Special Report 213

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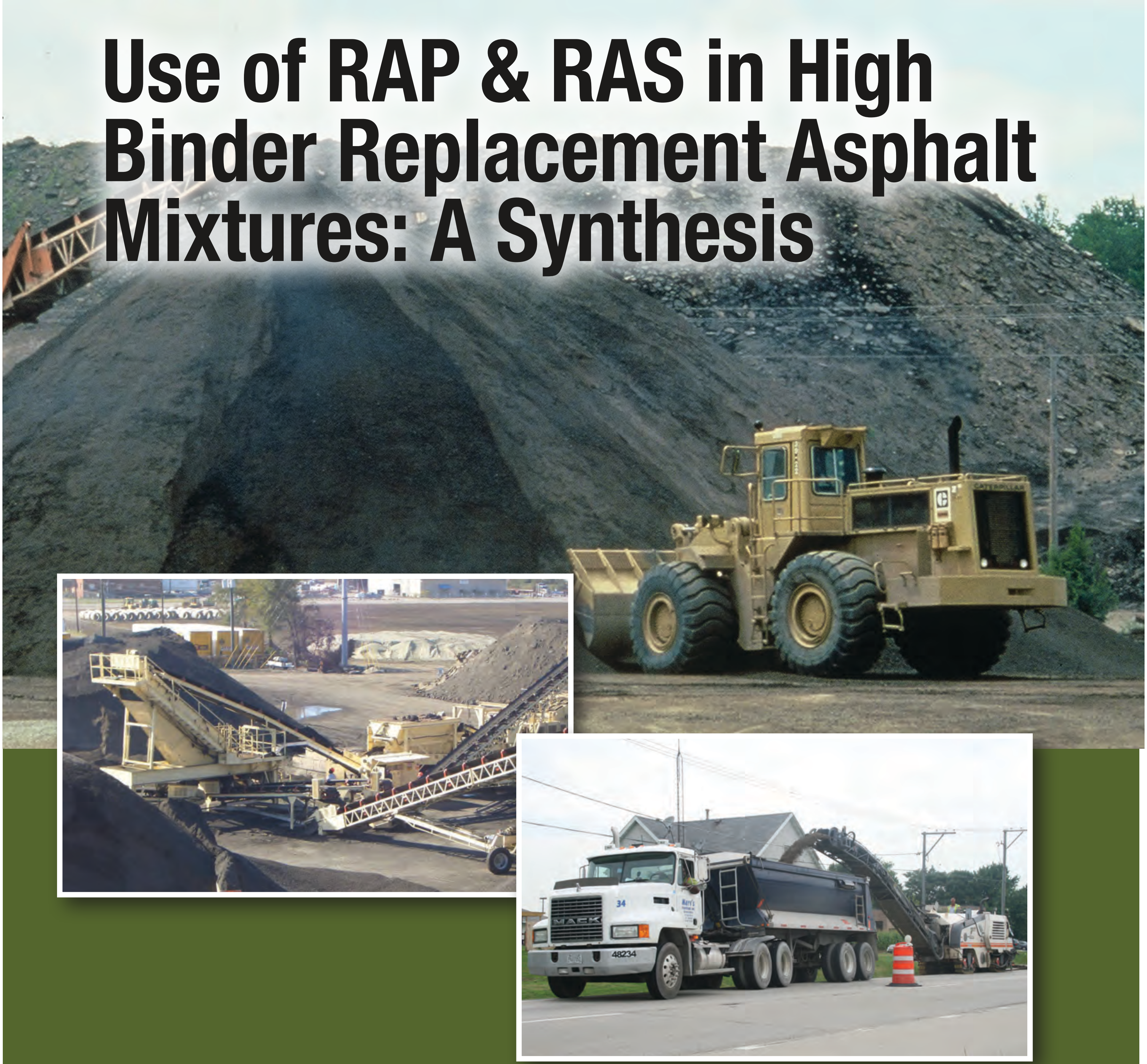
Use of RAP & RAS in High Binder Replacement Asphalt Mixtures: A Synthesis



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Use of RAP & RAS in High Binder Replacement Asphalt Mixtures: A Synthesis

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Notice

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CONTENTS

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ACM	Asbestos-containing material
APA	Asphalt Pavement Analyzer
CO_2eq	Carbon dioxide equivalent
DC(T)	Disk-shaped compact tension test
E*	Dynamic modulus
EIO-LCA	Economic input-output life-cycle assessment
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
HMA	Hot-mix asphalt
HWTT	Hamburg wheel tracking test
IDT	Indirect tensile test
IDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
LTPP	Long-Term Pavement Performance Program
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MWAS	Manufactured Waste Asphalt Shingles
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal maximum aggregate size
OAC	Optimum asphalt content
OT	Texas overlay tester
PCAS	Post-consumer asphalt shingles
RAP	Reclaimed asphalt pavement
SCB	Semi-circular bend test
SMA	Stone-matrix asphalt
SSCHT	Simple shear constant height test
TSR	Tensile strength ratio
TSRST	Thermal stress restrained specimen test
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
VMA	Voids in mineral aggregate
WMA	Warm-mix asphalt

ES

Executive Summary

Reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) are readily available commodities that agencies and contractors can use to reduce the consumption of natural resources, improve their environmental position, and reduce the construction costs of the nation's pavements. The practice of using RAP and RAS with new asphalt binder and aggregate to create new asphalt pavement mixtures has become an everyday practice in the United States.

The use of RAP and RAS provides the following advantages:

1. Reduced cost in the production of asphalt mixtures due to binder and aggregate replacement.
2. Environmental benefits from the conservation of virgin binder and aggregates, including consideration of resource extraction, transportation, and processing.
3. Reduction in the cost of material disposal and a diversion of waste material from landfills.
4. Reduction in the production of greenhouse gases and other emissions.
5. Improved resistance to permanent deformation due to the utilization of harder binders.

Recycling of asphalt pavements began in earnest in the 1970s with the 1973 Arab Oil Embargo and the associated dramatic rise in crude oil prices and drop in asphalt supply levels. At that time, contractors and agencies examined mixtures with very high RAP contents (up to 80%), but the equipment of the time was not suited to producing such high RAP mixtures without generating excess emissions. As oil prices fell, RAP contents decreased to around 20%, and this trend lasted through the development and implementation of Superpave. During the 1980s and 1990s, researchers began to investigate the use of waste roofing shingles in asphalt mixtures. In the mid- to late-2000s the price of crude oil once again increased rapidly, and interest renewed in increasing the amount of binder replacement achievable through the use of RAP and RAS. For economic and environmental reasons, this interest continues into the present.

This synthesis provides a current state-of-the-practice for the use of RAP and RAS in asphalt mixtures produced in a central plant using either hot or warm processes. Specifically, it addresses the use of high-binder replacement mixes, which is typically defined as mixtures with more than 25% RAP content or more than 30% total binder replacement. In addition to mixture design and plant production practices, economic and environmental benefits of the use of RAP and RAS are discussed in detail, along with pavement design and pavement performance information.

Without a doubt, the use of RAP and RAS will leave an important legacy for future generations and sets an environmental benchmark for the country. RAP and RAS usage reduces the amount of aggregate and asphalt binder consumed by the construction industry. From estimates of the asphalt binder and aggregate available, the potential for replacing 6.0 million tons of asphalt binder and nearly 81.1 million tons of aggregate on a yearly basis is possible when recycling RAP and RAS. As shown in Figure ES-1, the total amount of asphalt and aggregate available on an annual basis can result in

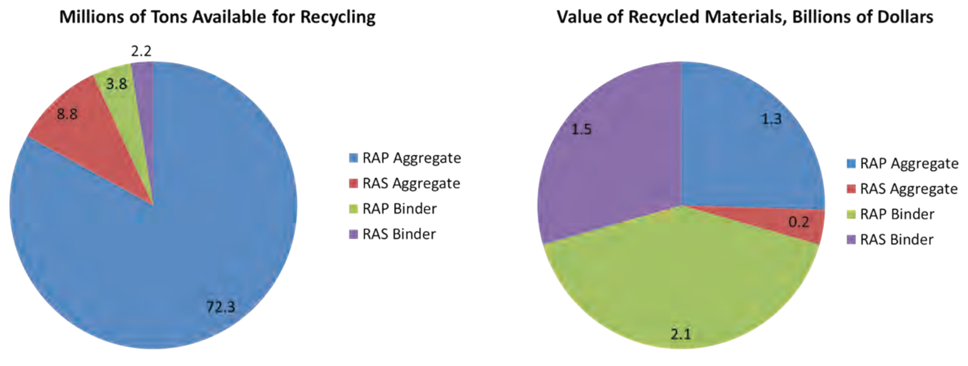


Figure ES-1. Total Materials Available from RAP and RAS and Their Value.

a $5.1 billion savings with 70% of that savings embodied in the binder. The amount of binder conserved in a typical asphalt mixture for various levels of RAP, manufactured waste asphalt shingles (MWAS), and post-consumer asphalt shingles (PCAS) are shown in Figure ES-2. The diversion of RAP and RAS from landfills is estimated to save up to 34% of landfill space in the U.S.

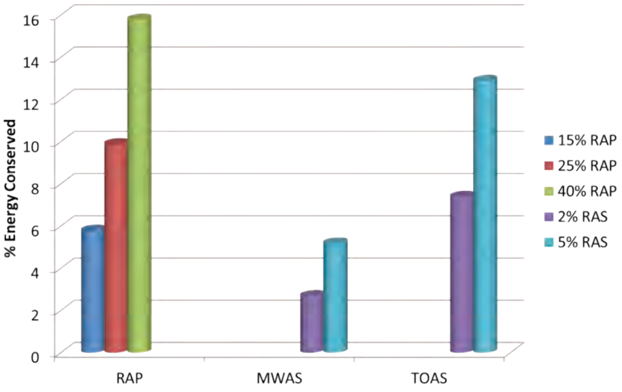


Figure ES-2. Amount of Asphalt Binder Conserved in a Typical Mixture for Various Levels of RAP and RAS (Robinette & Epps, 2010).

Furthermore, it has been estimated that using RAP and RAS will reduce asphalt mixture production and placement energy by up to approximately 15% while reducing greenhouse gas emissions by up to 10 to 20%. These savings result from reduced raw material production for aggregate and asphalt, as well as reduced transportation of raw materials. The% energy savings for using RAP and RAS are illustrated in Figure ES-3. Emissions reduction in terms of carbon dioxide equivalents (CO_2eq) from using RAP and RAS vary between 2 and 16%, depending upon the material and amount used. These reductions are shown in Figure ES-4 (Robinette & Epps, 2010). These environmental benefits can be achieved on a first-cost basis as shown and with life-cycle cost savings.

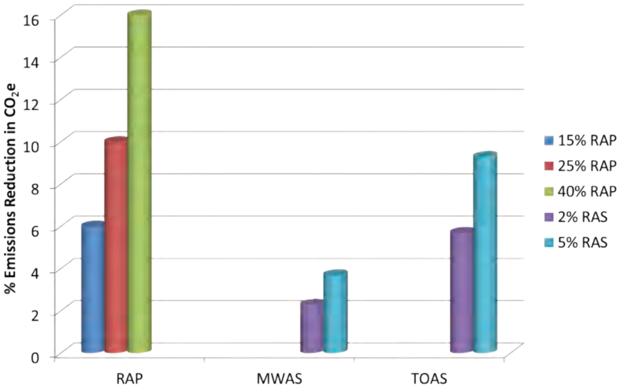


Figure ES-3. Energy Savings for a Typical Mixture at Various Levels of RAP and RAS (Robinette & Epps, 2010).

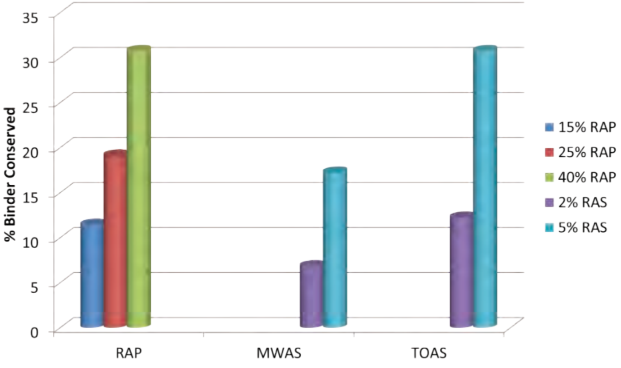


Figure ES-4. Possible Reduction in Emissions with Various RAP and RAS Contents (Robinette & Epps, 2010).

The use of RAP and RAS in asphalt paving mixtures is one of the few "green" activities that have been proven to provide significant environmental benefits while reducing costs.

Initial cost savings, through binder and aggregate replacement, is one of the most important advantages provided by RAP and RAS. The amount of savings depends upon the amount of binder and aggregate replacement that may be expected versus the cost of procurement, handling, and processing, as shown in Table ES-1.

Zhou et al. (2013b) indicates cost savings of the order of 2 to 5% at 5% RAS content. Other studies indicate a savings of the order of 10% compared to virgin asphalt paving mixtures. Brock (2008) projected a cost savings in excess of 16% when 20% RAP was used in mixtures and more than 40% savings when 50% RAP was used. NCAT (Willis et al., 2012) evaluated potential savings of using different amounts and stiffness of virgin binders used in mixtures with 25% RAP and 50% RAP. They concluded that the cost savings for 25% RAP varied from about 14 to 20%, and for 50% RAP it ranged from 29 to 35% over a mix with virgin binder only.

The design and mechanical behavior of mixtures containing RAP and RAS reveal that there are numerous issues in using the customary volumetric criteria as the only approach to determining the composition of mixtures. For instance, there is uncertainty concerning the amount of blending between RAP or RAS binders and virgin binders.

While some states require using a softer grade of virgin binder with certain levels of binder replacement, there is no assurance that it is necessary to use a softer binder unless some sort of performance testing appropriate to the mixture's intended use is employed.

Additionally, determination of voids in mineral aggregate (VMA), one of the more critical mixture volumetric parameters, is uncertain due to the difficulty of quantifying the specific gravity of RAP and RAS aggregates. A balanced approach to determining the optimum composition of mixtures is proposed in which performance testing for rutting and cracking replaces some of the volumetric criteria traditionally used.

The following laboratory performance characteristics can be deduced from the literature cited in terms of binder replacement from RAP or RAS:

1. At lower levels of binder replacement, combined binder grading tends to remain at or near the level of the virgin binder, but at higher levels of binder replacement the combined binder grading increases both the high- and low-temperature grades.
2. The stiffness of mixtures increases with binder replacement, more so at higher temperatures than at lower temperatures.
3. Rutting resistance improves at all levels of binder replacement.
4. Cracking resistance generally lowers with increasing RAP and RAS content, but this is not universally true. However, observed cracking has been at acceptable levels.
5. The use of softer binder grades and rejuvenators has been shown to improve cracking resistance for high recycled material content mixtures.
6. Moisture sensitivity of mixtures is not generally affected by the use of RAP and RAS.

Pavement design practices need to reflect the characteristics of high binder replacement mixtures and optimize their use in providing the load bearing and durability characteristics desired for performance.

Proper handling and processing of RAP and RAS are keys to producing mixtures that will perform well in the pavement. Avoiding contamination of the recycled materials with other debris, such as unwanted construction waste and vegetation, will help preserve the materials' integrity throughout processing. For PCAS, it is important that proper removal of paper, nails, and any other roofing contamination take place. Crushing and fractionation of RAP offers greater flexibility in the amount of RAP used in mixtures with different nominal maximum aggregate size (NMAS). Proper stockpiling techniques minimize the amount of moisture in the materials, improve consistency (gradation and asphalt binder content), and ensure proper blending of materials from different sources.

Numerous projects or test sections with high binder replacement have been constructed and monitored over the past several decades. Overall, the RAP/RAS test sections have demonstrated similar field performance to virgin mixture sections. Good performance with high RAP/RAS mixtures has been reported in projects with a wide range of climate and traffic conditions. Although the RAP/RAS mixtures did have more cracking, the extent of cracking, in most cases, was considered acceptable.

Table ES-1. Potential Cost Savings with RAP and RAS.

Reference	Material	Cost Savings
Zhou et al. (2013b)	5% RAS	2–5%
Brock (2008)	20% RAP 50% RAP	>16% >40%
NCAT (Willis et al., 2012)*	25% RAP 50% RAP	14–20% 29–35%

* Used different amounts and stiffness of virgin binders used in mixtures.

In addition, two important observations were made based on the performance of all field test sections. First, the use of a softer virgin binder does improve the durability and cracking resistance of RAP/RAS asphalt mixtures. Second, high RAP/RAS mixtures can be designed to have better performance than virgin mixtures when a proper mix design approach (such as the balanced mix design method) is employed.

The use of RAP and RAS in asphalt mixtures must continue if the efficiency, cost effectiveness, environmental benefits, and high performance of the U.S. system of pavements are to be maintained for future generations. Technology has been developed that allows for tailoring high binder replacement asphalt mixtures for their intended use in pavement structures. Mix design and performance testing procedures are available to appropriately evaluate the use of RAP and RAS in mixtures to maximize their potential while delivering the desired performance.

1

Introduction

Background

Since the 1970s the asphalt paving industry has embraced the concept of reusing materials in pavements and has developed and promoted innovations to maximize the amount of recycling in pavements. Since that time, it is safe to say that more than a billion tons of asphalt-bearing materials have been recycled in roadways, airports, parking lots, and other locations throughout the country, and partnerships between the asphalt industry and public agencies across the country have been instrumental in improving the processes for implementing recycling. The Federal Highway Administration (FHWA) in particular has long had a policy to "encourage appropriate use of secondary materials (i.e., waste and byproduct materials) and associated technologies in the construction and rehabilitation of highway infrastructure" (Wright Jr., 2006).

Putting reclaimed asphalt pavements and recycled asphalt shingles to use in new pavements is beneficial in a number of ways:

1. Reduced cost in the production of asphalt mixtures due to binder and aggregate replacement.
2. Environmental benefits from the conservation of virgin binder and aggregate, including consideration of resource extraction, transportation, and processing.
3. Reduction in the cost of material disposal and a diversion of waste material from landfills.
4. Reduction in the production of greenhouse gases and other emissions.
5. Improved resistance to permanent deformation due to the utilization of harder binders.

While the use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) has been an overwhelming success, challenges have been noted in some instances. Copeland (2011) stated that some public agencies have expressed concerns about high RAP content mixtures surrounding the effects of RAP binder on the overall binder properties of a mixture and the potential for premature cracking under high-stain conditions due to excessive hardening of the final mixture.

Other challenges facing acceptance of high RAP content mixes include restrictions dictated by traditional specification limits, a perceived lack of RAP uniformity, and a lack of RAP availability in some locations. RAS usage has produced similar concerns, along with concerns about potential for contamination from other building materials and the potential presence of asbestos. Despite these concerns, multiple publications have shown the viability in producing high-binder replacement mixtures with RAP and RAS that answer each of these concerns through proper care and attention to mix design, materials selection, processing, and construction.

Copeland (2011) provides the following definition of RAP and high RAP content mixes for FHWA:

> *Existing asphalt materials are commonly removed during resurfacing, rehabilitation, and reconstruction operations. Once removed and processed, the pavement materials become reclaimed asphalt pavement (RAP), which contains valuable asphalt binder and aggregate. RAP is a valuable, high-quality material that can replace more expensive virgin aggregates and binders. The most economical use of RAP is in the intermediate and surface layers of flexible pavements where the less expensive binder from RAP can replace a portion of the more expensive virgin binder. While RAP has been used for decades, there is a current interest in using higher RAP contents. High RAP content mixtures have greater than 25% RAP by weight of the mix.*

RAP is created as a result of the removal of existing asphalt pavement during construction, rehabilitation or maintenance; or as a result of plant-produced asphalt mix that is returned to stockpiles as a result of start-up, overages, or other operational situations. It may be derived from millings or from material crushed at a plant that is then sized and stockpiled. This sized material is typically fed into an asphalt plant at some planned percentage of either total weight of the mix or binder replacement during the production of a new asphalt mixture.

Recycled asphalt shingles used in asphalt mixtures may come from the waste generated during the manufacturing of roofing shingles, such as cut-out tabs or off-color shingles, or they may be generated from tear-off (post-consumer) waste generated during the reroofing of buildings. However, RAS does not include waste from membrane roofing such as built-up, thermoset, or thermoplastic materials. Manufactured asphalt shingle waste should be ground to a set size (typically less than ⅜ inch) before use. Tear-off shingles must be processed to remove all foreign materials, such as wood, nails, and other construction debris, prior to grinding to size.

Table 1-1 gives the general composition of roofing shingles; however, the exact proportions of the components varies according to manufacturer, intended climate, and the type of backing material used. The asphalts used for shingles are generally air-blown and polymer-modified, making them much stiffer than typical paving grade asphalts, with a typical penetration range of 20–70 dmm (0.1 mm) at 77°F (generally a high temperature PG grade in excess of 100). Two types of asphalts are generally used in the manufacture of shingles: one to saturate the backing material and another as the coating material (Newcomb et al., 1993). The proportions given in Table 1-1 generally agree with those reported by Brock (2007).

Table 1-2 lists the mineral materials used in shingle manufacturing and their characteristics. These include ceramic granules, headlap granules, backsurfacing sand, and asphalt stabilizer (Noone, 1991). The ceramic-coated colored granules are small crushed rock particles coated with a ceramic oxide. The headlap granules consist of coal slag or other non-carbonate aggregate and are about the same size as the ceramic-coated granules. The backsurfacing material is washed, and natural sand is added in small amounts to keep the shingles from sticking together during shipping. The powdered limestone is mineral filler used as a stabilizer for the asphalt. All the mineral materials used in the manufacture of roofing shingles are high-quality aggregates that perform well in asphalt mixtures.

Importance of Recycling

In a national view of RAP and RAS, Hansen & Copeland (2015) survey asphalt-mix producers annually concerning their recycling practices for FHWA and the National Asphalt Pavement Association (NAPA). They estimated that the total U.S. production of asphalt mix was 352 million tons for the 2014 construction season. They further reported that contractors were using 99.8% of the 76 million tons of RAP brought in to their plants, including almost 72 million tons that went into new asphalt pavements. The RAP was estimated to conserve about 20 million barrels of asphalt binder along with replacing some 68 million tons of virgin aggregate. Given a total production of 352 million tons of asphalt mix, and almost 72 million

Table 1-1. Components of Asphalt Shingles (Newcomb et al., 1993).

Component	Approximate Amount, % by weight	Notes
Asphalt Cement	25–35	Fiber Saturant and Coating
Granular Material	60–70	See Table 1-2
Backing	5–15	Paper, Fiberglass, or Felt

Table 1-2. Granular Materials Found in Shingles (Newcomb et al., 1993).

Component	Typical Quantity, % weight shingle	Typical Size
Ceramic Granules	10–20	–No. 12 (1.40 mm), +No. 40 (0.422 mm)
Headlap Granules	15–25	–No. 12 (1.40 mm), +No. 40 (0.422 mm)
Backsurfacing Sand	5–10	–No. 40 (0.422 mm), +No. 140 (0.104 mm)
Stabilizer	15–30	90% –No. 100 (0.152 mm), 70% –No. 200 (0.075 mm)

tons of RAP used, this would suggest the average RAP content in mixtures was over 20%.

The same FHWA/NAPA survey noted a rapid increase in the use of RAS. In 2014, it was reported that nearly 2.0 million tons of RAS were used in asphalt mixtures. This is nearly 15% of the approximately 13.2 million tons of waste shingles available each year.

The FHWA/NAPA survey also reports a combined saving of asphalt binder ($550/ton) and aggregate ($9.50/ton) by using RAP and RAS in asphalt mixes is more than $2.8 billion. This keeps asphalt pavement mixture costs competitive and allows owners to achieve more roadway maintenance and construction activities within limited budgets.

According to Williams et al. (2013), more than 20 states have specifications in place or are considering the development of specifications to allow the use of RAS in asphalt mixtures. Although exact proportions of allowable material vary according to state, most states allow either MWAS or PCAS at a level of up to 5% by weight of mix.

It is of vital economic and environmental importance that contractors, agencies, and researchers continue to use and improve the materials, design, and construction of pavements using RAP and RAS. The efficient reuse of these resources will have a significant impact on the sustainability of the pavement construction industry and ultimately the country's infrastructure.

Objectives

This synthesis provides a current state-of-the-practice for the use of RAP and RAS in asphalt mixtures produced in a central plant using either hot or warm processes. Specifically, it addresses the use of high-binder replacement mixes, which are generally considered to be those with more than 25% RAP content or more than 30% binder replacement. In addition to mixture design (Chapter 5) and plant production practices (Chapter 7), economic (Chapter 4) and environmental (Chapter 3) benefits are discussed in detail, along with pavement design (Chapter 6) and pavement performance (Chapter 8) information. Through the information given in this synthesis, the reader will understand the value of integrating recycled asphalt pavements and roofing shingles into new asphalt mixtures for economic and environmental reasons.

Scope

The scope of this synthesis includes a presentation of the history of asphalt recycling (Chapter 2) that details the motivation, development of mixing plant designs, materials developed, and problems confronted in the early days of recycling. The history also discusses how recycling at a modest level became integrated with standard practice and the economics that drive current initiatives to increase RAP and RAS usage.

The environmental benefits of RAP and RAS are presented in Chapter 3 in terms of emissions and energy consumption reductions. The economics of RAP- and RAS-bearing mixtures, discussed in Chapter 4, have become an integral part of the cost structure of asphalt mixtures in the United States. Chapter 5 discusses mixture design and the resulting performance properties of mixtures made with RAP and RAS, which tie to the pavement design considerations presented in Chapter 6.

The best practices for production operations with RAP/RAS mixtures are given in Chapter 7. The field performance of RAP/RAS mixtures is discussed in Chapter 8. Chapter 9 gives a summary of the entire report.

Summary

The recycling of asphalt materials in U.S. infrastructure is a key component to ensuring the economical transport of goods and people. The reduction of energy consumption in the generation of raw materials and reduced transportation requirements increase the efficiency of the asphalt paving industry and improve its already strong environmental record. In order to maximize the benefits of RAP and RAS usage, mix design approaches should evolve to focus on end-product properties, pavement design methods need to recognize the role of recycled materials in the pavement structure, and production and construction methods adapted to higher quantities of recycled materials.

2

History of Recycling

Crude oil prices have historically influence the cost of liquid asphalt, and the degree of interest in recycling asphalt pavements has been tied to spikes in the cost of liquid asphalt. Figure 2-1 shows the history of crude oil prices between January 1970 and February 2015 as presented by MacroTrends (2016) based upon data from the Energy Information Administration. For many decades preceding 1970, the price of crude oil remained very stable, fluctuating around $22 per barrel in 2016 dollars.

In the mid-1970s, the first dramatic rise in prices occurred during the 1973 Arab Oil Embargo when the price per barrel more than doubled. At this point, the industry began developing processes for recycling and field trials were constructed. In the late-1970s, another peak in crude oil prices occurred that was tied to the Iranian Revolution of 1979 and prices more than doubled again. This was followed by a decline in crude prices that ran from 1985 to about 2000 during which relatively little innovation took place in asphalt recycling, although contractors continued the practice as a means of managing costs and stockpiles of RAP.

During the 1980s, roofing shingle manufacturers began supporting research into the use of waste

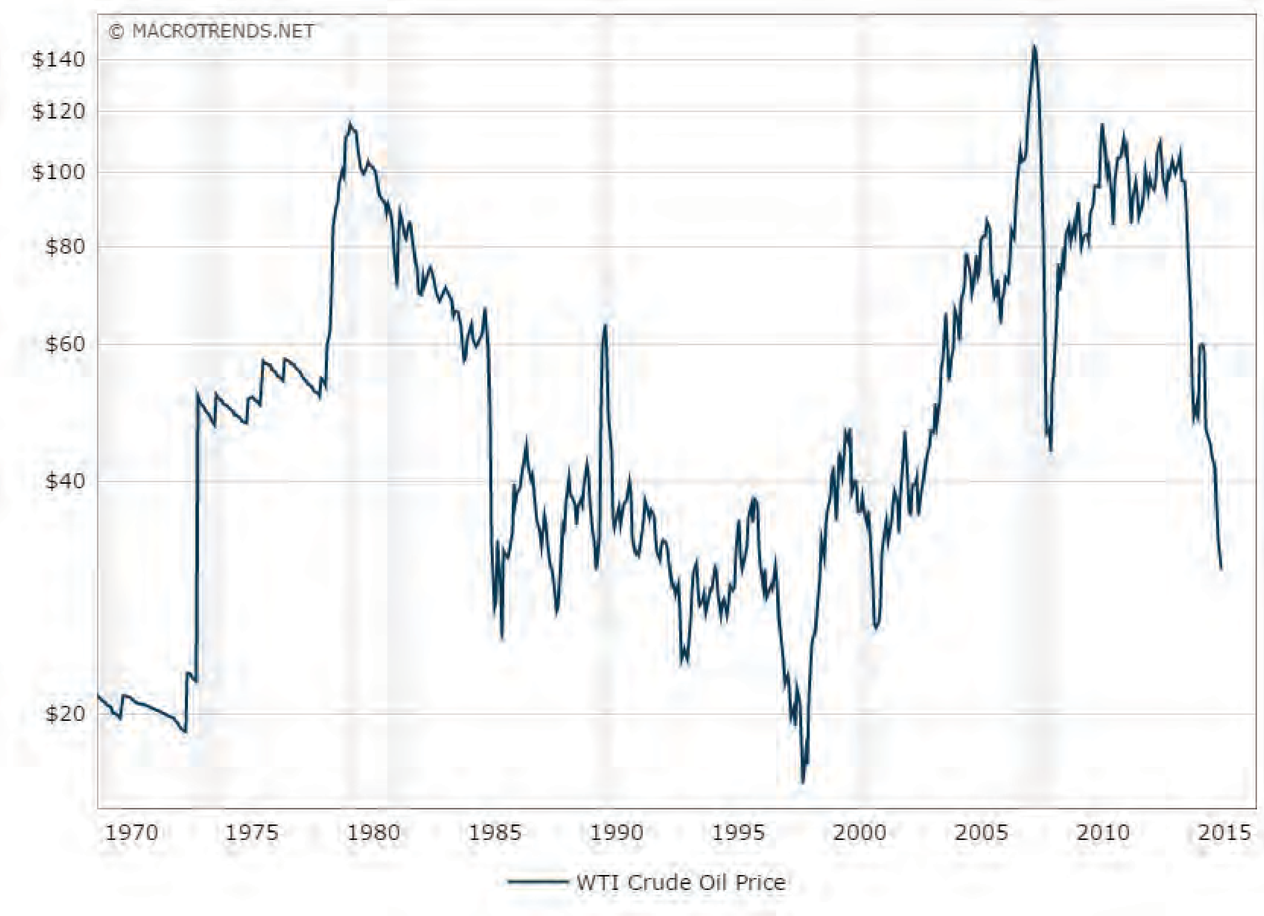


Figure 2-1. Historical Crude Oil Prices 1970–2016 (2016 dollars). Gray bars note recessions. (MacroTrends, 2016)

shingles from manufacturing processes and a few contractors began using processed waste shingles as a way of extending their asphalt supplies.

Beginning about 2000, there was a steady increase in oil prices that accelerated rapidly between 2006 and 2008. This increase in price was brought about by a rapidly expanding world economy and competition for energy.

At this point, there was renewed interest in increasing the amount of virgin asphalt binder replaced by reclaimed binder from RAP and RAS. The industry began promoting the use of high binder replacement mixtures using RAP and RAS (Newcomb et al., 2007; Hansen, 2008; Hansen, 2009), and FHWA and the National Cooperative Highway Research Program (NCHRP) began new research efforts to investigate improved methods for utilizing RAP and RAS. Shortly after this peak, a worldwide recession reduced energy demands and the price of crude fell very sharply to 2004 levels. Political upheaval in the Middle East and an improving economy kept prices at a relatively high level for the next decade, although increasing crude supplies led to a significant drop in oil prices starting in late 2014.

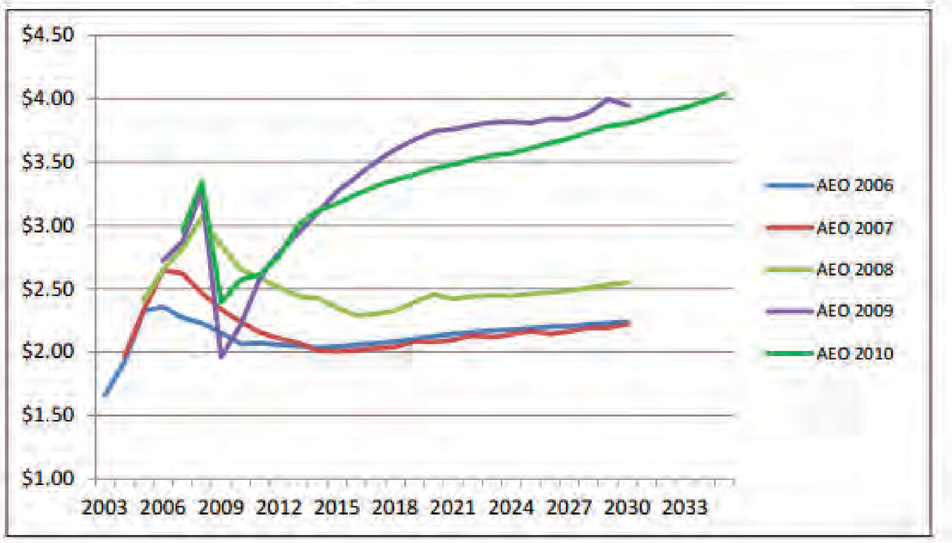


Figure 2-2: EIA Annual Energy Outlook Price Forecasts for a Gallon of Gasoline 2006–2010 (2010 dollars). (Skolnik & Brooks, 2012)

Economic forecasting is difficult because of the uncertainty of future conditions and situations in the present often influence predictions. This can be seen in Figure 2-2, which shows EIA Annual Energy Outlook forecasts of the price per gallon of gasoline in real 2010 dollars. For 2006–2008, prices were projected to be relatively flat well into the future, however with the rise of gasoline prices in 2008, forecasters switched to predictions of sustained price increases (Skolnik & Brooks, 2012). Similarly, examining the price trends in Figure 2-1 one might have been inclined to be overly pessimistic in 1974, 1979, and 2008 about future price trends for asphalt binder due to the very steep increases in crude oil prices. However, the long-term trend from 2000–2015 would seem to indicate continued fluctuations in oil prices.

Although there has historically been a connection between asphalt binder prices and oil prices, it is not the only factor. In addition to the absolute price of crude oil, asphalt prices are influenced by the differential in price between light and heavy crudes, coking economics, availability of heavy crudes and demand for sweet crudes, and supply and demand (Haverland, 2006). Thus, it is to the advantage of the industry and pavement owners alike to maximize the amount of binder replacement in asphalt mixtures while improving practices that maximize the life of asphalt pavements.

Pre-1970s: A Novelty (RAP)

The history of asphalt mix recycling is considerably older than might be imagined. The Warren Brothers Co. employed recycled asphalt mixtures at the beginning of the 20th Century. Recycling was used in Singapore as early as 1931 as a means of conserving petroleum when rehabilitating roads that showed premature distress. After the roads in Singapore were rehabilitated, they lasted for 14 years before any type of major work was needed despite multiple problems brought on by World War II (NAPA, 1977).

Recycling was used in Bombay (now Mumbai), India, as early as 1948, and, once these roads were rehabilitated with recycled mixtures they lasted almost 30 years before subsequent rehabilitation or reconstruction (Taylor, 1978). However, other than these examples, there was no great push to recycle asphalt prior to the 1970s.

1970–1985: Rising to Meet a Need (RAP)

The Arab Oil Embargo of the mid-1970s provided the impetus for the industry and agencies to find ways to save costs and stretch the existing supply of asphalt binder. In addition to experimentation with alternative binders and binder extenders, this led to the wide-scale production of recycled asphalt mixtures. It was during this period that the use of RAP became accepted as a means of controlling costs and improving the environmental profile of the road-building industry. Research provided guidance on a number of technical issues, including the control of RAP, mix design procedures, and plant operations.

One of the innovations introduced during this time was the use of recycling agents or rejuvenators. These are liquid additives, usually derived from petroleum, that are used to soften age-hardened binders. They are normally blended with virgin asphalt prior to its introduction to the asphalt mixture. Typically, recycling agents cost more than liquid asphalt, but they are able to rejuvenate aged binder more efficiently than the addition of liquid asphalt alone.

Some of the earliest documentation on the characteristics of recycled asphalt mixtures was provided by Little (1979). He presented a number of case studies of pavements in which asphalt recycling was used on an experimental basis. Those involving central plant recycling are shown in Table 2-1. The two most remarkable characteristics about these early projects are the high quantity of RAP employed (almost all greater than 50%) and the use of soft asphalts and recycling agents. At the time these projects were built, asphalt plants were largely either parallel-flow drum or batch plants. There were some double-drum, counter-flow drum, and heat-exchanger plants in use, but these were not common (Newcomb & Epps, 1981). Most of the reported problems with high RAP mixtures and excessive pollution during this time period can be traced to asphalt plant designs that were not optimized for the use of RAP.

Most of the early processing of RAP consisted of removing the asphalt pavement using front-end loaders or bulldozers, hauling the material to the plant, crushing and sizing it, and then stockpiling the processed RAP for future use. The advent of milling machines in the mid- to late-1970s greatly facilitated removal and processing RAP to the point that further crushing and sizing was not needed before incorporating RAP into asphalt mixtures (Hughes, 1977). However, Hughes did acknowledge some problems associated with the production of fines in the mix.

1985–2006: Standard Practices (RAP and RAS)

The use of RAP became a universally standard practice in the asphalt industry during the 1980s, even as oil prices began to recede from prior levels. Contractors found the savings that accompanied the use of RAP provided an impetus for its continued use. The advent of the Superpave design system tended to have a negative effect on recycling as agencies began applying new approaches to both binder selection and mix design. It was thought in many agencies that

Table 2-1. Early Central Plant Recycling Projects (after Little, 1979).

Project	Date	Pavement Layer	%RAP	Virgin Asphalt or Rejuvenator
I-8, Gila Bend, Ariz.	1978	Surface and Base	100	Cyclogen L (Recycling Oil)
US 666, Graham County, Ariz.	1977	Surface	80	AR-2000 and Extender Oil
Kossuth County, Iowa	1976	Surface	70	AC-10
I-94, Minnesota	1977	Surface and Base	50	AC (200/300 pen)
I-15, Henderson, Nev.	1974	Surface	100	AR-8000 and Paxole (Softening Agent)
Hillsboro to Silverton Hwy., Woodburn, Ore.	1977	Surface	70	AR-2000
I-20, Roscoe, Texas	1976	Base	85	AC-5
US 84, Snyder, Texas	1976	Base	30–100	E.A. 11-M (Emulsified Asphalt) and AC-10
Loop 374, Mission, Texas	1975	Surface	85–100	AC-10 and Softening Agent
US 50, Holden, Utah	1975	Surface	77–100	AC-10 and Softening Agent
Blewitt Pass, Wash.	1977	Surface	93	AC-5
I-90, Rye Grass, Wash.	1977	Surface	72	Cyclopave (Recycling Oil)

Table 2-2. Trends in RAS-Bearing Mixtures from University of Nevada, Reno Study (Paulsen et al., 1986).

Property	Increased RAS Content	Increased RAS Size	Increased Asphalt Content	Use of Recycling Agent
Resilient Modulus at 7777°F	Increase	Decrease	Decrease	Decrease
Tensile Strength	Increase	Decrease	None	Decrease
Marshall Stability	None	None	Decrease	Decrease
Temperature Susceptibility	Decrease	Increase	None	Decrease

RAP would have a confounding effect on performance during the transition, and some agencies reduced the amount of RAP allowed in mixtures in some instances. In the late 1990s, it was recognized that RAP needed to be accommodated in the Superpave system, and NCHRP Project 09-12 was undertaken by McDaniel & Anderson (2001) to accomplish this.

Research into the use of reclaimed asphalt shingles from manufactured waste (MWAS) began at the University of Nevada, Reno in the mid-1980s. This work included both an investigation of mixture properties and behavior (Paulsen et al., 1986) and an economic analysis (Epps & Paulsen, 1986). Table 2-2 shows the general trends noticed in the Nevada study. In general, it was shown that the incorporation of manufactured roofing waste resulted in greater mix stiffness and greater tensile strength. The increased mix stiffness may be countered through increased virgin asphalt content or through the use of a recycling agent. The conclusion from this study was that up to 20% RAS could be incorporated into asphalt mixtures with acceptable properties.

A study at the University of Minnesota (Newcomb et al., 1993) investigated the use of manufactured waste and post-consumer RAS in asphalt mixtures. The work included laboratory experiments with dense-graded and stone-matrix asphalt (SMA) mixtures, as well as field mixtures. Research showed:

1. The maximum amount of waste roofing shingles that should be used in dense-graded mixtures was 5% while up to 10% could be used in SMA mixtures;
2. The incorporation of RAS could improve the compactability of mixtures;
3. MWAS could significantly improve low-temperature properties (this was true to a lesser extent for PCAS); and
4. Field-produced mixtures showed the same general behavior as laboratory mixtures.

The result of this study was the adoption of a permissive specification by the Minnesota Department of Transportation for the use of up to 5% manufactured RAS in asphalt mixtures.

2006–2015: A Revival (RAP and RAS)

Up until the mid-2000s, agencies and contractors were comfortable with a nominal level of about 12% RAP in mixtures. However, liquid asphalt prices began to rise dramatically in late 2007, following the burst of the housing bubble that year, and they continued to rise as the country entered the Great Recession in late 2008, as shown in Figure 2-3. Prices have declined from their height and in 2012 they stabilized at a point above pre-2008 levels before starting to fall again as oil prices dropped in 2015.

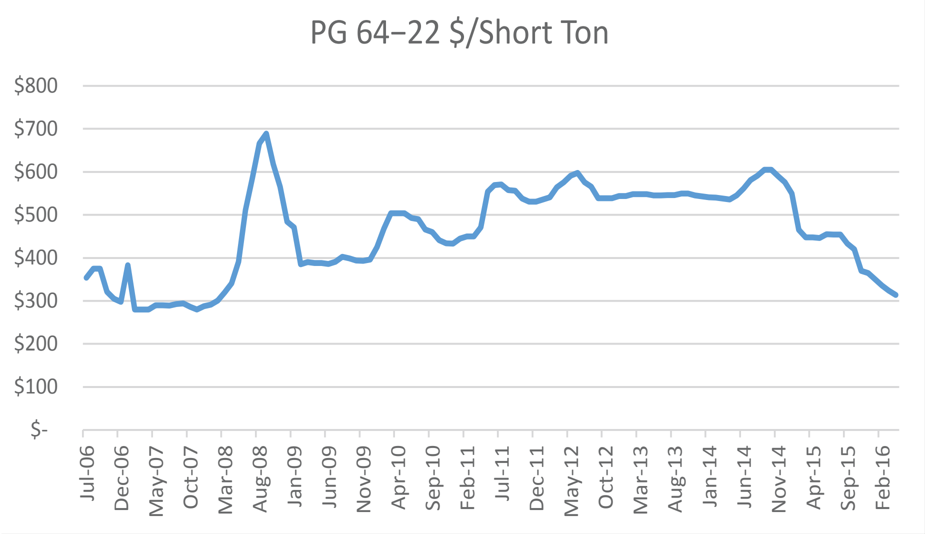


Figure 2-3. Kansas DOT Monthly Computed Asphalt Material Index, 2006–2016 (KDOT, 2016).

During the same time frame, FHWA established the RAP Expert Task Group in 2007 to coordinate, develop, and improve national guidance and recommendations for the asphalt pavement recycling program, and AASHTO and NAPA began efforts, working with FHWA, to benchmark the acceptance and use of RAP and RAS by state DOTs and the asphalt pavement industry.

Increased interest in using higher binder replacement from RAP and RAS has peaked in recent years. NCHRP Project 09-46 (West et al., 2013) concluded that mixtures with up to 50% RAP have performed well in a wide variety of climatic and traffic conditions, and that asphalt overlays with 30% RAP have demonstrated performance equivalent to virgin mixtures. Results from the National Center for Asphalt Technology (NCAT) Pavement Test Track have shown the benefit of using a softer grade of virgin binder to reduce raveling and cracking. It was also found that stiffer mixtures resulting from the use of RAP had lower tensile strains under heavy truck loads.

The state of Illinois enacted legislation in 2011 requiring the collection of waste roofing shingles and their incorporation into asphalt paving projects. The Illinois Department of Transportation (IDOT) allows contractors the option of including waste roofing shingles in as many projects as possible without mandating their use. IDOT has concluded that roofing shingles are not detrimental to the short-term performance of asphalt mixtures (IDOT, 2013).

Summary

The beginning of widespread asphalt recycling occurred as a result of the Arab Oil Embargo of the 1970s, but the cost–benefit have encouraged its continued use. Equipment for removing pavement surfaces, sizing the material, and introducing it into asphalt plants developed rapidly with the desire to make greater use of RAP. Very high RAP contents in the 1970s resulted in emissions problems that could only be addressed with the day’s technology by reducing the amount of RAP in the mixes. Investigations into the use of RAS began in the 1980s and continued into the 1990s.

It was shown that RAS could be successfully incorporated into asphalt mixtures, and permissive specifications were subsequently developed. Renewed interest in maximizing the amount of RAP and RAS occurred in the latter half of the first decade of the 21st Century as crude oil prices once again climbed very steeply. The industry was much better prepared at this time to deliver high-quality mixes containing higher amounts of recycled materials that could be produced without emissions problems.

Figure 2-4. Lines at a Gas Station During the 1970s Oil Crisis. *(Photo courtesy Library of Congress)*

3

Environmental Benefits of Recycling RAP and RAS

Using RAP and RAS in asphalt pavement mixtures can reduce costs while providing environmental benefits. The tonnage of RAP recycled on an annual basis is larger than any other household recycled material (paper, metals, glass, plastic, ceramics, etc.), and it is recycled at a greater rate (near 100%) than any other household or construction and demolition (C&D) product. The use of RAP and RAS in asphalt mixtures is a major contributor to the sustainability efforts underway in the pavement construction, rehabilitation, and maintenance industry.

The use of RAP and RAS reduces the amount of aggregate and asphalt binder consumed by the construction industry, reduces the amount of landfill space required for disposal of these C&D waste streams, reduces the amount of energy consumed in the construction of new asphalt paving materials, and reduces life-cycle emissions and the greenhouse gases associated with the production and placement of asphalt mixtures. These benefits can be achieved in both first-cost and life-cycle cost savings. The use of RAP and RAS in asphalt paving mixtures is traditionally one of the few "green" activities that provides significant environmental benefits while reducing costs. Utilization of recycled products in asphalt parking lots is one of the primary avenues for obtaining points in green rating systems.

In addition, it is generally recognized that in the hierarchy of improved waste management (Reduce, Reuse, Recycle), the reuse of materials in their original purpose, such as RAP, is considered the most preferred practice while recycling activities, such as the incorporation of RAS, is the next-best practice. The need for new materials in future projects are significantly reduced, too, because the binder and aggregate from previous pavement and roofing construction are reused in the new pavement layers. Thus, there is the benefit of reduction as well as reuse and recycling. The use of RAP and RAS in new construction materials is accompanied by some environmental concerns, however, which are identified and discussed at the end of the chapter.

Sustainability

As stated above, the use of RAP and RAS in asphalt paving mixtures is an important contributor to providing the public with sustainable pavements. The most commonly referenced multiuse definition of sustainability is from the United Nation's Brundtland Commission (1987) report:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

Applied Pavement Technology (APT, 2013) provides a definition for "pavement sustainability" based on definitions provided in *NCHRP Report 708: A Guidebook for Sustainability Performance Measurement*

Table 3-1. Resource Conservation Associated with the Use of RAP and RAS.

Item	RAP	RAS
Quantity of Materials Available (Millions of Tons)	75.8	13.2
Asphalt Binder Content by Total Weight of Mixture (Percentage)	5	20
Aggregate and Other Solids by Total Weight of Mixture (Percentage)	95	80
Asphalt Binder Available for Recycling (Millions of Tons)	3.8	2.6
Aggregate and Other Solids Available for Recycling (Millions of Tons)	72.0	10.6
RAP and RAS Asphalt Binder Available for Recycling (Millions of Tons)	6.4	
RAP and RAS Aggregate and Other Solids Available for Recycling (Millions of Tons)	82.6	

for Transportation Agencies (Zietsman et al., 2011) and affirmed in by FHWA's Sustainable Pavements Technical Working Group (Van Dam et al., 2015):

Sustainable Pavements refers to a system characteristic that encompasses pavements' ability to

1. *Achieve the engineering goals for which they were constructed*
2. *Preserve and restore surrounding ecosystems*
3. *Use resources (including money) wisely, and*
4. *Meet basic human needs such as health, safety, equity, employment, comfort, and happiness.*

RAP and RAS can clearly help achieve the above-mentioned sustainable pavement characteristics.

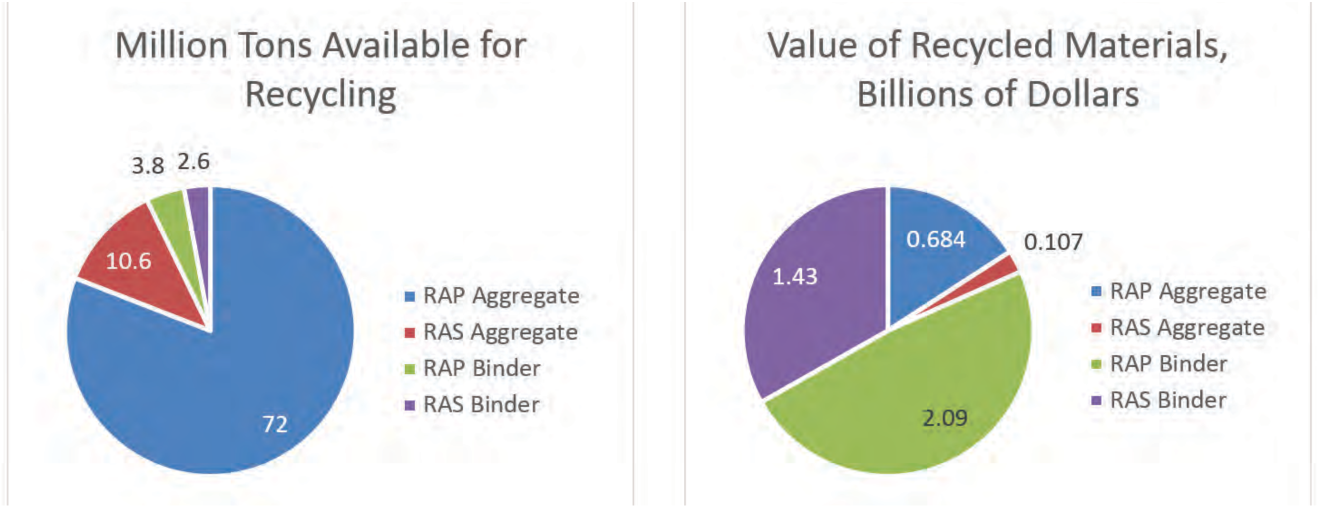


Figure 3-1. Total Amount of Available RAP and RAS and the Value of the Binder and Aggregate.

Furthermore, life-cycle assessment techniques and "green pavement" evaluation systems have been and are being developed to quantify the sustainable aspects of different approaches for producing "sustainable pavements" (Epps et al., 1980a; APT, 2013; Van Dam et al., 2015).

Resource Conservation

Although the tons of RAP available each year varies depending upon how much construction activity is funded by all levels of government, NAPA/FHWA surveys on the utilization of recycled materials have found that in recent years about 76 million tons of RAP have been accepted for recycling by asphalt producers annually (Hansen & Copeland, 2015). In the early 1990s, Collins & Ciesielski (1993) estimated that 100.3 million tons of asphalt millings were generated annually. At present most of the RAP (approximately 95%) is recycled into new hot- or warm-mix asphalt pavement mixes the year it is accepted. The remainder of the RAP is used in cold-mix recycling operations and as base course and shoulder backing materials, or stockpiled for use in future paving seasons. No more than 0.2% of RAP was reported as being landfilled annually (Hansen & Copeland, 2015).

It is estimated that about 13.2 million tons of asphalt shingles — 1.2 million tons of manufactured waste (MWAS) and 12 million tons of post-consumer shingles (PCAS) — are available for recycling in the United States annually, and that about 15% of available RAS is presently utilized by the asphalt paving industry (Hansen & Copeland, 2015).

Using the assumptions provided in Table 3-1 relative to the quantities of RAP and RAS available and the estimates of the asphalt binder and aggregate available in the materials, the potential for replacing nearly 6.4 million tons of asphalt binder and more than 82.6 million tons of aggregate is possible annually through the recycling RAP and RAS. Considering that about 352 million tons of asphalt mixes are produced annually in the United States at an average asphalt binder content of 5% by total weight of mixture, the amount of virgin asphalt binder that can be replaced with RAP and RAS is about 34.1% and the amount of virgin aggregate that can be replaced with RAP and RAS is 24.7%. Because not all RAP and RAS is recycled into asphalt mixtures and because not all virgin asphalt binder may be replaced with recycled asphalt binders, it is estimated that today about 19% of the virgin asphalt binder is replaced by asphalt

Table 3-2. Natural Resources Conservation with RAP and RAS.

Material/Process	Recycled Material Content, %	Recycled Asphalt Binder Content, %	Asphalt Binder Replacement*, %	Aggregate Replacement*, %
Virgin Asphalt Mixture	0	0	0	0
RAP	15	4	11.5	15.2
	25		19.2	25.3
	40		30.8	40.5
RAS: Post-Industrial Shingles (MWAS)	2	18	6.9	1.7
	5		17.3	4.3
RAS: Post-Consumer Shingles (PCAS)	2	32	12.3	1.4
	5		30.8	3.6

*relative to conventional asphalt mixtures at 5.2% asphalt binder content

binder from RAP and RAS and about 22% of virgin aggregate is replaced by aggregate from RAP and RAS. Figure 3-1 shows the total amount of material from RAP and RAS generally considered available on an annual basis and the total value of the aggregates and binders from those sources, assuming $550/ton for binder, $9.50/ton for RAP aggregate, and $10/ton for the finer RAS aggregate.

Table 3-2 contains this information in a different format and illustrates the natural resources conservation for different materials and quantities of materials. These calculations are based on assumptions contained in Robinette & Epps (2010) and should be considered representative. Figure 3-2 shows the amount of binder conserved in a typical asphalt mix with various levels of RAP and RAS.

Landfill Reduction

As indicated previously, almost all available RAP from pavement reconstruction, rehabilitation, and maintenance activities is recycled. The diversion of as much as 80 million tons of RAP from landfills to reuse is equivalent to about 48.4 million cubic yards of landfill volume saved on an annual basis. This is the same volume as 15,000 Olympic-size swimming pools or more than 12 times the volume of the Dallas Cowboys' AT&T Stadium. The majority of RAS is presently placed in landfills; Cascadia Consulting Group (2008) found that asphalt shingles made up 1.6% of all waste tipped at California landfills. Tipping fees at U.S. landfills vary from about $24/ton in Utah to $91/ton in Maryland (Green Power Inc., 2014). Assuming an average tipping fee of $50/ton, keeping the 9.3 million tons of shingles not currently being used in pavement mixes out of landfills would save $465 million per year. Table 3-3, based on Booz Allen Hamilton (2013), quantifies the landfill diversion savings of RAP and RAS at different usage levels in terms of weight and volume on a per-ton basis.

Energy Conservation

For more than six decades, the United States has been dependent on international energy supplies. The need for conservation of energy has long been recognized as a national goal. The 1973 Arab Oil Embargo had a significant economic impact on the United States and, consequently, energy independence and energy conservation became politically impor-

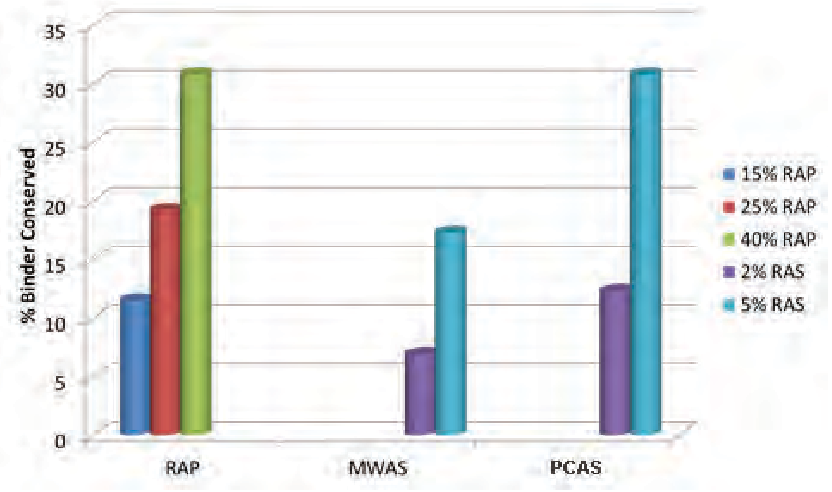


Figure 3-2. Amount of Binder Conserved with Various Levels of RAP and RAS.

tant. The recent development of hydraulic fracturing and horizontal drilling has allowed the cost-effective production of oil and gas from shale formations. This technology has allowed the United States to recently produce domestically more crude oil than it imports; however, for environmental and economic reasons, the desire to conserve energy and secure energy independence remain important.

Over the past four decades, the pavement community has directed considerable research, development, and implementation resources toward reducing its reliance on virgin petroleum asphalt binders and reducing the amount of energy consumed for construction, rehabilitation, and maintenance operations. Innovations developed during this period include drum mix plants, vibratory rollers, cold milling machines, warm-mix asphalt, and the development of many forms of pavement recycling. Estimates of the amount of energy consumed in pavement construction, reconstruction, rehabilitation, and maintenance operations are in the range of 0.5 to 1.5% of the total U.S. energy consumption (Horvath, 2003; 2007; Robinette & Epps, 2010; Chappat & Bilal, 2003). Reductions in energy consumption of construction operations will contribute to solving the energy independence problem.

Table 3-3. Landfill Impact, Mass and Volume Reductions from Recycling RAS and RAP (Booz Allen Hamilton, 2013).

Materials/Process	Recycled Material Content, %	Mass Avoided, lbs/ton	Volume Avoided, yd^3/ton
Virgin Asphalt Mixture	0	0	0
RAP	20	383	0.28
RAS	5	96	0.23
RAP+RAS	20+3	444	0.42
	20+5	485	0.52
	20+7	527	0.62
	17+3	386	0.38

As stated above, the 1973 Arab Oil Embargo stimulated not only an interest in recycling and innovation but also in energy conservation (Epps et al., 1980a). Information on energy consumption associated with various construction, rehabilitation, and maintenance operations was presented in a series of reports including multiple NCHRP Reports (Epps et al., 1980a; 1980b; Epps & Finn, 1980). In 2003, the Colas Group synthesized available information on the energy requirements for various construction operations (Chappat & Bilal, 2003). The analysis provided an energy-requirements breakdown for the manufacture of aggregate and binding agents, production of asphalt paving mixtures, transport of material to the project site, and laydown activities. This analysis indicated that the greatest consumption of energy occurs with the manufacturing of the asphalt binder and the production of the asphalt paving mixtures. In addition, this analysis indicated that the use of 20% RAP in an asphalt paving mixture reduced energy requirements for production and placement by about 14%.

The computer program Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) provides a framework for calculating the energy consumption associated with construction operations (Horvath, 2003; 2007). Energy consumption estimates for materials production in PaLATE are based on information obtained from the Economic Input-Output Life Cycle Assessment (EIO-LCA) model (Horvath, 2003; Green Design Institute, 2003). The EIO-LCA model assumes energy consumption of 18 million Btu for a ton of liquid asphalt binder, which differs significantly different from the 600,000 Btu figure identified in other studies (Epps et al., 1980a; 1980b; Epps & Finn, 1980; Chappat & Bilal, 2003). This difference is due to the EIO-LCA model considering the fuel value of asphalt binder. The information presented below does not consider the feedstock energy (energy that would be released if the asphalt binder were put to use as an energy source) of the asphalt binder because asphalt binder is not burned or otherwise consumed when it is used in asphalt paving mixtures (Robinette & Epps, 2010). If this energy were consumed, it would have additional environmental impacts not currently realized, including significant carbon and greenhouse gas emissions. EPA (2015) notes that 99.7% of potential carbon emissions in asphalt binder are effectively sequestered.

The representative range of life-cycle energy required for asphalt mixture production and placement ranges from 27,000 to 34,000 Btu/yd^2/in. The

Table 3-4. Energy Conservation Associated with the Use of RAP and RAS (Robinette & Epps, 2010).

Material/Process	Recycled Material Content, %	Recycled Asphalt Binder Content, %	Energy, Btu/yd^2/in	Energy, Btu/ton	Savings*, %
Virgin Asphalt Mixture	0	0	30,000	533,333	0
RAP	15	4	28,225	501,778	5.9
	25		27,042	480,741	9.9
	40		25,267	449,190	15.8
RAS: Post-Industrial Shingles (MWAS)	2	18	29,201	519,130	2.7
	5		27,772	493,724	7.4
RAS: Post-Consumer Shingles (PCAS)	2	32	28,454	505,850	5.2
	5		26,136	464,633	12.9

*relative to virgin mixtures with no RAP or RAS

analysis presented below uses a baseline of 30,000 Btu/yd^2/in (Robinette & Epps, 2010) as a basis for comparisons. Energy savings of 5% to nearly 15% are possible with the use of RAP and RAS (Table 3-4 and Figure 3-3) (Robinette & Epps, 2010). Given that the typical household uses 90 million Btu/year (EIA, 2012), a 10% energy savings on 350 million tons of asphalt mix would be equivalent to the energy needed to power approximately 205,000 homes (equivalent to Milwaukee, Wis., or Tucson, Ariz.) for one year.

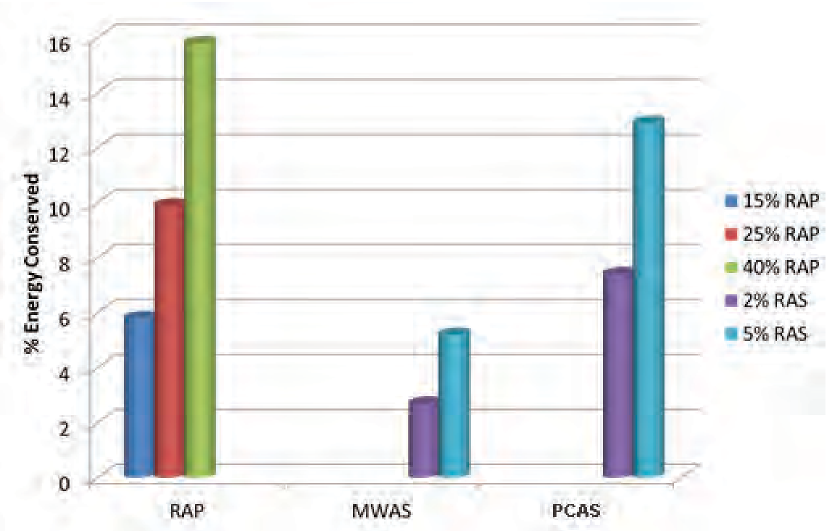


Figure 3-3. Amount of Energy Conserved with Various Levels of RAP and RAS.

Additional studies have been conducted that have evaluated the life-cycle energy impacts associated with the use of RAS. Cochran (2006) indicates that the energy associated with recycling shingles into asphalt paving mixtures is less than the energy associated with disposing of singles in a landfill and less than using virgin materials for asphalt mixtures.

Greenhouse Gas Emissions

In the United States, about 33% of the total greenhouse gas emissions are associated with the transportation sector (EPA, 2015). Within the transportation sector, greenhouse gas emissions associated with pavement construction operations are much less than those associated with vehicle operations. Estimates of greenhouse gas emissions associated with pavement construction, rehabilitation, and maintenance are available in the FHWA report prepared by Applied Pavement Technology (APT, 2013) and are based on annual expenditures for pavements of about $55 billion and using the EIO-LCA online calculator develop by the Green Design Institute (2003) at Carnegie Mellon University.

Worldwide, greenhouse gas emissions are estimated at 34.8 billion tons annually; the U.S. emits about 5.2 billion tons annually, and the U.S. transportation sector is responsible for about 1.7 billion tons annually. The total greenhouse gas emissions due to U.S. street and highway pavement construction is estimated at approximately 82 million tons annually, or about 5% of the U.S. transportation total and about 1.4% of all greenhouse gases emitted in the country (APT, 2013).

The most common measure of greenhouse gas emissions is carbon dioxide equivalents (CO_2eq). This unit measures not only carbon dioxide (CO_2) but also methane (CH_4) and nitrous oxide (NO_x), which are all considered contributors to the greenhouse gas effect. Two sources (Chappat & Bilal, 2003; Robinette & Epps, 2010) have been used to provide an estimate of savings in emissions associated with the use of RAP and RAS. The information presented in Table 3-5 includes emissions from the production of the raw materials, transportation, production and laydown of the materials in a project setting. Table 3-5 and Figure 3-4 indicate CO_2eq reductions of nominally 5 to 10%, depending on the amount and type of material recycled. Given that a single passenger car produces 10,560 lbs. of CO_2eq per year, reducing the CO_2eq emissions by 7.5% for 350 million tons of asphalt mix would be a reduction equivalent to the removal of 263,000 vehicles from U.S. roads.

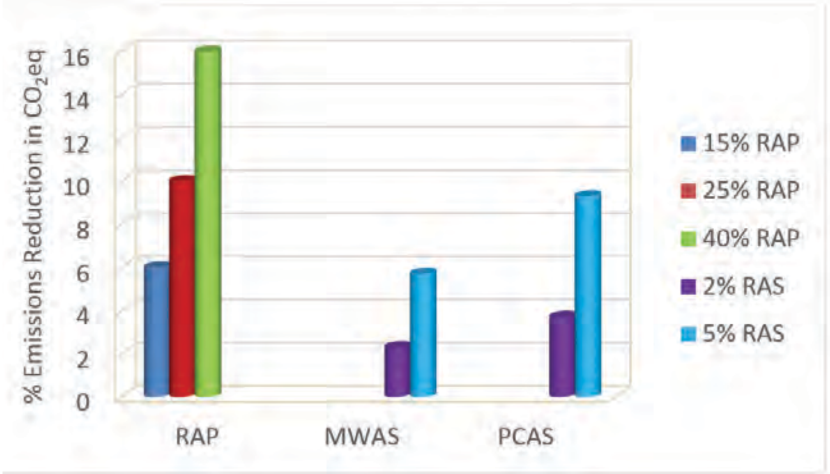


Figure 3-4. Emissions Reductions Possible with Various RAP and RAS Contents.

The Texas Department of Transportation (Lee & Epps, 2010) indicated a 3.8% reduction in CO_2eq (20,500 tons) was achieved through the use of RAP and RAS in TxDOT asphalt paving mixtures in 2010 as compared to conventional asphalt paving mixtures. In Texas, the savings in CO_2eq is equivalent to the CO_2eq produced from the use of 2.1 million gallons of fuel or the provision of electricity to more than 2,400 homes. The potential for additional emissions reductions in Texas through full implementation of TxDOT specifications utilizing RAP and RAS is up to 113,000 tons per year of CO_2eq or 21% reduction as compared to conventional hot-mix asphalt paving mixtures.

Other Environmental Considerations

As indicated above, the use of RAP and/or RAS can conserve materials, divert material from landfills, save energy, and reduce emissions. These environmental advantages are important and provide a cost savings.

As with the utilization of all materials in the construction industry, some environmental concerns have been raised with the use of RAP and RAS. These include water-quality issues associated with leaching from stockpiled RAP and RAS, emissions from the inclusion of RAP and RAS in the asphalt production process, and the potential presence of asbestos in shingles in RAS. These topics will be discussed below.

Table 3-5. Emission Reduction Associated with the Use of RAP and RAS.

Material/Process	Recycled Material Content, %	Recycled Asphalt Binder Content, %	Emissions, CO_2eq, lbs/yd^2/in	Emissions, CO_2eq, lbs/ton of asphalt mix	Savings*, %
Virgin Asphalt Mixture	0	0	5.900	104.89	0.0
RAP	15	4	5.546	98.59	6.0
	25	4	5.309	94.39	10.0
	40	4	4.955	80.09	16.0
Post-Industrial Shingles (MWAS)	2	18	5.766	102.51	2.3
	5	18	5.565	98.94	5.7
Post-Consumer Shingles (PCAS)	2	32	5.680	100.97	3.7
	5	32	5.349	95.09	9.3

*relative to virgin asphalt mixtures with no RAP or RAS

Water Quality

Kreich et al. (2002) provided data from a leaching study on four asphalt roofing materials. Twenty-nine polycyclic aromatic hydrocarbons (PAHs) were selected for detection. All test results were below the test method detection limit.

Townsend et al. (2007) reported on two other leaching studies using materials from Maine and Florida. These tests also indicated that PAHs in the water were below the detection limits. Wess et al. (2004) assessed runoff water from asphalt pavements in California to determine if PAHs and heavy metals — lead (Pb), zinc (Zn), and cadmium (Cd) — were present. Test results indicated that concentrations of PAHs in all streams and road runoff samples were below the detection limit.

Emissions — Polycyclic Aromatic Hydrocarbons (PAHs)

Townsend et al. (2007) published a review of environmental issues related to the use of RAS in asphalt paving mixtures. Because asphalt shingles contain a petroleum derived product (asphalt binder and polymers), they contain polycyclic aromatic hydrocarbons. PAHs describe a group of more than 100 chemicals; some of these are harmless, but some are known to have detrimental effects on human health.

Townsend et al. (2007) indicated that no data exists to suggest that the use of RAS in asphalt paving mixtures produced in central facilities would result in emissions any different from the production of conventional asphalt mixtures in hot-mix facilities. Townsend and his co-authors deduced that the environmental risks associated with PAH migration from asphalt mixtures incorporating RAS appear small and comparable to the use of other materials containing asphalt binders.

According to Rahim (2010), the risk pathways for PAH compounds from RAS to humans are not well understood or defined. Potential areas of concern include PAH migration into ground water (discussed above), dust inhaled during production and handling of RAS, as well as during the production of asphalt paving mixtures containing RAS, and the recycling of paving materials containing RAS. Little or no information is available that addresses these issues.

Asbestos

The most perceptible environmental concern associated with the use of asphalt singles is the potential for the presence of asbestos (Hansen, 2009; Krivit, 2007; Marks & Petermeier, 1997; NAHB, 1998; ARMA, 1998; Zickell, 2003; Lee et al., 2004) in post-consumer or tear-off asphalt shingles. The use of asbestos in residential shingles was discontinued in the manufacturing process in the late 1970s and has not been utilized for residential shingles in the United States for more than 30 years. With typical life of shingles for residential homes on the order of 15 to 25 years, most of the shingles manufactured with asbestos have been removed and replaced (Krivit, 2007; Townsend et al., 2007). According to McMullin (2007) the content of asbestos in shingles in 1962 was in the range of 0.02% by weight. By 1977, the content of asbestos in shingles was about 0.00016% by weight.

Based on a study of 11,770 asphalt shingle samples conducted by Zickell (2003) at the University of Massachusetts Lowell, asbestos was identified in 0.8% of the samples (0.5% of the samples indicated only a trace of asbestos, and less than 5% asbestos was found in the remaining 0.3% of the shingles). A study conducted by Grefe (2007) in Wisconsin indicated that about 1% of hundreds of samples tested indicated the presence of asbestos.

Townsend et al. (2007) reviewed information containing more than 27,000 asbestos test results from shingle processors with 1.5% indicating the presence of asbestos (samples that contained more than 1% asbestos), and many of the asbestos detections were attributed to the presence of mastic and not the asphalt shingle itself. A laboratory analysis of 191 samples from 88 loads of roofing shingles received at California landfills found only a single sample containing an asphalt mastic that tested positive for the presence of asbestos (Cascadia Consulting Group, 2009). Studies conducted by other recycling and asphalt mixture contractors also indicate a very low rate of occurrence of asbestos in processed tear-off shingles.

According to Schroer (2007), the National Emissions Standards for Hazardous Air Pollutants (NESHAP) from the U.S. Environmental Protection Agency (EPA) has an exemption for testing for the presence of asbestos based on some of the facts presented above. The exemptions apply to asphalt shingles from quadplex or smaller residential dwellings. Local regulators in some parts of the country have similar exemptions (Schroer, 2007; McMullin, 2007). Many shingle recycling companies routinely test for the presence of asbestos both in PCAS received from roofing contractors and after processing.

Other Emissions

Some concerns have been raised relative to the increase in emissions other than greenhouse gases connected with the use of RAP and RAS. Due to the energy reduction associated with their use, which includes reductions in production and transportation of asphalt binders and aggregates, it is doubtful that an increase in overall emissions will result from the use of RAP and RAS. Middleton & Forfylow (2009) conducted stack tests during the production of a conventional asphalt paving mixture and a mixture containing 15% RAP and 5% RAS utilizing a warm-mix system.

Reductions in CO_2, CO, and NO_X were noted. Oxygen (O_2) remained at the same level and SO_2 indicated an increase, although still well below regulatory limits, with the RAP/RAS mixture. A report prepared for the EPA by Booz Allen Hamilton (2013) showed reduced or equivalent emissions of particulate matter (PM_{10}), volatile organic compounds (VOC), CO, SO_x, and other materials for mixtures with varying levels of RAP and RAS in comparison to virgin mixes.

A second area of concern expressed surrounds the emissions associated with the recycling of mixtures containing RAP and RAS. Because RAP and RAS binders are typically harder than virgin asphalt binders, it is doubtful that additional emissions would result from their presence when new mixtures are produced with recycled materials containing RAP and/or RAS.

Typical production temperatures for recycled mixtures containing RAP and/or RAS are usually in the same range as conventional mixtures. However, if the production temperatures are increased when RAP and/or RAS are utilized, testing should be performed to determine if there is an impact on air quality. If low-viscosity recycling agents are utilized in the production of RAP and/or RAS mixtures, it is suggested that additional stack emission testing be performed on asphalt mixture facilities to ascertain any change in emissions. Warm-mix asphalt technology can be used to reduce the production temperature and plant emissions of asphalt mixtures containing RAP and RAS, but care must be taken to ensure that the recycled binder is fluid enough to mix with the other material components. This is especially important at high binder replacement levels (Advanced Asphalt Technologies, 2012).

Summary

The use of RAP and RAS in asphalt mixtures is key to the sustainability efforts underway in the asphalt pavement industry. RAP and RAS provide significant environmental benefits in terms of lower emissions, resource conservation, energy reduction, and landfill diversion.

Recycled asphalt materials have the added advantage of providing cost savings in addition to the environmental benefits inherent in the reuse of asphalt binder and aggregate. These environmental benefits are recognized in various construction environmental and sustainability rating systems. Significant emissions and energy reductions are possible with the use of 40% RAP in asphalt mixtures, and keeping RAP out of landfills saves, about 48.4 million cubic yards of space each year.

Although RAS use is not as ubiquitous as RAP, where processing is available it provides considerable benefits over disposal in terms of energy conservation, emissions reductions, landfill space, and tipping fees.

4

Cost–Benefit of Recycling

A determination of the cost–benefit associated with the use of RAP and RAS is dependent upon a number of factors and should be determined on a job-by-job basis. Prices of construction materials and the expected service life for the pavements in which these recycled materials are placed depend greatly on local market conditions, typical pavement structural designs, the environment and climate, and traffic volume and patterns. Some of the more important factors associated with costs saved from the use of RAP and RAS are listed below.

1. Quantity of RAP and/or RAS used in the asphalt paving mixture
2. Asphalt binder content of the RAP and/or RAS
3. Design asphalt binder content for the recycled mixture (quantity of virgin binder required)
4. Virgin asphalt binder grade
5. Cost of the virgin binder and rejuvenators, if necessary
6. Cost of virgin aggregate
7. Cost of RAP and/or RAS, including hauling, processing, and stockpiling
8. Expected service life of asphalt mixes containing RAP and/or RAS

A cost–benefit analysis should be based on life-cycle costs for a specific project. Despite this, cost–benefit are often only provided for first-cost considerations, and the first-cost benefits can be substantial for using high binder replacement mixtures.

However, both first-cost and life-cycle costs are utilized by pavement owners to determine pavement type and for selection of materials used. Information for use in cost–benefit analysis is provided below, and details are shown in Robinette & Epps (2010) for both first-cost and life-cycle cost analyses. A number of assumptions were made to provide these estimates of costs/prices.

The costs associated with pavement materials are a significant part of the total pavement cost. Robinette & Epps (2010) provides information based on a survey of state costs, as well as information available to contractors. Table 4-1 contains price information that can be used to estimate savings associated with the use of RAP and RAS. Savings on the order of 5–15% or

Table 4-1. Prices Associated with the Use of RAP and RAS (after Robinette & Epps, 2010).

Material/Process	Recycled Material Content, %	Recycled Asphalt Binder Content*, %	Price, $/ton	Savings, %
Virgin Asphalt Mixture	0	0	64.85	0
RAP	15	4	61.20	5.7
	25		58.70	9.5
	40		55.00	15.2
Post-Industrial Shingles (MWAS)	2	18	63.15	2.6
	5		60.60	6.6
Post-Consumer Shingles (PCAS)	2	32	61.80	4.8
	5		57.12	12.0

*There is not a consensus on the range of effective asphalt binder gained from roofing shingles. Estimates vary from 0.6 to 1.0 in terms of the amount of asphalt shingle binder contributed to the mix.

Table 4-2. Cost Savings with RAP and RAS from Other Sources.

Reference	Material	Cost Savings
Zhou et al. (2013b)	5% RAS	2–5%
Brock (2008)	20% RAP 50% RAP	>16% >40%
NCAT (Willis et al., 2012)*	25% RAP 50% RAP	14–20% 29–35%

*Used different amounts and stiffness of virgin binders used in mixtures.

greater are possible with the use of RAP and/or RAS. Cost savings identified in other studies is presented in Table 4-2, showing similar results with savings of 2% to more than 40%, depending on the quantity of RAP or RAS used.

Using the assumptions outlined in Table 4-1, if a mix made with completely virgin materials (with a cost of $64.85 per ton) was used to resurface an 11-mile stretch of a two-lane road with a 2-inch overlay, the total cost would be about $100,000. Assuming a cost reduction of 9.5% due to the use of 25% RAP, the total cost of that overlay would be $90,500 — a savings of $9,500.

Summary

Cost savings from the use of RAP and RAS are substantial and allow contractors to stabilize mix costs in the face of price fluctuations for virgin liquid asphalt.

Depending upon the amount of recycled materials used, cost savings can vary from less than 5% to 35% or more when 50% RAP is used. It should also be noted that when RAP is used, the amount of virgin aggregate required is reduced substantially, providing additional cost savings beyond the savings associated with reduced virgin binder demands.

Additional costs may be incurred if softer binders or rejuvenators are required as RAP/RAS levels increase (see Chapter 5, “Mixture Design and Characterization”), but these are not anticipated to exceed the cost savings associated with recycled materials.

It is safe to say that the cost structure of modern asphalt pavements is closely tied to the amount of recycled materials incorporated into the asphalt mix.

5

Mixture Design and Characterization

Approaches to the design of mixtures containing RAP and/or RAS have been topics of numerous studies (Epps et al., 1980a; Newcomb et al., 1993; McDaniel & Anderson, 2001; Shah et al., 2007; Newcomb et al., 2007; West et al., 2013; and Zhou et al., 2013b). In all cases it has been demonstrated that successful approaches to mix design exist and have been implemented. However, most of these have depended on volumetric considerations, and, in some instances, problems have been reported with respect to the embrittlement of mixtures (Mogawer et al., 2012; Zhou et al., 2013b). This section will describe approaches to the materials selection, volumetric proportioning, and performance testing of high binder replacement mixtures.

A study completed by Kandhal et al. (1998) indicated that the evaluation of recycled asphalt mixture should be based on a three-tier process. Tier 1 included up to 15% RAP and would not require any changes to the mix design process. Tier 2 included from 15 to 25% RAP and required the grade of new asphalt added be dropped one grade on the high and low ends of the PG grade. Tier 3 included more than 25% RAP and required the asphalt be recovered from the RAP and blended with the virgin asphalt to produce a binder with the desired properties. McDaniel & Anderson (2001) recommended similar tiers of RAP content for the amount of testing needed to properly characterize the materials. This ultimately became the process for designing the RAP mixtures adopted by AASHTO.

AASHTO has two standards that pertain to the use of RAS in asphalt paving mixtures. AASHTO MP 23-14, *Standard Specification for Use of Reclaimed Asphalt Shingles as an Additive in Hot-Mix Asphalt* (AASHTO, 2014a), gives a standard definition of RAS and presents requirements for shingle processing in terms of maximum particle size, deleterious materials, and blending of RAS and fine aggregate in stockpiling. It also requires additional testing of blended RAS and virgin binder if the amount of binder replacement exceeds 30%. AASHTO PP078-14, *Standard Practice for Design Considerations when Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures* (AASHTO, 2014b), provides guidance on determining the aggregate size in RAS and the contribution of shingle binder to the final mixture.

Evaluation of Recycled Materials and Their Interactions with New Materials

The use of RAP and/or RAS in asphalt mixtures requires some modifications in engineering and process control as another material is being added to the mixture. For higher binder replacement mixes, greater than 30%, this may take extra effort but the savings from higher binder replacement significantly outweigh the cost of any extra testing that may be required. Blending to meet gradation and the appropriate binder grade in the final product are keys to successful mix design, production, and performance.

Material selection for an asphalt paving mixture containing RAP and RAS is similar to that of a virgin mixture, except that the RAP and RAS must be tested to ensure they meet the governing specifications for aggregate gradation and quality, as well as binder quality when more than 25% binder replacement is used. Figure 5-1 (Newcomb et al., 2007) shows that stockpiled aggregates, along line 1, and virgin binder (line 4) go through a typical evaluation regimen prior to consideration of their interaction with the replacement binder. RAP must be prepared in a way that matches its expected state in the stockpile. Binder extraction is required for testing the aggregate (line 2) and recovery is necessary for high RAP content mixtures in order to ascertain the combined properties of the RAP and virgin binders (line 3).

RAP should be evaluated first with respect to its source. Some agencies allow RAP to be taken from a stockpile at the plant. In such cases, it is to the contractor's advantage to store the material according to the type of project it came from and to properly characterize its gradation and binder content. For

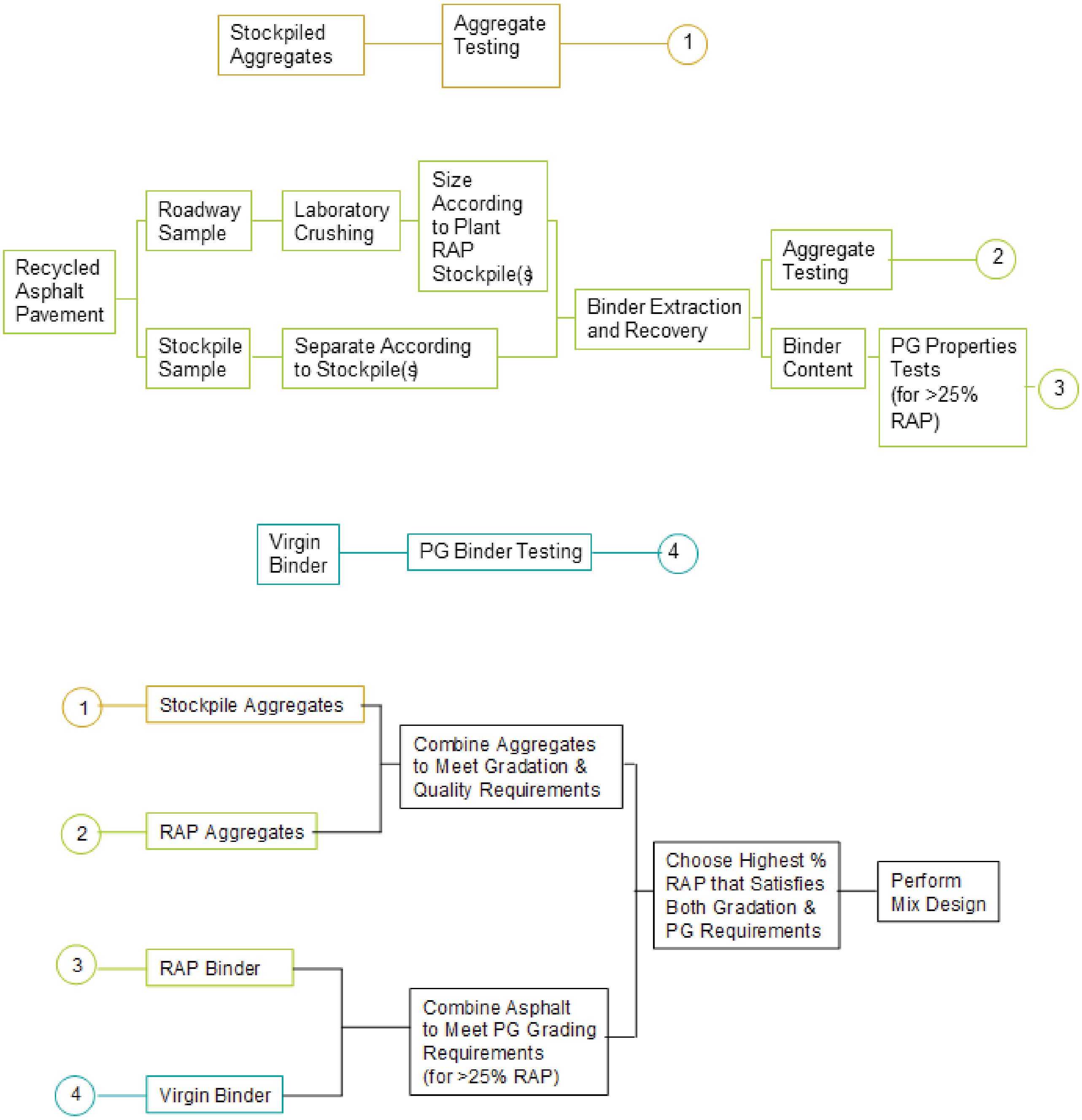


Figure 5-1. Materials Evaluation Prior to Mixture Design.

instance, RAP from commercial projects, such as parking lots, may be more likely to have lesser quality aggregate, a finer gradation, and perhaps higher asphalt content than RAP taken from a high-volume road or a commercial airport. Other considerations include different pavement ages and whether the RAP is from plant waste or returned asphalt mixture that has not been subject to in-service aging or milling.

One of the biggest issues surrounding RAP is what PG grade and how much virgin binder should be used to ensure adequate performance of RAP mixtures. Advanced Asphalt Technologies (2012) reported that RAP typically has a high-temperature PG grade between 82 and 100, and that RAP binders become fluid enough to mix at warm-mix asphalt production temperatures. This agrees with values reported by Hajj et al. (2007) for RAP materials in Nevada. Hajj et al. (2007) and Zofka et al. (2004) both suggested that the use of blending charts is an appropriate approach to determining the quantity and grade of virgin asphalt binder to be used in RAP mixtures. As shown in Figure 5-2, a blending chart assumes a linear relationship between the critical high temperature grade of the virgin asphalt and that of the RAP binder according to the proportion of the RAP.

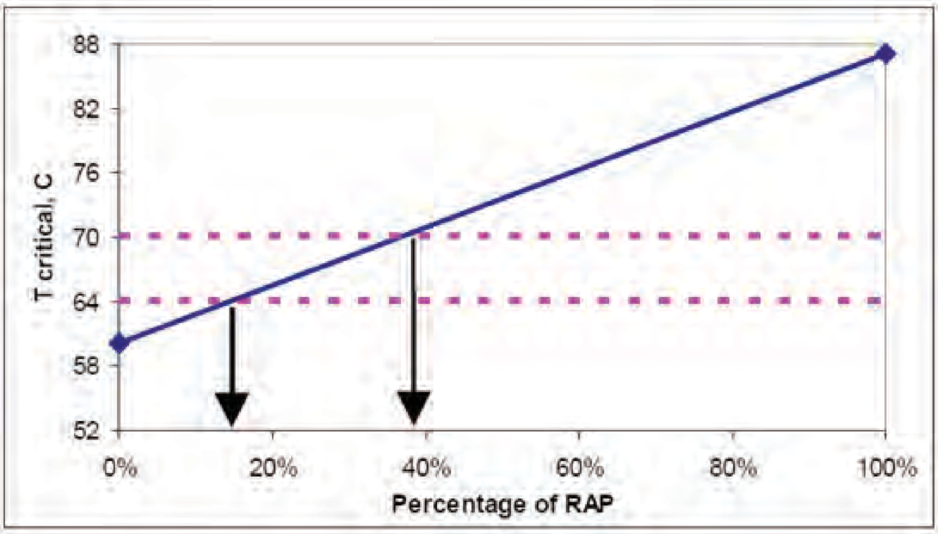


Figure 5-2. RAP Blending Chart Based on Critical High Temperature.

RAS should be characterized by its source according to whether it originates from manufactured waste (MWAS) or post-consumer (PCAS). Manufactured waste shingles are typically from punch-out tabs or off-color shingles. MWAS RAS typically has harder asphalt than RAP despite not having been aged, because roofing binders need added high-temperature viscosity to prevent the asphalt from running off roofs in hot weather (Hansen, 2009).

On the other hand, PCAS are considerably harder than MWAS because PCAS have typically been in service for 10 to 20 years. Zhou et al. (2013b) have shown that manufactured waste shingles have a high-temperature PG grade of between 115 and 140 while post-consumer shingles may have a high-temperature PG grade range of 160 to 215. As discussed in Chapter 7, "Production Operations," PCAS must undergo processing and evaluation to ensure that debris, such as nails, wood, and other materials, has not contaminated the shingle material. Typically, PCAS has a higher asphalt content than MWAS because of granular material lost during the shingles' service life (Willis, 2013).

The typical approach to incorporating RAP and RAS into mixtures has been to use a normal PG grade virgin binder in conjunction with the replacement binder. This has proven effective in instances where a relatively low amount of binder replacement (less than 25%) has been the target. However, at higher amounts of RAP and especially with RAS, it may be necessary to use a softer binder or an extender or rejuvenator in order to take full advantage of the replacement binders (Tran et al., 2012).

Past studies (Dunning & Mendenhall, 1978; Newcomb et al., 1984) have indicated that rejuvenating agents with high amounts of polar aromatics are most effective in restoring the binder properties. NCHRP Project 09-58 being conducted at Texas A&M University is investigating the use of recycling agents for asphalt mixtures containing RAP and RAS. It is scheduled to conclude in October of 2017.

For RAP and RAS mixtures with 25% or more binder replacement, the asphalt needs to be extracted and recovered (if it is to be tested) and the aggregate needs to be tested according to gradation and quality. McDaniel & Shah (2003) suggested that when less than 15% RAP was used in asphalt mixtures, the PG binder grade could remain the same as in a mixture made with virgin materials. When 15 to 25% RAP was used, it was suggested that the PG binder grade be dropped by one grade on both the low and high temperature ends.

At RAP levels greater than 25%, it was suggested that both the RAP and virgin binders or recycling agents be tested and that a blending chart be used to determine the allowable amount of RAP and the mechanical properties of the HMA be determined. However, McDaniel and her colleagues (2012a) re-evaluated their position in a later study involving mixtures from a number of Midwestern contractors in which they found that up to 25% RAP could be incorporated before using one grade softer asphalt, and that between 25 and 40% RAP could be produced using an asphalt that was one grade softer.

Many states have opted to use different percentages of RAP based on local experience rather than these guidelines. It is important to note that while guidelines are often based on total RAP content, the binder stiffness in the recycled mix is affected more by the RAP age and RAP binder content. Thus, the term “binder replacement” has come into use recently to denote the fraction of the total binder that is comprised of recycled binder from RAP or RAS.

Extracting asphalt binder from RAS is problematic due to the presence of polymers and fibers, as well as the overall hardness of the shingle binders. It is also difficult to determine the asphalt content of shingles from the ignition oven test as, in addition to incinerating the asphalt, it is likely that fiber material will be lost during the process.

For RAS mixtures, it is recommended that the virgin binder grade be compensated for the anticipated stiffness of the RAS binder. As shown in Figure 5-3 below from Zhou et al. (2013b) , MWAS will have a lower stiffness than PCAS. It is recommended that, in the absence of better information, the average high temperature values of MWAS presented in Figure 5-3 be used for consideration of selecting a suitable virgin binder grade or recycling agent.

Aggregate gradation and quality influence mix performance and therefore must be checked to investigate their impact on the total asphalt mixture gradation and quality according to consensus properties. Certain types of testing may be superfluous, such as testing the cleanliness or plasticity of the finest fraction, but issues such as degradation or abrasion resistance may be important, especially in the larger sizes.

Adjusting Volumetrics

The variability in RAS and RAP materials is often questioned because they can come from multiple sources. Proper processing, sizing, and blending (see Chapter 7, “Production Operations”) can minimize the amount of variability in the recycled materials and the final product. While these are discussed in greater detail later, a summary of good practices will be presented here.

The processing of RAS is dependent upon the source of the material. Post-construction material must have contaminants, such as nails, wood, roofing felt, etc., from demolition activities removed before use. Both PCAS and MWAS need to be ground to a usable size before stockpiling. AASHTO MP 23-14 requires a maximum size of less than 12.5 mm, although some states and contractors have found that a maximum size of less than 9.5 mm allows for greater use of the available asphalt and a better appearance in the pavement. It is advisable to separately stockpile PCAS and MWAS as tear-off shingles will have a greater asphalt content due to loss of granules during service and a harder binder due to environmental aging (Willis, 2013).

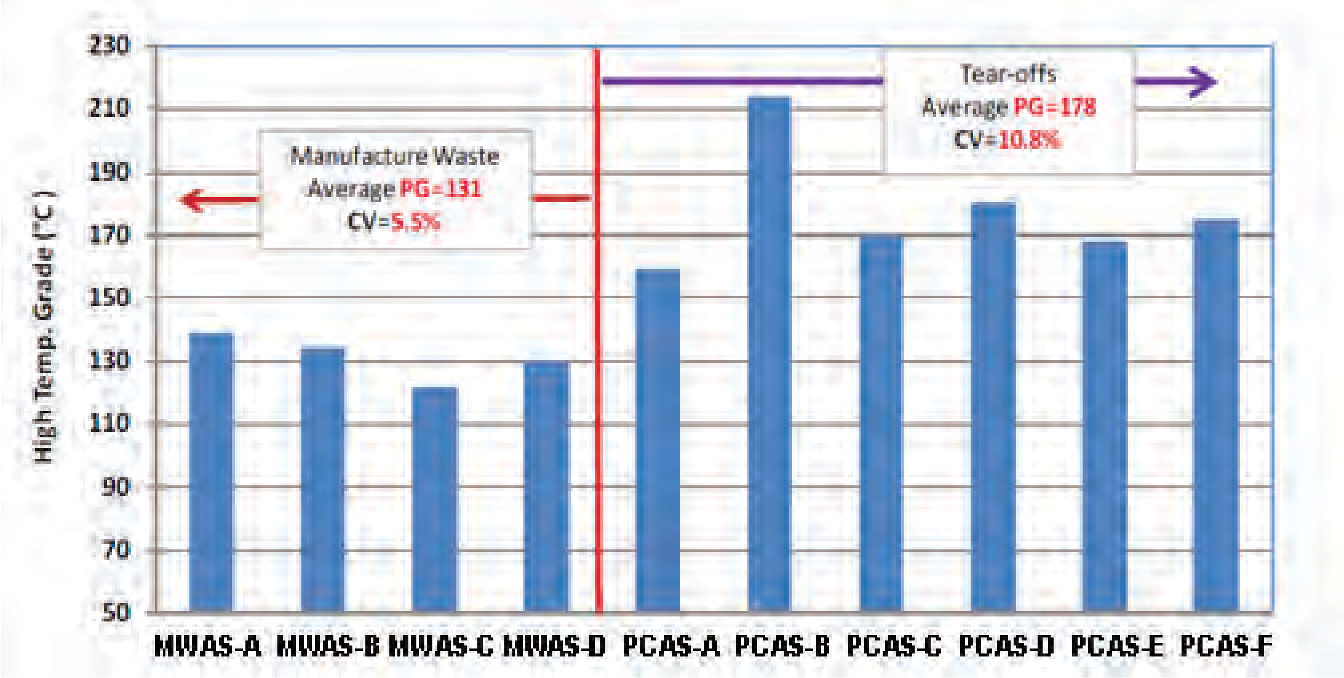


Figure 5-3. High Temperature Grades of Selected Manufactured Waste and Post-Consumer Shingles.

RAP processing begins with crushing and sizing of the material. While much of the crushing is done by milling machines during pavement surface preparation, there are also cases where slabs of material are removed from a work site and transported back to the asphalt plant.

In most cases, RAP from a number of sources is placed in a single stockpile to await further processing; however, some states require the segregation of material from different types of mixes or projects (e.g., interstate surface courses, low volume roads, etc.) (Newcomb et al., 2007). Further crushing, if needed, takes place at the plant along with the potential blending of material from different sources.

Next fractionating or sizing the particles is often done to provide flexibility for using RAP in different nominal maximum aggregate size (NMAS) mixtures. As with RAS, it is important to determine the RAP binder content of the final stockpiles so that appropriate volumetric adjustments can be made to the mixture. West (2008) in a national study and Zhou et al. (2012) in a Texas research project both found that RAP materials are very consistent in terms of gradation and asphalt content.

As more contractors use RAP and RAS in the same mixtures, the practice of combining RAP and RAS in the same stockpile is sometimes employed. It is imperative that the blending of the two recycled materials be done in a way that ensures homogeneity throughout the stockpile so that fluctuations in asphalt content and segregation of particles do not occur. Typically, anywhere from 10 to 25% RAS is combined with 75 to 90% RAP. Aside from reducing the amount of equipment needed to feed the material into the plant (one conveyor instead of two), this practice also avoids problems with shingle materials agglomerating together, something that can be problematic in warm weather.

Some agencies require RAS and RAP be fed separately into asphalt plants. Accurate scale calibration is important because RAS percentages are relatively low while RAS asphalt content is high. In these cases, some contractors have combined the RAS with fine aggregates to avoid issues with agglomeration, per AASHTO MP 23-14.

As suggested in Chapter 1 in Table 1-1, the amount of asphalt binder in RAS can vary anywhere between about 25 and 35% and, according to Scholz (2010), will depend upon whether the RAS is manufactured waste (19 to 20% asphalt binder) or post-consumer shingles (30 to 36% asphalt binder). According to Willis (2013), the amount of asphalt binder in RAS that is considered usable in asphalt mixtures varies among agencies, generally between 67 and 100%.

Most asphalt mixture design approaches focus on volumetric criteria, which may be a problem for high RAP mixtures. The calculation of voids in mineral aggregate (VMA) is dependent upon the bulk specific gravity of the uncoated aggregate in order to determine the space available for binder and air voids. In high RAP mixtures, a significant portion of the aggregate is coated with RAP binder and thus it plays a large role in the mixture VMA. Different schemes have been suggested for determining RAP aggregate specific gravity, such as:

1. Using the effective specific gravity (G_{se}),
2. Estimations based upon historical source data, and
3. Extracting or burning the asphalt from the RAP and then measuring the bulk specific gravity.

While these approaches offer the ability to estimate VMA, none have been shown to be particularly accurate. West et al. (2013) recommends extracting the asphalt and testing the uncoated RAP aggregate. Rather than relying purely on volumetric considerations, it would be preferable to develop mechanical tests that relate to the performance of the mixture in service.

Balanced Mix Design

An approach to a balanced mix design for RAP and RAS mixtures was presented by Zhou et al. (2012) in which volumetric factors, cracking resistance, and rutting resistance are all considered. This approach is presented in Figure 5-4 with the RAP/RAS and virgin aggregates proportioned according to the desired amount of recycled material content needed to meet the gradation requirements. Three virgin asphalt contents in 0.5% increments are selected. The RAP/RAS is left to heat overnight in a 140°F oven, while the virgin aggregates are heated to the desired mixing temperature. The RAP/RAS and the virgin aggregates are combined with the virgin asphalt, which has been heated to the mixing temperature.

Compaction is done at two levels: one for volumetric purposes and one for performance testing. The volumetric criterion is based upon a level of density (98% of maximum) necessary to prevent bleeding of the pavement. VMA is not considered in this approach because of problems in ascertaining the specific grav-

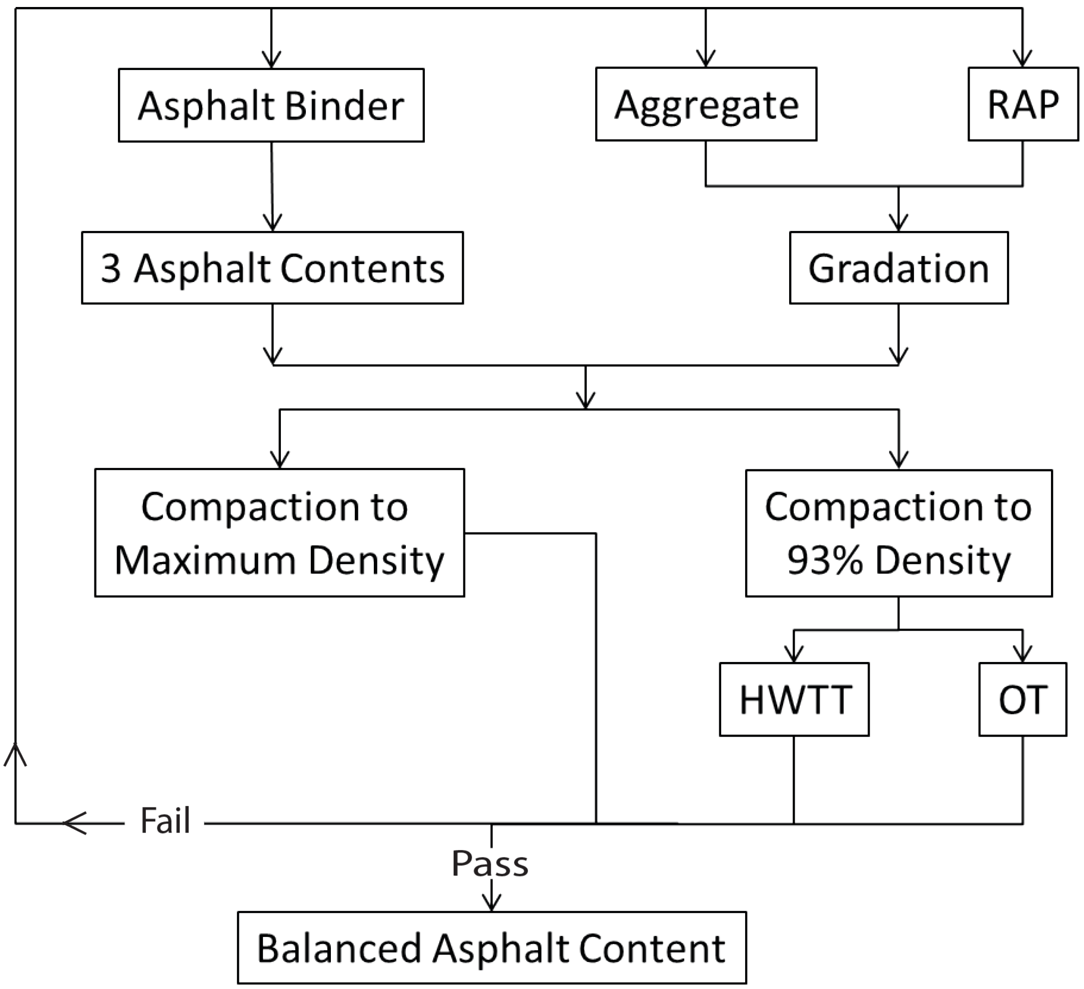


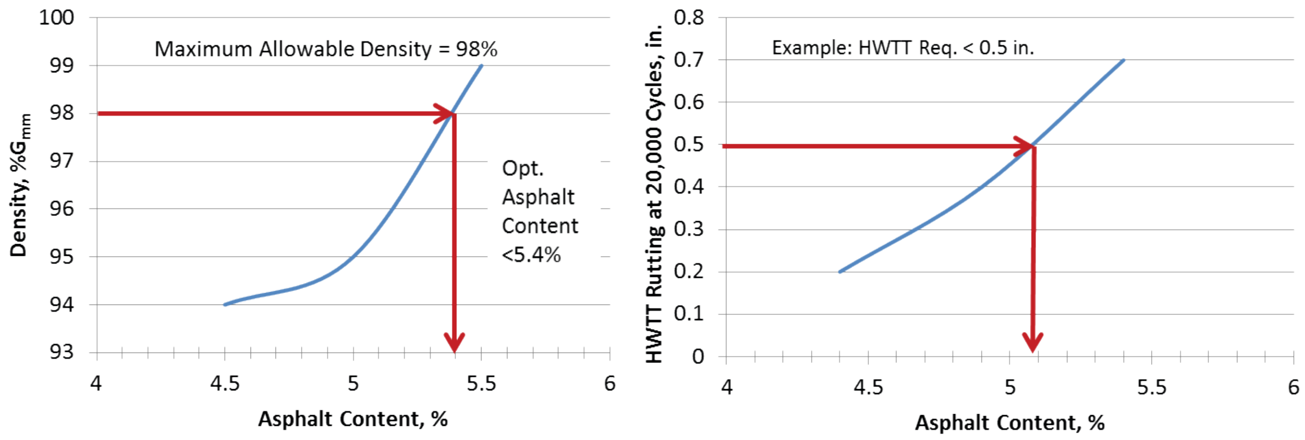
Figure 5-4. Balanced Mix Design Approach (Zhou et al., 2012).

ity of the coated RAP aggregate, a concern that was substantiated by Hajj et al. (2012b). A density level of 93% of maximum is used for the overlay tester (OT) and Hamburg wheel tracking test (HWTT). Graphs of asphalt content versus OT cycles to failure and HWTT rutting at 20,000 cycles are prepared. The lowest asphalt content that passes the density requirement, meets the maximum rut depth requirement in the HWTT, and passes the OT requirement is the optimum asphalt content (OAC).

An illustration of the principles of this approach is given in Figure 5-5 using a fictitious set of data. The following assumptions apply:

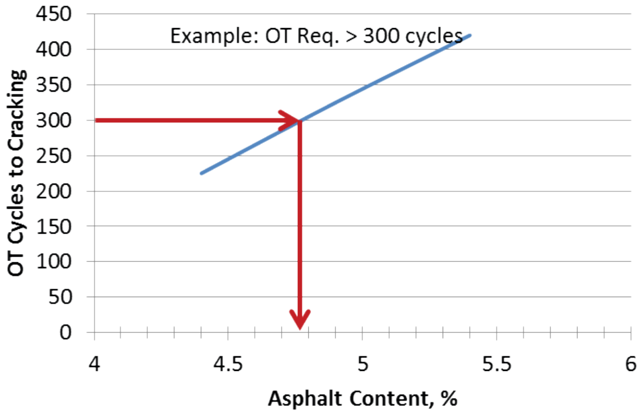
1. The total asphalt content is the sum of the virgin plus binder replacement in the recycled mix.
2. A criterion of a minimum of 300 cycles for the OT is applied.
3. A criterion of a maximum of 0.5 inches of rutting is applied for the HWTT.
4. OAC is the higher of the two values from the cracking and rutting criteria that still passes the other criterion.

To begin, the asphalt content is plotted against the maximum density achieved in a gyratory compactor for the volumetric analysis. The maximum asphalt content (5.4%) is set as the asphalt content at 98% density in order to avoid bleeding and rutting, as shown in Figure 5-5a. Next, samples are prepared and tested at three asphalt contents: 5.4, 4.9, and 4.4%. The overlay tester results show that 300 cycles corresponds to 4.9% asphalt as a minimum (Figure 5-5b), and the HWTT shows that 0.5 inches of rutting corresponds to 5.1% asphalt (Figure 5-5c). Since asphalt contents greater than 5.1% would exceed the rutting criteria, and asphalt contents less than 4.8% would fail to meet the minimum number of cycles in the overlay tester, the OAC is the higher of the two values, i.e., 5.1% (Figure 5-5d).



a. Volumetric Analysis to Set Max. Asphalt Content

c. HWTT Results



b. Overlay Tester Results

- Maximum Asphalt Content = 5.4%
- Opt. Asphalt Content (OAC)= Lowest Asphalt Content for Cracking Resistance or Highest Asphalt Content for Rutting Resistance
- OAC = 5.1%

d. Summary of Results

Figure 5-5. Illustration of Balanced Mix Design Approach.

Mechanical Properties of Mixtures Containing RAP and RAS

Performance testing of asphalt mixtures has become more important as asphalt mixtures have changed from low binder replacement mixtures produced at hot-mix temperatures to higher binder replacement mixtures produced over a range of temperatures from 240°F to 325°F.

As previously discussed, volumetric criteria, such as VMA, become more nebulous as asphalt paving mixtures change from their traditional compositions to new mixtures containing higher polymer levels and higher binder replacement levels manufactured under different conditions, such as lower temperatures with workability additives or foamed asphalt binders.

This section contains information pertinent to the effects of RAP and RAS on the mechanical behavior of binders and mixtures.

Binders

Generally speaking, RAP or RAS binders have been characterized by their incremental or continuous PG grading according to AASHTO M 320 or by stiffness as measured in a dynamic shear rheometer (DSR). These tests are performed on materials extracted according to AASHTO T 164 or T 176 and recovered by means of AASHTO T 170 or ASTM D5404, or by using the combined extraction and recovery process described in AASHTO TP 2. The main issue with testing binders that have been extracted and recovered is the assumption that the binder properties reflect the behavior of a completely blended binder rather than the possible virgin and replacement binders acting in different phases within the mix. It is widely acknowledged that there is some degree of blending between recycled and virgin binders, but the degree of blending is governed by the compatibility of the two binders and temperature.

McDaniel et al. (2012a) reported that high-temperature stiffness increased with increasing RAP binder content for mixtures containing up to 40% RAP. Daniel et al. (2010) concluded that for 28 field mixtures containing up to 25% RAP, the PG grade remained the same as the base (virgin) asphalt or increased one grade for high or low temperature. Willis et al. (2012) examined binders in RAP mixtures with up to 50% RAP content and tested the blends in a linear amplitude sweep (AASHTO TP 101-12-UL) using a DSR. They found that the use of a softer base binder was the best approach to improving the fatigue behavior of the blended binder. Hajj et al. (2012a) found for a project in Manitoba that binder from a 15% RAP mixture could successfully meet the requirements of a PG 58–28 binder, but that a 50% RAP mixture could not, even with a softer PG 58–35 virgin binder.

The use of RAS has the potential to significantly affect the binder properties in an asphalt mix because the binder used in manufacturing shingles is much stiffer than paving grade asphalts (Hansen, 2009). A study in Minnesota (McGraw et al., 2007) examined the effect of the combined use of RAP, PCAS, and MWAS. They compared the impact of a mix with 20% RAP with those having 15% RAP and 5% either PCAS or MWAS. They found that the inclusion of MWAS had no effect on the critical temperature, and that PCAS only increased the critical temperature by a few degrees. Middleton & Forfylow (2009) also investigated the effects of 15% RAP with 5% MWAS, and found that, compared to a virgin binder grade of PG 70–22, the low and high temperature grades were increased by one increment to PG 76–16.

Stiffness

The stiffness of mixtures containing recycled binders has been measured using various approaches. AASHTO T 342 (formerly AASHTO TP 62) is used to assess the dynamic modulus (E*) of a mixture in which a sinusoidal load is applied axially to a sample with a 100 mm diameter and approximately 150 mm high. The mixture is tested at various temperatures and frequencies. This results in a plot of E* versus reduced frequency to show the stiffness of the mixture across a spectrum of frequency.

The resilient modulus (M_R) (ASTM D7369) is determined from a vertically diametrically loaded sample on which the horizontal displacement is measured. Unlike, the dynamic modulus test, the resilient modulus uses a haversine load 0.1 second in duration followed by a 0.9 second rest period. The test is performed at various temperatures to provide a plot of MR at various temperatures.

Another stiffness measurement is the simple shear constant height test (SSCHT) described in AASHTO T 320. The sample tested is cylindrical with the load being horizontally applied to the top surface. It may be run in either monotonic loading or repeated loading conditions. With the repeated loading approach, a range of frequencies may be used at a constant temperature to determine the stiffness of the material across those frequencies. Typically, the shear modulus is determined from a frequency sweep test, while permanent deformation is assessed by a simple shear or repeated load test.

Researchers have found that stiffness tested by any of the three methods mentioned above increases with RAP content (Stroup-Gardiner & Wagner, 1999; McDaniel & Anderson, 2001; McDaniel et al., 2012a; 2012b; Li et al., 2004; Hajj et al., 2012a). It was noted by Stroup-Gardiner & Wagner (1999) and McDaniel et al. (2012a) that stiffness tended to increase more at high and intermediate temperatures than at low temperatures. McDaniel et al. (2012a) also noted that for RAP contents of up to 25%, the low-temperature stiffness did not change. McDaniel et al. (2012b) and Li et al. (2004) state that the source of the RAP had a major influence on stiffness with McDaniel et al. (2012b) concluding that some RAP sources actually reduce stiffness values.

Although the addition of PCAS or MWAS will stiffen the mixture binder, the effect on mixture stiffness depends upon the source of the shingles and the virgin binder. Middleton & Forfylow (2009) showed that there was an approximately 30% increase in resilient modulus at 5°C and 25°C when a mixture with 15% RAP and 5% MWAS was compared to a mix with a PG 70–22 asphalt. Newcomb et al. (1993) reported that the use of 5% MWAS and PCAS resulted in a decrease in temperature susceptibility where the cold temperature resilient modulus was not as high as it was for a virgin 85/100 pen asphalt mixture.

Permanent Deformation

Permanent deformation or rutting behavior is captured by a number of different methods. It is difficult to directly predict field performance from these tests because conditions such as confinement, aging, traffic loading, temperature, and aggregate orientation differ to some degree between laboratory-prepared and field mixtures. Usually these tests are used in research to provide a relative ranking between mixtures.

Laboratory rutting tests include the Asphalt Pavement Analyzer (APA) (AASHTO TP 63) and the Hamburg wheel tracking test (HWTT) (AASHTO T 324). The APA has a temperature-control chamber in which either a rectangular slab or cylindrical samples are placed. Two pressurized pneumatic tubes are placed over the samples and wheels run back and forth over the tubes.

Although a number of criteria have been developed, most often a rut depth of 7 or 8 mm after 88,000 cycles at a temperature matching the high-temperature PG grade of the asphalt is used as the definition of failure. The HWTT uses steel wheels that run directly over a slab or cylindrical samples in a 122°F water bath. Most agencies using the HWTT have adopted a failure criterion of 10 mm of rutting at 20,000 cycles. As stated earlier, these tests are used in research to provide a relative ranking of rutting resistance.

As stated above, the SSCHT (AASHTO T 320) may be operated in different modes to provide stiffness and permanent deformation data. Permanent deformation testing with this device usually consists of a repeated load and a measurement of non-recoverable (permanent) strain at different frequencies and/or temperatures. Comparisons of permanent strain after a certain number of cycles is used as the measurement for ranking.

The same testing configuration used for dynamic modulus testing (AASHTO T 342) described above is used for determining the flow number (F_n) of a material. A repeated load at an elevated temperature is employed as permanent strain is measured. The permanent strain is plotted against the number of loading cycles.

There are three phases of deformation considered in this test. The first is characterized by a steep slope, which is known as the primary or consolidation phase. The second is characterized by a less steep slope called the secondary phase. The third, or tertiary phase, has a steep slope as the material begins to fail. The F_n is the number of cycles at which the slope of the secondary permanent strain intersects the slope of the tertiary phase.

Considering the increased stiffening attributed to RAP and RAS discussed above, it is logical that regardless of how permanent deformation characteristics are measured, these mixtures almost always show appreciably less rut susceptibility than mixtures made with all virgin binder. Stroup-Gardiner & Wagner (1999), Willis et al. (2012), Tran et al. (2012), and Maupin Jr. et al. (2008) all demonstrated that RAP and RAP/RAS blend mixtures had significantly shallower rut depths in the APA than virgin mixtures.

Zhao et al. (2012) reported the same results for the HWTT, as did McDaniel et al. (2012b) for the SSCHT. The exception to the general trend was reported by Apeagyei & Diefenderfer (2011) where the high RAP mixtures actually showed a lower F_n (greater tendency for rutting) than virgin binder or lower (10 and 15%)

Table 5-1. Some of the Tests Used to Define Cracking Potential in Asphalt Mixtures

Test	Geometry	Parameters	Reference
Indirect Tensile (IDT) Test	Cylindrical	Tensile Strength Tensile Strain Dissipated Creep Strain Energy (DCSE)	ASTM D6931 AASHTO TT 322
Beam Fatigue	Beam	Number of Cycles to Failure Number of Cycles to 50% Initial Stiffness Strain Energy	ASTM D7640 AASHTO TT 321
Texas Overlay Tester	Beam	Number of Cycles to Failure	Tex-248-F
Thermal Stress Restrained Specimen Test (TSRST)	Beam	Temperature at Cracking	AASHTO TP 10
Semi-Circular Bend (SCB) Test	Half Cylinder	Fracture Toughness Crack Propagation	AASHTO TP 105-13
Disk-Shaped Compact Tension (DC(T)) Test	Partial Cylinder	Fracture Toughness Crack Propagation	ASTM D7313-07b

RAP mixtures. They explained these results by pointing out that the high RAP mixtures had lower effective asphalt contents, and that the binder blends of these mixtures had lower stiffness characteristics.

Cracking

There are different mechanisms for cracking in pavement structures that existing cracking tests attempt to mimic. One of the most frequently cited causes of cracking is fatigue due to repeated traffic loading of a pavement structure. In relatively thin asphalt structures, fatigue cracking is initiated at the bottom and propagates upward. In thicker asphalt sections, on the other hand, cracking begins at the surface and grows downward. Reflection cracking occurs in asphalt overlays of existing cracked asphalt or jointed and cracked concrete pavement structures. Finally, low-temperature cracking of an asphalt pavement can occur due to the contraction of the material in cold climates or repeated expansion and contraction in climates with pronounced and frequent daily temperature changes.

Cracking tests for asphalt mixtures may be divided into those that maintain a monotonically increasing load at a constant rate of displacement to failure, those that use a repeated constant stress level or constant strain level that is applied until the material cracks, and those that use a decreasing temperature to induce loading on a restrained sample. In addition, different specimen geometries have been employed for mixture cracking tests, including cylindrical and prismatic beams.

The analysis of the resulting data may include tensile strength and strain, number of cycles to complete cracking, the number of cycles to 50% loss of modulus, the dissipated strain energy, or the critical cracking temperature. As might be surmised, there are a large number of approaches to testing and analyzing materials for their cracking potential. Table 5-1 presents a list of cracking tests used for asphalt mixtures along with the AASHTO or ASTM procedures or references that describe them.

General Tensile Strength and Strain. Indirect tensile strength is a relatively simple test to perform and depending upon the study both stress and strain at failure may be reported. Stroup-Gardiner & Wagner (1999) concluded that tensile strengths were not significantly different between mixtures with RAP or completely virgin binders; however, RAP mixtures showed an increase in stiffness even at RAP contents as low as 15%. Huang et al. (2011) came to a different conclusion regarding strength (increased with RAP content), and they also reported that the brittleness of the mixtures increased with RAP content. Newcomb et al. (1993) showed that mixtures containing MWAS had the same or lower tensile strengths than their corresponding control mixtures, but that PCAS mixtures had higher tensile strengths. Thus, it can be concluded that it is not only the content of RAP or RAS in a mixture that is important to tensile strength, but possibly binder compatibility and mixture characteristics.

Fatigue Cracking. Beam fatigue testing offers the advantage of simulating repeated wheel loading patterns, but it is somewhat time consuming. This type of testing has shown that RAP and RAS binders will stiffen the resulting mixture binder, but this does not always result in a lower fatigue life for the mixture. Laboratory fatigue testing only considers the material's response to repeated loading; it cannot account for differences in loadings and pavement thickness considerations, both of which may result in longer rest periods and lower strains in the field.

McDaniel & Anderson (2001) reported that fatigue life decreases with increasing amounts of RAP. Huang et al. (2011) reported conflicting results with the dissipated creep strain threshold from IDT testing at 25°C showing lower fatigue life with RAP, but higher plateau values of the ratio of dissipated energy change were observed with higher RAP content, which should mean greater fatigue resistance. They also stated that beam fatigue testing showed that the number of cycles to 50% decrease in stiffness was greater for higher RAP, which means greater fatigue resistance.

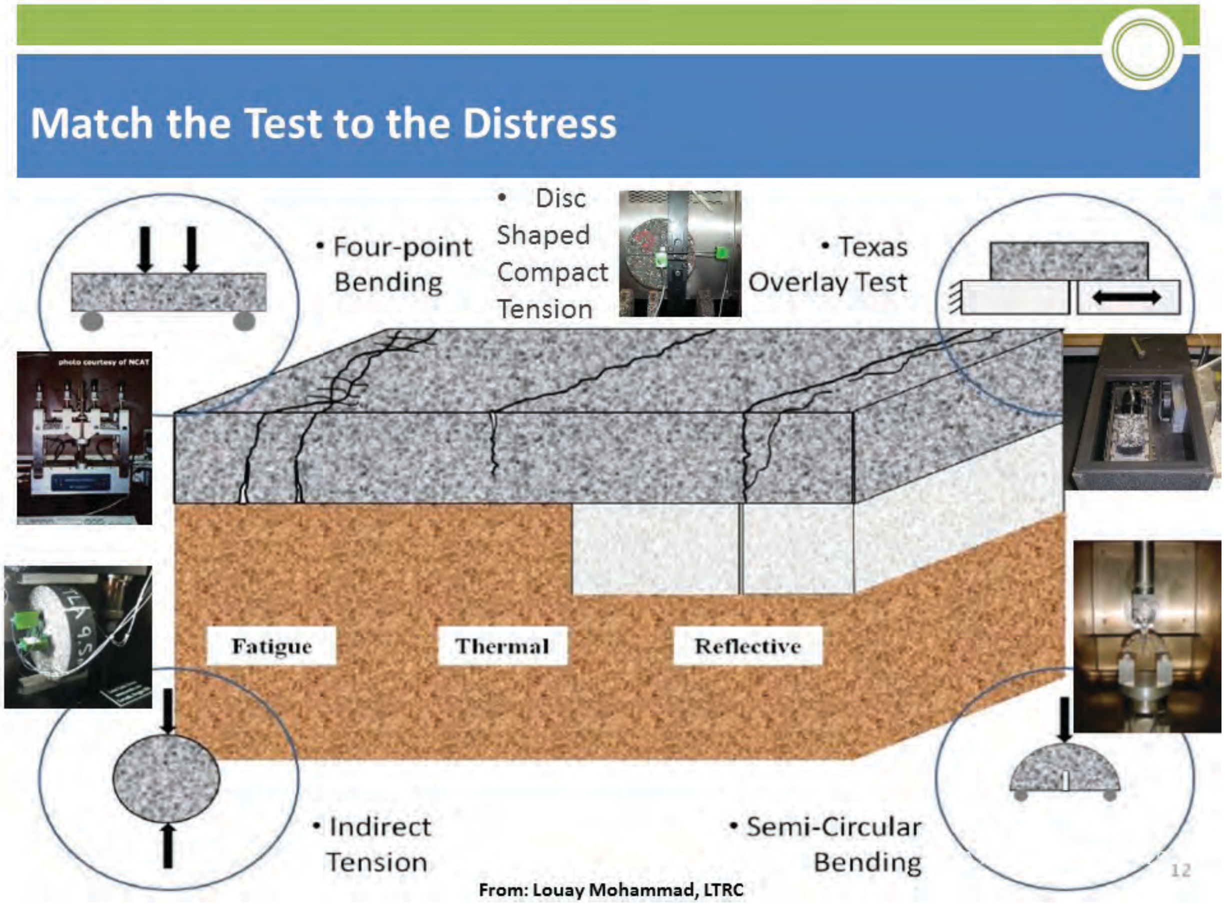
According to Hajj et al. (2007) RAP mixtures had lower numbers of cycles to failure in beam fatigue than virgin polymer-modified mixtures but better results than virgin neat binder mixtures. An improvement in fatigue behavior was noted by Zhao et al. (2012) when up to 30% RAP was used in warm-mix asphalt, but a decline was observed when RAP was used in the same mixes produced at hot-mix temperatures. In a study of 10 plant-produced mixtures with more than 20% RAP, Maupin Jr. et al. (2008) concluded that there were no significant differences between RAP and the control mixtures.

McDaniel et al. (2012b) reported results from a relatively new testing approach using a push-pull method developed by FHWA's Turner-Fairbank Highway Research Center. This testing showed that 40% RAP mixes had the greatest life in many cases and that using a softer binder could increase fatigue life for 25% RAP mixes.

Reflection Cracking Testing. The Texas Overlay Tester (OT) was developed at the Texas A&M Transportation Institute to assess the resistance of asphalt mixtures to the reflection of existing cracks and joints due to repeated openings and closings. One side of a prismatic sample is glued to two plates with a small gap between them. The two plates are pulled apart and pushed together over a distance of 0.025 inches, simulating the opening and closing of a crack.

The test is normally performed at 77°F at a rate of 10 seconds per cycle. Although this is a repeated load test used to simulate reflection cracking in overlays, it should not be confused with beam fatigue testing. Mogawer et al. (2012) tested 18 plant-produced mixtures with up to 40% RAP content, and found that RAP mixtures showed decreased fatigue resistance in the OT compared to virgin mixtures. The use of a softer grade of virgin binder showed mixed results in terms of improvement with RAP mixtures. Willis et al. (2012) tested mixtures at a reduced displacement of 0.013 inches with up to 50% RAP. In this study, OT results were improved for 25% and 50% RAP mixtures when a softer virgin binder was used. Tran et al. (2012) investigated mixtures with no replaced binders, 50% RAP, and 20% RAP with 5% RAS along with the addition of 12% rejuvenating agent (by weight of binder). The addition of the rejuvenating agent improved the fatigue behavior of the mixtures.

Low-Temperature Cracking. Low-temperature cracking is conducted in cold conditions with a very slow rate of loading to mimic the gradual loading imposed on a pavement structure due to contraction of the material during cooling. In cold climates, this distress is one of the primary concerns for mixtures with brittle binders. Stroup-Gardiner & Wagner (1999) found that RAP mixtures were less compliant (more brittle) in low-temperature IDT creep compliance than


Match the Test to the Distress

- Four-point Bending
- Disc Shaped Compact Tension
- Texas Overlay Test
- Indirect Tension
- Semi-Circular Bending

From: Louay Mohammad, LTRC

Figure 5-6. Different Tests Measure Different Distresses and Failure Mechanisms.

a virgin mixture at 0°C and –10°C, but were similar to the virgin mixture at –20°C. Li et al. (2008) presented Semi-Circular Bend (SCB) test results showing that a mixture with 20% RAP was similar to a control mixture, but that a 40% RAP mixture had significantly lower low-temperature fracture resistance.

Behnia et al. (2010) investigated mixtures made from four RAP sources at 0 and 30% RAP with PG 64–22 and PG 58–28 virgin binders. They used the disk-shaped compact tension test (DC(T)) and found that RAP mixtures with softer binders had acceptable low-temperature fracture properties compared to the PG 64–22 control mix. Tran et al. (2012) found that a rejuvenating agent improved the low-temperature critical cracking temperature in the IDT creep mode for mixes containing high amounts of binder replacement from RAP and RAS.

Hajj et al. (2012) used the TSRST to evaluate the low-temperature behavior of 0, 15, and 50% RAP mixtures. The TSRST fracture temperatures for the 15% RAP content specimens were very similar to the virgin binder low critical temperature. The 50% RAP content specimens had TSRST fracture temperatures several degrees warmer than the virgin binder, indicating decreased thermal cracking resistance. However, using a softer virgin binder (PG 52–34) improved the TSRST fracture temperature for the 50% RAP mix over the mixture using the virgin binder with no grade change (PG 58–28).

Moisture Sensitivity

Moisture susceptibility is most often evaluated using the tensile strength ratio (TSR) from AASHTO TT 283 or the HWTT test from AASHTO T 320. The TSR is determined by the ratio of the tensile strength of a moisture-conditioned sample to the tensile strength of an unconditioned sample. HWTT test, as described earlier, produces a rutting measurement of a sample in a 50°C water bath after 20,000 cycles of loading. None of the studies reviewed (Stroup-Gardiner & Wagner, 1999; Mogawer et al., 2012; and Hajj et al., 2012) showed any discernible influence of RAP on the moisture sensitivity of asphalt mixtures.

Summary

This section has discussed the design and mechanical behavior of mixtures containing RAP and RAS. There are numerous issues in using volumetric criteria as the only approach to determining the composition of mixtures. For instance, there is uncertainty concerning the amount of blending between RAP or RAS binders and virgin binders.

While some states require using a softer grade of virgin binder with certain levels of binder replacement, there is no guarantee that it is either necessary to use a softer binder or that a softer binder will have the desired results.

Determination of VMA, one of the more critical mixture volumetric parameters, is uncertain due to the difficulty of determining the specific gravity of RAP aggregate. A balanced approach to determining the optimum composition of mixtures using appropriate performance tests may be considered in developing high binder replacement mixes.

The following can be deduced from the literature cited in terms of increasing binder replacement from RAP or RAS:

1. At lower levels of binder replacement, combined binder grading tends to remain at or near the level of the virgin binder, but at higher levels of binder replacement the combined binder grading increases both the high- and low-temperature grades.
2. The stiffness of mixtures increases with binder replacement, more so at higher temperatures than at lower temperatures.
3. Rutting resistance improves at all levels of binder replacement.
4. Cracking resistance generally lowers with increasing RAP and RAS content, but this is not universally true. However, when observed, cracking has been at acceptable levels.
5. The use of softer binder grades and rejuvenators has been shown to improve cracking resistance for high recycled material content mixtures.
6. Moisture sensitivity of mixtures is not generally affected by the use of RAP and RAS.

As discussed in the next section, Chapter 6, “Pavement Design Considerations,” there are different requirements for mixtures according to where they are placed in the pavement structure.

Generally, higher binder replacement mixtures should be used where rutting resistance is of higher importance and the cracking potential should be evaluated through performance testing.

This section has shown that there are ways to enhance the performance of binder replacement mixtures through thoughtful mix design and careful evaluation.

6

Pavement Design Considerations

Pavement design is often perceived as being the practice of determining the thickness of various layers of materials to withstand the traffic load over a given period of time. However, there is more to pavement design than merely determining layer thicknesses. The materials selected for the various layers must be engineered to perform specific functions within the pavement system in order to obtain the desired performance and economy. The incorporation of RAP and RAS mixtures in pavement layers must be considered with respect to the requirements of the structure and their placement within it.

Mixture Type Selection

Pavement design and mixture type selection are interdependent activities that reflect a mixture's role in ensuring the desired pavement performance, as well as making the structure as economical as possible. Usually, the more expensive materials are used in the top layers of the pavement where there is a greater demand for performance. The surface layer of a pavement is subjected to the highest vehicle load-induced stresses and the greatest thermal stresses due to temperature swings while also providing friction for safety and smoothness for comfort. Because of these requirements, the surface layer demands the greatest consideration in material selection, mixture design, and construction.

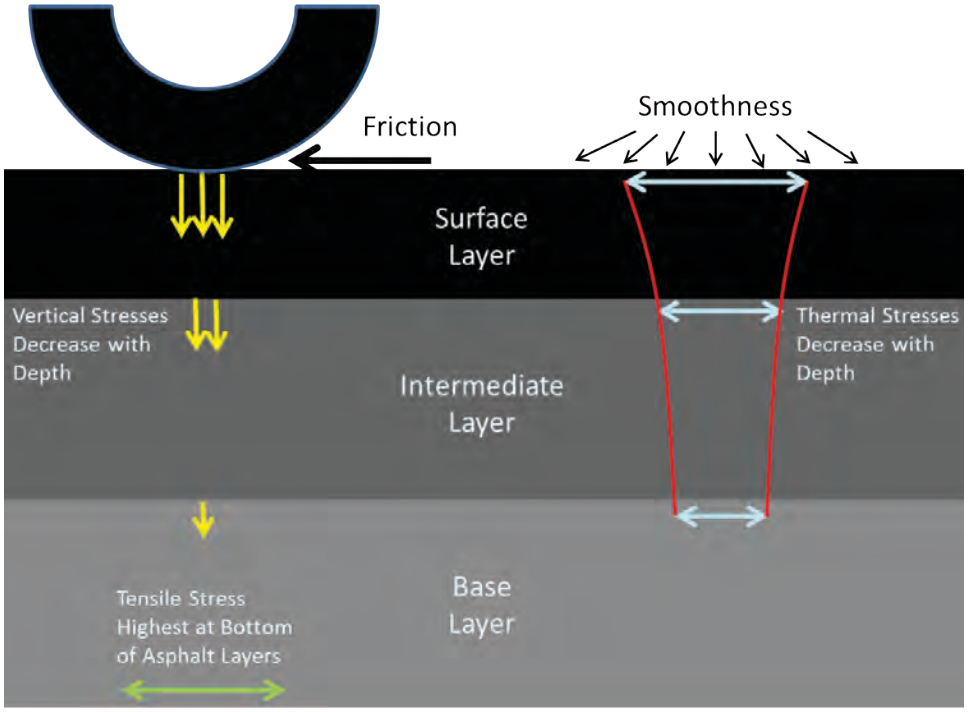


Figure 6-1. Loading and Surface Demands on Asphalt Pavements.

On high-volume roads and in more severe climates, the surface layer usually has stricter requirements for aggregates to provide skid resistance and a wider range between the high and low PG grades of the binder to prevent thermal cracking and rutting due to temperature extremes at the surface. The intermediate layer, while subjected to lower stresses, must still resist rutting under high loads at high temperatures and therefore requires a high degree of aggregate interlock. Finally, the base layer should be comprised of materials that resist cracking either by being flexible enough to bend without fracturing or by being rigid enough so that tensile strains remain below what is required to initiate cracking. The demands on materials in various asphalt pavement layers are illustrated in Figure 6-1.

Most state agencies allow greater levels of binder replacement in lower layers than in surface layers (Copeland, 2011). This is due to the concern that cracking in the upper layers may be exacerbated by brittleness that can occur in some high binder replacement mix-

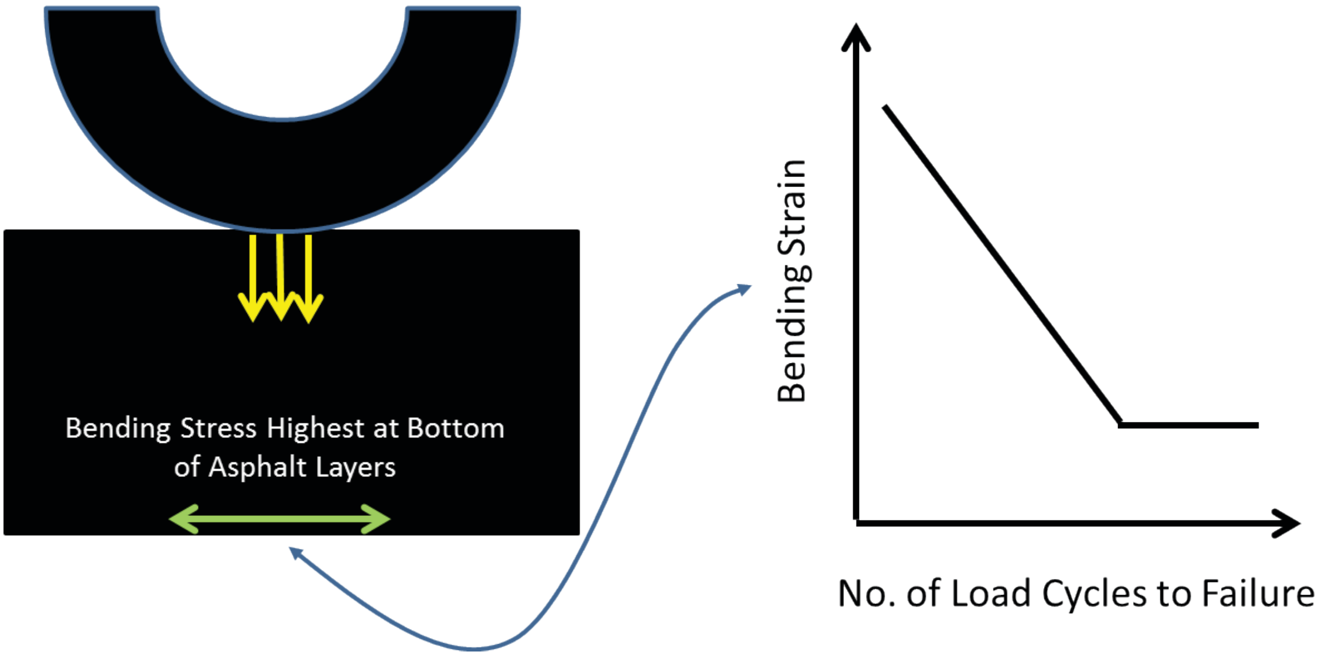


Figure 6-2. Depiction of Bending Strain Related to Fatigue Failure.

tures. However, as discussed in Chapter 5, "Mixture Design and Characterization," it is both mix stiffness and binder content that affect cracking. Mixtures with stiffer asphalt binders can be designed so that a greater effective asphalt content can be employed to provide a greater asphalt film thickness to reduce cracking while also providing rutting resistance.

Performance Considerations

The overall thickness of asphalt used in a pavement must also be considered. Low-volume roads are often comprised of relatively thin asphalt layers over a flexible aggregate base. In these applications, the asphalt layer must remain flexible to resist cracking due to higher deflections under heavy loads. In these instances, RAP and RAS bearing mixtures may benefit from a higher overall binder content.

Flexibility is also an important consideration for asphalt overlays, especially when the existing pavement structure has cracking that may reflect through the surface. However, the best method to avoid reflection cracking from existing asphalt pavements is to remove surface defects by means of milling prior to applying an overlay. For asphalt overlays over concrete pavements, the concrete slabs should be fractured (crack and seat, break and seat, or rubblization) to reduce both horizontal and vertical movement.

Pavement performance as it relates to asphalt mixture characteristics is typically described in terms of distresses to be avoided in service. These include bottom-up fatigue cracking, top-down cracking, thermal cracking, rutting, and moisture damage (stripping). In designing a pavement to resist these distresses, mix design and material selection principles play a key role, along with pavement thickness. As such, the amount and stiffness of replacement binder will have an impact on the overall performance of the pavement.

Bottom-up fatigue cracking has long been recognized as one of the more catastrophic pavement distresses. It initiates at the boundary between the lowest asphalt layer and the layer below, which may be soil, aggregate base, or stabilized base. It occurs when the material is subject to a bending strain under load that is large enough to initiate cracking usually after many loading cycles, as shown in Figure 6-2. It is possible to reduce bending strain in an asphalt pavement through a combination of total asphalt thickness and mixture stiffness to achieve fatigue resistance.

Mahoney (2001) suggests that bottom-up fatigue cracking in highway pavements is generally restricted to asphalt pavements of 6 inches or less. Research at the NCAT Pavement Test Track has shown that stiff pavements made with high percentages of RAP (45%) have load-induced strains below the limiting strain or endurance limit of the mixture (Vargas-Nordcbeck & Timm, 2012). Therefore, reducing the strain in the lowest pavement layer may be accomplished either by increasing the total thickness of the asphalt layers or by increasing the stiffness of the pavement system.

Combining the effects of mix stiffness with pavement thickness can be very successful in avoiding bottom-up fatigue cracking. Using high binder replacement in lower layers is feasible and is frequently featured in specifications for asphalt base mixtures. However, to ensure the best long-term performance for asphalt base mixtures containing high binder replacement, it may be best to use a low air void mixture design to obtain the greatest cracking resistance.

The exact mechanism of top-down cracking is currently [2014] being investigated through NCHRP Project 01-52 at Texas A&M University. Because the cracks propagate downward through the pavement in the longitudinal direction, it is thought that tensile strains due to wheel loading are primarily responsible (Zou & Roque, 2011). As the cracks propagate downward, their growth tends to slow as the distance from the surface increases because the energy available for crack growth decreases. The same strategy for reducing cracking at the bottom of the pavement can be used for surface mixtures as well.

Employing high-binder content mixtures, such as stone-matrix asphalt (SMA), can significantly reduce the likelihood of top-down cracking. This approach has been tried with success in a laboratory study (Newcomb et al., 1993) and in field projects in Canada where a contractor combined RAS with an SMA gradation (Hughes & Lum, 2007). To help crack resistance in high binder replacement surface mixtures, it may be best to use a softer binder or a rejuvenator to prevent an overly stiff mixture.

Thermal cracking also propagates from the top of the pavement downward. It is associated with thermal stresses that develop due to temperature changes at the surface of the pavement, causing the asphalt material to contract, resulting in transverse cracks. These may be slow-to-develop stresses that occur in cold climates, or they may be repeated stresses due to daily temperature fluctuations that often occur in desert climates. While not directly attributable to the effects of traffic loading, higher traffic volumes seem to increase the frequency of these types of cracks (Haas & Phang, 1988).

It has long been acknowledged that thermal cracking can be minimized or mitigated through the use of a softer binder and a greater volume of binder. The Superpave Performance Grading system for asphalt binders was developed so that the low-temperature portion of the PG designation could help mitigate thermal cracking. In colder or more arid climates where thermal cracking is more problematic, a lower temperature PG grade or a rejuvenator may be needed to soften the replacement binder. Beyond using the proper low-temperature PG grade, the same material selection and mix design approaches discussed above for top-down cracking can be employed to control thermal cracking.

The ability of asphalt mixtures containing RAP and RAS to resist rutting is well documented in both laboratory (Mogawer et al., 2012; Zhou, 2012) and field studies (West et al., 2013; Vargas-Nordcbeck & Timm, 2012). The stiffening of the overall binder in the mixture provides protection against rutting in addition to the aggregate structure. In some cases, the added stiffness of the binder can allow for more binder in the mixture, which may improve cracking resistance and durability. Using a small NMAS mixture with a combination of fine-sized RAP and RAS in a surface or intermediate course may reduce the need for polymer-modified binders.

Summary

Pavement design is an evolving practice where not only the thickness of the total asphalt is important, but also the type of asphalt mixture, its characteristics, and its location in the pavement structure. This allows designers to engineer a pavement according to economic considerations and the anticipated demands from traffic and the environment. High-RAP/RAS mixtures can perform well in thick pavement sections, as shown at the NCAT Test Track.

Resistance to cracking is affected both by the Performance Grade of binder in the mix, as well as by the amount of binder in the mix. Thus, it is possible to use high quantities of RAP and RAS to help mitigate cracking provided that the mix has a corresponding increased volume of binder. The greater volume of binder in these mixtures should not create problems with rutting as binders in RAP and RAS are usually much harder than virgin binders.

7

Production Operations

The construction practices associated with the use of RAP and RAS in asphalt paving mixtures are well established. This portion of the synthesis briefly describes RAP and RAS processing and stockpiling as individual materials. The production of asphalt paving mixtures containing RAP and/or RAS is jointly presented in this chapter.

It should be noted that considerable variation exists within the industry in regards to processing, stockpiling, and utilizing RAP and/or RAS in asphalt paving mixtures. Best practices associated with the use of these materials are described below and are based, in part, on Hansen (2009), Newcomb et al. (2007), Zhou et al. (2011a, 2013a, 2013b), Maupin Jr. (2010), Krivit (2007), Button et al. (1996), Chesner et al. (1998), West (2008), and West et al. (2013). Additional information can be found in the NAPA Quality Improvement Series 129 publication, *Best Practices for RAP and RAS Management* (West, 2015).

RAP Processing and Stockpile Management

RAP processing and stockpile management are key to ensuring high-quality RAP and consistent RAP mixes. The best practices described below are largely based on Young (2007), Zhou et al. (2013b), and Newcomb et al. (2007), as well as the experiences of the authors. A five-step RAP processing and stockpile management guideline is provided, discussing receiving and storage of materials; stockpile blending prior to crushing; crushing and sizing; RAP storage; and characterization of the produced RAP.

Receiving and Storage of Materials

Multiple sources of RAP are often used at asphalt mixture production facilities in urban areas. These sources may include a limited quantity of construction debris, RAP millings from overlay or rehabilitation projects, and asphalt mix plant clean-out and asphalt mix returned from paving sites.

While it is desirable to have a completely clean RAP stockpile, it is often unavoidable to have construction debris in small amounts including large-sized pieces

Figure 7-1. RAP Stockpiles. (a) Contaminated Stockpile (left); (b) Well-Maintained Stockpile (right).

of RAP, base course material, subgrade material and vegetation, and portland cement concrete together with a variety of other waste products from the site (Figure 7-1a). Contractors often visually screen loads of debris and accept or reject individual loads based on the degree of contamination. In addition, if contamination is at more than a minimal level, hand or machine removal of portions of these types of stockpiles may be necessary. A well-maintained, fractionated stockpile is shown in Figure 7-1b.

RAP millings can come from a variety of different pavements in an urban area. When all millings are placed in a single stockpile from a variety of different pavements, variability of RAP properties can be high unless stockpile blending is utilized prior to crushing and sizing. Some contractors store materials from different milling projects in different stockpiles. This stockpiling practice will likely produce the most uniform RAP, but requires considerable area for the multiple stockpiles, something that is often limited in an urban location.

Plant clean-out and/or asphalt mix returned to the plant from a paving site is often stored in a separate stockpile. This RAP source typically will contain an asphalt binder that is "softer" than the asphalt binders in debris and millings as the later material sources are usually from older pavements that have hardened during service.

Asphalt mixture production facilities in rural areas also receive RAP from multiple sources. However, some of the larger "mill and fill" projects in rural areas will receive significant quantities of RAP from a single overlay or inlay project. Very uniform RAP can be obtained on these types of projects provided the pavement removed was all placed at the same time. While this is often the case, cold mill depth may intersect layers of asphalt paving mixtures placed at different times and designed with different properties.

Data obtained from processed RAP stockpiles (West, 2008) indicate that very uniform RAP can be produced from multiple sources whether these locations are in urban or rural areas. Uniform processed RAP starts with receiving and stockpile storage of the material.

Stockpile Blending

If stockpiles are separated at the time RAP is received at a facility, it may be necessary to blend the stockpiles prior to crushing and sizing to ensure greater consistency in the makeup of the RAP. The need to blend will depend on the sources of the material in the various stockpiles and the properties of the asphalt binders and aggregates in the various stockpiles. This blending can be performed with front-end loaders extracting materials from various stockpiles and placing them in a single stockpile, or it can be performed during the crushing and sizing operations by using "one bucket" from stockpile A and "one bucket" from stockpile B, etc. Blending is critical if the stockpiles contain materials that are significantly different from one another.

Similarly, if different pavement materials sources are all placed in a single stockpile, it may be necessary to "mix" the stockpile with a front-end loader prior

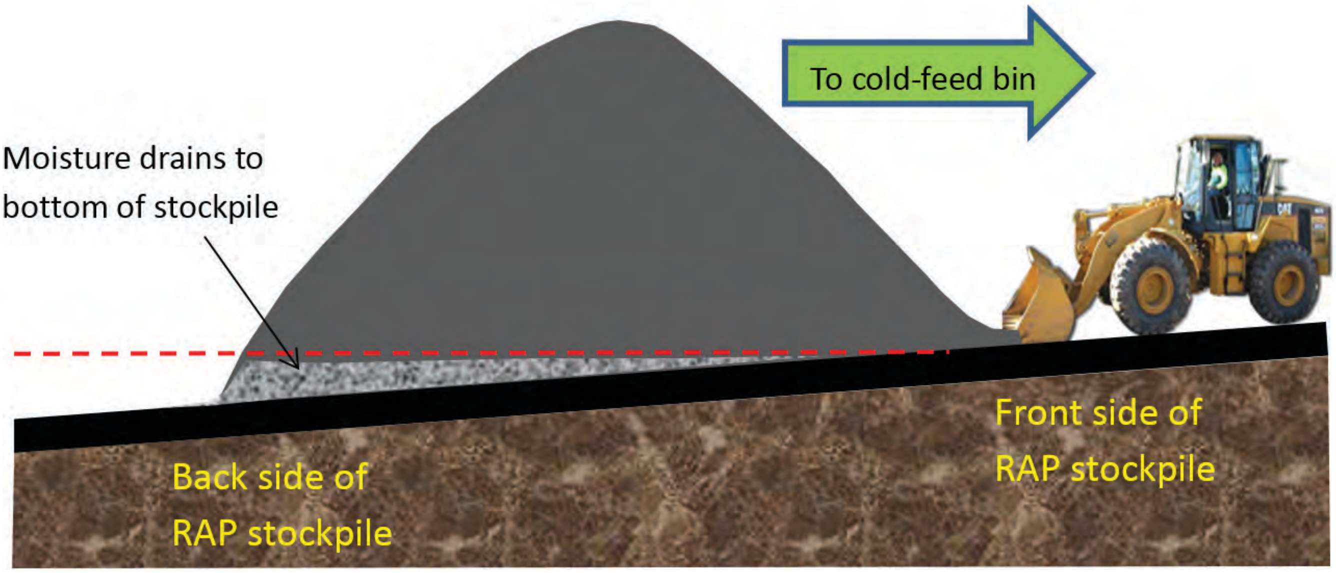


Figure 7-2. Illustration of Paved, Sloped Surface Under RAP Stockpiles.

to crushing and sizing. Another technique utilized is to load the hopper at the crushing and sizing facility from different areas of the one large stockpile, and by scooping through layers of the stockpile to feed the crusher. Again, the objective of mixing prior to crushing and sizing is to obtain a uniform RAP product.

If a stockpile contains only plant clean-out and asphalt material returned from a paving site, it may be desirable to process and produce a RAP from this and only this stockpile. The RAP produced from this type of stockpile will contain a low stiffness asphalt binder and will typically be more easily incorporated into recycled mix is at high percentages.

For large quantities of RAP, it may be important to separate RAP stockpiles obtained from different sources. In most cases, it is unnecessary to crush or fractionate a single-source RAP stockpile with a known source. Well-separated stockpiles can save time and cost for crushing or fractionating RAP. In particular, when a large quantity of millings is reclaimed from a single project, it is always worthwhile to keep that milled RAP separate from other RAP stockpiles. In some instances, state or local specifications may require the segregation of RAP stockpiles according to the source of the RAP so that, for instance, millings from interstate surfaces are separated from RAP obtained from multiple sources.

Crushing and Sizing

The purpose of crushing and sizing of RAP includes reducing the amount of oversized material and separation of the RAP into different size fractions. Most contractors crush materials and place them in a single stockpile with a maximum size particle of ½ inch or ⅜ inch. RAP produced to a smaller maximum size is typically more easily incorporated into a recycled mixture due to the larger surface area and ability of the aged asphalt binder on the RAP to blend with the virgin asphalt binder. Crushing to the smaller maximum size can increase the amount of No. 200 (0.075 mm) materials in the RAP and thus may limit the amount of RAP that can be incorporated into a recycled mixture.

Fractionating RAP refers to the separation of the produced RAP into two or more stockpiles of different sizes. Typically, two stockpiles are formed. Materials retained on the ⅜-inch or perhaps the ½-inch screen and those materials that pass the screen. Some contractors will separate RAP into three stockpiles such as ¾ inch to ⅜ inch, ⅜ inch to 3⁄16 inch, and –3⁄16 inch. Other screens are also occasionally used for these separations.

Fractionized RAP offers several advantages. The amount of materials contained on the No. 200 sieve can be controlled at high RAP contents by using more of the +⅜-inch materials and less of the –⅜-inch materials, for example. This will allow for the use of increased percentages of RAP. It should be noted that the asphalt binder content on the +⅜-inch RAP is typically lower than the –⅜-inch materials. Because the asphalt binder savings offered from the RAP asphalt binder is the major contributor to cost savings for recycled mixtures, economics dictate the use of higher quantities of –⅜-inch RAP compared to +⅜-inch materials.

RAP Storage

RAP has a tendency to hold water from rainfall and snow. In some instances, the RAP moisture content can limit the percentage of RAP that can be used in a recycled mixture. Moisture in RAP or other aggregates will reduce overall mix production rates and raise drying and heating costs. The heat of the virgin aggregate is largely responsible for heating and removing the water from the RAP. Moisture in the RAP and virgin aggregate will have a significant impact on the resulting asphalt binder content and, subsequently, on the mixture volumetric measurements and possibly on pavement performance. Therefore, it is beneficial and critical to minimize the RAP moisture content. Several measures are proposed to reduce RAP moisture content during stockpiling of the processed RAP.

Stockpile Shape

In the early years of RAP recycling, NAPA (Young, 2007) states that contractors were encouraged to form RAP stockpiles in low, horizontal piles for fear that high, conical stockpiles would cause RAP to pack together under the weight of the pile. However, experience indicates that such compaction is typically not experienced except in extremely hot climates. In addition, RAP has a tendency to hold water and low, horizontal stockpiles collect and retain higher moisture contents than tall, conical stockpiles. In general, tall, conical stockpiles are preferred.

Paved and Sloped Storage Areas

Using a paved surface under RAP stockpiles not only helps drainage but it also provides an even, hard-surfaced area to minimize material loss and contamination of underlying materials. Sloping the paved surface away from loadout (Figure 7-2) allows rainwater to drain away, ensuring drier RAP materials are used in the production of recycled mixes.

Cover RAP Stockpiles

Covering RAP stockpiles is encouraged and is can be cost effective. Covered stockpiles minimize RAP moisture content and their use is more economical than covering virgin aggregate stockpiles. RAP should never be covered with a tarp or plastic. It is best to store RAP materials under a roof of an open-sided building (Figure 7-3). Air can pass over the RAP while the RAP remains protected from precipitation.

Figure 7-3. Storing RAP Under a Covered Roof.

Characterize RAP

After the RAP stockpile has been produced, it is good practice to characterize the material properties of the RAP. At a minimum, the gradation and the% asphalt binder should be determined. These results are needed for mixture design and to characterize the variability of the RAP stockpile. It is recommended that a minimum of five samples be obtained from an individual stockpile. Sampling material during stockpiling is often a good practice.

If the variability of an individual stockpile is high, as measured by standard deviation, it may be necessary to reprocess the materials if they are to be used in high quantities. If the variability of properties between or among stockpiles is high, it may be necessary to blend RAP stockpiles either by using a front-end loader to form one stockpile from multiple stockpiles or during production. Blending of RAP stockpiles during production is preferably accomplished by using multiple RAP feeders or, only if these are not available, by charging the RAP cold-feed bin with alternating front-end loader buckets from the stockpiles of RAP.

Each produced RAP stockpile should be labeled and a sign provided on or near the stockpile for field identification purposes. These stockpile identification numbers allow the engineer to blend the materials and help the field personnel identify the correct materials for charging the RAP cold-feed bin.

RAS Processing and Stockpile Management

RAS processing and stockpile management are keys to having high-quality RAS and a consistent recycled mixture that contains RAS. The best practices described below are largely based on Hansen (2009), Zhou et al. (2010, 2011a, 2013b), Maupin Jr. et al. (2008), Maupin Jr. (2010), Krivit (2007), Button et al. (1996), and Willis (2013), as well as the experiences of the authors. A six-step RAS processing and stockpile management guideline is provided, discussing receiving, storage, and sorting operations; asbestos testing; stockpile blending prior to sizing; grinding and sizing; storage; and characterization.

Shingle Receiving, Storage, and Sorting

As stated previously, two main types of RAS are available for recycling in asphalt mixtures: manufactured waste asphalt shingles (MWAS) and tear-off/post-consumer asphalt shingles (PCAS). Manufactured waste asphalt shingles are more uniform materials than tear-off asphalt shingles (Hansen, 2009; Maupin Jr. et al., 2008). The asphalt binder in the MWAS is lower in stiffness (Button et al., 1996) and contains fewer contaminants than PCAS. However, the available quantity of PCAS is roughly 10 times that of MWAS. PCAS is available throughout the United States, but MWAS is available only in regional locations, usually near asphalt binder sources and population centers. PCAS availability is dependent on housing stock and population density.

MWAS requires little or no sorting prior to grinding and sizing, does not require testing for asbestos, and has uniform asphalt binder, aggregate, and fiber contents and characteristics. Receiving, storage, and sorting operations for asphalt shingles prior to the grinding and sizing operation are discussed below.

The term “recycler” in this section of the synthesis

Figure 7-4. Covered Shingle Stockpile with Hard Surface Behind RAS Feeding System.

refers to either the recycling company that receives MWAS and/or PCAS and processes the materials for use by the asphalt mixture contractor or the asphalt mixture contractor that processes the MWAS and/or PCAS for use. Several recycling companies receive and produce RAS for use in asphalt pavement mixtures.

Receiving

Contractors may use both MWAS and PCAS from the same recycling facility or asphalt mix plant to produce a recycled asphalt mixture. If sufficient quantities of both types of materials are available, they should be stored in separate stockpiles as the RAS produced can be significantly different.

If MWAS is received from two or more shingle manufacturing plants, the properties of the produced RAS should be determined. Different manufactures often use slightly different asphalt binders, granules, and, perhaps, filler materials. These differences are typically insignificant. The need for different stockpiles for the MWAS sources should be determined based on the binder properties and quantities.

Typically, only one PCAS receiving stockpile is formed. PCAS is received from a wide variety of reroofing sites or operations and a number of reroofing recyclers. Recyclers often assign one of their plant crew members to visually inspect arriving PCAS trucks. The inspector is often trained and certified in the identification of asbestos-containing materials. Typically, the recycler will use the visual examination to accept or reject a load of PCAS. Recyclers typically notify roofing contractors of their quality standards for acceptance. Rejected loads remain under the control of the roofing contractor.

Storage

Trucks or other construction equipment should not be allowed to operate on the shingle stockpiles to prevent stockpile compaction. Note that some recyclers allow selected construction equipment to operate on the “as received” materials without encountering compaction and without a great degree of difficulty in moving and sorting these stockpiles.

MWAS and PCAS stockpiles should be covered, as shown in Figure 7-4, to protect the material from rain and snow. If possible, stockpiles should be placed on hard, sloped surfaces to reduce contamination from the underlying material, to allow for easier clean up if asbestos-bearing materials are detected, and to allow for stockpile water drainage.

Sorting

Because it is received from a manufacturing facility, MWAS typically is not contaminated. If loads of MWAS do arrive contaminated, meetings with representatives of the asphalt shingle manufacturing plant can usually resolve any problems quickly because the material is completely under their control.

After PCAS is “tipped” at the recycling plant, a second stage of quality inspection and sorting occurs. There is no standard for processing equipment to accomplish this task and in most cases the debris is sorted manually. Most facilities use “hand” or manual sorting (“dump and pick,” sorting, conveyors, etc.) and/or mechanical equipment (screens, air classifiers, etc.). Shingle recyclers have used a wide variety of techniques to cost-effectively meet minimum waste sampling and asbestos testing requirements. Common debris found with PCAS includes nails, wood, insulation, roofing felt, cardboard, plastics, and metals. Many single recycling facilities will recover metal and cardboard as secondary recycling materials. Secondary recovery rates for PCAS are in the range of 15–90%, depending on the type of facility (Krivit, 2007).

Asbestos Testing

The federal National Emission Standards for Hazardous Air Pollutants (NESHAP, 1984) regulation states: “No person may construct or maintain a roadway with asbestos tailings or asbestos-containing waste material on that roadway….” NESHAP further defines "asbestos-containing material" (ACM) as a material containing more than 1 percent asbestos.

The use of asbestos in residential shingles was discontinued in the manufacturing process in the late 1970s, and has not been used for residential shingles in the United States for more than 30 years. Therefore, testing of MWAS is not required. While asphalt shingles are typically replaced every 15 to 25 years, many roofers place a layer of new asphalt shingles over older shingles, covering shingles that may contain asbestos. Therefore, asbestos can be present in PCAS even after more than 30 years.

Krivit (2007) advises shingle recycling operators to attend state-sponsored training courses to become licensed asbestos inspectors. Trained personnel should inspect each load to visually detect possible ACM. This helps increase awareness of potential asbestos-containing materials and allows company personnel to provide accurate, timely, and state-approved information and related technical assistance to material suppliers and other customers. Shingle recycling operators should contact their state NESHAP representative to learn of technical assistance resources, including a list of organizations that provide asbestos inspector training. Whatever techniques are used for asbestos testing, recyclers need to continually work with reroofing contractors to ensure that no asbestos-containing material is accepted at a recycling operation (Krivit, 2007).

Figure 7-5. Nails Taken from PCAS Material During Processing.

Stockpile Blending Prior to Sizing

Accepted loads are placed in a receiving stockpile at the recycler's facility. A few recyclers test individual truckloads of PCAS for asbestos during the startup of their facility to avoid contamination of larger stockpiles with asbestos. Once a truckload is determined to be asbestos-free, the materials are placed in larger stockpile of material that has tested asbestos-free.

Grinding and Sizing

The vast majority of RAS used in asphalt paving mixes is ground into pieces smaller than ½-inch (13 mm) using a shingle grinding or shredding machine consisting of a rotary shredder and/or a high-speed hammer mill. *AASHTO MP 23-14: Standard Specification for Reclaimed Asphalt Shingles for Use in Asphalt Mixtures* states "Reclaimed asphalt shingles shall be processed so that 100 percent passes the 9.5 mm (⅜-inch) sieve" (AASHTO, 2014a).

Figure 7-6. Processed RAS Should Have the Consistency and Appearance of Coffee Grounds (Surti, 2012).

According to Krivit (2007), each grinder manufacturer uses a unique combination of material-handling and size-reduction designs. In general, the grinder will include a loading hopper; a grinding chamber that includes cutting teeth, sizing screens, and exit conveyor; and a feeding drum to present the shingles into the grinding chamber. A pulley head magnet at the end of the exit conveyor is standard equipment for removing nails and other ferrous metal (Figure 7-5). The final RAS product is stacked using a stacking conveyor and/or front-end loader.

To prevent agglomerating during grinding, the material is typically passed through the grinding equipment only once to reduce heating, or it is kept cool using a water spray system at the hammer mill. However, the application of water to shingles is not desirable, because the processed material becomes quite wet and must be dried (thus incurring additional fuel cost) prior to introduction into the mixture (Chesner et al., 1998).

After processing, shingles should have the consistency and appearance of coffee grounds (Figure 7-6) which are uniform in size, shape, and asphalt content. Ground shingles may contain oversize pieces that do not meet the specification requirement. To remove these oversized pieces, the operators ideally should screen the processed RAS using a trommel screen. This equipment can help customize the size of processed RAS, helping to guarantee that the specifications are met.

RAS Storage

Storing of processed RAS is similar to stockpiling RAP. Because the average gradation of RAS is very small, a stockpile can absorb a large amount of water, which can cause problems during asphalt mix production (inadequate coating), compaction (mat tenderness), and performance (greater stripping potential), as well as require more fuel and time for drying. For these reasons, RAS stockpiles should ideally be covered or, at a minimum, ensure adequate drainage to prevent excess moisture (Willis, 2013). Loaders should be kept off RAS stockpiles, and high-AC RAS (PCAS) should be stockpiled separately from low AC-RAS (MWAS).

Button et al. (1996) deduced that, during static storage in a stockpile, shredded roofing shingle material can agglomerate. High temperatures and stickier MWAS can magnify this issue. Significant agglomeration or consolidation of processed roofing material necessitates reprocessing and rescreening prior to introduction into the asphalt plant. To mitigate this problem, processed RAS may be blended with a small amount of a less-sticky carrier material, such as sand or RAP, to prevent the RAS particles from clumping together.

Characterize RAS

Willis (2013) provides the following best practices for characterizing RAS. It is recommended that a minimum of five tests (10 is preferred) be used to characterize a RAS stockpile in at least three locations using AASHTO T 2 sampling procedures.

Unless determining the Performance Grade of the RAS asphalt, RAS can be dried in an oven; however, oven drying may drive off additional light oils, which will stiffen the RAS binder. If the binder is to undergo Performance Grade testing, dry RAS using a fan.

RAS asphalt is stiffer than RAP or virgin asphalt because it has been air-blown and/or aged on rooftops. Rolling thin film oven (RTFO) and pressure aging vessel (PAV) aging make the material more challenging to mold and characterize. Standard waterbath DSRs cannot be used to conduct Performance Grade testing because RAS asphalt often has a PG grade greater than the boiling point of water.

RAS asphalt content should be determined by chemical extraction, unless an appropriate ignition oven correction factor can be determined. Comparisons should be conducted to determine the relative closeness of ignition oven and chemical extraction asphalt contents of same-source RAS.

Do not use an assumed RAS aggregate gradation. Conduct RAS aggregate gradation of materials recovered from chemical extraction or ignition oven testing to ensure the correct gradation is used in the mixture design process. Use the effective specific gravity (G_{se}) of the RAS aggregate as the bulk specific gravity (G_{sb}) of the RAS aggregate in volumetric mixture designs. This can be determined using standard theoretical maximum specific gravity testing or using vacuum saturation to backcalculate G_{se} for the material.

Summary

The processing, handling, stockpiling, and incorporation of RAP and RAS are critical to the ultimate performance of pavements containing higher quantities of these ingredients. Sizing RAP for its use in new asphalt mixtures needs to be such that compaction can be achieved. The contractor needs to minimize any contamination of RAP by granular base, oversized RAP particles, and other associated materials. Good RAP stockpiling practices include allowing for drainage away from the material and even providing a covered area.

RAS requires more on-site processing than RAP. There needs to be a receiving, storing and sorting area. The receiving operations should include separating MWAS from PCAS materials and sampling to test for the presence of asbestos. Sorting is done both before and after grinding the shingles. Large pieces of debris are removed by hand prior to grinding and then smaller particles, such as nails, are removed mechanically after grinding. Storage of RAS should be done in a covered facility to allow water to drain out of the stockpile and prevent excess moisture from building up in the material.

8

Field Performance

This section summarizes studies that have documented and analyzed the field performance of asphalt pavements containing RAP and RAS.

NCAT Pavement Test Track

In recent years a variety of test sections with asphalt mixtures containing moderate and high RAP/RAS were constructed and trafficked at the NCAT Pavement Test Track (Willis et al., 2009; West et al., 2012). Two test sections with mixtures containing 20% RAP and four sections with mixtures containing 45% RAP were built in 2006. The same virgin aggregates and RAP were used for all six mixtures.

The main difference among the RAP mixtures was virgin binder type. The virgin binders used in the 20% RAP mixtures were PG 67–22 and PG 76–22; the virgin binders used in the 45% RAP mixtures were PG 52–28, PG 67–22, PG 76–22, and PG 76–22 plus 1.5% Sasobit warm-mix additive. All six mixtures were placed in the 2-inch surface layers.

After more than 20 million ESALs of traffic loading within five years, all test sections performed very well in terms of rutting and cracking. West et al. (2009; 2012) reported that all sections had very little rutting (less than 5 mm). As shown in Table 8-1, low-severity cracking was observed in all the sections except for the 20% RAP section with the PG 67–22 virgin binder.

The amount of cracking correlated closely with the virgin binder grade: The softer the virgin binder, the less cracking. The 45% RAP section with PG 58–28 had only 3.5 feet of very-low-severity cracking, followed by the 45% RAP section with PG 67–22 binder containing 13.9 feet of cracking, then the 45% RAP section with PG 76–22 containing 53.9 feet of cracking. The 45% RAP section with PG 76–22 with Sasobit had 145.5 feet of total crack length. This observation indicates the importance of using a softer virgin binder grade for high RAP mixtures.

In 2009, additional high RAP test sections were constructed and evaluated during the fourth NCAT testing cycle. A 45% RAP (by weight) test section sponsored by Mississippi had only 3 mm rutting and 61 feet of low severity cracking after 10 million ESALs of traffic loading within 25 months. Furthermore, two 50% RAP sections with PG 67–22 virgin binder were investigated as part of a structural design experiment. Both sections had 50% RAP in each of the three layers of the 7-inch asphalt pavement. The only difference between them was that one of the 50% RAP sections was produced as hot-mix asphalt (HMA) and the other

Table 8-1. Cracking Measurements from RAP Sections at the NCAT Test Track (West et al., 2012).

Test Section	RAP Content[1]	RAP Binder percentage[2]	Virgin Binder Grade	Date of First Crack	ESALs at First Crack	Total Length of Cracking after 2 Cycles
W4	20%	17.6%	PG 67–22	no cracking		
W3	20%	18.2%	PG 76–22	4/7/2008	6,522,440	34.0
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 76–22+S[3]	1/28/2008	5,587,906	145.5

[1] RAP content as a percentage of the total aggregate
[2] The percentage of RAP binder relative to the total binder content
[3] This virgin binder contained 1.5% Sasobit.

Table 8-2. Comparison of High RAP and HMA and WMA Virgin Sections at the NCAT Test Track.

Section	Cracking, %	Rutting, mm
Control HMA	2	2
50% RAP HMA	0	4
50% RAP WMA	3	5
WMA Foam/No RAP	11	12
WMA Additive/No RAP	18	18

as warm-mix asphalt (WMA) using plant foaming technology. These two 50% RAP test sections were compared to a control section of HMA and two WMA sections with the same thickness but used all virgin materials and a polymer-modified PG 76–22 binder in the top two layers.

Table 8-2 shows the results of the comparisons as of February 2014 (West, 2014). It should be noted that the two 50% RAP sections have considerably less cracking and rutting than the two warm-mix sections.

LTPP

As a part of the FHWA's Long-Term Pavement Performance (LTPP) program, the Specific Pavement Study 5 (SPS-5) focused on the influence of asphalt overlay rehabilitation. A total of 18 projects were constructed in the United States and Canada and monitored over the past 25 years through the LTPP program. Each project included eight test sections and one control section. One of the main factors considered in SPS-5 test sections was virgin mixtures versus a mixture with 30% or more RAP.

West et al. (2011) reviewed the 20-year performance history of the 18 projects and compared the seven distresses of virgin mix sections with those of RAP sections, including International Roughness Index (IRI), rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling. Statistical analyses indicated that the 30% RAP mixtures had equivalent performance to virgin mixtures in

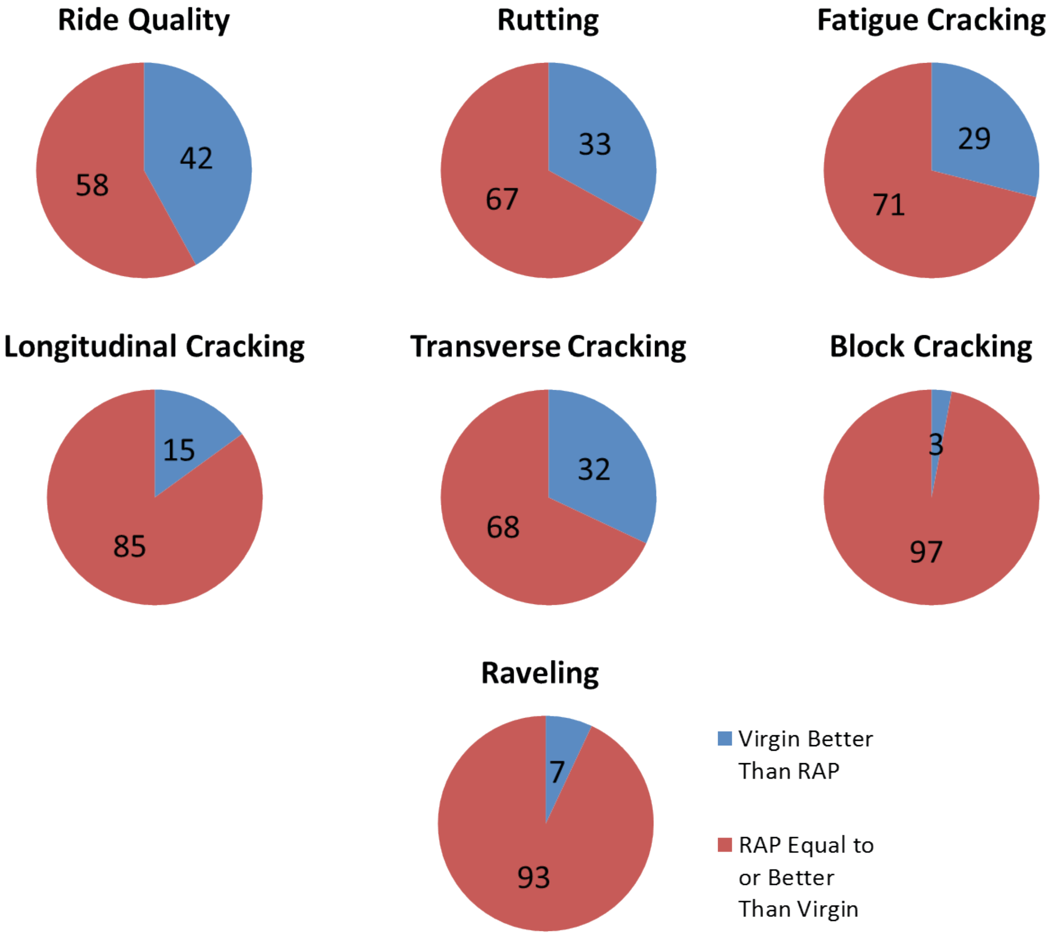


Figure 8-1. Comparison of Performance for Virgin and RAP Mixtures in the LTTP SPS-5 Sections (after West et al., 2011).

Table 8-3. Comparison of Performance Sections: Virgin vs. 30% RAP Mixtures (after West et al. 2011).

Distress Parameter	Difference Between RAP and Virgin Mixes Not Significant (%)	Virgin Mixes Better Than RAP Mixes (%)	RAP Mixes Better Than Virgin Mixes (%)	RAP Mixes Equal to or Better Than Virgin Mixes (%)
IRI	19	42	39	58
Rutting	38	33	29	67
Fatigue Cracking	61	29	10	71
Longitudinal Cracking	75	15	10	85
Transverse Cracking	53	32	15	68
Block Cracking	96	3	1	97
Raveling	78	7	15	93

terms of IRI, rutting, block cracking, and raveling, as shown in Table 8-3 and Figure 8-1. West et al. (2011) also reported that about one-third of the projects had more longitudinal cracking or transverse cracking in the RAP sections compared to the virgin mix sections. In a later report, West & Willis (2014) attributed the increased cracking in the RAP sections to the high dust content in those mixes.

Dong & Huang (2014) also analyzed SPS-5 performance data with a focus on initiation of cracking. It was found that the use of 30% RAP in the overlay accelerated the initiation of longitudinal cracks in the wheel path, but did not influence the initiation of the alligator cracking, non-wheel-path longitudinal cracks, and transverse cracks.

Hong et al. (2010) evaluated the performance of the SPS-5 test sections on US 175 in Texas in terms of ride quality, transverse cracking, and rutting. The overlay sections contained 35% RAP. The RAP sections had a relatively higher amount of cracking, less rutting, and similar roughness. The overall conclusion was that a well-designed RAP mixture (even 35% RAP) could perform as well as the virgin mixtures. Carvalho et al. (2010) also concluded that, in most cases, RAP mixtures performed statistically equivalent to virgin mixtures. In addition, RAP overlays provided structural improvement similar to the virgin mix overlays in terms of the maximum deflections measured with falling-weight deflectometer on the 18 SPS-5 projects studied by Hong et al. (2010).

Texas Sites

Over the past five years, 15 field test sections with RAP/RAS have been constructed and monitored (Zhou et al., 2011b; 2013b). Table 8-4 presents a brief summary of those test sections. There was no rutting observed in any test section. Although reflective cracking was the main distress observed in most asphalt overlay sections, the test sections with RAP contents of up to 35% had similar or better performance to virgin mixtures.

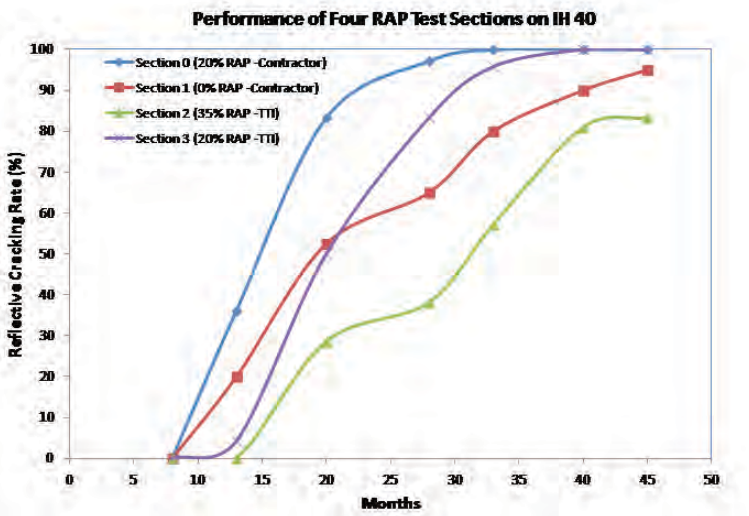


Figure 8-2. Field Performance of Four RAP Test Sections on I-40, Texas.

For example, four RAP test sections were constructed on Interstate 40 near Amarillo, Texas, on August 11, 2009. The existing pavement has a total of 8 inches of existing asphalt pavement with severe thermal-related transverse cracking extending the full depth of the asphalt layer.

The pavement design called for 4 inches of milling and a 4-inch overlay section. The control (virgin) mixture and one of the 20% RAP mixtures were designed by the contractor following Texas Department of Transportation (TxDOT) specifications; the other two mixtures with 20% and 35% RAP were designed by TTI following the balanced mix design approach presented in Chapter 5, “Mixture Design and Characterization,” of this synthesis. Since construction in 2009, seven field surveys have been conducted.

After about four years of service, there was no rutting, but some reflective cracking has been observed. Detailed reflective cracking development for each section is shown in Figure 8-2. The 35% RAP mixture had the best performance under severe weather and extremely heavy traffic truck loads.

A field test section on SH 146 in the Houston area was constructed on October 8, 2010. A dense-graded TxDOT Type C mixture with 15% RAP/5% RAS was used in the top 2-inch surface layer. After three years of service, the test section was in perfect condition: no rutting and cracking, as shown in Figure 8-3.

The overall conclusion from these field test sections is that high RAP/RAS mixtures can have similar or better performance than the virgin mixtures, but

Table 8-4. Texas RAP/RAS Test Sections and Performance (after Zhou et al., 2011b; 2013b).

Test Section				Weather	Traffic (MESAL/20 Years)	Overlay/ New Construction	Existing for Overlays	Performance
Highway	**RAP/ RAS**	**Virgin Binder**	**HMA/ WMA**					
I-40 Amarillo	20% RAP[1]	PG 64–28	HMA	Hot summer; cold winter	30	4" overlay	Severe transverse cracking	100% reflective cracking after 3 years
	0% RAP	PG 64–28						
	20% RAP[2]	PG 64–28						
	35% RAP	PG 58–28						57% reflective cracking after 3 years
FM 1017 Pharr	0% RAP	PG 76–22	HMA	Very hot summer; mild winter	0.8	New 1.5" surface	N/A	Limited, fine cracking after 2.5 years
	20% RAP	PG 70–22						
	35% RAP	PG 70–22						
SH 359 Laredo	20% RAP	PG 70–22	HMA	Hot summer; mild winter	1.0	3" overlay	Severe transverse cracking	No cracking after 2.5 years
SH 146 Houston	15% RAP/5% PCAS RAS	PG 64–22	HMA	Hot summer; mild winter	1.5	New 2" surface	N/A	No cracking after 2 years
US 87 Amarillo	5% PCAS RAS	PG 64–28	HMA	Hot summer; very cold winter	3.5	3" overlay	Severe transverse cracking	50% reflective cracking after 2.5 years
		PG 64–28 with 0.4% more virgin binder						20% reflective cracking after 2.5 years
Loop 820 Fort Worth	15% RAP/5% MWAS RAS[3]	PG 64–22	WMA	Hot summer; mild winter	15	2" overlay	Fine transverse cracks in existing CRCP	Perfect condition after 1 year
		PG 64–22	WMA					
		PG 64–28	WMA					
		PG 64–22 (+0.4% binder)	WMA					

[1] Contractor supplied mix design.

[2] TTI supplied mix design.

[3] All mixtures contained 1% zeolite as an anti-clotting measure for the RAS.

Figure 8-3. Good Condition of the RAP/RAS Test Section on SH 146, Houston.

they must be well designed following appropriate mix design methods.

Iowa State

Over the past several years, a national pooled fund study, TPF-5(213): Performance of Recycled Asphalt Shingles in Hot Mix Asphalt, was conducted at Iowa State University (Williams, 2013). Under the study a series of demonstration projects were built in the participating states, as described below.

Minnesota DOT Demonstration Project

The Minnesota demonstration project is located at the MnROAD Cold Weather Road Research Facility in Albertville, Minn. (Yu, 2012). The project is 3.5 miles long with 18 test sections on the passing and driving lanes of the westbound I–94 mainline. The mixture placed in Cell 20 contains 30% RAP and serves as the control section. Mixtures in Cells 5, 6, 13, and 14 contain 5% MWAS RAS. Mixtures in Cells 15 to 23 contain 5% PCAS RAS. Each cell is 500 feet long, including a 50-foot transition area. The Minnesota demonstration project used a 12.5 mm (0.5 inch) NMAS aggregate gradation and PG 58–28 virgin binder for all test mixes. The gradations of mixes containing 5% RAS are similar to each other. Construction of the test sections was completed in September 2008.

The main distress observed was transverse cracking (Williams et al., 2012). Two interesting observations from these test sections are (1) the 30% RAP mix, compared to the mixes with RAS, has the best performance in terms of transverse cracking, although it had the highest binder replacement (33.4%); and (2) the existing pavement structure (before asphalt overlay) had significant influence on cracking performance. Cell 15 with jointed concrete pavement has the longest transverse cracks.

RAS Test Sections of Iowa DOT Demonstration Project

The Iowa DOT demonstration project is located on State Highway 10 west of Paullina, Iowa (Yu, 2012). The project was constructed in June and July 2010. The total project is 32.5 lane-miles including four test sections. Every test section has a 2-inch thick asphalt overlay atop an existing jointed concrete pavement. The mixes were designed with the same aggregate gradations and virgin binders but different RAS contents, ranging from 0–6%. The observed transverse cracking data indicated that there was no difference among these four test sections in terms of transverse cracking (Williams et al., 2012).

Missouri DOT Demonstration Project

The Missouri DOT (MoDOT) constructed a demonstration project in May and June 2010 (Yu, 2012). The 8.8-mile project is located on US 65 south of Springfield, Mo. The total project is 17.6 lane-miles with a 3.75-inch surface layer over a concrete pavement. MoDOT developed this demonstration project to study the influences of RAS grind size on pavement performance and the economic feasibility of incorporating ground tire rubber (GTR) into asphalt mixes containing RAS and RAP.

A PG 64–22 asphalt was selected as the virgin binder. The virgin binder was modified with GTR and a Vestenamer polymer to achieve a 70–22 Performance Grade. The control section contains 15% RAP and

Table 8-5. Design Asphalt Binder Content of Each Test Section (after Williams et al., 2012).

Mix Property	Control Section	Fine RAS Section	Coarse RAS Section
% RAS	0	5	5
% RAP	15	10	10
% Total AC	4.7	5.3	5.3
% Virgin AC	4.0	3.7	3.7
% Binder Replacement	14.9	30.2	30.2
% Effective Asphalt	4.2	4.6	4.6
% Asphalt Absorption	0.5	0.7	0.7

0% RAS. Section 2 contains 5% fine-ground RAS in which 100% of the RAS particles pass the ⅜-inch sieve and 95% pass the No. 4 sieve. Section 3 contains 5% coarse ground RAS in which 100% of the RAS particles pass the ½-inch sieve.

Both Sections 2 and 3 contain 10% RAP so that all mixes have 15% recycled materials. The same aggregate gradations were designed for the three test sections. Table 8-5 details the design asphalt binder information for each test section. Again, transverse cracking was the main distress. As shown in Figure 8-4, the control section with 15% RAP has the least transverse cracking (Williams et al., 2012).

Indiana DOT Demonstration Project

The Indiana DOT (INDOT) demonstration project was completed in July 2009 (Yu, 2012). The project is located on US 6 east of Nappanee, Ind. A 1.5-inch surface layer was placed atop a previously existing asphalt surface with an underlying concrete pavement. INDOT developed the demonstration project to evaluate the performance of RAS and WMA in asphalt concrete pavements.

A total of three test sections were constructed. The control section used an HMA mixture containing 15% fractionated RAP. Test Section 2 used the same HMA with 3% PCAS RAS. A foaming method was applied to produce WMA with 3% PCAS RAS in Test Section 3.

Figure 8-5 shows the observed transverse cracking development of each test section. Clearly, the foaming WMA technology did not improve the performance of the PCAS RAS mix in this case. The 15% RAP mixture had similar performance to the 3% PCAS RAS mixture produced at HMA temperatures. It should be noted that the warm-mix section with 3% PCAS RAS shows a moderate to high amount of transverse cracking as of March 2012 while the other two sections show low to moderate transverse cracking.

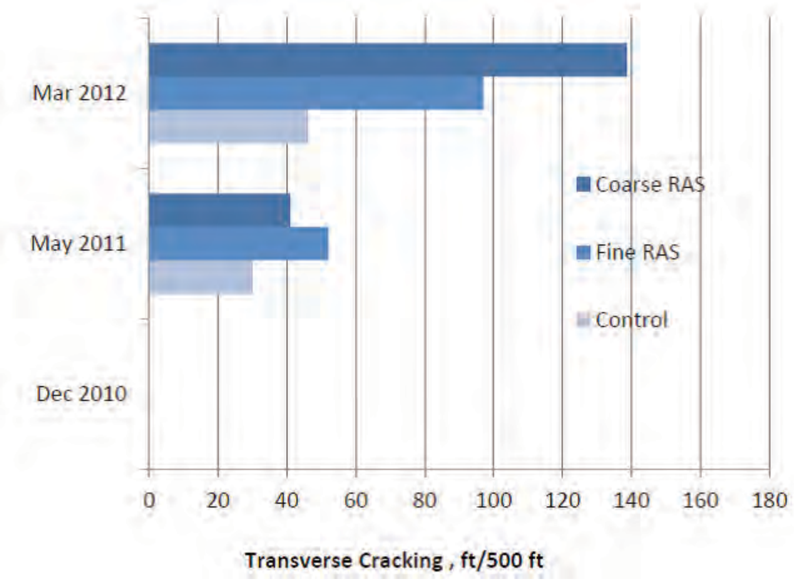


Figure 8-4. Observed Transverse Cracking on US 65, Missouri (after Williams et al., 2012).

Others

In 1981, the Arizona Department of Transportation constructed eight asphalt overlay test sections on Interstate 8 in Arizona to compare long-term performance of recycled and virgin asphalt mixtures in an arid climate (Hossain et al., 1993). The recycled overlay sections contained 50% RAP and used a softer virgin binder compared to the virgin mix sections. Roughness, skid number, and cracking data were collected on the test sections over a period of nine-year service life. Performance data through the service life indicated that the recycled and virgin mixture overlays performed similarly.

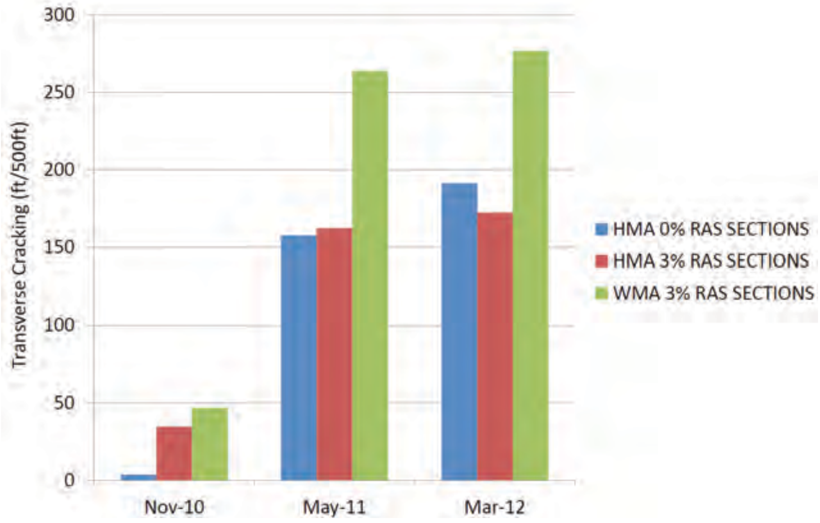


Figure 8-5. Observed Transverse Cracking on US 6, Indiana (after Yu, 2012).

Kandhal et al. (1995) evaluated five Georgia pavements containing between 10 and 25% RAP and compared them with virgin asphalt mixture sections. At the end of the 2.25-year monitoring period, the RAP sections were performing as well as the virgin mix sections. Paul (1996) also reported the performance of five early projects containing up to 50% RAP built between 1978 and 1981 in Louisiana. At the time of the study, the oldest project was nine years old and the other four projects were six years old.

Structural integrity, serviceability index, and distress type and severity rating were used to evaluate the performance of the five projects. Paul (1996) concluded that there was no significant difference between the recycled and virgin asphalt mixture pavements in that study. The recycled asphalt mixture pavements did show slightly more distress regarding longitudinal cracking.

In addition, Anderson (2011) reviewed the long-term performance data of high RAP pavement sections from eight states and one Canadian province; these pavements had been in service for more than 10 years and contained at least 20% RAP. In each case, performance of the RAP sections was compared to that of similar pavements built with virgin mixtures.

Specifically, a field project in Wyoming included sections with 0 to 45% RAP and 12 years of performance history. The virgin mixture section had a better ride quality and serviceability index in the beginning and, in general, maintained the slightly better performance throughout the evaluation period. Two high RAP projects in Washington state had comparable performance ratings with other pavements.

Anderson (2011) concluded that high RAP pavements performed at a level comparable to virgin mixture pavements. On average, the high RAP sections tended to have more cracking and rutting, but the differences were generally not significant.

Summary

Numerous projects or test sections containing RAS and up to 50% RAP have been constructed and monitored over the past several decades. Overall, the RAP/RAS test sections had similar field performance to virgin mixture sections. Good performance with high RAP/RAS mixtures has been reported in projects under completely different climates and traffic conditions. Although the RAP/RAS mixtures did have more cracking, the extent of cracking, in most cases, was acceptable.

In addition, two important observations were made based on the performance of all field test sections. First, the use of a softer virgin binder does improve the durability and cracking resistance of RAP/RAS asphalt mixtures. Second, high RAP/RAS mixtures can be designed to have better performance than virgin mixtures when an engineered mix design approach is employed using performance testing, such as the balanced mix design method, as opposed to a purely volumetric approach.

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Summary

RAP and RAS are readily available commodities that can be used by contractors to reduce the consumption of natural resources and reduce price volatility in the construction of the nation's pavements. The practice of using reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) with new asphalt binder and aggregate has become the standard way to produce new asphalt pavements.

The use of RAP and RAS provides the following advantages:

1. Reduced cost in the production of asphalt mixtures due to binder and aggregate replacement.
2. Environmental benefits from the conservation of virgin binder and aggregate, including consideration of resource extraction, transportation, and processing.
3. Reduction in the cost of material disposal and a diversion of waste material from landfills.
4. Reduction in the production of greenhouse gases and other emissions.
5. Improved resistance to permanent deformation due to the utilization of harder binders.

Environmentally speaking, the use of RAP and RAS reduces the amount of aggregate and asphalt binder consumed by the construction industry, reduces the amount of landfill space required for disposal of these construction wastes, reduces the amount of energy consumed in the construction of asphalt paving materials, and reduces emissions and the amount of greenhouse gases emitted during the production and placement of asphalt mixtures.

These environmental benefits can be achieved with both first-cost and life-cycle cost savings. The use of RAP and RAS in asphalt paving mixtures is a green activity that provides significant environmental benefits while reducing costs.

From estimates of the asphalt binder and aggregate available, the potential for replacing 5.9 million tons of asphalt binder and nearly 78.5 million tons of aggregate is possible when recycling RAP and RAS. Assuming that 350 million tons of asphalt pavement mixtures are produced annually in the United States during periods of adequate funding at an average asphalt binder content of 5% by total weight of mixture, the amount of virgin asphalt binder that can be replaced with RAP and RAS is about 33.7% and the amount of virgin aggregate that can be replaced with RAP and RAS is about 23.6%. The diversion of RAP and RAS from landfills is estimated to save nearly 49 million cubic yards of landfill volume on an annual basis in the United States. Furthermore, it has been estimated that using RAP and RAS will reduce asphalt mixture production and placement energy by up to approximately 15%, while reducing greenhouse gas emissions by up to 10–20%.

The binders, aggregates, fillers, and fibers found in RAP and RAS are the same materials commonly found in new paving mixtures, and, when used in moderate amounts, they generally do not change mixture characteristics appreciably. At higher levels of binder replacement, these materials require greater consideration to ensure their effective use. The design and mechanical behavior of mixtures containing RAP and RAS reveal several shortcomings in the reliance on customary volumetric criteria as the only approach to determining the composition of a mixture.

For instance, there is uncertainty concerning the degree of blending between RAP or RAS binders and virgin binders. While some states require using a softer grade of virgin binder at certain levels of binder replacement, there is no guarantee that a softer binder is necessary or that it will have the desired results. Determination of VMA, one of the more critical mixture volumetric parameters, is uncertain due to the difficulty of determining the specific gravity of RAP aggregate.

Given these concerns, a balanced approach to determining the optimal composition of mixtures is proposed, replacing some of the volumetric criteria traditionally used when designing asphalt mixtures with performance testing for rutting and cracking. Pavement design practices need to reflect the characteristics of high binder replacement mixtures and optimize their use in providing the load-bearing and durability characteristics desired for performance.

The following can be deduced from the literature cited in terms of the effects of increasing binder replacement from RAP or RAS:

1. At lower levels of binder replacement, combined binder grading tends to remain at or near the level of the virgin binder; but at higher levels of binder replacement, the combined binder grading increases both the high- and low-temperature grades.
2. The stiffness of mixtures increases with binder replacement, more so at higher temperatures than at lower temperatures.
3. Rutting resistance improves at all levels of binder replacement.
4. Cracking resistance generally lowers with increasing RAP and RAS content, but this is not universally true. However, observed cracking has been at acceptable levels.
5. The use of softer binder grades and rejuvenators has been shown to improve cracking resistance for high recycled material content mixtures.
6. Moisture sensitivity of mixtures is not generally affected by the use of RAP and RAS.

Proper handling and processing of RAP and RAS are key to producing mixtures that perform well in a pavement. Avoiding contamination of recycled materials with other debris, such as construction waste and vegetation, helps preserve the materials' integrity throughout processing. For PCAS, it is important that proper removal of paper, nails, and any other roofing contamination take place.

Crushing and fractionation of RAP can offer greater flexibility in the amount of RAP used in mixtures with different NMAS. Proper stockpiling techniques will minimize the amount of moisture in the materials and will help promote blending of materials from different sources.

Numerous projects or test sections containing RAS and up to 50% RAP have been constructed and monitored over the past several decades. Overall, the RAP/RAS test sections have had similar field performance to virgin mixture sections. Good performance with high RAP/RAS mixtures has been reported in projects under completely different climates and traffic conditions. Although the RAP/RAS mixtures did exhibit more cracking, the extent of cracking, in most cases, was acceptable.

Two important observations have been made based on the performance of all field test sections. First, the use of a softer virgin binder does improve the durability and cracking resistance of RAP/RAS asphalt mixtures. Second, high RAP/RAS mixtures can be designed to have better performance than virgin mixtures when an engineered mix design approach using performance testing, such as the balanced mix design method, is employed.

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Further Reading


Quality Improvement Series 129

NAPA
NATIONAL ASPHALT PAVEMENT ASSOCIATION

Best Practices for RAP and RAS Management

Information Series 139

NAPA
NATIONAL ASPHALT PAVEMENT ASSOCIATION

High RAP Asphalt Pavements
Japan Practice — Lessons Learned
アスファルト舗装廃材

To help asphalt pavement mix producers, engineering consultants, and road owners make the most effective utilization of reclaimed asphalt pavement (RAP), the National Asphalt Pavement Association also offers two new (2015) publications:

- *Best Practices for RAP and RAS Management* (Quality Improvement Publication 129) by Randy C. West, Ph.D., P.E., covers pavement milling, inventory management, processing, sampling, and testing of RAP and recycled asphalt shingles (RAS), as well as a discussion of production concerns.
- *High RAP Asphalt Pavements: Japan Practice — Lessons Learned* (Information Series 139) by Randy C. West, Ph.D., P.E., and Audrey Copeland, Ph.D., P.E., reports out the findings of a 2014 industry scanning tour of Japan to study that country's use of high levels of RAP in its pavements. Information about Japanese innovations for porous asphalt pavements are also included.

Both publications were produced under NAPA's cooperative agreement with the Federal Highway Administration (FHWA) and are available as free, high-quality PDF electronic documents through the NAPA Online Store along with many other technical publications.

http://store.asphaltpavement.org.

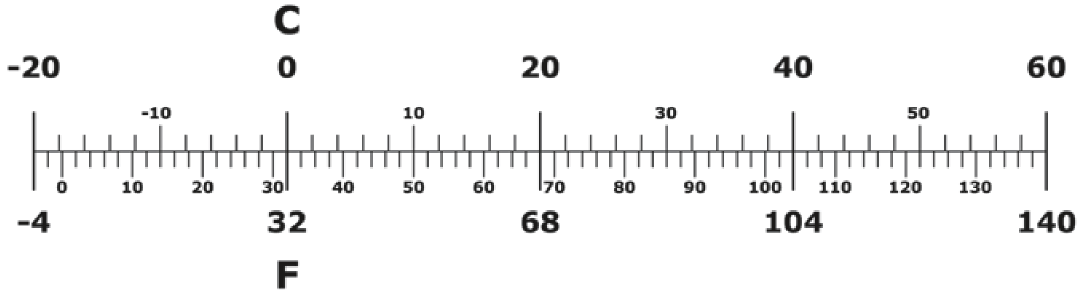
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSION TO SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	645.2	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L should be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lbs	pounds	0.454	kilograms	kg
T	short tons	0.907	megagrams	Mg
T	short tons	0.907	metric tonnes	t
NOTE: A short ton is equal to 2,000 lbs				
TEMPERATURE (exact)				
°F	Fahrenheit	$\frac{5(F-32)}{9}$	Celsius	°C

APPROXIMATE CONVERSION FROM SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lbs
Mg	megagrams	1.102	short tons	T
t	metric tonnes	1.102	short tons	T
NOTE: A short ton is equal to 2,000 lbs				
TEMPERATURE (exact)				
°C	Celsius	(1.8×C)+32	Fahrenheit	°F



*SI is the symbol for the International System of Units

NAPA: THE SOURCE

This publications is one of the many technical, informational, and promotional resources available from the National Asphalt Pavement Association (NAPA). NAPA also produces training aids, webinars, and other educational materials. For a full list of NAPA publications, training aids, archived webinars, and promotional items, visit *http://store.AsphaltPavement.org/*.

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