregates.

Eighteen agencies assume that the RAP source properties are acceptable because they came from a state project (Table 35). Only two agencies determine the LA abrasion values for RAP aggregate (after ignition oven) and another two agencies use the micro-Deval (after solvent extraction). One agency evaluates RAP sodium sulfate soundness and another evaluates soundness of RAP aggregate using magnesium sulfate.

Ten agencies assume that the source properties of the RAS aggregate are acceptable rather than evaluate with testing.

TABLE 34
CONSENSUS AGGREGATE PROPERTIES DETERMINED FOR RECYCLED MATERIAL AGGREGATE

Material	Particle Size						Particle Shape						Responses per Row
	Gradation (sieve analysis)		Minus 0.075-mm (No. 200) by washing		Sand* equivalent (AASHTO T176)		Flat and elongated (ASTM D4791)		Fractured faces (ASTM D5821)		Fine aggregate angularity (AASHTO T304)		
	%	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*n*
After Ignition Oven Testing													
RAP	100	15	80	12	33	5	53	8	60	9	60	9	15
RAS	100	6	50	3	0	0	0	0	0	0	0	0	6
After Solvent Extraction													
RAP	100	9	67	6	0	0	33	3	55	5	44	4	9
RAS	100	5	40	2	0	0	0	0	0	0	0	0	5

*Evaluates clay-sized particles.
Not all survey respondents answered all questions.
Total of 27 individual agencies responded to this question.

TABLE 35
SOURCE AGGREGATE PROPERTIES FOR RECYCLED MATERIAL AGGREGATES

Survey Question: Indicate the aggregate source property tests that are conducted on the recycled material aggregates. (Check all that apply.)											
Materials	**LA Abrasion (toughness)**		**Micro-Deval (toughness)**		**Sodium Sulfate Soundness**		**Magnesium Sulfate Soundness**		**Assume Source Properties Are Acceptable**		**Responses per Row**
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	*n*
After Ignition Oven Testing											
RAP	10	2	0	0	5	1	5	1	95	18	19
RAS	0	0	0	0	0	0	0	0	100	6	6
After Solvent Extraction											
RAP	0	0	13	2	13	2	8	1	93	14	15
RAS	0	0	0	0	0	0	0	0	100	4	4

Not all survey respondents answered all questions.
*Assumption for acceptable RAP provided on the survey was because material came from state project.
Total of 34 individual agencies responded to this question.

Additional respondent comments noted that one agency conducts source tests when investigating polish resistance quality of the aggregate. Another agency noted that the contractor has the option to conduct these tests.

Recycled Material Aggregate Property—Section Summary

- Gradations of the RAP and RAS materials are the most frequently evaluated recycled material aggregate property after either ignition oven or solvent extraction.
- RAP source aggregate properties are typically considered acceptable, usually because RAP was obtained from state projects.
- RAS source aggregate properties are also considered acceptable (specific reasons not explored with survey questions).
- Only a limited number of agencies measure the recycled material aggregate shape, clay-sized particle content, soundness, and toughness.

SELECTING THE VIRGIN ASPHALT GRADE

When multiple asphalt grades are routinely used by the agency, it is likely contractors in the state will have multiple asphalt tanks at the plant so that a range of different mixtures can be produced. However, some agencies specify only two asphalt grades that can be used in the state, which implies that the contractors in the state will likely have, at most, two asphalt storage tanks. The percentage and/or type of recycled material that can be used in a given state is limited to the availability of the virgin asphalt needed to produce the desired combined asphalt properties. When a range of asphalt grades is available, the percentage and/or type of the recycled materials can be selected and the asphalt grade selected to meet asphalt specifications. A limited availability of different asphalt grades usually means that the percentage and/or type of recycled material is restricted to what can be used and still meet the asphalt specifications, usually without changing the virgin asphalt grade.

One question was included in the survey to determine which approach was used by each agency. Ten agencies set the percentage of recycled material to be used and then select the virgin asphalt grade required to meet specification requirements (Table 36). Four agencies specify the virgin asphalt grade then select the percentage of recycled materials. Only one agency noted they use a softener or rejuvenating additive.

Additional respondent comments included:

- Use an established binder selection table.
- Only specify virgin binder grade, then perform AASHTO M320 (Standard Specification for Performance-Graded Asphalt Binder) to verify.
- Only PG 64-22 and PG 76-22 binders permitted in our state.
- Currently, we do not adjust the grade for mixtures with less than 30% RAP, but will evaluate both blending charts and defined grade bumping in the future.

TABLE 36
VIRGIN ASPHALT GRADE SELECTION APPROACH

Survey Question: Indicate which approach is used to ensure the blended binder meets the required PG grade.		
Value	%	*n*
Establish (select) percent of RAP to be used, then determine the virgin asphalt PG grade needed	67	10
Choose virgin asphalt PG to be used, then determine the percent of recycled material	27	4
Use softening or rejuvenator additive to soften the recycled material binder, then proceed with determining the virgin asphalt PG	7	1

Not all survey respondents answered all questions.
n = 15.

- Contractor may choose any of these approaches. Most of the time, the contractor selects the RAP percentage and then determines the virgin binder grade they have to use.
- No softening or rejuvenating additive is allowed.

Eleven agencies “bump” the upper and/or lower virgin asphalt temperature even when not using high RAP (Table 37). Ten agencies “bump” the virgin asphalt grades for high RAP mixtures. Two agencies “bump” the virgin asphalt grade when using a combination of RAP and RAS. At most, four agencies extract, recover, and test the recycled material asphalt to determine the true asphalt grade. None of the agencies “bump” the virgin asphalt grade when using RAS.

Other respondent comments about selecting the virgin asphalt grade included:

- Difficult to determine PG grade because of the high softening point of RAS binder.
- If contractor recovers and grades binder, they can use any percent recycled material.

Selecting Virgin Asphalt—Section Summary

- Various agency approaches are used to select the percentage of recycled materials used in mixtures:
  - Most agencies select the percentage of recycled materials and then adjust the virgin PG grade required to meet the binder specification requirements.
  - Several agencies set the virgin binder PG grade and then select the maximum percentage of recycled material that can be used and still meet the specifications.
  - There appears to be a limited use of softening or rejuvenating additives to modify the recycled material asphalt properties.

MATERIAL PROPERTIES REQUIRED FOR VOLUMETRIC CALCULATIONS

Recycled Material Asphalt Specific Gravities

Asphalt binder-specific gravity values are used in various mix design volumetric calculations and the testing of the virgin asphalt-specific gravity is straightforward. However, determining the specific gravity of the recycled material asphalt content requires recovery of the asphalt after solvent extraction and any solvent not completely removed during recovery influences the specific gravity measurements. Other factors that make asphalt recovery and testing more variable are the additives used in the original manufacture of the recycled materials such as polymer modifiers, crumb rubber (i.e., contained in some RAP), fibers, fillers, and proprietary additives.

Ten agencies use an assumed value for the RAP asphalt-specific gravity and six assume the RAS asphalt-specific gravity (Table 38). Assumed values used by the various agencies include:

- Same as virgin asphalt (six agencies)
- 1.03 (three agencies)
- 1.035
- 1.01
- Use supplier data for virgin asphalt binder-specific gravity.

Recycled Material Aggregate Specific Gravity

The recycled material aggregate specific gravities (RAP, RAS, or a combination of RAP and RAS) are most often determined by measuring the theoretical maximum specific gravity of the recycled material, calculating the effective specific gravity, and finally calculating the recycled material aggregate bulk specific gravity (Table 39).

TABLE 37
METHODS FOR SELECTING THE VIRGIN ASPHALT PG GRADE

Survey Question: Please indicate how your agency determines the virgin PG grade used in mixtures with recycled materials. (Check all that apply.)

Materials	Upper PG Temp.		Lower PG Temp.				Determine True PG with Testing		Responses per Row
	1 Grade Lower		1 Grade Lower		2 Grades Lower				
	%	*n*	%	*n*	%	*n*	%	*n*	*n*
≤ 25% RAP	73	8	82	9	0	0	9	1	11
>25% RAP	50	5	60	6	10	1	30	3	10
>50% RAP	0	0	0	0	0	0	100	3	3
≤5% RAS	0	0	0	0	0	0	0	0	0
>5% RAS	0	0	100	1	0	0	0	0	1
RAP and RAS	33	1	67	2	0	0	33	1	3

Not all survey respondents answered all questions.

TABLE 38
NUMBER OF AGENCIES THAT USE ASSUMED VALUES FOR CALCULATIONS

Survey Question: Mix design calculations require a number of individual material properties. If your agency assumes, rather than measures, any of the properties in the table below, please enter the typical estimated values in the appropriate text boxes.

Materials	Recycled Material Asphalt Specific Gravity		Virgin Asphalt Specific Gravity		Responses per Row
	%	*n*	*%*	*n*	*n*
RAP, unfractionated	90	9	50	5	10
Coarse RAP fraction	87	7	50	4	8
Fine RAP fraction	87	7	50	4	8
RAS	85	6	43	3	7
RAP and RAS combination	80	4	40	2	5

Not all survey respondents answered all questions.
n = 10.

Some agencies directly measure specific gravities after ignition oven and only a few agencies measure this property after solvent extraction. The solvent extraction or the ignition oven are known to influence aggregate property test results, but are the only methods currently available for removing asphalt if an agency wants to obtain measurements, rather than estimates, of the recycled material specific gravities.

Additional respondent comments included:

- Extraction method used only during design phase for mixtures with more than 25% RAP; ignition oven method used the rest of the time.
- Assume same as virgin aggregate.
- Currently introducing bulk specific gravity testing of the RAP aggregate as a design requirement instead of the effective specific gravity (historically used by our agency).
- Effective specific gravity is calculated based on the total asphalt content and maximum specific gravity after 2% to 3% virgin asphalt is added.
- Asphalt absorption is estimated at 0.3% (for calculation of aggregate specific gravity from theoretical maximum specific gravity).
- Do not test; materials too variable.

Recycled Material Specific Gravities—Section Summary

- Recycled material asphalt-specific gravities are frequently assumed.
  - Assumed values range from 1.01 to 1.035.
  - Several agencies use the specific gravity of the virgin asphalt for the specific gravity of the recycled material asphalt.
- Recycled material aggregate specific gravities are frequently calculated from measurements of the recycled material, theoretical maximum specific gravity.

TABLE 39
RECYCLED MATERIAL AGGREGATE SPECIFIC GRAVITY

Survey Question: Indicate which test methods are used to determine the specific gravities of the recycled materials aggregate.

Materials	Bulk Specific Gravity				Estimate Bulk Specific Gravity Based on Experience		Theoretical Maximum Specific Gravity (AASHTO T209)		Responses per Row
	After solvent extraction		After ignition oven						
	%	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*n*
RAP, unfractionated	24	4	47	8	0	0	65	11	17
Coarse RAP fraction	7	1	36	5	0	0	79	11	14
Fine RAP fraction	7	1	36	5	0	0	79	11	14
RAS	0	0	18	2	9	1	82	9	11
RAP and RAS combination	13	1	38	3	13	1	75	6	8

Not all survey respondents answered all questions.
n = 17.

TABLE 40
FRACTIONATING RECYCLED MATERIALS FOR BATCHING

Survey Question: Does the percent or type of recycled materials used in the mixture change how you fractionate, or don't fractionate, the materials in the laboratory?							
Materials	**Yes**		**No**		**Sometimes**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	***n***
25% or less RAP	12	3	85	22	4	1	26
More than 25% RAP	15	3	60	12	25	5	20
Shingles, manufacturer waste	0	0	100	15	0	0	15
Shingles, tear-offs	0	0	100	15	0	0	15
Shingles, combination	0	0	100	13	0	0	13
RAP and RAS	13	2	73	11	13%	2	15

Not all survey respondents answered all questions.
n = 30.

SAMPLE PREPARATION

The steps for the preparation of materials for fabricating mix design samples are:

- Sizing of aggregates and recycled materials,
- Drying recycled materials prior to batching samples,
- Heating (time and temperature) of materials for mixing,
- Order of addition to mixing bowl,
- Short-term aging before compaction, and
- Compaction of samples.

Sizing (Fractionating) Particles

Most of the responding agencies use the same procedures for preparing recycled materials for batching their mix design samples, regardless of the type or percentage of recycled materials used in the mixture (Table 40).

A range of practices is used to prepare coarse virgin or recycled materials for batching (Table 41). Some agencies separate both the virgin and recycled coarse material into individual sizes, whereas other agencies sieve the virgin aggregated into individual sizes, but only use the percent retained on a given sieve size (i.e., 4.75 mm or 2.36 mm).

Additional respondent comments showed that:

- Five agencies batch materials based on the stockpiles as prepared by the contractor.
- Three agencies noted that definitions of "coarse" and "fine" for the recycled materials are established by the contractor.
- Four agencies responded that the contractor determines how to fractionate RAP. More than 25% RAP.
- One agency *does not* fractionate for batching.
- One agency *does* fractionate for batching, even if the contractor does not.

TABLE 41
FRACTIONATING COARSE RECYCLED MATERIALS

Survey Question: Indicate which individual sizes and/or percent retained on a given sieve size are used for batching ***coarse*** particles when using various percentages and types of materials in the mixtures.															
Materials	**25 mm (1 in.)**		**12.5 mm (1/2 in.)**		**9.5 mm (3/8 in.)**		**4.75 mm (No. 4)**		**2.36 mm (No. 8)**		**Retained on 4.75 mm (No. 4)**		**Retained on 2.36 mm (No. 8)**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	***n***
Aggregates	44	7	63	10	63	10	69	11	50	8	56	9	25	4	16
25% or less RAP	15	2	39	5	46	6	39	5	23	3	62	8	15	2	13
25% or more RAP	29	2	43	3	57	4	29	2	14	1	57%	4	0	0	7
Shingles, manufacturer waste	0	0	0	0	67	2	67	2	33	1	0	0	0	0	3
Shingles, tear-offs	0	0	0	0	67	2	67	2	33	1	0	0	0	0	3
Shingles, combination	0	0	0	0	67	2	67	2	33	1	0	0	0	0	3
RAP and RAS	33	1	33	1	67	2	33	1	0	0	33	1	0	0	3

Not all survey respondents answered all questions.
n = 21.

TABLE 42
FRACTIONATING FINE RECYCLED MATERIALS

Survey Question: Indicate what individual sizes and/or percent passing a given sieve are used for batching ***fine*** particles when using various percentages and types of materials.															
Materials	**Passing 4.75 mm (No. 4)**		**Passing 2.36 mm (No. 8)**		**1.18 mm (No. 16)**		**0.6 mm (No. 30)**		**0.30 mm (No. 50)**		**0.15 mm (No. 100)**		**0.075 mm (No. 200)**		**Responses per Row**
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	*n*
Aggregates	80	12	73	11	20	3	20	3	20	3	20	3	27	4	15
25% or less RAP	80	8	40	4	20	2	20	2	20	2	20	2	20	2	10
More than 25% RAP	67	4	50	3	17	1	17	1	17	1	17	1	17	1	6
Shingles, manufacturer waste	50	2	50	2	25	1	25	1	25	1	25	1	25	1	4
Shingles, tear-offs	50	2	50	2	25	1	25	1	25	1	25	1	25	1	4
Shingles, combination	50	2	50	2	25	1	25	1	25	1	25	1	25	1	4
RAP and RAS	67	2	33	1	33	1	33	1	33	1	33	1	33	1	3

Not all survey respondents answered all questions.
n = 21.

- One agency noted they use 19 mm (¾ in.) as a maximum size because we ask that RAP be screened on a 25-mm (1-in.) grizzly before introduction to the plant.

A wide range of practices for preparing fine virgin and recycled materials for batching was also reported. Some agencies fractionate fine virgin and RAP materials into the full range of individual fine aggregate sizes (1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm), whereas other agencies just use the materials passing either the 4.75-mm or 2.36-mm sieve size (Table 42). Only one agency separates RAS into individual sieve sizes.

Three agencies commented that they batch materials as prepared by the contractor and the contractor defines which sieve size is used to define "coarse" and "fine." One agency noted that fines are defined as passing the 4.75-mm (No. 4) sieve for production, but are defined as passing the 2.36-mm (No. 8) sieve for mix design purposes. The smaller sieve size is used for mix designs to provide better control of the mix design gradations. One agency indicated the RAS is batched as a single stockpile with at least 90% passing the 4.75-mm (No. 4) sieve.

Drying Recycled Materials

Nineteen agencies dry recycled materials before using them to prepare mix design samples (Table 43). About two-thirds of these agencies use oven drying, whereas the remaining one-third dry materials under a fan at room temperature (Table 44). Fan drying of either RAP or RAS samples is typically completed overnight (between 16 and 24 hours). Oven temperatures used for drying to a constant mass include 100°F, 125°F, and 230°F (38°C, 52°C, and 110°C). No consistent oven temperature or time in the oven was evident.

Parameters used to identify when materials were dried to a "constant mass" were inconsistent. Several agencies use a maximum change in mass of 0.1% between subsequent weighings, but vary by use of drying method (oven, fan), temperatures, and times between subsequent weighings (e.g., 15 minutes, 30 minutes, 1 hour, and none specified). Additional variations in parameters include using changes in mass of 0.05% or 0.5% over 30 minutes in an oven (300°F or 230°F), respectively. One agency uses a maximum change of 0.5 gram over 30 minutes in an oven at 300°F (149°C).

Several agencies use oven drying of either RAP or RAS for a specified time rather than drying to a constant mass. One

TABLE 43
RECYCLED MATERIAL DRYING PRACTICES

Survey Question: Is the recycled material dried prior to using to prepare mix design samples?				
Answer	**RAP**		**RAS**	
	%	*n*	%	*n*
Yes	91	29	83	19
No	9	3	17	4

Not all survey respondents answered all questions.
n = 32.

TABLE 44
METHODS OF DRYING RECYCLED MATERIALS

Survey Question: What method of drying is used?				
Method	**RAP**		**RAS**	
	%	*n*	%	*n*
Under fan at room temperature	34	10	24	7
Oven	66	19	45	13

Not all survey respondents answered all questions.
n = 29.

agency reported using from 125°F to 175°F (52°C to 80°C) for a maximum of 2 hours. Another agency reported using 200°F (93°C) for a maximum of 2 hours.

Agencies that only use RAP reported a range of times and temperatures for drying recycled material prior to batching:

- 140°F (60°C) overnight.
- 230°F (110°C) for a maximum of 1 hour.
- 275°F (135°C) for a maximum of 16 hours.
- 280°F or 300°F (138°C or 149°C) depending on the required compaction temperature to a constant mass.
- Dry RAS using an oven temperature of 125°F for a maximum of 16 hours.

Heating Materials for Mixing

The length of time and the temperature used to heat the components can influence the uniformity of the virgin asphalt coating, blending of the recycled asphalt with the virgin asphalt, and the separation of the agglomerated recycled materials. Additional aging of the recycled asphalt may also occur if too high of a temperature or too long of a preheating time at elevated temperatures is used. A series of survey questions explored the heating times and temperatures, the order of the addition of materials into the mixing bowl, and approximate times used by agencies.

Eleven agencies heat aggregates, RAP, and RAS separately, and 12 combine these materials and heat together (Table 45). Six agencies using RAS in their mixtures combine the RAS with sand before heating to avoid clumping of the RAS during heating. Seven agencies combine RAP and RAS materials before heating, when both are used in the same mixture.

Additional respondent comments included:

- All components are combined before heating for mixing and compaction.
- Recycled material is kept separate and added 1 hour before mixing in the mix design process in a 350°F oven.
- Verify mixtures on plant-produced samples; do not replicate mix designs using lab batched samples.
- Because the plant heats RAP separately prior to adding to drum mixtures, this is recommended but not required.
- RAP and RAS are heated approximately 30 minutes before mixing.
- Do not heat the RAP or RAS for mix design purposes. These materials are not preheated in real world production; preheat virgin aggregate and then add RAP and/or RAS at room temperature before introducing the new asphalt cement.

Times and temperatures are grouped by each of the four AASHTO regions (Region 1—Northeastern, Region 2—Southeastern, Region 3—Mid-America, Region 4—Western). Respondents only provided information about what recycled materials are used in their laboratories; therefore, certain data sets such as RAS heating times and temperatures are limited. In general, the times and temperatures used to heat the materials prior to mixing vary considerably within each region (Table 46). Most, but not all, respondents reduce heating temperatures for the recycled materials. Some, but not all, agencies also reduce the time used to heat the recycled materials.

Although the database is small and not complete, the average and standard deviations of the times and temperatures show general trends (Table 47). Average heating times for aggregates vary from 2.5 to 6 hours and from 1.4 to 3.8 hours for RAP. There is a trend for agencies to reduce the heating times for recycled materials regardless of type or AASHTO region. There is also a trend for agencies to use higher temperatures for heating aggregates than for heating recycled materials (Figure 25). Temperatures tend to be slightly higher for heating RAS or combinations of RAP and RAS then when heating just RAP. Heating temperatures for recycled materials are generally more variable than for heating virgin aggregates.

Twelve respondents use a temperature probe placed in the aggregate material while it is heated and eight agencies use the

TABLE 45
HEATING OF PARTICULATE MATERIALS FOR MIXING

Survey Question: Indicate how the materials are, or are not, combined for heating.					
Materials	**Heated Separately**		**Combined and Heated Together**		**Responses per Row**
	%	***n***	**%**	***n***	***n***
Aggregate and RAP	52	11	57	12	21
Aggregate and RAS	50	6	58	7	12
RAP Fractions	25	2	75	6	8
RAS Fractions	0	0	100	6	6
RAS with Sand (to avoid clumping)	0	0	100	6	6
RAP and RAS	29	2	71	5	7

Not all survey respondents answered all questions.
n = 21.

TABLE 46
MIXING HEATING TIMES AND TEMPERATURES FOR RAP AND/OR RAS MIXTURES

AASHTO Region	Heating Time, hours				Temperature, °F (°C)			
	Aggregates	RAP	RAS	Combination RAP and RAS	Aggregates	RAP	RAS	Combination RAP and RAS
Northeastern								
1	2	0.5	0.5	—	265 (129)	230 (110)	230 (110)	230 (110)
1	6	2	2	—	310 (154)	290 (143)	290 (143)	—
1	—	—	—	—	315 (157)	—	—	315 (157)
1	3	2	—	—	325 (163)	325 (163)	—	—
1	3.75	1	1	1	350 (176)	350 (176)	350 (176)	350 (176)
Southeastern								
2	1.5	1.5	1.5	—	—	—	—	—
2	—	—	—	—	300 (149)	300 (146)	—	—
2	—	—	—	—	320 (160)	320 (160)	320 (160)	320 (160)
2	—	—	—	—	325 (163)	295 (146)	295 (163)	295 (163)
2	6	6	—	—	335 (168)	335 (168)	—	—
2	—	—	—	—	340 (171)	245 (118)	—	—
2	2	—	—	—	375 (190)	—	—	—
Mid-America								
3	—	—	—	—	290 (143)	290 (143)	—	290 (143)
3	6	1.5	—	—	325 (163)	230 (110)	—	—
3	—	—	—	—	345 (173)	300 (149)	300 (149)	300 (149)
3	6	1	—	—	350 (176)	335 (168)	—	—
Western								
4	1.5	1.5	1.5	—	—	—	—	—
4	—	—	—	—	290 (143)	175 (81)	175 (80)	175 (80)
4	—	—	—	—	290 (143)	290 (143)	290 (143)	290 (143)
4	4	4	4	4	295 (146)	295 (146)	295 (146)	295 (146)
4	2	—	—	2	325 (163)	—	—	325 (163)
4	—	—	—	—	340 (171)	—	—	—

— No information provided.
n = 22.

time in the oven to confirm the mixing temperature is reached (Table 48). Agencies are inclined to use the time in the oven more often for defining "at temperature" for recycled materials than actual temperature measurements.

Order of Addition to Mixing Bowl

Agencies begin their mixing process by adding the preheated aggregates to the mixing bowl (Table 49). When the RAP is added to the bowl depends on whether the RAP is heated separately or combined with the virgin aggregate for heating. RAS may be added at the same time as the RAP or added after the aggregate and RAP is either dry mixed or mixed with asphalt. There is no consistent order for the addition of RAS to the mixing bowl. Liquids are usually, but not always, added to the bowl after all of the nonliquid materials. If any additive or rejuvenator is used, it is usually preblended with the asphalt before mixing.

Additional respondent comments included:

- Mix for 5 minutes after adding asphalt.
- Chemical WMA mixing temperature and mixing is performed according to the manufacturer's recommendation or appendix in AASHTO R35.

Visual inspection is usually used to assess when materials are satisfactorily mixed and only a few agencies use a time frame for mixing (Table 50).

Short-Term Aging

The short-term aging of the asphalt mixture is used to simulate any heat-induced aging of the binder during production. Long-term aging of the asphalt mixture is used to simulate aging of the asphalt mixture that occurs over 7 to 10 years of service life. When recycled materials are included in the mixture, the short-term aging provided the elevated temperatures essential to help the blending of the virgin asphalt binder with the recycled asphalt binder. The most frequently used short-term aging time reported by agencies is 2 hours at temperatures between 275°F and 335°F, depending on the virgin asphalt grade (Table 51). Other times used for short-term aging include 1.5 and 4 hours. One agency uses 15 h ± 3 h at a temperature of 140°F.

Sample Compaction

Compaction levels, controlled by the number of gyrations used for mix designs, are also representative of the position

TABLE 47
AVERAGE HEATING TIMES AND TEMPERATURES FOR MIXING

AASHTO Region	Statistics	Aggregates	RAP	RAS	Combination RAP and RAS
Heating Time, hours					
Northeastern	Average	3.7	1.4	1.2	1.0
	Std. Dev.	1.7	0.8	0.8	—
Southeastern	Average	3.2	3.8	1.5	—
	Std. Dev.	2.5	3.2	—	—
Mid-America	Average	6.0	1.3	—	—
	Std. Dev.	0.0	0.4	—	—
Western	Average	2.5	2.8	2.8	3.0
	Std. Dev.	1.3	1.8	1.8	1.4
Temperature, °F					
Northeastern	Average	313	299	290	298
	Std. Dev.	30.9	52.0	60.0	61.7
Southeastern	Average	333	299	308	308
	Std. Dev.	25.0	34.2	17.7	17.7
Mid-America	Average	328	289	300	295
	Std. Dev.	27.2	43.7	—	7.1
Western	Average	308	253	253	271
	Std. Dev.	23.1	67.9	67.9	66.0
Temperature, °C					
Northeastern	Average	156	148	143	148
	Std. Dev.	17.2	28.7	33.0	34.0
Southeastern	Average	162	148	162	162
	Std. Dev.	8.5	19.0	2.1	2.1
Mid-America	Average	164	143	149	146
	Std. Dev.	14.9	24.1	—	4.2
Western	Average	149	123	123	133
	Std. Dev.	9.6	36.7	37.3	36.4

— No data provided or only one value so standard deviation cannot be calculated.
$n = 22$.

of the mixture in the pavement layer and/or traffic levels. That is, a higher number of gyrations suggest mixture designs for mixtures closer to the surface (i.e., wear courses) or higher traffic levels. Most agency specifications allow for a range of compaction levels, but several states use a single number of gyrations for all mixtures (Table 52). A few states commented that the Marshall mix design method is still used to design larger aggregate size (i.e., bases) and SMA mixtures (typically more gap-graded surface mixtures).

Respondent comments included:

- Use kneading compactor for mix design.
- Do not change the gyrations N_{Design} when using RAP; do not use RAS at this time, but do not anticipate changing gyration level if RAS is used.
- Use different N_{Design} values based on ESAL Class. Class 2 = 30 million ESALs $N_{Design} = 100$.
- Use Marshall compaction, AASHTO T245, at 75 blows/side. Mixtures may be designed using Superpave gyratory compactor at 65 gyrations; OGFC mixtures designed at either 50 Marshall blows or 50 gyrations, but no recycled materials are allowed.
- N_{Design} gyrations are based on the traffic level of the mix design: TL-A = 50, TL-B = 65, TL-C = 75, TL-D and TL-E = 100.
- RAP/RAS is not allowed in SMA or surface courses; 12% asphalt replaced by recycled material is allowed in surface course if not SMA and the RAP/RAS Special Provision is used. Our specs are by virgin asphalt type with no distinction by course.

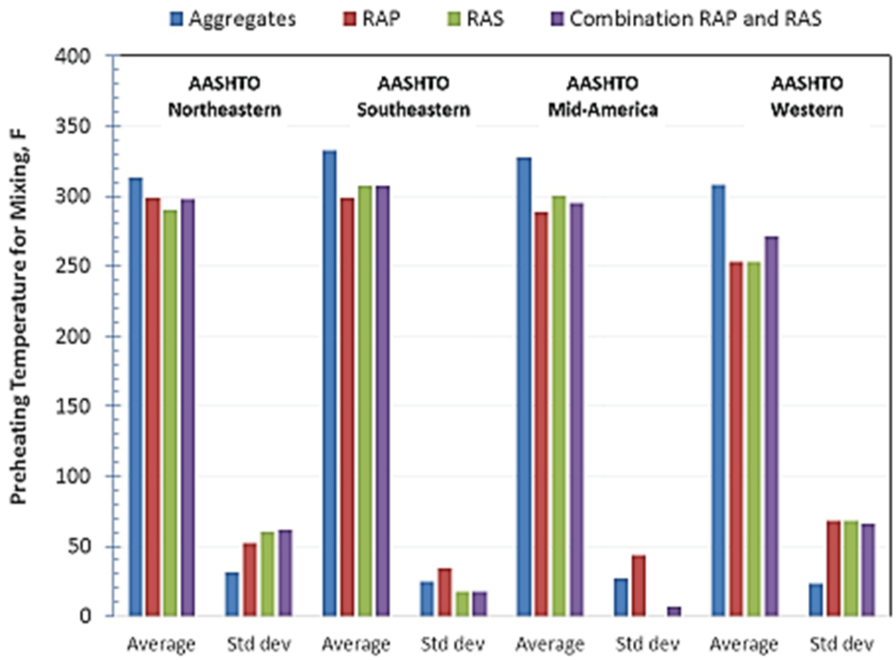


FIGURE 25 Statistics for times and temperatures used for mixing.

TABLE 48
DETERMINING REQUIRED MIXTURE TEMPERATURES

Survey Question: Indicate how you know the material is at required temperature for mixing.							
Materials	**Based on Time in Oven**		**Temperature Probe in the Material While it Is in the Oven**		**Temperature Measured Immediately after Removing from Oven**		**Responses per Row**
	%	*n*	%	*n*	%	*n*	*n*
Aggregates	38	8	57	12	19	4	21
RAP	61	11	44	8	17	3	18
RAS	55	6	46	5	18	2	11
Combined RAP and RAS	44	4	56	5	22	2	9

Not all survey respondents answered all questions.
n = 22.

TABLE 49
ORDER OF ADDITION OF MATERIALS INTO MIXING BOWL

Materials	*Survey Question*: Indicate which materials are added to the mixing bowl and in what order.							
	Order of Addition of Materials to Mixing Bowl							
	1st		**2nd**		**3rd**		**4th**	
	%	*n*	%	*n*	%	*n*	%	*n*
Aggregates								
Aggregates, all fraction (sieve sizes)	95	19	5	1	0	0	0	0
Recycled Materials								
RAP, coarse	35	7	55	11	5	1	0	0
RAP, fine	35	7	45	9	10	2	0	0
RAS	25	5	15	3	10	2	0	0
Liquids								
Asphalt	10	2	25	5	45	9	10	2
Rejuvenator	0	0	0	0	0	0	0	0
Asphalt and rejuvenator preblended prior to start of mix design sample prep	5	1	10	2	10	2	5	1

Not all survey respondents answered all questions.
n = 20.

TABLE 50
MIXING TIMES AFTER THE ADDITION OF EACH GROUP OF MATERIALS TO THE MIXING BOWL

Survey Question: Indicate how long materials are mixed (mixing time).								
Value	**Mixing Times After Each Material(s) Are Added to the Mixing Bowl**							
	Added 1st		**Added 2nd**		**Added 3rd**		**Added 4th**	
	%	*n*	*%*	*n*	*%*	*n*	*%*	*n*
1 minute	0	0	0	0	0	0	0	0
2 minutes	8	1	17	2	8	1	0	0
Based on visual inspection of uniformity	83	10	92	11	100	12	25	3

Not all survey respondents answered all questions.
n = 12.

TABLE 51
SHORT-TERM AGING PRACTICES

Survey Question: If used, enter time and temperatures used for short-term aging of the compacted samples.						
Mix with RAP		**Mix with RAP and RAS**		**Mix with RAS**		**Comments**
Time, h	**Temp., °F**	**Time, h**	**Temp., °F**	**Time, h**	**Temp., °F**	
2	300	2	300	2	300	Temperatures estimated; use AASHTO R30, which requires conditioning for 2 h ± 5 min at the required compaction temperature ±3°C. Mixing and compaction temperatures are provided by the asphalt supplier.
2	275	2	275	2	275	Compaction temperature is specific to virgin binder
—	300		300	—	300	Chemical WMA aged according to AASHTO R30.
—	—	—	—	—	—	2 hours at compaction temp.
2	—	2	—	2	—	Mixing and compaction temperatures. These temperatures are specified by the contractor and listed on the mix design.
2	275–280	—	—	2	275–280	Curing temps are based on suppliers recommended compaction temperatures for a binder.
2	300	2	300	2	300	—
2	275	—	—	—	—	—
2	compaction				—	—
2	—	2	—	2	—	Held at compaction temperatures; depends on binder grade.
1	10°C above mixing temp	—	—	—	—	Follow ASTM D6926 and AASHTO T312
15 ± 3	140	—	—	—	—	—
AASHTO Spec	—	—	—	—	—	—
2	—	2	265/300	2	—	Use 265°F for PG 64-22 conditioning and compaction. Use 300°F for PG 76-22
4	—	4	295–335	4	—	Aging per R30. Compaction temperatures vary based on virgin binder grade.
1.5	315	—	—	—	—	—
2	280/300	—	—	—	—	—
4	295	4	295	4	295	—
2	300 ± 25	2	300 ± 25	2	300 ± 25	300°F–325°F depending on PG binder grade of 67-22 or 76-22.
2	300 ± 20	2	300 ± 20	2	300 ± 20	Guidelines say to age for 2 hours in a forced air draft oven at compaction temperature, which is about 280°F–320°F, which is typical JMF temperature.

Not all survey respondents answered all questions.
— No answers were provided.

TABLE 52
NUMBER OF DESIGN GYRATIONS (N_{design})

Survey Question: Enter the typical number of gyration(s), N_{Design}, which is (are) used to compact recycled material mixtures in the text boxes.

Agency Number	Wear Course				Binder Course				Base Course			
	25% or less RAP	**More than 25% RAP**	**RAS**	**RAP and RAS**	**25% or less RAP**	**More than 25% RAP**	**RAS**	**RAP and RAS**	**25% or less RAP**	**More than 25% RAP**	**RAS**	**RAP and RAS**
1	75	—	—	—	75	—	—	—	75	—	—	—
2	50 to 125	50 to 125	—	—	—	—	—	—	—	—	—	—
3	100	80	—	—	—	—	—	—	100	80	—	—
4	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80	50, 65, 80
5	50, 75	50, 75	—	—	50, 75	50, 75	—	—	50, 75	50, 75	—	—
6	40, 60, 90	40, 60, 90	40, 60, 90	40, 60, 90	40, 60, 90	40, 60, 90	40,60,90	40,60,90	40, 60, 90	40, 60, 90	40, 60, 90	40, 60, 90
7	—	—	—	—	—	—	—	—	—	—	—	—
8	50	50	—	—	50	50	—	—	50	50	—	—
9	75, 100	—	—	—	—	—	—	—	—	—	—	—
10	65	65	—	—	65	65	65	—	70 blow	70 blow	70 blow	70 blow
11	80	—	—	—	80	—	—	—	80	—	—	—
12	65	65	65	—	65	65	65	—	65	65	65	—
13	50	—	—	—	50	—	—	—	50	—	—	—
14	85	—	—	—	85	—	—	—	50	50	—	—
15	75, 100	—	—	—	—	—	—	—	—	—	—	—
16	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100
17	60	60	60	60	60	60	60	60	60	60	60	60
18	65	65	65	65	65	65	65	65	65	65	65	65

Agency Number	SMA				Pervious/Permeable				Comments
	25% or less RAP	**More than 25% RAP**	**RAS**	**RAP and RAS**	**25% or less RAP**	**More than 25% RAP**	**RAS**	**RAP and RAS**	
1	—	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—	—	Gyrations depend on ESALs. Typically, binder and base course are the same as the wearing course.
3	—	—	—	—	—	—	—	—	100 gyration mixtures used in severe duty applications; stricter limits on allowable recycled materials in 100 gyration wearing courses. RAS equally likely to be in our 100, 80, or 65 gyration mixtures.
4	50	50	50	50	50	50	—	—	RAP/RAS not allowed in SMA or surface course. 12% binder replaced is allowed in surface course if not SMA and the RAP/RAS Special Provision is used.
5	—	—	—	—	—	—	—	—	—
6	—	—	—	—	—	—	—	—	40, 60, and 90 gyrations typically used levels
7	—	—	—	—	50	—	—	—	—
8	60–75	60–75	—	—	—	—	—	—	—
9	—	—	—	—	—	—	—	—	—
10	65	—	—	—	—	—	—	—	Base mixture is 6 inch Marshall
11	—	—	—	—	—	—	—	—	Gyration requirements based on traffic load
12		—	—	—	50	50	—	—	—
13	50	—	—	—	50	—	—	—	—
14	75	—	—	—	50	—	—	—	Number of gyrations depends on traffic.
15	100	—	—	—	—	—	—	—	—
16	50, 75, 100	50, 75, 100	50, 75, 100	50, 75, 100	—	—	—	—	—
17	60	60	60	60	—	—	—	—	—
18	35	35	35	65	—	—	—	—	Use Marshall hammer for pervious mixtures. Marshall hammer may be also used for SMA mixtures.

Not all survey respondents answered all questions.
— No data provided.

Sample Preparation—Section Summary

Sizing of Aggregates and Recycled Materials

- If the contractors submit RAP samples from fractionated stockpiles, a number of agencies appear to use what is submitted as individual fractions for batching.
- Definitions of coarse and fine RAP fractions vary. The most frequently used screens for retained on/passing are the 4.75-mm (No. 4) and 2.36-mm (No. 8). The sieve size used for designation may be specified by the agency or determined by the contractor.
- Definitions of coarse and fines for production testing may be different from those used for design purposes.
- A few agencies fractionate aggregates and RAP into the full range of individual fine aggregate sieve sizes (1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm) for batching.
- Comments received indicate an agency may fractionate RAP for batching, even if the contractor does not fractionate for production or an agency may not fractionate RAP.

Drying of Recycled Materials Prior to Batching

- There is no standardized method for drying recycled materials prior to batching.
- There is a high level of variability in what is "constant mass" (0.05%, 0.1%, 0.5% maximum change in mass; change of 5 grams maximum), how to dry the material (fan, oven), at what temperature [from room temperature to 300°F (149°C)], and for how long (from 1 hour to overnight).
- Particulate sizes used for batching mix design samples are dependent on how each contractor manages its asphalt plant stockpiles for both aggregates and recycled materials.
- Additional sizing (fractionating) may be used in the laboratory to improve laboratory control over the gradation.

Heating (Times and Temperatures) of Materials Prior to Mixing

- Some agencies heat virgin aggregates, RAP, and RAS separately, whereas others combined aggregated and RAP before heating.
  - Agencies that use a combination of RAP and RAS typically combine these recycled materials before heating.
  - RAS may be combined with sand before heating to avoid RAS clumping.
- Although heating times and temperatures vary widely, there appear to be a few general trends:
  - Virgin aggregates tend to be preheated at higher temperatures than recycled materials when these materials are not combined before heating.
  - Preheating temperatures for recycled materials are generally lower than those used for virgin aggregates.
  - There appear to be more variability in preheating temperatures for recycled materials than for preheating virgin aggregates.
  - Some agencies do not preheat the recycled materials.

Order of Addition to Mixing Bowl

- Virgin aggregates, followed by the recycled materials (if not already mixed with the aggregate), are usually added to the mixing bowl followed by the asphalt binder and any liquid additives.
- Materials are typically mixed until they appear to be uniformly coated, although a few agencies use specified times to achieve adequate mixing.

Short-Term Aging Prior to Compaction

- Short-term aging time is most frequently 2 hours at temperatures between 275°F and 335°F, depending on the virgin asphalt grade. Other practices include 1.5 h, 4 h, and 15 h ± 3 h at a temperature of 140°F.

Compaction of Samples

- Gyratory compaction is fixed by mixture type (which reflects different traffic levels) by a number of agencies, regardless of the percentage or type of recycled material.
- Other agencies use the traffic (ESALs) to define N_{Design}.
- A few agencies still use Hveem or Marshall mix designs for base mixtures, SMA, OGFC, and other specialty mixtures.

MIXTURE TESTING

A number of questions were included in the agency survey to document the impact of high RAP percentages, RAS materials and/or a combination of RAP and RAS recycled materials have on the required mix design volumetrics anticipated mixture performance from laboratory testing and perceptions of pavement performance.

Volumetrics

Survey respondents were asked about their perception of any changes in the mix design volumetrics resulting from the addition or percentage of recycled materials compared with similar mixtures without recycled materials (Table 53). Between 18 and 22 agencies consistently answered specific questions about preparing, mixing, and compacting recycled material asphalt mixtures. However, at most, 10 agencies indicated that it can be difficult to obtain the required mixture volumetrics, which suggests that at least half of the agencies responding to these questions do not consider that the recycled materials adversely impact mixture volumetrics.

TABLE 53
INFLUENCE OF RECYCLED MATERIAL ON ACHIEVING DESIRED MIX DESIGN VOLUMETRICS

Survey Question: Check the box if it is more difficult to obtain acceptable properties when compared to similar mixtures without any recycled material content.								
Materials	**Air Voids, %**		**VMA, %**		**VFA, %**		**Dust-to-Asphalt Ratio**	
	%	***n***	*%*	***n***	*%*	***n***	*%*	***n***
25% or less RAP	50	5	40	4	20	2	50	5
More than 25% RAP	90	9	100	10	60	6	100	10
RAS mixtures	60	6	70	7	30	3	60	6
RAP and RAS combination mixtures	70	7	70	7	30	3	80	8

Not all survey respondents answered all questions.
n = 10.

The dust-to-asphalt ratio, air voids, and VMA criteria are more difficult to meet when there is more than 25% RAP, RAS, and a combination of RAP and RAS in the mixtures. Lower percentages of RAP can make it difficult to meet these requirements, but not as frequently.

Performance-Based Mixture Testing

Performance-based mixture testing is used to determine if the asphalt mixtures, as designed, can achieve the desired service life and successfully resist showing evidence of key pavement distress(es).

Long-Term Aging

Samples used for evaluating performance-based mixture properties may be subjected to long-term aging to simulate the heat and oxidation hardening of asphalt binders that occurs during 7 to 10 years of in-service use. Only two agencies indicated they use long-term aging (Table 54), whereas a number of agencies commented they do not use long-term aging.

Performance-Based Mixture Testing

Survey respondents were asked which test methods and test temperatures are used to evaluate mixture rutting, stiffness, traffic-related cracking, and thermal cracking. Twenty-five agencies indicated they use some type of testing to evaluate the rutting potential of asphalt mixtures (Table 55). The most frequently used devices are the APA and Hamburg loaded wheel devices, which are used during mix designs and/or for approving material changes during construction. Nine agencies are exploring the use of the AMPT device for studies that are investigating the dynamic modulus frequency sweeps over a range of temperatures and for determining creep characteristics (i.e., flow number and flow time) of the mixtures at warmer temperatures. Two agencies noted that they are using the AMPT device for research purposes only at this time. One agency uses the Hveem Stabilometer.

Additional respondent comments noted that they evaluate the rut resistance of the mixture using the:

- Hamburg device for every 20,000 tons produced,
- APA when questions arise about a submitted design, or
- Only for high gyration mixtures (N_{Design} of 100 and 125).

Eight agencies evaluate the mixture stiffness by measuring the dynamic modulus over a range of temperatures or at a single temperature for research purposes (Table 56). Only two agencies evaluate mixture stiffness during the mix design process. Another agency noted it will get an AMPT test device for dynamic modulus testing at the end of its fatigue research project. One agency commented that it does not conduct performance mixture testing in the laboratory.

TABLE 54
LONG-TERM AGING PRACTICES

Survey Question: If used, enter time and temperatures used for long-term aging of the compacted samples.						
Mix with RAP		**Mix with RAP and RAS**		**Mix with RAS**		**Comments**
Time, h	**Temp., °F**	**Time, h**	**Temp., °F**	**Time, h**	**Temp., °F**	
4	300	4	300	4	300	For chemical WMA, use AASHTO R30.
120	185	120	185	120	185	—

Not all survey respondents answered all questions.
n = 2.

TABLE 55
TEST METHODS FOR EVALUATING RUTTING POTENTIAL

Survey Question: **Rutting**: If you evaluate the rutting potential of mixtures in your lab, please indicate which method(s) you use. (Choose all that apply.)							
Test Method	**Used Routinely for Our Mix Designs**		**Use When Approving Changes in Materials During Construction**		**Use for Research Studies**		**Response per Row**
	%	*n*	%	*n*	%	*n*	*n*
Asphalt Pavement Analyzer (APA)	63	8	15	2	62	8	13
Hamburg Rut Tester	63	5	13	1	88	7	8
Wet rut testing to determine stripping inflection point	67	2	0	0	100	3	3
Asphalt Mixture Performance Test (AMPT)	0	0	0	0	100	9	9
Dynamic modulus	0	0	0	0	100	9	9
Flow number	0	0	0	0	100	8	8
Flow time	0	0	0	0	100	4	4
Hveem Stabilometer	100	1	100	1	0	0	1

Not all survey respondents answered all questions.
n = 25.

At this time, only three agencies investigate traffic-related cracking of mixtures in their state (Table 57). Two agencies use the disc-shaped compact tension for research purposes (DCT). One agency uses the SCB test results at intermediate temperatures as a means of allowing the contractor to use higher percentages of fractionated RAP. Two agencies indicated that the DCT test is currently in development or is only used for information. Another two agencies are considering selecting a fatigue test or evaluating the SCB test.

Four agencies currently use the IDT test to evaluate the thermal cracking potential of their mixtures for research purposes (Table 58). Two of these agencies use this test method to approve changes in materials during construction and one agency uses the test method during mix designs. Only one agency uses the SCB test method for approving changes in materials during construction. Three agencies are currently researching the SCB and DCT methods.

Volumetric and Performance-Based Mixture Testing—Section Summary

Mix Design Volumetrics

- Mix design volumetrics are perceived to be more difficult to obtain for mixtures with recycled materials.
- When the percentage of RAP increases above 25%, the likelihood of having difficulty in achieving the desired mix design volumetrics increases.

Performance-Based Mixture Testing

- Rutting potential is the most frequently evaluated performance characteristic during mix designs, to approve material changes during construction, and for research studies. A single agency may have more than one device for different applications. A range of devices are currently used.

TABLE 56
TEST METHODS USED TO EVALUATE MIXTURE STIFFNESS

Survey Question: **Mixture Stiffness**: If you evaluate mixture stiffness in your lab, please indicate which method(s) you use. (Choose all that apply)						
Materials	**Used Routinely for Our Mix Designs**		**Use When Approving Changes in Materials During Construction**		**Use for Research Studies**	
	%	***n***	**%**	***n***	**%**	***n***
Resilient modulus at a single temperature	13	1	13	1	38	3
Resilient modulus at several temperatures	0	0	0	0	38	3
Dynamic modulus at a single temperature	13	1	13	1	75	6
Dynamic modulus over a range of temperatures to develop a master curve	0	0	0	0	100	8
Indirect tensile strength	13	1	13	1	13	1

Not all survey respondents answered all questions.
n = 8.

TABLE 57
EVALUATING NONTHERMAL CRACKING POTENTIAL

Survey Question: **Cracking (Nonthermal):** If you evaluate cracking potential of mixtures in your lab, please indicate which method(s) you use. (Choose all that apply.)						
Materials	**Used Routinely for Our Mix Designs**		**Use When Approving Changes in Materials During Construction**		**Use for Research Studies**	
	%	***n***	**%**	***n***	**%**	***n***
Fatigue cracking, bending beam (AASHTO T321)	0	0	0	0	0	0
Overlay tester	0	0	0	0	0	0
Disc-shaped compact (DCT) tension test (ASTM D7313)	0	0	0	0	67	2
Semi-circular bend (SCB) test	0	0	0	0	33	1

Not all survey respondents answered all questions.
n = 3.

TABLE 58
EVALUATING THERMAL CRACKING POTENTIAL

Survey Question: **Thermal Cracking**: If you evaluate the thermal cracking potential of mixtures in your lab, please indicate which method(s) you use. (Choose all that apply.)						
Materials	**Used Routinely for Our Mix Designs**		**Use When Approving Changes in Materials During Construction**		**Use for Research Studies**	
	%	***n***	**%**	***n***	**%**	***n***
Indirect tensile strength (AASHTO T322)	20	1	40	2	80	4
Semi-circular bend (SCB) test	0	0	20	1	60	3
Disc-shaped compact (DCT) tension test (ASTM D7313)	0	0	0	0	60	3

Not all survey respondents answered all questions.
n = 5.

- Mixture stiffness is evaluated using either resilient modulus or dynamic modulus, primarily for research purposes.
- Cracking potential is evaluated primarily for research purposes at this time using one or more methods (DCT and SCB at low temperatures, SCB at intermediate temperatures).
- One agency allows fractionated RAP to be used at higher percentages as long as SCB testing is conducted.

PERCEIVED INFLUENCE OF RECYCLED MATERIALS ON PAVEMENT PERFORMANCE

Respondents were asked to indicate their level of agreement or disagreement with a series of statements about the impact of recycled materials on pavement performance based on their experiences. Most either agree or strongly agree that rutting resistance is improved when using RAS or a combination of RAS and RAP, and increasing percentages of RAP (Table 59). Additional comments provided by the respondents included:

- Recycled materials improve rutting resistance because of stiffer materials.
- Although everyone understands that recycled material typically increases stiffness and decreases rutting potential, because recycled asphalt does not homogenously mix with virgin binder, the use of softer grades required by very high RAP mixtures could lead to rutting when mixing is incomplete.
- The answer given is based on today's specs. If we would increase the required film thickness, or VMA or asphalt content required in design, my answer will likely change.
- There are many factors that can increase a mixture's rutting potential. Increasing the percentage of RAP alone is not one of them.

Agency responses are about evenly divided between believing that the types and percentages of recycled material do not noticeably influencing mixture moisture sensitivity and noting they believe the moisture sensitivity increases (Table 60). Similar responses were received with regard to changes in the mixture IDT. Respondents are about evenly split between noting little change is expected and the tensile strength is expected to increase with increasing percentage and/or type of recycled materials. Additional respondent comments received about no significant problems with moisture sensitivity included:

- Have not experienced any moisture sensitivity issues regardless of the percentage of RAP used.

TABLE 59
PERCEIVED INFLUENCE OF RECYCLED MATERIAL ON RUTTING POTENTIAL

Survey Question: **Rutting Potential**: Based on your experience, indicate your level of agreement with the following statements.											
Statement	**Strongly Agree**		**Agree**		**Neutral**		**Disagree**		**Strongly Disagree**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	***n***
Rutting potential is *increased* with increasing percentages of recycled RAP	0	0	4	1	13	3	46	11	38	9	24
Rutting potential is *increased* with increasing percentages of recycled shingles	0	0	0	0	28	5	28	5	44	8	18
Rutting potential is *increased* with a combination of RAP and RAS	0	0	0	0	18	3	35	6	47	8	17

Not all survey respondents answered all questions.
n = 24.

- Virtually all of our agency mixtures employ a liquid anti-stripping agent with some hydrated lime used as well.
- Using the proper asphalt binder and/or other additives can counteract the negative effects of increased RAP percentages.

Respondent comments about why they experience moisture sensitivity problems included:

- RAS, if from tear-offs, have the potential for greater issues with tensile strength ratio (TSR) testing than do manufactured waste shingles.
- Observed increased dust with recycled materials, less active or soft binder to promote coating, and high strength resulting from increased stiffness.

Other respondent comments about moisture sensitivity included:

- Test Hamburg wet and require the TSR (Lottman) to be 80% retained after freeze/thaw cycle.
- Differentiate between wet or dry strength.
- Use Immersion Compression test for moisture susceptibility.

The majority of respondents agree or strongly agree that the percentage or type of recycled materials increases the traffic-related cracking potential (Table 61). Additional respondent comments about traffic-related cracking potential included:

- Successful implementation of mix design parameters that include crack testing may mitigate my concern in this area.
- Depends on where the mixtures are used within the pavement structure.
- This is why we do not allow RAP in surface courses.
- Answered neutral here because an increase in the percentage of RAP could increase the potential for non-thermal cracking if the proper virgin binder is not used to rejuvenate the RAP binder.

The majority of respondents agrees or strongly agrees that the percentage or type of recycled material increases the thermal cracking potential (Table 62). Additional comments by respondents included:

TABLE 60
PERCEIVED INFLUENCE OF RECYCLED MATERIAL ON MIXTURE DURABILITY POTENTIAL

Survey Question: **Mixture Durability Potential**: Based on your experience, indicate your level of agreement with the following statements.											
Statement	**Strongly Agree**		**Agree**		**Neutral**		**Disagree**		**Strongly Disagree**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	***n***
Moisture Sensitivity											
Moisture sensitivity is *increased* with increasing percentages of recycled RAP	4	1	30	7	57	13	9	2	0	0	23
Moisture sensitivity is *increased* with increasing percentages of recycled shingles	12	2	35	6	47	8	6	1	0	0	17
Moisture sensitivity is *increased* with a combination of RAP and RAS	12	2	35	6	47	8	6	1	0	0	17
Mixture Strength											
Indirect tensile strength is *increased* with increasing percentages of recycled RAP	10	2	45	9	40	8	5	1	0	0	20
Indirect tensile strength is *increased* with increasing percentages of recycled shingles	12	2	47	8	35	6	6	1	0	0	17
Indirect tensile strength is *increased* with a combination of RAP and RAS	12	2	41	7	41	7	6	1	0	0	17

Not all survey respondents answered all questions.
n = 23.

TABLE 61
PERCEIVED INFLUENCE OF RECYCLED MATERIAL ON NONTHERMAL CRACKING POTENTIAL

Survey Question: **Cracking Potential (Nonthermal Cracking)**: Based on your experience, indicate your level of agreement with the following statements.											
Statement	**Strongly Agree**		**Agree**		**Neutral**		**Disagree**		**Strongly Disagree**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	***n***
Cracking potential is *increased* with increasing percentages of recycled RAP	21	5	50	12	29	7	0	0	0	0	24
Cracking potential is *increased* with increasing percentages of recycled shingles	50	9	39	7	11	2	0	0	0	0	18
Cracking potential is *increased* with a combination of RAP and RAS	35	6	53	9	12	2	0	0	0	0	17

Not all survey respondents answered all questions.
n = 24.

TABLE 62
PERCEIVED INFLUENCE OF RECYCLED MATERIAL ON THERMAL CRACKING POTENTIAL

Survey Question: **Thermal Cracking Potential**: Based on your experience, indicate your level of agreement with the following statements.											
Statement	**Strongly Agree**		**Agree**		**Neutral**		**Disagree**		**Strongly Disagree**		**Responses per Row**
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	***n***
Thermal cracking potential is *increased* with increasing percentages of recycled RAP	5	1	77	17	18	4	0	0	0	0	22
Thermal cracking potential is *increased* with increasing percentages of recycled shingles	25	4	63	10	13	2	0	0	0	0	16
Thermal cracking potential is *increased* with a combination of RAP and RAS	20	3	60	9	20	3	0	0	0	0	15

Not all survey respondents answered all questions.
n = 22.

- Do not have a problem with this as our specified asphalt grade is PG xx-22 and our low temp design requirement is closer to a PG xx-16.
- Depends on where the mixtures are used within the pavement structure.

PERCEPTIONS OF INFLUENCE OF RECYCLED MATERIALS ON PAVEMENT PERFORMANCE—SECTION SUMMARY

Based on respondent's experience and perceptions it is likely that:

- Rut resistance can decrease with increasing percentages of any of the recycled material.
- Moisture sensitivity may increase with increasing percentages of recycled materials; however, almost half the respondents believe that the recycled materials may not have any influence one way or the other (i.e., neutral position).
- Nonthermal cracking increases with increasing percentages of RAP and combinations of RAP and RAS.
  – Respondents are more likely to strongly agree that increasing RAS increases nonthermal types of cracking.
- Thermal cracking potential increases as the percentage of RAP increases.
  – Respondents are more likely to strongly agree that increasing RAS or combinations of RAP and RAS percentages increases thermal cracking.

CHAPTER FOUR

STATE CONSTRUCTION ENGINEER SURVEY

The State Construction Engineer survey (Appendix B) focused on topics that can are beneficial to the production and placement of high RAP, RAS, and a combination of RAP and RAS mixtures. A total of 45 responses were received; a response rate of 88% (50 states and the District of Columbia), including agencies that indicated they do not currently use at least 25% RAP or RAS in their mixtures, which are the focus of this synthesis. The main survey topics and the organization of this chapter are as follows:

- Availability of recycled materials
- Recycled material processing and stockpiling practices
- Recycled materials properties and testing (as they are used in production)
- Asphalt mixture production and placement
- Volumetric quality control testing
- Key points for field inspectors.

AVAILABILITY OF RECYCLED MATERIALS

Which types and percentages of recycled materials used in asphalt mixtures can be limited by the availability of materials? The potential economic benefits that can be achieved when using recycled materials can be offset by increased transportation costs when materials are only available in limited areas within the state. At least 80% of the responding State Construction Engineering surveys noted that RAP supplies are generally available across the state. However, only about one-third of these agencies have excess supplies of RAP either statewide or in limited locations in one or more state (Table 63).

Additional respondent comments about RAP included:

- No excess supply of RAP (four agencies).
- RAP is plentiful in cities and urban areas (three agencies).
- Some districts keep millings for other uses and that creates a local low supply, and the urban districts have an oversupply.
- Industry would like access to more RAP.

There is significantly less availability of RAS that is, if available, typically limited to only one or more districts or local areas within the state. When RAS is available, there appears to be an excess of RAS in those areas. Additional respondent comments about RAS included:

- No excess supply of RAS (four agencies).
- RAS is plentiful in cities and urban areas (two agencies).
- RAS less available in the southern part of the state.
- RAS is available, but contractors do not use.
- Have not used RAS yet; unsure of availability.

RECYCLED MATERIALS PROCESSING AND STOCKPILING PRACTICES

This section outlines the State Construction Engineer survey responses about stockpiling and processing practices used by their state. RAP and RAS information is presented in separate sections.

RAP Processing and Stockpiling

The State Construction Engineers indicated that contractors frequently process the RAP at the asphalt plant site and occasionally process the RAP off site, but rarely have it processed by a third party (Table 64; $n = 36$ for this table). Only 25% of the agencies require the contractor to have sufficient RAP processed and stockpiled at the start of a project to complete the project, and 36% have no requirements for having sufficient quantities of RAP on hand at the beginning of the project.

Large quantities of RAP are typically collected and stockpiled prior to processing, but unprocessed or processed RAP is rarely covered. Less than 10% of the agencies frequently fraction coarse and/or fine RAP fractions. The 19-mm (¾-in.) sieve size is typically used to scalp the oversize RAP, and the definition of coarse and fine RAP fractions varies between agencies:

- 4.75-mm (No. 4) sieve is the most common (Table 65).
- 2.36-mm (No. 8) or 9.5-mm (⅜-in.) sieve sizes are used less frequently.

Additional respondent comments about fractionating stockpiles included:

- The ¼ in. can be used in lieu of No. 4 sieve (bottom sieve), ¾ and 9⁄16 in. are commonly used to scalp top size and recrush.
- In general, contractors do not fractionate unless it is necessary to meet volumetric requirements or control the properties.

TABLE 63
AVAILABILITY OF RAP AND RAS THROUGHOUT STATE

Survey Question: **Supply and Demand**: Also, indicate if there is any excess of recycled materials (i.e., more supply than demand).				
Locations	**Materials**			
	RAP		**Shingles (RAS)**	
	%	***n***	**%**	***n***
General Availability				
Statewide	81	29	17	6
In One or More Districts	3	1	33	12
Limited to Local Areas	0	0	25	9
Excess of Recycled Materials				
Statewide	28	10	0	0
In One or More Districts	28	10	11	4
Limited to Local Areas	11	4	33	12

Not all survey respondents answered all questions.
$n = 36$.

- Contractors have the option of fractionating and generally they only do so if it is necessary to control mix design volumetrics. Consistency in the RAP is often maintained with milling and stockpiling procedures. Most of the time RAP from different sources is stockpiled separately. If multiple layers must be milled from a roadway, these layers may be milled up individually and stockpiled separately.
- One large contractor that works nearly state-wide does fractionate on high-profile projects. All of our other contractors use inline crushers to process RAP at the plant.
- RAP from cold-milling (used immediately) is screened to remove oversized partials. Occasionally, RAP is used from either state- or contractor-owned stockpiles. Processing of these can be as simple as remixing and screening for oversized, to crushing, and screening.

TABLE 64
RAP PROCESSING AND STOCKPILING PRACTICES

Survey Question: Indicate how frequently each of the following RAP processing and stockpiling practices is used in your state.								
Statement	**Frequently**		**Occasionally**		**Rarely**		**Not Applicable**	
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***
Processing RAP								
RAP is processed at the asphalt plant site	47	17	17	6	3	1	6	2
RAP is processed elsewhere by asphalt mixture contractor and stockpiled at plant	8	3	39	14	25	9	0	0
RAP is processed by third party and delivered to asphalt mixture contractor	0	0	8	3	39	14	14	5
Asphalt mixture contractor required to have sufficient processed RAP material stockpiled at the beginning of the construction project	25	9	0	0	6	2	36	13
Stockpiling RAP								
Large quantity of RAP collected, then processed	33	12	31	11	0	0	0	0
Unprocessed stockpiles are covered	0	0	6	2	39	14	19	7
Stockpiles are stored in covered areas only covered after processing	3	1	8	3	42	15	11	4
*Coarse RAP stockpile is fractionated	8	3	22	8	22	8	17	6
Fine RAP stockpile is fractionated	6	2	17	6	25	9	17	6
Impact of Weather and Processing Times								
*Weather impacts RAP crushing and sizing operations (e.g., clumping, blinding screens, etc.)	0	0	17	6	22	8	6	2
*We have time limitations between RAP processing and using	0	0	3	1	11	4	53	19

*Respondents were asked to provide additional information about these statements.
Not all survey respondents answered all questions.
$n = 36$.

TABLE 65
SIEVE SIZE USED TO DEFINE "COARSE" RAP FRACTION

Survey Question: Select the "retained on" sieve size used to define the coarse RAP fraction.		
Sieve Size	**%**	***n***
+9.5-mm (3/8 in.)	28	5
+4.75-mm (No. 4)	61	11
+2.36-mm (No. 8)	11	2

This question was only provided to respondents indicating a frequent or occasional use of fractionating.
n = 18.

Weather conditions and the time between processing and using the RAP may influence RAP processing; however, 53% of the responding agencies do not have any time requirements in their state. Additional respondent comments about the influence of weather on RAP processing included:

- Typically, contractors will not process RAP during bad weather.
- Moisture and speed of processing affect crushing and sizing operation; do not focus on tons/h, but on quality of finished RAP screened product.
- Not to an extent that it cannot be accomplished. Rain has a greater impact.
- This is rarely a problem. Sometimes have problems when RAP comes from a thin cold-milling operation (e.g., chip seals) and the percentage of oil is high. In these cases, water or water with a surfactant is sprayed on the belt to prevent sticking.

Additional respondent comments about time constraints between processing and using RAP included:

- Currently we do not have any time constraints specified, but we prefer to keep time between processing and using RAP to a minimum.
- We do not have time limitations, but prefer to use RAP that is not more than a year old. If there is a problem with HMA/WMA consistency or compliance with project specifications, additional efforts are taken to achieve acceptable levels of consistency and compliance with contract specifications at contractor's discretion.

RAS Processing and Stockpiling

The State Construction Engineers noted that RAS is occasionally processed at the plant site, off-site by the contractor, or by third parties and supplied to the contractors (Table 66; *n* = 21 for this survey question). Manufacturer waste RAS are stockpiled separately from tear-off RAS and large quantities of RAS is frequently or occasionally stockpiled and then processed. Most agencies have no requirements for having sufficient RAS stockpiled for the entire project at the beginning of the project. Only four agencies cover unprocessed and/or

TABLE 66
RAS PROCESSING AND STOCKPILING PRACTICES

Survey Question: Indicate how frequently each of the following shingles (RAS) processing and stockpiling practices are used in your state.								
Statement	**Frequently**		**Occasionally**		**Rarely**		**Not Applicable**	
	%	***n***	**%**	***n***	**%**	***n***	**%**	***n***
Processing RAS								
RAS is processed at the asphalt plant site	14	3	33	7	10	2	33	7
RAS is processed elsewhere by asphalt mixture contractor and stockpiled at plant	5	1	38	8	5	1	33	7
RAS is processed by third party and delivered to asphalt mixture contractor	19	4	38	8	5	1	29	6
Stockpiling RAP								
Manufacturing waste and tear-offs are kept separate	57	12	0	0	5	1	29	6
Large quantity of RAS collected, then processed	29	6	19	4	0	0	29	6
Asphalt mixture contractor required to have sufficient processed RAS material stockpiled at the beginning of the construction project	10	2	0	0	0	0	81	17
Unprocessed stockpiles are covered	5	1	0	0	29	6	33	7
Stockpiles are stored in covered areas only covered after processing	14	3	14	3	24	5	29	6
Sand is added during processing or after processing to prevent clumping	10	2	10	2	14	3	43	9
Impact of Weather and Processing Time								
*Weather impacts RAS crushing and sizing operations (e.g., clumping, blinding screens, etc.)	24	5	14	3	5	1	29	6
*We have time limitations between RAS processing and using	0	0	0	0	0	0	90	19

*Respondents were asked to provide additional information about these statements.
Not all survey respondents answered all questions.
n = 21.

TABLE 67
MAXIMUM PARTICLE SIZE ALLOWED FOR RAS

Survey Question: Select the maximum shingle (RAS) particle size allowed.		
Sieve Sizes	**%**	***n***
12.5-mm (1/2 in.)	12	2
9.5-mm (3/8 in.)	35	6
4.75-mm (No. 4)	12	2
2.36-mm (No. 8)	12	2
Other	29	5

Not all survey respondents answered all questions.
n = 17.

processed RAS and four agencies either frequently or occasionally blend processed RAS with sand to help minimize clumping.

Eight agencies (38% of those agencies answering this question) believe that weather conditions are likely to impact the processing or handling of the RAS. Additional respondent comments about the impact of weather on RAS processing included:

- Clumping occurs and recrushing or lump breaking is necessary almost daily.
- Some RAS processing plants use water to mitigate heat generation. Most only process during good weather.
- RAS has seen limited use for highway work; however, it appears to best fit commercial work when the asphalt is subsidiary to mixture.

Currently the most commonly used maximum RAS size is 9.5 mm (⅜ in.) (Table 67); however, additional comments about “Other” sizes noted that RAS is sized:

- As needed for total gradation (two agencies), and
- Use maximum of 6.35-mm (¼-in.) sieve.

Suggested Changes to Current RAP and RAS Processing Requirements

Respondents were asked to comment about any potential changes to their current RAP or RAS processing and stockpiling practices that can increase the percentage and/or type of recycled material used in their state. Thirteen agencies provided suggestions for useful changes when processing and stockpiling RAP (Table 68). The comments provided included:

TABLE 69
ADJUSTMENTS NEEDED FOR PROCESSING AND STOCKPILING RAS

Survey Question: Do your current processing and stockpiling practices need to be adjusted or changed so that RAS or combinations of RAP/RAS can be more widely used? If yes, please indicate what changes are needed in the comment box below.		
Answer	**%**	***n***
Yes	28	5
No	72	13

Not all survey respondents answered all questions.
n = 18.

- Fractionate RAP (six agencies):
  - Need to fractionate to meet mix design volumetrics.
  - Regularly approve mix designs incorporating 30% RAP in all mixture types and currently specify a maximum 40% RAP in drum mix plants, and producers are beginning to push to that limit. Those producers who have evaluated using more than 40% or 50% have indicated that fractionating would be necessary.
- Occasionally millings from projects are used with no additional processing. Higher RAP content mixtures necessitate more advanced processing.
- Covering the stockpiles (three agencies).
- Most contractors are unable to incorporate more that 25% RAP. Most RAP comes from micro-milling in our state, which makes it mostly a fine-graded material. Fractionating is difficult because of the large amount of rejected material [i.e., passing 0.075-mm (No. 200)] that would be created.
- Increase QC testing.
- Currently conducting research into required adjustments.

Five agencies provided suggestions for improving RAS processing and stockpiling practices (Table 69) that included:

- RAS asphalt availability factor (two agencies):
  - A better determination of (RAS) asphalt contribution.
  - Adopt rule on amount of effective asphalt that is available from the RAS.
- Sand is sometimes blended into RAS to keep it from clumping.
- Stockpiles must be kept in the shade.

The fifth comment, related to the economic incentives associated with using RAS, noted that “more than anything,

TABLE 68
NEED TO ADJUST RAP PROCESSING AND STOCKPILING PRACTICES

Survey Question: Do your current processing and stockpiling practices need to be adjusted or changed so that higher percentages of RAP can be used? If yes, please indicate what changes are needed in the comment box below.		
Answer	**%**	***n***
Yes	50	13
No	50	13

Not all survey respondents answered all questions.
n = 26.

the processing and storage costs for RAS prohibit their use in rural areas."

Recycled Material Processing and Stockpiling—Section Summary

RAP processing and stockpiling

- RAP is fractionated for better control of mix design volumetrics when using higher percentages.
  - The sieve size used to fractionate coarse and fine sizes is usually the 4.75-mm (No. 4) sieve, although the 9.5-mm (⅜-in.) and, less frequently, the 2.36-mm (No. 8) sieves can be used.
  - The 19-mm (¾-in.) or (9⁄16-in.) sieves are typically used for scalping the top size RAP.
  - RAP from micro-millings is mostly fine-graded materials and is most efficiently used at lower percentages. Fractionating the micro-millings would likely result in an overabundance of rejected materials [i.e., too much passing the 0.075-mm (No. 200) sieve].
- Increased QC testing may be necessary when using higher percentages of RAP.
- Moisture (e.g., rain) can influence quality and speed of crushing and sizing operations.
- If there is a high asphalt binder content in the RAP, water or water with a surfactant may have to be sprayed on the conveyor belt to prevent sticking.

RAS processing and stockpiling

- The majority of the agencies keep separate stockpiles for RAS manufacturer waste and RAS tear-offs.
- Clumping and recrushing or lump breaking may be necessary.

RECYCLED MATERIAL PROPERTIES AND TESTING

Asphalt contents and aggregate gradations of the individual recycled material, as well as the final asphalt mixture, are determined using the ignition by most of the agencies responding to this question (Table 70; *n* = 18). More than 70% of the agencies measure RAP asphalt contents and RAP aggregate gradations of both the individual recycled materials and the total asphalt mixture. At most, 33% of the agencies use solvent extraction to determine asphalt content and aggregate

TABLE 70
TESTS AND ASSUMPTIONS USED TO DETERMINE RECYCLED MATERIAL PROPERTIES DURING PRODUCTION

Survey Question: Indicate what tests or assumptions are used to determine asphalt content, aggregate properties, and other material or mixture properties are determined. (Check all that apply.)

Testing	RAP		Shingles (RAS)		Recycled Material Properties Certified by Supplier		Recycled Material Properties Estimated		Asphalt Mixture with Recycled Materials Is Tested	
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*
Asphalt Content										
Ignition oven asphalt content	76	16	38	8	14	3	10	2	71	15
Solvent extraction asphalt content	33	7	19	4	10	2	5	1	24	5
Gradations										
Ignition oven gradation	71	15	29	6	14	3	14	3	71	15
Solvent extraction gradation	33	7	14	3	10	2	5	1	29	6
Consensus Aggregate Properties										
Flat and elongated aggregate properties from recycled materials	19	4	5	1	5	1	0	0	24	5
Fine aggregate angularity of aggregates from recycled materials	29	6	5	1	5	1	0	0	19	4
Specific Gravities										
Bulk specific gravity	52	11	33	7	14	3	24	5	76	16
Theoretical maximum specific gravity (i.e., Rice method; AASHTO T209)	57	12	33	7	5	1	14	3	90	19
Moisture and Contaminates										
Moisture content	52	11	33	7	19	4	0	0	33	7
Contaminates	29	6	24	5	14	3	5	1	14	3

Not all survey respondents answered all questions.
n = 21.

gradations. Only a limited number of agencies determine flat and elongated coarse aggregate and fine aggregate angularity shape for either the individual RAP or total asphalt content mixture.

More than 50% measure both the RAP bulk specific gravities and RAP theoretical maximum specific gravities, and almost all of the agencies (90%) measure the theoretical maximum specific gravity of the total asphalt mixture.

The moisture content is a key factor in how hot the virgin aggregate needs to be to dry the RAP; however, only 52% of the agencies measure the RAP moisture content and 33% measure the moisture content of the total asphalt mixture. Contaminates in the RAP are evaluated by 29% of the agencies. No additional comments were received about testing for contaminates.

Eight agencies provided information about RAS in response to this question. RAS asphalt content and gradation is most frequently determined using the ignition oven method, although some agencies do use solvent extractions. RAS aggregate shape is only determined by one agency.

RAS bulk and theoretical maximum specific gravities, as well as moisture content, are almost always determined by the agencies that responded to this question. Contamination in the RAS is also frequently measured. Additional respondent comments about RAS contaminates included:

- Mixture is visually evaluated. The RAS suppliers handle RAS testing for contaminants using limits of 1.0% for delirious materials and 0.1% for metals.
- Visual inspection is used by four agencies that noted:
  - The use material retained on the 2.36-mm (No. 8) sieve.
  - A search for steel contaminates.
  - RAS processors have methods to remove metal and other materials during the grinding and screening process.

The moisture content is determined for both RAP and RAS; however, the method used to dry the material is agency-dependent. Additional information was provided by respondents about drying recycled materials and included:

- Oven drying:
  - Moisture content by the oven method (AASHTO T329, three agencies).
  - Oven dried (no test method information supplied) (four agencies).
  - Oven at 230°F (110°C); constant mass is defined as less than 0.1% change in mass between two dry all samples to a constant mass at 122°F (50°C) so as not to overheat.
  - Use intervals of 15 minute weights (two agencies).
- Dried in a microwave oven to a constant mass.
- Air dried.
- Rapid drying technology is used.

Recycled Material Properties and Testing—Section Summary

- Asphalt content and gradations are most frequently determined for individual recycled material and asphalt mixtures with recycled materials using the ignition oven.
  - Solvent extraction is used by some agencies; however, about the same number of agencies mentioned that they no longer use any extraction method in their laboratory.
- Bulk specific gravities are measured for individual recycled material and asphalt mixtures with recycled materials; however, several agencies estimate these values from other test results.
- Theoretical maximum specific gravities are determined for individual recycled materials and the total asphalt mixtures.
- Flat and elongated as well as fine aggregate angularity properties are determined by some agencies for RAP, but rarely determined for RAS.
- Moisture contents are measured for both RAP and RAS recycled materials; however, agency drying methods and times and definitions of “dry to a constant mass” vary widely.
- Recycled materials, both RAP and RAS, are checked for contaminates by some agencies.

ASPHALT MIXTURE PRODUCTION AND PLACEMENT

The survey included questions about how recycled materials are handled and fed into the asphalt plant, and potential changes that may be needed to the plant operations. The following observations are made with the caveat that there are about as many responses indicating there is no difference between recycled and conventional mixtures as there are agencies noting differences owing to the recycled material content (Table 71).

Handling recycled materials that tend to form a crust over the surface of the stockpiled materials, clump in the stockpile, and bridge over belt weigh scales are more difficult to uniformly feed into the plant. The majority of the eight agencies that consistently answered questions about RAS considered this a concern. Five agencies also considered this an issue when using more than 25% RAP.

Asphalt plant options for feeding recycled materials into the plant include adding more cold feed bins, in-line crushing and sizing, and screening and sizing. Screen and sizing or in-line crushing and screening methods are used

TABLE 71
RECYCLED MATERIAL HANDLING AND PROCESSING ADJUSTMENTS AT THE ASPHALT PLANT

Survey Question: Indicate if any of the following are seen or adjustments are needed when using higher than typical RAP% mixtures, RAS mixtures, or a combination of RAP/RAS mixtures on asphalt plant operations. (Check all that apply.)

Statement	>25% RAP%		Shingles (RAS)		Combination of RAP/RAS		No Difference from Conventional Mixtures	
	%	*n*	%	*n*	%	*n*	%	*n*
Handling Recycled Materials								
Recycled material stockpile crusting, clumping, and bridging of materials influence handling and feeding into plant	24	5	29	6	24	5	29	6
Difficult to obtain uniform feed of recycled materials	14	3	29	6	19	4	33	7
Feeding Recycled Materials into Plant								
Additional cold feed bins are used to meet the required recycled material gradation	24	5	19	4	29	6	29	6
Recycled material screened and sized as it is fed into asphalt plant	29	6	19	4	14	3	38	8
In-line crushing and sizing is used (i.e., recycled material is processed as it is added to the plant)	29	6	5	1	5	1	43	9
Point of introduction of the recycled material into the plant needs to be changed (e.g., RAP collar relocated closer to the drum discharge point or the recycled material fed directly into pugmill at batch plant)	10	2	5	1	5	1	38	8
Separate dryer drum used to dry recycled materials	0	0	0	0	0	0	48	10
Adjustments of either metering methods or sensors are needed to properly measure small percentages of recycled materials	0	0	19	4	10	2	29	6
Plant Operations								
Production rates need to be slowed (e.g., extra drying time needed)	29	6	14	3	19	4	33	7
Plant temperatures need to be *lowered* when using recycled materials	5	1	5	1	5	1	38	8
Plant temperatures need to be *raised* when using recycled materials	35	7	35	4	35	4	35	6
Minimum silo storage times are needed	0	0	0	1	0	0	0	9
Maximum silo storage times are needed	16	3	16	2	16	3	16	6
Mixture Characteristics								
Difficult to obtain mixture uniformity	38	8	19	4	24	5	38	8
Mixtures with recycled material content tend to segregate more frequently during load out	10	2	5	1	5	1	52	11

Not all survey respondents answered all questions.
n = 21.

for producing mixtures with more than 25% RAP. Plant production rates are to be slowed and temperatures raised when producing mixtures with more than 25% RAP and mixtures with a combination of RAP and RAS. Additional respondent comments about plant temperature constraints included:

- Temperatures required to be ±15°F of the job mix formula temperature.
- Mixture temperatures cannot reach more than 325°F.
- Kept lower than 325°F to 330°F.
- Not more than 10% than the target temperatures specified in the mix design
- Disincentives:
  - Not to exceed 90% pay for "hot-leg" (discharge) temperatures between 350°F and 400°F.
  - 40% pay or removal for "hot-leg" temperatures 400°F, 350°F for HMA mixtures, and not to exceed 275°F for WMA mixtures.

General comments about the uniformity of mixtures with either RAP and/or RAS included:

- Weigh recycled materials separately—separate weigh bridges for RAP and RAS (two agencies).
- Test regularly to account for nonuniformity (two agencies):
  - Spend more time on selection and processing of recycled materials.
  - Use more cold feed bins.
- Specific to RAP:
  - Use good stockpiling procedures (five agencies)
  - Different RAP sources are stockpiled separately, and if multiple layers are being milled from the roadway then the individual layers may be milled-up and stockpiled separately.
  - Fractionate RAP (three agencies).
  - Use consistent milling processes.
  - Age of the plant and flighting is important to ability to produce high RAP mixtures.
- Specific to RAS:
  - Blend RAS with manufactured sand.

One set of seven statements was presented to the respondents for each of the three types of mixtures that are the focus of this survey (i.e., more than 25% RAP, RAS, and combination RAP and RAS mixtures). Respondents were asked to indicate their level of agreement or disagreement about how mixtures behave when they are transferred from the haul truck to the paver, flow through the paver, any defects or difficulties behind the paver, and how difficult the mixtures are to work once placed.

Mixtures with more than 25% RAP are more likely to form a crust on the mixture in the paver wings, somewhat more likely to segregate, and it can be difficult to obtain joint density (Table 72). Additional respondent comments about the flow of the mixture out of the haul truck included:

- Flows out of the truck in portions instead of being continuous.

TABLE 72
OBSERVED MIXTURE BEHAVIOR FOR MIXTURES WITH MORE THAN 25% RAP

Survey Question: When placing asphalt mixtures with more than 25% RAP, how frequently each of the following is observed.

Statement	Always		Often		Sometimes		Rarely		Never	
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*
Stiffer mixtures flow differently from end dump haul truck to paver hopper	20	4	5	1	15	3	15	3	10	2
Crusting of mixtures when deposited in windrows can be a problem (e.g., clumps deposited into hopper)	0	0	5	1	25	5	5	1	10	2
Mixture in paver wings more likely to build up and form crust on top	10	2	0	0	30	6	15	3	15	3
Visible "lines" in the direction of paving more noticeable between screed and extension	10	2	5	1	25	5	10	2	15	3
Uniformity and density at the joint is more difficult to obtain	5	1	5	1	45	9	5	1	10	2
Hand work is more difficult	15	3	5	1	15	3	25	5	5	1
Mixtures are more likely to segregate	5	1	0	0	45	9	5	1	15	3

Not all survey respondents answered all questions.
Responses for "Don't Know" choice not shown.
n = 20.

- Less fluid and moves in a stiff, harsh mass that is very temperature sensitive.
- Stiff and crusty.

Additional respondent comments about windrow crusting included:

- Drag marks are seen when clumps get in front of the screed.
- Visible temperature segregation.
- Small chunks of the mixture can be seen in the mat surface. This is more of an issue with an equipment breakdown than with the high RAP content.

RAS mixtures tend to flow differently from the haul truck into the paver and sometimes crust over in the windrow or in the paver wings (Table 73). Other difficulties associated with placing stiffer mixtures are also sometimes seen, such as visible lines in the mat behind the paver, difficulty in achieving joint density, and being more difficult to work by hand (e.g., luting). Similar responses were provided that used a combination of RAP and RAS in the mixtures (Table 74).

Asphalt Mixture Production and Placement—Section Summary

Handling and Processing Recycled Material Mixtures

- Recycled materials can be more difficult to feed into the asphalt plant because of crusting on the stockpile surface, clumping, and bridging of recycled materials over weigh belt scales.
- Recycled materials are routinely fed into the plant using in-line crushing and screening, screening and crushing as material is fed into the plant, and by using additional cold feed bins.
- Additional cold feed bins appear to be a preferred method.

TABLE 73
OBSERVED MIXTURE BEHAVIOR FOR MIXTURES WITH RAS

Survey Question: When placing asphalt mixtures with shingles (RAS), how frequently each of the following is observed.

Statement	Always		Often		Sometimes		Rarely		Never	
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*
Stiffer mixtures flow differently from end dump haul truck to paver hopper	17	3	6	1	11	2	6	1	6	1
Crusting of mixtures when deposited in windrows can be a problem (e.g., clumps deposited into hopper)	0	0	0	0	22	4	0	0	0	0
Mixture in paver wings more likely to build up and form crust on top	11	2	6	1	28	5	0	0	6	1
Visible "lines" in the direction of paving more noticeable between screed and extension	6	1	0	0	22	4	6	1	6	1
Uniformity and density at the joint is more difficult to obtain	6	1	0	0	28	5	11	2	0	0
Hand work more difficult	17	3	6	1	17	3	6	1	0	0
Mixtures are more likely to segregate	6	1	0	0	22	4	22	4	0	0

Not all survey respondents answered all questions.
Responses for "Don't Know" choice not shown
n = 18.

TABLE 74
OBSERVED MIXTURE BEHAVIOR FOR MIXTURES WITH A COMBINATION OF RAP AND RAS

Survey Question: When placing asphalt mixtures with a combination of RAP and shingles (RAS), how frequently each of the following is observed.										
Statement	**Always**		**Often**		**Sometimes**		**Rarely**		**Never**	
	%	*n*	*%*	*n*	*%*	*n*	*%*	*n*	*%*	*n*
Stiffer mixtures flow differently from end dump haul truck to paver hopper	17	3	6	1	11	2	11	2	6	1
Crusting of mixtures when deposited in windrows can be a problem (e.g., clumps deposited into hopper)	0	0	0	0	22	4	0	0	6	1
Mixture in paver wings more likely to build up and form crust on top	6	1	11	2	17	3	11	2	6	1
Visible "lines" in the direction of paving more noticeable between screed and extension	6	1	11	2	17	3	6	1	6	1
Uniformity and density at the joint is more difficult to obtain	6	1	0	0	28	5	11	2	0	0
Hand work more difficult	11	2	11	2	17	3	11	2	0	0
Mixtures are more likely to segregate	6	1	0	0	28	5	17	3	0	0

Not all survey respondents answered all questions.
n = 18.

- Production rates may need to be slowed down for drying the recycled materials, obtaining the desired mixture temperature, and to provide adequate mixing times.
- Maximum silo storage times may be required to keep the mixture from getting too stiff.
- Stiffer mixtures can be more difficult to place without screed lines, drag lines from clumps of material in front of, or under, the screed, and to work by hand.
- Blend RAS with sand to help prevent clumping.
  - Update or upgrade existing plant equipment.
    - △ Add more cold feed bins, and
    - △ Change drum flighting.
  - Provide separate weigh systems for different types of recycled materials.
- Transport and placement:
  - Use proper paver operations to keep mixture from crusting in the windrow or in the paver wings.

VOLUMETRIC QUALITY CONTROL TESTING

QC and QA density testing once the mixture is placed can be accomplished using nuclear gauges, nonnuclear gauges, or by taking and testing cores. The majority of respondents take cores for laboratory testing (Table 75). Although some agencies use nuclear density gauges, none of the respondents mentioned that they use nonnuclear density gauges. Most respondents do not believe that the recycled materials influence nondestructive test method density results; however, seven agencies were not sure if the recycled material influences any of the nondestructive density test measurements (Table 76).

Agencies may obtain mixture from either the haul truck or from behind the paver so that samples are compacted in the laboratory for density testing. Some respondents indicated that they use a QC compaction level (i.e., number of gyrations) based on traffic levels and mixture types per AASHTO M323 for compacting the samples, whereas others use agency-defined levels of gyrations (Table 77).

Respondents were asked to indicate if it is more difficult to obtain required volumetrics with recycled material asphalt mixtures compared with conventional mixtures. Most of the respondents that answered this question (eight agencies) believe it is more difficult to meet air voids and VMA requirements, and some agencies believe it is also more difficult to meet the VFA requirements (Table 78).

KEY POINTS FOR FIELD INSPECTORS

A survey question was included to collect information about what field inspectors need to be aware of when working with high percentage RAP, RAS, or RAP and RAS combination

TABLE 75
METHODS USED FOR DETERMINING THE IN-PLACE MAT DENSITY

Survey Question: Indicate the method used to determine the density testing of the finished mat.		
Method	*%*	*n*
Nuclear density gauge	24	5
Nonnuclear gauge	0	0
Cores	76	16

Not all survey respondents answered all questions.
n = 21.

TABLE 76
IMPACT OF RECYCLED MATERIALS ON IN-PLACE DENSITY MEASUREMENTS

Survey Question: Do any of the recycled materials seem to influence the nondestructive test results?		
Answer	*%*	*n*
Yes	0	0
No	65	13
Maybe	35	7

Not all survey respondents answered all questions.
n = 20.

TABLE 77
COMPACTION LEVEL USED FOR PREPARING SAMPLES FOR DENSITY TESTING

Survey Question: Indicate the number of gyrations used to prepare samples for lab density testing.											
Information	N_{Design}							N_{Max}		**Based on Traffic Level (ESALs)**	**AASHTO M323 Mixture Type**
	40*	**50****	**65****	**75**	**80**	**95**	**100**	**115**	**160**		
AASHTO M323 ESALs for Given N_{Design}		<0.3		0.3 to <3			3 to 30				
Number of Agencies Using a Given Compaction Level	1	4	3	4	1	1	2	1	1	5	4

*Shoulder mixtures.
**Low traffic volume roadways.
Not all survey respondents answered all questions.
n = 20.

TABLE 78
IMPACT OF RECYCLED MATERIALS ON MIX DESIGN VOLUMETRICS

Survey Question: Check the box if it is more difficult to obtain acceptable properties (within specification limits) when compared to similar mixtures without any recycled material content.						
Properties	**25% or More RAP**		**Shingles (RAS)**		**RAP and RAS Combination Mixtures**	
	%	***n***	**%**	***n***	**%**	***n***
Air Voids, %	88	7	75	6	75	6
VMA, %	88	7	50	4	38	3
VFA, %	63	5	50	4	50	4

Not all survey respondents answered all questions.
n = 8.

mixtures. The comments received for this question are separated into those generally related to all recycled materials, specifically for RAP, and specifically for RAS.

General comments:

- Ensure mixture characteristics are being controlled by the contractor.
- Check for consistency in recycled products.

Comments for high RAP mixtures:

- Start milling with a clean road free of debris, etc.
- Important to monitor the quality of stockpiles and watch milling operations.
- We have found that the mixtures are "cleaner" in the field with the higher RAP percentages, but we believe the preprocessing used for these mixtures is the major factor for this.
- Temperature segregation, clumping, or overheated mixtures can be a problem when placing high RAP mixtures. Check mixture temperatures and follow good paving practices.
- Streaking, pulling, tearing, segregation, and foreign material from the RAP stockpile can be seen in the finished mat. Check for texturing and uniformity of the mat.
- On high RAP projects stay on top of segregation and joint density checks.
- Generally, inspection is the same, except constituent percentages may have to be verified if various RAP sources are used. This is because incentive payments offered to contractors are dependent on who owns the RAP being used.

Comments for RAS mixtures:

- Ensure that the proper amount of RAS is going into the mixture.
- Watch for foreign materials, visible RAS, and dry-looking mixtures.
- Check for clumping and dust balls in the mat when using RAS. These balls may form in the drum.
- Look for dry, bony mixture with uncoated aggregate that can lead to segregation and premature raveling.

CHAPTER FIVE

CASE EXAMPLES

This chapter presents examples from those agencies that provide additional information for five topics:

1. Georgia Department of Transportation (GDOT) specification development that encourages the routine contractor submittals of high RAP mixtures.
2. Contractors' perspectives for routinely produced high RAP mixtures for GDOT, as well as mixtures for other clients in surrounding states that use RAS and/or a combination of RAP and RAS.
3. Contractor suggestions for producing and placing RAS asphalt mixtures.
4. Locating and using county databases increases pavement performance evaluation information.
5. Evaluating the amount of recycled material asphalt transfer to the virgin aggregate during dry mixing at the plant (i.e., the time before the liquid virgin asphalt is added).

CASE EXAMPLE NO. 1: GEORGIA DEPARTMENT OF TRANSPORTATION SPECIFICATION DEVELOPMENT FOR HIGH RAP MIXTURES

This section describes GDOT's implementation and refinement of specifications for high RAP mixtures that resulted in contractors routinely submitting mix designs using from 30% to 40% RAP in any pavement layer. A timeline summary of GDOT's specification implementation and refinement follows:

- 1998—Implement Superpave mix design methodology.
- 1998–2005—Percentage of RAP used in Georgia mixtures increases from 10% to 25% and a variety of early pavement distresses associated with low asphalt film thickness are documented.
- 2005—One level of gyration for N_{Design} is selected based on the aggregate structure locking point of Georgia mixtures (65 gyrations).
- 2005–2010—Additional performance (rut testing) and durability (permeability) testing is added for mix design approval.
- 2012—Percentage of RAP asphalt considered useful in mixtures is reduced from 100% to 75% and the original optimum mix design asphalt content is increased by adding additional virgin asphalt that is calculated as the percentage of nonuseful RAP asphalt. Performance testing is conducted on samples prepared at the increased virgin asphalt level.
- 2015—High RAP (>25% RAP) mixtures can be used in any pavement lift and mix designs with 30% RAP are routinely approved. High RAP surface coarse mixtures were placed in 2012 and at the beginning of 2015.

GDOT started using the Superpave mix design methodology during 1998, using four gyratory compaction levels: 50, 75, 100, and 125. The initial Superpave mix designs tended to produce coarser mixtures with lower optimum asphalt contents to resist rutting. At the same time, the mix design methodology changed; approximately 10% RAP was used in GDOT mixture. Between Superpave implementation in 1998 and 2005, the percentage of RAP gradually increased from 10% to 25%.

By 2005, feedback from the GDOT maintenance division noted concerns with increased evidence of early pavement distresses on projects that used around 25% RAP and were less than 3 years old. The documented problems included permeable areas of the pavements (i.e., low density, which allows water to infiltrate) leading to increased moisture damage, more frequent evidence of segregation followed by segregation-related moisture damage, visible coarse streaking in the freshly placed mat surface, and a generally dry, aged look within a short period of time (Figure 26).

All of these in-place problems with early pavement distresses can be linked to inadequate asphalt film thickness (low asphalt content), which is the likely reason for the "dry" look and the mixture is more:

- Difficult to handle;
- Likely to segregate;
- Difficult for the mixture to move uniformly as it is transferred from the silo into the haul truck, from the truck into the paver, through the paver, and across the back of the screed;

FIGURE 26 Examples of pavement conditions after initial implementation of Superpave and increasing percentages of RAP (*Source*: Hines 2015).

- Likely to show an accumulation of coarser particles behind the paver screed at the auger gear box (center of screed), at screed extensions, and at the outside edges of the screed (e.g., longitudinal joints); and
- Permeable mixtures at locations that hold moisture longer after rain events.

GDOT identified two critical factors related to low asphalt contents and low film thicknesses that were evaluated with extensive investigations:

- Potential overcompaction of mix design samples [i.e., number of design gyrations (N_{Design}) too high], and
- Overestimation of the contribution of RAP asphalt content to the total effective asphalt content of the mixture.

The first extensive GDOT study evaluated the initially selected Superpave levels of compaction (50, 75, 100, and 125 for N_{Design}) may be overcompacting the mixtures. Overcompacting the mixtures would result in selecting a too low design asphalt content. GDOT explored this possibility by determining the number of gyrations necessary to reach the locking point for a large number of samples and a wide range mixture types. The locking point is when the sample height is constant for three or more consecutive gyrations.

Results showed the locking point for GDOT mixtures was consistently between 60 and 68 gyrations for dense-graded mixtures. Based on this study, a single N_{design} of 65 gyrations was selected for the majority of Georgia DOT mixtures. Exceptions to the single gyration level include the GDOT's 4.75-mm (No. 4) mixtures, which have a locking point of 50 gyrations and SMA mixtures are designed using 35 gyrations. GDOT had the National Center for Asphalt Technology (NCAT) verify locking point selections.

Between 2005 and 2010, performance testing for mixture approval was added to GDOT's mix design procedures. The Hamburg wheel tracking device is used to evaluate the mixture rutting potential. Permeability is evaluated using the ASTM PS129-01 Standard Provisional Test Method for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter.

These changes in N_{Design} encouraged the use of finer, more uniformly-graded gradations that are less prone to segregation. However, the mixtures still looked dry when using RAP percentages approaching 25%. At this time the entire RAP asphalt was considered to contribute to the total asphalt content of the mixture. That is, the asphalt availability factor for the RAP was 1.

In 2012, GDOT conducted a second extensive laboratory study to investigate the possibility that not all RAP asphalt was contributing to the total useful (effective) asphalt content. Because no methodology was, and still is not, standard methodology for determining the RAP asphalt availability factor, GDOT used an approach based on its experience and performance-based testing. The steps used for the laboratory study are:

- ***Step 1***: Determine the amount of RAP asphalt that is transferred to virgin aggregate in the plant before the addition of virgin asphalt (dry mixing).
- ***Step 2***: Visually estimate the percentage of RAP asphalt remaining on the surface of the RAP particles after dry mixing (effective RAP asphalt).
- ***Step 3***: Correct the original optimum asphalt content from the mix design procedure to account for RAP asphalt that is not useful (i.e., asphalt availability factor).
- ***Step 4***: Ensure the mixture still meets performance-based mixture testing.

Step 1: Transfer of RAP Asphalt to Virgin Aggregate

The following methodology was used to visually estimate the likelihood of RAP asphalt transfer to virgin aggregate:

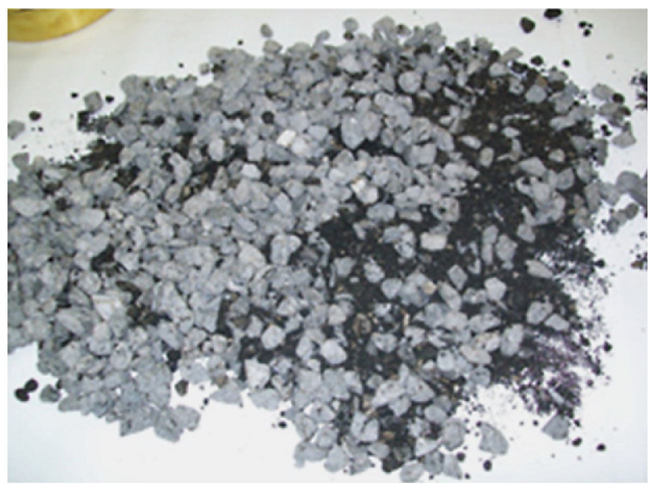
- 25% RAP by mass of virgin aggregate was batched and kept at room temperature.
- Known mass of light-colored virgin aggregate (No. 6 stone) was preheated at 400°F (204°C), which was used to approximate superheating the virgin aggregate at the asphalt plant before dry mixing.
- Laboratory pugmill mixer was preheated, the superheated virgin aggregate was added, followed by the room temperature RAP. Materials were mixed for one minute.
- Mixture was removed from pugmill, cooled, and the light-colored coarse virgin aggregate particles were separated from the RAP.
- Change in the mass of virgin aggregate owing to the transfer of the RAP asphalt was calculated.

The results showed only a limited transfer of RAP asphalt was transferred to the virgin aggregate (Figure 27). The RAP asphalt remained on the RAP surface and did not appreciably liquefy and transfer. Based on these results, the RAP asphalt was considered to act more like a partial precoating of the RAP particles rather than an asphalt replacement that can completely and homogeneously blend with the virgin asphalt.

Step 2: Estimating Effective RAP Asphalt

The second step was to visually estimate the amount of asphalt remaining on the RAP aggregate that acts as a precoating of the RAP aggregate surface. Multiple RAP stockpiles were sampled from around the state and evaluated by the following methodology:

- Part 1:
  - Determine RAP asphalt content using the ignition oven.



Pugmill-mixed No. 6 Stone (light color) and RAP

Manually separated No. 6 Stone with limited evidence of RAP binder transfer

FIGURE 27 Georgia evaluation of *potential* RAP binder transfer to virgin aggregate during production (*Source*: Hines 2015).

  – Mix RAP aggregate remaining at the end of ignition oven testing increasing percentages of virgin asphalt in increments of 0.25% to 0.5%.
- Part 2:
  – Preheat RAP to a temperature achieved during dry mixing at the plant.
- Part 3:
  – Compare coating on the RAP aggregate mixed with various percentages of virgin asphalt (Part 1) to the coating on the preheated RAP (Part 2) (Figure 28).

The effective RAP asphalt content was calculated as the ratio of the percentage of virgin asphalt that is to be added to the RAP aggregate so that it appeared similar to the preheated RAP:

Effective Asphalt Content Ratio

$$= \left(\frac{\left(\begin{array}{c} \text{Match of AC\% of virgin} \\ \text{asphalt and RAP aggregate} \end{array} \right)}{\text{RAP AC\% from ignition oven}} \right) 100$$

For example, the preheated RAP in Figure 28 had an asphalt content of 4.46% and it took 2.75% of virgin asphalt added to the RAP aggregate (after ignition oven testing) to produce a mixture with a similar appearance:

$$\text{Effective Asphalt Content Ratio} = \left(\frac{2.75\%}{4.46\%} \right) 100 = 61.7\%$$

The effective asphalt content contribution from the RAP is about 61.7%.

After discussions of the results with GDOT contractors, a compromise was reached that assumes an effective asphalt

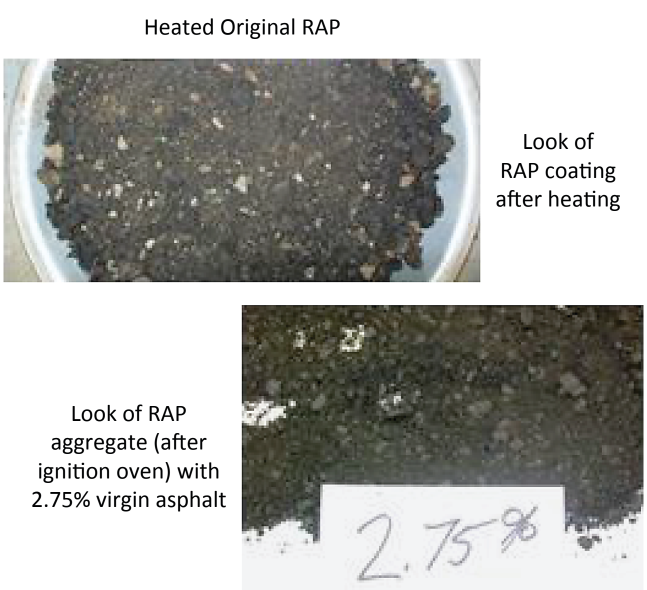


FIGURE 28 Visual comparison of coating of original RAP material with RAP aggregate (*Source*: Hines 2015).

content ratio of 75% (i.e., asphalt availability factor of 0.75 for RAP). Georgia contractors are credited with (paid for) 75% of the asphalt content in their RAP stockpiles.

Step 3: Corrected Optimum Asphalt Content

The original optimum asphalt content, OOAC, from the initial mix design is still calculated as:

$$\text{OOAC} = \%\ \text{virgin asphalt} + (\%\ \text{RAP})(\%\ \text{RAP asphalt content})$$

The effective RAP asphalt, which is referred to as the credited asphalt content (CAC) to the contractor, is calculated as:

$$\text{CAC} = (\%\ \text{RAP})(\%\ \text{RAP asphalt content})(0.75)$$

and the noncredited asphalt content (NCAC) is the difference between the RAP asphalt content and the percentage of RAP credited to the contractor (75%):

$$\text{NCAC} = (\%\ \text{of RAP})(\%\ \text{RAP asphalt content}) - (\%\ \text{RAP})(\%\ \text{RAP asphalt content})(0.75)$$

GDOT increases the original optimum asphalt content adding this percentage of virgin asphalt. This value is the corrected optimum asphalt content:

$$\text{COAC} = \text{OOAC} + \left[(\%\ \text{RAP}) \left(\begin{array}{c} \%\ \text{RAP asphalt content} \\ -\ \text{CAC} \end{array} \right) \text{virgin asphalt} \right]$$

For example, a mix design for a 12.5-mm gradation asphalt mixture with 30% RAP (0.30 in decimal format) and a RAP asphalt content of 5.75% has an OOAC of 5.50%:

$$\text{OOAC} = (5.75\%)(0.30) + 3.78\% = 5.50\%$$

The originally determined percentage of RAP asphalt used to calculate the optimum asphalt content is 1.73% and the virgin asphalt content is 3.78%.

The percentage of NCAC RAP asphalt content is:

$$\text{NCAC} = (5.75\%)(0.30)(0.25) = 0.43\%$$

The contractor is credited with a RAP asphalt content of 1.29% and the original percentage of virgin asphalt is increased by 0.43%. The COAC is:

$$\text{COAC} = 5.50\% + 0.43\% = 5.93\%$$

Technically, the useful optimum asphalt content is still 5.50% [i.e., 1.29% + 3.78% virgin asphalt + 0.43% (additional) virgin asphalt = 5.50%]; however, the total asphalt content that would be measured for the asphalt mixture produced at the plant will be 5.93%.

Step 4: Performance and Durability Check

Additional samples are prepared using the COAC, and rutting potential (APA rut testing) and the moisture sensitivity (durability) are evaluated. As expected, the slight increase in the percentage of virgin asphalt results in a corresponding decrease in air voids that helps improve the mixture durability. The aggregate structure (gradation) selected during the initial mix design typically still provides the mixture with acceptable rut resistance even with the increases asphalt content.

The corrected optimum asphalt content calculation changes were incorporated into the GDOT 2012 specifications and the agency is routinely approving contractor mix designs with 30% RAP. The first high RAP and increased asphalt content surface mixtures were placed in 2012. Mixtures looked well-coated and uniform when placed, and after more than 2 years show no initial evidence of early pavement distresses (Figure 29). An additional benefit to GDOT is the reduction in contractor penalties for out of specification mixtures (Figure 30).

FIGURE 29 Look of high RAP pavements after implementation of the corrected optimum asphalt content (*Source*: Hines 2015).

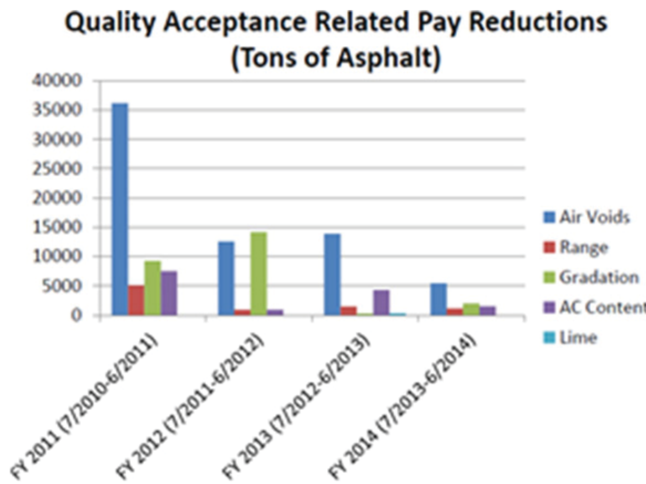


FIGURE 30 Impact of RAP mix design changes on contractor disincentives (*Source*: Hines 2015).

CASE EXAMPLE NO. 2: SOUTHEASTERN CONTRACTOR'S WORKING WITH GEORGIA DEPARTMENT OF TRANSPORTATION

Contractors who typically produce and place high RAP asphalt mixtures for GDOT were asked to complete the same survey that was sent to state construction engineers. These large contractors also have some experience placing RAS and/or combination RAP and RAS mixtures for nonstate agency clients. Five large contractors with multiple plants and contractor laboratories responded to the request for information. These contractors conduct business in five other Southeastern states (Alabama, Florida, North Carolina, South Carolina, and Tennessee) and provided information about different laboratory practices, various types and ages of asphalt plant types, and placing these mixtures for different clients. All six of the contractors indicated that RAP is available in their states, but noted the availability of RAS is limited to one or more state districts or to only local areas within some states (Table 79).

Contractors report using various asphalt availability factors for recycled materials (Table 80). Four contractors use a factor of 1 for RAP (i.e., 100% RAP asphalt is useful) and two contractors use agency-specified asphalt availability factors. As

TABLE 79
AVAILABILITY OF RECYCLED MATERIALS IN SIX SOUTHEASTERN STATES

Supply and Demand: Which types and percentages of recycled materials used in asphalt mixtures can be limited by the available supplies. Also, an overabundance of recycled material(s) can result in various supply–demand competitions. Please indicate if recycled materials supplies are available statewide, on a district-by-district basis, or only through a few local material recyclers. Also, indicate if there is any excess of recycled materials (i.e., more supply than demand).			
Availability of Materials	**Statewide**	**In One or More Districts/Regions**	**Limited to Local Areas**
	Number of Contractors		
How widely available is RAP throughout your state?	4	1	0
How widely available is RAS throughout your state?	2	1	0
Is there an excess of shingles (RAP) in your state?	0	2	2
Is there an excess of shingles (RAS) in your state?	0	0	2
Do RAP and RAS compete for use in the tonnage of asphalt mixtures produced in your state?	0	1	2

the percentage of RAP increases to 25% or more, the clients are more likely to specify the RAP asphalt availability factor. From four to six agencies specify the RAS or combination of RAP/RAS asphalt availability factors.

One contractor noted that one of its clients used an ABR of 40% for RAS mixtures. Two contractors have experience with clients using the RBR (recycled binder ratio). South Carolina clients typically set a limit on the percentage of recycled asphalt rather than using one of the established ratios for controlling the percentage of virgin asphalt in the recycled material asphalt mixture.

The contractors provided a wide range of responses for selecting the virgin asphalt grade that reflects the wide range of their client's preferences:

- Two contractors noted that they have the option for selecting the virgin asphalt grade.
- None of the contractors "bump" the virgin asphalt grade temperatures.
- One contractor bases the virgin asphalt grade selection on the recovered asphalt properties.
- One contractor does not make any adjustments.
- Four contractors noted that the agency, or other clients, specify the grade of the virgin asphalt.
- One contractor indicated that the state agency defines the virgin asphalt grade based on the percentage of RAP in the mixture.
- Two contractors set the percentage of recycled materials to be used in the mixture and then select the virgin asphalt grade.
- One contractor uses a softening or rejuvenator additive for the stiffer recycled material asphalt, then selects the virgin asphalt grade.
- One contractor verifies that the combined mixture asphalt properties meet composite viscosity requirements.

Recycled Material Properties

Recycled material asphalt content is determined by all of the contractors that use the ignition oven method. The following comments about ignition oven correction factors were provided:

- None used (two contractors).
- Use a (ignition oven) correction factor on all mixtures by mixing samples at optimum (asphalt content) then

TABLE 80
CONTRACTOR EXPERIENCE USING ASPHALT AVAILABILITY FACTORS

Survey Question: For the purposes of mix designs, indicate which "philosophy" is used to establish the contribution of the recycled material asphalt.			
Materials	**Number of Contractors**		
	100% Available for Mixture (availability factor = 1)	**0% ("Black Rock") (availability factor = 0)**	**Agency-Assumed Percentage of the Total Recycled Asphalt Content**
25% or less RAP	4	0	2
More than 25% RAP	3	0	3
RAS, manufacturer waste	2	0	4
RAS, tear-offs	1	1	4
RAS, any combination	0	1	5
RAP and RAS combination	0	0	6

n = 6.

TABLE 81
RECYCLED AGGREGATE TESTING

Survey Question: Indicate which aggregate specification tests are conducted for the recycled material aggregate. (Check all that apply.)						
Material	**Gradation**	**Minus 0.075-mm by Washing**	**Flat and Elongated**	**Fractured Faces**	**Fine Aggregate Angularity**	**Sand Equivalent**
	Number of Contractors					
Ignition Oven						
RAP, after ignition oven	6	6	2	2	2	2
RAS, after ignition oven	2	2	1	1	1	0
Solvent Extraction						
RAP, after solvent extraction	0	0	0	0	0	0
RAS, after solvent extraction	1	1	1	1	1	0
Only determine properties for entire mixture with the recycled materials after either solvent or ignition oven testing.	0	0	0	0	0	0

burning. The difference between what is burned and the optimum is the (ignition oven) correction factor.

- (Ignition) oven correction based on known batched sample of total mixture.
- No correction for RAP stockpile burns.

The recycled material asphalt is extracted and recovered by five contractors. Only one contractor's laboratory uses vacuum solvent extraction with Bioact. Recovery methods include Abson (three contractors), Rotavapor (one contractor), or the combination extraction/recovery AASHTO T319 method (one contractor). Four contractors indicated that recycled asphalt is recovered for asphalt testing in some of their laboratories; however, the samples are then submitted to the client for testing. Two contractors work with clients that perform their own extractions and recoveries.

Once the recycled material asphalt is recovered, the asphalt high temperature shear modulus, *G*, is determined using the DSR. The *G** of the as-recovered asphalt (three contractors) and after RTFO conditioning (one contractor) are the only asphalt properties that are usually evaluated. One contractor uses absolute viscosity testing for some of its clients and back calculates to determine the absolute viscosity for another client.

All six of the contractors determine the washed aggregate gradations (i.e., sieve analysis, washed sieve for minus 0.075%) for RAP after ignition oven testing and two contractors measure these properties for RAS aggregates (Table 81). Source RAP or RAS aggregate properties are not evaluated, although two contractors mentioned that they look at the aggregate group, class, or petrographic analysis.

Mix Design Samples

Four of the contractors dry recycled materials prior to batching, use additional sieving of the recycled materials for batching, and heat the virgin aggregate and RAP separately (Table 82). One contractor considers heating prior to mixing sufficient to dry out the recycled materials.

TABLE 82
CONTRACTOR PRACTICES FOR DRYING AND COMBINING MATERIALS

How Materials Are Batched for Heating	**Number of Contractors**
Drying Before Batching	
Dry before batching	4
Consider heating for mixing sufficient	1
How Material Is Processed for Batching	
Batch as stockpiled	1
Additional sieving for tighter gradation control	4
How Material Is Combined, or Not, for Heating	
Heat aggregate and RAP separately	4
Combine aggregate and RAP before heating	1
Heat aggregate and RAS separately	1
Combine aggregate and RAS before heating	1
Heat combined RAP and RAS separately	1
Combine RAP and RAS before heating	1

TABLE 83
ORDER OF ADDITION OF MATERIALS FOR MIXING

Materials	Order of Materials Added to Mixing Bowl		
	1st	2nd	3rd
Aggregates, all Fractions	4	0	0
RAP, Coarse	0	3	0
RAP, Fines	0	4	0
RAS	0	1	0
Asphalt	0	0	3
Rejuvenator	0	0	1

Additional comments provided by the contractors included:

- Recycled materials are dried before batching:
  - In air
  - In an oven at:
    - △ 140°F (60°C)
    - △ 220°F (140°C)
    - △ 300°F (149°C).
  - RAS is dried at 150°F (66°C) by one contractor.
- Recycled materials are occasionally visually checked for contaminates including extra sand.

The order of addition of materials to the mixing bowl is generally consistent between the different contractor laboratories. Aggregates are added first, followed by the recycled materials, with the asphalt last (Table 83). All mixing is done until the components look uniformly distributed or coated. None of the contractors use a specific time for mixing. When lime is used as an anti-stripping additive, it is added between the aggregate and the RAP.

Although the order of addition for mixing is consistent, the temperatures and times used to preheat the materials vary considerably, as indicated by respondent's comments:

Aggregates are heated for:

- 4 hours at 230°F (110°C)
- 3 to 4 hours at 390°F (199°C)
- 2 hours at 325°F (163°C)
- 1 hour at 300°F (149°C)
- 2 hours at 375°F (191°C).

RAP is heated for:

- 1 hour at 300°F (149°C)
- 2 hours at 325°F (163°C)
- 30 minutes at 300°F (149°C)
- 2 hours at 140°F (60°C).

RAS or a combination of RAP and RAS is heated for:

- 2 hours at 325°F (163°C)
- 8 hours at 140°F (60°C).

Short-term aging for mixtures with RAP is accomplished using:

- 2 hours at 300°F (149°C) (three contractors)
- 2 hours at 310°F (154°C) (one contractor).

The short-term aging for mixtures with RAS or a combination of RAP and RAS is completed using:

- 2 hours at 300°F (149°C) (one contractor)
- 2 hours at 325°F (163°C) (one contractor).

The temperature of the mixtures is measured using a probe in the material while in the oven (two contractors) or immediately after removing from the oven (three contractors).

The levels of compaction vary by client and by the type of mixture:

- 50 to 75 wear and binder courses (one contractor)
- 65 for any mixture type (two contractors)
- 50 for SMA (can only use 25% or less RAP) courses (one contractor)
- 35 for SMA courses (one contractor).

Three of the contractors responding to the survey believe it is more difficult to meet air void requirements when the mixtures have more than 25% RAP (Table 84). Only one of these contractors believes it is difficult to meet VMA, VFA, and dust-to-asphalt ratio requirements with high RAP mixtures. One contractor believes that any of the volumetric requirements may be difficult to meet when using a combination of RAP and RAS.

TABLE 84
PERCEPTIONS OF INCREASED DIFFICULTY IN OBTAINING VOLUMETRIC PROPERTIES

Recycled Materials	Difficult to Obtain Mix Design Volumetric Properties			
	Air Voids, %	VMA	VFA	Dust-to-Asphalt Ratio
25% or less RAP	0	0	0	0
More than 25% RAP	3	1	1	1
RAS mixtures	0	0	0	0
RAP and RAS combination mixtures	1	1	0	1

Performance testing of mixtures is limited to using the APA to evaluate the rutting potential during the mix design. A few of the contractors indicated that they do not evaluate rut resistance; however, some of their clients do use the Hamburg (dry, wet) or AMPT. None of the contractors or their client laboratories evaluates stiffness or any type of cracking. This may be because rutting is the primary type of pavement distress of concern in the hot, wet southeastern region of the country.

Recycled Material Stockpiling and Processing

Collecting, processing, and stockpiling recycled materials can require additional permits, additional storage area, and well-drained stockpiling areas for both RAP and RAS stockpiles. Fugitive dust control is essential during RAP (one contractor) and RAS grinding (two contractors). Certification documents for contaminate-free recycled materials are not necessary; however, one contractor does evaluate the RAP for contaminates. Noise permits are not required for grinding operations.

Contractor perspectives about RAP and RAS processing are described here.

RAP Processing

All of the contractors collect large quantities of RAP before processing, which is usually done in optimum weather conditions. Hot and/or wet weather can bog down the crushing process, blind screens, and reduce the rate of processing. Only one contractor noted any need for time limitations between processing and using RAP.

Contractors typically process RAP at the asphalt plant site and sufficient RAP is frequently or occasionally (three contractors) stockpiled at the start of a project to complete the project. Only two contractors noted that they fractionate RAP, regardless of the percentage of RAP used in the mixture, by splitting on a single size screen. The coarse RAP is the material retained on the screen and the fine RAP is the material passing the screen. Contractors reported that the screens and sizes used are:

- Split on the 4.75-mm (No. 4) sieve.
- 19.0-mm to 4.75-mm (¾-in. to No. 4) and passing the 4.75-mm (No. 4) sieve.
- Minus 12.5-mm (½-in.).

RAP QC testing is conducted for every 1,000 tons (three contractors). One contractor tests every 500 tons for both RAP and RAS. Asphalt content is determined with the ignition oven and the remaining aggregate is used to determine the gradation. Only one contractor evaluates the fine aggregate angularity for the RAP aggregate. None of the contractors determine the aggregate bulk specific gravity or the bulk specific gravity or theoretical maximum specific gravity of the recycled materials. Four contractors determine the moisture content of the RAP using AASHTO T329 (three contractors) and another method (not defined, one contractor). Contaminates in the RAP stockpiles are evaluated by two contractors.

RAS Processing

Three contractors indicated that they do not use RAS, and only one contractor rarely uses RAS. However, several of the contractors have placed test sections either for their own research or at the request of their clients. Only two contractors have experimented with using a combination of RAP and RAS, but no additional information was provided.

Based on their limited previous experience, the contractors have used various maximum RAS grinding sizes (i.e., 100% passing):

- 19-mm (¾-in.) sieve (two contractors).
- 12.5-mm (½-in.) sieve (three contractors).
- 9.5-mm (⅜-in.) sieve (two contractors).

Sufficient RAS was processed by one contractor to complete the project prior to the start of construction. Trying to grind RAS in hot, rainy weather caused problems by blinding screens, clumping, and sticking to conveyors. Adding sand to the RAS during or after processing helped keep the RAS from clumping (two contractors) and approximately 1% of the water was used to cool the grinding teeth (one contractor).

RAS stockpiles, either unprocessed or processed, are rarely covered. One contractor noted a time delay because of the approval process required for testing the recovered RAS asphalt and only one contractor commented that the contaminates in the RAS stockpiles were measured.

Asphalt Mixture Production and Placement

Large contractors produce asphalt mixtures in multiple states and have a range of plant types. Each contractor provided information about the plant adjustments and modifications needed to produce high RAP, RAS, and/or a combination of RAP and RAS mixtures for multiple types of plants.

Contractors generally believe their current metering methods and sensors are capable of feeding the appropriate amount of recycled materials into the plant. Any type of recycled material stockpiles can crust, clump, or bridge over the belt weigh scales. One contractor uses in-line crushers to size recycled materials as they are fed into the plant, which helps with breaking up any clumping. Additional cold feed bins help increase the percentage of RAP or the use of RAS in the mixture.

Plant operations occasionally find it necessary to slow the production rates for longer drying times and better mixing when using more than 25% RAP or RAS. Plant temperatures may also have to be raised. Mixtures with more than 25%

RAP may need to limit the silo storage time to prevent the mixture from getting too stiff.

Batch plant (three contractors) adjustments and/or modifications that help improve the amount of recycled material that can be used in the plant include:

- Screw conveyor or belt scale moving recycled materials into the pug mill.
- Additional venting capability on weigh box to accommodate steam produced when cold recycled materials are combined with hot aggregate.
- Plant configuration for adding recycled material bypasses main vibrating screen and drops directly into the No. 1 bin.
- Using a separate unit for drying, proportioning, and feeding recycled materials directly into the pug mill.

Parallel flow drum plant (four contractors) adjustments and/or modifications include:

- High percentages of RAP (>25%), RAS, or combinations of RAP and RAS frequently cause a problem with higher drum exhaust entering the baghouse.
- Changes to the fighting in drum to help with heat transfer, mixing, and retention time in drum.
- Recycled material enters the drum near the center.
- Entry collar moved closer to the discharge end of the drum to accommodate higher percentages of recycled materials.

Counterblow drum plants (five contractors) for which information was provided is either a single drum (one contractor) or a double drum (three contractors). Adjustments and/or modifications include:

- High percentages of RAP (>25%), RAS, or combinations of RAP and RAS tend to cause a problem with higher drum exhaust entering the baghouse.
- Changes to fighting in drum to help with heat transfer, mixing, and retention time in drum.
- Improved heat transfer to dry and heat the increased amount of RAP.
- Have used warm mix asphalt technology to help reduce exhaust gas temperatures.

Mixtures with more than 25% RAP typically flow differently from the haul truck into the paver hopper. One respondent described “differently” as “moves in clumps more than it flows.” Kicker paddles help move the stiffer mixtures under the gear box. With uniformity and density at joints, contractors generally think their current metering methods and sensors are capable of feeding the appropriate amount of recycled materials into the plant. Any type of recycled material stockpiles can crust, clump, or bridge over the belt weigh scales. One contractor uses in-line crushers to size recycled materials as they are fed into the plant, which can also be useful in breaking up any clumping. Additional cold feed bins help increase the percentage of RAP or the use of RAS in the mixture.

Plant operations occasionally slow the production rates for longer drying times and better mixing when using more than 25% RAP or RAS. Plant temperatures may also need to be raised. Mixtures with more than 25% RAP may find it necessary to limit the silo storage time to prevent the mixture from getting too stiff.

Joint density can be more difficult to achieve and visible “lines” in the direction of paving can be more noticeable between screed and extensions. Difficulty in moving in a uniform manner tends to make the mixture more likely to segregate. Additional remarks from the contractors included:

- High RAP mixtures are stiffer and more temperature sensitive.
- RAP asphalt does not transfer or blend; mixtures essentially have less film thickness.

Nuclear density gauges and cores are used by two contractors to monitor mat density and one contractor uses nonnuclear gauges. None of the contractors believe that the recycled material content in the mixture influences any of the gauge readings.

One contractor believes that the recycled material content of the mixture may influence the pavement ride quality, whereas two other contractors do not believe this makes any difference to smoothness measurements.

Key Points for Field Inspectors

Contractors noted that inspectors look for:

- Thermal segregation,
- Coating of the material, and
- Visible contaminates and oversized chunks of RAP.

CASE EXAMPLE NO. 3: CONTRACTOR’S VIEW OF PRODUCING AND PLACING ASPHALT MIXTURES WITH SHINGLES (MISSOURI)

A Missouri contractor presented key issues with designing and producing RAS mixtures for the North Central Asphalt Users and Producers Group (NCAUPG) (Jackson 2012). The major problems identified were:

- Contaminates,
- Maximum RAS size,
- Lift thickness,
- Virgin asphalt content,
- Virgin asphalt PG grade,
- RAS specific gravities, and
- RAS moisture content.

Contaminates do not mix with the other mixture components and result in a nonuniform asphalt mixture. Contaminates can sometimes be identified in the finished pavement surface. RAS mixtures that are placed in lifts that are 25 mm (1 in.) or thinner often show signs of segregation or “shadowing.”

Mixtures with too little virgin asphalt can meet the mix design criteria, but still look “dry.” Insufficient virgin asphalt content mixtures are less durable and exhibit early signs of pavement distresses related to insufficient asphalt film thickness. Mix design calculations for the amount of new (virgin) asphalt depend on a number of other test results, estimates of other properties from historical records (e.g., ignition oven correction factors for problematic aggregate mineralogy), materials suppliers (e.g., virgin asphalt-specific gravities), and estimates of how much of the recycled material asphalt actually contributes to the total asphalt content.

RAS Contaminates

It is important that the preprocessed shingles be as free of contaminates as possible (Figure 31). If the asphalt contractor

Shingles collected in 2003

Shingles collected in 2010

FIGURE 31 Clean supply of RAS is needed prior to processing (*Source*: Jackson 2012).

When deleterious materials (contaminates) are not removed from the RAS supply, they are ground up along with the shingles

FIGURE 32 Deleterious materials, if not removed before grinding, end up in the RAS supply (*Source*: Jackson 2012).

obtained the ground shingles from a recycled material supplier, the supplier needs to have a good QC program in place. If the contaminates are not removed prior to processing, then they are ground up along with the shingles and the resulting processed RAS will contain appreciable amounts of deleterious materials that will not likely meet agency specification requirements (Figure 32).

Any asphalt that can be contributed by the RAS may be overestimated because larger sizes have lower surface areas. This limits the contact area between the RAS asphalt and virgin asphalt and therefore limits the blending of the two asphalts. The end result is an underasphalted mixture that looks dry behind the paver.

Maximum RAS Size

Large particles are difficult to uniformly distribute throughout the mixture, clog up going into the drum (Figure 33), and can be sufficiently large so that they are visible in the mixture behind the paver. A smaller maximum RAS particle size (i.e., a finer grind) helps minimize clumping and improve uniform distribution in the asphalt mixtures. Missouri DOT reduced the maximum size to 9.5 mm (⅜ in.) to achieve better distribution of the RAS in the mixture, more potential for contributing to the total asphalt content, and reduce the chance of larger RAS particles popping up in the finished pavement surface (Figure 34).

Lift Thickness

RAS mixtures tend to cool more quickly than conventional mixtures (less thermal mass). Lifts thicker than 25 mm (1 in.)

FIGURE 33 Clumps of RAS can be difficult to feed through RAP chute (*Source*: Jackson 2012).

do not cool as quickly as thin lifts. Using a material transfer device helps keep the mixture blended (i.e., limits segregation) and slows heat loss because of the mass of material in the surge bin.

Virgin Asphalt Content

The three problems that can lead to calculating an optimum asphalt content during the mix design phase that is too low are described here.

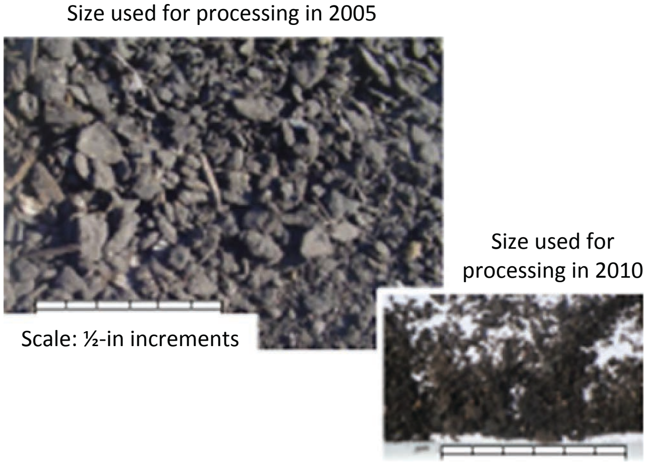


FIGURE 34 Reduced shingle size helps with a more uniform distribution of the RAS in the mixture (*Source*: Jackson 2012).

Trying to Use Too High a Percentage of RAS Contributing to the Total Asphalt Content

If the mixture looks dry coming out of the plant, more virgin asphalt is required and the asphalt availability factors are to be re-evaluated. Mix design worksheets are to include the asphalt availability factor for reducing the RAS asphalt included in the calculated total asphalt content.

Overestimating the Measured RAS Asphalt Content

Measuring the RAS asphalt content requires an understanding of the limitations of the test method used to measure the value. For example, mass loss in an ignition oven needs an ignition oven correction factor for the nonasphalt material that burns off. A lower oven temperature or shorter time is typically used when testing RAS.

Mix Design Calculations for the Optimum Asphalt Content Are Acceptable, But the Mixtures Look Dry When Produced at the Plant

This is a function of the credit given to the RAS asphalt contribution and the percentage of virgin asphalt determined in the mix design calculations. The mixture has to perform in the field and the contractor's crew still needs to get it placed. If it does not look right or is too stiff to place correctly, then the reasonableness of the asphalt correction factor used for the mix design should be assessed. Jackson (2012) suggests an inventory of RAS mix designs with proven success in both placement and performance should be developed.

Missouri DOT changed its specifications in 2012 to address previously identified mix design problems for BP-1, BP-2, BP-3, and bituminous base mixtures. The specification changes include:

- Lowered design air voids to 3.5%.
- Increased requirements for the BP-1 and BP-2 mixtures to 13.5% and 14.0%, respectively.
- Reduced design gyrations from 50 to 35; 35 blow Marshall mix design is still acceptable.

Virgin Asphalt PG Grade

RAS asphalt is very stiff compared with typical paving grade asphalts. RAS asphalt critical upper and lower PG temperatures are significantly higher and do not meet agency specifications. Although the higher upper critical temperature is useful for improving the rut resistance of an asphalt mixture by increasing the mixture stiffness, the mixture may be too stiff to resist traffic-related cracking. The increased lower critical temperature indicates an increased potential for thermal cracking. Also, using RAS with polymer-modified asphalt can also lead to a stiffer, cracking-prone asphalt mixture.

The proper selection of the virgin asphalt PG low temperature helps minimize any increased cracking potential. In Missouri, a PG xx-28 offers better low temperature cracking resistance.

RAS Aggregate Specific Gravity

The RAS aggregate-specific gravity is required for calculating the VMA. More work is necessary to develop procedures and/or practices for determining this RAS material property. Missouri DOT adjusted its volumetric requirements for BP-2 or surface leveling mixtures. The VMA requirements increased from 13% to 14%. A range of air voids from 3.5% to 4.5% requirement was changed to a single air void content of 3.5%. The field tolerance for the asphalt content was reduced from 0.5% to 0.3%.

RAP Moisture Content

Too much moisture in the RAS stockpile can cause the RAS to clump, which interferes with uniform feeding of the material into the plant. Clumps of RAS can clog the RAP chute on a drum mix plant that is also used to add the RAS to the mixture. If the RAS is not fully dried during mixing, then the clumps of RAS do not always fully disperse during mixing. Covering the stockpiles (Figure 35) helps reduce RAS moisture contents and a warm mix asphalt additive with a good surfactant may help disperse clumps during mixing.

FIGURE 35 Cover stockpiles to minimize moisture content (*Source*: Jackson 2012).

The RAS moisture content is to be removed during the dry-mixing phase of asphalt mixture production. This requires the asphalt plant operator to increase the temperature used to superheat the virgin aggregate to remove moisture from the recycled material. The increased plant temperatures also help soften the very stiff RAS asphalt, which improves blending with the virgin asphalt. However, the plant temperatures are to be kept low enough so that the mixture temperature at the point of discharge meets the agency requirements. These maximum temperature requirements can have a pay factor (disincentive, penalty) for too-hot asphalt mixtures. In Missouri, the maximum mixture temperature is 350°F (177°C).

CASE EXAMPLE NO. 4: LOCATING AND USING COUNTY DATABASES FOR COLLECTING HIGH RAP PERFORMANCE DATA (MINNESOTA)

One of the barriers for agencies to increase the percentage of RAP in their mixtures is the lack of performance data. Currently agencies use higher percentages of RAP in asphalt mixtures that are placed in the lower pavement layers. This makes it difficult to directly link the percentage of RAP to individual pavement distresses that are measured on the pavement surface. Information from contractor associations indicate high RAP mixtures are used in surface courses, but not on state agency projects. This case example demonstrates where distress data can be collected for high RAP surface mixtures and used to evaluate pavement performance.

The primary distress of concern for MnDOT is low temperature cracking (Johnson et al. 2013). A search of county road databases was conducted for projects that had been constructed with 30% or more RAP and one of two virgin asphalt grades (PG xx-34 and PG xx-28). MnDOT requested that the Minnesota county engineers provide information about roadways that had been constructed using RAP and could be accessed using the MnDOT pavement management network. The information to access the pavement condition information was:

- County name,
- Highway number,
- Project limits,

TABLE 85
SUMMARY OF DATA COLLECTED FROM COUNTY ENGINEERS

Virgin Asphalt PG	Design Asphalt Content, %	Virgin Asphalt Content, %	% RAP	Age, Years	No. of Projects
58-28	4.8 to 6.3	3.0 to 6.3	0 to 40	1 to 11	22
52-34	5.2 to 6.1	3.0 to 6.1	0 to 40	3 to 11	39
58-34	5.5 to 6.2	4.3 to 6.2	0 to 20	1 to 5	6
64-28	6.2	6.2	0	8	1

Source: Johnson et al. (2013).
Mix design data were used for asphalt content information. Results may change if using production data.
% RAP information includes 37 high-RAP data points (30% or more RAP content).

- Year constructed,
- Design type (wear or nonwear),
- Mix design record,
- Asphalt performance grade,
- Total asphalt content (recycled asphalt plus virgin asphalt), and
- Percentage RAP.

The search of the Minnesota databases provided a collection of project information that was used to link pavement performance to the virgin asphalt grade, design asphalt content, percentage of RAP, age of the roadway, and the number of projects for each group of variables (Table 85). Projects with no RAP content were also identified that were used as control sections for the pavement performance analysis.

The Minnesota County Highway Testing Program was used to further locate specific roadway segment information to access the pavement performance information in the Pavement Management database. This information included county name, highway number, project limits, survey year, distance, transverse crack count, and other observations (not defined). Once this information was assembled, the county highway performance was developed from a combination of video-log reviews and field inspections (Table 86).

The results from this effort produced a good database of high RAP mixtures in wear courses that can be used for continued monitoring of the cracking potential of these mixtures in a cold climate. The analysis of the data allowed MnDOT to identify the percentage of the virgin asphalt in the mixtures as a key factor in the pavement performance. MnDOT specifications now limit the minimum percentage of virgin asphalt in the total asphalt content. In this example, nonstate agency projects were used to provide performance information for adjustments to state agency project specifications.

CASE EXAMPLE NO. 5: INVESTIGATING TRANSFER OF RECYCLED MATERIAL ASPHALT DURING DRY MIXING

Recent research projects have evaluated the amount of recycled material asphalt that can be transferred to the virgin aggregate during the dry mixing time before the virgin asphalt is added. The objectives of these studies were to:

- Calculate an approximate amount of RAP asphalt that is available to blend with the virgin asphalt (Georgia study; Hines 2015).
- Find out how much of the RAP asphalt is blended with the virgin asphalt under normal (i.e., plant) mixing conditions (Tennessee study; Huang et al. 2005).
- Explore how the mixing temperature can soften RAS asphalt so that it can coat the virgin aggregate (Texas study; Zhou et al. 2013).
- Investigate the activation (i.e., transfer) of RAP asphalt to virgin aggregate during dry mixing at a batch plant and compare with the transfer obtained with laboratory (dry) mixing (Minnesota study; Johnson et al. 2013).

Georgia RAP Study

The GDOT RAP transfer study was a part of laboratory studies used to modify GDOT specifications presented in Case Example No. 1 and will only be summarized here for comparison to other recycled material asphalt dry mixing transfer studies.

Light-colored No. 6 stone [25-mm (1-in.) to 4.75-mm (No. 4) sieve sizes] was used so that the finer RAP could be separated from the virgin aggregate after dry mixing. The virgin aggregate was preheated to 400°F (204°C) and RAP was kept at room temperature to simulate the material temperatures as they are added to the asphalt plant. Both materials were added to a preheated laboratory pugmill and dry mixed for 1 minute. After dry mixing, the virgin aggregate was visually separated into one of two groups: uncoated and partially coated. The percentage of the aggregate in each group is measured based on the change in weight (mass) of the virgin aggregate. The results showed that only a limited amount of RAP asphalt was transferred to the virgin aggregate (Figure 36).

Tennessee RAP Study

Researchers evaluated the amount of RAP asphalt that was transferred to virgin aggregate during dry mixing (Huang et al. 2005). Fine RAP [minus 4.75 mm (No. 4)] was dry mixed with various percentages of coarse virgin aggregate (10%, 20%, and 30%). The virgin aggregates were preheated to 374°F (190°C) and the RAP was kept at ambient temperature. The results showed that only about 11% of the RAP asphalt was transferred to the virgin aggregate.

TABLE 86
EXAMPLE OF AVAILABLE PERFORMANCE DATA FOR SURFACE MIXTURES FOR MINNESOTA COUNTY ROADWAYS

Year	Type (lift in.)	PG Grade	Lift Thickness	RAP, %	Total Asphalt Content	Virgin Asphalt Added	No. of Cracks	Length, miles	ABR	Cracks per Mile
PG 52-34 Data (control sections)										
2009	Wear (1.5), 1	52-34	1.5	0	6.1	6.1	80	2.059	1.00	38.9
2009	Wear (1.5), 1	52-34	1.5	0	5.9	5.9	170	4.999	1.00	34.0
2009	Wear (1.5), 1	52-34	1.5	0	6.3	6.3	56	1.120	1.00	50.0
PG 52-34 Data (30% RAP)										
2009	Wear (0.5), 2	52-34	0.5	30	5.4	4.0	1	0.303	0.74	3.3
2009	Wear (0.5), 2	52-34	0.5	30	5.4	4.0	1	0.037	0.74	27.0
2009	Wear (0.5), 2	52-34	0.5	30	5.4	4.0	25	0.848	0.74	29.5
2009	Wear (0.5), 2	52-34	0.5	30	5.4	4.0	14	1.019	0.74	13.7
2009	Wear (0.5), 2	52-34	0.5	30	5.4	4.0	22	0.199	0.74	110.6
2009	Wear (1.5), 1	52-34	1.5	30	5.1	3.8	14	1.019	0.75	13.7
2009	Wear (1.5), 1	52-34	1.5	30	5.1	3.8	3	0.040	0.75	75.0
2009	Wear (1.5), 1	52-34	1.5	30	5.1	3.8	1	0.303	0.75	3.3
2009	Wear (1.5), 1	52-34	1.5	30	5.1	3.8	9	0.381	0.75	23.6
2009	Wear (1.5), 1	52-34	1.5	30	5.1	3.8	1	0.037	0.75	27.0
2009	Wear (1.5), 1	52-34	1.5	30	5.1	3.8	25	0.848	0.75	29.5
2006	Wear (1.5), 1	52-34	1.5	30	5.3	3.6	130	5.100	0.68	25.5
2009	Wear (1.5), 1	52-34	1.5	30	5.3	3.6	1	0.044	0.68	22.7
PG 58-28 Data (control sections)										
1999	Wear (1.5)	58-28	1.5	0	6.1	6.1	410	4.872	1.00	84.2
2003	Wear (1.5)	58-28	1.5	0	6.1	6.1	766	3.196	1.00	239.7
2009	Wear (1.5), 1	58-28	1.5	0	5.8	5.8	14	1.510	1.00	9.3
2007	Wear (1.5), 1	58-28	1.5	0	6.1	6.1	14	1.510	1.00	9.3
PG 58-28 Data (30% and 40% RAP)										
2003	Wear (1.5)	58-28	1.5	30	5.3	3.6	51	1.837	0.68	27.8
2007	Wear (1.5), 1	58-28	1.5	30	5.3	3.6	109	2.727	0.68	40.0
2007	Wear (1.5), 1	58-28	1.5	30	5.3	3.6	88	2.765	0.68	31.8
2007	Wear (1.5), 1	58-28	1.5	30	5.3	3.6	225	8.163	0.68	27.6
2009	Wear (2.5), 2	58-28	2.5	40	5.2	3.0	51	1.837	0.58	27.8
2009	Wear (3.0), 1	58-28	3	40	5.2	3.0	109	2.727	0.58	40.0
2009	Wear (3.0), 3	58-28	3	40	5.2	3.0	88	2.765	0.58	31.8
2005	Wearing (1.5)	58-28	1.5	40	5.2	3.0	225	8.163	0.58	27.6

Source: After Johnson et al. (2013).

FIGURE 36 Appearance of No. 6 limestone after dry mixing with RAP in laboratory pugmill (*Source*: Hines 2015).

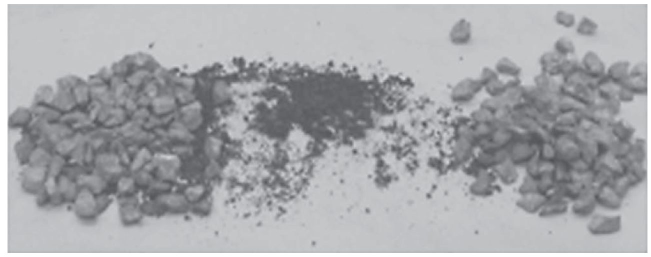


FIGURE 37 Example of RAP asphalt transfer to virgin aggregate after 3 minutes of laboratory mixing at 190°C (*Source*: Huang et al. 2005).

Texas RAS Study

Researchers at the Texas A&M University Texas Transportation Institute in cooperation with TxDOT and FHWA conducted a study to characterize and identify the most effective uses of RAS in asphalt mixtures (Zhou et al. 2013). A component of this research was an evaluation of the plant production temperatures required for the RAS asphalt to transfer to the virgin aggregate during dry mixing. The virgin white limestone aggregate was dry mixed with each of two types of RAS (manufacturer waste and tear-offs) at one of four temperatures [143°C, 149°C, 163°C, and 200°C (290°F, 300°F, 325°F, and 392°F)] using a batching ratio of 80% virgin aggregate to 20% RAS (Figure 37). Mixing of the two materials was accomplished by:

- Screening the virgin aggregate to obtain the material passing the 12.5-mm (½-in.) sieve and retained on the 9.5-mm (⅜-in.) sieve, which was then washed, dried, and heated overnight at mixing at the test temperature.
- Heating the RAS overnight at 60°C (140°F).
- Manually mixing the virgin aggregate and RAS followed by short-term aging of the mixed materials at the test temperature.
- Mixing the short-term aged blend of virgin aggregate and RAS in a bucket mixer for 2 to 3 minutes.
- Short-term aging of the blend again at the test temperature for another 2 hours.
- Sieving the virgin aggregate and RAS blend over a 9.5-mm (⅜-in.) sieve.
- Visually evaluating the virgin aggregate that is retained on the 9.5-mm (⅜-in.) sieve to estimate the percentage of RAS asphalt transfer (Figure 38).

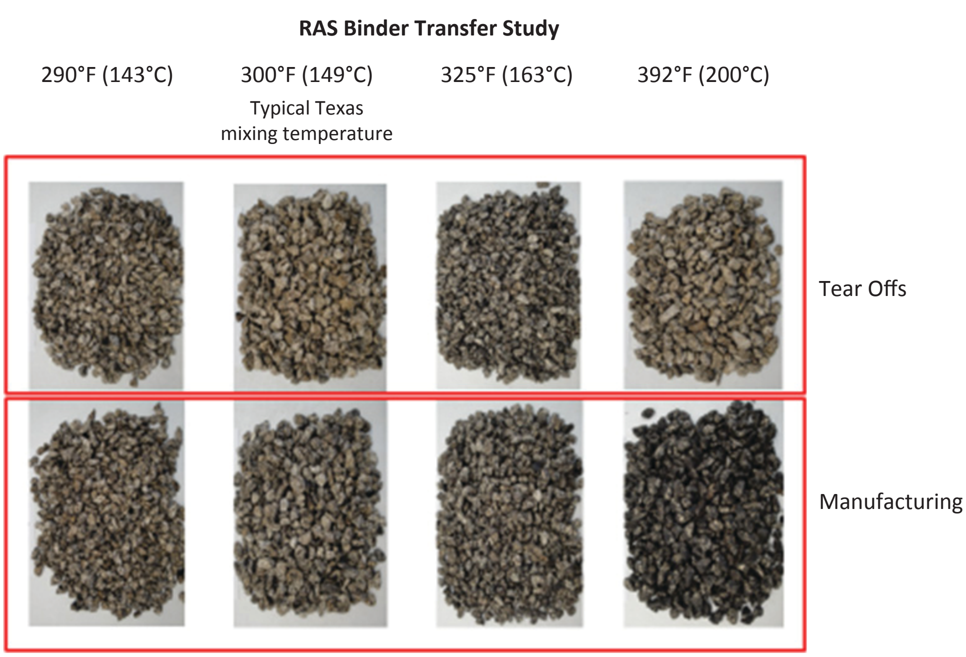


FIGURE 38 RAS asphalt transfer to virgin aggregate over a range of temperatures (*Source*: Zhou et al. 2013).

TABLE 87
VARIABLES FOR DRY MIXING VIRGIN AGGREGATE AND RAP AT THE BATCH PLANT

Run No.	Plant Temp, °F	RAP Content, %	Dwell Time, Seconds	Sample Temp., °F
1	420	10	30	320 (front of haul truck) 344 (back of haul truck)
2	490	24	30	290 to 300
3 (1st half)	400	24	30	230 (front of haul truck)
3 (2nd half)	375	24	30	225 (back of haul truck)

Source: Johnson et al. (2013).

The visual evaluations showed the manufacturer waste RAS transferred more asphalt to the virgin aggregate than did the tear-off RAS and most transfer was obtained at the highest temperature of 200°C (392°F). Although the study showed that RAS asphalt may become sufficiently soft to blend with the virgin asphalt, the high temperature necessary to achieve the best blending (transfer) and the extended time needed for the RAS asphalt to soften enough to transfer were not reasonable conditions for the actual production of asphalt mixtures.

Minnesota RAP Study

MnDOT conducted a study to assess the transfer of the RAP binder during dry mixing using a batch plant and in a laboratory setting. The recycled asphalt transfer was evaluated using a modified AASHTO T195-67 Standard Method of Test for Determining the Degree of Particle Coating of Bituminous–Aggregate Mixtures.

The plant was a three-tiered batch plant equipped with six cold feed bins and one RAP belt feed bin. The mixing unit was a twin pugmill type with at most a 0.75-in. clearance from the walls and timer controls for wet and dry mixing. Plant temperatures and the percentage of RAP added to the pugmill with the virgin aggregate varied (Table 87). The temperature of the aggregate–RAP mixtures was measured at the point of discharge using the integrated plant sensor and a hand-held thermometer. Temperatures were also measured when the materials were loaded into the haul truck. The aggregate–RAP dry-mixed material in the haul trucks was sampled and retained for comparisons of laboratory-produced, dry-mixed materials.

Visual observations of the dry-mixed material sampled from the haul trucks showed:

- More RAP asphalt transfer (Figure 39) was achieved with the higher RAP content (24%) and at higher temperatures.
- RAP asphalt was uniformly transferred to the virgin aggregate at all of the dry-mixing temperatures.
- Recycled asphalt and aggregate fines formed balls in all of the dry-mixed materials (Figure 40).

Four dry-mixed batches were produced in the laboratory using the batch plant temperatures, time allowed for preheating the RAP, and the mixing (dwell) time (Table 88).

Most of the laboratory mixture batches were approximately 2,500 grams and prepared in a bucket mixer. The normal preheating temperature used by MnDOT with the bucket mixer is 290°F (143°C) and the standard mixing time is 10 minutes. The upper temperature for the laboratory study was limited by the practical operating range of the laboratory oven, which was 320°F (160°C). The majority of the laboratory studies used one of two temperatures, four RAP preheating times, and two mixing times in the laboratory pugmill (Table 89). A limited number of larger batches (15,000 grams) was produced at 300°F (149°C) using 23% RAP and 50% RAP.

Once the virgin aggregate and RAP were dry mixed, the material was manually separated into three groups: uncoated, partially coated, and coated (Figure 41). The percentage of material in each group was determined and the results used

Temperatures and % RAP

420°F 10% RAP	490°F 24% RAP	400°F 24% RAP

Samples from haul trucks for Run 1, Run 2, and Run 3

FIGURE 39 RAP asphalt transferred to virgin aggregate after dry mixing for 30 seconds in batch plant (*Source*: Johnson et al. 2013).

FIGURE 40 Balls of asphalt and fines after dry mixing in batch plant (no virgin asphalt) (*Source*: Johnson et al. 2013).

TABLE 88
LABORATORY DRY MIXING STUDY USING BATCH PLANT VARIABLES

Plant Run No.	RAP, %	Aggregate Temperature, °F (°C)	Time Used to Heat RAP, Minutes	Mixing Time, Minutes	Completely Coated Particles, %*	Partially Coated Particles, %*	Uncoated Particles, Particles, %*
1	10%	420 (215)	0.5	0.5	67	33	0
2	23%	490 (254)	0.5	0.5	48	52	0
2, washed	23%	490 (254)	0.5	0.5	53	47	0
3	23%	400 (204)	0.5	0.5	44	56	0

Source: Johnson et al. (2013).
*Estimated values from source figure.

TABLE 89
TEMPERATURE AND TIMES USED IN MINNESOTA LABORATORY STUDY

Temperature, °F (°C)	Time Used to Heat RAP, Minutes	Mixing Time, Minutes
290 (143)	1, 90	10
	180	1, 5
320 (160)	10, 20, 180, 190	10

Source: After Johnson et al. (2013).

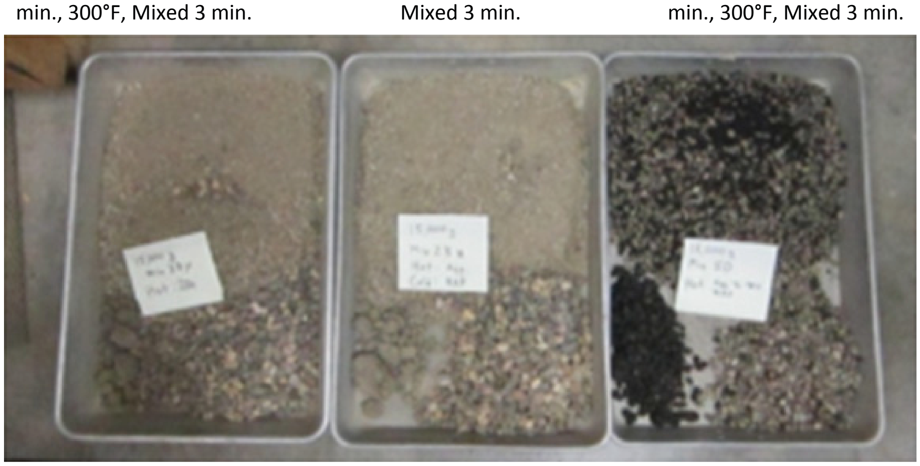


FIGURE 41 RAP transfer to virgin aggregate in laboratory pugmill (*Source*: Johnson et al. 2013).

to calculate the percentage of uncoated, partially coated, and completely coated particles.

Visual evaluations showed:

- Duplication of dry mixing at the batch plant was not replicated in the laboratory.
- No clumping or balling of fines was seen in the laboratory-prepared, dry-mixed batches.
- Partially coated aggregates in the laboratory study showed signs of abrasion with little transfer of RAP asphalt.
- Large percentages of uncoated particles were seen in all laboratory dry-mixed blends.
- The 10% RAP mixtures tended to have higher percentages of partially coated, but nearly 0% of fully coated particles (laboratory study; smaller batches).

The percentages of the three levels of particle coating were used for various statistical analyses (Pearson's correlation coefficients, multi-variable regression equations) to determine which variables had the most significant impact on the transfer of the RAP asphalt to the virgin aggregate by dry mixing in the laboratory. The statistical analysis showed the:

- Complete coating model—Most strongly dependent on the total aggregate retained on the ⅜-in. (9.5-mm) sieve and the percentage RAP.
- Partial coating model—Most strongly dependent on the total aggregate retained on the ⅜-in. (9.5-mm) sieve, mixing time, and the heating time of the RAP.
- No coating model—Most strongly dependent on the percentage RAP and the temperature of the aggregate.

The key finding was that a significant amount of recycled material asphalt is uniformly transferred to the virgin aggregate during dry mixing at the asphalt plant; however, this transfer cannot be replicated with dry mixing in the laboratory.

CHAPTER SIX

CONCLUSIONS

Information reported in the literature review and from each of the state agency surveys is summarized in this chapter. The information is organized by the key topics that include general availability of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) materials, recycled material properties and testing, selection of the virgin asphalt grade, recycled material mix design practices and procedures, perceived and reported pavement performance of recycled material asphalt mixtures, asphalt plant practices including RAP and RAS stockpiling, asphalt plant operations and equipment, transfer and placement of recycled material mixtures, and information for field inspectors.

Suggestions for future work are included at the end of this chapter.

AVAILABILITY OF RECYCLED MATERIALS

- Recycled materials are generally available:
  - Statewide for RAP, with some excess of RAP in cities or urban areas, or in one or more districts within a state.
    - △ Some agencies note that they would prefer to have more access to RAP supplies.
  - Only in limited areas for RAS.
    - △ Supplies, usually in excess of demand, are available in urban or limited locations within a state.

RECYCLED MATERIAL PROPERTIES AND TESTING

- Recycled material asphalt content is most frequently determined using the ignition oven method, although the majority of these agencies also use either centrifuge and/or reflux solvent extraction. Trichloroethylene solvent is typically used, although some agencies use *n*-propyl bromide.
  - Eight agencies specifically noted that they no longer use any solvent extraction in their laboratories.
  - Ignition oven correction factors are essential for mixtures with aggregates that degrade during testing or nonasphalt material components that burn off (i.e., RAS backing) and can be determined by:
    - △ Comparing results from the ignition oven to those from solvent extraction.
    - △ Preparing mixtures with known material contents and material properties and evaluating changes after ignition oven testing.
- Recycled material aggregate gradations are the most frequently determined aggregate property.
  - Other consensus and/or source properties are infrequently measured during mix design.
  - Quality control/quality assurance consensus and/or source property testing during production, if done at all, is usually conducted using the total asphalt mixture sample.
- Recycled material asphalt is recovered with either the Abson or Rotavapor recovery method and the properties are determined for the high temperature shear modulus, G^*, using the dynamic shear rheometer, and low temperature stiffness and m-value with the bending beam rheometer are determined.
  - However, agencies may determine these properties for any *one* of the following:
    - △ As-recovered asphalt;
    - △ After recovery and rolling thin film oven (RTFO); and
    - △ After recovery, RTFO, and pressure aging vessel aging.
  - Recycled material asphalt increases both the upper and lower critical performance grade (PG) temperatures; however, the upper critical temperature increases about twice as much as the lower critical temperature.
    - △ A strong linear correlation exists between the change in the upper critical temperature and the change in the lower critical temperature.
- Specific gravities of the recycled material asphalt and aggregates are typically:
  - Assumed for the asphalt to be between 1.01 and 1.035, or the virgin asphalt-specific gravity is used for the recycled material asphalt.
  - Calculated for the aggregate using measured theoretical maximum specific gravity of the recycled material.

SELECTING VIRGIN ASPHALT GRADE

- Selecting the virgin asphalt grade is accomplished by:
  - Extracting, recovering, and testing the recycled material asphalt so that properties for blending charts can be measured.
  - Limiting the percentage of recycled material so that blending charts are not needed.
  - Development of agency-specific virgin asphalt selection tables that define the required virgin asphalt for a full range of recycled material percentages.
  - Using agency-defined asphalt grade “bumping.”

RECYCLED MATERIAL MIX DESIGNS

- For adjusting calculations of the total asphalt content.
  - Review appropriate asphalt availability factors for both RAP and RAS.
  - Consider limiting the contribution of the recycled material asphalt to the total asphalt content by using a:
    - △ Minimum asphalt binder ratio for ensuring that a minimum percentage of virgin asphalt is included in the mixture.
    - △ Maximum recycled binder ratio to limit the amount of recycled material asphalt that is included in the mixture.
- Review the batch weight (masses) used to prepare materials for the mix design sample preparation.
  - The mass of the asphalt content in the recycled material that does not contribute to the asphalt content [i.e., 1 – (asphalt availability factor)] is considered with the mass of the recycled material aggregate.
- Consider checking compaction levels and increasing asphalt content:
  - Overcompaction of mix design samples can lead to the selection of an asphalt content that is too low. Higher RAP and/or RAS mixtures tend to look dry.
    - △ Some agencies found that dry looking mixtures have difficulties during construction and show early signs of pavement distress(es).
      - ○ These agencies reduced compaction levels and/or increased the percentage of virgin asphalt to improve constructability and performance.
- Sizing (sieving) recycled materials for batching may or may not be done. The recycled materials can be batched:
  - As-received without any additional fractionating into individual sieve sizes.
    - △ Definitions of coarse and fine fractions depend on how the contractor separates the recycled materials for stockpiling.
  - Sieved into individual sieve sizes for better control of gradations for mix design purposes for:
    - △ Only the coarse fraction,
    - △ Both the coarse and fine fraction, or
    - △ Only the fine fraction (typically for dust control).
- Drying recycled materials for batching is agency-specific.
  - Materials may be dried:
    Not at all;
    - △ Under a fan, in a conventional oven, or in a microwave oven;
    - △ From 1 h to overnight;
    - △ At temperatures from room temperature to 300°F (149°C); and
    - △ There is no standardized definition for "dry."
  - If defined as "dried to a constant mass," the times between subsequent weighing vary or are not well-defined, and the acceptable change in mass ranges from 0.05% to 0.5% of mass.
- Preheating temperatures for virgin aggregate and recycled materials before mixing are variable and agency-specific, however:
  - Most agencies use higher preheating temperatures for virgin aggregates.
  - Agencies may or may not preheat recycled materials.
    - △ If preheated, the temperature used is generally lower than that used for virgin aggregate.
  - Some agencies combine the virgin aggregate and recycled materials and heat together (i.e., use the same temperature for virgin and recycled materials).
- Order of addition of materials to the mixing bowl is agency-specific; however, there are general trends that indicate the:
  - Virgin aggregates are added first, followed by the recycled materials (if not batched with the virgin aggregate), and may or may not be briefly dry mixed, before the addition of the virgin asphalt.
  - Mixing is complete based on a visually uniform coating of materials, although some agencies use set mixing times that typically range from 1 to 10 minutes depending on the type of laboratory mixer.
- Short-term aging of the mixture most frequently uses 2 hours; however, other times used for short-term aging included 1.5 h, 4 h, and 15 h ± 3 h.
  - Short-term aging temperatures of 140°F to 335°F (60°C to 168°C).
- N_{Design} for compacting mix design samples range from a single value of 65 for almost all of the agency's dense mixtures to multiple numbers of gyrations based on traffic levels or positions in the pavement structure.
  - Marshall mix designs are still used with:
    - △ 70 blows per side for base course mixtures.
    - △ 35 blows per side for stone matrix asphalt mixtures.
    - △ 6-in. (150-mm) sized molds for large stone mixtures by one agency.
- Mixture volumetric calculations require accurate information about the asphalt content, asphalt specific gravity, and aggregate specific gravities and asphalt absorption capacities for each source of aggregates in the mixture.
- Air void, voids in mineral aggregates, and dust–to-asphalt ratio specification requirements can be more difficult to meet when:
  - The percentage of RAP increases above 25%.
    - △ These volumetric properties can be difficult to achieve, although less frequently, even when the percentage of RAP is less than 25%.
  - The mixture contains RAS (any percentage).
  - The mixture contains a combination of RAP and RAS (any percentage).
- Performance-based mixture property testing by agencies:
  - Most frequently evaluate the rutting resistance using either the Asphalt Pavement Analyzer or Hamburg loaded wheel devices.
  - Less frequently evaluates the mixture stiffness using either resilient modulus or dynamic modulus testing and usually for research purposes rather than as a part of the mix design process.
  - Occasionally use either the disc-shaped compact tension or semi-circular bend to evaluate low tem-

perature, reflective, and/or top-down fatigue cracking potential primarily for research purposes.
    - △ One agency allows the contractor to use a higher percentage of RAP based on acceptable semi-circular bend test results.

PAVEMENT PERFORMANCE OF RECYCLED MATERIAL MIXTURES

- Agency perceptions of pavement performance for mixtures with increases in the RAP percentage or when RAS and/or a combination of RAP and RAS is used are that:
  - Rutting decreases with the use of either RAP or RAS, or increasing percentages of RAP, because these materials increase the mixture stiffness.
  - Cracking potential, either traffic-related or reflective, may increase, depending on where the mixture is located in the pavement structure.
  - Thermal cracking potential increases because of the increasing mixture stiffness.
  - Moisture sensitivity may, or may not, increase.
- Literature review pavement performance for recycled material asphalt mixtures found that:
  - Pavement performance can be related to the percentage of virgin asphalt in the mixtures.
  - Decreasing the upper performance-grade temperature reduced the traffic-related cracking without significantly influencing the rutting resistance.
  - After between 5 and 10 years of performance, mixture with up to 30% RAP had similar performance compared with control sections almost half of the time (Long Term Pavement Performance SPS-5 sections).
    - △ When there was a difference in the pavement performance, the control sections (no RAP) performed better than the RAP sections approximately 30% of the time.
    - △ RAP sections performed better than the control sections approximately 20% of the time.
  - Projects that documented construction difficulties also showed early signs of pavement distresses.
  - At least 3 to 5 years of performance data are required to see a significant difference between mixtures with and without recycled materials.
  - Pavements constructed over, or next to portland cement jointed or cracked concrete pavements are typically prone to reflective cracking.
  - Additional sources of pavement performance data may be obtained by retrieving data for nonagency projects.

ASPHALT PLANT PRACTICES AND OPERATIONS

Recycled Materials Stockpiling and Processing

- RAP stockpiling and processing use:
  - Terminology, when used by agencies, to identify and differentiate between different types of RAP stockpiles is agency-specific. There are no standardized terms at this time.
  - RAP scalping screen sizes that are typically:
    - △ 19 mm (¾ in.)
    - △ 12.5 mm (½ in.)
    - △ 9⁄16 in.
  - RAP screen sizes for fractionating into coarse RAP (retained on) and fine RAP (100% passing) include:
    - △ 4.75-mm (No. 4)
    - △ 9.5-mm (⅜ in.)
    - △ 2.36-mm (No. 8).
  - Separate stockpiles are used for RAP obtained with micro-milling machines because of the high fines (dust) content.
  - Separate stockpiles can be continuously built, maintained, and tested (quality control)
    - △ Variability is minimized when RAP is separated by mixture types with similar mixture characteristics (i.e., gradations, asphalt content).
  - Additional quality control testing is important to manage RAP asphalt and RAP gradation variability when using a higher percentage of RAP.
  - Contaminates in the RAP stockpiles are to be evaluated.
- Examples of contaminates in RAP include crack filling materials, geotextile fabrics, vegetation growing on stockpiles, or trash.
- RAS stockpiling and processing:
  - Remove contaminates from the RAS supply prior to processing.
    - △ Any contaminates left in the RAS are ground up along with the RAS.
  - Keep separate stockpiles for manufacturer waste RAS and tear-off RAS.
  - Maximum size no larger than 100% passing the ⅜-in. (9.5-mm) sieve.
    - △ Some agencies use smaller sieve sizes for 100% passing.
  - Add sand to RAS to help prevent clumping.
  - Avoid grinding in hot, wet weather.
- RAP and RAS quality control/quality assurance testing at the asphalt plant and during production and placement:
  - Asphalt content is frequently measured using the ignition oven.
  - Washed aggregate gradations are usually evaluated using aggregates retained after ignition oven testing.
  - Aggregate specific gravities are most frequently calculated using theoretical maximum specific gravity measurements for a RAP stockpile sample.
  - Aggregate consensus and source properties, when measured, typically use samples of asphalt mixtures from haul truck or behind the paver for testing.

Asphalt Plant Operations and Equipment

- Feeding recycled materials into asphalt plant can be:
  - More difficult because of crusting on the stockpile surface, clumping, and bridging of materials over weigh belt scales.

        - △ In-line crushing and/or sizing systems breaks up, or scalps off, oversized materials.
    - – Easier when using additional cold feed bins.
        - △ Bins with nonstick surfaces, steeper side slopes, or a self-relieving bottom help material that tends to stick and clump in the bin flow out more uniformly.
    - – Metered into the plant more uniformly when:
        - △ Separate weigh belt scales are provided for each type of recycled material.
- At times, asphalt plants slow production rates and increase plant temperatures for better drying when using more than 25% RAP.
- Asphalt plant modifications that help use or increase the percentage of recycled materials include:
    - – Addition of a separate system to any type of plant for drying and preheating recycled materials.
    - – Batch plants:
        - △ Consider screw conveyor or belt scale to move recycled materials into pugmill.
        - △ Add venting capability to remove steam produced by moisture in the recycled materials.
        - △ Bypass main vibrating screen and add recycled materials directly into the No. 1 bin.
        - △ Add a separate unit for drying, proportioning, and feeding recycled materials directly into pugmill.
    - – Parallel flow drum mix plant:
        - △ Review flighting inside drum to improve heat transfer, mixing, and retention time in drum.
        - △ Adjust location of RAP collar on drum.
    - – Counterflow drum mix plant:
        - △ Change flighting inside drum to improve heat transfer, mixing, and retention time in drum.

Recycled Material Placement

- Recycled material transfer to paver and placement:
    - – Stiffer recycled material mixtures:
        - △ Tend to move from haul truck into the paver hopper in large clumps rather than flowing like virgin asphalt mixtures.
        - △ Kicker paddles to move stiffer material under gear box at center of screed.
        - △ Inclined to crust because of cooling in the paver wings or on the top of windrows.
        - △ Can make it more difficult to achieve the required density at joints.
        - △ May be more temperature sensitive.

INFORMATION FOR FIELD INSPECTOR

- Field inspectors check the following for:
    - – RAP mixtures:
        - △ Ensure contractor starts with clean pavement surface before milling.
        - △ Watch milling operations.
        - △ Monitor quality (i.e., variability) of RAP stockpiles.
        - △ Ensure consistency of mixture during production.
        - △ Monitor temperature segregate, clumping, mixture temperature.
        - △ Evaluate mat behind paver for evidence of foreign materials (e.g., crack filling material), clumps of asphalt and fines, texture (e.g., segregation, pulling, tearing, and streaking).
        - △ Closely monitor joint density and mat density (i.e., air voids).
    - – RAS mixtures:
        - △ Ensure that the uniform amount of RAS, at the correct percentage, is fed into the plant.
        - △ Evaluate mat behind the paver for evidence of foreign materials, visible RAS, clumps, and dust balls.
        - △ Check and/or adjust asphalt content if RAS mixture looks dry.
        - △ Closely monitor mat density (i.e., air voids).

SUGGESTIONS FOR FUTURE RESEARCH

- Evaluate the recycled material asphalt transfer to virgin aggregate under actual plant conditions and develop laboratory mixing methods that replicate the transfer that occurs during production.
- Improve laboratory procedures for drying, preparing, preheating, mixing, and compacting mixtures to more closely replicate what happens during production at the asphalt plant.
- Investigate the potential for high RAP, RAS, and RAP/RAS combination mixtures to be effectively recycled during future maintenance and reconstruction projects. Information is essential as to how these mixtures can influence milling operations, affect the choice(s) of pavement preservation surface treatments, and address any issues with in-place recycling methods (hot in-place, cold in-place, and full-depth reclamation).
- Develop information about the expected service life of high RAP, RAS, and RAP/RAS combination mixtures that can be used for estimating life-cycle costs. The development of expected service life could be aided by a significantly large performance database that represents performance for a wide range of environmental and traffic conditions.
- Investigate the impact of minimum and maximum silo storage times on recycled material asphalt mixtures.
- Investigate the impact of reduced temperatures when using warm mix asphalt technologies on the percentage of recycled material asphalt that contributes to the total asphalt content.

ABBREVIATIONS AND ACRONYMS

ABR	Asphalt binder ratio
AFT	Adjusted film thickness
ALDOT	Alabama Department of Transportation
ALF	Accelerated loading facility
AMPT	Asphalt mixture performance tester
APA	Asphalt Pavement Analyzer
ASTM	American Society for Testing and Materials
BBR	Bending beam rheometer
CAC	Corrected asphalt content
CAST	Coaxial shear test
COAC	Corrected optimum asphalt content
COV	Coefficient of variation
DCT	Disc-shaped compact tension
DOT	Department of Transportation
DSR	Dynamic shear rheometer
E*	Elastic modulus
ER	Energy ratio
G*	Shear modulus
LTPP	Long-Term Pavement Performance
MnROAD	Minnesota Road Research facility on interstate highway (Minnesota DOT)
MSCR	Multiple stress creep recovery
NAPA	National Asphalt Pavement Association
NCAC	Non-credited asphalt content
NCAT	National Center for Asphalt Technology
NCAUPG	North Central Asphalt User Producer Group
NESHAP	National Emissions Standards for Hazardous Air Pollutants
nPB	*n*-propyl bromide
OAC	Optimum asphalt content
ODOT	Oregon Department of Transportation
OGFC	Open-graded friction course
OOAC	Original optimum asphalt content
PAV	Pressure aging vessel
PG	Performance grade
PLM	Polarized light microscopy
QC	Quality control
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingles
RBR	Recycled binder ratio
RTFO	Rolling thin film oven
SA	Surface area
SAF	Shingle availability factor
SCB	Semi-circular bend
SMA	Stone matrix asphalt
SOM	Subcommittee on Materials
TAC	Total asphalt content
TCE	Trichloroethylene
TFHRC	Turner–Fairbanks Highway Research Center
TSR	Tensile strength ratio
TSRST	Thermal stress restrained specimen test
TTI	Texas Transportation Institutes
TxDOT	Texas Department of Transportation
VFA	Voids filled with asphalt
VFD	Variable frequency drive
VMA	Voids in mineral aggregate
VTS	Viscosity temperature susceptibility
WMA	Warm mix asphalt

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APPENDIX A

State Materials Engineer Survey

NCHRP 46-05—RAP and RAS—Materials Engineers

Introduction

Standard laboratory practices and procedures have been developed and/or adapted in order to handle, mix, and test these mixtures within each agency. The main focus of this survey is to document mix design and testing experiences of those folks by actually working with high RAP, RAS, or RAP/RAS combinations in the laboratory.

Survey organization:

- Determining the asphalt content
- Determining the binder grade
- Determining aggregate properties
- Preparing materials for mixing and compaction
- Compaction and long-term aging
- Volumetric testing
- Durability and performance testing

Please provide your contact information.

First Name: ____
Last Name: ____
Agency: ____
State: ____
E-mail Address: ____
Phone Number: ____

Determining the Asphalt Content

1. For the purposes of mix designs, indicate which "philosophy" is used to establish the contribution of the recycled material asphalt.

Material	100% Available for Mix	0% ("Black Rock")	Agency-Assumed Percentage of the Total Recycled Asphalt Content
25% or Less RAP			
More than 25% RAP			
RAS, manufacturer waste			
RAS, tear-offs			
RAS, any combination			
RAP and RAS combination			

Comments:

2. Indicate which equation(s) is (are) used to calculate the total binder content of the mixture and/or limit the percent of recycled asphalt in the total asphalt content.
   2.a. We use the sum of the new asphalt and recycled asphalt material content:
   Total asphalt content = (RAP asphalt content %) (% of RAP in mixture) + (RAS asphalt content %) (% of RAS in mixture) + (new asphalt content %)
   ( ) Yes
   ( ) No
   Comments:

2.b. We use the asphalt binder ratio (ABR) equation:

ABR = (New asphalt %) / (Total asphalt %)

( ) Yes
( ) No
We use a minimum ABR value of: ______________________________

2.c. We use the recycled binder ratio (RBR)

RBR = (Recycled binder content %) / (Total binder content %)

( ) Yes
( ) No
We use a maximum RBR value of: _________________________

2.d. If you do not use either ABR or RBR, briefly describe how the total binder content is calculated.

2.e. Is a reduction factor applied to recycled asphalt content? That is, do you correct for the likelihood that not all of the recycled binder content is actually incorporated into the total effective asphalt content of the mixture?

3. Preparation of recycled material before testing

Materials	Is the recycled material dried prior to using to prepare mix design samples?		What method of drying is used?		What temperature is used for drying?		How long is sample dried?	
	Yes	No	Under fan at room temperature	Oven	^{o}C	^{o}F	Hours, max.	Until constant mass
RAP								
RAS								

3.a. If material is dried to a constant mass, indicate the variables used to determined "constant mass."
3.b. Maximum percent change between consecutive weighings:
3.c. Time between consecutive weighings:
3.d. Drying method (e.g., oven, counter under fan, etc.):
3.e. At what temperature:

4. The asphalt content of the recycled materials is determined for: (Check all that apply.)
( ) RAP (not fractionated)
( ) Coarse RAP fraction
( ) Fine RAP fraction
( ) RAS
( ) RAP and RAS combined prior to testing
( ) Other (please explain in comment box below):
Comments:

5. If you separate RAP into coarse and fine fractions for testing, please indicate which sieve size is used for "retained on" / "percent passing."
( ) 4.75-mm (No. 4)
( ) 2.36-mm (No. 8)

6. If you use solvent extraction to determine the recycled binder content, indicate which method(s) is (are) used.

Materials	Solvent Extraction Centrifuge	Solvent Extraction Reflux	Solvent Extraction Vacuum	Extraction Vessel, AASHTO	Soaking (non-standard option)
RAP, unfractionated					
Coarse RAP fraction					
Fine RAP fraction					
RAS					
RAP and RAS combination					

Comments:

6.a. And indicate which solvent(s) is (are) used.

Materials	Trichloroethylene (TCE)	n-Propyl Bromide (nPB)	Toluene	Toluene and Ethanol Blend
RAP				
Coarse RAP fraction				
Fine RAP fraction				
RAS				
RAP and RAS combination				

Comments:

7. Indicate when the ignition oven is used and how materials other than asphalt and aggregate are considered.
   7.a. Do you use the ignition oven to determine the recycled material asphalt content?

Materials	Yes	No	Sometimes, depending on aggregate type
RAP, unfractionated			
Coarse RAP fraction			
Fine RAP fraction			
RAS			
RAP and RAS combination			

7.b. If a correction factor is used, what value(s) do you use?

7.c. If you use the ignition oven method for testing shingles, how do you correct for burning off any paper (backing, roofing felt, etc.) products?

Comments:

Determining the Binder Grade

8. Indicate if you recover the recycled material binder for any of the following. (Check all that apply.)

Materials	5% or Less Recycled Material	15% or Less Recycled Material	25% or Less Recycled Material	More than 25% Recycled Material
RAP, unfractionated				
Coarse RAP fraction				
Fine RAP fraction				
RAS				
RAP and RAS combination				

9. Which recovery methods(s) do you use? (Check all that apply.)
   ( ) Abson (AASHTO T170)
   ( ) Rotavapor (ASTM D5404)
   ( ) Combination Extraction / Recovery (AASHTO T319)

Comments:

10. ***Virgin PG grade adjustment based on various percentages of individual recycled materials.*** Please indicate how your agency determines the virgin PG grade used in mixtures with recycled materials by:

Materials	Upper PG Temperature			Lower PG Temperature		
	Bump one grade lower	Bump two grades lower	Determine true grade with testing	Bump one grade lower	Bump two grades lower	Determine true grade with testing
15% or less RAP						
25% or less RAP						
15%< RAP						
More than 25% RAP						
More than 50% RAP						
5% or less RAS						
More than 5% RAS						
RAP and RAS combination						

Comments:

11. Indicate which binder tests you use to determine the ***true (continuous) recycled binder grade***.
( ) As-recovered high binder temperature (DSR, AASHTO T315)
( ) Condition recovered binder in rolling thin film oven (AASHTO T240)
( ) RTFOT high binder temperature (DSR, AASHTO T315)
( ) RTFOT intermediate binder temperature (DSR, AASHTO T315)
( ) RTFOT low binder temperature for m-value (Bending beam rheometer, AASHTO T313)
( ) RTFOT low binder temperature for stiffness (Bending beam rheometer, AASHTO T313)
( ) RTFOT + PAV intermediate binder temperature (DSR, AASHTO T315)
( ) RTFOT + PAV low binder temperature for stiffness (Bending beam rheometer, AASHTO T313)
( ) RTFOT + PAV low binder temperature for m-value (Bending beam rheometer, AASHTO T313)

Comments:

12. Indicate ***which approach*** is used to ensure the blended binder meets the required PG grade.
( ) Establish (select) percent of RAP to be used, then determine the virgin asphalt PG grade needed
( ) Choose virgin asphalt PG to be used, then determine the percent of recycled material
( ) Use softening or rejuvenator additive to soften the recycled material binder, then proceed with determining the virgin asphalt PG

Comments:

13. If you use softening and/or rejuvenating additive (e.g., flux oil, proprietary product, etc.) to modify stiffer and aged recycled binder indicate the product(s) you use.

Determining Aggregate Properties

14. This question collects information about sieving (fractionating) dry materials (aggregates, RAP, shingles) for batching mix design samples.
14.a. Does the percent or type of recycled materials used in the mixture change how you fractionate, or don't fractionate, the materials in the laboratory?

Materials	Yes	No	Sometimes
25% or less RAP			
More than 25% RAP			
Shingles, manufacturer waste			
Shingles, tear-offs			
Shingles, combination			
RAP and RAS			

Comments:

14.b. Indicate which individual sizes and/or percent retained on a given sieve size are used for batching *coarse particles* when using various percentages and types of materials in the mixture.

Materials	25-mm (1-in)	12.5-mm (1/2-in)	9.5-mm (3/8-in)	4.75-mm (No. 4)	2.36-mm (No. 8)	Retained on 4.75-mm (No. 4)	Retained on 2.36-mm (No. 8)
Aggregates							
25% or less RAP							
25% or more RAP							
Shingles, manufacturer waste							
Shingles, tear-offs							
Shingles, combination							
RAP and RAS							

Comments:

14.c. Indicate what individual sizes and/or percent passing a given sieve are used for batching ***fine particles*** when using various percentages and types of materials.

Materials	Passing 4.75-mm (No. 4)	Passing 2.36-mm (No. 8)	1.18-mm (No. 16)	0.6-mm (No. 30)	0.30-mm (No. 50)	0.15-mm (No. 100)	0.075-mm (No. 200)
Aggregates							
25% or more RAP							
More than 25% RAP							
Shingles, manufacturer waste							
Shingles, tear-offs							
Shingles, combination							
RAP and RAS							

Comments:

15. Indicate when the aggregate properties of the ***individual recycled materials*** need to be determined.
( ) 15% or less RAP
( ) 25% or less RAP
( ) More than 25% RAP
( ) RAS, manufactured waste
( ) RAS, tear-offs
( ) RAS, combination
( ) RAP and RAS combination
( ) We test aggregates for the mixture (after solvent extraction or ignition oven) rather than individual recycled aggregate properties

Comments:

16. Indicate which test methods are used to determine the specific gravities of the recycled materials aggregate. ***For clarification:*** When the maximum specific gravity is measured, the effective specific gravity (G_{se}) is calculated, then used to estimate the bulk specific gravity (G_{sb}).

Materials	Bulk Specific Gravity (AASHTO T166) after Solvent Extraction	Bulk Specific Gravity (AASHTO T166) after Ignition Oven	We Estimate Bulk Specific Gravity Based on Experience	Theoretical Maximum Specific Gravity (AASHTO T209)
RAP, unfractionated				
Coarse RAP fraction				
Fine RAP fraction				
RAS				
RAP and RAS combination				

17. Indicate the ***aggregate specification*** tests used to determine the ***recycled material aggregate properties.*** (Check all that apply.)

Materials	Flat and Elongated (ASTM D4791)	Fractured Faces (ASTM D5821)	Fine Aggregate Angularity (AASHTO T304)	Sand Equivalent (AASHTO T176)	Minus 0.075-mm (No. 200) by Washing	Gradation (sieve analysis)
RAP, after solvent extraction						
RAP, after ignition oven						
RAS, after solvent extraction						
RAS, after ignition oven						
Only determine properties for entire mixture with the recycled materials after either solvent or ignition oven testing.						

Comments:

18. Mix design calculations require a number of individual material properties. If your agency assumes, rather than measures, any of the properties in the table below, please enter the typical estimated values in the appropriate text boxes.

Materials	Binder absorbed by recycled material aggregates	Recycled material asphalt specific gravity	Virgin asphalt specific gravity
RAP, unfractionated			
Coarse RAP fraction			
Fine RAP fraction			
RAS			
RAP and RAS combination			

19. Indicate the ***aggregate source*** property tests that are conducted on the ***recycled material aggregates.*** (Check all that apply.)

Material	LA Abrasion (toughness)	Micro-Deval (toughness)	Sodium Sulfate Soundness	Magnesium Sulfate Soundness	Assume Source Properties Are OK if RAP Came from State Highway Project
RAP, after solvent extraction					
RAP, after ignition oven					
RAS, after solvent extraction					
RAS, after ignition oven					
We determine properties for entire mixture after either solvent or ignition oven testing.					

Comments:

Preparing Materials for Mixing and Compaction

20. This question collects information on how materials are heated for mixing.
    20.a. Indicate how the materials are, or are not, combined for heating.

Materials	Heated Separately	Combined and Heated Together
Aggregate and RAP		
Aggregate and RAS		
RAP Fractions		
RAS Fractions		
RAS with Sand (to avoid clumping)		
RAP and RAS		

Comments:

20.b. Indicate how you know the material is at required temperature for mixing.

Materials	Based on Time in Oven	Temperature Probe in the Material While it Is in the Oven	Temperature Measured Immediately After Removing from Oven
Aggregates			
RAP			
RAS			
Combined RAP and RAS			

20.c. Indicate the maximum allowable heating time for each material before mixing.
Aggregate:
RAP:
RAS:
Combination of RAP and RAS:

20.d. Indicate the units preferred for temperature choices:
( ) Celsius
( ) Fahrenheit

20.e. Indicate the temperature used to heat each material before mixing.
Aggregates
RAP
RAS
Combined RAP and RAS

20.f. Indicate the temperature used to heat materials before mixing.
Aggregates
RAP
RAS
Combined RAP and RAS

22. In what order are materials added to the mixing bowl, and how long is the material mixed before adding additional materials?

Materials Added to Bowl							Mixing Time		
Aggregates, all Fraction (sieve sizes)	RAP, Coarse	RAP, Fine	RAS	Asphalt	Rejuve nator	Asphalt and rejuvenator preblended prior to start of mixture design sample prep	1 min.	2 min.	visual inspection of uniformity

23. Indicate the time and temperature used for short-term aging of the loose mixture.

Materials	Short-Term Aging Time, Hours	Temperature	Units	
			Celsius	Fahrenheit
Mix with RAP				
Mix with RAS				
Mix with RAP and RAS				

Compaction and Long-term Aging

24. Enter the ***typical*** number of gyration(s) (N_{design}) which is (are) used to compact recycled material mixtures in the text boxes.

Materials	Wear Course Dense Mix	Binder Course	Base Course	SMA	Pervious/Permeable Mixtures
25% or less RAP mixtures					
More than 25% RAP mixtures					
RAS mixtures					
RAP and RAS combination mixtures					

Comments:

25. If used, enter time and temperatures used for long-term aging of the compacted samples.

Materials	Long-Term Aging Time, Hours	Temperature	Units	
			Celsius	Fahrenheit
25% or less RAP samples				
More than 25% RAP samples				
RAS mixtures				
RAP and RAS combination mixtures				

Comments:

Volumetric Testing

26. Indicate if it more difficult to meet volumetric requirements when mixtures contain various amounts and types of recycled materials.

Materials	Check the box if it is more difficult to obtain acceptable properties when compared with similar mixtures without any recycled material content.			
	25% or less RAP	More than 25% RAP	RAS mixtures	RAP and RAS combination mixtures
Air Voids, %				
VMA, %				
VFA, %				
Dust to Asphalt Ratio				

Comments:

Durability and Performance Based Testing

27. ***Rutting:*** If you evaluate the rutting potential of mixes in your lab, please indicate which method(s) you use (Choose all that apply.)

	Used routinely for our mix designs	Use when approving changes in materials during construction	Use for research studies
Asphalt Pavement Analyzer (APA)			
Hamburg Rut Tester			
Wet Rut Testing to Determine Stripping Inflection Point			
Asphalt Mixture Performance Test (AMPT)			
Dynamic Modulus			
Flow Number			
Flow Time			

Comments:

28. ***Mix Stiffness:*** If you evaluate mixture stiffness in your lab, please indicate which method(s) you use (Choose all that apply.)

Testing	Used routinely for our mix designs	Use when approving changes in materials during construction	Use for research studies
Resilient Modulus at a single temperature			
Resilient Modulus at several temperatures			
Dynamic Modulus at a single temperature			
Dynamic Modulus over a range of temperatures to develop a master curve			

Comments:

29. ***Cracking (Non-Thermal):*** If you evaluate cracking potential of mixtures in your lab, please indicate which method(s) you use. (Choose all that apply.)

Testing	Used routinely for our mix designs	Use when approving changes in materials during construction	Use for research studies
Fatigue cracking, bending beam (AASHTO T321)			
Overlay tester			
Disc-Shaped Compact (DCT) Tension Test (ASTM D7313)			
Semi Circular Bend (SCB) Test			

Comments:

30. ***Thermal Cracking:*** If you evaluate the thermal cracking potential of mixtures in your lab, please indicate which method(s) you use (Choose all that apply.)

Testing	Used routinely for our mix designs	Use when approving changes in materials during construction	Use for research studies
Indirect Tensile Strength (AASHTO T322)			
Semi-Circular Bend (SCB) Test			
Disc-Shaped Compact (DCT) Tension Test (ASTM D7313)			

Comments:

31. ***All Cracking Testing:*** If you evaluate any type of cracking potential, what temperature or temperatures do you use?

Testing	High Temperature (summer temperatures)	Intermediate (around ambient)	Low Temperature (winter temperatures)
Bending Beam Fatigue			
Overlay Tester			
Disc-Shaped Compact (DCT) Tension Test (ASTM D7313)			
Semi Circular Bend (SCB) Test			

Comments:

32. ***Rutting Potential:*** Based on your experience, indicate your level of agreement with the following statements.

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Rutting potential is increased with increasing percentages of recycled RAP					
Rutting potential is increased with increasing percentages of recycled shingles					
Rutting potential is increased with a combination of RAP and RAS					

Comments:

33. ***Cracking Potential (Non-Thermal Cracking) Potential:*** Based on your experience, indicate your level of agreement with the following statements.

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Cracking potential is increased with increasing percentages of recycled RAP					
Cracking potential is increased with increasing percentages of recycled shingles					
Cracking potential is increased with a combination of RAP and RAS					

Comments:

34. ***Thermal Cracking Potential:*** Based on your experience, indicate your level of agreement with the following statements.

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Thermal cracking potential is increased with increasing percentages of recycled RAP					
Thermal cracking potential is increased with increasing percentages of recycled shingles					
Thermal cracking potential is increased with a combination of RAP and RAS					

Comments:

35. ***Mix Durability Potential:*** Moisture sensitivity (TSR) and indirect tensile strength: Based on your experience, indicate your level of agreement with the following statements.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Moisture sensitivity **is increased with increasing percentages of recycled RAP**					
Moisture sensitivity **is increased with increasing percentages of recycled shingles**					
Moisture sensitivity **is increased with a combination of RAP and RAS**					
Indirect tensile strength **is increased with increasing percentages of recycled RAP**					
Indirect tensile strength **is increased with increasing percentages of recycled shingles**					
Indirect tensile strength **is increased with a combination of RAP and RAS**					

APPENDIX B

State Construction Engineer Survey

NCHRP 46-05 RAP and RAS—Construction Engineers

Introduction

This survey is collecting information about individual recycled material properties, processes, and practices. ***The focus is on asphalt mixtures with >25% RAP mixtures, recycled asphalt shingles (RAS) mixtures, and mixtures with a combination of RAP and RAS.***

The survey is organized as follows:

- Recycled Materials Supply (availability)
- Recycled Materials Stockpiling and Processing Practices
- Testing for Asphalt Content and Aggregate Properties
- Asphalt Plant Operations
- Paving and Finished Mat Practice
- Identification of projects for case studies (looking for successes AND failures).

Respondent Information

First Name: ____
Last Name: ____
Agency: ____
State: ____
E-mail Address: ____
Phone Number: ____

1. ***Supply and Demand:*** Which types and percentages of recycled materials used in asphalt mixtures can be limited by the available supplies. Also, an overabundance of recycled material(s) can result in various supply-demand competitions. Please indicate if recycled materials supplies are available statewide, on a district by district basis, or only through a few local material recyclers. Also, indicate if there is any excess of recycled materials (i.e., more supply than demand).

Material	RAP	Shingles (RAS)
Recycled material is available:		
There is an excess of the recycle material:		

Comments:

RAP Stockpiling and Processing Practices

2. Select the "retained on" sieve size used to define the coarse RAP fraction.
( ) +9.5-mm (⅜-in.)
( ) +4.75-mm (No. 4)
( ) +2.36-mm (No. 8)

3. Indicate how frequently each of the following *RAP* processing and stockpiling practices are used in your state.

Topic	Frequently	Occasionally	Rarely	Not Applicable	Don't Know
RAP is processed at the asphalt plant site					
RAP is processed elsewhere by asphalt mix contractor and stockpiled at plant					
RAP is processed by third party and delivered to asphalt mix contractor					
Large quantity of RAP collected, then processed					
Coarse RAP stockpile is fractionated					
Fine RAP stockpile is fractionated					
Asphalt mix contractor required to have sufficient processed RAP material stockpiled at the beginning of the construction project					
Weather impacts RAP crushing and sizing operations (e.g., clumping, blinding screens, etc.)					
We have time limitations between RAP processing and using					
Sand is added during processing or after processing to prevent clumping					
Unprocessed stockpiles are covered					
Stockpiles are stored in covered areas only covered after processing					

Comments:

3.a. Indicate which sieve sizes are used to fractionate RAP. (*Check all that apply. If the sizes you use are not listed, you can add the sizes in the "other" boxes at the bottom of the list or in the comment box.*)
( ) 19.0-mm to 4.75-mm (¾-in. to No. 4)
( ) 12.5-mm to 9.5-mm (½-in. to ⅜-in.)
( ) 12.5-mm to 6.4-mm (½-in. to 1/4-in.)
( ) 9.5-mm to 4.75-mm (⅜-in. to No. 4)
( ) 9.5-mm to 2.36-mm (⅜-in. to No. 8)
( ) Other: ______________________________
( ) Other: ______________________________
Comments:

3.b. Does hot and/or wet weather affect RAP crushing and screening (e.g., build up in feeder or crushers, blind screens, stick to conveyor belts)?

3.c. What are the time constraints between processing the RAP and using it in asphalt mixture?

4. Do your current processing and stockpiling practices need to be adjusted or changed so that higher percentages of RAP can be used? If yes, please indicate what changes are needed in the comment box below.
( ) Yes
( ) No

Comment

Shingles (RAS) Stockpiling and Processing Practices

5. Select the maximum ***shingle*** (***RAS***) particle size allowed.
( ) 12.5-mm (½-in.)
( ) 9.5-mm (⅜-in.)
( ) 4.75-mm (No. 4)
( ) 2.36-mm (No. 8)
( ) Other:

6. Indicate how frequently each of the following *shingles* (*RAS)* processing and stockpiling practices are used in your state.

Topic	Frequently	Occasionally	Rarely	Not Applicable	Don't Know
RAS is processed at the asphalt plant site					
RAS is processed elsewhere by asphalt mix contractor and stockpiled at plant					
Manufacturing waste and tear offs are kept separate					
RAS is processed by third party and delivered to asphalt mix contractor					
Large quantity of RAS collected, then processed					
Asphalt mix contractor required to have sufficient processed RAS material stockpiled at the beginning of the construction project					
Weather impacts RAS crushing and sizing operations (e.g., clumping, blinding screens, etc.)					
We have time limitations between RAS processing and using					
Sand is added during processing or after processing to prevent clumping					
Unprocessed stockpiles are covered					
Stockpiles are stored in covered areas only covered after processing					

Comments:

6.a. Does hot and/or wet weather affect shingles (RAS) crushing and screening (e.g., build up in feeder or crushers, blind screens, stick to conveyor belts)?

6.b. What are the time constraints between processing the shingles (RAS) and using it in asphalt mixture?

7. Do your current processing and stockpiling practices need to be adjusted or changed so that RAS or combinations of RAP/RAS can be more widely used? If yes, please indicate what changes are needed in the comment box below.
( ) Yes
( ) No

Comments:

Additional Contacts with Experience

8. We would like to collect specific information on plant and paving modifications which may be needed to work with high RAP mixtures, shingles, and/or a combination of RAP/RAS. Please provide contractor contact information below. The *contractor's experience does not have to be on state projects.*

Contractor with experience using > 25% RAP (company, name, phone, and/or e-mail).

Contractor with experience using shingles RAS (company, name, phone, and/or e-mail).

Contractor with experience using a combination of RAP and RAS (company, name, phone, and/or e-mail).

QC/QA Testing and Assumptions

9. Indicate what tests or assumptions are used to determine asphalt content, aggregate properties, and other material or mixture properties are determined. (Check all that apply.)

Testing	RAP	Shingles (RAS)	Recycled Material Properties Certified by Supplier	Recycled Material Properties Estimated	Asphalt Mix with Recycled Materials Is Tested
Bulk specific gravity					
Theoretical maximum specific gravity (i.e., Rice method; AASHTO T209)					
Moisture content					
Contaminates					
Ignition oven asphalt content					
Ignition oven gradation					
Solvent extraction asphalt content					
Solvent extraction gradation					
Flat and elongated aggregate properties from recycled materials					
Fine aggregate angularity of aggregates from recycled materials					

Comments:

9.a. What test method is used for determining recycled material or mixture with recycled material specific gravity?

9.b. Briefly describe how moisture content is determined. That is, how dried (microwave, oven, air dry, rapid drying technology), temperature, definition used to determine "dry" or the maximum allowable moisture content.

9.c. What contaminates are assessed? How is the presence of contaminates determined (e.g., visual observation, testing, etc.)?

9.d. What extraction method (e.g., centrifuge, reflux, vacuum) and solvent is used?

Asphalt Plant Operations

10. Indicate if any of the following are seen or adjustments are needed when using *higher than* typical RAP% mixtures, RAS mixtures, or a combination of RAP/RAS mixtures on asphalt plant operations. (Check all that apply.)

Topics	> 25% RAP%	Shingles (RAS)	Combination of RAP/RAS	No Difference from Conventional Mixtures	Don't Know
Recycled material stockpile crusting, clumping, and bridging of materials influence handling and feeding into plant					
Additional cold feed bins are used to meet the required recycled material gradation					
Recycled materials screened and sized as it is fed into asphalt plant					
Separate dryer drum used to dry recycled materials					
Difficult to obtain uniform feed of recycled materials					
Adjustments of either metering methods or sensors are needed to properly measure small percentages of recycled materials					
In-line crushing and sizing is used (i.e., recycled material is processed as it is added to the plant)					
Point of introduction of the recycled material into the plant needs to be changed (e.g., RAP collar relocated closer to the drum discharge point or the recycled material fed directly into pugmill at batch plant)					
Production rates need to be slowed (e.g., extra drying time needed)					
Plant temperatures need to be LOWERED when using recycled materials					
Plant temperatures need to be RAISED when using recycled materials					
MINIMUM silo storage times are needed					
MAXIMUM silo storage times are needed					
Difficult to obtain mixture uniformity					
Mixes with recycled material content tend to segregate more frequently during load out					

Comments:

10.a. What can be done to minimize non-uniformity of recycled materials as they are added to the plant?

10.b. What are the plant temperature constraints?

10.c. What are the time constraints on silo storage time(s)?

Paving Operations

11. When placing asphalt mixtures with ***more than 25% RAP***, how frequently each of the following is observed.

Topic	Always	Often	Sometimes	Rarely	Never	Don't Know
Stiffer mixtures flow differently from end dump haul truck to paver hopper						
Crusting of mixtures when deposited in windrows can be a problem (e.g., clumps deposited into hopper)						
Mix in paver wings more likely to build up and form crust on top						
Visible "lines" in the direction of paving more noticeable between screed and extension						
Uniformity and density at the joint is more difficult to obtain						
Hand work is more difficult						
Mixtures are more likely to segregate						

12. When placing asphalt mixtures with shingles (RAS), how frequently each of the following is observed.

Topic	Always	Often	Sometimes	Rarely	Never	Don't Know
Stiffer mixtures flow differently from end dump haul truck to paver hopper						
Crusting of mixtures when deposited in windrows can be a problem (e.g., clumps deposited into hopper)						
Mix in paver wings more likely to build up and form crust on top						
Visible "lines" in the direction of paving more noticeable between screed and extension						
Uniformity and density at the joint is more difficult to obtain						
Hand work more difficult						
Mixtures are more likely to segregate						

13. When placing asphalt mixtures with a combination of RAP and shingles (RAS), how frequently each of the following is observed.

Topic	Always	Often	Sometimes	Rarely	Never	Don't Know
Stiffer mixtures flow differently from end dump haul truck to paver hopper						
Crusting of mixtures when deposited in windrows can be a problem (e.g., clumps deposited into hopper)						
Mix in paver wings more likely to build up and form crust on top						
Visible "lines" in the direction of paving more noticeable between screed and extension						
Uniformity and density at the joint is more difficult to obtain						
Hand work more difficult						
Mixtures are more likely to segregate						

13.a. What word or words would you use to describe the flow of mixture from haul truck to hopper as "different"?

13.b. What problem(s) with the finished mat is (are) associated with crusting of the windrow?

14. Determining finished mat properties.

    Number of gyrations used to prepare samples for lab density testing: _

    14.a. Density testing of the finished mat:
    ( ) Nuclear density gauge
    ( ) Non-nuclear gauge
    ( ) Cores

    14.b. Do any of the recycled materials seem to influence the non-destructive test results?
    ( ) Yes
    ( ) No
    ( ) Maybe

    Comments:

    14.c. If smoothness is a pay item, do the recycled materials make it more difficult to meet the requirements or to obtain incentives?
    ( ) Yes
    ( ) No
    ( ) Maybe

    Comments:

    14.d. Check the box if it is more difficult to obtain acceptable properties (within specification limits) when compared with similar mixtures without any recycled material content.

Volumetric Property	25% or More RAP	Shingles (RAS)	RAP and RAS Combination Mixtures
Air Voids, %			
VMA. %			
VFA, %			
Dust to Asphalt Ratio			

    Comments:

15. What do field inspectors need to look for when evaluating mixtures with high recycled RAP content, RAS, or combinations of RAP and RAS?

16. Do you have a project that you would like to have considered for a case study? The project can be one which worked well, was a disaster (major learning lessons), or anywhere in between. If so, please provide contact information (name, project name/location, email, phone). Any projects identified as “not successful” will be diplomatically and generically framed to provide information on lessons learned.

APPENDIX C

Responding Agencies

Alabama Department of Transportation	Nebraska Department of Roads
Alaska Department of Transportation and Public Facilities	Nevada Department of Transportation
Arkansas State Highway and Transportation Department	New Hampshire Department of Transportation
California Department of Transportation	New Jersey Department of Transportation
Colorado Department of Transportation	New Mexico Department of Transportation
Connecticut Department of Transportation	New York State Department of Transportation
Delaware Department of Transportation	North Carolina Department of Transportation
District of Columbia Department of Transportation	Ohio Department of Transportation
Florida Department of Transportation	Oklahoma Department of Transportation
Idaho Transportation Department	Oregon Department of Transportation
Illinois Department of Transportation	Rhode Island Department of Transportation
Indiana Department of Transportation	South Carolina Department of Transportation
Iowa Department of Transportation	South Dakota Department of Transportation
Kansas Department of Transportation	Tennessee Department of Transportation
Kentucky Transportation Cabinet	Texas Department of Transportation
Louisiana Department of Transportation and Development	Utah Department of Transportation
Maine Department of Transportation	Virginia Department of Transportation
Maryland Department of Transportation	Washington State Department of Transportation
Massachusetts Department of Transportation	West Virginia Department of Transportation
Michigan Department of Transportation	Wisconsin Department of Transportation
Minnesota Department of Transportation	Wyoming Department of Transportation
Mississippi Department of Transportation	
Missouri Department of Transportation	
Montana Department of Transportation	

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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