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# Recycled Industrial and Construction Waste for Mutual Beneficial Use

Arizona Department of Transportation Research Center

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## SPR-725

## August 2016

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16. Abstract

Instead of going to landfills, certain waste materials from industry and building construction can be recycled in transportation infrastructure projects, such as roadway paving. The beneficial use of waste materials in the construction of transportation infrastructure results in environmental benefits, as well as economic savings over the pavement life cycle. This study focused on the use of waste — i.e. reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), ground tire rubber (GTR), recycled concrete aggregate (RCA), construction and demolition waste (CDW), and mine spoil — as raw materials for building transportation infrastructure in Arizona. Technical feasibility, availability, and economics were considered in making recommendations regarding expanding the use of the most-promising materials. Recommendations included targeting slight increases in the RAP replacement level (especially in non-surface hot-mix layers and in unbound base and subbase layers), increasing use of GTR through terminal blending, and increasing use of RCA as base and subbase. Other opportunities identified for further investigation include significant increases in RAP replacement level in hot mix asphalt, use of RCA to replace virgin aggregate in new concrete, and facilitation of the use of CDW in some markets. Further research is encouraged on the use of construction and other waste materials to improve the performance of these materials to reduce risk and improve cost effectiveness.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS 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 yard | 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 | 29.57 | 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 shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^{o}F$ | Fahrenheit | 5 (F-32)/9<br>or (F-32)/1.8 | Celsius | $^{o}C$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS 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 | 1.195 | 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 | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^{o}C$ | Celsius | 1.8C+32 | Fahrenheit | $^{o}F$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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## LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AASHTO............ American Association of State Highway and Transportation Officials
ACPA................ American Concrete Pavement Association
ADOT.................Arizona Department of Transportation
AMPT................ Asphalt Mixture Performance Tester
APA....................Asphalt Pavement Analyzer
ARSR..................Asphalt Roofing Shingles Recycling
Caltrans............ California Department of Transportation
CDOT................. Colorado Department of Transportation
CDRA ................ Construction and Demolition Recycling Association
CDW.................. Construction and Demolition Waste
CU......................Current Usage
DOT................... Department of Transportation
EU...................... Experimental Usage
FHWA............... Federal Highway Administration
FN...................... Flow Number
GTR .................. Ground Tire Rubber
HMA ................ Hot-Mix Asphalt
HWTT................ Hamburg Wheel Tracking Test
IDOT.................. Illinois Department of Transportation
IU.......................Incremental Usage
LTPP.................. Long Term Pavement Performance
MDOT............... Michigan Department of Transportation
NAPA................ National Asphalt Pavement Association
NCAT.................National Center for Asphalt Technology
NDOT................ Nevada Department of Transportation
NMDOT.............New Mexico Department of Transportation
OT...................... Overlay Test
PCC................... Portland Cement Concrete
PFC.................... Porous Friction Course
RAP .................. Reclaimed Asphalt Pavement
RAS .................. Recycled Asphalt Shingles
RCA .................. Recycled Concrete Aggregate
RCWM ............. Recycled, Co-Product, and Waste Materials
RMA.................. Rubber Manufacturers Association
RMRC................ Recycled Materials Resource Center
SPS.....................Special Pavement Studies
TxDOT............... Texas Department of Transportation
UDOT................ Utah Department of Transportation
USEPA............... United States Environmental Protection Agency
WMA ............... Warm-Mix Asphalt

# EXECUTIVE SUMMARY

Reclaiming and recycling certain industrial and building construction waste materials into the construction of transportation infrastructure, specifically into paving projects, benefits the environment and produces economic savings over the pavement life cycle. This Arizona Department of Transportation (ADOT) study focused on using industrial waste — referred to as recycled, co-product, and waste materials (RCWMs) — as the raw resources for constructing transportation infrastructure in Arizona. Specific materials considered in this study included:

- Reclaimed asphalt pavement (RAP) as a partial replacement for asphalt binder and virgin aggregate in asphalt concrete mixtures and for other applications.
- Recycled asphalt shingles (RAS), including tar paper, as a partial replacement for asphalt binder in asphalt concrete mixtures.
- Ground tire rubber (GTR) as an addition in asphalt mixtures to create rubberized asphalt or as a binder modifier to create asphalt-rubber.
- Recycled concrete aggregate (RCA) from existing structures (e.g. pavements, barrier walls, and so on) for use as aggregate or as base/subbase material or as an aggregate in new concrete.
- Construction and demolition waste (CDW), including refuse concrete, bricks and masonry, to be crushed and used as aggregate in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill.
- Mine spoil as aggregate in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill.

This study reviewed existing information and conducted surveys to assess the potential sources of RCWMs for use in the construction of transportation structures in Arizona. The following summarizes the results regarding the use of RCWMs as it pertains to Arizona.

*Reclaimed Asphalt Pavement*

RAP is used by most departments of transportation (DOTs) in asphalt mixtures, base, and subbase. High RAP (25 percent or greater replacement) asphalt mixtures are currently of great interest as they provide the opportunity to replace significant amounts of virgin binder and aggregate, resulting in significant cost savings and the potential for increased sustainability. It is widely recognized that the risk of failure increases as RAP content increases, and thus the average RAP usage rate in the United States remains below 15 percent.

Keys to increasing RAP utilization in Arizona include:

- Providing specifications that specifically allow for increased RAP utilization.
- Training the local paving industry in methods that will allow for the successful incorporation of higher levels of RAP into asphalt mixtures.
- Improved quality control throughout the mixture design and construction processes.
- Incorporation of incentives to encourage contractors to increase RAP utilization beyond 15 percent.

Key technologies that will assist in this implementation include the use of RAP fractionation, in which RAP is separated by size into two or more fractions. Fractionation may result in greater stockpiles of coarse RAP, which may provide opportunities for the use of coarse RAP in other applications.

*Recycled Asphalt Shingles*

RAS usage is on the rise in asphalt mixtures around the country. It is recognized that the risk of negative impacts on asphalt mixture performance increases as RAS content increases, particularly with regards to binder oxidation.

Keys to increasing RAS utilization in Arizona include:

- Demonstrating that a viable supply of consumer shingles exists. Shingles are most common in alpine areas of the state.
- Cooperation between ADOT and industry to implement RAS usage.
- Modification to existing specifications to allow the use of RAS, considering potential negative effects of binder oxidation.
- Training to better understand how to successfully incorporate RAS into asphalt mixtures.
- Improved quality control throughout the mixture design and construction processes.
- The incorporation of incentives to encourage contractors to increase RAS utilization.

Once a viable source of refuse shingles is demonstrated in Arizona, RAS recycling facilities will need to be incentivized to produce quality RAS material will increase supply.

*Ground Tire Rubber*

Arizona is a national leader on the use of GTR. Traditionally, asphalt-rubber was produced as a field blend, being highly viscous and thus able to be used at relatively high binder contents. The increase in availability of terminal blend asphalt-rubber binders has changed the market, the implications of which are not yet fully understood. Concerns exist regarding the use of RAP containing high amounts of GTR, as well as the moisture susceptibility of gap-graded mixtures containing GTR, and additional research needs to be conducted to alleviate these concerns.

*Recycled Concrete Aggregate*

RCA has been used in highway applications for decades but has gained popularity as virgin aggregate sources have become scarcer and hauling prices have increased. It is most common to find RCA used in aggregate bases, but coarse RCA has also proven effective as an aggregate in new concrete.

The key to increasing RCA utilization in Arizona is to specifically allow it as an option in construction specifications for both aggregate base and as a coarse aggregate in new PCC. ADOT's *2008 Standard Specifications* are silent on the use of RCA. Increasing the use of RCA will require training to better understand how to incorporate RCA into aggregate bases and new PCC, improved quality control, and the incorporation of incentives to encourage contractors to increase RCA utilization.

*Construction and Demolition Waste*

The use of CDW in highway applications is feasible, but the market demand is not apparent. Additionally, increased efforts are required to recycle CDW into quality material and there appears to be a lack of recycling facilities. Thus there has been little use of CDW by highway agencies to date.

As virgin materials become less available and more sustainable or "green" efforts become more accepted, the use of CDW in highway applications has the potential to increase. To increase utilization of CDW in Arizona transportation infrastructure would require a concerted, long-term effort by ADOT to study the material characteristics, encouragement of the recycling industry and contractors through incentives, and adoption of specifications that allow its use.

*Mine Spoil*

Waste rock and mill tailings, or mine spoil, have been investigated for use in highway applications since the 1970s, but there is a widespread lack of specifications specifically addressing their use. Further, the mine spoil is often located far from where it is needed. That, coupled with potential hazards associated with many sources of mine spoil, has made such waste materials more of a hindrance for most DOTs.

Increasing mine spoil utilization in Arizona will require a better understanding of the type and location of available materials and the development of mine spoil stockpiles that possess acceptable characteristics. Standards for incorporation of mine spoil into highway applications, along with improved quality control, can increase mine spoil utilization.

**BENEFIT-COST ANALYSIS AND OPPORTUNITIES**

A benefit-cost analysis was conducted to determine those applications that offered the best opportunities for ADOT. The applications discussed next represent opportunities that either are immediately implementable with little need for additional research (i.e., the RCWMs can be utilized in demonstration projects) or that may offer future potential after additional research is conducted.

Opportunities that could be implemented immediately include:

- Target slight increases in RAP replacement level (up to 25 percent or more) in asphalt concrete (HMA/WMA) pavement, especially in asphalt concrete base and binder levels.
- Increased use of RAP in unbound roadway base and subbase, especially for in-place recycling.
- Increased use of GTR through the use of terminal blend binders.
- Increased use of RCA in roadway base and subbase (unbound layers) applications.

Potential opportunities for the future include:

- Investigate opportunities to significantly increase RAP replacement level (30 percent or greater) in lower lifts of asphalt concrete (HMA/WMA) pavement.
- Investigate RCA as a partial replacement of coarse aggregate in highway concrete, especially for non-structural applications and some pavements.
- Facilitate the use of CDW in transportation applications through a coordinated effort between to establish source control and a market for the use of CDW.
- Conduct research to improve the performance of RCWMs identified as having comparable or diminished performance to reduce risk and make them more cost-effective.

In closing, the use of RCWMs, provides an opportunity for the transportation construction industry within Arizona to have an overall beneficial effect in terms of the environment, societal impacts, and economic costs. However, with the inherent variability and reduced understanding that is introduced with the inclusion and increased use of RCWMs, and the need to identify, mitigate and/or prevent potential adverse effects as identified, a continued effort is needed to study and quantify the associated benefits and costs so that the net benefit of using RCWMs can be better understood. In order to capitalize on the use of RCWMs in the future, effort should be made now to ensure that their full benefits are recognized and can be fully leveraged in future reconstruction projects.

# CHAPTER 1. INTRODUCTION

Instead of being dumped or going to landfills, certain waste materials from industry and building construction can be recycled into the construction of transportation infrastructure, specifically into paving projects. Recycling waste materials into pavement benefits the environment and produces economic savings over the pavement life cycle. This study focused on the broad consideration of waste from construction and other industries for use as raw materials in Arizona transportation construction.

If fully implemented, the results of this study would help guide the Arizona Department of Transportation (ADOT) in selecting those waste materials that are available and that show promise for increased utilization in ADOT construction projects. This project considered materials that included some common recycled materials currently used by ADOT in pavements (e.g. asphalt millings, tire rubber), as well as less-commonly used waste materials, such as asphalt shingles and tar paper, refuse concrete, masonry, and mine spoil. These materials have application in highway projects and are often classified as recycled, co-product, and waste materials, or RCWMs (Van Dam et al. 2015):

- Recycled materials are those obtained from an old pavement or transportation structure that is being demolished at the end of its life and are used back in the construction of a new pavement or transportation structure; common recycled materials include: reclaimed asphalt pavement (RAP) or recycled concrete aggregate (RCA). Depending on the regional market, these materials, if not recycled, would end up in a landfill.
- Co-products are derived from other industrial or agricultural processes, yet add value to the overall process. For pavement and other transportation applications, some common co-products including slag cement and air-cooled iron blast furnace slag aggregate, both of which result from the production of pig iron for steel making.
- Wastes are materials that normally would be sent to a landfill, for which the cost of transport and processing is the only source of economic value. If the material has value beyond this, it is no longer considered a waste, but instead a co-product. Recycled asphalt shingles (RAS) is an example of a waste material as long as the economics stay consistent with the above definition. The classification of fly ash or ground tire rubber (GTR) is more complex; in some regional markets, these materials fit the definition of waste, whereas in other markets they have value beyond the cost of transport and disposal and therefore would be classified as co-products.

This study evaluated sources of RCWM that are available and provide a potential for use in the construction of transportation structures in Arizona. Specific opportunities were identified and a foundation laid for more detailed studies to examine specific applications. For this study, the following RCWMs were considered:

- Reclaimed Asphalt Pavement (RAP) – In 2013, an estimated 67.8 million tons of RAP were produced in the United States and almost all of them (over 99 percent) were recycled into pavements (Hansen and Copeland 2014). RAP is universally accepted as a component in hot-mix asphalt (HMA) and warm-mix asphalt (WMA) (generally referred to as asphalt mixtures), as well as being used as base and subbase material and as surfacing in some low-volume traffic applications. Efforts are focused on increasing the allowable limits for RAP in asphalt mixtures, as RAP provides a reclaimed source of both binder and aggregate. This is a higher-value application than using RAP simply as aggregate in base or subbase.

- Recycled Asphalt Shingles (RAS) and Tar Paper – According to the NAHB Research Center (1998), an estimated 7 to 10 million tons of asphalt roofing shingle tear-off waste and installation scrap, along with another 0.75 to 1 million tons of manufacturing shingle scrap, are generated each year in the United States, of which it is estimated that 1.6 million tons were beneficially used in asphalt mixtures in 2013 (Hansen and Copeland 2014). In some markets, such as Chicago, the use of RAS is commonplace (shingle Recycling 2016). The major benefit of RAS is that it has high asphalt content (15 to 35 percent depending on type of shingle) and thus can effectively replace virgin binder.
- Ground Tire Rubber (GTR) – In 2013, approximately 233 million tires were discarded in the United States, with roughly 96 percent being beneficially used (RMA 2014). Of these, almost 60 million were converted into GTR. GTR is used in asphalt mixtures, either as a substitute for fine aggregate to create rubberized asphalt (dry process) or as an asphalt modifier in which 18 to 25 percent GTR is blended and chemically reacted with the asphalt binder to create asphalt-rubber (known as a wet process). In some parts of the country, asphalt-rubber is commonly used in HMA, pavement surface treatments, and various stress-absorbing pavement interlayers.
- Recycled Concrete Aggregate (RCA) – According to the CDRA (2016), 140 million tons of concrete are recycled in the United States each year, being derived from such sources as foundations, curbs and gutters, highways, and airports. RCA is used in transportation applications as aggregate for road base, soil stabilization, pipe bedding, and as aggregate in new concrete and asphalt mixtures.
- Construction and Demolition Waste (CDW) – Considerable waste is generated in the construction of new buildings and demolition of existing buildings. This waste is often co-mingled, producing a mix consisting of wood, brick, masonry, gypsum board, and other materials, making it difficult to reuse. However, in many locales, active programs exist that require this waste be separated on-site and transported and processed by certified construction waste recyclers to ensure it is recycled. It is unclear how much of this type of waste is currently being used for transportation applications.
- Mine spoil – Non-hazardous mine spoil offers a potential source of aggregate for use in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill. Its viability depends on the properties of the mine spoil, its proximity to transportation, and its accessibility to markets.

This final report consists of five chapters. Chapter 2 presents a detailed literature review on the utilization of RCWM in the construction of transportation infrastructure. As the amount of information available on RCWMs is significant, the specific focus of the literature review was on the life-cycle economic aspects of RCWM utilization, although environmental and societal aspects were also considered.

Chapter 3 addresses the surveys that were conducted to ascertain the quantity of suitable RCWMs that are available in Arizona and to what degree those materials are currently being used as construction materials in ADOT and non-ADOT projects. The results of these surveys were used to establish levels of current use, gauge availability, establish perceived barriers to increased use, and identify opportunities for increasing use of RCWMs. This information was developed into the matrices used in the benefit-cost analysis.

Chapter 4 describes the benefit-cost analysis that investigated the potential usability of the RCWMs in various highway applications in Arizona. From this analysis, a number of opportunities were identified to increase the use of RCWMs by ADOT, categorized as either being immediately implementable or having a potential future after further study.

The final chapter, Chapter 5, summarizes the results of the study and provides recommendations regarding future needs to support the continued use of RCWMs in Arizona.

# CHAPTER 2. LITERATURE REVIEW

## INTRODUCTION

This chapter provides a brief background regarding the following six RCWMs that are the focus of this research:

- Reclaimed asphalt pavement (RAP)
- Recycled asphalt shingles (RAS)
- Ground tire rubber (GTR)
- Recycled concrete aggregate (RCA)
- Construction and demolition waste (CDW)
- Mine spoil

The approach taken in this review is to provide a brief summary of the national literature, a summary of regional state/agency practices (with a focus on states within the region including California, Nevada, Utah, Colorado, and Texas), and a review of ADOT's past experience and current practice. The emphasis is placed on the practical application of the materials in transportation infrastructure. Further, some materials, such as GTR, are covered in greater detail than others, reflecting high regional use and experience. Each section concludes by reviewing the challenges that exist in increasing the use of the material in transportation infrastructure.

## RECLAIMED ASPHALT PAVEMENT (RAP)

### Review of National Practice

RAP is an important source of aggregate and asphalt binder that can be used in a variety of transportation applications, from asphalt concrete and granular base/subbase, in embankments or as fill, or as a surfacing for alleyways and pathways. In the last decade, the amount of RAP used in asphalt concrete mixtures has increased significantly. For instance, in 2013, the amount of RAP used was 67.8 million tons, a 21 percent increase from 2009 (56 million tons). In the last few years (2011 to 2013), the growth in the amount of RAP used has slowed reflecting a decrease in total HMA/WMA tonnage for the industry, yet the average percent RAP used in mixes increased modestly over the same time period. Of the RAP produced in the United States in 2013, almost all (over 99 percent) was recycled back into pavements, and in 2012, the amount of RAP beneficially used exceeded the amount produced (Hansen and Copeland 2014).

Recycling asphalt pavements became widespread in the United States during the 1973 oil embargo. Since then, using RAP has not only been considered a beneficial strategy to reduce consumption of virgin materials, but as a necessary strategy in asphalt concrete to reduce costs and support broader sustainability goals. Over the last few decades, the equipment and procedures for processing RAP have advanced significantly. Today, RAP is typically processed by cold-milling the existing asphalt pavement surface, and then undergoing additional crushing and fractionation, with the fractionated RAP being stockpiled into two or three size fractions for better control during production. Fractionated RAP, combined with proper stockpiling management techniques, is less variable and thus can be used in higher percentages in asphalt concrete without compromising quality. The higher quality RAP, combined with asphalt plants that are more adept at handling higher quantities without detrimental effects including those that use warm-mix asphalt (WMA) foaming technologies, has resulted in the ability to consistently produce high-quality asphalt concrete containing 25 percent RAP or more.

A number of studies have been completed evaluating the performance and feasibility of high RAP (beyond 25 percent) applications. In 2009, the National Center for Asphalt Technology (NCAT) completed a study comparing virgin and recycled asphalt pavements using data from the Long-Term Pavement Performance (LTPP) program (NCAT 2009). The data used were from the LTPP SPS-5 *Strategic Study of Rehabilitation of Asphalt Concrete Pavements*, which compared thin (2-in thick) and thick (5-in thick) overlays placed on milled and non-milled surfaces, with the asphalt concrete being made of 100 percent virgin material or with 30 percent RAP. The SPS-5 experimental design permitted direct comparisons to be made for the unique combinations of surface preparation, overlay thicknesses, and overlay material, without the confounding effects introduced by different in situ conditions. The study determined that in most cases the same overall overlay performance was observed whether the asphalt concrete was composed of 100 percent virgin material or with 30 percent RAP in the asphalt concrete. In a separate analysis of data from Arizona's own SPS-5 study located near Casa Grande, it was found that performance was most greatly affected by overlay thickness with the use of a 5-in thick overlay providing the best performance. This same analysis found that overlay performance was improved when virgin materials were used compared to asphalt concrete containing 30 percent RAP, although the relationship was not as strong as it was for overlay thickness. It is noted that these data represent test sites constructed prior to the use of improved RAP processing, including fractionation, and the adoption of WMA technologies in the United States.

One concern with using increased RAP content in asphalt concrete is the level of blending that occurs between the aged residual binder in the RAP and the virgin asphalt binders added during mixing. The two extremes in what could be occurring are as follows:

- The RAP is acting as a "black rock" in which the aged binder does not blend with the virgin binder.
- The residual binder in the RAP blends completely with the virgin binder, creating a composite binder.

If the RAP is acting as a "black rock" when it has been assumed that complete blending has occurred, the added virgin binder will be too soft and insufficient binder will be present in the mixture. Conversely, if the aged residual binder in the RAP is actually blending with the virgin binder when it is assumed that the RAP is acting as "black rock," the composite binder will be greater in volume and stiffer than expected. In reality, the degree of blending that occurs between the aged residual binder in the RAP and the virgin binder is somewhere between the two extremes. It has been determined that the effect of RAP binder on the composite binder, and thus mix properties can become significant, and the grade of the virgin binder added to the mixture often requires adjustment, especially as the percent RAP increases (Al-Qadi et al. 2007). The current national guideline for determining the binder grade adjustment in asphalt concrete mixtures containing RAP has three levels depending on the RAP percentage in the mixture by total weight of the mixture (AASHTO M 323). These recommendations are summarized in Table 1.

**Table 1. Binder Selection Guidelines for Mixtures Containing RAP (AASHTO M 323)**

| Recommend Virgin Binder Grade | RAP Percentage |
|---|---|
| No change in binder | Less Than 15 |
| Select a binder one grade softer than standard (e.g., Select PG 58-28 if PG 64-22 is the original binder) | 15 to 25 |
| Follow recommendations from blending charts | Greater than 25 |

Additional methods to address blending of the virgin and RAP aged residual binder have been developed. These include a test protocol to estimate the low-temperature properties of the RAP aged residual binder without extraction (Ma et al. 2010), as well as proposed approaches involving the measurement of asphalt concrete dynamic modulus (Bonaquest 2005, Bennert and Dongre 2010). For example, in the Southeast and mid-Atlantic regions researchers have proposed using the high-temperature grade of the residual binder in 100 percent RAP and the high-temperature grade of virgin binder as the model for 0 percent RAP to plot the high-temperature binder grade versus the RAP content to estimate the effect of RAP on the asphalt concrete mixture stiffness. NAPA (2009) recommends that in colder regions that the low-temperature binder grade also be checked when using this method. NCHRP Report 752, which considers asphalt concrete mixtures with up to 55 percent RAP, recommends the selection of the grade of virgin binder be based on the following (West et al. 2013):

- Knowledge of the true grade of the RAP binder.
- The high and low critical temperatures of the project.
- And one of the following additional specifications:
    - The approximate ratio of RAP binder divided by the total binder content.
    - The high and low critical temperatures for the available virgin binders.

States have also initiated and performed studies to improve the design methodologies and construction specifications for high RAP content mixtures (high RAP content is defined as greater than 25 percent). For example, the Texas Department of Transportation (TxDOT) conducted a study that initially addressed the variability of RAP stockpiles within the state and determined that the materials were consistent within individual stockpiles (Zhou et al. 2011). The study proposed a balanced mixture design approach where the final asphalt content is selected after optimizing the mixture density, Hamburg wheel tracking test (HWTT) results, and Overlay Test (OT) requirements. The authors of the study recommend the use of the HWTT test to evaluate rutting/moisture resistance and OT to directly measure cracking resistance of asphalt concrete mixtures containing RAP. Additionally a maximum density requirement of 98 percent was included to avoid over-compaction and possible bleeding. The final balanced asphalt content is selected after optimizing the HWTT, OT, and density results.

The developed mixture design methodology was applied by TxDOT on two different field sites with different climate, traffic levels, and construction (new versus rehabilitation). The study varied the RAP percentage between 0, 20, and 35 percent. The performance observation of the RAP test sections indicated that high RAP mixes (i.e., 35 percent) can have performance similar to or even exceeding that of virgin mixtures as long as they are based on a mixture design methodology that incorporates performance-related testing.

Researchers at the Illinois Center for Transportation (Al-Qadi et al. 2012) performed laboratory experiments to characterize the performance of HMA with high amounts of RAP. The experimental program was designed to determine the structural and durability characteristics of HMA with high RAP, and to compare results to an HMA control without RAP. Two control HMAs and six RAP mixtures with 30, 40, and 50 percent RAP were developed using the Bailey method (Vavrik et al. 2002) of aggregate packing. The performance of all the HMAs with RAP was determined using various performance tests, including complex modulus, beam fatigue, fracture, wheel tracking, and moisture susceptibility. The effect of softer binders on the performance of mixtures with RAP was also evaluated using two relatively soft binders (PG 58-22 and PG 58-28). All properties were then compared with HMA made with virgin material (control mixture). The results of the study showed that high RAP content HMAs outperformed the control mixtures in most performance tests. The high RAP showed reduced rutting potential, improved fatigue resistance, and resistance to moisture susceptibility. Additionally, mixtures made with the softer PG 58-22 binder exhibited improved fatigue behavior. The study suggests that HMAs with high RAP content (up to 50 percent) can be designed that possess the desired volumetrics and performance criteria.

In a more recent study, Vargas-Nordcbeck and Timm (2013) performed laboratory and field evaluations on various “sustainable” asphalt pavement sections constructed at NCAT’s facility in Opelika, Alabama to characterize material properties and assess pavement performance. The mixtures evaluated were WMA, with high RAP content and capped with a porous friction courses (PFC). The field operation applied a total of 10 million ESALs to the closed loop track over a two year period. Based on observed field performance, it was concluded that the high RAP and WMA-RAP mixtures (both containing 50 percent RAP) had the least rutting and the smoothest profile as assessed by the International Roughness Index (IRI). At the end of the research cycle, no cracking had been observed on any test section. An estimate of predicted cycles to failure from beam fatigue tests determined that the high RAP mixture would have slightly better performance than the control, and the WMA-RAP would carry close to six times the expected cycles to failure than the control. Laboratory evaluation found high RAP mixtures to be stiffer than the control, which would be expected to increase susceptibility to cracking but provide higher rutting resistance. Also, high RAP mixtures were more resistant to moisture damage than the control and WMA mixtures. The laboratory assessment also found that results from the Advanced Pavement Analyzer (APA) and the flow number (FN) from the Asphalt Mixture Performance Tester (AMPT) correlated poorly with field results, while the HWTT and properties of the extracted binder tests appeared to be more predictive.

**State and Agency Practices**

In addition to the national trend of increased RAP usage overall, Figure 1 shows that there is a trend among states to permit a high percentages of RAP (25 percent or greater replacement) in mixtures used in one or more asphalt concrete pavement layers (Copeland 2011). Yet, Figure 2 illustrates that fewer than half the states actually use more that 20 percent RAP in asphalt concrete pavement layers, although quite a few have experimented with or routinely use high RAP mixtures (Figure 3) (Copeland 2011). Figure 4, from a more recent report, shows the estimated percent RAP usage by state in 2013 (Hansen and Copeland 2014).

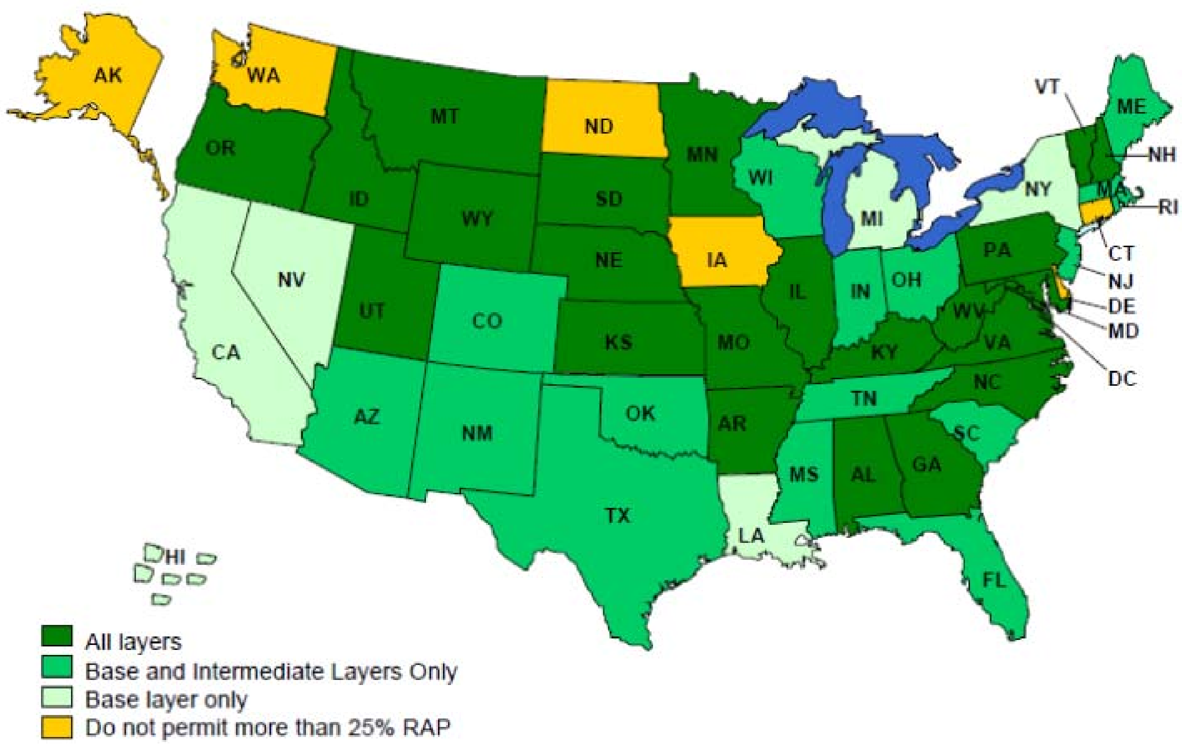


**Figure 1. States that Permit High RAP (25 Percent RAP or Greater) Content in Asphalt Concrete Layers (Copeland 2011)**

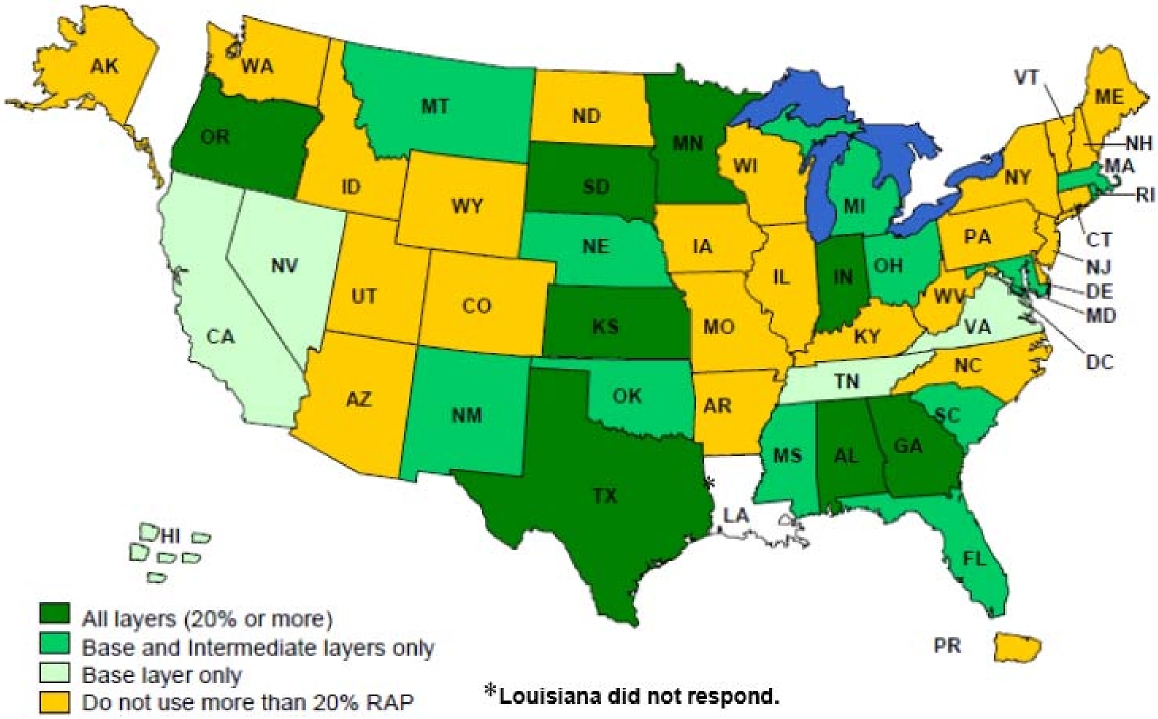


**Figure 2. States Using More Than 20 Percent RAP in Asphalt Concrete (Copeland 2011)**

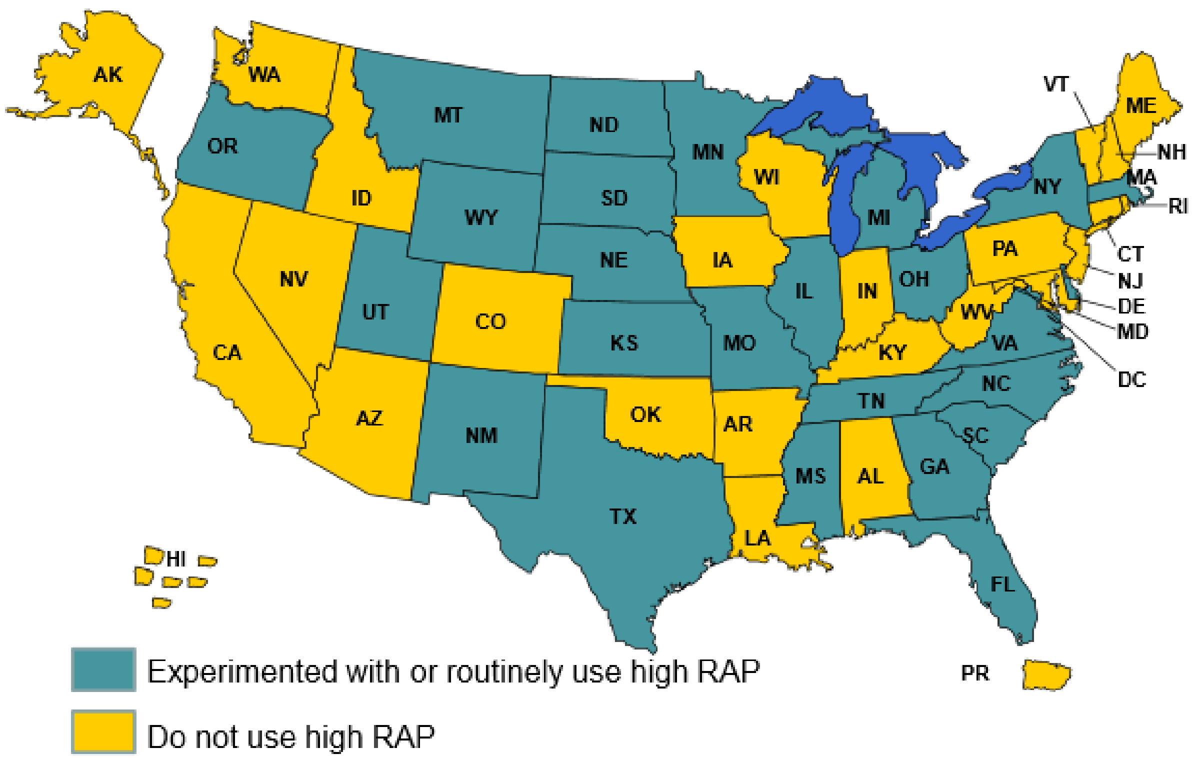


**Figure 3. States that Use, Have Experimented With, or Routinely Use High RAP (25 Percent RAP or Greater) Asphalt Concrete Mixtures (Copeland 2011)**

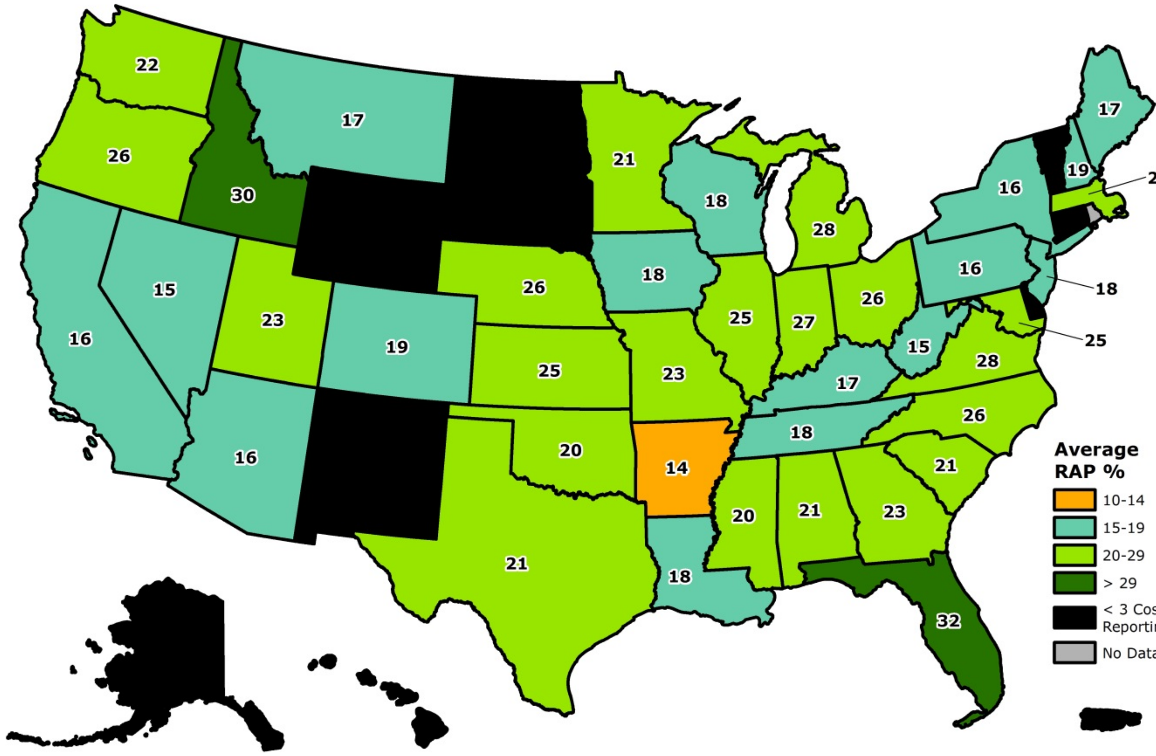


**Figure 4. Estimated Average Percent of RAP in Asphalt Concrete Mixtures by State for 2013 (Hansen and Copeland 2014)**

### *Regional State-of-the-Practice*

As seen in Figure 1, regional states (California, Colorado, New Mexico, Texas, and Utah) vary in whether they use high RAP contents in their asphalt concrete; only Utah permits it in all layers and California and Nevada restrict its use to the base layer. Arizona has specification limits similar to Texas, New Mexico, and Colorado, allowing high RAP content in the base and intermediate layers, but not in the surface. Below are summaries of the regional state specifications with regards to RAP use.

**California.** The California Department of Transportation (Caltrans) allows up to 25 percent RAP in all layers, and up to 40 percent for Type A hot-mix in layers 0.2 feet below the surface, but the RAP must be fractionated if substitution is greater than 15 percent as specified in *Section 39, Asphalt Concrete* (Caltrans 2015).

**Colorado.** The Colorado Department of Transportation (CDOT) permits that up to 23 percent of the effective binder can be recovered from RAP for all lifts provided all other specifications for asphalt concrete are met. If the binder content of the RAP is the same as that of the new mixture, this effectively limits the RAP content to 23 percent. CDOT's RAP specification for asphalt concrete is entitled, *Revision of Section 401 – Reclaimed Asphalt Pavement* (CDOT 2013A).

CDOT also has a specification for RAP being used as an aggregate base, in which 100 percent of the RAP can be recycled. That specification is *Revision of Sections 304 and 703 – Aggregate Base Course (RAP)* (CDOT 2013b).

**Nevada.** The Nevada Department of Transportation (NDOT) allows the use of RAP under Section 404 - Cold Recycled Bituminous Surface and Premixed Bituminous Paving Material in their standard specifications (NDOT 2014). RAP is not mentioned specifically for use in paving mixtures but it is known that a maximum RAP content of 15 percent is allowed on most projects.

**New Mexico.** The New Mexico Department of Transportation (NMDOT) introduced new specifications in 2014. The specifications for *Section 423: Hot Mix Asphalt – Superpave and Section 424: Warm Mix Asphalt* state that a maximum of 15 percent RAP can be used without changing the asphalt binder. For RAP quantities greater than 15 percent to 25 percent, the asphalt binder's high and low temperature grades should be lowered by one grade (e.g., lower a PG 76-22 to a PG 70-28). Alternatively, the aged residual binder can be extracted, recovered, and combined with a virgin asphalt binder per AASHTO M 323, Appendix A, to ensure the resultant binder meets the required Project PG asphalt binder properties. For RAP quantities greater than 25 percent to 35 percent, the aged residual binder must be extracted, recovered, and combined with a virgin asphalt binder per AASHTO M 323, Appendix A. Testing is then conducted on the resulting binder to ensure that it meets the required Project PG asphalt binder properties. The maximum allowable RAP content is 35 percent (NMDOT 2014).

**Texas.** TxDOT permits no more than 10 percent unfractionated RAP for dense-graded surface asphalt concrete mixtures as cited in the TxDOT *Item 340 – Dense-Graded Hot-Mix Asphalt (Small Quantity)* and *Item 341 – Dense-Graded Hot-Mix Asphalt* (TxDOT 2014). If fractionated, the maximum allowable RAP increase to 20 percent for surface, 30 percent for intermediate, and 40 percent for base layers. Up to 5 percent of the RAP can be replaced with RAS (TxDOT 2014).

TxDOT permits up to 20 percent unfractionated RAP and up to 30 percent fractionated RAP in plant-mixed base or foundation mixtures as found in *Item 292 Asphalt Treatment (Plant-Mixed)* (TxDOT 2014).

Up to 20 percent RAP is allowed in *Item 247 Flexible Base. Item 346 Stone-Matrix Asphalt* allows up to 15 percent fractionated RAP in the surface and 20 percent fractionated RAP in non-surface layers (TxDOT 2014).

**Utah.** According to UDOT, RAP can be used up to 15 percent without requiring adjustment to the asphalt binder. If the RAP content is between 15 to 25 percent, the asphalt binder grade must be adjusted according to AASHTO M 323 by selecting one grade softer than the grade specified. Test reports must be provided that indicate that the PG grade and quantity of the recovered asphalt binder is consistent throughout the stockpile. The limit on RAP is 25 percent of the total weight of the hot mix and RAP binder to 25 percent of the total binder. The UDOT specifications can be found in *Section 02741 – Hot-Mix Asphalt (HMA)* (UDOT 2012).

As illustrated in Figure 2, the implementation of high RAP contents allowed in state specifications is not always reflected in practice (based on 2011 data). Only Texas used more than 20 percent RAP in all layers and only New Mexico had this level of utilization in base and intermediate layers. California and Nevada managed to use more than 20 percent RAP in their base layers, but Arizona, Utah, and Colorado do not use more than 20 percent RAP in any asphalt concrete pavement layer even though, according to the survey, high RAP contents were permitted. Figure 4, which presents data from 2013, shows that although there has been a significant increase in the number of states averaging more than 20 percent RAP in asphalt concrete (from 9 states in 2009 to 25 states in 2013), of the regional states of interest, Arizona has one of the lower RAP utilization rates at 16 percent (Hansen and Copeland 2014).

**Use of RAP in Arizona**

According to Figures 1 through 3, ADOT allows high RAP content (25 percent or above) mixtures in base and intermediate layers but in practice does not exceed 20 percent RAP in any layer. Also, ADOT has conducted only limited experimentation with using high RAP mixtures, although in 2016, ADOT will be constructing some high RAP test sections with up to 30 percent RAP and warm-mix technology (McCarty 2015). These ADOT usage values were developed from data from 2010, and reflect the asphalt mixtures described in ADOT's *Standard Specifications for Road and Bridge Construction 2008* (ADOT 2008).

Sections 416 and 417 in these specifications are for asphalt concrete. Although the words "RAP," "recycled," or "reclaimed" do not appear in these specification sections, these terms appear in ADOT 2008 Stored Specifications (416 ACES & 417 SHRP). These stored specifications modify the 2008 ADOT Standard Specifications (Section 416 and Section 417) to include RAP material in regular mix, and also, introduce WMA technology.

During bidding, the contractor is provided these stored specifications as part of "Special Provisions" along with the "Project Plans." These stored specifications are available to be downloaded (ADOT 2016a). The following modifications are provided in these ADOT 2008 Stored Specifications that are of relevance to this project:

- Section 416 ACES (07/16/13) – Asphaltic Concrete – End Product: This document allows up to a maximum of 25 percent RAP in asphalt concrete mixtures used in a pavement layer placed a minimum of 2 inches below the finished surface. A maximum of 20 percent RAP is allowed in surface mixtures.
- Section 417 SHRP (7/16/13) – Asphaltic Concrete (End Product) SHRP Volumetric Mix: This document allows up to a maximum of 25 percent RAP in asphalt concrete mixtures used in a pavement layer placed a minimum of 2 inches below the finished surface. A maximum of 20 percent RAP is allowed in surface mixtures.
- Section 416d (09/13/13) – Asphaltic Concrete – End Product (Base Mix)(PCCP Base). This modification is directed specifically at plant mixed asphalt mixtures for use as a base.

In each of these modifications, the following statement is made:

> *Reclaimed asphalt pavement (RAP), as defined in Subsection 416-3.04, may be used in the mixture provided all requirements of the specifications are met; however, RAP will not be allowed in the mixture when asphalt cement type PG 76-22 TR+ or PG 70-22 TR+*

*is specified in Subsection 416-3.03(B). References to the use of RAP in this section apply only if RAP is utilized as part of the mixture. ADOT Materials Policy and Procedure Directive No. 20, "Guidance on the Use of Reclaimed Asphalt Pavement (RAP) in Asphaltic Concrete", shall be used in conjunction with the requirements of the specifications.*

The ADOT Materials Policy and Procedure Directive No. 20 (PP&D No. 20) is dated April 19, 2013, and states that RAP may be used in asphalt concrete as long as it is allowed in the specification (ADOT 2010). This suggests that, contrary to Item 416 in the 2008 specification, RAP was being used in some projects and that this document was being issued to provide guidance for its use.

PP&D No. 20 stipulates that if less than or equal to 15 percent RAP is used, it must pass through the 1-1/4 inch sieve, whereas if greater than 15 percent RAP is used, it must be fractionated into uniform coarse and fine stockpiles meeting gradation requirements of the specifications. Further, if less than or equal to 15 percent RAP binder is used by total binder in the mixture, no testing is required on the RAP binder properties. However, when more than 15 percent RAP binder is used, the binder must be extracted, recovered, and tested; then depending on the results, the grade of the virgin binder may need to be different than what was specified in the bid documents.

In addition, the following is provided in ADOT 2008 Stored Specifications (303SALV, 9/07/11) that is relevant to RAP for this project:

- Aggregate subbase and aggregate base material may be comprised in part of salvaged asphaltic concrete, as approved by the Engineer.
- A maximum of 50 percent salvaged material will be allowed. The 50 percent maximum shall include all salvaged materials, including any underlying base material recovered during full-depth reclamation.
- A layer of virgin aggregate must be placed immediately above the prepared underlying subgrade and beneath the layer containing salvaged material.

**Challenges to Increasing the Use of RAP**

According to Copeland (2011), average RAP use as a percentage of total mixture is estimated at only 12 percent in the United States and less than half of State DOTs use more than 20 percent RAP even though their specifications allow for significantly higher RAP contents. The barriers commonly cited by State DOTs for not using more RAP include (Copeland 2011):

- Quality concerns.
- RAP consistency.
- Grade of resultant binder and degree of blending.
- Mix design procedures.
- Volumetric requirements.
- Durability and cracking performance due to binder stiffening.
- Use with polymers (or tire rubber).

Contractors cite their own barriers to greater RAP usage which include (Copeland 2011):

- State DOT specifications.
- Control of RAP.
- Dust and moisture content.
- Increased quality control (QC).

It is interesting to note that specifications are considered a barrier by contractors even though it is recognized that “specifications” often permit the use of high RAP content. This is because most specifications require additional binder and mixture testing and increased material handling during construction if more than 15 percent RAP is used. AASHTO M 323, for example, provides the recommendations provided in Table 1. This de facto barrier is necessary as the risk of failure increases as RAP content increases, but it is a disincentive to contractors to pursue the use of high RAP mixtures if the burden for testing and stockpile management increases significantly (as would occur if the development of a binder blending chart is required as presented in Table 1).

The variability of RAP is another barrier. As a reclaimed material, the RAP not only possesses the variability inherent in the original pavement but also that associated with the processing, handling, and stockpiling of the material. The in-situ variability is compounded by the fact that asphalt pavements are composed of multiple lifts that may have been placed at various times with varying materials. A single milling may reclaim three or more lifts, each of which has very different properties, and as lift thickness varies over a project, so will the variability in the RAP. Further, although processing and stockpiling of RAP on large projects can be done in a relatively uniform fashion, for smaller projects this is much more difficult as multiple sources of RAP might be co-mingled.

Uncertainty also exists associated with the use of RAP containing polymer- or rubber-modified asphalt or the effect RAP might have on the properties of polymer-modified virgin asphalt. Either way, this uncertainty increases as RAP content increases, and thus additional guidance is needed on how best to address the effects of polymer- and rubber-modified binders on the use of RAP in new asphalt concrete.

One of the biggest barriers to the use of high RAP mixtures is past experience, especially when that experience has been bad. It is not uncommon to find state DOT personnel or contractors that may have had a bad experience in using RAP, especially high content RAP, and this experience diminishes their desire to try it again. But the industry’s understanding of RAP processing and behavior have advanced considerably over the last decade, and this requires training and outreach to communicate to potential users, along with well-designed demonstration projects.

It has been reported that an additional barrier restricting the use of high RAP mixtures by ADOT is caused by insufficient funding for highway construction and as a result, pavements that might otherwise be reconstructed (thereby allowing for high RAP mixtures to be used in base and intermediate mixtures) are only milled to a depth of a few inches and overlaid with a single lift of AC (within 2 inches of the final riding surface) for which, specifications do not permit the use of high RAP mixtures.

### Concluding Remarks on RAP Usage

RAP has been used in asphalt concrete mixtures since the early 1970s and has become an established material for most DOTs. High RAP (25 percent or greater replacement) mixtures are of great interest to the industry as they offer the replacement of significant amounts of virgin binder and aggregate, resulting in significant cost savings and the potential for increased sustainability. Yet it is recognized that the risk of failure increases as RAP content increases, and thus even though most State DOT specifications allow for relatively high RAP contents, the average RAP usage as a percentage of total asphalt concrete mixture in the United States remains below 15 percent.

Keys to increasing RAP utilization is training to better understand how to successfully incorporate higher levels of RAP into asphalt mixtures, improved quality control throughout the mixture design and construction processes, training and outreach, and the incorporation of incentives to encourage contractors to increase RAP utilization.

## RECYCLED ASPHALT SHINGLES (RAS)

### Review of National Practice

The use of reclaimed asphalt shingles (RAS) from both manufacturers' waste (pre-consumer) and tear-off post-consumer waste is on the rise nationwide. From 2009 to 2013, the use of both pre- and post-consumer asphalt shingles in asphalt mixtures increased 135 percent, to a level of nearly 1.6 million tons in 2013 (Hansen and Copeland 2014). It is estimated that the 1.67 million tons of RAS utilized resulted in approximately 320,000 tons (1.7 million barrels) of virgin asphalt binder being conserved. The estimated savings (at $600 per ton for asphalt binder) is $192 million.

A diagram of the RAS production stream is shown in Figure 5 (IDOT 2013), whereas post-consumer shingles and processed RAS are shown in Figure 6 (ARSR 2012).

As is true with RAP, the use of RAS reduces the amount of materials going to landfill while reducing the amount of virgin binder used in new asphalt concrete mixtures. On average, RAS contains about 20 percent asphalt binder by weight compared with about 5 percent for RAP, along with aggregates, mineral filler, and fibers. There are two sources of shingles used in RAS, manufacturer's salvaged (pre-consumer) shingles and tear-off (post-consumer) shingles. Pre-consumer shingles are either those rejected by the manufacturer as being unsuitable for sale due to imperfections or are from the tabs punched out of the three-tab shingle. Post-consumer shingles are obtained from roof tear-offs. One potential problem with post-consumer shingles is that asbestos fiber was used by some shingle manufacturers into the 1980s, and thus sources must be screened to ensure asbestos is not present.

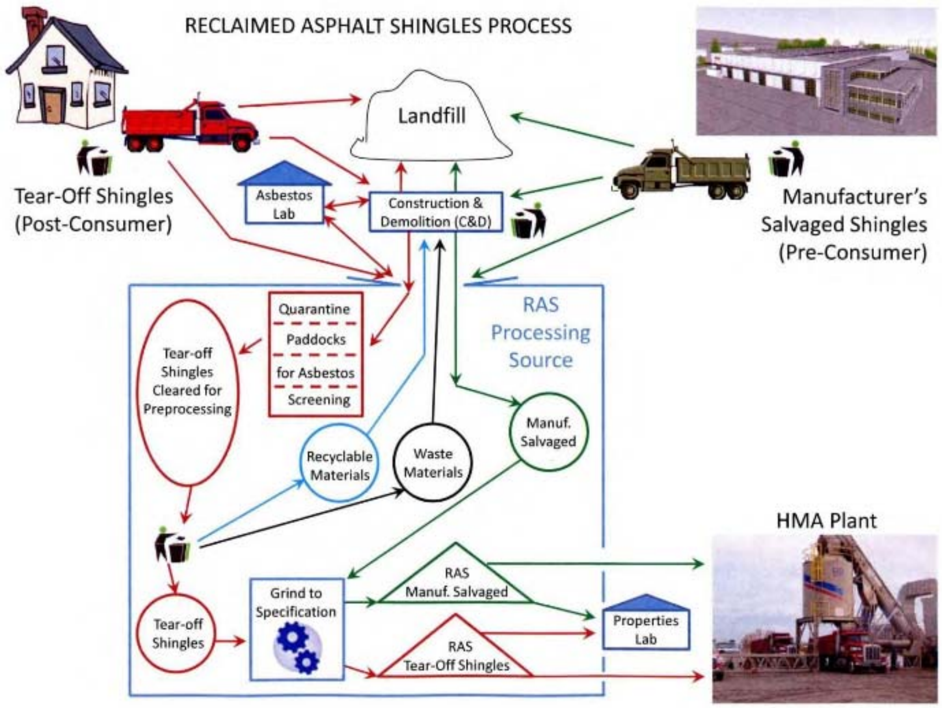


**Figure 5. Diagram of RAS Production Stream (IDOT 2013)**

**Figure 6. Unprocessed Post-Consumer Shingles (Left) and Processed RAS (Right) (ARSR 2012)**

To create RAS, the shingles are shredded to a maximum size of 0.25 inch and sorted for use. Shingles obtained post-consumer as part of a roof tear off require additional processing to remove nails and other impurities. Typical use is limited to about 5 percent RAS by weight of the total mixture because of potential for variability, the higher stiffness of roofing asphalt compared to asphalt used for pavements, and the limited degree to which RAS blends with virgin and residual RAP asphalt. But because of its high binder content, even at such low replacement levels, a significant reduction in virgin asphalt binder can be obtained.

A number of high profile projects have been constructed with asphalt concrete mixtures containing both RAS and RAP, including an overlay of Michigan Avenue in Chicago (Illinois Interchange 2012). RAS/RAP mixtures are also being used by the Illinois Tollway to lower costs and reduce the environmental impacts of pavement materials (Illinois Tollway 2014). The EPA (2013a) recently performed a limited environmental life cycle inventory (LCI) and life cycle assessment (LCA) on the use of RAS, evaluating only GHG emissions, and concluded that there are environmental benefits to the use of RAS in asphalt production for use in asphalt concrete, and that the addition of RAS to pavement mixtures containing RAP helps further increase environmental reductions relative to the baseline of using virgin asphalt.

**State and Agency Practices**

Figure 7 presents the states where asphalt concrete plant-mix producers reported using RAS in 2009 through 2013 (Hansen and Copeland 2014). It is noted that a big swath of rocky mountain and southwest states report no use of RAS, whereas the majority of the states reported RAS usage.

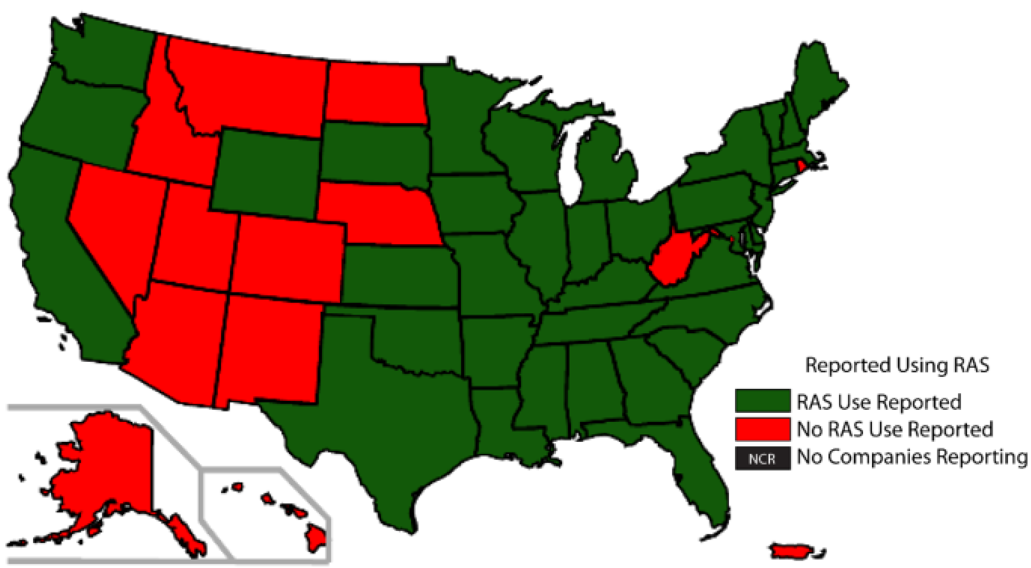


**Figure 7. States with Companies/Branches Reporting RAS Usage (Hansen and Copeland 2014)**

Some states in the Great Lakes region have been using RAS in asphalt concrete mixtures since 2009. For example, the Illinois DOT (IDOT) has been using RAS in asphalt mixtures since 2010. In January 2012, Illinois Public Act 097-0314 became effective. It targeted the use of RAS as a material that had the potential to promote environmental stewardship while reducing project costs (IDOT 2013). IDOT reports that the use of RAS is rapidly increasing. Although the early performance of pavements constructed with RAS has been satisfactory, concerns remain regarding the long-term performance. IDOT, which allows up to 5 percent RAS by weight of total mix, uses a special provision to include RAS in asphalt concrete mixtures. The intent is to include RAS in the *Standard Specifications for Road and Bridge Construction* once the special provision becomes "stable" (IDOT 2013).

In August 2013, the Institute for Transportation at Iowa State University produced the findings of a pooled fund study, a collaboration of seven state transportation agencies in the United States with the goal of researching the effects of RAS on the performance of asphalt applications (Williams et al. 2013). The study focused on evaluating different factors affecting asphalt mixtures containing RAS in both laboratory and field demonstrations, and included:

- Utilizing WMA technology with RAS.
- Replacing RAP with RAS in HMA.
- Replacing fibers and virgin asphalt with RAS in HMA.
- Using various RAS grind sizes and modified asphalt binder.
- Using different RAS percentages.
- Comparing post-manufactured to post-consumer RAS.

Observations showed that RAS pavements can be successfully produced to meet state agency asphalt mixture quality requirements for asphalt content, gradation, and volumetrics. Flow number and dynamic modulus results from the mixtures studied show that using RAS, or a combination of RAS and RAP in HMA, improves rutting resistance; pavement condition surveys performed on field pavements confirmed the high rutting resistance of the mixtures as there was no measureable amount of wheel path deformation. Four-point bending beam laboratory results concluded that HMA with RAS should perform as well as HMA without RAS with respect to fatigue performance. Semi-circular bend test results provided evidence that the addition of RAS materials to HMA is not detrimental to its fracture resistance. Field pavement condition surveys observed differing cracking performance results between the state sites. However the differences in cracking between RAS pavements and non-RAS pavements were slight in all cases.

***Regional State-of-the-Practice***

As is seen in Figure 7, states within the region have little reported experience with the use of RAS, with Arizona, New Mexico, and Utah reporting that RAS has never been used, Nevada indicating that RAS was used in 2010, but not in 2012. Colorado, on the other hand has used RAS since 2009 and California began using RAS in 2010.

**California.** Caltrans has recently finalizing standard specifications for use of RAS in HMA. This specification includes consideration of the impacts both from the shingle provided aggregate and binder. With regards to the aggregate, it is required that shingle asphalt binder be extracted in accordance with AASHTO TP 2, the shingle fiber removed, and the aggregate gradation determined in accordance with AASHTO T 30. The shingle aggregate is then considered as part of the overall aggregate gradation that must meet required specifications.

For the binder, if the total available shingle asphalt binder content, expressed as a fraction or percentage of the new hot mix asphalt content, is greater than 0.75 percent, the virgin asphalt binder and shingle binder combination shall be further evaluated to ensure that the performance grade of the final blended binder complies with the performance grade requirements of the specifying jurisdiction.

The specification detailing the procedure is the *Standard Specification for Use of Recycled Asphalt Shingle as an Additive in Hot Mix Asphalt* (Caltrans 2016a).

In addition, the *Standard Recommended Practice for Design Considerations when using Recycled Asphalt Shingles in New Hot Mix Asphalt* are also available (Caltrans 2016b).

**Colorado.** CDOT permits up to 5 percent of the total weight of the mix can be from RAS in HMA, provided all specifications for HMA are met. Only RAS as defined by AASHTO MP 15 is allowed. The total binder replaced by the binder in RAS, or RAP cannot exceed 30 percent of the effective binder content of either the mix design or produced mix. CDOT's RAS specification are entitled, *Revision of Section 401 – Reclaimed Asphalt Shingles* (CDOT 2012).

**Texas.** TxDOT permits up to 3.0 percent of the weight of the total mixture can be from RAS in mixtures meeting *Item 292 – Asphalt Treatment (Plant-Mixed)* dense-graded HMA; additionally 100 percent of the particles must pass the 3/8 inch sieve (TxDOT 2014). TxDOT Item 340 – *Dense-Graded Hot-Mix Asphalt (Small Quantities)* and *Item 341 – Dense-Graded Hot-Mix Asphalt* both allow for up to 5 percent replacement with RAS, either alone or in combination with RAP (TxDOT 2014).

### Use of RAS in Arizona

Currently, ADOT has no standard specification allowing the use of RAS in asphalt concrete mixtures in any layer, nor has the department experimented with the use of RAS mixtures. ADOT's *Standard Specifications for Road and Bridge Construction 2008* (ADOT 2008) only notes the use of roofing paper, which is not RAS or shingle-related, and only twice:

- Section 501 – *Pipe Culvert and Storm Drains – Slotted Pipe*: This section states that prior to backfilling and paving operations the slot shall be covered to prevent infiltration of material into the pipe. Roofing paper, among other materials, may be used and the coverings shall be removed when the paving operations have been completed.
- Section 708 – *Permanent Pavement Marking – Road Service Rating*: This section states that roofing paper is allowed to aid in obtaining the correct film thickness of test stripes of paint applied transversely across the road.

The ADOT *Construction Manual*, Chapter 4 (ADOT 2016b**)** states that roofing paper may be used in placing asphalt concrete transverse joints whenever paving is stopped for long periods.

### Challenges to Increasing the Use of RAS

From Figure 7, it appears that 13 states have never reported the use of RAS. Yet according to NAPA, the number of states where plant-mix producers reported using RAS has increased from 22 in 2009 to 38 in 2013, with more than 130,000 tons of RAS used (Hansen and Copeland 2014). Although RAS use is increasing, there are still barriers to overcome including (Bauman 2005):

- Performance of post-consumer material (elasticity diminishes with time).
- Complexity of the material (differing asphalt, stone dust, backing, and adhesives).
- Predictability and availability of supply feedstock.

Additional barriers cited by contractors and State DOTs include (Stroup-Gardiner and Wattenberg-Komas 2013):

- Lack of documented performance.
- Lack of material specifications.
- Lack of agency experience, particularly with RAS obtained from tear-offs.
- Asbestos and additional testing when using RAS from tear-offs.
- Increased testing for QC programs.

Specifications are considered one barrier, even though it is recognized that "specifications" often permit the use of RAS. This is because most specifications require additional binder and mixture testing and increased material handling during construction if RAS is used.

The variability of RAS is another barrier. As a reclaimed material, the RAS not only possesses the variability inherent in the original product but also that associated with the handling and stockpiling of the material. The stockpiling variability is compounded by the fact that shredded roofing shingle material can agglomerate (Button et al. 1996). High temperatures and the stickier manufacturing waste shingles can magnify this issue. This necessitates reprocessing and rescreening prior to introduction into the asphalt concrete plant. To mitigate this problem, processed RAS may be blended with a small amount of less adhesive carrier material, such as sand or RAP, to prevent the RAS particles from clumping together.

The fact that RAS obtained from post-consumer shingles may contain asbestos is also a barrier. Due to liability concerns, manufacturers are reluctant to divulge previous use of asbestos in production and thus regional distribution of RAS from older shingles cannot be established (NAHB 1998). As a result, asphalt shingle recycling facilities are required to meet NESHAP and Occupational Safety and Health Act (OSHA) requirements (Williams et al. 2013). NESHAP requirements state that asbestos-containing roofing materials may not be ground up for recycling and defines asbestos containing material (ACM) as any material containing more than 1 percent asbestos as determined using polarized light microscopy. To ensure that delivered loads of post-consumer shingle scrap do not contain asbestos, many state agencies require the owner of the recycling facility to follow a specified sampling and testing plan. Samples are required to be obtained and tested for ACM using the polarized light method by an accredited laboratory. Typical sampling and testing frequencies require a sample to be obtained every 50 to 100 tons. In the event that a sample is found to contain greater than 1 percent ACM, the pile is required to be stockpiled separately and disposed of in accordance with state environmental regulations.

And in Arizona, although asphalt shingles exist (particularly in alpine areas), the majority of RAS that could be made available would be post-consumer and consist of a highly oxidized binder. Additionally, industry within Arizona has not formerly opened a dialogue with ADOT to inquire as to the possibility of using post-consumer RAS for highway construction (McCarty 2015).

### Concluding Remarks Regarding RAS Usage

RAS usage is on the rise in asphalt concrete mixtures. As seen in Figure 7, RAS availability and subsequent use is lower in the rocky mountain and southwest regions of the United States compared to the Great Lakes region, however post-consumer recycling can provide these states with quality RAS for use in asphalt mixtures if adequate supplies exist. Yet it is recognized that the risk of negative impacts on asphalt concrete mixture performance increases as RAS content increases, and thus even though most State DOT specifications allow for 5 to 7 percent RAS content, the amount of RAS used is significantly lower. In addition, long-term performance of pavements made with mixtures containing RAS is not available.

Keys to increasing RAS utilization is training to better understand how to successfully incorporate RAS into asphalt mixtures, improved quality control throughout the mixture design and construction processes, and the incorporation of incentives to encourage contractors to increase RAS utilization. Similarly, incentivizing RAS recycling facilities to produce quality RAS material will increase supply. Additionally, if transportation agencies receive more consistent and appropriate levels of funding for transportation infrastructure, it is likely that full-depth reconstruction will become more common due to the increased expense of performing frequent surface repairs and overlay operations to address deficiencies caused by failures in underlying asphalt courses and/or poor subgrade. This will provide an opportunity to increase the use of high RAP mixtures in base and intermediate pavement layers as opposed to surface repairs and overlays of only the uppermost layer of pavement where specifications often prohibit the use of high RAP mixtures.

## GROUND TIRE RUBBER (GTR)

### Review of National Practice

There are 280 million tires discarded each year by American motorists, approximately one tire for every person in the United States (RMRC 2008). The three largest scrap tire markets are tire derived fuel, civil engineering applications, and ground rubber applications/rubberized asphalt (EPA 2013b). For highway uses, the FHWA (2012) lists embankment construction, aggregate substitute, asphalt modifier, and retaining walls as applications of scrap tires.

For construction of embankments, shredded or chipped tires have been used as a lightweight fill material. However embankments have been known to have spontaneous combustion issues, which have led to ASTM standards. Ground rubber has been used as a fine aggregate substitute in asphalt pavements**.** Crumb rubber can be used to modify the asphalt binder in a process in which the rubber is blended with asphalt binder. The modified binder is commonly referred to as asphalt-rubber. Lastly, although not a direct highway application, whole tires have been used to construct retaining walls. They have also been used to stabilize roadside shoulder areas and to provide channel slope protection.

One of the largest applications of scrap tires is the ground rubber applications and rubberized asphalt, and from this application comes the use of crumb rubber in asphalt products. There are different methodologies of incorporating crumb rubber into paving mixtures for paving applications. In the dry process, crumb rubber is added to the aggregate prior to mixing with asphalt binder, whereas in the wet process, the crumb rubber is added to the asphalt binder prior to mixing with aggregate. While this may seem like a minor distinction, the process chosen greatly affects the interaction between the rubber and asphalt, and has a significant effect on the properties of the final product. Due to construction and performance issues, the dry process is rarely used any more, and thus, the focus is on the wet-process.

There are currently two distinct forms of wet-process crumb rubber-modified asphalt used in paving applications in the United States. It is noted that in the literature different authors have used different terminology for these two forms.

- **Field Blend** is also known as "Wet-Process, High Viscosity" and "Asphalt-Rubber." This material is typically manufactured by blending asphalt binder and crumb rubber at the asphalt concrete plant (hence the term "Field Blend"). While chemical interactions occur between the crumb rubber and asphalt binder, the material remains a mixture of discrete crumb rubber particles in an asphalt matrix that must be continually agitated to prevent separation. This material has significantly higher viscosity than typical paving asphalts (hence the term "High Viscosity"), and cannot be graded using conventional procedures such as the performance grade (PG) grading system, although there is ongoing work on developing a grading system for field blend materials. When the term "asphalt-rubber" is used without further clarification, generally it is in reference to field blend materials.

- **Terminal Blend** is also known as "Wet-Process, No Agitation." This material is typically manufactured by blending asphalt binder and crumb rubber at the refinery or distribution terminal (hence the term "Terminal Blend"), and is usually delivered to the hot-mix plant in a blended state similar to that of conventional and polymer modified binders. This process uses a more finely-ground crumb rubber than field blend, and there is longer and more thorough mixing, yielding a material with more continuous and homogeneous properties that does not require agitation to prevent separation. This material has a lower viscosity than field blend, and is graded using the PG grading system.

In general, terminal blend binders are similar to conventional and polymer-modified asphalt binders. This means that the mix design methods, specifications, and construction procedures used for conventional asphalt materials can largely be applied to terminal blend asphalt rubber materials. Supply of terminal blend products in a given area depends on the asphalt producers that serve that area and on their perception of market demand. Depending on the market, terminal blend asphalts are available in the form of paving grade asphalts, emulsions, and cutbacks (liquid asphalts).

As previously described, field blend binders are produced by mixing conventional asphalt and crumb rubber at or near the job site. Field blend binders have significantly higher viscosity than conventional asphalt binders and thus mixture design methods, specifications, and construction procedures are different than for conventional asphalt materials. Field blend binders can be used with hot- and warm-mix asphalt concrete, and hot chip seals, but not with cold mixes, conventional chip seals or slurry seals. The availability of field blend binder is determined by the availability of the specialized mixing equipment at the asphalt concrete plant, but is not dependent on the local asphalt producers.

It is commonly believed that the high viscosity of field blend binders allows higher binder contents to be used without undue risk of rutting, bleeding, drain-down (in the case of gap graded or open graded mixes) or runoff (in the case of chip seals). This higher binder content is generally considered to increase resistance to cracking. The higher viscosity also decreases the compactability of field blend materials, requiring either higher than normal placement and compaction temperatures or the use of a warm mix additive. Similarly, the higher viscosity requires higher-than-normal application temperatures for hot-applied chip seals.

For pavement applications, rubber-modified asphalt can be used in the production of asphalt concrete, chip seals, and slurry seals/microsurfacing as described below.

**Asphalt Concrete**

There are three forms of asphalt concrete used with wet-process crumb rubber modified binders.

- **Dense-graded mixtures** are the most common form of asphalt concrete, and are usually what is meant by the terms “asphalt concrete” (AC) or “hot-mix asphalt” (HMA) unless further clarification is included. Dense-graded mixtures cannot be produced with field blended binders, but are producible with terminal blended binders.
- **Gap-graded mixtures** have been specifically developed for use with field blended binders, and are the most common form of crumb rubber modified (CRM) mixes used in many locales including California (Caltrans 2006). Compared to dense-graded mixtures, gap-graded mixtures have reduced quantities of aggregate in the intermediate size ranges to provide space for the undigested crumb rubber particles that are present in the field blended binders. Gap-graded mixtures are moderately permeable to water.

- **Open-graded mixtures** are used both with and without CRM binders. Compared to dense-graded mixtures, open-graded mixtures have reduced quantities of aggregate in the intermediate and fine size ranges. Further, open-graded mixtures are typically considered to have no structural contribution to a pavement system. Instead, they are typically used to reduce splash and spray, improve skid resistance, and reduce noise generated through tire-pavement interaction on high-volume and high-speed roads such as limited access highways. A more generic term for open-graded mixtures, with or without asphalt-rubber binder, is “open-graded friction course” (OGFC).

Figure 8 shows a typical 0.45 gradation plot (for 0.5 inch maximum aggregate size mixtures) with target value ranges for these materials (Caltrans 2010). The dense-graded mixture closely follows the maximum density line, whereas both the gap-graded and open-graded mixtures dip below the maximum density line.

### *Chip Seals*

A chip seal consists of asphalt binder sprayed on a pavement surface and covered by a thin, embedded layer of aggregate. Chip seals are most commonly used for preventive and routine maintenance of an existing pavement surface, but can be placed directly over an unsealed surface, such as aggregate base. Chip seals, especially those using a CRM binder, are also used as a stress-absorbing membrane interlayer (SAMI) between an existing pavement and an overlay to retard crack reflection.

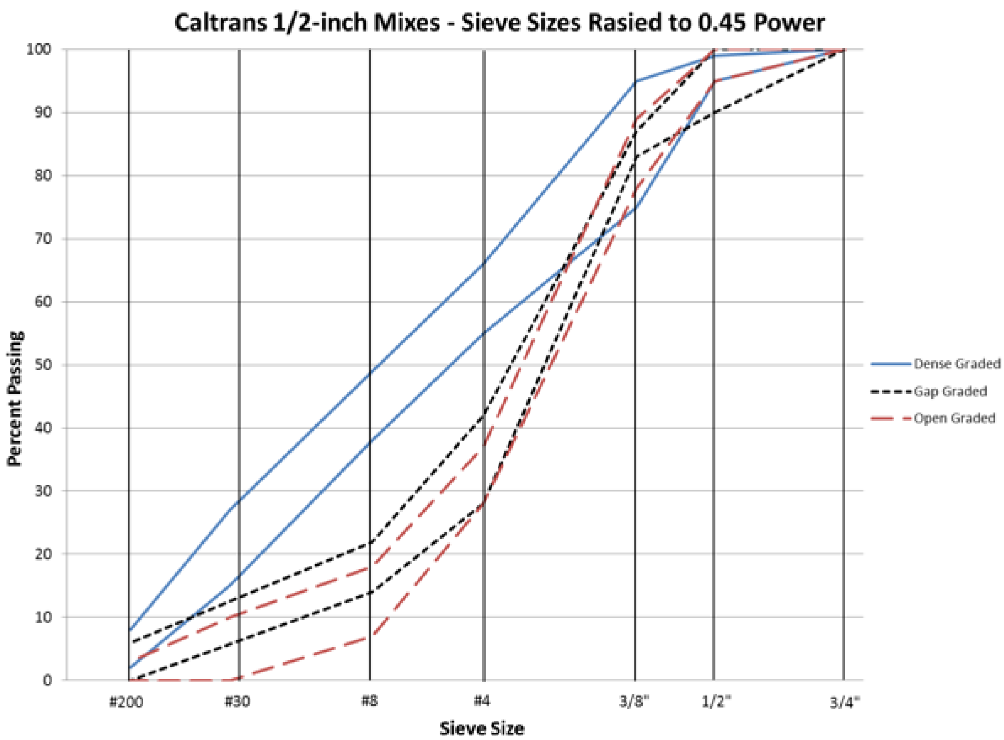


**Figure 8. Typical Dense-Graded, Gap-Graded, and Open-Graded Asphalt Concrete Mixture Gradations (Caltrans 2010)**

The binder in a chip seal may be an emulsion, cutback or hot-applied asphalt binder, with emulsions being the most common for conventional chip seals. Aggregates are typically a nearly one-size material and the gradation plots as a steep line on a 0.45 power plot. Figure 9 shows the gradations for a typical ½-inch maximum aggregate size hot-applied CRM chip seal and a conventional emulsion chip seals (Caltrans 2010). The emulsion chips are slightly finer and more well-graded.

When used with an emulsion, aggregates are typically applied damp and uncoated. In contrast, when used with a hot-applied binder, the aggregates must be dry and are usually pre-heated and pre-coated with asphalt. Hot, pre-coated chips are produced in an asphalt concrete plant.

Typical binder application temperatures for field-blend asphalt-rubber chip seals are approximately 400 °F. Chips are pre-heated to approximately 300 °F, and are pre-coated with asphalt (Caltrans 2006).

Binder application rate is substantially higher for field-blend chip seals than with conventional emulsion chip seals, typically 0.5 to 0.7 gallons per square yard for the former, and 0.15 to 0.4 gallons per square yard for the latter. Note that as a significant portion (typically 40 percent) of an asphalt emulsion is water, thus the effective application rate of binder is even lower.

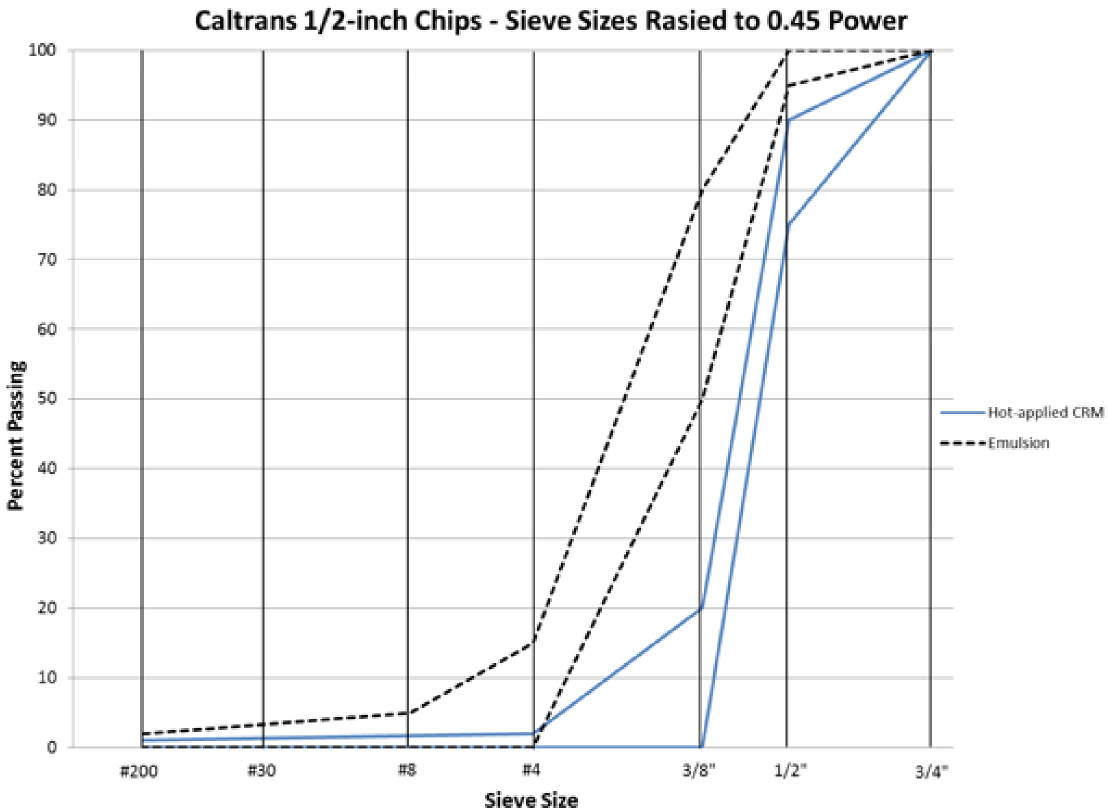


**Figure 9. Gradation curves for ½-inch chip gradations (Caltrans 2010)**

Terminal blend asphalt-rubber binders have been used with both emulsion and hot-applied chip seals. Hot-applied terminal blend asphalt-rubber chip seal practices are similar to those for field blended binders, although temperatures and application rates are slightly less. Construction practices for emulsified terminal blend binders are similar to conventional emulsion chip seals.

***Slurry Seals and Microsurfacing***

A slurry seal is a mixture of asphalt emulsion and graded aggregate. It is applied to a pavement in a thin layer, typically as a maintenance treatment. Microsurfacing is a very similar treatment that has improved ability to fill minor ruts and surface irregularities. Microsurfacing always includes mineral filler and a modified binder, whereas slurry seals may or may not. Because slurry seals and microsurfacing require an emulsified binder, they cannot be applied with field blended binders yet terminal blend emulsions have been used with slurry seals. However, this application is not currently widespread and little information is available in the literature with regards to practices and performance.

Rubberized Emulsion Aggregate Slurry (REAS) is a type of slurry seal that contains approximately 7 percent crumb rubber. The crumb rubber is added to the asphalt emulsion at ambient temperatures, with little or no expected chemical interaction between the asphalt and crumb rubber addition. Thus, this product should not be considered a wet-process crumb rubber modified asphalt.

**State and Agency Practices**

Crumb rubber modified (CRM) asphalt is a routinely used material in certain areas of the United States, including California, Arizona, Texas, and Florida. More recently Georgia and Missouri have reported increased usage of ground tire rubber (NAPA 2013). Table 2 presents the quantities and states where asphalt concrete plant-mix producers reported using GTR and CRM in 2013 (Hansen and Copeland 2014).

**Table 2. 2013 Reported Tons Ground Tire Rubber (Hansen and Copeland 2014)**

| State | Reported Tons of Mix Using GTR | Reported Tons of GTR Used |
|---|---|---|
| Arizona | 26,300 | 380 |
| California | 523,213 | 3,748 |
| Florida | 250,779 | 531 |
| Georgia | 65,000 | 260 |
| Illinois | 4,500 | 20 |
| Indiana | 13,000 | 30 |
| Louisiana | 104,395 | 550 |
| Maine | 14,000 | 219 |
| Massachusetts | 24,897 | 324 |
| Michigan | 12,000 | 71 |
| Missouri | 50,000 | 180 |
| New Hampshire | 28,000 | 358 |
| New York | 10 | - |
| Ohio | 1,500 | 8 |
| Pennsylvania | 18,000 | 140 |
| Puerto Rico | 10,000 | 170 |
| Texas | 50,000 | - |
| **Total** | **1,195,594** | **6,989** |

Many state DOTs experimented with CRM materials in the 1970s and 1980s, using either the dry process or the field blend wet-process. These initial experiences varied, with only Arizona, California, Florida, and Texas implementing the use of CRM on a large scale. More recently, the introduction and availability of terminal blend binders has resulted in several states to reconsider the use of CRM. With the exception of California, these states used CRM primarily as a *functional* maintenance treatment to improve skid resistance and ride quality, to reduce noise from tire-pavement interaction, or to seal minor cracks on pavements that were deemed to be otherwise structurally adequate.

Caltrans has developed a design process for gap-graded asphalt-rubber mixtures that are structurally superior to conventional dense-graded hot mix, allowing for up to a 50 percent reduction in overlay thickness (FHWA 1995). The current version of the Caltrans *Highway Design Manual* retains a thickness reduction procedure when using gap-graded asphalt-rubber in cases where the basis of the overlay thickness determination is to retard reflective cracking (Caltrans 2012). The initial basis for these recommendations was demonstrated field experience in California and Arizona, along with a rational argument that the higher binder content common in gap-graded CRM mixtures and the resilience added by the rubber modifier should result in better cracking resistance. Subsequent laboratory and heavy vehicle simulator (HVS) testing has validated these recommendations. A recent study performed for Caltrans compared four different overlays with asphalt-rubber CRM gap-graded mixtures (three terminal blended mixes and one field blended mixes) to a dense-graded mixture with a conventional binder (Jones et al. 2007).

The 1.8-inch thick asphalt-rubber overlays outperformed the 3.6-inch thick conventional asphalt overlay with respect to reflective cracking mitigation, although the rutting performance was worse. The study also found that the mixtures containing terminal blend asphalt-rubber binder had superior performance to the field blend mixture with regards to reflective cracking whereas rutting performance was mixed.

In 2004, Caltrans constructed a pavement experiment on an in-service portion of CA-33 in Fresno County. This project included a dense-graded conventional asphalt overlay, a gap-graded field blend overlay, a dense-graded terminal blend overlay, and a gap-graded terminal blend overlay. An AR-4000 binder was used in the conventional mixture, and the same binder was used as the base binder for the field blend mixture. After seven years, the conventional and terminal blend dense-graded mixtures had the best performance. This was in contrast to laboratory testing, which predicted that those mixtures had the least fatigue resistance (Cook et al. 2006). The field blend gap-graded mixture had significantly more cracking, and the terminal blend gap-graded mixture exhibited rutting and bleeding in the wheel path (Holikatti et al. 2012).

Conflicting results were reported in a study performed at the FHWA Accelerated Load Facility which found that field blend mixtures are more resistant to reflective cracking but less resistant to rutting than terminal blend mixtures (Gopal et al 1997; Gibson et al 2012). This experiment included several technologies other than CRM, including polymer-modified, fiber-reinforced, and air blown asphalts. The field blend mixture was the best performer with regards to cracking, but placed fourth out of seven with regards to rutting. The terminal blend mix was the best performer with regards to rutting, but placed fifth out of seven with regards to cracking.

A study of dense-graded mixtures performed by the University of Nevada found that terminal blend binders performed quite similarly to the polymer-modified binders used by Nevada DOT and Caltrans (Hajj et al 2011). This study included both laboratory testing and evaluation of field test sections. The laboratory investigation found that the terminal blend mixture was slightly stiffer than the polymer-modified mix, but slightly less fatigue resistant (since the laboratory fatigue testing was performed in a strain-controlled mode, it was considered that the higher stiffness of the terminal blend would offset its lower fatigue resistance). In other words, the actual traffic loading should result in slightly lower stress in the terminal blend material, which in turn would result in a similar fatigue life compared to the polymer-modified material. The field performance study found no difference between the mixtures, but only three years of performance data were available.

Warm mix technologies have special relevance to field blend asphalt-rubber, as one of the main drawbacks to that material is the elevated temperatures required for production, placement, compaction, and attendant issues with haul times, weather windows, and emissions/fumes. There are many well-documented paving projects using field blend asphalt-rubber and warm mix technologies in California and elsewhere (Hicks et al 2010). All four types of warm mix technologies (foaming process, foaming additive, chemical additive, and organic additive) have been used, and reductions in production and compaction temperature of 30 °F to 60 °F have been consistently achieved. Laboratory and heavy vehicle simulator studies of Caltrans field blend gap-graded mixtures have been performed to compare performance both with and without warm mix technologies (Jones et al. 2011a; 2011b). In these studies, no changes were made to the mixtures other than the addition of warm mix technologies and decreased production and compaction temperatures. No substantial change in the performance were observed, with the exception that mixtures using water-based technologies (foaming process and foaming additive) exhibited increased moisture susceptibility, which may be a concern in areas where stripping is an issue. Anti-strip additives were not used in this study.

Warm mix technologies have also been used with terminal blend binders (Lane et al. 2011; Hajj et al. 2011). There is less discussion of warm mix terminal blends than warm mix field blends in the literature, perhaps because the benefits of reduced temperatures are greater with field blends. There is no reason to believe that the behavior of warm mix terminal blend asphalts is different from warm mix conventional asphalts.

***Regional State-of-the-Practice***

**California.** *Field Blend.* The Caltrans Standard Specifications state that crumb rubber modifier should be added at 20 percent ± 2 percent by total weight of modified binder. Furthermore, 75 percent of the crumb rubber modifier must come from scrap tires and 25 percent from high natural rubber sources. Specifications are given for cone penetration, resilience, field softening point, and viscosity after 45 minutes of reaction between the binder and the crumb rubber modifier. Aggregate gradations are provided for ¾ inch and ½ gap-graded mixtures, and 1 inch, ½ inch and 3/8 inch open-graded mixtures. The Caltrans field blend specifications are found in *Section 39- Asphalt Concrete* of their standard specifications (Caltrans 2015).

*Terminal Blend*. The 2015 Caltrans *Standard Specifications* accommodate terminal blend binders (Section 92-1). Modified asphalt binders are now defined as "Asphalt binder modified with polymers, crumb rubber or both." If using crumb rubber, the supplier must certify a minimum of 10 percent crumb rubber content by weight. Specifications are provided for PG58-34M, PG64-28M, and PG76-22M (Caltrans 2015).

Caltrans standards for field blend hot-applied chip seals are contained in section 37-2.05B of the *Standard Specifications* (Caltrans 2015). CRM content of the binder must be 21 percent ± 1 percent by weight, of which 76 percent ± 2 percent must be scrap tire crumb rubber, and 24 percent ± 2 percent must be high natural rubber. The binder must be sprayed at a temperature of 385 °F to 415 °F, at a rate between 0.55 to 0.65 gallons per square yard. Chips must be pre-coated with 0.5 percent to 1.0 percent asphalt by weight, and applied at a temperature between 260 °F and 325 °F and a rate of 28 to 40 pounds per square yard. Caltrans does not have standard specifications for terminal blend hot-applied chip seals and the binder application rates in the above specifications may be too high for use with a terminal blend binder. Caltrans field blend specification for chip seals and terminal blend binders can be found at in *Section 37 – Bituminous Seals* of the Caltrans Standard Specifications (Caltrans 2015)

Caltrans does not have standard specifications for terminal blend emulsions.

**Colorado.** CDOT is currently in the process of developing specifications for CRM asphalt. A field evaluation of both the terminal and field blend process is currently being conducted on a stretch of US 34 near Greeley and and interim report for crumb rubber use is available (Shuler 2011).

**New Mexico.** The New Mexico 2014 standard specifications for *Section 402: Asphalt Materials, Hydrated Lime, and Anhydrite Based Material* state that a terminal blended polymer-modified asphalt binder has a minimum of 5 percent tire rubber content and can meet the requirements for a PG 70-28 per AASHTO M 320. *Section 404: Rubberized Open Graded Friction Course* states the asphalt-rubber binder shall contain a minimum of 10 percent tire rubber modifier (TRM) by total weight. The TRM shall have a specific gravity of 1.15 ± 0.05. The fiber content shall be less than 0.5 percent by weight for all other applications. The TRM shall contain no metal particles and mineral contaminates shall be less than 0.25 percent by weight (NMDOT 2014).

**Nevada.** NDOT's 2014 standard specification do not mention asphalt-rubber or CRM for HMA per se but do specify PG 64-28NVTR and PG 76-22NVTR binders that is a terminal blend (NDOT 2014). NDOT has been using CRM on projects throughout the state, with the material and construction specifications being updated on a per-project basis. In 2008, NDOT used asphalt-rubber in an overlay of portland cement concrete (PCC) on Interstate 515 with the help of ADOT. The asphalt binder contained approximately 20 percent crumb rubber. Currently NDOT is in the process of resurfacing a portion of Interstate 15 with an asphalt-rubber modified binder.

**Texas.** TxDOT specifications for *Item 300: Asphalts, Oils and Emulsion*, has gradation requirements for CRM along with simple characteristics such as the CRM must be free from contaminants, free flowing, and non-foaming when added to hot asphalt binder. The section also has specifications for rubber-asphalt crack sealer, and asphalt-rubber binders, which must have a minimum of 15 percent CRM by weight. For *Item 316: Seal Coat*, the material specifications set forth in *Item 300* establish the requirement for CRM use (TxDOT 2004). *Item 342: Permeable Friction Course* follow the material requirements set forth by *Item 300* as well. A minimum of 15 percent CRM is allowed in *Item 346: Stone-Matrix Asphalt* and again the material requirements are set forth in *Item 300* (TxDOT 2014). *Item 348 Thin Bonded Friction Courses* also allow for the use of a minimum of 15 percent CRM with the material requirements set forth in *Item 300* (TxDOT 2014).

**Utah.** UDOT currently does not have specifications or allow for the use of GTR in pavement. A technical bulletin published in 2003 list barriers to why GTR is not used routinely in Utah (UDOT 2003). Some of the barriers listed are:

- Ambient pavement temperature requirements for placing CRM asphalt limits the paving season.
- No CRM plants exist in Utah.
- The higher cost of CRM asphalt.

**Use of GTR in Arizona**

ADOT is a national leader in the use of GTR. The history of GTR in Arizona goes back to the 1960s when Charles McDonald created the “asphalt-rubber band aid” for the City of Phoenix (Way 2012). By the late 1960s ADOT began research and development projects involving asphalt-rubber under the direction of Gene Morris. By the mid-1970s, crumb rubber had been successfully incorporated into HMA in Arizona (Epps 1994). From there the use of GTR grew to include several asphalt-rubber patents, use in chip seals, and the development of asphalt-rubber gap-graded and open-graded mixtures.

ADOT also incorporated asphalt-rubber into the LTPP SPS-6 Project: Strategic Study of Rehabilitation Techniques (Puccinelli et al. 2013). The project studied the rehabilitation techniques for jointed PCC pavement, including various surface preparations and overlays. Included in the project were combinations of asphalt-rubber and conventional asphalt concrete. The study found a large majority of the asphalt-rubber sections outperformed the sections without asphalt-rubber over the 10-year-plus monitoring period in roughness and distress performance.

The asphalt-rubber mixtures are described in ADOT’s *Standard Specifications for Road and Bridge Construction 2008* (ADOT 2008). Section 414 and 415 in these specifications are for asphalt concrete with field blend asphalt-rubber and are modified by ADOT 2008 Stored Specifications “414ACFAR” and “415AREP.”

In addition to the Section 414 and 415, Section 1005 (modified by ADOT 2008 Stored Specification “1005 PG”) contains requirements for a PG 76-22 TR+ modified asphalt binder to be used for surfacing. In that specification the binder is to contain a minimum of 8 percent digested CRM, 2 percent styrene-butadiene-styrene polymer, and conform to the requirements of AASHTO M 320 as well as the requirements listed in Table 3.

Section 1009, modified by ADOT 2008 Stored Specification “1009ASRM,” also contains the standards for furnishing, proportioning, and mixing to produce an asphalt-rubber material. In this section, the crumb rubber properties are very similar to those specified by TxDOT in meeting two gradation requirements, having a specific gravity of 1.15 ± 0.05, and be free of contaminating materials. Also allowed is the use of up to 4 percent calcium carbonate by weight of crumb rubber. Asphalt-rubber proportions shall contain a minimum of 20 percent crumb rubber by weight of asphalt cement.

**Table 3. Section 1005 PG 76-22 TR+ Asphalt Binder Requirements (ADOT Standard Specs 2008)**

| Test Property | Test Method | Requirement | Test Result | Percent of Contract Unit Price Allowed |
|---|---|---|---|---|
| Solubility in Trichloroethylene, %, minimum | ASTM D 2042 | 97.5 | ----- | ----- |
| Softening Point, ºC, minimum | AASHTO T 53 | 60 | ≥ 60<br>57-59<br>< 57 | 100<br>85<br>70 (1) |
| Elastic Recovery, @ 10 ºC, %, minimum | AASHTO T 301 | 55 | ≥ 55<br>50-54<br>< 50 | 100<br>85<br>70 (1) |
| Phase Angle (δ), @ 76 ºC @ 10 rad/sec, degrees, maximum | AASHTO T 315 | 75 | ≤ 75<br>76-83<br>> 83 | 100<br>85<br>65 (1) |
| (1) Reject Status: The pay adjustment applies if allowed to remain in place. | | | | |

Another key specification is the handling requirements set forth in Section 1009 (modified by ADOT 2008 Stored Specification "1009 ASRM"); they are:

- Once the asphalt-rubber has been mixed, it shall be kept thoroughly agitated to prevent settling of the crumb rubber particles. The temperature of the asphalt-rubber shall be maintained between 325 °F and 375 °F.
- If in the first 10 hours after the completion of the reaction period the temperature of the asphalt-rubber drops below 325 °F, it may be reheated to a temperature between 325 °F and 375 °F.
- In no case shall the asphalt-rubber be held at a temperature between 325 °F to 375 °F for more than 10 hours after the completion of the reaction period. Asphalt-rubber held for more than 10 hours shall be allowed to cool and gradually reheated to a temperature between 325 °F and 375 °F before use.
- The reheating of asphalt-rubber that has cooled below 325 °F shall not be allowed more than one time.
- Asphalt-rubber shall not be held at temperatures above 250 °F for more than four days after the completion of the reaction period.

ADOT is continuing to use GTR and CRM asphalt, especially as part of its Quiet Pavement Program. The three-year, $34 million project will surface about 115 miles of freeways with rubberized asphalt in the Phoenix-area (ADOT 2014). In 2014, ADOT successfully placed three CRM asphalt OGFC test sections on I-17 between Cherry Road and Dugas Road in which a different warm mix technology was used for each test section including a foaming additive, chemical additive, and organic additive.

For the higher elevations of northern Arizona, specifically within ADOT's Northcentral District (formerly the Flagstaff District), the regular use of binders modified with both terminal blended CRM and SBS polymer, referred to as a "TR+" binder for OGFC applications, is common practice due to the apparent increase in resistance to snowplow-induced damage.

**Challenges to Increasing the Use of GTR**

In general, laboratory studies show increased cracking resistance and decreased rutting resistance for field blend mixtures relative to conventional dense-graded HMA. Terminal blend binders and mixtures are considered to be quite similar to polymer-modified binders and mixtures. Results from full-scale accelerated load and field studies are much more equivocal. This is not surprising since laboratory studies allow researchers to carefully control the conditions of their study, whereas pavements in the field are subject to variations in construction, climate, and traffic loading that can be difficult to control and assess in analysis. One interpretation of these results is that there are real performance benefits for asphalt-rubber materials, although those benefits can be outweighed by inconsistent construction quality, variability in support conditions (such as existing pavement condition for overlay projects) and significantly higher traffic loadings.

Another factor confounding the interpretation of research results is that “conventional asphalt” is a moving target for comparison. There have been tremendous changes in asphalt technology in recent decades, as exemplified by the “PG” binder grading system, Superpave mixture design, and adoption of WMA technologies. Many of the studies discussed above used binders and mixture design for the conventional HMA control sections that are no longer used today and the results may not apply to current materials, especially to polymer-modified binders.

ADOT has observed several applications of field blended CRM gap-graded asphalt mixtures, placed in the mid-2000s, which have exhibited signs of excessive to complete stripping of binder from the mineral aggregate. This has led to a suspension of the use of gap-graded mixtures with GTR. Despite investigation, no definitive conclusions have been drawn as to the cause of the premature failure of this material. Discussions are on-going between ADOT and industry regarding the future use of field blended/wet-process CRM asphalt mixtures (McCarty 2015).

During the summer of 2015, ADOT placed three test sections of asphalt rubber-asphalt concrete friction course (AR-ACFC) on US 180 north of Flagstaff to monitor the performance of two terminal blended CRM binders as well as an SBS polymer-modified binder with increased SBS content. The terminal blended CRM binders consisted of a typical TR+ binder with 97.5 percent solubility in trichloroethylene (ASTM D 2042) and a TR+ binder with 92 percent solubility. If similar performance between the 97.5 percent and 92 percent solubility TR+ binders is achieved, this would potentially lead to further investigation and subsequent revision of the current ADOT specification for TR+ binder.

**Concluding Remarks Regarding GTR Usage**

One of the most promising technologies to emerge in recent years is WMA technology, and it should be considered for broader application to GTR. WMA technology allows production, placement, and compaction at more moderate temperatures, which provides a better working environment, enables longer hauls, quicker opening to traffic, reduced costs, lower environmental footprint, and placement at night or in cooler temperatures. Field blend materials also require specialized equipment at the asphalt concrete plant to mix asphalt binder and crumb rubber. This equipment is typically mobile, and travels from plant to plant to follow the availability of work. This can make smaller projects uneconomical unless the contractor is given flexibility to schedule the work to coincide with larger projects.

## RECYCLED CONCRETE AGGREGATE FROM REFUSE CONCRETE

### Review of National Practice

A growing demand for construction aggregates and an increase in the amount of construction waste are two issues of concern with regards to transportation infrastructure construction. Production of aggregate within the United States is expected to increase to more than 2.5 billion tons per year by the year 2020 (FHWA 2004). Conversely, construction waste produced from building demolition alone is estimated to be 123 million tons per year. Historically, the most common method of managing this material has been through disposal in landfills, but as cost, environmental regulations, and land use policies for landfills become more restrictive, the need to seek alternative uses of the waste material increases. This situation has led state agencies and the aggregate industry to consider increased recycling of concrete debris as an alternative aggregate.

The focus of this section is on recycled concrete aggregate (RCA) from refuse concrete. Other terminology used includes reclaimed concrete material (RCM), recycled concrete pavement (RCP), crushed concrete, and crushed concrete aggregate (CCA). RCA can be used as soil stabilization, aggregate for bound and unbound road bases, an aggregate for flowable fill, pipe bedding, and as aggregate in new PCC and asphalt concrete. It can also be used as a bulk fill material, a gabion basket fill, or a granular aggregate for base and trench backfill. For highway uses, the FHWA (2004) has limited the definition of RCA to PCC byproduct obtained from the removal, crushing, and sizing of old PCC pavements, bridge structures/decks, sidewalks, curbs, and gutters.  Embedded steel is removed during processing. The processed aggregate is generally stockpiled in two sizes, a coarse aggregate retained on the No. 4 sieve, and a fine aggregate passing the No. 4 sieve.

#### *RCA as Base and Subbase Material*

One of the most common applications for RCA in the United States is as aggregate in base and subbase layers for new pavements. A review of the state of practice in 2004 in California, Texas, Minnesota, Virginia, and Michigan found RCA to perform better than or similar to virgin aggregate in base and subbase applications, and  a large number of states within the United States are using RCA as an aggregate base, as seen in Figure 10 (FHWA 2004).

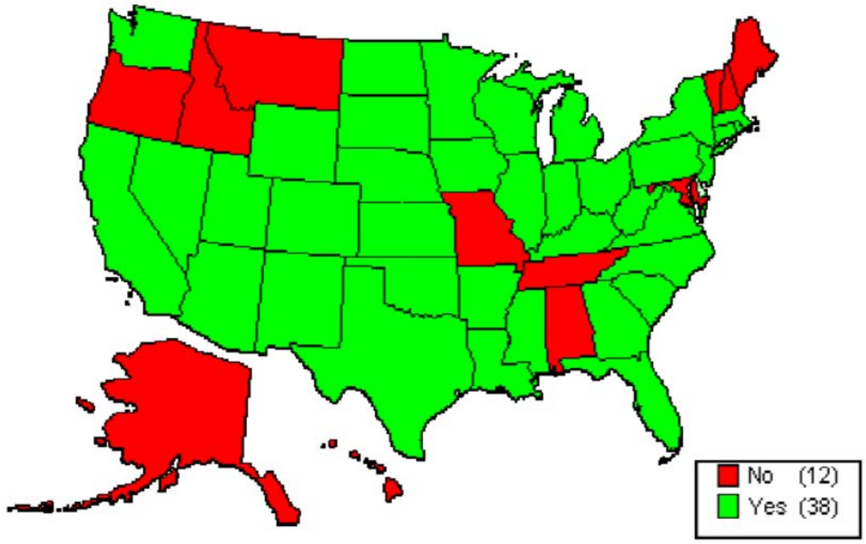


**Figure 10. States Recycling Concrete as Aggregate Base (FHWA 2004)**

A recent review and study of recycled unbound materials, specifically for use in road base, was performed by the University of Wisconsin for the Minnesota DOT (MnDOT) (Edil et al. 2012). The literature review found RCA to be the one of the most commonly recycled construction materials used as base course. A survey was conducted to better define the current state-of-the-practice and RCA was the most commonly used recycled material for road base, followed by RAP and recycled pavement material (RPM) (defined to include HMA, base course, and possibly some subgrade as produced in full-depth reclamation). The most common test used for specification with recycled materials is Grain Size Analysis using a dry sieve. The survey found the California Bearing Ratio test was used to evaluate aggregate strength, LA Abrasion for toughness, and the Sulfate Soundness test for durability.

To identify the characteristics of RCA typically available in different parts of the United States, the study obtained samples from eight states, covering a geographically diverse area. A conventional base course meeting MnDOT standards was used as a control material as well as a 50/50 blend of RCA and a standard MnDOT base material. The materials, although obtained from eight different states, had reasonably consistent properties. The average impurity content (predominately asphalt aggregate, aggregate with plastic fibers, brick, and wood chips) was 1 percent for RCA, indicating that the recycling industry has developed sufficient controls to maintain product quality. The broad analysis included:

- Resilient modulus testing.
- The effects of climate.
- Unsaturated hydraulic characteristics.
- Compaction testing.
- Falling Weight Deflectometer (FWD) testing on field pavements.
- Leaching characteristics.

The investigation indicated that RCA is suitable for unbound base course applications, showing equal or superior performance characteristics compared to natural aggregates in terms of stiffness, freeze-thaw and wet-dry durability, and toughness.

An investigation for the New Jersey DOT (NJDOT) determined that as RCA percentage in unbound bases increases, the permeability decreases (Bennert and Maher 2005). The study found the addition of RCA increased the CBR and resilient modulus properties and also lowered the accumulated permanent strain; however RCA/DGAB blends over 75 percent RCA create a "tight" aggregate structure with minimal to no drainage. Permeability test results of the 100 percent RCA bases found it to be almost impermeable. To mitigate this without sacrificing improved bearing strength, laboratory results showed the best blend to be 50/50 original virgin aggregate base and RCA (Bennert and Maher 2008). Also observed in the study is increasing the top size of the processed RCA (from 1.5 inches to 2.0 inches) helped to increase the permeability without an associated loss of bearing strength.

MnDOT has also almost 100 percent of the concrete pavement removed from its pavements as an aggregate base (FHWA 2004). One of the most economical uses of RCA is placing it as a base using an in-place concrete recycling train (ACPA 2009). Mobile units have been employed in Iowa, Michigan, and by the Illinois Tollway (RMI 2014).

RCA has also been used as subbase material and in conjunction with edge drains. MnDOT has provided recommendations for RCA as a filter/separation layer under a permeable aggregate base drainage layer in accordance with the applicable drainage specifications (FHWA 2004). The RCA with new aggregate could be used near drainage systems when at least 95 percent of the RCA was retained on the 4.75 mm sieve. Fines need to be minimized in drained, unstabilized RCA pavement foundation layers and drainage systems need to be designed to accommodate increased fines. Again, as a subbase, the angularity of RCA and potential residual cementation provide a strong and durable platform, with crushing and sizing operations accommodating the desired aggregate gradation (ACPA 2008).

Another aspect to aggregate bases is modification through stabilization (RCA) used in cement-stabilized subbase and base layers that reduce the migration of leachates and fines. This prevents the transport of large amounts of calcium hydroxide, which form a precipitate in the drainage pipes and filter fabrics. When utilizing RCA in a hydraulic cement stabilized layer, there will be the potential for increased water demand, premature stiffening, and difficulty in achieving the proper air void distributions (ACPA 2009). Methods have been developed to address these concerns. Research in Texas has shown that RCA can re-cement, and thus a reduction in cement addition from the customary 3 percent to 1.5 percent should be made for RCA stabilized base layers (Guthrie et al. 2002). This re-cementation can cause these bases to set more quickly than cement-treated bases made with virgin aggregates while providing higher densities and better long term strength (Lim et al. 2003).

RCA has been used successfully in asphalt-stabilized subbase applications. As with cement-treatment, the use of asphalt reduces leachate migration and the potential for clogging of drainage structures in subbase applications. Unfortunately, the more absorptive nature of typical RCA particles significantly increases asphalt binder demand, which often prohibitively increases costs (ACPA 2009). Evaluations of asphalt stabilized base have shown that RCA requires 50 percent more moisture than virgin limestone aggregate to reach optimum moisture content (Lim et al. 2003). The same study found that the RCA mixtures evaluated failed to meet moisture susceptibility criteria for flexible bases.

***RCA as Aggregate in Asphalt Concrete***

The absorptive nature of RCA also creates the same barriers for use in asphalt concrete as in asphalt-stabilized bases. Besides this absorptive issue, RCA has been successfully utilized in HMA, especially on low-volume roads (Mills-Beale and You 2010). This study, performed for Michigan DOT, determined RCA to be acceptable for asphalt pavement by passing Superpave requirements for absorption, uncompacted void content, flat and elongated particles, percent fractured faces, and L.A. abrasion. The study determined that RCA can be used in HMA up to 75 percent replacement of virgin aggregate. For use in HMA, deleterious materials should be limited, as they will increase asphalt cement demand and decrease overall quality (NCHRP 2000).

***RCA as Aggregate in New Concrete***

A recent agency survey found the second most common use for RCA in highway applications is as aggregate in new PCC (Stoup-Gardiner and Wattenberg-Komas 2013). In the U.S., RCA has been used in new PCC since at least the 1940s, providing an economical alternative while reducing waste from reconstruction (ACPA 2008). RCA in PCC has been used from non-structural applications to traditional structural pavement applications, and most recently in the lower lift of what is known as two-lift concrete paving.

Non-structural RCA concrete applications include concrete aprons, sidewalks, and precast storm water boxes (FHWA 2004; Cleary 2013).

RCA concrete has been used on a number of conventional concrete pavements. For example, the Illinois DOT used RCA in a typical construction of a 10-inch thick continuously reinforced concrete pavement (CRCP) in 1986 (Roesler and Huntley 2009). In that project the longitudinal reinforcement bars were placed using the tube feeding method. Early abnormal longitudinal cracking patterns appeared, being attributed to the tube feeding process and the higher shrinkage of the RCA concrete. The study found that after 20 years of performance, the future use of RCA is completely feasible. Compared to other CRCP throughout Illinois, the RCA pavement had similar performance in terms of age, and it was recommended that moist curing be employed to combat cracking from drying shrinkage.

The state highway agencies in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming have successfully designed pavements containing RCA (Cuttell et al. 1997). The pavements in the study included all three common rigid pavements: jointed reinforced concrete pavements (JRCP), jointed plain concrete pavement (JPCP), and CRCP. The field study found no reoccurrence of aggregate freeze-thaw deterioration (D-cracking). Minimal reoccurrence of alkali-silica reactivity (ASR) was potentially observed in a few of the Wyoming sections. The study recommended reducing the slab length of JPCP panels to reduce mid-slab cracking. It is believed that reducing the amount of residual mortar content (original mortar adhering to the aggregate particles) from the original PCC aggregate results in improved

PCC properties. The study also recommended that dowel bars be used for all jointed pavements as rapid loss of serviceability was noted in sections with undoweled joints due to poor load transfer efficiency.

The FHWA has produced a technical advisory for use of RCA in new PCC (FHWA 2007a). Some pavement design issues that need to be addressed when using RCA:

- Reduced strength.
- Increased shrinkage.
- Changes to thermal expansion, creating higher curling stresses.

These issues can be mitigated through increased pavement thickness and/or shortened joint spacing. Additionally, properties of the specific concrete proposed for RCA should be determined and used in a mechanistic-empirical design procedure.

Michigan DOT experience has shown that concrete made with RCA should not be used in long-jointed JRCP. The smaller aggregates sizes and the low abrasion resistance of the RCA create poor aggregate interlock which results in poor load transfer efficiency across intermediate crack faces (Van Dam et al. 2011). This degrades quickly under traffic loading and the low level of steel reinforcement is unable to withstand the higher than-expected stress, leading to rupturing of the steel and deterioration of the crack. Similarly, this phenomenon necessitates the use of dowel bars at all transverse joints in JPCP.

To compensate for the low abrasion resistance of RCA and to protect the RCA concrete from the harsh conditions present at the pavement surface, two-lift concrete paving can be implemented. Two-lift construction is different from the common single lift approach in that two separate concrete layers are placed in a wet-on-wet process that promotes bonding between the two layers (FHWA 2007b). In this process, the thicker bottom lift is often constructed using marginal or recycled aggregates (i.e. RCA), followed by a relatively thin surface lift of higher-quality, wear resistant natural aggregate (Hiller et al. 2011). Two-lift concrete construction is not a new idea, being routinely used internationally in France, Austria, and Germany for decades. In the United States, it had been studied in 11 projects constructed from 1970 to 1994 (Cable and Frentress, 2004). Many of the two lift projects in the United States were still in service as of 2004. Recently, two-lift concrete pavements have been placed in the United States as demonstration projects in Kansas and Missouri, both of which were driven largely by overall sustainability considerations, given the scarcity of high-quality natural aggregates. Also two-lift concrete paving has been implemented as standard practice by the Illinois Tollway to maximum the utilization of RCA and coarse fractionated RAP in the bottom lift.

**State and Agency Practices**

As shown previously in Figure 10, RCA is used as aggregate base in the vast majority of states. Figures 11 shows the distribution of states that use RCA as aggregate in new PCC.

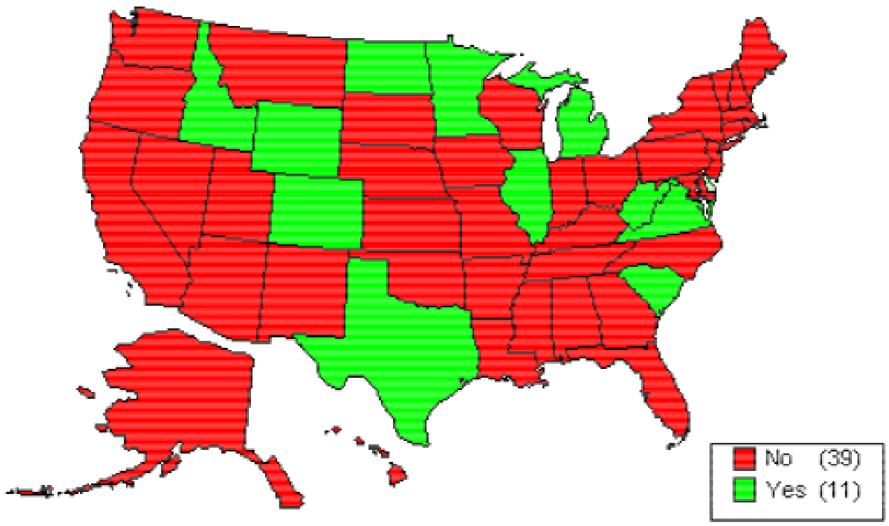


**Figure 11. States Using RCA as Aggregate for PCC (FHWA 2004)**

This figure illustrates that the most common use of RCA according to a number of surveys is as an aggregate base (FHWA 2004; Stroup-Gardiner and Wattenberg-Komas 2013; ACPA 2008). Many of the States surveyed by the FHWA (2004) indicated that almost all of the concrete removed from State Highway pavements is being reused as aggregate base. California, for example, allows the base aggregate to be a mixture of RCA and RAP at any desired percentage.

RCA was permitted to be used as aggregate in new concrete pavement in specifications for Michigan, Minnesota, and Texas (FHWA 2004). TxDOT evaluated the performance of concrete pavements using RCA and designed new pavements in the Dallas and Houston Metro areas with RCA as the intended aggregate. TxDOT also employed on-site crushing to minimize transportation costs and still maintain a quality product.

A moratorium had been in place on the use of RCA in paving concrete in Michigan since the early 1990s, stemming from failures of long-jointed JRCP concrete pavements built using RCA; however, recent research and developments have lifted many of the previous restrictions. A manual of practice for RCA was produced for Michigan Department of Transportation (MDOT) in 2011 (Van Dam et al. 2011). The manual recommends that RCA should meet similar requirements of natural aggregate, regardless of application. MDOT currently allows RCA in fill/subbase, dense graded aggregates, and open-graded aggregates and also allows coarse RCA in HMA and new PCC (MDOT 2012).

***Regional State-of-the-Practice***

**California.** The Caltrans *Standard Specifications* (Caltrans 2015) state that reclaimed concrete is a useable material in shoulder backing (Section 19), in aggregate subbases (Section 25), and aggregate bases (Section 26), so long as it meets grading requirements and sand equivalent, R-value, and durability index quality requirements.

Additionally, reclaimed aggregate recovered from washing away cementitious material from unused plastic concrete is allowed for use in new concrete so long as it meets the same requirements for other virgin and natural aggregates in concrete (Section 90).

**Colorado.** CDOT (2015) specifications allow RCA as an aggregate for bases (Section 703.03). The crushed reclaimed concrete shall conform to the quality of AASHTO M 147, except for the requirements of the passing No. 200 sieve fraction ratio to the passing No. 40 sieve shall not apply. In addition to the AASHTO M 147 gradation requirements are set forth, and the plasticity index shall not exceed six when tested in accordance to AASHTO T89 and T90.

**New Mexico.** The NMDOT specifications (NMDOT 2014) *Section 303: Base Course* state that a base course can consist of recycled concrete pavement not to exceed 75 percent by weight, and the combined RAP and RCA shall not exceed 75 percent by weight.

To increase efficiency and reduce costs, NMDOT also allows the contractor to use the cold-milled pavement material as RCA in accordance to the specific contract (Section 414) when cold milling is used within the project.

Lastly, RCA is not allowed in mechanically stabilized earth retaining structures.

**Nevada.** The *NDOT Standard Specifications* (NDOT 2014) do not mention reclaimed or recycled concrete. However, NDOT has used RCA in projects throughout the state, with project specific specifications being updated on a per-project basis. In 2012, NDOT used RCA on U.S. 395, most likely as a base (NDOT 2012).

**Texas.** TxDOT permits RCA for Type D base mixtures in flexible and cement-treated bases. The material must comply with DMS-11000, "Evaluating and Using Nonhazardous Recyclable Materials Guidelines," be free from reinforcing steel, and contain no more than 1.5 percent deleterious materials. These are found in *Item 247 – Flexible Base* (TxDOT 2004).

Coarse aggregate from RCA is allowed in non-structural concrete listed under *Item 421 – Hydraulic Cement Concrete* (TxDOT 2004). The aggregate must pass the same requirements as all other aggregates, however is not subject to the soundness test.

**Utah.** UDOT (2012) currently allows recycled PCC in embankment, borrow, and backfill applications under Section 02056. The material must be free of chemical or petroleum contamination and must meet the grading requirements of other virgin aggregates.

### Use of RCA in Arizona

According to Figures 10 and 11, ADOT allows the uses of RCA as an aggregate base. Specifications for embankments and road bases are described in ADOT's *Standard Specifications for Road and Bridge Construction 2008* (ADOT 2008). Although the words "RCA," "recycled," or "reclaimed" do not appear in this specification, these terms appear in ADOT 2008 Stored Specifications (303Salv, 9/07/11). This stored specification modifies the 2008 ADOT Standard Specifications (Section 303) to include the use of both RCA and RAP material in aggregate subbase and base material.

During bidding, the contractor is provided these stored specifications as part of "Special Provisions" along with the "Project Plans." These stored specifications are available to be downloaded. The following modifications are provided in these ADOT 2008 Stored Specifications that are of relevance to RCA for this project:

- Aggregate subbase and aggregate base material may be comprised in part of salvaged portland cement concrete, as approved by the Engineer.
- A maximum of 50 percent salvaged material will be allowed. The 50 percent maximum shall include all salvaged materials, including any underlying base material recovered during full-depth reclamation.
- A layer of virgin aggregate must be placed immediately above the prepared underlying subgrade and beneath the layer containing salvaged material.

In addition to the *Standard Specifications*, the ADOT *Preliminary Engineering and Design Manual* contains rehabilitation methods that are dated from 1989. Of relevance to this project is *Section 400.02—Rigid Pavement Rehabilitation*. This document sets forth the use of break and seat along with an overlay. Break and seat refers to cracking the existing PCC into small pieces, and seating the pieces in place with a heavy roller. This effectively reuses the existing the PCC as a base layer to the new overlay.

In a special provision for mechanically-stabilized earth walls dated August 2013, *Section 929-3.05 Reinforced Backfill Material* states the following:

> *No salvaged material, such as asphaltic concrete millings or Portland Cement Concrete rubble, etc., will be allowed.*

**Challenges to Increasing the Use of RCA**

One of the largest challenges to increasing the use of RCA in highway applications is that RCA consists of natural aggregate and reclaimed mortar that is still adhered to the aggregates. The reclaimed mortar is can responsible for the production of a high pH leachate at early ages in unbound base layers. Because of this, the drainage outlets require close monitoring and proactive cleaning of the drain system may also be required (Hiller et al. 2011). Furthermore, the high absorption of RCA is caused by the mortar, creating higher water demand in new PCC, and increased binder demand in asphalt concrete and high shrinkage in concrete if stockpiles are not kept wet. The reclaimed mortar fraction is much higher in the fine RCA than coarse RCA, and thus fine RCA is more difficult to use than coarse RCA due to the increased absorption.

Additional barriers noted in the survey conducted by Stroup-Gardiner and Wattenberg-Komas (2013) include:

- Increased variability of RCA.
- Considerations in designs for fines contents and lower quality RCA.

- Lack of availability.
- Economic competition with new virgin aggregate.
- Increased need for QC/QA testing.

The increased variability is one reason why many agencies prefer the RCA come from already existing agency structures, where knowledge of the material composition and its use is well known to the agency. The issue with the fines content is why many applications of RCA use only the coarse material byproduct. Finally the lack of availability for RCA may be due, at least in part, to the increased life (upwards of 50 years) of many in-service PCC pavements, resulting in few reconstruction projects.

**Concluding Remarks on RCA Usage**

RCA has been used in highway applications for many decades but has increasingly gained popularity as virgin aggregate sources have become scarcer and aggregate transportation costs increased. RCA used in aggregate bases is currently used by many in the industry as it offers the replacement of significant amounts of virgin aggregate. Conventional PCC mixtures using coarse RCA have proven effective in many states including Texas, Wyoming, and Illinois (Cuttell et al. 1997, Roesler and Huntley 2009). Additionally, the recent increase in two-lift paving increases the feasibility of using RCA and could be used to meet emerging needs in the surface characteristics area when using RCA (Cable and Frentress 2004).

The key to increasing RCA is to develop training to better understand how to successfully incorporate RCA into aggregate bases and new PCC through conventional and two-lift paving, improved quality control through the mixture design and construction processes, and the incorporation of incentives to encourage contractors to increase RCA utilization.

## CONSTRUCTION AND DEMOLITION WASTE (CDW)

### Review of National Practice

While the FHWA definition of RCA is limited to previous highway pavements and bridges, other recycled and reclaimed concrete, along with brick, masonry and other construction waste, have potential uses in highway applications. These are generally classified as construction and demolition waste (CDW) reflecting their source as being either waste from near construction or materials produced during demolition. Very little work has been done involving the use of CDW in highway applications.

Many barriers still exist for the use of CDW in highway applications. Identified barriers include:

- Lack of recycling facilities.
- Lack of national and state standards.
- Low cost of dumping.

Internationally, CDW applications have been explored for use in cement bound bases and pavement layers. Specifically, researchers in Spain investigated the possibility of using mixed recycled aggregates containing crushed concrete and crushed masonry from different sources including the demolition of a building for use in cement-treated bases (Sainz 2012). The study found the cement-treated base to exhibit adequate compressive strength, low deflections, and suitable roughness values.

In another Spanish study, asphalt concrete mixtures made with 0 percent, 20 percent, 40 percent, and 60 percent recycled aggregates from CDW were evaluated (Perez et al. 2010). The CDW aggregate was sieved, washed, and pollutants were removed. The study found the optimum asphalt content, VMA, VFA, flow, and stability to increase with the increasing percentage of recycled aggregate. The CDW mixtures analyzed in the study met the minimum specification requirements.

**State and Agency Practices**

While explicit and regular use of CDW in highway applications is rare, some states are leading the way with specifications for the inclusion of such materials. For example, the Washington State DOT encourages the use of recycled materials and contractors can even purchase recycled products for use in pavement mixtures, guardrail posts and compost. Additionally, if the CDW is generated and processed on site to meet specifications, it can be used on a construction project. This includes broken unspecified concrete, ground asphalt, wood waste and excavated soils.

The West Virginia DOT has a supplemental specification for CDW material for use in highway projects. Under the special provision is the statement:

> *The legitimate beneficial reuse of clean bituminous concrete, portland cement concrete and other clean masonry substance for the purpose of fill, riprap, road surfacing or road base material is exempt from the West Virginia Department of Environmental Protection permitting of the rule, provided that any such fill will not be placed in natural wetlands, adheres to the best management practices… and provided further that bituminous concrete may not be used for riprap material.*

The specification goes on further to allow concrete, stone, brick, or other masonry materials broken into pieces no longer than 2 ft. in embankments, but not within 2 ft. of the subgrade or 1 ½ ft. from the top of the side slopes.

***Regional State-of-the-Practice***

The use of CDW is rare in regional transportation applications. For most specifications, the use of this material appears to be encompassed by the recycled and processed PCC. The explicit use of brick and masonry was not found in regional specifications.

**California**. As mentioned under the section on RCA, Caltrans specifications for base and subbase allow reclaimed processed PCC, however there is no explicit statement regarding the source of the PCC (Caltrans 2015).

**Colorado.** CDOTs reclaimed concrete specifications do not mention requirements regarding the source of the PCC (CDOT 2011) and thus non-transportation sources are not explicitly excluded.

**New Mexico**. NMDOT does not mention brick, masonry or other construction waste in their specifications, and reclaimed concrete is limited to a previous use as pavement only.

**Texas.** TxDOT crushed concrete specifications do not mention a requirement for the source of the concrete, so long as the crushed concrete can meet gradation and strength requirements and certify compliance under the DMS-11000 (TxDOT 2004).

**Utah.** UDOT specifications *Section 02056* do not state the previous application requirements of recycled PCC in embankment, borrow and backfill applications, and thus the source could potentially be from other construction waste (UDOT 2012) . The material must be free of chemical or petroleum contamination and must meet the grading requirements of other virgin aggregates.

**Use of CDW in Arizona**

ADOT currently does not specifically allow the use of CDW in highway applications.

In a special provision for mechanically-stabilized earth walls dated August 2013, Section 929-3.05 Reinforced Backfill Material states the following:

> *No salvaged material, such as asphaltic concrete millings or Portland Cement Concrete rubble, etc., will be allowed.*

**Challenges to Increasing the Use of CDW**

Barriers to increased use of CDW noted in the synthesis conducted by Stroup-Gardiner and Wattenberg-Komas (2013) include:

- Lack of a stable market for recycled materials.
- Lack of appropriately located recycling facilities.
- Lack of awareness of byproduct potential.
- Absence of appropriate technology for processing some byproducts (e.g., CDW).
- Lack of government support.
- Lack of standards and policies.
- Low cost dumping fees.
- Small amounts of byproducts generated at widespread locations.
- Lack of data on waste management byproducts.
- Lack of understanding of environmental impact.
- Lack of necessary expertise.

The increased variability is one reason why many agencies prefer RCA over CDW, as RCA often comes from agency structures that are being reconstructed, and thus some knowledge of the material composition and its performance is known to the agency.

**Concluding Remarks Regarding CDW Usage**

While the use of CDW in highway applications is feasible, the market demand is not apparent. Additionally, with the increased effort needed to recycle CDW into quality material and the lack of recycling facilities, the economic issues of the material has led to its little use by highway agencies.

However, as virgin materials become less available and more sustainable, or "green" efforts become more normalized, the use of CDW in highway applications has the potential to increase.  As an example, the City of Chicago has implemented strict policies regarding construction waste generation that has fueled the development of a construction waste recycling industry.

**MINE SPOIL**

**Review of National Practice**

Mine spoil (mining wastes) are waste materials generated during the extraction, beneficiation, and processing of minerals and ores. Under Subtitle C of the Resource Conservation and Recovery Act (RCRA) most spoil from hardrock mining (the mining of metallic ores and phosphate rock) and 20 specific mineral processing wastes are categorized by EPA as "special wastes" and have been exempted by the Mining Waste Exclusion from federal hazardous waste regulations (EPA 2012).

Mine spoil can be subdivided into the following categories (FHWA 2012a):

- Waste rock.
- Mill tailings.
- Coal refuse.
- Wash slimes.
- Spent oil shale.

In 1980 and 1982 it was estimated that 1.3 and 2 billion metric tons of aggregate waste was generated from mine spoil, respectively (EPA 1985). Collins and Ciesielski (1994) estimated annual quantities of waste rock at approximately 1 billion tons per year. Additionally, annual mill tailing generation has been estimated at 500 million tons whereas coal refuse has been estimated at 120 million tons per year. Wash slime quantities have been estimated at 100 million tons of phosphate slimes and 5 million tons of alumina mud (Collins and Ciesielski 1994). The use and production of spent oil shale has not developed due to early economic and support issues (FHWA 2012a). The current use of mine spoil in highway applications is not common practice. In 2000, the highest production levels of mine-related mineral byproducts were found in the western United States. Arizona, California, Idaho, Michigan, Minnesota, Montana, Nevada, and New Mexico are states with the highest levels of productions (NCHRP 2000).

Many mine spoil materials have limited potential for use as aggregates because of their fineness, high impurity content, trace metal leachability, propensity for acid generation, and/or being found in remote location (i.e., away from aggregate markets). However, when quality material  is available at an advantageous location, waste rock and mill tailings can be suitable for use as granular base/subbase, railroad ballast, portland cement concrete aggregate, asphalt aggregate, flowable fill aggregate or fill, and engineered fill or embankment. Additionally, coarse coal refuse has been used in highway embankments, stabilized road bases and, when burnt, the coal refuse is referred to as "red dog," which has been used as an unbound aggregate in shoulders and minor roads (FHWA 2012a). Wash slimes currently do not have a practical use as the material has low solids content and is difficult to dry (RMRC 2008).

In asphalt paving applications, waste rock and mill tailings have been successfully used. Asphalt concrete mixtures containing these materials can be designed using standard laboratory procedures. The potential for stripping of asphalt mixtures containing waste rock should be assessed in the laboratory as part of the overall hot mix asphalt mixture design and stripping resistance can be enhanced by adding hydrated lime or an anti-stripping additive (RMRC 2008). Table 4 contains a summary of mine spoil used in HMA applications whereas Table 5 presents a summary of embankment and fill uses of mine spoil in the US (Collins and Ciesielski 1994).

There are no standard specifications for the use of waste rock and mill tailings in granular base applications (RMRC 2008). However, specifications applicable to granular base aggregates can be used for most waste rock and mill tailings. For mill tailings, the material can be evaluated under standard Proctor tests, AASHTO direct shear and triaxial compression tests (T 236 and T 234), and the California Bearing Ratio test (AASHTO T 193).

Waste rock, mill tailings, and coarse coal refuse have been successfully used to construct highway embankments and fill. The design requirements for mine spoil in embankment construction are the same as for conventional aggregates or soils. However, for coal refuse, tests for standard Proctor moisture-density and spontaneous combustion potential should be done. Also leaching and swelling indexes, porosity, freeze-thaw tests, and wet-dry swelling tests are required (FHWA 2012a).

Mill tailings have been used previously in embankment and fill applications by some state and local highway agencies. Generally, the coarser, sand-size fractions of mill tailings can also be used as a construction aggregate provided there are no harmful or reactive chemical components concentrated from the host rock. Despite the fine size of most mill tailings, these materials can be blended with coarser materials, such as gravel, to bring the overall fines content to an acceptable range, or can often be classified prior to initial disposal in order to recover the coarser fraction for possible use. However, the metal leaching potential of these materials can be a cause for environmental concern and should be thoroughly investigated prior to embankment use.

Figure 12 illustrates states where highway agencies reported using mill tailings and waste rock in 2009 (Stroup-Gardiner and Wattenberg-Komas 2013). In the survey, no agencies reported the use of coal refuse. The numbers inside each state represent the total number of applications reported.

MnDOT recently produced a report studying the use of taconite waste rock and mine tailings in various highway applications (Clyne et al. 2010). The study involved the evaluation of five applications including:

- Low traffic Superpave asphalt mixture (constructed in 2004).
- PCC pavement (constructed in 2004).
- High traffic thin asphalt mixture (constructed in 2008).
- Railroad ballast as an aggregate base (constructed in 2008).
- Low volume railroad ballast as an aggregate base (constructed in 2008).

**Table 4.** HMA Uses of Mine Spoil in the US (Collins and Ciesielski 1994)

| State | Mine Spoil Material | Location |
|---|---|---|
| California | Gold dredge tailings<br>Iron ore tailings | Sacramento Freeways<br>County Road near Eagle Mountain |
| Illinois | Lead-zinc tailings | Local Roads in Northwest Illinois |
| Kansas | Lead-zinc tailings (chert/chat) | Southeast corner of Kansas |
| Kentucky | Bituminous coal refuse | Low volume roads |
| Louisiana | Iron ore waste rock | Location not known |
| Minnesota | Coarse taconite tailings | Roads and bridge decks in Duluth and Minneapolis-St. Paul areas |
| Missouri | Barite tailings (tiff chert)<br>Lead-zinc tailings (chert/chat)<br>Iron waste rock (trap rock<br>Lead waste rock | Local roads in east central Missouri<br>Southwest corner of Missouri<br>Southeast part of Missouri<br>Street paving in St. Louis area |
| Nevada | Barite Tailings (chert) | I-80 Resurfacing near Battle Mountain |
| New Jersey | Iron ore tailings | Northwest part of New Jersey |
| New Mexico | Molybdenum tailings and waste rock | North central part of New Mexico |
| New York | Iron ore waste rock | Essex and St. Lawrence Counties |
| Oklahoma | Lead-zinc tailings (chert/chat) | Northeast corner of Oklahoma |
| Pennsylvania | Anthracite coal refuse<br>Burnt Anthracite refuse (red dog)<br>Iron ore waste rock | 4 experimental test sections -Luzerne Co.<br>PA Turnpike N.E. Extension - Luzerne Co.<br>PA Turnpike - Berks & Chester Cos. |
| South Dakota | Gold waste rock | Seal Coat Rt. 35 near Lead |
| Tennessee | Zinc Coarse Tailings | Eastern part of Tennessee |
| Utah | Classified Copper Mill Tailings | Mineral Filler in Salt Lake City area |
| Washington | Lead-Zinc Waste Rock | Northeast corner of Washington |
| Wisconsin | Coarse Iron Ore Tailings and Waste Rock<br>Lead-Zinc Tailings | U.S. Rt. 141 north of Milwaukee<br>Local roads in southwest WI |
| Wyoming | Coarse Iron Ore Tailings | Southeastern part of Wyoming |

**Table 5.** **Embankment and Fill Uses of Mine Spoil in the US (Collins and Ciesielski 1994)**

| State | Type of Mining Waste Used | Project Location(s) |
|---|---|---|
| Alaska | Mill tailings | Location not known |
| California | Gold dredge tailings | Sacramento area |
| Colorado | Gold mill tailings<br>Coal mine wastes | North central part of Colorado<br>Location not known |
| Idaho | Lead-zinc tailings<br>Gold dredge tailings | I-90 near Kellogg<br>Forest Road in Custer Co. |
| Illinois | Coal refuse | I-57 in Franklin Co. |
| Indiana | Coal overburden | Two interstate highways |
| Michigan | Copper waste rock<br>Copper stamp sands<br>Iron waste rock | US Rte 45 in Military Hills<br>U.S. Rte 41 near Houghton<br>U.S. Rte 2 near Ironwood |
| Minnesota | Taconite tailings | Northeast part of Minnesota |
| Missouri | Iron waste rock | Southeast part of Missouri |
| New York | Iron waste rock | Northwest part of New York |
| North Carolina | Feldspar tailings | Western part of North Carolina |
| Ohio | Bituminous coal refuse | Southeast part of Ohio |
| Pennsylvania | Anthracite coal refuse<br>Anthracite coal refuse<br>Bituminous coal refuse | Cross Valley Expressway near Wilkes Barre<br>I-81 near Hazleton<br>US Rte 219 relocation near Ebensburg |
| South Dakota | Gold mill tailings | Western part of South Dakota |
| Utah | Copper mill tailings<br>Copper mill tailings | I-215 west of Salt Lake City<br>Other roadways near Salt Lake City |

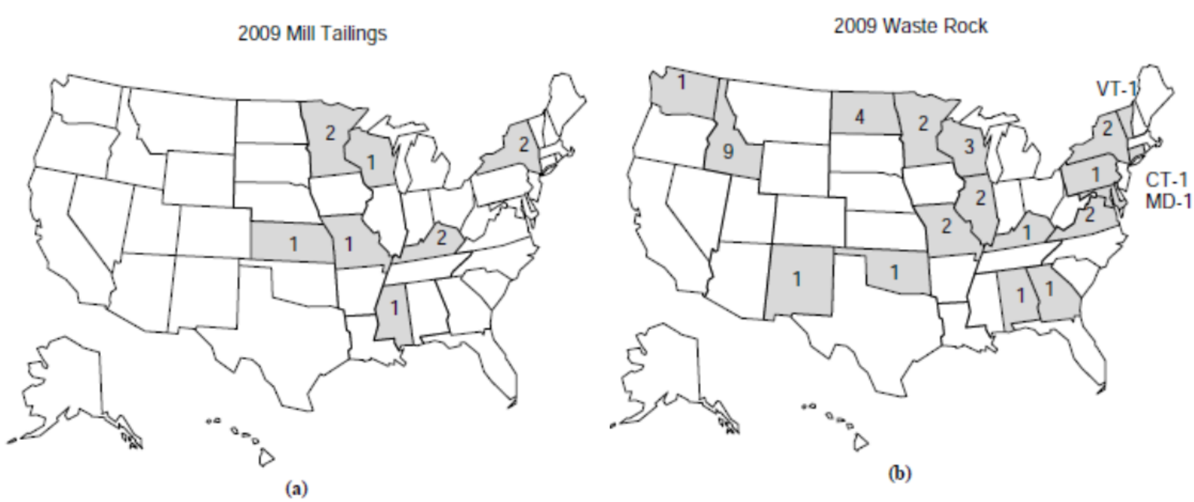


**Figure 12. 2009 Survey of State Highway Agencies for Use of Mine Spoil in Highway Applications. Number in Shaded States Indicates Sources Available (Stroup-Gardiner 2013)**

The low traffic Superpave mixture contained 80 percent taconite waste rock and tailings and was constructed on MnDOT's MnROAD facility. The structure is 4 inches thick and the 20-year design ESALs are 110,000. The PCC pavement is an 8-inch thick JPCP dowelled pavement. The thin lift pavement is a 2-inch thick HMA overlay of a new 5-inch thick concrete pavement, and contains millings from two different tailing sources. The low volume railroad ballast is 4 inches of taconite railroad ballast replacing the top 4 inches of the original base material.

The PCC pavement has been performing well as of the date of the report (2010). At that time, minimal cracking had been observed without faulting, and the ride quality was largely unchanged. The low traffic Superpave mixture has had favorable performance as well, with only two thermal cracks spanning the test lane and exhibiting suitable rutting performance with rut depths under ¼ inch. The thin asphalt mixture has not performed as well as the other two pavements, exhibiting a number of transverse and longitudinal cracks along with some reflective cracking. FWD testing has indicated that the railroad ballast aggregate base is significantly stronger (25 percent more) than the traditional aggregate used by MnDOT, however an issue has occurred when the compactive effort used to place the taconite base fractured particles in the bottom of the base layer. While rutting has not been an issue, the researchers are concerned that the base will continue to fracture under traffic loading and cause moderate rutting. Pothole patch mixture was also developed using taconite waste, and the pothole patch that was installed is performing similarly to traditional pothole patches. In general, the applications using taconite aggregates have performed as well as or better than conventional aggregates.

Another study done in Oklahoma evaluated the use of lead and zinc chat (chert) in HMA surface mixtures (Wasiuddin et al. 2007). The study found the raw chat can be used to produce a S5 Superpave surface mixture, with up 80 percent of the aggregate being the mine spoil material. The study also found chat increased the voids in minerals aggregates (VMA) in HMA. The chat-asphalt mixtures also exhibited desirable moisture susceptibility, rutting, and permeability performance. In addition, leaching potential tests of heavy metals (lead, zinc, and cadmium) in chat found the leachate concentrations to be below the EPA limits. The environmental tests indicated that chat-asphalt can be used safely as a roadway surface.

***Regional State-of-the-Practice***

As is seen in Figure 12, States within the region have little reported experience with the use of mine spoil, with Arizona, California, Nevada, Texas, and Utah reporting that mine spoil is currently not used in highway applications.

**New Mexico**. While NMDOT responded to the survey used to develop Figure 12 with one use of wasted rock, its current 2014 specifications have no mention of "waste rock" "tailings" or even "molybdenum" as this was the specific mine spoil material stated in Table 4.

**Use of Mine Spoil in Arizona**

An early feasibility study of using stabilized copper mill tailings evaluated several tailings from Arizona, Idaho, and Utah (Sultan 1979). Engineering qualities evaluated included compaction characteristics, compressive, tensile, and shear strength; compressibility; permeability; and erodability by rainfall. The study determined that copper mill tailings have excellent engineering properties and can be successfully used in road construction particularly as compacted fill in embankments, compacted foundation, and subgrade material.

The current 2008 specifications contain no mention of waste rock, tailings or mine spoil of any kind.

However, despite the current lack of specifications for the use of mine spoil, an ongoing study at the University of Arizona is evaluating the utilization of mine tailings through geopolymerization (Yohem 2011). Geopolymerization is a technology that creates a hardened paste through transformation of short molecular chains of aluminosilicate materials into a long-chain geopolymer. A chemical reaction between aluminosilicate oxides and an alkaline activation solution at ambient or slightly higher temperatures produces the amorphous structure that is comparable to portland cement concrete in many applications (Zhang 2012). Early production of this geopolymer has proved successful with both mill tailings and RCA, with hopes of constructing a test pavement in the near future (Yohem 2011; Zhang 2012).

**Challenges to Increasing the Use of Mine Spoil**

The FHWA (2012) states that there is a need to establish general environmental criteria for the selection of mine spoil byproducts to be used in paving applications that addresses concerns regarding the variation of the material from mineral processing operations. Additionally, the level of leachability from mine spoil materials needs to be closely assessed as they may contain inorganic metals and sulfide-based metallic ore elements. Finally, the material needs to be logistically available in large quantities for highway projects, as most mines are located in remote areas.

**Concluding Remarks Regarding Mine Spoil Usage**

While waste rock and mill tailings have been investigated in highway applications since the 1970s, the lack of specifications and logistic availability of the material has become a hindrance for most DOTs. Additionally, leachability issues and the tests required to determine if the material is suitable enough for use in the environment have provided more hurdles for DOTs looking to use the material.

Increasing mine spoil utilization will require more understanding and development of suitable mine spoil stockpiles. Standards for incorporation of mine spoil into highway applications, along with improved quality control, can increase mine spoil utilization. Early results of geopolymerization have shown some potential for mine spoil utilization, suggesting that mine spoil might see some use in future highway applications.

## SUMMARY

The following summarizes the literature review results on the use of RCWMs as it pertains to Arizona:

### Reclaimed Asphalt Pavement

RAP is an established material for most DOTs for use in asphalt mixtures, base, and recently some agencies are even using coarse fractionated RAP as aggregate in concrete. High RAP (25 percent or greater replacement) mixtures are currently of great interest to the industry as they provide the opportunity to replace significant amounts of virgin binder and aggregate, resulting in significant cost savings and the potential for increased sustainability. Yet it is widely recognized that the risk of failure increases as RAP content increases, and thus the average RAP usage as a percentage of total asphalt concrete mixture in the United States remains below 15 percent.

Keys to increasing RAP utilization in Arizona include:

- Providing specifications that specifically allow for increased RAP utilization.
- Training the local paving industry in methods that will allow for the successful incorporation of higher levels of RAP into asphalt mixtures.
- Improved quality control throughout the mixture design and construction processes.
- Incorporation of incentives to encourage contractors to increase RAP utilization beyond 15 percent.

Key technologies that will assist in this implementation include broader adoption of WMA technologies and the use of RAP fractionation. With regards to the latter, fractionation may result in greater stockpiles of coarse RAP (as it has in some markets), which may provide opportunities for the use of coarse RAP as aggregate in concrete.

### Recycled Asphalt Shingles

In many markets, RAS usage is on the rise in asphalt concrete mixtures. Yet RAS availability and subsequent use is lower in the western United States compared to the Great Lakes region. For Arizona, it needs to be demonstrated that a viable supply of consumer generated shingles exists to produce quality RAS for use in asphalt mixtures. It is recognized that the risk of negative impacts on asphalt concrete mixture performance increases as RAS content increases, and thus even though most State DOT specifications allow for 5 to 7 percent RAS content, the amount of RAS used is significantly lower.

Keys to increasing RAS utilization in Arizona include:

- Demonstrating that a viable supply of consumer shingles exists.
- Cooperation between ADOT and industry to implement RAS usage.
- Modification to existing specifications to allow the use of RAS.
- Training to better understand how to successfully incorporate RAS into asphalt mixtures.
- Improved quality control throughout the mixture design and construction processes.
- The incorporation of incentives to encourage contractors to increase RAS utilization.

Once a viable source of refuse shingles is demonstrated in Arizona, RAS recycling facilities will need to be incentivized to produce quality RAS material will increase supply.

**Ground Tire Rubber**

Arizona is a national leader on the use of GTR, particularly in surface mixtures that are both quiet and have good skid resistance. Traditionally, asphalt-rubber was produced as a field blend, being highly viscous and thus applicable at relatively high binder contents. The increase in terminal blend asphalt-rubber binders has added a new twist, the implications of which are not yet fully understood. In recent years, WMA technology has been adopted across the country, and it should be considered in Arizona for broader application to GTR as it allows production, placement, and compaction of asphalt-rubber mixtures at more moderate temperatures. This provides a better working environment, enables longer hauls, quicker opening to traffic, reduced costs, lower environmental footprint, and placement at night or in cooler temperatures. Field blend materials require specialized equipment at the asphalt concrete plant to mix asphalt binder and crumb rubber. This equipment is typically mobile, and travels from plant to plant to follow the availability of work. This can make smaller projects uneconomical unless the contractor is given flexibility to schedule the work to coincide with larger projects. Concerns exist regarding the use of RAP containing high amounts of GTR, and additional research needs to be conducted to alleviate these concerns.

**Recycled Concrete Aggregate**

RCA has been used in highway applications for decades but has increasingly gained popularity in many states as virgin aggregate sources have become scarcer and hauling prices have increased. It is most common to find RCA used in aggregate bases as it offers the replacement of significant amounts of virgin aggregate, but coarse RCA has also proven effective as an aggregate in new concrete. Two-lift concrete paving increases the feasibility of using RCA in the concrete bottom lift as the virgin aggregate in the top lift can be used to meet emerging needs in the surface characteristics area.

The key to increasing RCA utilization in Arizona is to specifically allow it as an option in construction specifications for both aggregate base and as a coarse aggregate in new PCC. ADOT's *2008 Standard Specifications* are silent on the use of RCA. Further, RCA implementation will require training to better understand how to successfully incorporate RCA into aggregate bases and new PCC through conventional and two-lift paving, improved quality control throughout the mixture design and construction processes, and the incorporation of incentives to encourage contractors to increase RCA utilization.

**Construction and Demolition Waste**

The literature has revealed that the use of CDW in highway applications is feasible, but the market demand is not apparent. Additionally, increased efforts are required to recycle CDW into quality material and there appears to be a lack of recycling facilities. Thus there has been little use of CDW by highway agencies to date.

However, as virgin materials become less available in Arizona and more sustainable or “green” efforts become more accepted, the use of CDW in highway applications has the potential to increase. As an example, the City of Chicago has implemented strict policies regarding construction waste generation which has fueled the development of a construction waste recycling industry. To increase utilization of CDW in Arizona transportation infrastructure would require a concerted, long-term effort by ADOT to study the material characteristics, encouragement of the recycling industry and contractors through incentives, and adoption of specifications that allow its use.

**Mine Spoil**

Waste rock and mill tailings have been investigated for use in highway applications since the 1970s, but there is a widespread lack of specifications specifically addressing their use. Further, the materials are often located far from where they are needed, and coupled with potential hazards associated with many sources of mine spoil, the material has become a hindrance for most DOTs.

Increasing mine spoil utilization in Arizona will require a better understanding of the type and location of available materials and the development of mine spoil stockpiles of materials possess acceptable characteristics. Standards for incorporation of mine spoil into highway applications, along with improved quality control, can increase mine spoil utilization.

# CHAPTER 3. SURVEYS

## INTRODUCTION

This chapter provides the details regarding the surveys conducted to ascertain the types and volume of suitable waste materials that are available in Arizona and to what degree this waste is being recycled for use as construction materials. Surveys were conducted among a limited number of heavy construction contractors, material suppliers, and industry associations to determine their current utilization of recycled and waste materials in pavement construction projects; and to gauge their willingness to increase the amounts of these materials used. Solid waste/landfill operators and roofing and demolition associations were identified and queries were made regarding the availability of sources of recycled materials suitable for beneficial use.

Web resources were used to identify companies and organizations that were good candidates to survey. Once identified, the organizations were contacted and surveyed with regards to their practices and preferences towards use of recycled and waste materials.

## APPROACH

### Selection of Contractors

The ADOT list of contracts awarded from 2010 through 2013 was used to create a list of construction contractors that had recently worked on ADOT projects. This list was compiled and sorted by contractor, and the total amounts of awards over the four year period tallied for each. Contractors who were not directly involved in heavy construction with little potential to use recycled and waste materials (e.g. landscaping, electrical, paint marking, drainage, and so on) were eliminated, as were those associated with projects in which a description was not provided. The contractors, combined four year award totals, number of projects awarded, location, and region are shown in Tables 6 and 7.

Table 8 combines the award data by the home region of the contractor (<u>not</u> by where the work was conducted), showing the total award value by ADOT District, number of contracts awarded, and average award value. Of the nearly $2 billion for 416 projects awarded, it is observed that contractors with their home office in the Phoenix District are the dominate recipients of ADOT funded work, receiving $1,475,060,520 over the four year period for the construction of 277 projects. The award value per project of $5,325,128 is the second highest of all regions, the first being the $12,425,144 per award for projects conducted by contractors from out-of-state. The out-of-state contractor observation is explained by the fact that extremely large projects are often conducted by contracting consortia that are led by large national or international firms.

**Table 6. List of Contractors in Phoenix District Awarded AZDOT Contracts 2010-2013**

| Road/Bridge Contractor | Combined | No. Jobs | Location | District |
|---|---|---|---|---|
| Ames Construction | $164,953,587 | 11 | Scottsdale AZ | Phoenix |
| Bison Contracting Co. | $25,651,948 | 16 | Phoenix AZ | Phoenix |
| C S Construction | $19,302,648 | 19 | Phoenix AZ | Phoenix |
| C.S. and W. Contracting | $7,850,996 | 1 | Phoenix AZ | Phoenix |
| Cactus Transport/Asphalt | $11,372,923 | 19 | Tolleson AZ | Phoenix |
| Cholla Pavement Maintenance | $507,351 | 1 | Apache Junction AZ | Phoenix |
| Coffman Specialties | $15,057,665 | 4 | Scottsdale AZ | Phoenix |
| Combs Construction Company | $54,876,486 | 48 | Phoenix AZ | Phoenix |
| Contractors West | $6,654,792 | 4 | Mesa AZ | Phoenix |
| DBA Construction | $4,084,929 | 3 | Phoenix AZ | Phoenix |
| Fisher Sand & Gravel | $114,375,762 | 15 | Phoenix AZ | Phoenix |
| FNF Construction | $149,729,880 | 21 | Tempe AZ | Phoenix |
| Grey Mountain Construction | $1,042,745 | 2 | Chandler AZ | Phoenix |
| Haydon Building Corp. | $20,786,025 | 4 | Phoenix AZ | Phoenix |
| Hunter Contracting | $2,562,991 | 1 | Gilbert Az | Phoenix |
| Intermountain West Civil Constrs | $14,343,437 | 11 | Tempe AZ | Phoenix |
| International Surfacing Systems | $5,323,635 | 7 | Chandler AZ | Phoenix |
| J. Banicki Construction | $7,651,995 | 8 | Tempe AZ | Phoenix |
| Kiewit/Sundt | $89,955,200 | 1 | Phoenix AZ | Phoenix |
| Knochel Bros. | $1,232,905 | 2 | Phoenix AZ | Phoenix |
| Lawrence Construction Co. | $8,947,166 | 3 | Phoenix AZ | Phoenix |
| Markham Contracting | $17,492,895 | 5 | Phoenix AZ | Phoenix |
| Meadow Valley | $99,370,462 | 15 | Phoenix AZ | Phoenix |
| Michael J. Valente | $2,816,403 | 4 | Phoenix AZ | Phoenix |
| Nesbitt Contracting | $10,272,514 | 8 | Tempe AZ | Phoenix |
| Pulice | $523,791,064 | 6 | Phoenix AZ | Phoenix |
| R.K. Sanders | $957,250 | 4 | Phoenix AZ | Phoenix |
| Royden | $11,777,183 | 1 | Phoenix AZ | Phoenix |
| Rummel Construction | $2,537,443 | 2 | Scottsdale AZ | Phoenix |
| Sandstorm-GMA | $267,598 | 1 | Phoenix AZ | Phoenix |
| Skanska | $41,032,788 | 6 | Phoenix AZ | Phoenix |
| Southwest Concrete Paving | $9,249,586 | 6 | Phoenix AZ | Phoenix |
| Southwest Slurry | $4,817,194 | 6 | Phoenix AZ | Phoenix |
| Standard Construction | $397,028 | 2 | Avondal | Phoenix |
| Sundland | $22,270,606 | 9 | Tempe AZ | Phoenix |
| Sunrise Cross Construction | $1,745,440 | 1 | Glendale AZ | Phoenix |

**Table 7. List of Contractors in Other Districts Awarded AZDOT Contracts 2010-2013**

| Road/Bridge Contractor | Combined | No. Jobs | Location | District |
|---|---|---|---|---|
| C and E Paving and Grading | $1,632,223 | 2 | Flagstaff AZ | Flagstaff |
| Tonto Supply Co. | $424,546 | 1 | Colorado City AZ | Flagstaff |
| Show Low Construction | $13,030,699 | 14 | Show Low AZ | Globe |
| Hatch Construction and Paving | $15,677,537 | 5 | Taylor AZ | Globe |
| McCormick Construction | $21,849,101 | 7 | Bullhead City AZ | Kingman |
| Technology Construction | $1,836,378 | 3 | Bullhead City AZ | Kingman |
| CKC Construction & Materials | $12,583,505 | 5 | Safford AZ | Safford |
| K E & G Construction | $7,456,596 | 5 | Sierra Vista AZ | Safford |
| A & S Paving | $685,228 | 2 | Tucson AZ | Tucson |
| Borderland Construction Co. | $27,602,268 | 1 | Tucson AZ | Tucson |
| Granite Construction | $24,678,242 | 10 | Tucson AZ | Tucson |
| K.A.Z. Construction | $1,905,120 | 7 | Tucson AZ | Tucson |
| Meridian Engineering | $6,498,206 | 1 | Tucson AZ | Tucson |
| Southern Arizona Paving and Const. | $9,496,363 | 13 | Tucson AZ | Tucson |
| The Ashton Company | $32,424,818 | 2 | Tucson AZ | Tucson |
| CEMEX | $1,879,573 | 4 | Yuma AZ | Yuma |
| DPE Construction | $3,759,918 | 1 | Yuma AZ | Yuma |
| DRB Mining | $903,066 | 1 | Yuma AZ | Yuma |
| Intermountain Slurry Seal | $431,431 | 1 | Lewisville TX | NA |
| Interstate Rock Products | $6,680,406 | 2 | Hurricane UT | NA |
| J.A.R. Concrete | $5,469,188 | 1 | El Paso TX | NA |
| R.E. Monks | $2,979,738 | 2 | Colorado Springs CO | NA |
| Ralph L. Wadsworth Construction | $71,415,248 | 1 | Draper UT | NA |

**Table 8. Summary of AZDOT Contracts Awarded 2010-2013 by Contractors' Home Region**

| District | Total Award Amount | Number of Projects | Average Award Amount |
|---|---|---|---|
| Flagstaff | $2,056,769 | 3 | $685,590 |
| Globe | $28,708,236 | 19 | $1,510,960 |
| Holbrook | $0 | 0 | $0 |
| Kingman | $23,685,479 | 10 | $2,368,548 |
| Phoenix | $1,475,060,520 | 277 | $5,325,128 |
| Prescott | $208,324,497 | 48 | $4,340,094 |
| Safford | $20,040,101 | 10 | $2,004,010 |
| Tucson | $103,290,245 | 36 | $2,869,173 |
| Yuma | $6,542,558 | 6 | $1,090,426 |
| N/A (Out of State) | $86,976,012 | 7 | $12,425,145 |
| Totals | $1,954,684,417 | 416 | $4,698,761 |

Based on this information, efforts were made to contact various contractors, materials suppliers, associations, waste processors, and agencies. It was found that this effort was stifled by an inability to identify and engage knowledgeable individuals within the various organizations, resulting in a general lack of responsiveness. Further, there was reluctance by some to discuss practices that may be perceived as providing a competitive advantage. Even though these difficulties were encountered, surveys were completed with the following organizations:

<u>Contractors</u>

- Fann Contracting
- Cemex
- FNF Construction
- Granite Construction
- Kiewit Infrastructure West

<u>Materials Suppliers</u>

- CRM
- Holly Frontier
- Liberty Tire Recycling
- Paramount Petroleum Corporation

<u>Associations</u>

- Arizona Rock Products Association
- Arizona Roofing Contractors Association
- Rubber Pavements Association

<u>Landfill Operator</u>

- Cinder Lake Landfill

<u>Transportation Agencies</u>

- Maricopa County
- City of Phoenix
- ADOT

The results of the surveys provided insight into the current practices and perceptions regarding the use of RCWMs as well as the availability of certain RCWMs in the Arizona market. The following is a summary of the survey results.

## SUMMARY OF RESULTS

### Reclaimed Asphalt Pavement (RAP)

The use of RAP has increased in recent years in the Arizona market, rising from almost no use in the mid-2000's to approximately 13 percent RAP usage in asphalt mixtures on a mass basis in 2013 (NAPA 2014). Although RAP is allowed to be used in both asphalt mixtures and as base material, the recent increase in utilization is closely related to ADOT now permitting RAP use in asphalt mixtures. The main driver is that direct economic incentives exist for contractors to increase RAP use as it lowers the cost of asphalt mixtures. Yet the general consensus amongst those surveyed is that even greater amounts of RAP above current utilization could be used if supported by ADOT.

A limitation cited by contractors to increased use was that ADOT specifications limit RAP to 15 percent, after which the RAP needs to be fractionated and the binder characterized. It was stated that this has not only created the need for additional testing, but complicates stockpile management during construction. One contractor cited routine experience of using up to 25 percent RAP in other states. Another contractor stated that it is also becoming more common for ADOT to specify the *Miscellaneous Structural 409* mixture, which does not allow RAP. This same contractor stated that many of the local municipalities still do not allow the use of RAP due to poor performance in the distant past. A further limitation cited was that RAP is not allowed in asphalt mixtures using terminal blend GTR binder. One contractor specifically felt that rubberized asphalt could be used with RAP, both in gap-graded mixtures and in friction courses.

In response to the ADOT 409 mixture requirements precluding the use of RAP, ADOT has adopted the practice of allowing mixtures approved under Section 416 or 417, which may include RAP, to be utilized in lieu of mixtures meeting Section 409 requirements. Furthermore, ADOT is in the process of revising Section 409 requirements to allow for the inclusion of RAP in a similar fashion to that provided in Section 416.

In combination, the contractors felt that a perception still remains among some that the use of RAP in asphalt mixtures is undesirable. This sentiment was somewhat confirmed in discussions with ADOT personnel who felt that they are only now getting back into the use of RAP after a long hiatus brought about by a failure that occurred long ago and that they feel it is important to increase RAP utilization slowly to ensure good performance.

With regards to the use of RAP as a base material, one contractor stated that they had used RAP as a base material but that issues arose with the ability to use the nuclear density gauge to accurately assess field density.

**Recycled Asphalt Shingles (RAS)**

It was stated by the majority of respondents that the supply of asphalt shingles in the Arizona market is too limited to support recycling. Although asphalt shingles were commonly used in residential construction pre-1988, almost all new residential roof construction in the most populated areas of the state is done with tiles although shingles are still the predominant roofing material used in snow country and in higher elevations. But since the older roofs will not withstand the weight of tiles, there is currently asphalt shingle tear-off and replacement and thus some supply exists. And disposal of asphalt shingles is a problem as few landfills accept them. This results in long transport distances and high tipping fees for disposal. Yet it was stated that shingles from the 1970’s and earlier are often contaminated with asbestos, and since these are not separated from non-asbestos contaminated shingles, the entire supply of waste shingles is suspect making recycling them much more difficult.

Regardless, the roofing industry would support recycling efforts, but feel that it would only be potentially viable in the greater Phoenix-area and Tucson. For asphalt shingle recycling to be practical, it would take considerable efforts to ensure that asbestos contamination is properly addressed. Further, supply is not as steady as it is in mid-Western states where a major factor in roof replacement is hail storms; these are not common in the major metropolitan areas of Arizona. As a result, there is currently little motivation to recycle asphalt shingles in Arizona. Yet the one landfill operator responding to the survey noted that they receive shingles and that they believe there is a potential for beneficial use.

One asphalt binder supplier had a different perspective on supply, saying that supply has not been the issue with utilization of RAS in Arizona, but instead it is a matter of performance. Asphalt in shingles is much stiffer than paving grade asphalt and thus the addition of RAS would harden the binder in an environment in which binder hardening is already a concern. Further, concerns exist with regards to quality control, especially for field additions. The fear of binder stiffening was echoed by ADOT, who stated that anything that makes binders stiffer is considered highly undesirable.

**Ground Tire Rubber (GTR)**

GTR is used in the production of field blend and terminal blend asphalt rubber binder. Arizona is considered a leader in the use of GTR and many Arizona contractors and suppliers are members of the Rubber Pavement Association (RPA), compromising the largest group of users of waste tire rubber in the state. A number of respondents commented on the welcoming environment in Arizona compared to other states in which they work regarding the use of GTR, citing the benefits of ADOT's new specifications and lamenting the lack of favorable specifications in other states.

The advent of terminal blending is being well-received by ADOT and contractors and it is perceived that this will result in increased use of GTR. Yet the tire rubber industry felt that the use of GTR continues to be a largely untapped market, particularly as pertains to using terminal blend asphalt rubber binder in lieu of SBS-type polymers in highly modified binders. As mentioned previously, one contractor also felt that rubberized asphalt could be used with RAP, both in gap-graded mixtures and in friction courses.

A focal point amongst suppliers centered on testing requirements of GTR-modified binders as a limitation. For instance, a respondent stated that Arizona does not waive solubility requirements, effectively limiting the amount of GTR that can be blended into the binder. Another discussed the need to move the plates in the dynamic shear rheometer (DSR) further apart when testing particulated GTR binder compared to standard binders. Another cited testing limitation is that certain compatibility issues can arise with GTR binders during the rolling thin film oven test.

Beyond testing concerns, a cited obstacle to continued growth in this market is effective on-site quality control. This point was partially supported by another supplier who cited difficulties in maintaining the quality of field blends, recognizing the limited number of ADOT personnel available to conduct testing in the field.

An interesting perceived barrier provided by a supplier is that the contracting community is resistant to adopting broader use of GTR as they are uncertain how the added longevity will affect their long-term business (i.e. better long-term performance could mean less work).

Looking to current specifications some cited the need to expand the applications for which GTR is allowed to be used. For example, one supplier stated that current ADOT specification limit GTR to friction courses and surfacing courses, not allowing it to be used in lower pavement layers, such as in base layers. The reluctance to use GTR in a broader range of application stems from a past failure, in which six late season placements that occurred in 2007 failed due to a purported lack of compaction. The concern expressed was that the failure was largely blamed on the GTR, leaving GTR as the "scapegoat" even though other factors played a stronger role. It was expressed that this has unfairly tainted the reputation of GTR and now it is difficult to change the perception of poor performance.

Another commonly cited limitation is that the GTR-binder reaction is complex and difficult to understand. One supplier felt that the asphalt binder-GTR reaction was such that current specifications do not ensure that the rubber is being properly matched to the binder. This has resulted in some isolated cases of poor performance that create a broad negative image of the GTR industry. Another supplier felt that ADOT should move towards performance-based specifications and away from prescriptive specifications, emphasizing the need for a high-quality final product as that will result in growth for GTR applications. This point was echoed by yet another supplier who felt that ADOT should get away from GTR-modified binder testing and instead conduct performance testing on mixtures. It was also stated by a supplier that good collaboration between ADOT and environmental groups is essential.

A positive development cited by one supplier was that ADOT now permits the use of GTR in gap-graded mixtures and also recognizes of the structural contribution of the rubberized friction course to the overall pavement structure. It was felt that this new specification would increase the use of GTR and decrease risk of failure.

**Recycled Concrete Aggregate**

From the survey results, it is clear the recycling of concrete is not a common practice in Arizona and that the majority of returned plastic concrete and construction refuse concrete is landfilled. A small percentage of refuse concrete is crushed and used as base material, but at a much lower percentage than RAP. Other refuse concrete is used as fill/embankment, but there often is little refuse concrete to work with in most projects so this is not a common practice although the one landfill operator that responded to the survey noted that they do routinely handle refuse concrete. One cement and ready-mix concrete supplier said that the only time that they use RCA as aggregate in new concrete is on federal jobs in which it is required to meet environmental goals such as in LEED construction. In those cases, the use of RCA has been very effective. But they have never used RCA as coarse aggregate in new concrete for an ADOT or local agency transportation project.

It was stated that the major barrier to the increased use of recycled concrete appears to be pure economics, as the cost of natural aggregates and landfilling refuse concrete are both relatively low, and thus there is little to no cost advantage for using RCA compared to virgin natural aggregate materials. One supplier said it costs more for them to transport and crush concrete than it does to dispose of it and buy high-quality natural aggregate, and thus it would be necessary to incentivize the use of reclaimed materials if utilization is to be increased. It is likely that cost to recycle concrete will remain relatively high unless conditions change that make concrete recycling more common.

The second major barrier cited was the lack of acceptance by ADOT and local agencies which do not allow RCA to be used as aggregate in new concrete and limit its use as a base material to a maximum of 50 percent replacement of virgin natural aggregate. A number of respondents stated that these specifications were a barrier to increased use of RCA. Local agencies also stated that they could accept increased use of RCA as an aggregate base if the specifications allowed it. One contractor that does structural work specifically identified the risk of failure as a major impediment to using RCA as aggregate in structural concrete.

Another factor is that the Arizona concrete production primarily caters to the residential and commercial markets, with the transportation market only accounting for roughly 15 percent of concrete production. Thus there is little incentive amongst concrete ready-mix suppliers to change practices specifically to meet agency needs. This is not necessarily true for larger projects in which contractors set up designated concrete plants to exclusively supply concrete to that specific job.

From the perspective of using RCA as a base material, contractors cited limitations on available space to set up and conduct the required crushing and blending operations within a crowded urban environment. As stated earlier, it is easier and cheaper for them to simply dispose of the refuse concrete versus crushing it and blending it with natural material to meet the ADOT base specifications. One contractor stated that they liked the stability of the base made with RCA, but had some production issues with rebar that got past the magnets chewing up their belts.

In combination, the low cost of high-quality natural aggregates, the low cost of landfilling waste concrete, and the relatively small presence of ADOT in the concrete production market means that although an opportunity exists to increase the use of RCA, it would take a concerted effort by ADOT (and local agencies) to increase the use of RCA. Pure economics would likely not drive initial implementation, although it is likely that RCA would become more cost-effective in time if its use was allowed/ encouraged. An exception might be if ADOT allowed in-place recycling of existing concrete pavement into subbase as this would eliminate the need to establish a site crushing and multiple stockpiles as well as the need to transport the crushed concrete off- and back on-grade. This would significantly reduce costs.

**Construction and Demolition Waste (CDW)**

In addition to reclaimed asphalt pavement and refuse highway concrete, there are a number of construction waste landfills in operation that typically accept soils, brick, and masonry, and non-DOT generated concrete. These materials are part of the operators' aggregate pit "reclamation" plans, and such materials have been used as fill where economically viable. The one landfill operator that responded to the survey stated that they receive all types of CDW, include brick and masonry, concrete, and aggregates, as well as wood and metal. Although they feel there is a potential for increased use of these materials, none of them have been procured for use in new construction.

One major limitation cited in the Phoenix area is lack of supply. There is little brick and masonry construction and thus little waste being generated. Further, as a relatively new city with new buildings and infrastructure, little demolition waste is being generated through tearing down of old structures. In combination, the abundant supplies of quality natural aggregates, the relatively inexpensive costs of disposal, and the overall lack of supply of CDW means there is little incentive to improved CDW handling/processing facilities at this time.

**Mine Spoil**

Mine spoil, particularly overburden material, is used as fill or for landfill site management. Certain mine spoils can also be used as aggregate if it passes applicable specifications. The major limitation cited was availability, as most mine spoil sources are located long distances from urban areas where materials are needed. A second cited barrier was accessibility, as mining companies are often not willing to accept the liability of having an aggregate production operation on-site. In one case near Tucson, an agreement was struck between and aggregate supplier and mining company and high quality aggregates were being produced from mine spoil. In this case, the mining company minimized liability by having the aggregate supplier transport crushed material off-site for sorting and stockpiling.

In areas where it is available, mine spoil derived from overburden can offer an attractive alternative to natural sources of fill and aggregates. But in general, there are adequate supplies of high-quality natural aggregate available throughout most markets in Arizona, and thus an economic incentive for the use of mine spoil does not exist.

In contrast to aggregates derived from mine generated overburden, environmental concerns were expressed regarding mine spoil that is a result of additional processing, including fines produced from crushing and slags resulting from metallurgical operations. In particular, leaching was considered to be potentially problematic and little interest was expressed in using this type of material. A couple of respondents suggested that slag from copper smelting might have opportunities for beneficial use.

## PERCEIVED BARRIERS

### Contractors'/Suppliers'/Associations' Perspective

The most commonly cited barriers to the use of RCWMs cited by contractors, suppliers, and associations are the combination of the lack of acceptance by DOT and lack of acceptance by others. It was commonly expressed that ADOT and local agency specifications were a barrier to increased use of RCWMs, including limits on where and how much RAP could be used. Other examples included the limitation that aggregate base course material must contain, at a minimum, 50 percent virgin aggregate material. One respondent summarized this sentiment by simply stating, "If it is not in the specification, it won't get done."

A number of respondents specifically cited the lack of availability of RAS as a barrier to its use. It was not a lament, but simply a statement that RAS is not available in the market and thus not being considered for use. Similar concerns were expressed regarding the use of RCA and CDW, as there is an overall lack of supply as most of the existing infrastructure is relatively new and thus demolition is relatively uncommon, and that much of the residential construction is “stick” construction with little masonry or brick usage. A few cited a lack of quality control and a lack of knowledge as potential barriers. These are topics that can usually be addressed through training. Minor concerns were expressed regarding lack of performance, increased expense, and risk of failure. One contractor listed the risk of failure when using recycled materials in aggregate base, stating that severe failures have been observed in past projects.

One statement that seemed to sum up the general feelings of industry was that the use of RCWMs is market-driven and since ADOT has had relatively good success with current practice and that good natural aggregate sources are abundant, there really is not a major incentive to increase the amount of RCWMs used.

**Landfill Operator’s Perspective**

Only one landfill operator responded to the survey so the perspective given is by definition narrow. Nonetheless, some interesting observations were made. A wide-range of CDW was received by the operator, including asphalt shingles, refuse concrete, asphalt pavement, and bricks and masonry, as well as aggregate, wood, and metals. Of the materials that the landfill operator felt had potential for utilization, asphalt shingles, refuse concrete, and asphalt pavement were listed. Although these are available, none are currently being beneficially used. Barrier cited included lack of demand, lack of equipment to process the materials, and the added expense of processing. In combination, it seemed from the perspective of the landfill owner that CDW materials are available, but there is not currently a demand or economic incentive to invest in the equipment needed to process the waste into suitable construction materials.

**Agencies’ Perspective**

The two barriers cited by ADOT regarding increased use of RCWMs were lack of acceptance by ADOT and the increasing risk of failure attributed to increasing the amounts of RCWMs used. ADOT’s response indicated that some past attempts to increase the amount of RCWMs has resulted in failure, and that this has had a chilling effect on further efforts to increase utilization. One cited example was of an asphalt surface recycling project conducted “some years ago” in which multiple factors contributed to a poor product, but that RAP took the majority of the blame. As a result, the use of RCWMs in general gained a bad reputation amongst ADOT engineers. ADOT is comfortable with the use of GTR and is now gaining experience and comfort in the limited use of RAP in some asphalt mixtures. The use of RAS has been discussed by ADOT, but not positively due to supply issues and concerns regarding the use of the highly oxidized RAS binder in Arizona where binder oxidation in service is a big concern. Further, concerns were expressed regarding potentially negative impacts of using mine spoil, especially slags, where leaching could be an issue.

It was felt that the increased use of RCWMs would require a cultural shift in the way ADOT and contractors currently work together, sharing in the risk associated with applying innovations. The contractors seem willing to attribute the limitations on the use of RCWMs to ADOT, but do not seem anxious to offer solutions. It was stated that ADOT must stay on top of the technologies to allow innovation to occur, but manage risk for the good of the public. A sentiment was expressed that the general lack of competition between industries might be contributing to the lack of desire to innovate. The one exception is on the supply side, where binder suppliers are the ones that have advanced innovations to increase the use of GTR. Mine spoil was viewed as a potential aggregate source as long as leaching was not a problem.

From a local agency perspective, the barriers seem to be even greater. GTR is one of the only RCWMs that are readily accepted, although RAP has been used on some projects. Barriers identified to increased use include a lack of knowledge, lack of performance, lack of quality control, and risk of failure. The sentiment was expressed that the risk is all on the agency, and for increased quantities of RCWMs to be used, the local agencies shared ADOTs concern that the contractor/supplier must share in that risk.

**POTENTIAL OPPORTUNITIES**

The identification of perceived barriers allows for consideration of potential opportunities to increase the use of RCWMs in transportation projects. The following are opportunities that were identified:

- Increased use of RAP – Current specifications limit the amount of RAP that can be incorporated into asphalt mixtures. It was expressed by contractors and suppliers that the RAP content could be increased, especially for non-surface layers, without negatively impacting performance.
- Increased use of GTR – Although GTR is commonly used, it was expressed by suppliers more GTR could be incorporated into a broader range of applications with the advent of terminal blending.
- Increased use of RCA – Currently there is little use of RCA on ADOT projects and little pure economic incentive to explore its use further. The identified barriers include prohibition of its use is specifications as well as no perceived economic case for its use as both natural aggregates and landfilling refuse concrete are currently relatively inexpensive.
- Use of CDW – The market for CDW in Arizona could not be fully assessed as only one landfill operator responded to the survey. Based on their response, suitable CDW materials are likely available but there is currently little incentive to invest in the equipment to process these materials to make the suitable for use in transportation projects. This may change in time as buildings/infrastructure ages and sufficient quantities of CDW become available along with the adoption of policies that favor increased recycling. In addition, other pressures may result in increased cost of natural aggregates and landfilling thus making CDW more attractive.
- Mine spoil – Mine spoil is plentiful in some locations throughout the state and its use is permitted if it meets standard specifications. Yet, these sources are often located far from population centers in which demand for aggregate is highest. Further, the use of these materials typically requires cooperation with a mine owner who is often averse to the risk

inherent to having an aggregate processing facility operating on their land. Concerns regarding potentially hazardous materials inherent in some mine spoil also need to be overcome.

For an opportunity to come to fruition, the environment must be such that the use of an acceptable alternative material is either economically viable and/or mandated by the specifying agency. With regards to the former, an excellent example is the use of RAP, which is allowed in a number of mixtures currently specified by ADOT; but its use is not mandated. In most cases, contractors choose to incorporate RAP into their asphalt mixtures as it is cost effective for them to do so, reducing the unit price of the mixture as well as eliminating the need to dispose of the RAP material. Further, it became clear in the surveys that contractors would like to see ADOT revise current restrictions on RAP allowing them to use even higher volumes in more applications. It is noted that ADOT must ensure that any changes to existing specifications are done with diligence and without compromising the future performance of the pavements constructed.

An example of a mandated use of a RCWM is the requirement that, in instances where the available equivalent alkalis in portland cement exceed a specified threshold, concrete mixtures contain a minimum of 15 percent ASTM C618 Class F fly ash to mitigate alkali-silica reactivity and additionally, for increased durability by reducing permeability and heat generated during hydration, a minimum of 20 percent fly ash is required for bridge deck applications. Although there was a time when this may have reduced the cost of the concrete mixtures, current increases in demand and restriction in supply have increased the cost of fly ash and it is possible that at some time in the future it may actually cost more than the portland cement it replaces or may become unavailable due to mandated reductions in carbon emissions forcing closure of coal-fired electrical generating facilities, the primary source of fly ash as an RCWM. Regardless, the mandated minimum Class F fly ash content is perceived to be necessary to ensure concrete mixture durability and thus likely will remain even if it increases costs. Similarly, the use of GTR is mandated for certain asphalt surface mixtures as it provides mixture properties that are deemed societally important, including good skid resistance and low noise.

The next chapter describes a benefit-cost analysis used to consider multiple opportunities and identify those that are most worthy of pursuit by ADOT.

# CHAPTER 4. BENEFIT-COST ANALYSIS

## INTRODUCTION

The objective of this chapter is to conduct a benefit-cost analysis to investigate the potential usability of the following RCWMs in various highway applications in Arizona:

- RAP as a partial replacement of asphalt binder and virgin aggregate in asphalt mixtures and for other applications.
- RAS and tar paper as a partial replacement of asphalt binder in asphalt mixtures.
- GTR as an addition in asphalt mixtures to create rubberized asphalt or as a binder modifier to create asphalt-rubber.
- RCA from existing highway structures (e.g. pavements, barrier walls, and so on) for use as aggregate in new concrete or as base/subbase material.
- CDW including refuse concrete, bricks and masonry, to be crushed and used as aggregate in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill.
- Mine spoil as aggregate in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill.

## APPROACH

The following three-step approach was adopted to conduct the benefit-cost analysis:

- **Step 1:** Develop a matrix summarizing the potential applications for each of the RCWMs being considered in this study (see Table 9). The ratings assigned to each potential applications for each RCWM considered in this study are based on the information gathered in the review of existing literature presented in Chapter 2 and the results of the surveys of Arizona agencies, material suppliers, construction contractors and other industry stakeholders conducted to gain insights into RCWM use and availability as discussed in Chapter 3.

- **Step 2:** Develop rating scales for each of the following:
  - Risk of using the RCWM in each application as replacement for conventional materials in terms of the likelihood of premature failure and consequence of premature failure (see Table 10).
  - Relative cost and performance (when compared to pavements constructed using materials and designs per current state-of-the-practice) that can be reasonably expected from using each RCWM for each application (see Table 11).
  - Environmental and societal impacts of using each RCWM for the application (see Table 12).
  - Potential opportunity for future application by ADOT.

- **Step 3:** Study each application indicated in the matrix (developed under Step 1); assign ratings for risk, relative cost and performance, environmental and societal impacts (using methodology outlined under Step 2) and discuss the benefits, advantages, issues to consider when using these materials; and establish a final rating for ADOT's opportunity to use these materials beneficially in the near future (see Tables 13 through 22).

**Table 9. Benefit-Cost Analysis Matrix**

| | Potential Application of Recycled, Co-Products, and Waste Materials (RCWMs) as: | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Replacement of coarse aggregate in asphalt concrete pavement (HMA/WMA) | | | Replacement of fine aggregate in HMA/WMA mixtures | | | Replacement of asphalt binder (in HMA/WMA) | | |
| | CU | IU | EU | CU | IU | EU | CU | IU | EU |
| Reclaimed Asphalt Pavement (RAP) | | | | | | | | | |
| Recycled Asphalt Shingles (RAS) | | | | | | | | | |
| Ground Tire Rubber (GTR) | | | | | | | | | |
| Recycled Concrete Aggregate (RCA) | | | | | | | | | |
| Construction Demolition Waste (CDW) | | | | | | | | | |
| Mine Spoil | | | | | | | | | |

| | Potential Application of Recycled, Co-Products, and Waste Materials (RCWMs) as: | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Replacement of coarse aggregate in concrete pavement | | | Replacement of virgin aggregate in roadway base and subbase (unbound | | | Non-structural fill | | |
| | CU | IU | EU | CU | IU | EU | CU | IU | EU |
| Reclaimed Asphalt Pavement (RAP) | | | | | | | | | |
| Recycled Asphalt Shingles (RAS) | | | | | | | | | |
| Ground Tire Rubber (GTR) | | | | | | | | | |
| Recycled Concrete Aggregate (RCA) | | | | | | | | | |
| Construction Demolition Waste (CDW) | | | | | | | | | |
| Mine Spoil | | | | | | | | | |

| | |
|---|---|
| | Indicates No Application |
| | Indicates No Supply Issue |
| | Indicates Supply Issue/ Lack of Material Availability |
| | Indicates Supply Issue in Some Parts of the State |

| | |
|---|---|
| Current Usage (CU) | Indicates that ADOT is currently using the material for the applications shown in the matrix |
| Increased Usage (IU) | Indicates potential opportunity for increased usage for applications shown in the matrix |
| Experimental Usage (EU) | Indicates opportunity for experimental usage for applications shown in the matrix |

The project team adopted a subjective benefit-cost analysis approach because of the following considerations:

- Lack of performance data – There is little to no actual performance data from projects in Arizona for applications using many of the RCWMs, especially at higher dosage levels than is currently accepted. Therefore it is impossible to base anticipated future performance on specific data.
- Fluidity in material cost – The cost of materials has undergone significant changes in recent years. Furthermore, it is not easy to anticipate the introductory (cost of a material when first introduced to the market) or steady-state (once a material becomes accepted as state-of-the-practice) costs of RCWMs that are not currently in the Arizona market.
- Uncertainty in availability – There is considerable uncertainty regarding the current and future availability of many of the RCWMs being considered.

Pavement performance is a function of several interdependent factors of which material quality and performance are just two considerations. In order to conduct a quantitative benefit-cost analysis, data on life-cycle performance and costs are essential. In the absence of detailed performance and cost data, the subjective approach used in this study gives ADOT a starting point to understand the potential risks and benefits when considering the expanded use of these materials. ADOT can then prioritize and pursue the applications that are most feasible and expected to yield maximum benefits in the long-term.

## BENEFIT-COST ANALYSIS

This section describes the scales used to rate: (a) the risk of using each RCWM, (b) the relative cost and performance of each RCWM when compared to conventional materials, (c) the relative environmental and societal impacts of using the RCWM, and (d) the opportunity for ADOT to use each RCWM in pavement applications.

### Risk Analysis Framework

Risk is defined as the "effect of uncertainty on objectives" (ISO 3100: 2009). Though risk management is not a new concept, the adoption of a formalized framework for managing risk in transportation assets in the U.S. has gained popularity only in the last five years with the FHWA publishing a series of documents summarizing the purposes and applications of risk management analysis within the realm of transportation asset management (FHWA 2012b, FHWA 2012c, FHWA 2012d, FHWA 2013a, FHWA 2013b).

For the purposes of this study, acknowledging and understanding the risks associated with a particular type of RCWM as a replacement for a conventional material in highway infrastructure (e.g. asphalt and concrete pavements, embankment, and so on) can help ADOT prioritize the best use for each RCWM. Hence, a simplified subjective risk assessment was conducted as a part of this study, wherein risk ratings (low, medium, and high) were assigned to the likelihood (when using an RCWM in lieu of a conventional material) and the associated consequences (related to economic, environmental, and societal implications) of premature failure to develop an overall risk rating as shown in Table 10.

**Table 10. Risk Rating Framework**

| | | Consequence of Failure | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Likelihood of Premature Failure | Low | Low | Med | High |
| | Medium | Med | Med | High |
| | High | High | High | High |

### Benefit-Cost Analysis Framework

A simplified benefit-cost analysis framework was then used to rate the relative monetary cost and performance of each RCWM considered in this study compared to the conventional material it would replace in accordance with the rating framework shown in Table 11.

**Table 11. Benefit-Cost Analysis Rating Framework**

| | | Relative Cost* | | |
|---|---|---|---|---|
| | | Lower | Comparable | Higher |
| Relative Performance* (In Terms of Pavement Service Life) | Diminished | - | -- | -- |
| | Comparable | ++ | + | + |
| | Better | ++ | ++ | + |

*When compared to pavements constructed using designs and materials as per current state of practice

The ratings "+" and "++" indicate that the material (and its intended application) are expected to have a good to very good benefit-cost ratio whereas ratings of "-" and "--" indicate that the materials have relatively low to very low benefit-cost ratios and hence, are not likely suitable options for ADOT to pursue further.

### Environmental and Societal Impact Analysis Framework

With the growing importance of sustainability within the pavement engineering discipline, it is important to recognize the environmental and societal impacts of using the RCWMs considered in this study. In order to do that, a very simple rating schematic was developed to rate the relative negative environmental and societal impacts (see Table 12). The considerations for environmental impacts include energy use, resource usage, carbon emissions, waste/landfill impacts. Societal considerations can be broadly broken down to include user costs, aesthetics, noise, and safety.

**Table 12. Environmental and Societal Impact Rating Framework**

| | Relative Impact*** | | |
|---|---|---|---|
| | **Lower** | **Comparable** | **Higher** |
| **Negative Environmental Impact*** | | | |
| **Negative Societal Impact**** | | | |

*Environmental impact factors include: energy usage, resource usage, emissions, waste/landfill impact etc.

** Societal factors include: user costs, aesthetics, noise, safety etc.

***Relative impact when compared to conventional materials used in pavement construction

### Potential Opportunity for ADOT

The following three point rating scale was used to rank ADOT's opportunity to increase the use of each RCWM beneficially for various highway applications:

- **Good:** Indicates good potential for immediate increased use by ADOT.
- **Fair:** Indicates that increased use of the material should be considered for limited applications after further investigation on the material availability, quality and performance is conducted.
- **Low:** Indicates that the material is not currently a good candidate (for the application shown) for consideration by ADOT.

### Ratings

Tables 13 through 22 summarize the ratings for risk, relative cost and performance, environmental and societal impacts (using the methodology outlined under Step 2 of the Study Approach); the benefits, advantages, and issues to consider when using each RCWM; and finally, a rating for ADOT's opportunity in using each RCWM beneficially for various applications. Tables 13 through 16 presents RAS, RAP, and GTR scenarios (labelled 1 through 8); Tables 17 through 19 presents RCA applications (labelled 9 through 13); and Tables 20 through 22 presents CDW and mine spoil applications (labelled 14 through 19).

**Table 13. Risk Ratings for RAP, RAS, and GTR Applications**

| S.No | Potential Application of RCWMs | Risk Assessment | | |
|---|---|---|---|---|
| | | Likelihood of Premature Failure | Consequence of Premature Failure | Risk Rating |
| 1 | RAP as replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | Low | Low | Low |
| 2 | RAP a replacement of fine aggregate in HMA/WMA mixtures | Low | Low | Low |
| 3 | RAP as replacement of asphalt binder in HMA/WMA mixtures | Low | Low | Low |
| 4 | RAP as replacement of coarse aggregate in concrete pavement | Medium | Medium | Medium |
| 5 | RAP as replacement of virgin aggregate in roadway base and subbase (unbound layers) | Low | Low | Low |
| 6 | RAP as non-structural fill | Low | Low | Low |
| 7 | RAS and Tar Paper as replacement of asphalt binder in HMA/WMA mixtures | Medium | Medium | Medium |
| 8* | GTR as replacement of asphalt binder in HMA/WMA mixtures | Low | Low | Low |

* For S.No. 8, GTR used in HMA/WMA has resulted in improved mixture performance such as increased resistance to reflective cracking when placed as an overlay over distressed pavement. Some mixtures with GTR, however, have shown to be prone to premature failure with high consequences due to moisture susceptible with regard to stripping of the binder from the mineral aggregate.

**Table 14. Benefit-Cost and Environmental/Societal Impact Ratings for RAP, RAS, and GTR Applications**

| S.No | Potential Application of RCWMs | Benefit-Cost Assessment | | | Environmental and Societal Impacts | |
|---|---|---|---|---|---|---|
| | | Relative Performance | Relative Cost | Benefit-Cost Rating | Negative Environmental Impact | Negative Societal Impact |
| 1 | RAP as replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | Comparable | Lower | ++ | Lower | Comparable |
| 2 | RAP a replacement of fine aggregate in HMA/WMA mixtures | Comparable | Lower | ++ | Lower | Comparable |
| 3 | RAP as replacement of asphalt binder in HMA/WMA mixtures | Comparable | Lower | ++ | Lower | Comparable |
| 4 | RAP as replacement of coarse aggregate in concrete pavement | Comparable | Lower | + | Comparable | Comparable |
| 5 | RAP as replacement of virgin aggregate in roadway base and subbase (unbound layers) | Comparable | Comparable | + | Comparable | Comparable |
| 6 | RAP as non-structural fill | Comparable | Higher | + | Higher | Comparable |
| 7 | RAS and Tar Paper as replacement of asphalt binder in HMA/WMA mixtures | Diminished | Lower | - | Lower | Comparable |
| 8* | GTR as replacement of asphalt binder in HMA/WMA mixtures | Comparable | Lower | ++ | Lower | Lower |

* For S.No. 8, GTR used in HMA/WMA has resulted in improved mixture performance such as increased resistance to reflective cracking when placed as an overlay over distressed pavement. Some mixtures with GTR, however, have shown to be prone to premature failure with high consequences due to moisture susceptible with regard to stripping of the binder from the mineral aggregate.

**Table 15. Benefits, Advantages, Issues to Consider, and ADOT Opportunity to Increase Usage for RAP Applications**

| S.No | Potential Application of RCWMs | Benefits/ Advantages/ Use | Issues to Consider | Opportunity for ADOT |
|---|---|---|---|---|
| 1 | RAP as replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | - Positive environmental and societal impacts.<br>- Lower cost.<br>- Comparable performance with asphalt mixtures using virgin aggregate.<br>- Potential for increased usage in bound base layers.<br>- Improved rutting resistance resulting from higher stiffness. | - Aged binder may not blend with virgin binder.<br>- Residual binder in RAP may not combine with virgin binder to create a composite binder.<br>- Quality and consistency not as good as with virgin aggregate/binder.<br>- Different mix design procedures and requirements.<br>- Durability and cracking issues due to binder stiffening.<br>- Potential issues related to use with polymers (or rubber).<br>- Fractionating RAP is expected to improve consistency, but results in coarse RAP stockpiles.<br>- Performance of RAP in WMA has not been studied extensively. | Good |
| 2 | RAP a replacement of fine aggregate in HMA/WMA mixtures | | | Good |
| 3 | RAP as replacement of asphalt binder in HMA/WMA mixtures | | | Good |
| 4 | RAP as replacement of coarse aggregate in concrete pavement | - Can be used in the lower lift of two-lift concrete pavement.<br>- Positive environmental and societal impacts.<br>- Lower cost if coarse RAP stockpiles exist. | - Issues in determining moisture content of RAP aggregate.<br>- Potential issues due to asphalt coating on RAP aggregates (washing is expected to address this issue partly). | Fair |
| 5 | RAP as replacement of virgin aggregate in roadway base and subbase (unbound layers) | - Can be recycled in-place.<br>- Can use higher levels of replacement.<br>- Positive environmental and societal impacts.<br>- Lower cost. | - Usage in base courses is considered a lower use which does not take full advantage of the existing binder. | Fair |
| 6 | RAP as non-structural fill | - Can use higher levels of replacement. | - Usage in non-structural fills is wasteful as it does not take full advantage of the existing binder. | Low |

**Table 16. Benefits, Advantages, Issues to Consider, and ADOT Opportunity to Increase Usage for RAS and GTR Applications**

| S.No | Potential Application of RCWMs | Benefits/ Advantages/ Use | Issues to Consider | Opportunity for ADOT |
|---|---|---|---|---|
| 7 | RAS and Tar Paper as replacement of asphalt binder in HMA/WMA mixtures | - Reduces virgin binder.<br>- Positive environmental and societal impacts as a waste is being beneficially used.<br>- Lower cost (once established). | - Asbestos fibers in some post-consumer shingles (manufactured into the 1980s).<br>- Unacceptable hardening of the binder, compounded by the hard binder grades used by ADOT.<br>- Currently no supply. Potential supply particularly in alpine locations.<br>- Post-consumer shingles require additional processing to remove nails and impurities. | Fair |
| 8 | GTR as replacement of asphalt binder in HMA/WMA mixtures | - Can be used in chip seals, gap-graded and open-graded mixtures.<br>- Laboratory studies have shown increased cracking resistance.<br>- Terminal blends offer increased opportunities.<br>- WMA technologies in conjunction with GTR application can be considered to improve environmental sustainability and reduce project costs. | - Higher temperatures must be maintained while mixing and storing.<br>- Quality control in the field during construction is key to ensure good performance. | Good |

**Table 17. Risk Ratings for RCA Applications**

| S.No | Potential Application of RCWMs | Risk Assessment | | |
|---|---|---|---|---|
| | | Likelihood of Premature Failure | Consequence of Premature Failure | Risk Rating |
| 9 | RCA as partial replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | Low | Medium | Medium |
| 10 | RCA a replacement of fine aggregate in HMA/WMA mixtures | Medium | Medium | Medium |
| 11 | RCA as replacement of coarse aggregate in concrete (e.g. non-structural applications, pavement) | Low | Medium | Medium |
| 12 | RCA as replacement of virgin aggregate in roadway base and subbase (unbound layers) | Low | Low | Low |
| 13 | RCA as non-structural fill | Low | Low | Low |

**Table 18. Benefit-Cost and Environmental/Societal Impact Ratings for RCA Applications**

| S.No | Potential Application of RCWMs | Benefit-Cost Assessment | | | Environmental and Societal Impacts | |
|---|---|---|---|---|---|---|
| | | Relative Performance | Relative Cost | Benefit-Cost Rating | Negative Environmental Impact | Negative Societal Impact |
| 9 | RCA as partial replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | Comparable | Comparable | + | Lower | Comparable |
| 10 | RCA a replacement of fine aggregate in HMA/WMA mixtures | Diminished | Comparable | -- | Lower | Comparable |
| 11 | RCA as replacement of coarse aggregate in concrete (e.g. non-structural applications, pavement) | Comparable | Comparable | + | Lower | Comparable |
| 12 | RCA as replacement of virgin aggregate in roadway base and subbase (unbound layers) | Comparable | Comparable | + | Lower | Comparable |
| 13 | RCA as non-structural fill | Comparable | Higher | + | Lower | Comparable |

Table 19. Benefits, Advantages, Issues to Consider, and ADOT Opportunity Rating for RCA Applications

| S.No | Potential Application of RCWMs | Benefits/ Advantages/ Use | Issues to Consider | Opportunity for ADOT |
|---|---|---|---|---|
| 9 | RCA as partial replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | - Potential usage in low-volume roads.<br>- May reduce stripping.<br>- Can be used in bound base layers.<br>- Positive environmental and societal impacts. | - Absorption issues resulting in increased asphalt binder demand.<br>- Deleterious materials should be limited as they decrease quality.<br>- Supply issues in some parts of the state. | Fair |
| 10 | RCA a replacement of fine aggregate in HMA/WMA mixtures | - Potential use as filler material.<br>- May reduce stripping. | - Will increase the need for asphalt cement to achieve desired material properties, potentially increasing cost. | Low |
| 11 | RCA as replacement of coarse aggregate in concrete (e.g. non-structural applications, pavement) | - Potential usage in lower-lift of two lift concrete pavements, other non-structural applications.<br>- Positive environmental and societal impacts. | - Potential reduction in concrete strength.<br>- Increased shrinkage which could potentially accelerate tendency for early age cracking.<br>- Material quality variability.<br>- Supply issues in some parts of the state.<br>- Increase in need for QC/QA testing. | Fair |
| 12 | RCA as replacement of virgin aggregate in roadway base and subbase (unbound layers) | - Decrease cement requirement when used as cement-stabilized layer.<br>- Positive environmental and societal impacts.<br>- Potential for in-place recycling. | - Migration of leachates and fines into drainage pipes (can be mitigated through cement or asphalt stabilization).<br>- Absorptive nature of RCA significantly increases asphalt binder demand and costs when asphalt stabilization is used.<br>- Supply issues in some parts of the state. | Good |
| 13 | RCA as non-structural fill | - Positive environmental and societal impacts. | - Supply issues in some parts of the state. | Fair |

**Table 20. Risk Ratings for CDW and Mine Spoil Applications**

| S.No | Potential Application of RCWMs | Risk Assessment | | |
|---|---|---|---|---|
| | | Likelihood of Premature Failure | Consequence of Premature Failure | Risk Rating |
| 14 | CDW as non-structural fill | Low | Low | Low |
| 15 | Mine Spoil as replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | Low | Low | Low |
| 16 | Mine Spoil as replacement of coarse aggregate in concrete pavement | Low | Low | Low |
| 17 | Mine Spoil a replacement of fine aggregate in HMA/WMA mixtures | Low | Low | Low |
| 18 | Mine Spoil as replacement of virgin aggregate in roadway base and subbase (unbound layers) | Low | Low | Low |
| 19 | Mine Spoil as non-structural fill | Low | Low | Low |

**Table 21. Benefit-Cost and Environmental/Societal Impact Ratings for CDW and Mine Spoil Applications**

| S.No | Potential Application of RCWMs | Benefit-Cost Assessment | | | Environmental and Societal | |
|---|---|---|---|---|---|---|
| | | Relative Performance | Relative Cost | Benefit-Cost Rating | Negative Environmental Impact | Negative Societal Impact |
| 14 | CDW as non-structural fill | Comparable | Comparable | + | Lower | Comparable |
| 15 | Mine Spoil as replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | Comparable | Lower | ++ | Lower | Comparable |
| 16 | Mine Spoil as replacement of coarse aggregate in concrete pavement | Comparable | Lower | ++ | Lower | Comparable |
| 17 | Mine Spoil a replacement of fine aggregate in HMA/WMA mixtures | Comparable | Lower | ++ | Lower | Comparable |
| 18 | Mine Spoil as replacement of virgin aggregate in roadway base and subbase (unbound layers) | Comparable | Lower | ++ | Lower | Comparable |
| 19 | Mine Spoil as non-structural fill | Comparable | Lower | ++ | Lower | Comparable |

**Table 22. Benefits, Advantages, Issues to Consider, and ADOT Opportunity Rating for CDW and Mine Spoil Applications**

| S.No | Potential Application of RCWMs | Benefits/ Advantages/ Use | Issues to Consider | Opportunity for ADOT |
|---|---|---|---|---|
| 14 | CDW as non-structural fill | - Use in non-structural applications does not require rigorous quality control.<br>- Helps reduce landfill and improve environmental sustainability.<br>- Reduction in availability of virgin materials is likely to improve utilization of CDW in non-structural fill applications in the future. | - Lack of recycling facilities.<br>- Lack of standards and specifications.<br>- Low cost of dumping.<br>- Lack of supply in rural areas.<br>- Lack of a stable market.<br>- Lack of government support and awareness.<br>- Lack of understanding of detrimental environmental impacts.<br>- Contamination issues. | Fair |
| 15 | Mine Spoil as replacement of coarse aggregate in asphalt concrete (HMA/WMA) pavement | - Potential for use in highway embankment and fill applications.<br>- Despite fine size of some sources, these materials can be blended with coarse materials such as gravel, to bring overall fines content to acceptable range or be classified prior to initial disposal to recover coarser fractions for possible use.<br>- Some sources have properties similar to natural aggregate deposits. These can be used if they meet applicable specifications. | - Limited potential application for some sources due to fineness and impurity content, trace metal leachability, and propensity for acid generation. These must not be used.<br>- Must meet existing specifications.<br>- Availability issues (for high quality material).<br>- Application in paving concrete has not been well documented, hence performance is uncertain. | Fair |
| 16 | Mine Spoil as replacement of coarse aggregate in concrete pavement | | | Fair |
| 17 | Mine Spoil a replacement of fine aggregate in HMA/WMA mixtures | | | Fair |
| 18 | Mine Spoil as replacement of virgin aggregate in roadway base and subbase (unbound layers) | - Potential application for use in highway embankments, stabilized roadway bases.<br>- When burnt, coal refuse (called "red dog") can be used as unbound aggregate in shoulders and minor roads..<br>- Use in non-structural applications does not require rigorous quality control. | - Lack of specifications.<br>- Metal leaching potential can be a cause for environmental concern and should be thoroughly investigated prior to embankment use.<br>- Availability issues can be an impediment for use. | Fair |
| 19 | Mine Spoil as non-structural fill | | | Fair |

## SUMMARY

Based on this analysis, some clear direction has emerged on how ADOT can prioritize the potential use of RCWMs in suitable highway applications based on material cost and availability. The applications discussed in the final chapter are presented as implementable opportunities that can be considered with little additional need for research (i.e., the RCWMs can be utilized in demonstration projects) and those opportunities that may offer potential after additional research is conducted.

# CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This study focused on the use of industrial waste (asphalt millings, asphalt roof shingles and tar paper, rubber tires, refuse concrete, brick, mine spoils, etc.), referred to as recycled, co-product, and waste materials (RCWMs), as resources for constructing transportation infrastructure in Arizona. Specific materials that were considered included:

- RAP as a partial replacement for asphalt binder and virgin aggregate in asphalt mixtures and for other applications (e.g. base, subbase, fill, and so on).
- RAS and tar paper as a partial replacement for asphalt binder in asphalt mixtures.
- GTR as an addition in asphalt mixtures to create rubberized asphalt or as a binder modifier to create asphalt-rubber.
- RCA from existing concrete structures (e.g. pavements, barrier walls, and so on) for use as aggregate in new concrete or as base/subbase material.
- CDW, including refuse concrete, bricks and masonry, to be crushed and used as aggregate in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill.
- Mine spoil as aggregate in asphalt mixtures, concrete, roadway base and subbase, or as non-structural fill.

The potential sustainability benefits associated with the use of these materials are many, including the preservation of natural resources, the reduced environmental impacts associated with both the production of new materials and the disposal of the RCWM (often expressed in terms of greenhouse gas emissions and energy consumption), and cost savings achieved by incorporating the recycled material. Such benefits can only be realized, however, if the materials perform in a manner comparable to conventional materials.

## RECOMMENDATIONS

This study thoroughly reviewed existing information and surveys to assess the potential sources of RCWM that may offer a potential for use in the construction of transportation structures in Arizona. Based on this analysis, the following applications are presented as implementable opportunities that can be considered immediately with little additional need for research (i.e., the RCWMs can be utilized in demonstration projects) and those that may offer potential after additional research is conducted:

*Immediate Opportunities*

- Target slight increases in RAP replacement level (up to 25 percent or more) in asphalt concrete (HMA/WMA) pavement, especially in asphalt concrete base and binder levels.
- Increase the use of RAP in unbound roadway base and subbase, especially for in-place recycling.
- Increase the use of GTR as replacement of asphalt binder in HMA/WMA mixtures through the use of terminal blend binders.
- Increase the use of RCA as replacement of virgin aggregate in roadway base and subbase (unbound layers) applications, especially for in-place recycling.

*Mid-Term Opportunities*

- Investigate significantly increasing RAP replacement level (30 percent or greater) in lower lifts of asphalt concrete (HMA/WMA) pavement.
- Investigate RCA and potentially coarse-fractionated RAP as a partial replacement of coarse aggregate in highway concrete, especially for non-structural applications and some pavements.
- Facilitate the use of CDW in transportation applications through a coordinated effort between ADOT, local agencies, contractors, and waste haulers/landfill operators to establish source control and a market for the use of CDW.
- Conduct research to improve the performance of RCWMs identified as having comparable or diminished performance to reduce the risk associated with their use and make them more cost-effective.

The use of RCWMs, as discussed here, provides an opportunity for the transportation construction industry within Arizona to have an overall beneficial effect in terms of the environment, societal impacts, and construction costs without diminishing performance of transportation infrastructure (and in some cases even improving the performance). However, with the inherent variability and reduced understanding that is introduced with the inclusion and increased use of RCWMs in construction, and the need to identify, mitigate and/or prevent potential adverse effects as identified, there should be a continued effort to study and quantify the associated benefits and costs so that the net benefit of using each particular RCWM can be better understood.

As Arizona's transportation network continues to age, the rehabilitation and reconstruction of existing facilities will become more critical. In order to capitalize on the use of RCWMs in the future, effort should be made now to ensure that their full benefits are recognized and can be fully leveraged prior to the impending need. Otherwise the reconstruction of transportation infrastructure will not be able to fully utilize the mass quantities of RCWMs generated through the demolition of the existing infrastructure.

*Long-Term Opportunities*

This project represents an initial effort to evaluate opportunities that exist for ADOT to increase the utilization of RCWMs in transportation infrastructure. The following is a list of recommended actions to support the continued use of RCWMs in Arizona:

- Re-evaluate existing construction specifications to identify barriers to the use of RCWMs, then modify specifications as appropriate to become more accommodating when technically sound.
- Collaborate with materials suppliers and contractors to identify potential barriers to the use of RCWMs and develop and execute research to support greater use.
- Conduct training and technology transfer activities within Arizona on best practices for using RCWMs.
- Construct and monitor test sections designed to investigate the performance of RCWMs. Establish a rigorous monitoring and reporting program to collect and disseminate the results.

- Work with ADOT’s pavement management system to identify future facilities that are scheduled for reconstruction, and develop plans for incorporating into the reconstruction those materials recovered during demolition. Much of original ADOT interstate system in the Phoenix area is concrete pavement, so should work begin now on investigating ways to incorporate RCA into future applications.
- Develop a database to track materials usage, supply and demand, including RCWMs. This database can be tied to pavement performance, possibly through ADOT’s pavement management system in an effort to link materials (particularly RCWMs) to performance in future studies.
- Adopt techniques to begin quantifying environmental impacts using a more structured approach such as environmental life cycle assessment. This could be tied to the database development effort discussed in the previous bullet to provide inventory data on commonly used materials.
- Develop a framework for a systematic, quantitative approach to consider costs and benefits of using RCWMs. This may include both environmental life cycle assessment and economic life cycle cost analysis.
- Work to understand sustainability benefits and how they are quantified. Consider benchmarking current practices.

## REFERENCES


American Concrete Pavement Association (ACPA). 2008. “Subgrade and Subbases for Concrete Pavements.” Engineering Bulletin 204P. American Concrete Paving Association, Skokie, IL.

American Concrete Pavement Association (ACPA). 2009. “Recycling Concrete Pavements.” Engineering Bulletin 043P. American Concrete Paving Association, Skokie, IL.

Al-Qadi, I.L., M. Elseifi, and S.H. Carpenter. 2007. *Reclaimed Asphalt Pavement – A Literature Review*. Research Report FHWA-ICT-07-001. Illinois Center for Transportation. Urbana, Illinois.

Al-Qadi, I.L., Q. Aurangzeb, S.H. Carpenter, W. Pine, and J. Trepanier. 2012. *Impact of High RAP Content on Structural and Performance Properties of Asphalt Mixtures*. Research Report FHWA-ICT-12-002, Illinois Center for Transportation. Urbana, Illinois.

Arizona Department of Transportation (ADOT). 2008. *Standard Specifications for Road and Bridge Construction.* Phoenix, AZ. http://www.azdot.gov/docs/business/2008-standards-specifications-for-road-and-bridge-construction.pdf?sfvrsn=0.

Arizona Department of Transportation (ADOT). 2010. *Policy and Procedure Directive PPD No. 20 – Guidance on the Use of Reclaimed Asphalt Pavement (RAP) in Asphaltic Concrete.* Phoenix, AZ. A[ril 14. http://www.azdot.gov/docs/default-source/businesslibraries/no-20.pdf?sfvrsn=21.

Arizona Department of Transportation (ADOT). 2013. *Specifications for Preparing ADOT Research Reports.* Arizona Department of Transportation Research Center. Phoenix, AZ. https://apps.azdot.gov/files/ADOTLibrary/Publications/Writing_Specifications/Research_Ctr_Writing_Specs-1311.pdf.

Arizona Department of Transportation (ADOT). 2014. “Quiet Pavement Program.” ADOT Website. http://www.azdot.gov/business/environmental-services-and-planning/programs/quiet-pavement-program Accessed, March 2014.

Arizona Department of Transportation (ADOT). 2016a. *Contracts and Specifications.* Web site accessed January 25, 2016. http://www.azdot.gov/business/ContractsandSpecifications/Specifications.

Arizona Department of Transportation (ADOT). 2016b. *ADOT Construction Manual: Chapter 4.* Website accessed January 26, 2016. http://www.azdot.gov/docs/default-source/businesslibraries/CMchapter-4.pdf?sfvrsn=8.

Asphalt Roofing Shingles Recycling (ARSR). 2012. “Why Homeowners Should Choose Asphalt Roofing Shingles Recycling.” http://www.roofingshinglerecycling.com/. October 18.

Bauman, A. 2005. “Asphalt Shingle Recycling in Massachusetts.” http://www.greengoat.org/pdf/asphalt.pdf. March 15.

Bonaquest, R. 2005. *New Approach for the Design of High RAP HMA*, Presented at 2005 Northeast Asphalt User/Producer Group Meeting, Burlington, Vt., Oct. 19–20.

Bennert, T. and A. Maher. 2005. *The Development of a Performance Specification for Granular Base and Subbase Material.* Report FHWA-NJ-2005-003. New Jersey Depart of Transportation. Trenton, NJ.

Bennert, T. and A. Maher. 2008. *The Use of Recycled Concrete Aggregate in a Dense Grade Aggregate Base Course.* Report FHWA-NJ-2008-002. New Jersey Depart of Transportation. Trenton, NJ.

Bennert, T. and R. Dongre. 2010. "Backcalculation Method to Determine Effective Asphalt Binder Properties of Recycled Asphalt Pavement Mixtures," *Transportation Research Record 2179*, Transportation Research Board, Washington, D.C. pp. 75–84.

Button, J.W., D. Williams, and J. Scherocman. 1996. *Roofing Shingles and Toner in Asphalt Mixtures.* Research Report 1344-2F. Texas Transportation Institute. College Station, Texas.

Cable, J.K., and D.P. Frentress. 2004. "Two Lift Portland Cement Concrete Pavements to Meet Public Needs." Report DTF61-01-X-00042. Center for Transportation Research and Education. Ames, IA.

California Department of Transportation (Caltrans). 2006. *Asphalt Rubber Usage Guide*. Caltrans, Office of Flexible Pavement Materials. Sacramento, CA.

California Department of Transportation (Caltrans). 2010. "Standard Specifications." Caltrans, Publication Distribution Unit. Sacramento, CA.

California Department of Transportation (Caltrans). 2012. *Highway Design Manual*. Sacramento, CA.

California Department of Transportation (Caltrans). 2015. *Standard Specifications.* State of California. California State Transportation Agency. Department of Transportation. Sacramento, CA. http://www.dot.ca.gov/hq/esc/oe/construction_contract_standards/std_specs/2015_StdSpecs/2015_StdSpecs.pdf.

California Department of Transportation (Caltrans). 2016a. *Standard Specification for Use of Recycled Asphalt Shingle as an Additive in Hot Mix Asphalt.* Website accessed January 25, 2016. http://www.dot.ca.gov/hq/maint/Pavement/RPC/Task_Groups/PDF/ATG_STG_RAP-RAS_2013-06-24_Handout_Standard_Spec_RAS.pdf.

California Department of Transportation (Caltrans). 2016b. *R-2005A TS-2c – Standard Recommended Practice for Design Considerations when using Recycled Asphalt Shingles in New Hot Mix Asphalt.* Website accessed January 25, 2016. http://www.crushcrete.com/pdf/Considerations_shingles_hot-mix.pdf.

Cleary, D.B. 2013. *Recycled Concrete Aggregate in Portland Cement Concrete.* Report FHWA-NJ-2013-001. Rowan University. Glassboro, NJ.

Clyne, T.R., E. Johnson, and B. Worel. 2010. *Use of Taconite Aggregates in Pavement Applications.* Report No. MN/RC-2010-24. National Technical Information Services. Springfield, VA.

Collins R. J. and S. K. Ciesielski. 1994. Recycling and Use of Waste Materials and By-Products in Highway Construction. National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 199, Transportation Research Board, Washington, D.C.

Colorado Department of Transportation (CDOT). 2011. *2011 Construction Specifications.* Denver, CO. https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs.

Colorado Department of Transportation (CDOT). 2012. *Revision of Section 401 – Reclaimed Asphalt Shingles.* Denver, CO. April 26. https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/recently-issued-special-provisions/2012-04-26/401-reclaimed-asphalt-shingles/view.

Colorado Department of Transportation (CDOT). 2013A. *Revision of Section 401 – Reclaimed Asphalt Shingles.* Denver, CO. May 2. http://www.dot.ca.gov/hq/construc/CPDirectives/SSP39-010_Asphalt_Concrete.pdf.

Colorado Department of Transportation (CDOT). 2013b. *Revision of Sections 304 and 703 – Aggregate Base Course (RAP).* Denver, CO. October 31. https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/standard-special-provisions/sections-200-500-revisions/304abcr.doc/view.

Construction & Demolition Recycling Assoication (CDRA). 2016. *Good Economic Sense*. Website Accessed January 25, 2016. http://www.cdrecycling.org/concrete-recycling.

Construction & Demolition Recycling Assoication (CDRA). 2016. Website Accessed January 25, 2016. http://www.cdrecycling.org/.

Cook, M.C., T. Bressette, S. Holikatti, H. Zhou, and R.G. Hicks. 2006. “Laboratory Evaluation of Asphalt Rubber Modified Mixes.” Paper presented at the Asphalt Rubber 2006 Conference. Palm Springs, CA.

Copeland, A. 2011. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice.* FHWA-HRT-11-021. Federal Highway Administration. Washington, D.C.

Cuttell, G.D., Snyder, M.B., Vandenbossche, J.M., and Wade, M.J. 1997. “Performance of Rigid Pavements Containing Recycled Concrete Aggregate.” *Transportation Research Record 1574*. National Academy of Science. Washington, DC.

Edil, T.B., J. Tinjum, and C. Benson. 2012. *Recycled Unbound Materials.* Report MN/RC 2012-35. Madison, WI.

Environmental Protection Agency (EPA). 1985. *Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale*. December 1985 Report to Congress. Washington D.C.

Environmental Protection Agency (EPA). 2012. “Mining Waste.” Environmental Protection Agency, Washington, D.C. http://www.epa.gov/waste/nonhaz/industrial/special/mining/index.htm. Accessed March 2014.

Environmental Protection Agency (EPA). 2013a. *Analysis of Recycling of Asphalt Shingles in Pavement Mixes from a Life Cycle Perspective*. EPW07020. Environmental Protection Agency, Washington, D.C. (http://www2.epa.gov/region8/analysis-recycling-asphalt-shingles-pavement-mixes-life-cycle-perspective).

Environmental Protection Agency (EPA). 2013b. "Wastes - Resource Conservation - Common Wastes & Materials - Scrap Tires." Environmental Protection Agency, Washington, D.C. http://www.epa.gov/epawaste/conserve/materials/tires/markets.htm

Epps, J.A. 1994. *Uses of Recycled Rubber Tires in Highways.* NCHRP Synthesis of Highway Practice No. 198, Transportation Research Board, Washington, D.C.

Federal Highway Administration (FHWA). 1995. *Crumb Rubber Modifier (CRM) in Asphalt Pavement*. Report No. FHWA-SA-95-056. Washington, D.C.

Federal Highway Administration (FHWA). 2004. *Transportation Applications of Recycled Concrete Aggregate – FHWA State of the Practice National Review.* US DOT. Washington, D.C. September. https://www.fhwa.dot.gov/pavement/recycling/applications.pdf.

Federal Highway Administration (FHWA). 2007a. Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement. Technical Advisory T5040.37. Federal Highway Administration, Washington, D.C.

Federal Highway Administration (FHWA). 2007b. *Take a Look at Two-Lift Concrete Paving*. Report FHWA-HRT-07-016. Focus: Accelerating Infrastructure Innovations. Federal Highway Administration, Washington, D.C.

Federal Highway Administration (FHWA). 2012a. *User Guidelines for Waste and Byproduct Materials in Pavement Construction.* Report FHWA-RD-97-148. Washington, D.C. April. Accessed from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/index.cfm February 2014.

Federal Highway Administration (FHWA). 2012b. *Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities. Report 1: Overview of Risk Management.* FHWA-HIF-12-035. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2012c. *Risk-Based Transportation Asset Management: Examining Risk-based Approaches to Transportation Asset Management. Report 2: Managing asset risks at Multiple levels in a transportation agency.* FHWA-HIF-12-050. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2012d. *Risk-Based Transportation Asset Management: Achieving Policy Objectives by Managing Risks. Report 3: Risks to Asset Management Policies.* FHWA-HIF-12-054. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2013a. *Risk-Based Transportation Asset Management: Managing Risks to Networks, Corridors, and Critical Structures. Report 4: Managing Risks to Critical Assets.* FHWA-HIF-13-017. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2013b. *Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets. Report 5: Managing External Threats Through Risk-Based Asset Management.* FHWA-HIF-13-018. Federal Highway Administration, Washington, DC.

Gibson, N., X. Qi, A. Shenoy, G. Al-Khateeb, M. Kutay, A. Andriescu, K. Stuart, J. Youtcheff and T. Harman. 2012. *Performance Testing for Superpave and Structural Validation.* Publication FHWA-HRT-11-045. Washington D.C.: Federal Highway Administration: 2002.

Gopal, V., P. Sebaaly, and K. Troy. 1997. *Characterization of CRM Binders and Mixtures Used in Nevada.* Nevada DOT. Carson City, NV.

Guthrie, W.S., S. Sebesta and T. Scullion. 2002. "Selecting Optimum Cement Contents for Stabilizing Aggregate Base Materials." Report FHWA/TX-05/7-4920-2. Texas Transportation Institute. College Station, TX.

Hansen, K.R., and A. Copeland. 2014. *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009-2013.* Information Series 138. Lanham, MD. October. https://www.asphaltpavement.org/PDFs/IS138/IS138-2013_RAP-RAS-WMA_Survey_Final.pdf

Hajj, E., P. Sebaaly, E. Hitti, and C. Borroel. 2011. "Performance of Evaluation of Terminal Blend Tire Rubber Asphalt Mixtures – Case Studies." *Journal of the Association of Asphalt Paving Technologies.* Lino Lakes, MN.

Hicks, R.G., D. Cheng, and T. Teesdale. 2010. "Assessment of Warm Mix Technologies for Use with Asphalt Rubber Paving Applications." Report No: CP2C-2010-103TM. California Pavement Preservation Center. Chico, California.

Hiller, J. E., Y. S. Deshpande, Y. Qin, and C. J. Shorkey. 2011. "Efficient Use of Recycled Concrete in Transportation Infrastructure." Report RC-1544 Michigan Technological University, Houghton, MI.

Holikatti, S., H. Zhou, P. Vacura. 2012. "Seven Year Itch—Evaluation of Caltrans Full Scale Experiment on Asphalt Rubber Modified Pavements." Asphalt Rubber 2012 Conference. Munich, Germany.

Illinois Department of Transportation (IDOT). 2013. *Use of Reclaimed Asphalt Shingles in Illinois.* 2nd Edition. Physical Research Report No. 163. Illinois DOT. Springfield, IL. August.

Illinois Interchange. 2*012. Recycling/Reclaiming a Savings Spree*. Illinois Department of Transportation, Springfield, IL. (http://www.asphaltpavement.org/PDFs/IS138/IS138-2012_RAP-RAS-WMA_Survey_Final.pdf).

Illinois Tollway. 2014*. Building Green*. http://www.illinoistollway.com/construction-and-planning/environmental-initiatives/building-green-roadways Accessed March 2014.

International Organization for standardization (ISO). 2009. Risk Management—Principles and guidelines, ISO 3100:2009, International Organization for Standardization, Geneva, Switzerland.

Jones, D., J. Harvey, and C. Monismith. 2007. Reflective Cracking Study: A Summary Report. FHWA Report No: CA091073N. University of California Pavement Research Center. Davis, CA

Jones, D., R. Wu, B.W. Tsai, and J. Harvey. 2011a. "Warm-Mix Asphalt Study: Test Track Construction and First Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1)." FHWA Report No: CA132221A. University of California Pavement Research Center. Davis, CA

Jones, D., R. Wu, B.W. Tsai, and J. Harvey. 2011b. "Warm-Mix Asphalt Study: Test Track Construction and First Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2)." FHWA Report No: CA132221B. University of California Pavement Research Center. Davis, CA

Lane, L., R. Hicks, D. Cheng, and V. Sinha. 2011. "City of Stockton Terminal Blend Project with Warm Mix Additive." California Pavement Preservation Center. Chico, CA.

Lim, S., D. Kestner, D.G. Zollinger and D.W. Fowler. 2003. "Characterization of Crushed Concrete Materials for Paving and Non-Paving Applications." Report No TX-04/7-4954-1. Texas Transportation Institute and Center for Transportation Research. Austin, TX.

Ma, T., E. Mahmoud, and H. U. Bahia. 2010. "Estimation of Reclaimed Asphalt Pavement Binder Low-Temperature Properties Without Extraction: Development of Testing Procedure," *Transportation Research Record 2179*, Transportation Research Board, Washington, D.C. pp. 58–65.

McCarty, Nye. 2015. Personal correspondence in reviewing Chapter 2.

Michigan Department of Transportation (MDOT). 2012. 2012 Standard Specifications for Construction. Lansing, MI. http://mdotcf.state.mi.us/public/specbook/2012/.

Mills-Beale, J. and Z. You. 2010. "The Mechanical Properties of Asphalt Mixtures with Recycled Concrete Aggregates." Construction and Building Materials, Volume 24, Issue No. 3. Elsevier Ltd.

NAHB Research Center. 1998. *From Roofs to Roads – Recycling Asphalt Roofing Shingles into Paving Materials*. Upper Marlboro, MD. Produced under cooperative agreement with the U.S. Environmental Protection Agency. http://www3.epa.gov/epawaste/conserve/imr/cdm/pubs/roof_br.pdf.

National Asphalt Pavement Association (NAPA). 2009. *How to Increase RAP Usage and Ensure Pavement Performance.* National Asphalt Pavement Association. Lanham, MD.

National Center for Asphalt Technology (NCAT). 2009. "LTPP Data Shows RAP Mixes Perform as Well as Virgin Mixes," *Asphalt Technology News*, *21*, 2, National Center for Asphalt Technology. Auburn, AL.

National Cooperative Highway Research Program (NCHRP). 2000. *Waste and Recycled Materials in the Transportation Industry*. NCHRP 4-21 Information Database, Version 1.0.8. NCHRP. Washington, DC.

Nevada Department of Transportation (NDOT). 2012. *Northbound 395 Project (Reno) Named West's Best Ahead-of-Schedule Road Project.* Website accessed January 26, 2016. *http://www.nevadadot.com/News/Press_Releases/2012/Northbound_395_Project_%28Reno%29_Named_West_s_Best_Ahead-of-Schedule_Road_Project.aspx.*

Nevada Department of Transportation (NDOT). 2014. *Standard Specifications for Road and Bridge Construction.* Carson City, NV. https://www.nevadadot.com/uploadedFiles/NDOT/About_NDOT/NDOT_Divisions/Engineering/Specifications/2014,%20Standard%20Specifications%20for%20Road%20and%20Bridge%20Construction.pdf.

New Mexico Department of Transportation (NMDOT). 2014. *Standard Specifications for Highway and Bridge Construction. http://www.dot.state.nm.us/content/dam/nmdot/Plans_Specs_Estimates/2014_Specs_For_Highway_And_Bridge_Construction.pdf.*

Perez, I., A.R. Pasandin, and J. Gallego. 2010. "Impact of Construction and Demolition Waste Aggregates on Stripping in Hot Mix Asphalt." Compendium of Papers. TRB 2010 Annual Meeting CD-ROM. Transportation Research Board. Washington DC. January 10-14.

Puccinelli, J., S. Karamihas, K. Hall, and K. Senn. 2013. "Performance Evaluation of Arizona's LTPP SPS-6 Project: Strategic Study of Rehabilitation Techniques." Report FHWA-AZ-13-396(6). Nichols Consulting Engineers and University of Michigan Transportation Research Institute. Phoenix, AZ.

RMI. 2014. *In-Place PCC Recycling*. Website. http://www.resonantmachines.com/InPlaceRecycling/tabid/454/Default.aspx. Accessed April 18, 2014.

Recycled Materials Resource Center (RMRC). 2008. User Guidelines for Byproduct & Secondary Use Materials in Pavement Construction, University of Wisconsin–Madison. Madison, WI. http://rmrc.wisc.edu/ug-materials/

Recycled Materials Resource Center. 2016. Website accessed January 25, 2016. http://rmrc.wisc.edu/.

Roesler, J.R., J.G. Huntley. 2009. *Performance of I-57 Recycled Concrete Pavements*. Research Report FHWA-ICT-09-032, Illinois Center for Transportation. Urbana, Illinois.

Rubber Manufacturers Association (RMA). 2014. *2013 U.S. Scrap Tire Management Summary.* Rubber Manufacturers Association. Washington, DC. November. http://www.rma.org/download/scrap-tires/market-reports/US_STMarket2013.pdf.

Sainz, F.A., A. Rodriguez, A. Munoz, A. Galvin, J. Romero. 2012. Real Application of Cement Treated Mixed Recycled Aggregates on Road Bases in Malaga, Spain. 2012 Transportation Research Board Annual Meeting.

Shingle Recycling. 2016. *Illinois Shingle Recyclers*. Website. http://www.shinglerecycling.org/content/illinois-shingle-recyclers. Accessed January 25, 2016.

Stroup-Gardiner, M., T. Wattenberg-Komas. 2013. *Recycled Materials and Byproducts in Highway Applications – Mineral and Quarry Byproducts.* Volume 4. NCHRP Synthesis 435. Transportation Research Board. Washington, D.C. http://www.trb.org/Publications/Blurbs/169147.aspx.

Shuler, S. 2011. *Use of Waste Tires (Crumb Rubber) on Colorado Highways.* Report No. CDOT-2011-4. Interim Report. Colorado Department of Transportation. Denver, CO.

Sultan, H. A. 1979."Stabilized Copper Mill Tailings for Highway Construction." *Transportation Research Record: Journal of the Transportation Research Board* 734. Washington, D.C.

Texas Department of Transportation (TxDOT). 2014. *Standard Specifications for Constructions and Maintenance of Highways, Streets and Bridges.* Austin, TX. http://www.txdot.gov/business/resources/txdot-specifications.html.

Utah Department of Transportation (UDOT). 2003. *Technical Bulletin MT-03.06.* Salt Lake City, UT. October 21. https://www.udot.utah.gov/main/uconowner.gf?n=200511230848151. Accessed April 18, 2014.

Utah Department of Transportation (UDOT). 2012. *2012 Standard Specifications for Road and Bridge Construction.* Salt Lake City, UT. http://www.udot.utah.gov/main/uconowner.gf?n=7569028183854784.

Van Dam, T., K. Smith, C. Truschke, S. Vitton. 2011. "Using Recycled Concrete in MDOT's Transportation Infrastructure – Manual of Practice." Report RC-1544. Michigan Tech University. Houghton, MI.

Van Dam, T.J., J.T. Harvey, S.T. Muench, K.D. Smith, M.B. Snyder, I.L. Al-Qadi, H. Ozer, J. Meijer, P.V. Ram, J.R. Roesler, and A. Kendall. 2015. *Towards Sustainable Pavement Systems: A Reference Manual.* FHWA-HIF-15-002. Federal Highway Administration. Washington, D.C. January. https://www.fhwa.dot.gov/pavement/sustainability/hif15002/chapters/hif15002_00b.pdf.

Vargas-Nordcbeck, A. and D. Timm. 2013. *Physical and Structural Characterization of Sustainable Asphalt Pavement Sections at the NCAT Test Track.* NCAT Report 13-02 National Center for Asphalt Technology. Auburn, AL.

Vavrik, W.R., Huber, G., Pine, W.J., Carpenter, S.H., and Bailey, R. 2002*. Bailey Method for Gradation Selection in HMA Design.* TRB E-Circular E-C 044. Transportation Research Board, Washington, DC.

Wasiuddin N.M., W. Hamid, M. Zama, and R. Nairn. 2006. "Use of Raw Chat in HMA Surface: Environmental and Engineering Characterization." TRB 2007 Annual Meeting CD-ROM.

Way, G. 2012. "History of Asphalt Rubber in Arizona." Presentation given at 2012 Arizona Pavements/ Materials Conference. Tempe, Arizona 2012.

West, R., J.R. Willis, M. Marasteanu. 2013. *Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content.* NCHRP Report 752. Transportation Research Board. Washington, D.C.

Williams, R. Christopher, A. Cascione, J. Yu, D. Haugen, M. Marasteanu, and J. McGraw. 2013. *Performance of Recycled Asphalt Shingles in Hot Mix Asphalt.* Research Report TPF-5(213). Institute for Transportation. Ames, Iowa.

Yohem, R. 2011. "Recycled Mine Tailings Could Be Used to Build Roads, UA Researcher Finds." Inside Tucson Business. Retrieved from [http://www.insidetucsonbusiness.com/news/recycled-mine-tailings-could-be-used-to-build-roads-ua/article_113dfa26-71d8-11e0-8464-001cc4c002e0.html] March 2014.

Zhang, L. 2012. "Complete Recycling and Utilization of Waste Concrete Through Geopolymerization." C&D World 5(3): 30-34.

Zhou, F., S. Hu, G. Das, and T. Scullion. 2011. *High RAP Mixes Design Methodology with Balanced Performance*. Research Report FHWA/TX-11/0-6092-2. Texas Transportation Institute. College Station, Texas.