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TRANSPORTATION RESEARCH SYNTHESIS

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Recycled Materials in Unbound Aggregate Base Layers in Minnesota

The purpose of this TRS is to serve as a synthesis of pertinent completed research to be used for further study and evaluation by MnDOT and the Local Road Research Board. This TRS does not represent the conclusions of MSU Mankato, MnDOT or LRRB.

Introduction

The purpose of this Transportation Research Synthesis (TRS) is to provide an overview about the use of recycled materials in the base layers of pavements, and the design of these layers when using recycled materials. While the primary focus is on local streets and county roads, attention was also given to pavements constructed by state highway agencies. This TRS has at least two intended audiences: the Local Road Research Board (to aid in directing further research that may be needed) and engineers at local highway and street agencies (to assist in their immediate needs for guidance regarding recycled materials in maintaining their road networks).

The objectives of this TRS include the following.

- Summarize the current research and practice in the use of recycled materials in pavement base layers.
- Provide information to local agency pavement engineers to encourage the use of recycled materials where appropriate, and to promote realistic expectations of differences in construction and in long-term performance.
- Develop recommendations for the Local Road Research Board and regarding future research and the most effective use of research funding in this topic.

The most common recycled materials for pavement construction are the primary focus of this report, including recycled:

- Asphalt Pavement,
- Concrete Aggregate,
- Pavement Material,
- Roofing shingles, and
- Glass.

While other materials may be used in the design and construction of base layers, their use is minimal and they do not often comprise a major portion of the base layer, nor of the industry's total usage of recycled materials.

Two of the most common methods of recycling pavement materials are cold in-place recycling and full-depth recycling. These include the on-site milling, grinding, and/or crushing of the existing pavement materials and placement in the new pavement structure. Other methods include crushing materials and stockpiling them for later use. Each of these are described in more detail in the Literature Review section.

Figure 1. Recycled Material Stockpile.

In 2014, the Federal Highway Administration (FHWA) reported that there are about 4.2 million miles of public roads in the US (8.8 million lane miles). Of these, about 3.2 million files, or 77%, are under local jurisdictional control (FHWA, 2014). In Minnesota, as of 2014 there were over 293,000 lane miles of roads, divided by route system as shown in Table 1 (MnDOT, 2016).

Table 1. Minnesota Lane Miles by Route System

Route System	2014 Lane Miles	Percent of Total
Township Roads	117,373	40.0%
State Aid (Municipal and County)	70,277	23.9%
Municipal Streets	37,874	12.9%
Interstates, US Highways, State Highways	29,288	10.0%
County Roads	28,416	9.7%
State and National Parks, Military, Private Roads	10,362	3.5%

The paving and materials recycling industries often measure effectiveness of recycling efforts in terms of landfill area or volume not used due to recycling of materials into pavement structures or other beneficial uses (Townsend, 2015). With Minnesota's extensive road network, recycling has been and will continue to be a great source of materials for pavement structures, and promotes sustainability for future construction of pavement structures.

According to the National Asphalt Paving Association (NAPA), an estimated 81.3 million tons of recycled asphalt pavement was used nationwide in 2014 (Hanson and Copeland, 2014). Of this, about 8.5 million tons were used in aggregate base layers. In addition, nearly 2 million tons of manufacturing waste and post-consumer shingles was used. According to the report, only 0.17% of Recycled Asphalt Pavement (RAP) was send to landfills in 2014. The same report estimates that in Minnesota, RAP comprised about 24% of the materials used in asphalt pavement construction in 2014.

Only about 2% of the total Recycled Asphalt Shingles (RAS) used in 2014 was placed in aggregate base layers. Other materials reported in the 2014 NAPA survey, but at levels too low for statistical analysis include ground tire rubber (nationwide usage, but none reported in Minnesota), steel slag, blast furnace slag (none reported in Minnesota), cellulose fiber, and other materials.

It is estimated that about 310 million tons of bulk aggregate (primarily consisting of concrete) were generated in the United States in 2014 (Townsend, 2015). Of this, approximately 85% was recycled and used in other construction applications.

Many more publications have been produced detailing the need for recycling, and about the general benefits to the paving industry and society as a whole by recycling as much road pavement material as possible.

Report Organization

The remainder of this report is organized into three main sections – a survey of current practice among Minnesota local agencies and some others in nearby states, an extensive literature review on the use of recycled materials in pavement base layers, and recommendations for further research and implementation activities.

Agency Survey

A short survey of local transportation agencies in Minnesota was conducted in February and March 2016. An invitation to complete the survey was sent to all counties and cities in Minnesota through the Minnesota Department of Transportation (MnDOT) State Aid for Local Transportation Office. The questions asked are given below.

Survey Questions

1. Has your agency used recycled materials in its unbound aggregate base layers?

   If so:

2. How long / Since what year (approximately)?
3. How often do you consider recycled materials for unbound base layers?
4. What, if any, were your hesitations in using recycled materials for the first time?
5. What types of materials have been used? (Check all that apply)
   Recycled Asphalt Pavement (RAP) – Milled / ground hot-mix asphalt pavement
   Recycled Concrete Aggregate (RCA) – Crushed concrete without steel or deleterious material
   Recycled Pavement Material (RPM) – Hot-mix asphalt + some materials from base and other layers
   Recycled Road Surface Gravel (RSG) – Granular material from unpaved roads
   Building-derived Concrete (BDC) – Brick, block, cast-in-place or precast concrete
   Other (please specify)

6. What pavement design methods have you used to determine layer thicknesses and material properties when using recycled materials?

7. What methods have you used to determine appropriate proportions or blending of recycled and virgin material?

8. What material testing methods have you used to ensure material acceptability?

9. Which specifications, special provisions, or special construction practices have you used to control the material and construction?

10. What differences in performance have you noticed in pavements with recycled materials compared to those without?

If not:

11. What factors have prevented you from using recycled materials in unbound aggregate base layers?
12. If more guidance or past experience was available, would you consider it?

Final Questions

13. Do you feel that a set of guidelines or "Best Practices" published by the Local Road Research Board (LRRB), the Minnesota Department of Transportation (MnDOT), or some other entity would help with your or others' confidence and familiarity with using recycled materials?

14. If you are willing to be contacted by email or telephone for a few more specific questions, please enter your contact information.

There were 66 respondents to the survey from Minnesota, of which 18 provided contact information. From the contact information data it was determined that 50% represented counties, and 50% represented cities in Minnesota. A similar survey with slightly different questions (regarding local sources of guidance, etc.) was sent to North Dakota county engineers, and six responses were received.

The remainder of this section details the responses received from the Minnesota local agencies, with a short section at the end comparing those responses with the few received from North Dakota.

Survey results

The survey asked respondents to indicate if their agency (not necessarily the person responding to the survey) has used recycled materials in the past, if they currently use such materials, and then asks for some feedback on their experiences. Respondents were then asked which types of recycled materials have been used by their agencies, and what differences in performance and/or construction issues were noticed.

Of the 66 respondents in Minnesota, 89% indicated that their agencies have used recycled materials. The reasons provided by those indicating they had not used recycled materials included the following.

- Lack of available recycled materials
- Lack of guidance
- Lack of experience, or that the agency hadn’t used recycled materials before.

All of the respondents who hadn’t used recycled materials indicated that they would consider it, and would be willing to try, with more guidance and assistance.

The data in the figures in the remaining sections are based on the respondents who indicated that they or their agency have used recycled materials in the past (thus the title “Percent of Recycling Respondents”). Figure 2 indicates how long since an agency first began using recycled materials, based on the responses obtained in the survey. Over 20% have been recycling for more than 20 years, and 64% have done so for more than 10 years.

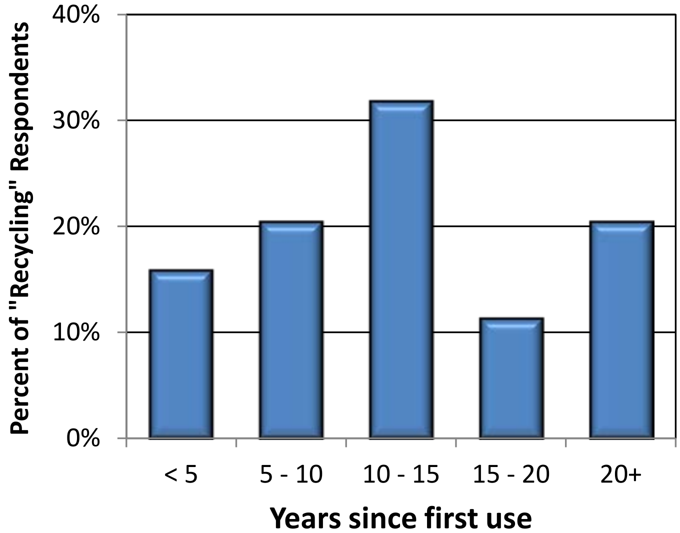

Figure 2. Agency's experience using recycled material in pavement applications.

Most agencies indicated that they use or at least consider using recycled materials for every project. Figure 3 shows the distribution of agencies that consider recycled materials for base layers for Every, Most, Some, or Very Few projects.

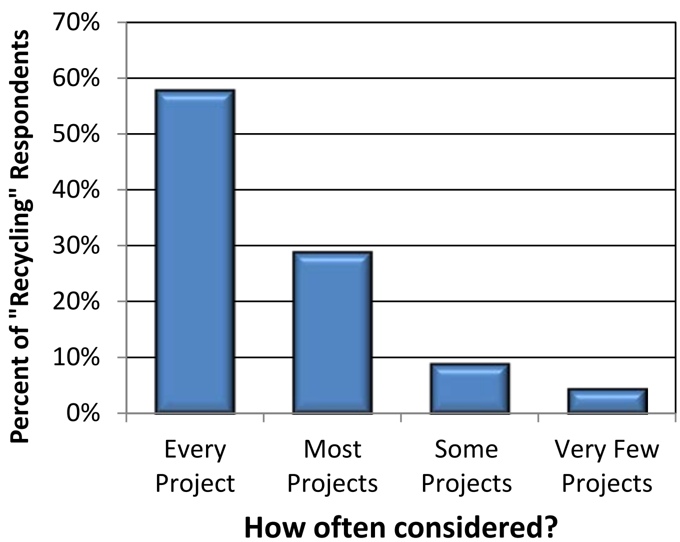

Figure 3. Frequency of considering recycled materials.

For those respondents who have used recycled materials, a question was asked about their hesitations in using such materials for the first time. Responses included hesitations and questions regarding:

- gradations,
- cost,
- durability,
- performance,
- drainage,
- regulatory uncertainty, and
- quality control.

The types of recycled materials that have been used by the responding agencies was asked. Definitions were provided to help in obtaining more uniform responses. The types of materials included in this survey were defined as follows.

- Recycled Asphalt Pavement (RAP)
  Milled / ground hot-mix asphalt pavement
- Recycled Concrete Aggregate (RCA)
  Crushed concrete without steel or deleterious material
- Recycled Pavement Material (RPM)
  Hot-Mix Asphalt + some materials from base and other layers
- Recycled Road Surface Gravel (RSG)
  Granular material from unpaved roads
- Building Derived Concrete (BDC)
  Brick, Block, Cast-in-place or precast concrete
- Other
  Glass
  Incinerator ash or slag
  Recycled Tire Derivatives

Figure 4 indicates the types of recycled materials, with the definitions given above, used by the survey respondents. Unlike the first two graphs, where all categories added up to 100%, each category in Figure 4 represents all of the respondents. So if one agency has used several types of recycled materials, it would be counted in each of the categories. The figure indicates that between 40% and 60% of the responding agencies have used RAP, RCA, and/or RPM, while only about 20% have used RSG, and that fewer have used building-derived concrete or other materials such as glass, slag, or tires.

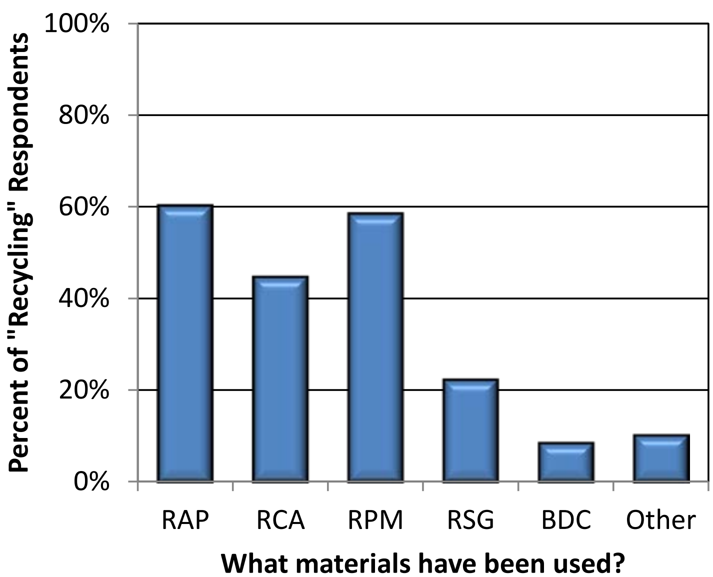

Figure 4. Percent of responding agencies that have used various recycled materials.

Another set of questions was asked regarding the methods for pavement design and determining the proper proportion of recycled material in the base layer. Figure 5 presents the methods of layer thickness design. About 40% use MnDOT's MnPAVE software or "MnDOT specifications". Another 26% indicated using the Granular Equivalent (GE) method. It is assumed that those using the GE method treat recycled materials with the same granular equivalent factor as a specific type of virgin aggregate. About 33% of respondents explicitly stated that the recycled material is treated the same as MnDOT Class 5 (18%), Class 7 (3%), or "Same as virgin material" (12%). The remaining 3% or respondents indicated the use of the "MSA Spreadsheet."

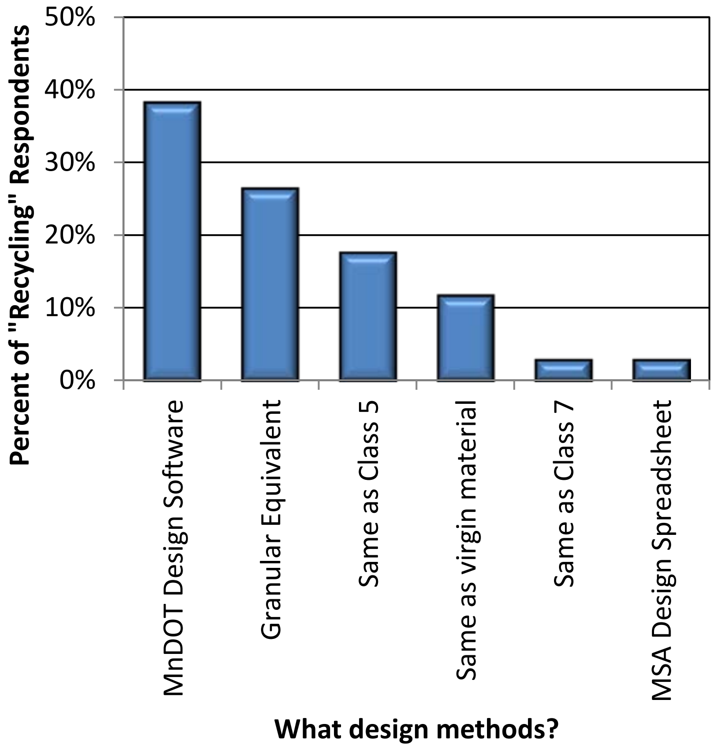

Figure 5. Pavement design methods used for base layer thickness determination.

Another important aspect is the amount of recycled material as a proportion of the total aggregate blend. In fact, one of the main purposes of the original LRRB needs statement was to identify good methods for making this determination. Based on the responses received, it became apparent that the question may have been worded improperly, as about 2/3 of the responses focused on *how* the proportion is determined, and the remainder addressed *how much* recycled material is used. While both sets of responses are included in Figure 6, there is a space between them to separate the types of response. Regarding the question of how the correct proportion is determined, 69% indicated that MnDOT specifications are used to make this determination, while 31% indicated that past experience or advice from others is the primary method. The question of how much recycled material is allowed in the base layer was answered by fewer respondents, where 25% of respondents allow up to 30% recycled, and another 13% allow up to 40% recycled. Half of the respondents allow up to 50% recycled material, and the remainder allow "up to 2/3 RAP".

One common concern among agencies is the ability to ensure material acceptability during construction, to be confident in good performance in the long term. The survey question regarding testing methods used to accomplish this was also met with varying types of responses. As shown in Figure 7, 21% of responses indicated that they use "MnDOT Specifications" for acceptance, although no additional information was given besides that the standards for "Class 2" or "Class 5" were required. Gradation tests were indicated in 28% of responses, while 10% cited asphalt content testing (ignition and/or solvent extraction) and 5% stated that little or no testing was conducted beyond the normal testing conducted by the agency.

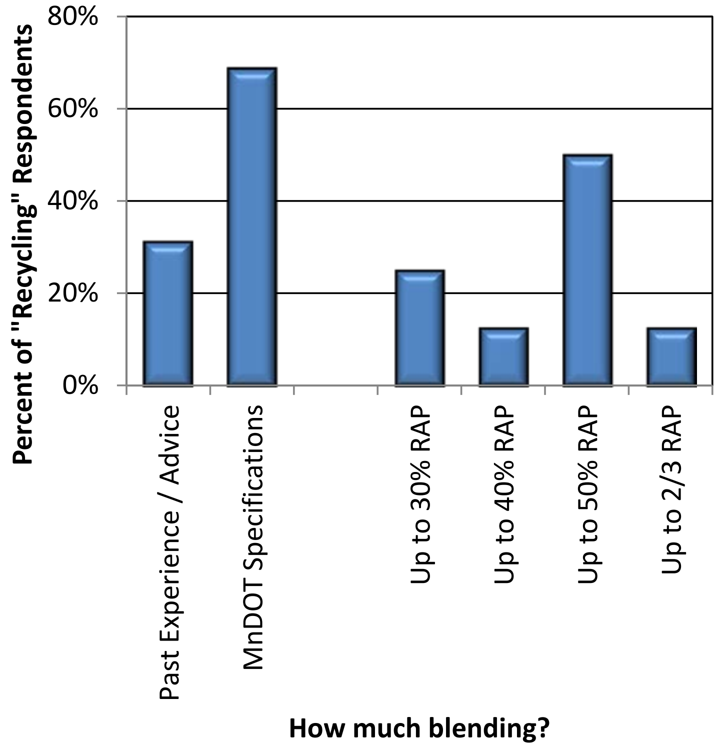

Figure 6. How agencies determine blending proportions, and what proportions are allowed.

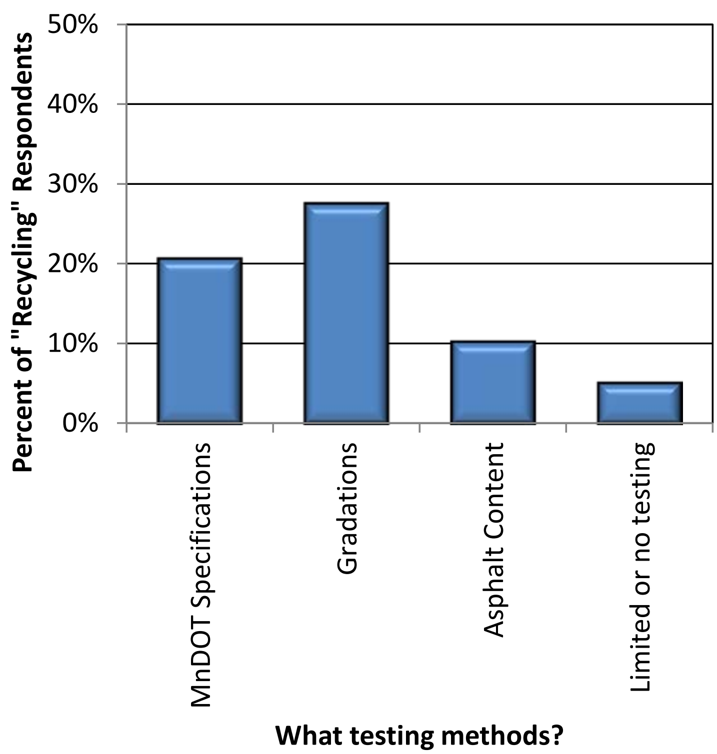

Figure 7. Material acceptance methods.

The final question regarding the agencies' use of recycled materials asked about any observed differences in performance that may have been observed between pavements with recycled vs virgin materials in the base layer. As shown in Figure 8, the great majority (81%) has not noticed any differences in their pavements with recycled materials, and the other 19% indicated noticing only "some" performance issues. An unsolicited response from 8% of the surveys indicated that "cost savings" was a difference observed in their experiences with recycled materials.

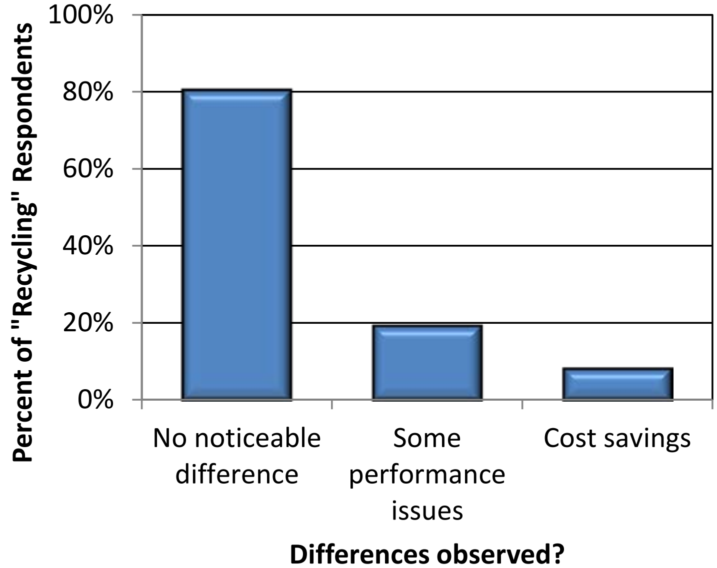

Figure 8. Differences observed in pavements with recycled materials.

Survey Follow-up

Respondents were asked to provide their name and contact information if they would be willing to discuss the topic in further detail. About 1/3 provided this information, and many of these were contacted for follow-up conversations. These discussions followed the topics that make up the structure of the literature review section, which includes materials, design and construction methods, potential problems, and pavement performance. Some of the information below repeats what appears above, but is included again due to the different, more direct source of information.

Materials

Many of the survey respondents and the follow-up phone calls indicated that RAP is often considered the same as MnDOT Class 7 material, and that as long as it meets the specifications for Class 7, it is used as such. Similarly, some agencies consider crushed concrete (RCA) to be similar to MnDOT Class 5 material. One city indicated that they do not use RCA in base layers of streets with drain tile.

One county has successfully used crushed glass in some projects, and another indicated that a successful implementation of crushed glass was done by covering the glass with a layer of Class 5 material. One problem with crushed glass occurred in one project where the glass punctured tires of several vehicles and construction equipment. This may have been a problem with the glass processing, and shouldn't be a common problem.

Consistent with the information obtained in the survey, some counties target 40% to 60% as the RAP replacement rate. One county engineer is quoted as saying "100% RAP is difficult to work with".

Design and Construction

Method of construction were discussed with the telephone participants. Many agencies use a cold in-place recycling method, and many others use full-depth reclamation or stabilized full-depth reclamation. Some counties use 100% RAP for shoulders, and one indicated that they only use 100% RAP for narrow (2-ft wide) shoulders because the material doesn't perform well on wider shoulders, when vehicles drive on it.

One county's standard practice is to mill enough hot-mix asphalt (HMA) from the surface so that a 40% or 50% blend of RAP and original base layer can be created, which is then compacted and used as the new base layer. A 5-inch layer of HMA is then constructed on that base.

A typical design for most city streets in one city is to create an 8-inch reclaimed layer from four inches of HMA and four inches of original base layer, with 3½ inches of HMA constructed in two lifts. This is a typical design and construction method for about 90% of the city's streets. The other 10% of the streets carry more and heavier traffic, and are designed using MnDOT's MnPAVE software.

In some cases, with smaller projects or lower-volume streets and less important routes, little testing is done to establish the existing conditions. For example, one county rarely does asphalt content tests on existing asphalt layers prior to reclaiming operations.

Maintenance
In the course of the phone call follow-up conversations, not much was said regarding maintenance of pavements constructed with recycled materials. It is generally assumed that once the pavement is constructed, standard maintenance procedures should be followed. One city provided a general schedule for the long-term maintenance of its streets.

- Crack seal at 5 years
- Seal coat at 6 years
- One more crack seal as needed prior to the scheduled Mill and Overlay
- Mill and Overlay at about 20-25 years
- Reclaim at about 40 years.

Potential Problems
Many survey respondents indicated that they did not observe or experience problems when using recycled materials in the base layer. Some comments related to potential problems include:

- the presence of wood chips, brick and other undesirable materials in the recycled material,
- crushed glass can get into the equipment and cause unexpected problems, and
- recycled asphalt pavement is often sensitive to changes in moisture and can cause stability problems during construction.

Others are likely, but these are the only problems mentioned in the survey follow-up conversations.

Performance
Most survey respondents indicated that no performance issues have been observed in pavements using recycled materials. One example is Sibley County CSAH 2 near Gibbon, Minnesota, which was recycled using the cold in-place recycling method. The pavement is showing very good performance, and few cracks after several years of service. Another county has been using recycled materials – primarily Full-Depth Reclamation (FDR) and Cold In-Place Recycling (CIR) methods for 15 years, and treats it like Class 5 material, without any problems. One county engineer stated that not many recycling projects have "gone bad" but that in those cases the problems were not with the recycled material base layers.

Literature Review

This section presents a review of the literature and of common practices throughout the United States and beyond. The topics reviewed for this section include the following.

- Common recycled materials
- Construction methods and practices
- Specifications
- Properties of recycled materials
- Pavement design methods
- Determining appropriate proportions
- Possible difficulties in using recycled materials
- Pavement performance
- Other sources of information

Varying degrees of research have been done on the topics listed above. In some cases, hundreds of papers and academic reports have been created, and for some topics only limited information is available. This section presents a cross-section of the published research and the states of practice and of research for these topics. As mentioned, much more research and testing has been conducted than are presented in this TRS. Anyone interested in more information should consult the resources at the end of this section to learn more.

The desire to incorporate recycled materials in the construction of new and rehabilitated pavements has led to a need for research and testing to give the engineer an idea of how they will perform over long periods of service carrying heavy traffic loads. The results of the agency survey indicated that many local highway engineers in Minnesota use recycled materials in place of natural aggregates, with the assumption that the properties are the same or similar. It is important to be able to characterize these materials to ensure that these assumptions are correct, or if they are not correct, that appropriate adjustments are made to the materials and layers to account for those differences.

Common Recycled Materials

This section describes the literature and the research that has been published regarding the various types of materials that have been used in pavement applications. The table below is adapted from Bolden et al. (2013) in which the authors suggest various applications in which different recycled materials could be used. While most of the materials in this table have not been used (or their use has not been published) in Minnesota, the table provides some additional ideas for using recycled materials in in pavements.

This section focuses on the most common recycled materials for base layer construction in Minnesota – concrete aggregate, asphalt pavement, other pavement materials, roof shingles, and some others which have been subjects of MnDOT and LRRB research in the past, including waste tires, bricks, and glass.

Reclaimed Asphalt Pavement

Reclaimed asphalt pavement (RAP) is also known as recycled asphalt pavement, and the two terms are often used interchangeably, even by the same authors. In 1998 the FHWA defined RAP as the "term given to removed and/or reprocessed pavement materials containing asphalt and aggregates." (Chesner et al., 2008). The report continues by stating "When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement." The FHWA report indicates that RAP had been used in granular base layers for "more than 20 years" as of 1998, and RAP that "has been properly processed and in most cases blended with conventional aggregates has demonstrated satisfactory performances as granular road base."

Edil et al. (2012) discuss the use of RAP as well as other recycled roadway materials, and provides a good definition of the terms RAP, FDR, and RPM, but concedes that there is some confusion in the industry's terminology. In their report, the authors state that these three terms are "collectively referred to as RAP" unless otherwise specified. This report is a comprehensive review of these types of recycled materials (also including

RCA) with testing for characterization of the materials in terms of gradation, moisture-density, design and performance, strength and stiffness, moisture susceptibility, durability, and permanent deflection.

Johnson and Olson (2009) found through a survey of local agency engineers that about one-third of their respondents prohibit the use of RAP in the wear course mixture.

Table 2. Possible Construction Applications for Various Recycled Materials

	Innovative Recycled Material in Construction Applications						
Recycled Material	**Hot-Mix Asphalt**	**Concrete Mixes**	**Embankments**	**Aggregate**	**Base Course**	**Mineral Filler**	**Soil Stabilizer**
Swine Manure	■						
Animal Fat		■					
Silica Fume	■	■					
Roof Shingles	■			■	■	■	■
Palm Bunch Fiber	■						
Cement Kiln Dust	■	■					■
Fly Ash		■	■	■		■	
Foundry Sand	■	■	■	■	■		
Slag		■	■		■		■
Glass			■	■			■
Plastic	■		■	■			
Carpet	■	■	■				
Tire Scraps	■	■	■		■	■	■
Asphalt Pavement	■			■	■		
Concrete Aggregate		■		■	■		
Gypsum	■						
Sewage Sludge	■	■					

Recycled Concrete Aggregate

The second most recycled material in pavement base layers is recycled concrete aggregate. As with recycled asphalt pavement materials, local Minnesota agencies have varying levels of experience with this material. Some have used it for many years and are comfortable with the construction methods and have good expectations for the performance of pavements built on an RCA-blended base layer. Recycled concrete aggregate is produced by breaking up existing, hardened concrete and removing any reinforcing steel. The material is then crushed and sized to be used as aggregates in pavement base layers, as aggregates in new concrete, or other uses.

Much research has been conducted regarding recycled concrete aggregates, with some publications as early as the 1970s. Halstead (1979) noted that "A relatively large number of articles dealing with the recycling of portland cement concrete pavements have appeared in the literature in the past few years." The report mentioned the potential uses for RCA in aggregate bases for asphalt and portland cement concrete pavements, cement-treated bases, and other uses. Conclusions from this report indicate that crushed concrete aggregate can be used as aggregate in "essentially all highway applications." In a discussion on the economics of recycling concrete, the report mentions the tradeoff between the cost of crushing and processing and the cost of delivering new materials, and that the energy required for both options should be considered in the analysis.

Figure 9. Concrete pavement and sidewalk for recycling.

Research at Purdue University by Burke et al. (1992) indicated that when feasible, the use of recycled concrete as aggregates in concrete pavements "should be allowed when it fulfills requirements of natural aggregates." The report expected the use of recycled aggregates to increase in the future and predicted cost declines as more material became available. It also states that the fines produced in concrete crushing operations should not be used in the subbase, locations surrounding filters, or other locations where drainage is important.

Snyder (1996) reported on laboratory studies performed to address concerns about the use of recycled concrete aggregates in pavement foundation layers. This research evaluated the potential for recycled concrete to cause unintended consequences related to the performance and environmental impacts. The presence of recycled concrete fines and the production of calcium carbonate precipitate due to freshly exposed cement from the crushing operations may significantly reduce the permeability or drainage capacity of the base layer and associated drainage structures. The report discusses possible mitigation strategies to reduce the precipitate potential significantly, and ways of eliminating the recementing of RCA material.

Lim et al. (2003) suggested, by way of an extensive laboratory testing program for the Texas Department of Transportation (TxDOT), that RCA be considered for use in "flexible base, cement treated base, HMA bond breaker, flowable fill, backfill, and roadway embankment" but that the fines should not be used in concrete mixes. The authors tested coarse and fine crushed concrete in TxDOT flexible base (100% crushed material) in several modes to determine the properties of the base layer. For the mixes, fine and coarse gradations were developed which used the #40 sieve as the smallest size, and allowed 42% passing this sieve for the fine mix and 22% for the coarse mix. The largest size was 1¾". The authors' conclusions indicated that additional study is needed to develop performance criteria for this type of aggregate base.

Asphalt Shingles

Minnesota has been using recycled asphalt shingles in HMA mixes since 1990 (Janisch and Turgeon, 1996). Much of the research conducted by MnDOT in the 1990s focused on the HMA uses of shingles (Janisch and Turgeon, 1996; Turgeon, 1991). A 2007 report by Krivit (2007) provides recommendations that "other non-HMA applications should be developed such as dust control, additive to aggregate base, etc." The report mentions internal research by an asphalt paving contractor in which scrap shingles were evaluated as a "supplement in Class 7 aggregate as base to assist in dust suppression on gravel roads." Krivit contends that RAS is not more widely used in pavement construction not necessarily due to poor reception by the pavement industry, but rather due to the lack of supply, since most shingle scrap is committed to other industries. The report states that "HMA producers would be willing to consider investments in shingle recycling if they knew they could obtain long-term supply commitments."

Figure 10. Post-consumer asphalt shingles.

Another 2007 report by Krivit (2007a) references some previous use of RAS in asphalt pavement base layers, and discusses concerns by materials engineers and shingle recyclers that the addition of RAS may "impede precipitation drainage within the aggregate base." The report also states that "RAS may improve the compaction of the sub-base". This report calls for further research and testing to determine appropriate blending ratios, and suggests that a maximum 10 percent recycled shingles by volume could be a reasonable amount to help limit the amount of asphalt cement in the blended aggregate, and to "help mitigate any potential negative impacts on infiltration" within the base layer.

Wood et al. (2014) estimated that more than 200,000 tons of shingle waste is produced in Minnesota each year. This report states that since current technology limits the amount of RAS in HMA to no more than 5 percent by weight, "this leaves a lot of underutilized shingle waste material throughout the state." The report focuses on the use of RAS as a method of controlling dust and maintaining smoothness on gravel roads.

Recycled Pavement Material

Recycled Pavement Material (RPM) is made by grinding or pulverizing the HMA layer and the underlying base layer (and sometimes a portion of the subbase layer or subgrade) and mixing it into a new base material, which is then compacted in place. A new HMA layer is then placed on the compacted RPM. This method of pavement construction is often termed Full-Depth Reclamation. Benson et al. (2009) conducted a research project in which they discuss potential problems due to materials which are inherently a part of RPM. The asphalt binder, fines, and other deleterious materials can adversely affect strength and stiffness. In their report, various chemical stabilizing agents were used to blend with RPM to increase strength and stiffness. The stabilized material is referred to as SRPM by Benson et al. (2009).

The work by Benson et al. (2009) described the use of Class C fly ash as a stabilizing agent to improve the GE of the base layer using RPM, to be structurally equivalent to a Class 5 base course. Fly ash content of the mix was maintained at 10%, which the authors state is common practice.

Tang et al. (2012) present a structural evaluation of asphalt pavements with base layers constructed with the FDR and stabilized FDR (SFDR) methods. They present analysis results of eight test sections throughout Minnesota, and conclude that the methods are very attractive alternatives to using all virgin materials in road construction.

The authors state that some local highway engineers believe that the GE of FDR material should be greater than 1.0 (its current level according to MnDOT pavement design requirements). While the authors don't recommend a change in GE for FDR material, they do suggest that stabilized FDR should be given a GE of 1.5.

Waste Tires

Waste tires are sometimes used in HMA layers, fills, embankments, and in subgrades as lightweight fill materials (Epps, 1994). Some names for waste tires include shredded, scrap, or chunked tires, rubber aggregate, waste rubber, crumb rubber. Little has been written about the use of waste tires in the base layer of pavements, although Pasalkar et al. (2015) have published a paper discussing the possibilities.

Brick

Several types of brick may be encountered in the recycling waste stream – structural, pavers, and refractory bricks. The quality and characteristics of bricks often vary by region of the world, as their properties depend highly upon the raw materials and the process for making the brick. In many cases recycled brick sources may be very old, and the production methods may be unknown to modern processes.

Reza (2013) researched various types of bricks and conducted extensive laboratory testing to assess their properties and to determine how closely the crushed brick material could meet the MnDOT specifications for aggregate bases. The bricks tested were sampled in three groups: new brick from a manufacturer or distributor (age and type should be known); old brick from a demolition site (age and type may be known); and old brick from a debris stockpile (type and age are unknown).

While many brick types met the specification requirements, some exhibited poor performance and were deemed unsuitable for use in an aggregate base. Reza noted that the poorly performing bricks were generally the refractory bricks. The material properties that were tested (specific gravity, absorption, Los Angeles Abrasion, and Magnesium Sulfate Soundness) displayed highly variable results in most cases. For example, the LAR test had a coefficient of variation greater than 25%.

Reza concluded that a maximum of 10% brick by weight should be specified when recycled brick is used. This level of aggregate replacement is supported by the testing results with high variability, and also due to the highly uncertain nature and source of recycled brick.

Construction Methods and Practices

In 2002, Marti and Mielke (2002) wrote an extensive summary of the Basic Asphalt Recycling Manual (ARRA, 2001) or "BARM", produced by the Asphalt Recycling and Reclaiming Association (ARRA) and endorsed by the FHWA. The ARRA manual was updated in 2014 (ARRA, 2014). The BARM provides a comprehensive study of the factors to consider when selecting construction methods for asphalt recycling, including existing pavement condition, availability of construction material, economics, and time constraints compared to other rehabilitation alternatives. The manual includes chapters on rehabilitation strategies, project evaluation, selection of construction methods, and detailed information regarding four different recycling methods:

- Full Depth Reclamation,
- Cold In-place Recycling,
- Hot In-place Recycling, and
- Cold Planing,

As mentioned previously in this report, most recycling of bituminous pavements in Minnesota by local agencies involves one of these methods. Each section, detailing one of these construction methods, includes chapters on detailed project analysis, mix design, construction, and specifications / inspection. The BARM is an excellent source of information regarding the specifics of selecting projects and construction methods, and determining appropriate mix designs and layer thicknesses. The ARRA web site (www.arra.org) has much more information regarding construction practices and specifics about equipment and other aspects of these four recycling methods. The FHWA's Recycling Asphalt Pavement Expert Task Group has published documents and linked to many others with much information on the topics. These and other sources, with Internet links, are listed at the end of this section.

Full-Depth Reclamation

The process of full-depth reclamation is becoming more popular in recent years, based partially on the results of the survey conducted for this project. Many research projects have been conducted to develop mix and thickness design procedures (Bang, et al., 2011; Scullion et al., 2012; Shuler, 2015). Each of these references discusses the design of FDR in terms of the mix, layer thickness, and construction practices. In the FDR process, the existing asphalt pavement layer is pulverized with the base layer and sometimes a part of the subgrade. This combined material is then recompacted and places as a base layer for the new pavement surface. The FDR material is either placed in an unbound condition, or it may be stabilized with the following materials.

- Portland cement
- Fly ash
- Asphalt emulsion
- Asphalt emulsion plus lime
- Foamed asphalt plus portland cement

Bang et al. (2011) give a thorough description of the use of these materials, and reasons for selecting a particular material based on project needs. The report evaluated and recommends engineering properties of FDR materials use in common pavement design methods or flexible pavements.

A 2011 National Cooperative Highway Research Program (NCHRP) report by Stroup-Gardner (2011) indicated several benefits of FDR (also of CIR). Related to the use of FDR as a base layer material, such benefits include the reduction in the number of hauling vehicles (with associated benefits), the reduction of the amount of waste material to be landfilled, and can decrease the construction time depending on the methods.

Figure 11. Stabilized Full-Depth Reclamation operation.

Scullion et al. (2012) provides recommendations for laboratory testing to select the optimal type and amount of stabilizing material, the use of Falling Weight Deflectometer (FWD) during construction to validate that the design assumptions are being met, modifications to FDR specifications to avoid working in freezing conditions, and other changes to the Texas DOT specifications for FDR construction. Two test procedures recommended by the authors are the Surface Treatment Bond Test, a modification of ASTM C 1583, the Direct Tensile Bond Test (ASTM, 2004); and a Tack Coat Adhesion Tester, Test Method TEX-243-F (TxDOT, 2011). Chapter 5 of the Scullion report (2012) presents a summary of investigations into premature distresses in FDR pavements.

The Colorado DOT published a "Best Practices" manual for Asphalt Emulsion FDR (AEFDR) design and construction (Shuler, 2015). The report states that while FDR is most commonly covered with hot mix asphalt wearing course, "a few projects have been constructed with [portland cement] concrete over FDR." The Colorado report presents several specifications in use by other states for design and construction of FDR projects, including:

- Compaction
  - 97% of laboratory density (Shuler, 2015)
  - 92% to 98% of theoretical maximum density (Thompson et al., 2009)
  - Maximum dry density and optimum moisture content (Franco et al., 2009)

- Minimum indirect tensile strength (Lane and Kazmierowski, 2005)
  - 43 to 50 psi – dry, and 22 to 25 psi – wet.
  - Tensile strength ratio greater than 70% (California) and greater than 50%

- Resilient Modulus
  - 120 to 150 ksi

- Moisture content
  - Less than 2.0% (Lane and Kazmierowski, 2005)

The report also provides guidance on structural design of pavements using FDR, construction specifications, construction methods (including equipment and operations) and for quality control and quality assurance. One appendix in the report provides a guide specification for AEFDR.

The Minnesota Department of Transportation published a Transportation Research Synthesis on the performance requirements of full depth reclamation stabilization (MnDOT, 2014) with a detailed description of the process, project selection, laboratory testing (including methods for determining strength and stiffness for use in design methods) and other tests.

Cold In-Place Recycling

Salomon and Newcomb (2000) published a report describing a literature review and a preliminary mixture design procedure for CIR. In CIR, the existing pavement is milled to depths of two to four inches, with the resulting layer used as a base course. According to the literature review conducted by Salomon and Newcomb (2000), advantages and disadvantages of CIR include the following.

Advantages

- Pavements exhibiting a wide range of distresses can be cold recycled
- Reflective cracking can be significantly reduced with CIR
  Pavements can be structurally improved without changing horizontal and vertical alignments and without reconstructing shoulders.
  CIR is less expensive than conventional rehabilitation methods. It reduces the amounts of energy, aggregate and binder required for construction.
  CIR is an environmentally sound process. It minimizes air quality problems, conserves natural resources and eliminates disposal problems.

Disadvantages

- Material and construction variation is greater than for conventional rehabilitation techniques.
- The CIR mixtures need to be cured for a period of time in order to gain strength.
- The construction process is influenced by ambient temperature and moisture conditions.

The report gives extensive recommendations for pavement evaluation, field testing (moisture content, gradation, asphalt content), and specifications. It also provides information about other materials used in the CIR process – primarily the emulsion used to rejuvenate the recycled asphalt cement.

The recommendations section of the report gives suggestions for designing a CIR project, including the type of emulsion and how to determine the optimum emulsion content. Appendix B of the report provides a mix design procedure for CIR projects, with the following steps.

- Evaluate existing pavement to determine suitability for CIR
- Conduct laboratory testing on RAP millings to determine its asphalt content and gradation
- Determine the PG grade of the asphalt cement in the RAP material, and which emulsion product should be used
- Prepare specimens and compact them in a gyratory compactor
- Determine an optimum demand range of emulsion, which occurs when all of the following characteristics are met.
    - The demand range results in the lowest air voids
    - Hand mixing is not difficult, and the RAP is 85% to 95% coated with emulsion
    - Compacted specimens within the emulsion demand range do not look shiny not feel sticky

Hot In-place Recycling

With Hot In-Place Recycling (HIR) the entire recycling operation is completed on site. Typical treatment depths range from ¾ to 2 inches (ARRA, 2001) and can be as deep as 3 inches. The HIR process requires the existing surface to be heated, softened, and scarified, after which the loosened asphalt pavement is mixed (and in most cases new asphalt and aggregates added) and replaced, compacted, and finished with conventional paving equipment.

Cold Planing

Cold Planing is more of a traditional method for recycling asphalt pavement, in that it involves the controlled removal of a specific depth of material. The material is often removed for processing at a plant, and the remaining pavement surface may be used for driving until a final surface is placed on it. Cold planing may also be used as a final surface treatment to improve friction and texture and to "eliminate slipperiness" (ARRA, 2001). According to the ARRA (2001), there are several advantages to Cold Planing, including the following.

- Removal of wheel ruts washboarding, etc.
- Correction of longitudinal profile and cross-slope
- Restoration of drainage
- Removal of crack sealant or seal coats prior to HMA overlays
- Improvement of friction numbers
- Removal of built up pavement at curbs
- Surface preparation prior to an additional form of asphalt recycling

Foamed Asphalt

Rather than a type of recycled construction, foamed asphalt is a type of binder used in stabilizing CIR and FDR projects, among others. Eller and Olson (2009) collected "information regarding best practices, construction techniques, mix design, specifications, and performance" of foamed asphalt recycled pavement. From this information, they developed a design guideline and specifications for the use of foamed asphalt in Minnesota.

They also monitored foamed asphalt pavement in two counties (Fillmore and Olmsted) constructed between 2004 and 2008.

Eller and Olson (2009) summarize the MnDOT requirements for foamed asphalt and stabilizing materials (as of 2009), including PG 52-34 for the foamed asphalt CIR, and mineral additives such as Type I portland cement, approved fly ash, hydrated lime meeting MnDOT 3106 specifications, and limestone fines from limestone crushing operations. As much as 1.5% by weight of RAP can be used "without significantly affecting the fatigue resistance of the stabilized layer, while simultaneously improving the recycled layer's strength retention when saturated with water."

Mix design is important, especially in FDR, due to the variability in the thickness of the existing base layer in many cases (Eller and Olson, 2009). Appendix A in the Eller and Olson report provides guidance on mix and layer thickness design when using foamed asphalt, and also provides information on selecting an appropriate foamed asphalt temperature and water content. Appendix B in their report provides general guidelines for design and construction.

Recycled Concrete Aggregate

In a 1993 article, Mack et al. described some basic construction methods for using recycled concrete aggregate in various pavement components, including the base layer. The article describes the recycling operation itself, including preparation of the pavement to be recycled, breaking the concrete slabs, removing reinforcing steel and then the broken-up pavement, and crushing. Mack et al. (1993) state that "recycled aggregate meeting the requirements for virgin aggregate can be included in the concrete mix or used in base courses." The authors mention the potential problems of high absorption. They mention that for unstabilized drainable bases, crushing operations may "produce dust and fine material that can cling to the larger coarse aggregate particles" and that water may carry away the dust from the larger particles and clog pipes and filter fabric.

A technical bulletin published by the American Concrete Paving Association (ACPA,1993) indicates that crushed recycled concrete is "suitable for both open or dense gradations" and provides several possible gradations for using RCA in base layer applications.

Specifications

Much has been published about specifications for recycled material in pavements. Several surveys of states and summaries of state construction specifications have been published. A recent publication by the Strategic Highway Research Program (SHRP) R23 team (AASHTO, 2013) provides a structure for developing individual state standard specifications for construction. The information in this report is organized to "illustrate the types of specification requirements that produce long-lasting pavements and can be considered by the designer for inclusion or modification of their project specifications."

Edil (2011) developed a report with recommended specifications and design of base layers with recycled concrete and asphalt materials. It is a good reference for developing specifications, and includes two draft ASTM specifications for grading requirements and the use of recycled aggregates as unbound roadbase.

Stroup-Gardiner (2011) included a chapter about specifications development. Although it is a short chapter, it provides basic information on specification development, results of a survey of states regarding the types of specifications used (method, end-result, performance, or warranty), and a listing of specifications by state found in the National Highway Specification Web Site.

Using these example specifications, those available from MnDOT (MnDOT, 2016a), and the guide specifications by SHRP (AASHTO, 2013), a local highway engineer should be able to develop specifications for paving projects using recycled materials.

Van Dam et al. (2011) prepared a manual of practice for using RCA in various components of the pavement structure. The manual includes chapters on processing and production of RCA, material properties and applications, the use of RCA in base layers and in other pavement layers. The report includes many references to Michigan DOT specifications on allowable use of RCA in base layer applications.

The Federal Aviation Administration (FAA) also allows the use of RCA in base layer applications. Item P-219 in the FAA's construction specifications (FAA, 2014) prescribes allowable materials for "Recycled Concrete Aggregate Base Course" which includes at least 90% crushed portland cement concrete, with the remaining 10% made up of asphalt concrete (10% maximum); brick, mica, schist, or other friable materials (4% maximum); and wood (0.1% maximum). Blends of virgin aggregates are allowed as part of the 90% minimum PCC requirement. Other components of the FAA Item P-219 include testing requirements, gradations, equipment, and construction methods.

Properties of Recycled Materials

The engineering properties of recycled materials vary greatly by material type, source (age, geographic location, processing methods), proportions of the original mixture (asphalt or concrete) and many other factors.

Edil et al. (2012) provide an extensive review of the relevant mechanical and physical properties of interest to pavement engineers. These include the following characteristics and testing results.

- **Material Gradation**
  Coefficient of variation for gradations was found to be about 40% for both the coarse and fine RAP, RPM, and RCA materials. This is normally considered highly variable. In most cases, reclaiming contractors are able to produce gradations for RAP, RPM, and RCA to meet the specifications needed, although with some large variability.

- **Moisture-Density Relationship**
  One of the studies related by Edil et al. (2012) indicated that an increase in RAP content led to a decrease in maximum dry density (γ_d) and of the optimum moisture content (w_{opt}) in tests using the Proctor Compaction test. It was assumed that as the RAP content increases, more aggregate particles are covered in asphalt, which decreases the specific gravity, and that more particles coated with asphalt would absorb less water and lead to lower inter-particle friction, which would lead to a reduction in the required water content to achieve γ_d. For other tests, using a gyratory compaction device, the w_o decreased with increasing RAP content, but the γ_d remained about the same.

  Typical γ_d and w_o values for RAP and RPM observed in these tests range from 1978 to 2332 kg/m^3 and between 5% and 10.3%, respectively. Typical values for RCA range from 1823 to 2020 kg/m^3 and 7.5% to 12.1%.

- **Strength and Stiffness**
  The tests most often used to characterize strength and stiffness of unbound materials are triaxial tests and resilient modulus. Other tests that have been used include the California Bearing Ratio (CBR), the Limerock Bearing Ratio (LBR) and the free-free resonant column test. One of the studies reviewed by Edil et al. (2012) indicated that shear strength for RAP was comparable in magnitude to shear strengths of the natural aggregates. RAP had a higher resilient modulus than RPM and RCA at 95% of γ_d according to one study. Increasing the relative density increased the resilient modulus in some of the materials. Another report indicated that shear strengths of 100% RAP and 100% RCA were both lower than that of a 100% natural dense-graded aggregate. However, contrary to the shear strength trends, the resilient modulus values increased with increasing RAP or RCA blends.

  One report discussing RPM and FDR found that at low confining pressures (about 20 kPa) and for blends of 50% RAP in the FDR material, the resilient modulus was about equivalent to that of the 100% aggregate. At higher confining pressures, the RAP blend became more stiff than the pure aggregate sample. In saturated conditions, laboratory-tested RAP blends showed a dramatic decrease in stiffness (40% to 90%) compared to the dry materials.

Strength of RCA increased with time, according to several of the studies reported by Edil et al. (2012). In freshly crushed concrete, in a constant 100% humidity regime, some tests indicated a 390% increase in stiffness for demolition material and up to 940% increase for “haul-back” material (concrete delivered to a job site but returned to the plant unused. After this material is crushed, it has a greater amount of exposed, unhydrated cement.

The addition of fly ash increased the stiffness of the RPM materials by at least a factor of 6, but still less than for a natural aggregate with fly ash.

- **Moisture Susceptibility**
  Using a Tube Suction test, some researchers quoted by Edil et al. (2012) indicated that the moisture susceptibility of the pavement material increased as the RAP content increased (from 25% to 50% RAP).

- **Durability**
  Various researchers have used the LA Abrasion test (LAR) and freeze-thaw cycling to assess durability. In many cases, the results of the LAR were indistinguishable with different levels of RCA in a blend. The researchers assumed that this is most likely due to “test severity.” Freeze-thaw cycling was performed, and some RPM materials exhibited a 30% loss in stiffness after two freeze-thaw cycles, and some experienced up to 90% loss after the first nine cycles. These two samples were tested for unconfined compressive strength after the freeze-thaw cycles, and exhibited strength losses of 52% and 28%, respectively.

- **Permanent Deformation**
  In tests comparing the permanent deformation of RCA and RAP samples loaded to 100,000 cycles, the RCA samples were found to have the least permanent deformation. Similar tests were conducted elsewhere and the opposite results were found. Plastic strains for RPM stabilized with fly ash were smaller than for those of unstabilized RPM.

Gupta et al. (2009) studied the “suitability of four recycled materials relative to virgin aggregates for use as base and subbase material in road construction.” They studied RAP, fly ash, reclaimed concrete material (RCM), and foundry sand. Some of the testing conducted was similar to that done by Edil et al. (2012), and similar results were found for maximum dry density and optimum moisture content. With the exception of some higher fines content in some of the RAP-aggregate mixtures, the gradations of all of the blends tested fell within the MnDOT specifications for Class 5 aggregate.

Other properties evaluated by Gupta et al. (2009) are as follows.

- **Hydraulic Conductivity**
  Hydraulic conductivity of the blends and various recycled materials (except for the foundry sand) ranged between 12-302 cm/day and 1-185 cm/day (saturated and unsaturated, respectively) and those for natural aggregates were k88 cm/day and 1 cm/day. This indicates that the drainage characteristics of these recycled materials “will be somewhat better or similar to that of 100% virgin aggregates.”

- **Leaching**
  Tests were conducted on the recycled materials to evaluate the concentration of heavy metals that might leach from the aggregates and into a groundwater source for drinking water. In general, the authors note that the heavy metal concentrations were lower than US Environmental Protection Agency (EPA) standards for drinking water, although some of the lead in the leachate from recycled concrete materials was higher than the drinking water standards. Other heavy metals (chromium and aluminum) were found in the leachate from fly ash mixtures. None of the materials leached arsenic.

With these tests and other results similar to those found by Edil et al. (2012), the authors concluded that recycling these materials "will be good substitutes for virgin aggregates as base and subbase materials." However, they caution that "further in-situ testing of these materials needs to be undertaken before field implementation" of their findings.

Cooley et al. (2007), in a report by the South Dakota Department of Transportation (SDDOT), evaluated recycled concrete aggregate properties in a research project to determine it RCA should be used by SDDOT as a base course and/or "gravel cushion". The authors evaluated gradations, Atterberg limits, moisture/density relationship, flat and elongated particles, uncompacted voids, specific gravities, sand equivalent, abrasion resistance, sodium sulfate soundness, freeze/thaw resistance, CBR, triaxial shear strength, and resilient modulus. Samples were tested from six locations in South Dakota, ranging from city streets to interstate highways.

- **Atterberg Limits**
  Of the six samples tested in the evaluation, all were non-plastic except one, which has a liquid limit of 31 and a plasticity index of 11. To meet the requirements for a South Dakota Aggregate Base Course for a Gravel Cushion, an aggregate must have a liquid limit below 25 and plasticity index less than 6. As is expected, however, most of the RCA samples were non-plastic and met the requirements.

- **Flat and Elongated Particles**
  The portion of flat and elongated particles in a recycled concrete aggregate is highly dependent on the crushing equipment and process. Recently more modern crushing equipment and handling processes have improved the ability to produce more cubicle and angular crushed aggregates than before (Estes and Fensome, 2014).

- **Sand Equivalence**
  Cooley et al. (2007) reported sand equivalence values for the six RCA samples tested ranging between 74 and 89 for five of their samples, and only 46 for the sixth. The sample with the low sand equivalency was the same sample which had plastic fines.

- **Abrasion Resistance**
  The Los Angeles Abrasion test on the coarse fraction of the RCA samples ranged from 25.8 to 40.7 percent loss. This indicates that almost all of these samples would be acceptable by MnDOT standards for aggregate bases and other applications (MnDOT, 2016a). The authors also conducted Micro Deval testing on the fine portion of the RCA samples. These tests indicated loss ranging from 15.2 to 19.4 percent.

- **Sodium Sulfate Soundness**
  The sodium sulfate soundness test results ranged from a low of 9 to 36 percent. MnDOT uses a magnesium sulfate soundness test, and limits loss to 15.0 percent for coarse aggregate.

- **New York Freeze/Thaw Test**
  The New York Freeze/Thaw test was also conducted on these samples, and loss ranged from 5 to 17 percent. The authors then tested a combination of Micro Deval and New York Freeze/Thaw and recorded losses ranging from 23 to 33 percent.

Cooley and Hornsby (2012) conducted similar tests for the Mississippi Department of Transportation (MDOT) and determined that RCA meeting all "applicable current MDOT requirements should be allowed for granular pavement layers."

Resilient modulus and triaxial strength testing was conducted on RAP samples by Kim and Labuz (2007) and reported in 2007. The objectives of their research was to "determine the strength and deformation characteristics of base material" produced by blending RAP and aggregate. They reported that resilient modulus increased with an increase in confining pressure, which is to be expected, but that it shows little change with deviator stress. Samples were tested at 65% and 100% of optimum moisture content. Those samples tested at 65% of optimum moisture content had higher stiffness than those at 100% at all confining pressures. This effect was more pronounced at higher confining pressures.

Kim and Labuz (2007) also tested the RAP samples in cyclic triaxial tests at two deviator stresses (35% and 50% of the estimated peak stress) to 5000 cycles. The RAP blends exhibited “at least two times greater permanent deformation than the 100% aggregate material.” As the percent RAP increased, more permanent deformation occurred. The authors suggest that when properly compacted, the “base material produced with various %RAP content performed at a similar level to 100% aggregate in terms of [resilient modulus] and strength”.

Stolle et al. (2014) found similar results in terms of triaxial test results, and they concluded that “the addition of RAP to natural aggregate (Ontario Granular A) reduces the shear strength slightly and tend to increase the accumulated strain (deformation) that develops due to repetitive loading.” They also found that “the influence of RAP on the mechanical properties, including ‘elastic’ modulus, was sensitive to specimen preparation and preconditioning.” Similar to Kim and Labuz (2007), Stolle et al. (2014) concluded that “for certain combinations of RAP and Granular A, the mechanical properties were similar to those of Granular A. The key to a stable blend was found to be compactive effort.”

Westover et al. (2007) reported on the development of resilient modulus testing of aggregates containing recycled bituminous and concrete materials for use in the Mechanistic-Empirical Pavement Design Guide (MEPDG) and MnPAVE design methods.

Summary

Based on the extensive testing on base material blended with recycled concrete and asphalt materials by the researchers discussed above and by many others, it appears that in general, RCA and RAP blends can be expected to have similar materials properties to natural aggregate materials. Other results contained in later sections of this report will indicate that the layers constructed with good quality recycled asphalt and concrete aggregates can be expected to perform similarly to those constructed with 100% natural aggregates.

Pavement Design Methods

To conduct a proper pavement design using recycled materials, as with any type of material, it is important to characterize the materials so that the layer thicknesses may be designed and construction methods may be selected. The material properties that are important to pavement design and long-term performance were discussed in the previous section.

In a survey of state highway agencies (Puppala, 2008), 32 states indicated that they conduct pavement designs using the American Association of State Highway and Transportation Officials (AASHTO) method (1993 or earlier). This seems to validate the survey results obtained for this TRS and reported in the Agency Survey section. Other responses discussed in that section include the R-value chart, or MnDOT’s MnPAVE software.

Although not specifically for recycled material, Skok et al. (2008) developed a report to help local agencies and MnDOT determine appropriate rehabilitation methods for specific pavement projects. Their work recommends the use of several parameters in a pavement management database, including cracking, ride, rutting, age, and traffic volume. The recommended parameters for describing the surface condition are Ride Quality Index (RQI) and Surface Rating (SR). The authors developed a decision tree or procedure to determine the most appropriate rehabilitation method. This procedure includes consideration of road geometrics, pavement condition, and evaluation of structural adequacy. They also developed a checklist to help local engineers follow the decision procedure. The procedure also includes mix and layer thickness design.

The 1997 FHWA report by Kandhal and Mallick (1998) includes a chapter on structural design. This chapter describes the implementation of the AASHTO 1993 method for pavement design, as well as other design methods. Essentially, this chapter suggests layer coefficients, equivalency factors, and conversion factors to assist pavement design engineers in determining the appropriate thickness of layers with recycled materials compared to those without such materials. Table 18.5 in the report by Kandhal and Mallick (1998) suggests the following structural layer coefficients for various recycled materials.

Kandhal and Mallick (1998) also provide extensive recommendations for gradations, traffic levels, and give several examples of the design method.

Table 3. Typical AASHTO Structural Layer Coefficients for Bases

Type of Recycled Material Used*	Range of a_i computed	Average a_i
Central plant recycled asphalt concrete surface	0.37-0.49	0.42
In-place recycled asphalt concrete stabilized with asphalt and/or an asphalt modifier	0.23-0.42	0.31
In-place recycled asphalt concrete and existing base material stabilized with cement	0.40	0.40

*Adapted from Kandhal and Mallick (1998).

A 2009 study of RCA usage in drainable base layers (Bosquez, 2009) cites the AASHTO 1993 pavement design guide (AASHTO, 1993) which gives an equation for estimating the layer coefficient for an unbound granular layer (a_3) using the "modulus of elasticity [E_{BS}] of granular base material" as

$$a_3 = 0.249(\log_{10}E_{BS}) - 0.977.$$

The Bosquez report provides the average structural coefficient for two RCA samples of 0.15, and that of a crushed limestone aggregate (for comparison) of 0.18.

A report by Locander (2009) at the Colorado Department of Transportation indicates that base layers constructed with RAP materials could be given layer coefficients as high as 0.19 in the AASHTO 1993 design method when their R-value is greater than or equal to 90. With an R-value between 79 and 89, the layer could be given a coefficient of 0.15.

Kim and Labuz (2007) did not present a design method, but discussed testing methods to characterize recycled materials so that they may be used in pavement design procedures. These properties include resilient modulus, shear strength, and cyclic triaxial tests (as summarized previously in this section).

The Wirtgen Group has developed a comprehensive manual for cold recycling asphalt pavements (Wirtgen, 2012). The steps in the rehabilitation design according to the manual include the following.

1. Data acquisition
2. Preliminary investigations
3. Detailed investigations
4. Preliminary pavement rehabilitation design options
5. Laboratory mix design
6. Finalize pavement design options
7. Economic analysis

The manual discusses the entire process of cold recycling including 100% RAP recycling, blended recycling, etc. It also presents information on stabilizing agents, and extensive information on various solutions for recycling applications, and the basics required for an appropriate economic analysis.

Le et al. (2016) performed a study of stabilized FDR in which they conducted several mechanical tests on material taken from different project sites and modeled the pavement structure in the MEPDG and in MnPAVE. Using these design methods, the authors found that predicted rutting by both the MEPDG and by MnPAVE matched closely with the rutting measured in the field.

There are many consulting firms in Minnesota and across the Nation that provide services related to pavement design, and who specialize in the mix design and thickness design of pavements using recycled materials. These firms typically conduct materials testing and then develop a pavement design based on the material properties determined in the laboratory or in the field.

As with any pavement design, developing a proper design using recycled materials requires some investigation and evaluation of the existing materials. Similar to the steps conducted by the Wirtgen Group (2012), most design methods will include steps such as the following.

- Conduct condition survey
- Obtain cores
- Test existing pavement with FWD
- Estimate strength contribution of the base layer to be constructed with recycled materials
- Develop pavement thickness design

In a presentation to the 2009 Midwestern States Recycling Conference, Bemanian (2009) suggested these steps, and the use of either MEPDG or the 1993 AASHTO Design Guide (AASHTO, 1993). Bemanian suggested using a structural number of 0.28 to 0.35 for CIR or a resilient modulus value which could be between “low 200,000” to 1 million psi. For FDR projects, Voth (2008) suggested structural coefficients of 0.10-0.12 for mechanically stabilized FDR, 0.20-0.28 for bituminous stabilized, and 0.15-0.20 for cement stabilized FDR. Bemanian also recommends steps in the mix design process:

- Obtain cores or grindings from the project,
- Mixing at various emulsion and water contents,
- Compaction of samples using a gyratory compactor,
- Curing of specimens for 48 hours,
- Testing of two sets of specimens – dry and soaked, and
- Select optimum emulsion content.

Jarem (2015) gave a comprehensive presentation to the 2015 Ohio Transportation Engineering Conference with detailed information on the design and construction of FDR. The presentation included information on the benefits of FDR, selecting candidate projects, strength-based design, structural properties, cement stabilization of FDR, the construction process, and special considerations for cul-de-sac construction.

The City of Lawton, Oklahoma (2011) utilizes a modified AASHTO 1993 pavement design method. As an alternative to a 6-inch granular base layer on city streets, and when the subgrade soil PI is less than 35, the city allows an 8-inch layer of “recycled asphaltic concrete” with a bituminous content between 2.0 and 7.5 percent. For a subgrade soil PI between 35 and 45, this layer thickness is increased to 12 inches. For soil PI between 45 and 55 the base layer must be 18 inches thick, and for PI greater than 55 then the base layer is increased to 24 inches of “Aggregate Base, recycled asphaltic concrete or Select Borrow.” This layer is an option for both flexible and rigid pavements. The recycled asphaltic concrete is given a layer coefficient of 0.11 in the determination of structural number.

The pavement design software MnPAVE, V. 6.304 / March 2014 incorporates three types of recycled materials as possibilities for the base layer: RPCC (Rubblized Concrete), CIR (Cold-Inplace Recycling), and SFDR (Stabilized Full-Depth Reclaim). However, under the "Basic" and "Intermediate" design levels, the "R-Value Design" gives a hard-coded Granular Equivalent of 1.50 for each of these materials. In the "Advanced" design level, these materials are given different resilient moduli values ranging from a fixed 78 ksi for RPCC, 109.5 to 452.3 ksi for both CIR and SFDR. The Advanced level also has "Seasonal Modulus Multipliers" for each material type, which range from 1 to 7 for RPCC and 0 to 1.2 for CIR and SFDR.

Chai et al. (2009) suggested the following stiffness values and "Gravel Factors" (for use in pavement design by the California Department of Transportation) shown in Table 4, for unbound aggregate layers with various proportions of RCA.

Table 4. Suggested Stiffness Modulus and Gravel Factor by Percent RCA

Percentage of Crushed Recycled PCC in Aggregate Base	Suggested Stiffness Modulus, MPa (psi)	Gravel Factor
100	2,500 ($350x10^3$)	1.4
50 to 100	1,000 ($150x10^3$)	1.2
<50	250 ($40x10^3$)	1.15

Determining Appropriate Proportions

Many design methods (and most of those referenced in the previous section) suggest conducting laboratory studies to determine the optimal proportions of recycled material, emulsions, moisture content, and other aspects. When any of the recycled materials discussed in the first section of this section (concrete, asphalt, glass, shingles, tires, etc.) are considered for use in a pavement base layer, an investigation into the strength, stiffness, and stability of the resulting material should be conducted. Very little was found in the literature suggesting design parameters for determining appropriate blending proportions for recycled and virgin materials. Most state highway agencies specify limits, and it is assumed that valid research was conducted to confirm these requirements.

The MnDOT Standard Specifications for Construction (MnDOT, 2016a) provide some guidance on mixture design, including the determination of appropriate proportions. Spec 3138 provides guidance on quality requirements for recycled materials as aggregates in surface and base courses, and gives gradation requirements, restrictions on certain recycled and deleterious materials. Spec 3149 provides similar requirements for granular material, and limits recycled concrete material to a maximum of 75% of a blend, and no greater than 10 percent masonry block. Many other construction specifications have similar limits.

A report by Lukanen and Cruse (2000) suggests that the maximum blending rate for RAP should be limited to 50 percent. Reasons for this include difficult compaction in the field with higher asphalt contents, "resulting in lower strengths and more rutting." The authors indicated that in their field trials, densities were similar for 25 and 50 percent RAP content, but that at 75 percent the layer was "significantly less dense."

Possible Difficulties

As with any material or pavement type, there are inherent difficulties that should be avoided if possible. The various recycled materials discussed in this TRS can present problems in terms of properties, construction, performance, contamination, and others. This section presents a short summary of the major difficulties that may be encountered.

Variability in Properties

Regarding RCA, SDDOT (Cooley, 2007) recommended that only recycled material from pavements owned by the DOT should be allowed in new DOT projects. The reason for this is so that the agency knows the origin of the material, and has a reasonable idea of its provenance and the variability of its engineering properties.

Scullion et al. (2012) discuss potential problems with varying RAP percentages in FDR construction. As it relates to cement stabilization, the researchers found that with 3% cement content for stabilization, RAP percentage could "reach up to 63 percent and still meet the minimum strength criterion of 175 psi." At a RAP content of up to 75%, approximately 4.5% cement stabilization would be required to meet the minimum strength criterion. The authors suggest that at above 50% RAP content, the additional cement needed to provide strength would offset the savings and make the FDR process less economically viable than other methods.

In general, since recycled materials may be of unknown source, it is best to obtain several samples from the stockpiles that will be used for the specific project and conduct tests on the base layer material that will be constructed. If possible, it is much preferred to have a single source of recycled material, and to establish the strength and stiffness properties and the variability of those properties in advance so that the design may account for the variability and avoid potential performance problems after construction.

The following sections describe some common problems that may be encountered when using various recycled materials in pavement base layers.

Stockpile Runoff

Sadecki et al. (1996) conducted a study of runoff water from recycled material stockpiles to develop best practices in managing such stockpiles to protect nearby water sources. The authors established three experimental stockpiles – two with recycled concrete (passing the #4 sieve, and between the ¾" and #4 sieve sizes) and one containing "salvaged bituminous material (recycled asphalt product)". The stockpiles were instrumented with tipping-bucket flowmeters to determine the quantity of water runoff, and chemical laboratory testing was conducted to determine the types and concentrations of chemicals, the pH of the water, and other items. The researchers found that the water coming from the concrete stockpiles exceeded the alkalinity standards for drinking water (pH = 8.5) with pH values of 9.5 for fine recycled concrete aggregate, and 9.8 for coarse concrete. The recycled asphalt material had a pH of 8.1, and so did not exceed clean water requirements. The chromium concentration in the runoff exceeded one of two clean water standards (depending on the ionic valence state of the chromium), but fell well below the other. The authors suggested some best practices for stockpile management to minimize harmful chemicals in the water.

Recementing of RCA Materials

In 1996, Snyder (1996) discussed the concern of recementing fine materials in RCA. One suggestion is the elimination of the use of fines from drained foundation layers, since "Mn/DOT stockpile experience suggests that coarse, open-graded materials do not become recemented in the short term (1 year of exposure)". Snyder further suggested that recementing of coarse aggregates would not occur in the long term "because there is insufficient contact between particles and insufficient unhydrated cement on the particle surfaces to bind the coarse (#4-plus) particles." Another remedy to counter the effects of possible recementing of fines for bases underlying concrete pavements is to design short joint spacings (or no joints at all, in the case of continuously reinforced concrete pavements).

Chai, Monismith and Harvey (2009) evaluated several case studies to develop recommendations for using RCA and accommodating the possibility of materials re-cementing in the base layer. In order to account for the increased stiffness of re-cemented aggregate bases with RCA, the authors suggested stiffness modulus values ranging from 40 to 350 ksi (250 to 2,500 MPa) depending on the percent of crushed RCA in the aggregate base.

Hazardous Chemicals / Contaminants

A report published by Grosenheider et al. (2006) described the potential for hazardous chemicals and other contaminants in common recycling materials and stabilizing agents. The report focuses primarily on coal combustion fly ash and "ground asphalt pavement". The report states that fly ash contains 21 trace elements "that may be potentially above risk assessment limits." These trace elements are termed "contaminants of concern" or COC. These include arsenic, barium, mercury, and vanadium. The authors state that asphalt contains polycyclic aromatic hydrocarbons (PAH), "some of which are carcinogenic". The report evaluated 17 PAHs through a risk assessment to evaluate their potential toxicity. Recommendations in the Grosenheider report (2006) suggested that most fly ash sources tested can be used up to 20% replacement of soil, but that some could only be used up to 10% replacement. Chemical problems could not be detected in the asphalt samples taken from Minneapolis roads, except when coal tar has been used (which has been very limited since about 1918.)

Leaching

When a base layer is compacted in place and a pavement surface layer constructed above it, the possibility of calcium-based compounds in RCA to leach and precipitate in the presence of atmospheric carbon dioxide (1996). In relation to RCA materials, Snyder (1996) suggests that "it does not appear that selective grading (to eliminate fines) or blending with virgin aggregates will *eliminate* precipitate potential" (emphasis in original). However such steps may significantly reduce the potential. Snyder (1996) mentions researchers at the University of Toledo (Gupta and Kneller, 1993) who found that about one-third of recovered tufaceous (or "tufa") material was insoluble residue that had washed out of the base.

Gupta et al. (2009) evaluated the leaching of contaminants from 17 mixtures of various combinations of recycled materials with virgin aggregates. Using several testing techniques (leaching tests in batch and flow-through, undersaturated and saturated conditions) the researchers measured the potential leachability of chemicals, and the hydraulic conductivities of the mixtures in both saturated and unsaturated conditions. The results of the research indicated that in general, mixtures with fly ash and RCM materials had higher pH values than those with RAP or foundry sand, and that materials consisting of 100% RCM had the highest leachate pH values (above 12). In addition, the researchers found that the pH of the leachate increased with an increase in the fine aggregate content of the mixture. The chapter on leaching in the Gupta et al. (2009) report concludes by stating that "there is minimal risk that these chemicals will enter the ground water system because of the presence of additional soil below the base and subbase layers."

Edil et al. (2012) also conducted extensive research into the leaching characteristics of RCA and RAP. In addition to laboratory studies, the researchers conducted two field leaching test sites (at MnROAD and in a parking lot at the University of Wisconsin – Madison). The researchers found that the pH of leachate effluent rose to as high as 12.9 in the two field sites, and up to 11.6 for the laboratory tests. In terms of heavy metals, column leaching tests of the samples showed that arsenic, chromium, lead, and selenium all exceeded their corresponding EPA maximum contaminant levels (MCLs). The conclusion within the leaching chapter indicate that through limited testing on RAP materials, the pH levels were seen to be within the EPA groundwater limits, and that the heavy metals concentrations were slightly higher than MCL for arsenic, selenium, and antimony.

Cooley et al, (2007) determined that since South Dakota uses relatively impermeable RCA layers in pavement construction, potential leachate problems will "likely not be an issue." The researchers did note, however, that since water passing through an RCA layer can become highly alkaline, they found instances in the literature of metal culvert and rodent guard corrosion, vegetation kill, and high pH levels. Again, the researchers indicated that since the "current intent" of SDDOT is to construct low-permeable unbound layers (including those with RCA material) the potential increase in alkalinity was not considered to be a problem.

Hoppe et al. (2015) concluded that "the use of RAP in road base and subbase materials is viable" and that "there seemed to be no major environmental concerns associated with using unbound RAP without chemical stabilization agents."

Stripping

Attia et al. (2009) studied RAP materials taken from MnROAD Cell 26 and their reaction to potential stripping. The testing program included resilient modulus, shear strength, freeze-thaw cycles, severe moisture conditions, and other properties, on various combinations of RAP blends with natural aggregates. The properties related to stripping included loss in resilient modulus, friction angle and cohesion, and none of these showed significant differences among recycled blends. The authors concluded that RAP "is a viable alternative to virgin aggregate as a base layer."

Absorption and Moisture Retention

Gupta et al., (2005) studied the water retention characteristics of 18 non-recycled base and subbase materials, and 7 recycled materials, including "concrete, crushed concrete, crushed concrete with shingles, and 4 samples of bottom ash." The researchers found a "slight difference in water retention of crushed concrete with and without shingles." The report also states that the "presence of shingle chips can alter the flow paths and in some cases it may provide a preferential pathway along the chip surface."

Problems with Stabilization

Scullion, et al. (2012) mention some materials properties that can cause problems with stabilization in FDR construction. Mechanical properties that may cause problems include the roundness, "sorting" (segregation) and sphericity of aggregates and recycled particles. Other problems may be cause by chemical reactivity of aggregates, primarily if the stockpile includes sulfates or organics, and perhaps iron oxide. The authors note that there is only anecdotal evidence that iron oxides cause stabilization problems.

Pavement Performance with Recycled Aggregate Bases

This section presents information and cases from the relevant literature highlighting performance of pavements made with recycled aggregate bases. Johnson et al., (2012) studied field and laboratory performance of RAP and Fractionated RAP (FRAP) on several test cells at MnROAD between 2008 and 2012. In terms of performance, the authors found that "RAP, FRAP, and other mixtures performed very well after four years of service." Some cracking was observed during the fourth year on several non-overlay study cells. Cell 18 was constructed with a RAP base layer. A comparison of the FWD data for these cells indicated that the maximum deflections for Cell 18 were within the range measured for the other 10 cells.

As recently as 2014, MnDOT TRS 1310 (2014) indicated that for FDR and SFDR, desired physical parameters for design are not well defined. The report states that the use of the MEPDG software and "collecting and analyzing samples from existing SFDR roadway bases that are performing well will validate the parameter values given by the MEPDG software."

Edil et al. (2012) conducted an extensive study of FWD results on base layers composed of various recycled materials and blends, including RAP, RCA, a 50/50 blend of RCA/Class 5, and a control section of 100% Class 5 material. The authors found that test cells that incorporated Class 5 as a base course "experienced the greatest elastic maximum deflections" followed by 50/50 RCA/Class 5, RAP and RCA, respectively. The report also notes that RCA and Class 5 had the highest and lowest resilient moduli, respectively. The RCA/Class 5 blend and the RAP had comparable resilient moduli.

Scullion et al. (2012) conducted FWD testing during construction to assess deflections before and after construction. Their results show good and poorly performing pavements, as shown in Figures 11 and 12, which show deflections taken just after construction on two projects that were considered "good" and "poor" construction, respectively. Notice the "Average before" and "Predicted from design" values, and the FWD validation test results.

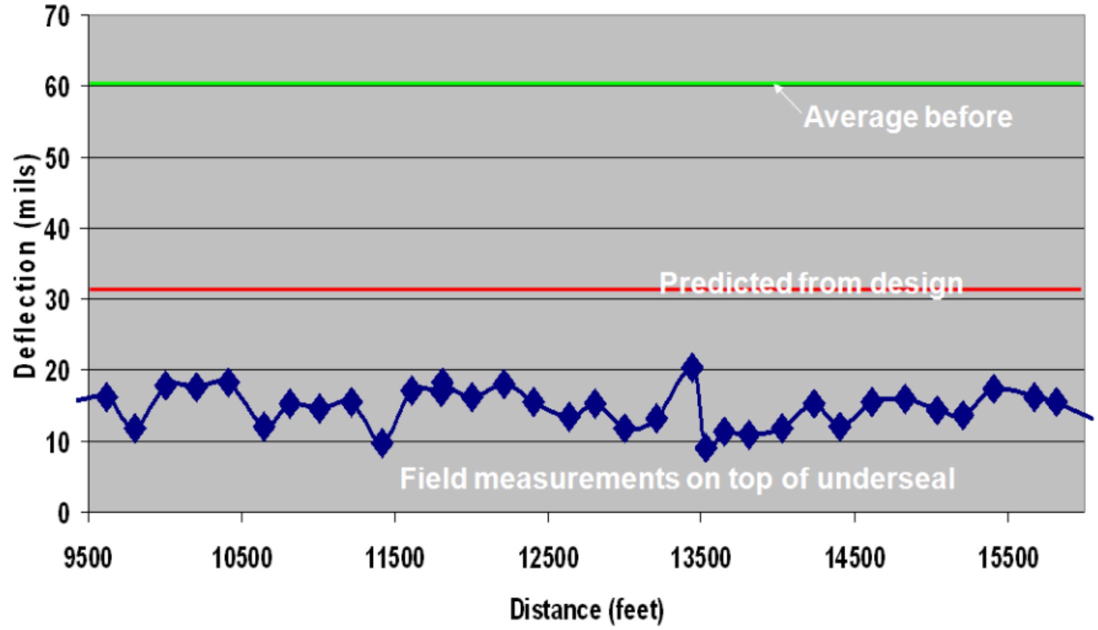

Figure 12. Validation Test Results from a "good" design and construction FDR project (Scullion et al., 2012).

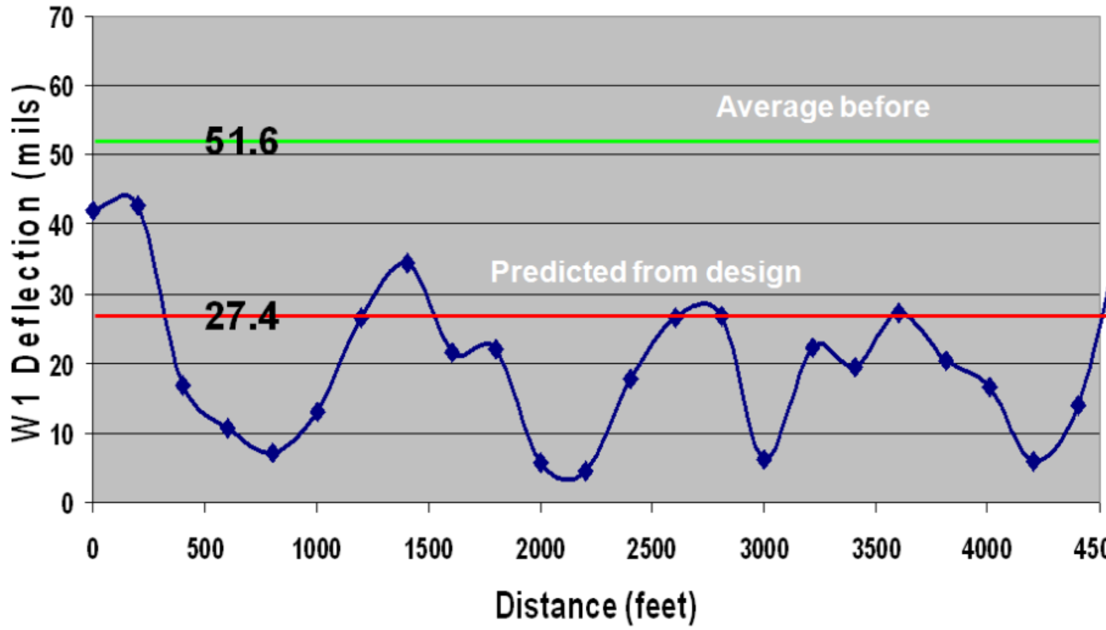

Figure 13. Validation Test Results from a poorly constructed FDR project (Scullion et al., 2012).

Diefenderfer and Apeagyei (2014) at The Virginia Department of Transportation, reported on a pavement performance study on Interstate 81 in Virginia where three in-place pavement recycling techniques were used – FDR, CIR, and cold central-plant recycling (CCPR). An asphalt pavement layer was placed on these A summary was published by Roads & Bridges magazine (Diefenderfer et al., 2016) in which the average rut depth after about four years and eight million ESALs is about 0.1 in. The IRI on this test section is approximately 53 and 44 in/mi in the left and right lanes, respectively.

NCHRP Synthesis 421 (Stroup-Gardiner, 2011), noted some "performance characteristics" found in the literature, including:

- Kansas: CIR sections with fly ash additives experienced twice the total amount of cracking compared to emulsion-lime slurry sections, and displayed longitudinal cracking in one or both wheel paths compared to little or no cracking in emulsion-lime slurry sections.
- Arizona: CIR projects with double chip seal provided good performance for up to 20 years when traffic was below 5,000 Average Annual Daily Traffic (AADT), and overlays of 2 to 3 inches provided excellent performance for at least 7 years.

The report also noted life expectancies of CIR projects assumed by various states (as of the time of its publication, in 2011).

Cold In-Place Recycling

- Pennsylvania: 13 years; 12 to 30 years with an overlay.
- Iowa: 17 to 25 years, 18 to 22 years when constructed on poor soil support (<5,000 psi); 26 to 34 years when constructed on good soil support (>5,000 psi).
- Arizona: 10 to 18 years with "consistently more reliable performance if a 2- to 3-in. HMA overlay is used with the CIR."

Full Depth Reclamation

The report (Stroup-Gardiner, 2011) noted that there is not significant information regarding pavement performance when using FDR. It did state, however, that other research had indicated a slight improvement in performance using FDR than CIR. The improvement was more pronounced after 8 to 10 years of age.

A lack of experience with recycled materials in base layers (or at least a lack of performance studies) is a significant barrier to using the in-place methods, according to Stroup-Gardiner (2011). The author found successful agency experiences with various in-place recycling projects in Colorado, Wisconsin, Kansas, Nevada, North Dakota, California, Georgia, Mississippi, Alabama, Texas, and Canada.

As mentioned previously, Van Dam et al. (2011) prepared a manual of practice for using RCA in various components of the pavement structure. The manual includes chapters on processing and production of RCA, material properties and applications, the use of RCA in base layers and in other pavement layers. As other research has shown, Van Dam et al. quote NCHRP (2000) and conclude that "when held to the same specifications as natural aggregates, [RCA] can perform very well as a base material and can be used without design adjustments."

Other Sources of Information

As mentioned previously, so much information has been published on a wide variety of topics related to recycled materials in pavement construction, that it is impossible to discuss them all in one TRS report. Other excellent sources of information exist which specialize in very detailed to very broad topics. Some of these are listed below. Most of these sources are trade associations, research centers, and others with interests in promoting recycled products, good pavement performance, construction practices, etc.

Recycled Materials Resource Center / UW-Madison, WisDOT
rmrc.wisc.edu

Construction & Demolition Recycling Association
www.cdrecycling.org

National Center for Asphalt Technology (NCAT)
www.ncat.us

National Center for Pavement Preservation
www.pavementpreservation.org

National Concrete Pavement Technology Center
http://www.cptechcenter.org/

Concrete Sustainability Hub at MIT
cshub.mit.edu

Asphalt Recycling and Reclaiming Association
www.arra.org

Recycling Asphalt Pavement Expert Task Group
www.morerap.us

Texas Department of Transportation – Roadway Recycled Materials Summaries
http://www.txdot.gov/inside-txdot/division/support/recycling/materials.html

Conclusions and Recommendations

The needs of local pavement engineers for guidance in the design, specification, construction, and maintenance of pavement structures built with recycled materials is evident from the survey responses discussed in the Agency Survey section. This TRS presents a summary of the materials, construction methods, specifications, design methods, and other topics to assist local engineers in finding more complete information. Another objective is to develop recommendations for further research and implementation so that the Minnesota Local Road Research Board and MnDOT may direct future funding more appropriately. This section summarizes the state of research in the use of recycled materials in base layers of pavement structures, and provides recommendations for future research and implementation activities. The recommendations are divided into topics aligned somewhat with the topics discussed in the previous section.

Pavement Design Methods

Many pavement design methods exist, and these should be used for natural as well as for recycled materials. The 1993 AASHTO Design Guide, the MEPDG (or its new name AASHTOWare PavementME), MnDOT's Granular Equivalent method, MnPAVE (flexible and rigid), or others are available to the pavement design engineer. The method of design is not necessarily an issue as much as the material characterization needed to input into the design methods. As was seen in the survey results, most local pavement engineers consider the recycled material as similar to other materials for which characterization inputs exist in the design methods.

One important aspect of future research could be the development of a method for local engineers to determine an appropriate Granular Equivalent factor so that the R-value / granular equivalent method can be used. One response to this suggestion could be that the process for determining an appropriate GE factor could be replaced by the resilient modulus testing needed for good pavement designs in the MnPAVE or PavementME software. However, in most cases, the local pavement engineer may conduct the necessary testing (or hire a testing firm) for a general type of material and is unlikely to perform the same test program for every project or every recycled material of similar nature.

The discussion of proportioning and determining the appropriate amount of recycled material to blend with natural material should be researched along with the GE factor topic. If a pavement layer with 100% natural material has different properties than one with 100% recycled material, then a blend of the two materials should have some blend of the properties, depending on the nature of the material behavior and that of the resulting blend. A laboratory testing program could be specified to develop appropriate blend rates and resulting GE factors. This could become an expensive (and thus underutilized) method of determining these parameters, and a more simple method would be more desirable.

Construction Methods
There are many aspects of construction that can lead to poor performance, and subsequent suspicions of a specific material or pavement type. Some of the recommendations below are already addressed by the MnDOT specifications.

- Specify cleanliness of recycled material, especially RCA (Cooley et al., 2007).
- Keep RCA stockpiles saturated or “maintained at a moisture content representative of a saturated surface-dry condition” (Cooley et al., 2007).
- Specify that RCA fines not be used near drainage structures to mitigate the possibility of precipitate and leaching problems (Snyder, 1996).
- Maintain asphalt content in RAP at less than 3.5% to avoid possible future permanent deformation in the base layer.
- Ensure that deleterious materials are kept at a minimum (within specified levels). Materials that are often most problematic include cinder block, lightweight materials such as expanded shale and clay.
- Use proper construction methods when using crushed glass to protect tires on construction equipment and other vehicles.

Specifications
A thorough review of construction specifications should be conducted by local agencies and/or MnDOT periodically to ensure that appropriate language is included, and that construction requirements are reasonable for the materials being used and the desired performance of the resulting pavement. Guide specifications such as those published by ASAHTO (2013), the National Highway Specification web site described by Stroup-Gardiner (2011) and others are good sources of information. As engineers and contractors become more comfortable with recycled materials, specifications can move away from “method” and more toward “performance” specifications.

Areas for Further Research
Throughout the development of this TRS, specific areas for further needed research have become apparent. In general, it seems that the industry for recycled materials in roadway applications has matured over the past 30 years. One of the main needs for future research is the development of standard tests and procedures so that local agencies feel as comfortable specifying or allowing recycled materials as they do with natural materials. Each of the suggestions below has some reference to this overall need.

- Develop a method for determining the Granular Equivalent (GE) of a material. Several authors have published suggested values for layer coefficients or correction factors, but a process for developing this value would be useful not only for recycled materials, but also for other materials that local pavement engineers may want to use in pavement structures.
- Develop a method or procedure for determining an appropriate blend rate of natural and recycled materials. This could be a laboratory test procedure or program, or a flowchart based on the important properties of the various recycled materials. If a laboratory method is developed, a compaction method for the samples should be specified to be “under field conditions” which would indicate gyratory compaction, a similar temperature regime, and similar moisture content.
- Develop maintenance and rehabilitation strategies for recycled pavements. Local pavement engineers will need guidance in how to maintain and rehabilitate pavements that have been constructed with recycled materials. Questions should be answered such as “Can I recycle the recycled material?” “What is an appropriate blending rate when the base layer is already 50% RAP?”

Possible Implementation Activities
As mentioned above, the recycled pavement material industry has advanced and matured significantly in the past 30 years. This TRS summarizes the state of the practice and of research in the use of various recycled materials.

The implementation of these concepts can be a difficult task for some local highway engineers with little experience in their use, however. A set of guidelines presenting the materials, methods, and potential problems, along with recommendations for solving problems that may arise and identification of potential difficulties could be a great asset for pavement engineers with all levels of experience. This section lists several implementation activities that could be undertaken to advance and improve the use of recycled materials in Minnesota, and to help engineers with less recycled materials experience be more confident and successful in their use.

- Develop guidance for the use of various recycled materials addressing their procurement, properties, appropriate pavement design and construction methods, potential problems that may be encountered (and likely solutions to them), and expected pavement performance. Such a guide should address the needs of new and experienced engineers conducting pavement design.
- Conduct a field test section with various blend rates of RAP, RCA, and combinations of the two materials are used. There may be benefits in combining RAP and RCA beyond costs savings. Other combinations and recycled materials could be included in such a test section. Performance should be monitored on the test section for several years, while interim research results are published and implemented.

References

AASHTO, Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, Washington, DC, 1993.

AASHTO, *Recommended Guide Specifications for Long Life Pavement Alternatives using Existing Pavements,* June 18, 2013.

ACPA, Recycling Concrete Pavement, TB-014P, American Concrete Paving Association, Skokie, IL, 1993.

ASTM, *ASTM C1583/C1583M-04 Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)*, ASTM International, West Conshohocken, PA, 2004.

Attia, M., M. Abdelrahman, and T. Alam, *Investigation of Stripping in Minnesota Class 7 (RAP) and Full-Depth Reclamation Base Materials*, Report NO. MN/RC 2009-05, Minnesota Department of Transportation, St. Paul, MN, 2009.

Bang, S., W. Lein, B. Moces, L. Nehl, J. Anderson, P. Kraft, M. deStigter, C. Leibrock, L. Roberts, P. Sebaaly, D. Johnston, and D Huft, *Quality Base Material Produced Using Full Depth Reclamation on Existing Asphalt Pavement Structure – Task 4: Development of FDR Mix Design Guide*, Report No. FHWA-HIF-12-015, Federal Highway Administration, US Department of Transportation, Washington, DC, 2011.

Basic Asphalt Recycling Manual, Asphalt Recycling and Reclaiming Association, 1st Edition, Annapolis, Maryland, 2001.

Basic Asphalt Recycling Manual, Asphalt Recycling and Reclaiming Association, 2nd Edition, Annapolis, Maryland, 2014.

Bemanian, S., *Project Selection Criteria for In-Place Recycling*, Presented at the 2009 Midwestern States Recycling Conference, 4-13 August 2009, Minneapolis, Minnesota, 2009.

Benson, C., T. Edil, P. Bloom, A. Ebrahimi, B. Koostra, and L. Li, *Use of Fly Ash for Reconstruction of Bituminous Roads*, Report No. MN/RC 2009-27, Minnesota Department of Transportation, St. Paul, MN, 2009.

Bolden, J., T. Abu-Lebdeh, and E. Fini, Utilization of Recycled and Waste Materials in Various Construction Applications, *American Journal of Environmental Science*, Vol. 9(1), pp14-24, Science Publications, 2013.

Bosquez, J., *A Comprehensive Study of Recycled Concrete Aggregates as a Drainable Base Layer for Pavements*, Ph.D. Dissertation, The University of Texas at Arlington, Arlington, TX, 2009.

Burke, T.T., M.D. Cohen, and C.F. Scholer, *Synthesis Study on the use of Concrete Recycled from Pavements and Building Rubble in the Indiana Highway System*, Publication FHWA/IN/JHRP-92-15, FHWA, US Department of Transportation, 1992.

Chai, L., C.L. Monismith, and J. Harvey, *Re-Cementation of Crushed Material in Pavement Bases*, Technical Memorandum UCPRC-TM-2009-04, California Department of Transportation, Sacramento, CA, 2009.

Chesner, W.H.,, R.J. Collins, and M.H. MacKay, *User Guidelines for Waste and By-Product Materials in Pavement Construction*, Publication FHWA-RD-97-148, FHWA, US Department of Transportation, 2008.

City of Lawton, OK, *Modified AASHTO Low-Volume Street Design Standards*, Lawton, OK, 2011.

Cooley, L.A., and H. Hornsby, *Evaluation of Crushed Concrete Base Strength*, Report No. FHWA/MS-DOT-RD-12-238, Mississippi Department of Transportation, Jackson, MS, 2012.

Cooley, L.A., J. Brumfield, J. Easterling, and P.S. Kandhal, *Evaluation of Recycled Portland Cement Concrete Pavements for Base Course and Gravel Cushion Material*, Report SD05-07-F, South Dakota Department of Transportation, Pierre, SD, 2007.

Diefenderfer, B.K., and A.K. Apeagyei, *I-81 In-Place Pavement Recycling Project*, Report No. FHWA/VCTIR 15-R1, Virginia Department of Transportation, Richmond, VA, 2014.

Diefenderfer, B., B. Bowers, and C. Schwartz, *Part of the Process*, Roads & Bridges Magazine, Vol. 54, No. 2, February 2016.

Edil, T., *Specifications and Recommendations for Recycled Materials Used as Unbound Base Course, Project 68 Final Report*, Recycled Materials Resource Center, University of Wisconsin – Madison, Madison, WI, 2011.

Edil, T.B., J.M. Tinjum, and C.H. Benson, *Recycled Unbound Materials*, Report MN/RC 2012-35, Minnesota Department of Transportation, St. Paul, MN, 2012.

Eller, A. and R. Olson, *Recycled Pavements Using Foamed Asphalt in Minnesota*, Report No. MN/RC 2009-09, Minnesota Department of Transportation, St. Paul, MN, 2009.

Epps, J.A., *Uses of Recycled Rubber Tires in Highways*, NCHRP Synthesis of Highway Practice 198, National Cooperative Highway Research Program, National Academy Press, Washington, DC, 1994.

Estes, B. and G. Fensome, *Crushing for Particle Shape*, Aggregates Manager Magazine, Vol 19, No. 11, November 2014.

FAA, *Standards for Specifying Construction of Airports*, Advisory Circular 150/5370-10G, Federal Aviation Administration, Washington, DC, 2014.

FHWA, *Highway Statistics 2014*, Office of Highway Policy Information, Federal Highway Administration, Washington, DC, 2014.

Franco, S., S.P. Moss, D. Yuan, and S. Nazarian, *Design, Constructability Review and Performance of Dual Base Stabilizer Applications*, Report FHWA/TX-09/0-5797-1, FHWA, Texas Department of Transportation, University of Texas at El Paso, Jan. 2009.

Grosenheider, K., P. Bloom, T. Halbach, and M. Simcik, *Chemical Inventory and Database Development for Recycled Material Substitutes*, Report No. MN/RC-2006-28, Minnesota Department of Transportation, St. Paul, MN, 2006.

Gupta, J.D. and W.A. Kneller, *Precipitate Potential of Highway Subbase Aggregates, Final Report*, University of Toledo Department of Civil Engineering, Toledo, OH, 1993.

Gupta, S., A. Singh, and A. Ranaivoson, *Moisture Retention Characteristics of Base and Sub-base Materials*, Report No. MN/RC-2005-06, Minnesota Department of Transportation, St. Paul, MN, 2005.

Gupta, S., D.H. Kang, and A. Ranaivoson, *Hydraulic and Mechanical Properties of Recycled Materials*, Report No. MN/RC 2009-32, Minnesota Department of Transportation, St. Paul, MN, 2009.

Halstead, W.J., *Recycled Portland Cement Concrete Pavements, Part II – State-of-the-Art Summary*, Report No. VHTRC 80-R12, Virginia Highway & Transportation Research Council, Charlottesville, VA, 1979.

Hanson, K.R. and A. Copeland, *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2014, Information Series 138 (5th Edition)*, National Asphalt Paving Association, Lanham, MD, 2015.

Hoppe, E.J., S. Lane, G.M. Fitch, and S. Shetty, *Feasibility of Reclaimed Asphalt Pavement (RAP) Use as Road Base and Subbase Material*, Report No. VCTIR 15-R6, Virginia Department of Transportation, Richmond, VA, 2015.

Janisch, D., and C. Turgeon, Minnesota's Experience with Scrap Shingles in Bituminous Pavements, Report No. MN/PR-96/34, Minnesota Department of Transportation, St. Paul, MN, 1996.

Jarem, T., *Full Depth Reclamation for Cities and Counties*, Presented at the 2015 Ohio Transportation Engineering Conference, 27-28 October 2015, Columbus, Ohio, 2015.

Johnson, E.N. and R.C. Olson, *Best Practices for RAP Use Based on Field Performance*, Report No. MN/RC 2009-15, Minnesota Department of Transportation, St. Paul, MN, 2009.

Johnson, E., M. Watson, and T. Clyne, *MnROAD Study of RAP and Fractionated RAP*, Report No. MN/RC 2012-39, Minnesota Department of Transportation, St. Paul, MN, 2012.

Kandhal, P.S. and R.B. Mallick, *Pavement Recycling Guidelines for State and Local Governments – Participant's Reference Book*, Publication FHWA-SA-98-042, US Department of Transportation, Washington, DC, 1998.

Kim, W., and J.F. Labuz, *Resilient Modulus and Strength of Base Course with Recycled Bituminous Material*, Report No. MN/RC-2007-05, Minnesota Department of Transportation, St. Paul, MN, 2007.

Krivit, D., *Increasing the Recycling of Manufactured Shingle Scrap in Minnesota: A Market Development Project*, Report No. MN/RC-2007-07, Minnesota Department of Transportation, St. Paul, MN, 2007.

Krivit, D., *Recycling Tear-Off Asphalt Shingles: Best Practices Guide*, Construction Materials Recycling Association, Milwaukee, WI, 2007a.

Lane, B. and T.J. Kazmierowski, Implementation of CIR with Expanded Asphalt in Canada, In *Transportation Research Record: Journal of the Transportation Research Board, No. 1905*, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 17–24.

Le, J., M. Marasteanu, and R. Milavitz, *Investigation of Performance Requirements of Full-Depth Reclamation Stabilization*, Report No. MN/RC 2016-09, Minnesota Department of Transportation, St. Paul, MN, 2016.

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

Locander, R., Analysis of Using Reclaimed Asphalt Pavement (RAP) as a Base Course Material, Report No. CDOT-2009-5, Colorado Department of Transportation, Denver, CO, 2009.

Lukanen, E.O., and C.G. Kruse, *Optimization of Recycled Asphalt Concrete and Base Materials for Bases of New Asphalt Concrete Pavements*, Report NO. SD97-03, South Dakota Department of Transportation, Pierre, SD, 2000.

Mack, J.W., C.E. Solberg, and G.F. Voigt, Recycling Concrete Pavements, Concrete Construction, pp. 470-473, The Aberdeen Group, Jul. 1993.

Marti, M.M. and A. Mielke, *Synthesis of Asphalt Recycling in Minnesota*, Report No. MN/RC-2002-32, Minnesota Department of Transportation, St. Paul, MN, 2002.

MnDOT, *Investigation of Performance Requirements of Full Depth Reclamation Stabilization*, TRS 1310, Minnesota Department of Transportation, St. Paul, MN 2014.

MnDOT, Minnesota Department of Transportation, *Roadway Data / Data Products*, www.dot.state.mn.us/roadway/data/data-products.html#VMT, Accessed March 2016.

MnDOT, *Standard Specifications for Construction, 2016 Edition*, Minnesota Department of Transportation, St. Paul, MN, 2016a.

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

Pasalkar, A.A., A.A. Wagh, Y.M. Bajaj, and J.D. Dalvi, Comprehensive Literature Review on use of Waste Tyre Rubber in Flexible Road Pavement, *International Journal of Engineering Research & Technology*, Vol. 4, Iss. 02, February 2015.

Puppala, A. J., *Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design*, NCHRP Synthesis 382, Transportation Research Board, National Research Council, Washington, DC, 2008.

Reza, F., Use of Recycled Brick in Aggregates, Report No. MN/RC 2013-21, Minnesota Department of Transportation, St. Paul, MN, 2013.

Sadecki, R.W., G.P. Busacker, K.L. Moxness, K.C. Faruq, and L.G. Allen, *An Investigation of Water Quality in Runoff from Stockpiles of Salvaged Concrete and Bituminous Paving*, Report No. MN/PR-96/31, Minnesota Department of Transportation, St. Paul, MN, 1996.

Salomon, A. and D.E. Newcomb, *Cold In-Place Recycling Literature Review and Preliminary Mixture Design Procedure*, Report No. MN/RC-2000-21, Minnesota Department of Transportation, St. Paul, MN, 2000.

Scullion, T., S. Sebesta, C. Estakhri, P. Harris, C. Shon, O. Harvey, and K. Rose-Harvey, *Full-Depth Reclamation: New Test Procedures and Recommended Updates to Specifications*, Report No. FHWA/TX-11/0-6271-2, Texas Department of Transportation, Austin, TX, 2012.

Shuler, S., *Best Practices for Full-Depth Reclamation Using Asphalt Emulsions*, Report No. CDOT-2-15-04, Colorado Department of Transportation, Denver, CO, 2015.

Skok, G., T. Westover, J. Labuz, S. Dai, and E. Lukanen, *Pavement Rehabilitation Selection*, Report No. MN/RC 2008-06, Minnesota Department of Transportation, St. Paul, MN, 2008.

Snyder, M.B., *Use of Crushed Concrete Products in Minnesota Pavement Foundations*, Report No. MN/RC 96/12, Minnesota Department of Transportation, St. Paul, MN, 1996.

Stolle, D.F.E., T. Guo, and J.J. Emery, Mechanical properties of reclaimed asphalt pavement – natural aggregate blends for granular base, *Canadian Journal of Civil Engineering*, 41(6), pp 493-499, 2014.

Stroup-Gardiner, M., *Recycling and Reclamation of Asphalt Pavements Using In-Place Methods*, NCHRP Synthesis 421, Transportation Research Board, Washington, DC, 2011.

Tang, S, Y. Cao, and J.F. Labuz, *Structural Evaluation of Asphalt Pavements with Full-Depth Reclaimed Base*, Report No. MN/RC 2012-36, Minnesota Department of Transportation, St. Paul, MN, 2012.

Thompson, M.R., Garcia, L., and Carpenter, S.H., *Cold In-Place Recycling and Full-Depth Recycling with Asphalt Products, (CIR & FDR w AP)*, Illinois Center for Transportation Series No. 09-036. Research Report ICT-09-036. March 2009.

Townsend, T., *The Benefits of Construction and Demolition Materials Recycling in the United States*, CDRA White Paper, Construction & Demolition Recycling Association, Aurora, IL, 2015.

Turgeon, C., *Waste Tire and Shingle Scrap Bituminous Paving Test Sections on the Willard Munger Recreational Trail Gateway Segment*, Interim Report No. 91-06, Minnesota Department of Transportation, St. Paul, MN, 1991.

TxDOT, *Lab Manual Test Method TEX-243-F "Tack Coat Adhesion"*, Texas Department of Transportation, Austin, TX, 2011.

Van Dam, T., K. Smith, C. Truschke, and S. Vitton, *Using Recycled Concrete in MDOT's Transportation Infrastructure – Manual of Practice*, Michigan Department of Transportation, Lansing, MI, 2011.

Voth, M., *Cold-In-Place Recycling in the Federal Lands Highway Program*, Presented at the 2008 Western States Recycling Workshop, 3-5 June 2008, Salt Lake City, Utah, 2008.

Westover, T.M., J.F. Labuz, and B.B. Guzina, *Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and Mn/Pave Pavement Design*, Report No. MN/RC-2007-25, Minnesota Department of Transportation, St. Paul, MN, 2007.

Wirtgen, *Wirtgen Cold Recycling Manual*, 2nd ed., Wirtgen GmbH, Hohner Strasse 2, 53578, Windhagen, Germany, 2012.

Wood, T.J., E.N. Johnson, and M.K. Cole, *Research Using Waste Shingles for Stabilization or Dust Control for Gravel Roads and Shoulders*, Report No. MN/RC-2014-06, Minnesota Department of Transportation, St. Paul, MN, 2014.