Utilization of Recycled Asphalt in Cold Mixes and Cold In-Place Recycling Processes

Guidelines

Commissioned by: Communities of Tomorrow
Leveraged Municipal Innovation Fund

Prepared by: Clifton Associates Ltd.

Sponsoring Municipalities: Moose Jaw, Saskatoon
Utilization of Recycled Asphalt in Cold Mixes and Cold In-Place Recycling Processes

GUIDELINES

Commissioned by:
Communities of Tomorrow
Leveraged Municipal Innovation Fund
June 2012

Prepared by:
Allan Widger, M.Sc., P.Eng.
Frank Skilnick, P.Eng.
Elena Zabolotnii, Engineer-In-Training
Clifton Associates Ltd.
EXECUTIVE SUMMARY

There are two common sources of reclaimed asphalt: reclaimed asphalt concrete (RAP) and recycled asphalt shingles (RAS). RAP comes in the form of lumps and millings. RAS can be obtained as construction waste or manufactured ends. Any of these materials can be crushed and blended, with or without the addition of virgin aggregate, to create blends. Reclaimed asphalt is used as a source of two materials: aggregate and bitumen.

RAP can be processed to produce a well-controlled material or used as is.

Rejuvenating agents are used to restore the aged bitumen by restoring the original ratio of asphaltenes to maltenes. This decreases the percentage required of new bitumen, cutback or emulsion for the new mix by reusing the binder already present in the reclaim asphalt material.

Testing of the reclaimed asphalt is required to determine its following engineering characteristics: gradation of RAP, gradation of extracted aggregate, binder content and binder properties. It is also important to identify any contaminants, impurities or additions, and establish their impact on the new mix as well as handling requirements.

The design methods for mixes with reclaimed asphalt are generally similar to conventional methods, with adjustments to best incorporate the old binder content. Suitable design methods used for cold mixes include: the modified Marshall Method, ASTM D4215, the modified Hveem Method, the Oregon Estimation, Chevron Mix Method and the Asphalt Institute Design Method. In testing the designed mix, it is critical to eliminate cutback and water content prior to compaction tests.

For base course design with reclaimed asphalt, the RAP % in the aggregate blend is determined by testing CBR values for different mixes. The bearing capacity of the base mix can be improved through the addition of emulsion, cutback, asphalt or rejuvenator, producing asphalt-bound base. There is potential to improve the stability and gradation of the mix by adding Portland cement, fly ash and sawdust ash.

The AASHTO “Guide for Design and Pavement Structures” is suitable for structural design using mixes with reclaimed asphalt content, with the structural capacity of these being considered equivalent to that of conventional structures.
Applications of reclaimed asphalt include:

- **Asphalt concrete surfaces:**
  - Using hot mix design methods with RAP content below 30%, for surface layers on roadways;
  - Using hot, warm and cold mix design methods with RAP content up to 100% on low volume roads, parking lots, back alleys, bicycle paths and driveways.

- **Granular base:**
  - In plant-processed mixes with RAP content below 30% used as base and subbase on primary roadways;
  - In mixes with 50% RAP content, stabilized with the use of hot asphalt, emulsified asphalt or foamed asphalt;
  - Using the full-depth reclamation process, and increasing the RAP % by decreasing the mixing depth and vice versa;
  - Improving the bearing strength of the base with Portland cement.

- **Shoulder base with RAP content up to 100%.
- Fill for embankments, trenches and utility cuts.
- Dust control on gravel roads.
- Slurry seals and chip seals.
- Backfill for temporary earth walls.

Asphalt recycling processes are divided into two major groups: central plant processes and in-place processes. Central plant processes involve transporting the reclaim offsite to a processing facility, and provide better control over the output quality. In-place processes include cold in-place, hot in-place, and full depth reclamation approaches. Each of these processes employs distinct equipment. Some equipment producers have developed proprietary equipment and processes similar to HIP, CIP and FDR.

The benefits of reclaiming asphalt include recycling aggregate and binder. Cold processes decrease energy input requirements, and in-place processes decrease hauling needs. With rising binder costs and increasing aggregate scarcity, there is a strong argument for economic benefit and sustainability in using reclaimed asphalt.

Training will allow the assessment of RAP properties and determination of appropriate uses.
# TABLE OF CONTENTS

1. Introduction 7
2. Definitions and Clarifications 8
3. Types of Reclaim Asphalt Mix 9
    3.1 Lumps of Reclaim 9
    3.2 Millings 9
    3.3 Blends 9
    3.4 Cold In-Place Recycled Material 9
    3.5 Asphalt Shingles 10
4. Processing of Reclaim Mix 12
5. Rejuvenating Agents 14
6. Testing of Reclaim Mix and Design Methods 15
    6.1 Testing Needs and Procedures 15
    6.2 Mix Design Methods 16
    6.3 Structural Design 19
7. Safety Considerations 20
8. Uses of Reclaimed Material 21
    8.1 Production of Cold Mix with RAP 21
    8.2 Hot and Warm Mixes 21
    8.3 Granular Base 22
    8.4 Shoulder Base 23
    8.5 Fill 23
    8.6 Dust Control on Gravel Roads 24
    8.7 Slurry Seals and Chip Seals 24
    8.8 Backfill for Temporary Earth Walls 25
    8.9 Other 25
9. Process and Equipment 27
    9.1 Central Plant Mix Process 27
    9.2 In-Place Recycling 29
    9.3 Full Depth Reclamation 31
    9.4 Recyclers 31
10. Assessment of Best Practices 32
    10.1 Economic Benefits 32
    10.2 Other Considerations 33
11. Areas of Future Research 34
12. Training 36
13. Conclusions and Recommendations 37
References 40
Photo Credits 45
Appendices 47
    Material Specifications
    Equipment
    Survey Summary
1. INTRODUCTION

This report has been commissioned by the public-private partnership Communities of Tomorrow on behalf of a number of Saskatchewan urban communities with the goal of developing a set of guidelines reviewing existing applications of reclaimed asphalt in cold mixes and cold in-place recycled processes. The scope includes materials, processes and equipment. The guidelines focus on the utilization of existing reclaim that has been stockpiled.

The anticipated end users of these guidelines comprise municipal road preservation administrators and supervisors, as well as municipal council in charge of road maintenance decision-making processes. While engineering input was necessary to develop the technical content of these guidelines, a significant effort was made to keep the information understandable and usable by the intended reader.

To provide the Saskatchewan municipalities with current guidelines on the matter, worldwide practices on the issue were reviewed, with special interest for places with similar climate.
2. DEFINITIONS AND CLARIFICATIONS

The utilization of reclaimed asphalt is a relatively new field of practice. As a result, many new terms and acronyms related to the various aspects of this practice have entered the language. The terms are individually defined and explained later in these guidelines. A list of their acronyms and synonyms is provided below.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIR</td>
<td>Cold In-Place Recycling or Cold In-Place Rehabilitation (interchangeable terms). Sometimes referred to as CIPR.</td>
</tr>
<tr>
<td>CIPR</td>
<td>Same as CIR</td>
</tr>
<tr>
<td>HIR</td>
<td>Hot In-Place Recycling</td>
</tr>
<tr>
<td>FDR</td>
<td>Full Depth Reclamation</td>
</tr>
<tr>
<td>RAP</td>
<td>Reclaimed Asphalt Pavement</td>
</tr>
<tr>
<td>RAS</td>
<td>Recycled Asphalt Shingles</td>
</tr>
<tr>
<td>Rotomixing</td>
<td>Also “mixing” or “remixing.” This term describes a step within the FDR process consisting of milling the pavement surface and, optionally, the top layer of subgrade to a specified depth in order to obtain a granular base material. In the industry, this term is sometimes used interchangeably with FDR.</td>
</tr>
</tbody>
</table>
3. TYPES OF RECLAIM ASPHALT MIX

3.1 LUMPS OF RECLAIM

Lumps of reclaim are obtained when ripping the asphalt concrete road surface with equipment discussed in Section 9.1. Lumps are loaded and hauled to a central site for storage and processing. Recycling asphalt concrete material as lumps allows a good control over the size and gradation of the final aggregate during processing (Kandhal et al, 1997 chap. 12). Crushing of RAP results in a minimal breakdown of the original aggregate, and the lumps are less likely to set up in stockpile. Crushing operations resulting in blending of materials from stockpiles and splitting crushed material also improves uniformity.

3.2 MILLINGS

Millings are the recycled asphalt material obtained as a result of removal by milling or planning with the use of equipment discussed in Section 9.2. The asphalt concrete surface material is milled to a relatively small size, resulting in the aggregate being degraded. The advantage of recycling asphalt concrete as millings is that it is fast and done in-place using equipment described in Section 9.2; the drawback is that there is poor control over gradation and size, often resulting in oversized particles (Kandhal et al, 1997, chap. 12) and non-uniformity due to patching materials. Unlike lumps, millings have a tendency to set up and harden in stockpile, making future processing difficult.

3.3 BLENDS

Crushed reclaimed asphalt lumps, millings and virgin aggregate can be combined to create a blend with the gradation required to produce a new mix.

Blended material does not set up as much in the stockpile. However, blended material that has been stockpiled for a considerable amount of time, particularly in warm weather, may harden and require re-crushing (FHWA 2) or reworking.

3.4 COLD IN-PLACE RECYCLED MATERIAL

Due to a very specific production process, the cold in-place recycled millings or remixing are classified as a separate material category. Produced by milling equipment which pulverize the existing pavement surface and then deposit it in place, this material is distinct from millings, discussed in Section 3.2, in that it is immediately reincorporated into the road structure with or without additives, rather than stored off-site and reprocessed. Cold in-place recycling material may conform to the same property requirements as any other reclaimed...
asphalt material; however, the in-place processing often results in lower quality control over the particle gradation. Existing base gravel is typically incorporated in the pulverized asphalt.

Additives to cold in-place recycled material are as follows:

- Water is mixed thoroughly together with the milled material to bring it up to its optimum compaction moisture content (Lewis et al);
- Cement: typically, 2 - 4% (w/w) of cement is added during the recycling process. The cement can be added in three different ways: spreading it onto the surface of the road ahead of the recycler; mixing it with water in a specially designed slurry mixer to form a slurry that is introduced directly into the mixing chamber; and using a specialised cement spreader incorporated in the recycler’s frame (Lewis et al);
- Bitumen emulsion: containing approximately 60% of bitumen and 40% of water, when used in the cold in place recycling process, bitumen emulsion is transported in a tanker that is pushed ahead of the recycling machine (Lewis et al). 0.5 – 3.0% of bitumen emulsion is added to granular road building materials (Kandhal et al, 1997, chap. 14);
- A combination of bitumen emulsion and cement: in many cases, combining bitumen emulsion with cement is found to be effective. The percentage of cement that is added may typically vary from 1% to 3%. It is introduced into the recycled mixture together with the bitumen emulsion (Lewis et al);
- Foamed bitumen: In the case of granular materials, 3 - 5% of foamed bitumen (w/w) is normally added. When the recycled material contains a high proportion of asphalt, a reduced content of foamed bitumen of 2 - 3% is common (Lewis et al).

3.5 ASPHALT SHINGLES

In North America, it is estimated that recycled asphalt shingles (RAS) constitute 8% of the total construction waste; recycled asphalt shingles can be used in paving applications, as aggregate for road construction, as dust control on gravel roads, in cold patch asphalt, and as feedstock/fuel for cement kilns and coal-fired boilers (NERC).

The primary use of recycled shingles has been in hot mix asphalt (NERC) in an attempt to reclaim the asphalt. Because of the high asphalt binder content in RAS (19-36%), even small percentage additions replace significant quantities of new asphalt binder. RAS can work in all asphalt mixes provided that all specifications are followed. Where virgin binder constitutes at least 70% of the total binder, no
change in binder grade is required; otherwise, a softer binder may be needed (CAPA).

Some manufacturers have developed processes to recycle asphalt shingles into manufactured shingles, used as a substitute to bitumen in asphalt concrete pavement, and process engineered fuel used in industrial burners (Gemaco).

Waste management practices are the primary barrier to effectively using asphalt shingles; waste and landfill administration practices can be locally adapted to collecting shingles for their recycling as opposed to disposal in the landfill. The US Environmental Protection Agency has developed a web site, shinglerecycling.org, as a comprehensive resource to such management practices.

Sources of asphalt shingles include landfills, shingle production plants and construction sites. Currently, there is no known effective way of processing used shingles from landfill sites. The City of Saskatoon allows asphalt shingle manufactured ends to be incorporated into the asphalt concrete mix. This eliminates the issue of separating shingles from nails, improves material uniformity and eliminates issues related to binder aging.

According to the NorthEast Recycling Council (NERC), approximately one million tons of scraps from asphalt shingle manufacturers are produced annually in US. A list of North-American shingle producers is provided below (from NERC).

<table>
<thead>
<tr>
<th>Producer</th>
<th>Web Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas Roofing Corporation (GA, US)</td>
<td>atlasroofing.com</td>
</tr>
<tr>
<td>Building Products of Canada (QC)</td>
<td>bpcan.com</td>
</tr>
<tr>
<td>CertainTeed Corporation (PA, US)</td>
<td>certainteed.com</td>
</tr>
<tr>
<td>EMCO (QC)</td>
<td>emcoltd.com</td>
</tr>
<tr>
<td>GAF/ELKA Materials Corporation (NJ, US)</td>
<td>gaf.com</td>
</tr>
<tr>
<td>IKO Production Inc (ON)</td>
<td>ikocom</td>
</tr>
<tr>
<td>Malarkey Roofing Products (OR, US)</td>
<td>malarkeyroofing.com</td>
</tr>
<tr>
<td>Owens Corning (OH, US)</td>
<td>roofing.owenscorning.com</td>
</tr>
<tr>
<td>Pacific Coast Building Products, Inc. (CA, US)</td>
<td>paccoast.com</td>
</tr>
<tr>
<td>W.R. Grace and Co</td>
<td></td>
</tr>
<tr>
<td>TAMKO Building Products, Inc.</td>
<td>tamko.com</td>
</tr>
</tbody>
</table>
4. PROCESSING OF RECLAIM MIX

Reclaimed asphalt processing pertains to crushing RAP and RAS material to the desired gradation in order to use it as aggregate and also to increase the contact surface area of bitumen so that it can be softened and reincorporated into the new mix. Crushing can be done on-site for in-place and full depth reclamation processes, and off-site for central plant cold mix processes.

Central plant crushing operations involve crushing equipment, screening equipment, and conveyors. The input materials include lumps (Section 3.1), millings (Section 3.2) shingles (Section 3.5), as well as virgin aggregate. The output material is a RAP aggregate of desired gradation. Central plant crushing is done best in winter conditions, as low temperatures render the bitumen fraction brittle, making it easier to process.

There are three main types of crushers, listed in order of preference:

- **Impact crushers**: the aggregate is crushed by the force of impact as it moves through the machine vertically or horizontally, depending on the model (SBM).
- **Jaw crushers**: these are equipped with two sets of vertical jaws, one of which is fixed and the other being movable. The aggregate is crushed by the pressure applied by the jaw plates as it travels downward (Ambica).
- **Cone crushers**: crush aggregate by means of a gyrating spindle as it travels downward.

These types of crushers can be both stationary and mobile.

Screening equipment includes screens with square openings, slotted openings and vibrating wire.

*In-place processes* either use mobile crushing and screening units discussed above, or incorporate crushing operations into the material reclamation step, as the material is pulverized during mixing. The latter approach generally provides less quality control over the aggregate gradation as compared to mobile unit crushing operations. This process produces the cold in-place recycled material (see Section 3.4) as output, which is a RAP aggregate of desired gradation, with or without additives. The key difference between this output graded aggregate and the graded aggregate obtained through central plant crushing processes is that the blending and quality control over gradation in the latter process is much better. On-road operations can only process and blend the material across the width of the cut and not along the surface.
The in-place pulverizing of the material is done with milling equipment. Equipment producers offer both basic milling machine models which simply pulverize the top layer of the asphalt concrete, and more sophisticated models which allow the addition of water, cement, foamed asphalt, etc. There are also milling and mixing attachments available for other equipment.

When selecting the appropriate milling machine, the direction of rotation of the mixing drum must be considered. Machines with the mixing drum rotating in the same direction as the wheels tend to pulverize the road surface and deposit it behind without significant mixing, whereas machines with the mixing drum rotating in a direction opposite to the wheels tend to pulverize, uplift and mix the material. Therefore, the first type is more suitable for shallow depth cold in-place recycling and the latter is more appropriate for deeper cold in-place recycling works. See graphic insert for Sections 9.2 and 9.3 (page 31) for equipment examples.

Full depth reclamation: in full depth reclamation processes, the asphalt concrete is milled, or pulverized in place, with the use of a rotomixer. Rotomixers generally have a mixing drum rotating in the direction opposite to the wheels, ensuring full depth turnover and better material breakdown.

In the industry, the terms “milling,” “remixing,” “rotomixing” and “mixing” are used interchangeably with “full depth reclamation” to refer to the pavement and base milling process.

Aggregate degradation: it is important to note that all of the processing approaches discussed above result in the degradation of the RAP aggregate. While the main purpose of the crushing, pulverizing and milling processes is to break down the cohesive pavement into aggregate-sized material, a portion of the aggregate is invariably crushed to a smaller size. This means that the RAP aggregate gradation is finer than the original gradation of the aggregate used in the original asphalt concrete mix.

There are some processes developed by equipment producers which minimize the degradation of aggregate. These processes involve:

- Using heat to soften the binder in the RAP lumps to break them down. See Section 9.2 for examples of this type of equipment employing this process;
- Using the heat in hot in-place processes to soften and rework the asphalt concrete pavement surface without milling it (see Section 9.2 for examples of equipment).
5. REJUVENATING AGENTS

Rejuvenating agents are intended to restore aged (oxidized) asphalt binders by restoring the original ratio of asphaltenes to maltenes. As most of these products are proprietary, there is no defined formula for them. However, their primary components are bituminous; a rejuvenating product must contain maltenes in order to improve the asphaltenes to maltenes ratio (Boyer). When used properly, rejuvenating agents will decrease the proportion of new asphalt, cutback or emulsion required in the mix; because of this ability, rejuvenators are considered more environmentally sustainable (Brownridge).

A number of studies have tested and compared various proprietary brands of rejuvenators. A summary of their findings is presented in the table below. It is important to note that, since rejuvenator formulae are proprietary, they may change in time. It is therefore beneficial for transportation agencies to share information on their own experience with these products; this can be achieved through such means as approved product lists.

<table>
<thead>
<tr>
<th>Product:</th>
<th>Notes:</th>
<th>More information:</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR2000</td>
<td>Tested with positive results by US Army Corps of Engineers (Shoenberger).</td>
<td>Appendix E17</td>
</tr>
<tr>
<td>APR 100 and SBRT SO</td>
<td>Produced by Mariani Asphalt Company. Successfully tested by US Army Corps of Engineers (Shoenberger).</td>
<td><a href="http://www.marianiasphalt.com">www.marianiasphalt.com</a></td>
</tr>
<tr>
<td>BCR2000 BCR3000</td>
<td>Successfully tested by US Army Corps of Engineers (Shoenberger).</td>
<td>See Shoenberger Appendix A</td>
</tr>
<tr>
<td>CPR</td>
<td>Produced by Reeves Enterprises Inc. of Selkirk, NY. Successfully tested by US Army Corps of Engineers (Shoenberger).</td>
<td>See Shoenberger Appendix A</td>
</tr>
<tr>
<td>CRF Restorative Seal</td>
<td>Produced by Tricor Refining, LLC, CA. Inconclusively tested by US Army Corps of Engineers (Shoenberger). Available in SK from Pounder Emulsions in Saskatoon (306.934.1500),</td>
<td><a href="http://www.tricorrefining.com">www.tricorrefining.com</a></td>
</tr>
<tr>
<td>GSB-series</td>
<td>Successfully tested by US Army Corps of Engineers (Shoenberger).</td>
<td><a href="http://www.asphaltsystemsinc.com">www.asphaltsystemsinc.com</a></td>
</tr>
<tr>
<td>LAS-320</td>
<td>Limited tests by US Army Corps of Engineers with acceptable results (Shoenberger).</td>
<td><a href="http://www.enviroseal.com">www.enviroseal.com</a></td>
</tr>
<tr>
<td>PAS</td>
<td>Limited tests by US Army Corps of Engineers with acceptable results (Shoenberger).</td>
<td><a href="http://www.marianiasphalt.com">www.marianiasphalt.com</a></td>
</tr>
<tr>
<td>PASS(R) Emulsion</td>
<td>A polymer-modified asphalt rejuvenator suitable for application at ambient temperatures between 7 and 49°C. California Transportation successfully used the product for a cold in-place recycling project to rebuild a section of Interstate 10 (Main Street Materials et al).</td>
<td>Appendix E18, E18-1</td>
</tr>
<tr>
<td>Reclamite</td>
<td>Tested by Air Force Weapons Laboratory (US) in 1970 with positive results, determining that manufacturer claims are correct (Rostler et al). Later studies have confirmed these findings. Available in SK from Pounder Emulsions in Saskatoon (306.934.1500).</td>
<td>Appendix E16</td>
</tr>
</tbody>
</table>
6. TESTING OF RECLAIM MIX AND DESIGN METHODS

6.1 TESTING NEEDS AND PROCEDURES

A Minnesota DOT study has concluded that the key engineering properties of recycled asphalt pavement – hydraulic conductivity, drainage, gradation, stiffness, strength – are similar or better than those of virgin aggregate, allowing the substitution of the latter with RAP in base, subbase and other materials in road construction. In addition, RAP was found not to leach substantial amounts of inorganic chemicals into the surrounding environment (Gupta).

To produce a good mix design, the recycled asphalt material must be tested in order to establish its engineering characteristics. The main characteristics of interest are:

- Gradation, which tends to be somewhat finer in RAP as compared to virgin aggregate;
- Asphalt content, which usually varies from 3 to 7% by weight and 10 to 20% by volume;
- Asphalt penetration and viscosity: depending on pavement age, RAP binder penetration values are known to range from 10 to 80, and absolute viscosity values at 60°C range from 2,000 to 50,000 poise (Thurston County, WA).

For testing, a minimum of five or six representative samples must be collected, and the following properties are determined (Kandhal et al, 1997, chap. 14):

- RAP gradation using AASHTO T27 sieve test (Appendix S1);
- Binder content, % using AASHTO T 164-93 test;
- Gradation of extracted aggregate using AASHTO T27-93 sieve test; and

Where reclaimed asphalt is known to contain steel slag, it renders to the recycled mix a number of desirable properties such as increased friction (hence increased strength) in aggregate (Deniz).
6.2 MIX DESIGN METHODS

The design process for hot or cold mix asphalt has two main aspects:

- The mix design defining the types and quantities of RAP and virgin aggregates, and of virgin AC binder, cutback, emulsion and/or additives; and
- The structural design defining the thickness of the new layer as a function of traffic loading.

According to the American Association of State Highway and Transportation Officials, the main challenge in the application of current mix design methods is that an assumption is made that the aged binder is fully reincorporated into the mix (AASHTO 1). However, lab tests indicate that the aged binder does not fully re-activate. This problem is exacerbated for mixes with high RAP content.

There are four distinctive mix design categories, based on the mix type and output material: cold mix design, hot mix design for low RAP content, hot mix design for high RAP content and base course mix design.

**Mix design**

The mix design methods for central plant hot or cold mix recycling and cold in-place recycling are generally the same. For both methods, samples of RAP are obtained to determine their characteristics and develop a suitable mix design. Following are the conventional design mix methods using RAP that are suitable for the two methods:

- Modified Marshall Method (Appendix S2): suitable for both CIR and central plant cold mix recycling processes, it allows design mixes with RAP content range of 0 to 100% (Hussain). It has been shown that, for CIR processes, the addition of 20-25% virgin aggregate decreases porosity and improves stability (Murphy et al). Also for CIR, the optimum content of recycling agent is 2-3% of dry RAP weight (Castedo).
- ASTM D4215: these design specifications are suitable for central plant cold mix recycling processes where used as surface, base or subbase course.
- Modified Hveem Method (Appendix S2).
- Oregon Estimation: for 100% RAP mixes (Appendix S2).
- Chevron Mix Method: allows up to 100% RAP use (Appendix S2).
- Asphalt Institute Design Method (Appendix S2).

In testing design mixes with RAP content, it is critical to correctly adjust asphalt concrete content for cutback and water. Specifically, it is
important to eliminate, through drying or other means, the cutback and water prior to compaction in lab tests.

Conventional asphalt hot mix design (RAP content from 5 to 30%)

Once the properties of RAP are known, the desired aggregate gradation of the new mix can be selected. Using various blends of RAP and virgin aggregate, this new gradation must be obtained. The fraction of RAP in the total aggregate can be as high as 30% without impacting the properties of the new mix (NCAT). In the lab, testing has shown that RAP mixes designed using the conventional Marshall Mix Design method perform the same or better than conventional mixes, but that for mixes with RAP percentage above 45% the flow properties were decreased below requirements (Hussain et al).

For a hot mix, the percentage of RAP in the final aggregate blend that is to be added determines the binder grade. For RAP content between 15 and 25%, select virgin binder one grade softer than normal to counter the stiffening effect of the aged binder in RAP; for RAP contents above 25%, use AASHTO M 323 testing procedures to determine binder type (Kandhal et al, 1997, chap. 3). Conversely, the RAP percent can be determined based on binder grade and percent of binder in RAP. As RAP may contain high percentages of fines, this could limit the percent of RAP in total aggregate.

For cold mixes, emulsions are the most common, and cutbacks are used less commonly. Cement, fly ash, lime and other chemical stabilizers can be used with the emulsions (Kandhal et al, 1997, chap. 14) for in-place applications.

The choice of rejuvenating or recycling agent depends on how it interacts with the aged binder; the softening of the binder is dependent on its properties, the mixing time and ambient temperatures. Some of the aged asphalt content will not soften and will act as aggregate. The coating of the aggregate can be tested as a measure of how compatible the recycling agent is with the aggregate mix (Kandhal et al, 1997, chap. 14).

Conventional asphalt hot mix design with high RAP content (RAP content from 30% to 100%)

Once the design gradation of the aggregate is obtained, through crushing and screening, as well as blending with virgin aggregate if necessary, the type and quantity of new binder must be determined. For aggregates with high reclaim asphalt percentage, proprietary emulsion agents may be more effective than conventional emulsions or cutbacks, as they contain rejuvenating agents designed to restore aged asphalt (Kandhal et al, 1997, chap. 14). For 100% RAP aggregates, a small amount of recycling (rejuvenating) agent can be added to soften
the aged binder without increasing binder content; however, it may be very difficult to disperse the binder if an insufficient amount is used (Kandhal et al, 1997, chap. 14).

When using conventional emulsions as new binder, 0.5 to 3.0% of new binder is required, with higher RAP content requiring less new binder. For design purposes, aggregate-binder mixes with new binder contents of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0% are prepared and tested (Kandhal et al, 1997, chap. 14) for workability and other relevant parameters. The percentage of residual asphalt in the emulsion should be used in the calculation of new asphalt percent.

While it is possible to design asphalt mixes with RAP content higher than 45%, the mix properties are impacted and the mix is not expected to perform as well under traffic loading. Generally, mixes with high RAP content are as stable as or more stable than mixes with virgin aggregates; however, they do not flow as well, indicating that aged binder is not participating well and the mixtures are under stress during loading (Hussain), making them less resistant to cracking. The water from emulsion and cutter from cutbacks tend to improve the workability of recycled mixes during laying and need to be released prior to final compaction.

A study by the Belgian Road Research Center has shown that, when using sound design procedures, it is possible to design high quality hot mix asphalts with high percentages of reclaimed asphalt. The performance related laboratory tests showed no relevant differences between the mixes with “common” percentages of reclaimed asphalt and those with “high” percentages of reclaimed asphalt, and that the amount of reclaimed asphalt used in hot asphalt mixes can be increased without affecting the performance of these mixes (Perez et al, 2004).

**Base course design**

The key design parameter for incorporating processed RAP into granular base material is the blending ratio of RAP to conventional aggregate that is needed to provide adequate bearing capacity. The ratio can be determined from laboratory testing of RAP aggregate blends using the CBR test method or previous experience (FHWA 1). Some US agencies are using up to 30% RAP content in the final base aggregate blend. In UK, the Waste & Resource Action Programme advises a RAP content of up to 50% in base courses (AggRegain). Bottom lift bases may incorporate up to 100% RAP content. Testing procedures are the same as for regular base materials.
There is potential to use higher percentages of RAP with a small amount of emulsion, cutback, asphalt or rejuvenator in order to produce black base or asphalt-bound base.

**Testing:** The following engineering properties of RAP and other reclaimed asphalt material are of interest when using it as base material:

- Gradation;
- Compacted density (which is usually lower than that of sand due to the presence of binder);
- Permeability (FHWA 1). The US Federal Authority specifies that the base permeability should be in the same range as sand, and that the material should be free-draining. In Saskatchewan, dense graded or soil stabilized base with generally low permeability has been used.

Shear strength and bearing strength (CBR value) are also properties of interest, and should fall in the acceptable ranges of regular aggregate. For a sample of draft specifications for RAP aggregate base, see Appendix S4, p.20.

### 6.3 STRUCTURAL DESIGN

The AASHTO “Guide for Design of Pavement Structures” is suitable for the structural design of CIR and central plant RAP asphalt mix recycling processes as the structural capacity of these can be considered equal to that of conventional asphalt mix structures, with a recommended structural layer coefficient of 0.25 to 0.35 (Thurston County, WA). CIR and central plant high RAP asphalt mix recycling processes are not recommended for use as a wearing course in high-traffic areas. Saskatchewan Ministry of Transportation and Infrastructure has successfully used cold mix layers as wearing course on low volume roads but has found that:

- Thin layers do not properly accommodate the maximum size of the RAP aggregate. This may result in poor compaction and lack of interlocking between aggregate particles in the lift. The rule of thumb is that the thickness of the asphalt concrete layer must be equal to or exceeding the size of the maximum aggregate size multiplied by 2.5.
- Cold Mix layers with a thickness above 35 mm tend to rut. This would also be the case for RAP cold asphalt mixes which may also require a seal of some kind. Therefore, cold asphalt mixes with RAP should be used in locations where some rutting can be accepted.
7. SAFETY CONSIDERATIONS

Prior to working with any recycled asphalt materials, consideration must be given to the composition of these materials. Depending on use, time of placement and location, recycled asphalt materials could contain asbestos, slag (used in pavements around Regina), glass, sulphur, etc. Any non-standard component (e.g. beside the granular aggregate and asphalt fractions) must be considered, primarily for reasons of handling safety. Also, the effect of these components on the mix performance must be considered.

*Recycled asphalt shingles* always contain some minor contaminants, notably asbestos. With proper screening and testing procedures, the risk of exposure is extremely low (CAPA).
8. USES OF RECLAIMED ASPHALT

8.1 PRODUCTION OF COLD MIX WITH RAP

Cold mixes generally fall into two categories: low ratio and high ratio, as a function of the RAP percentage in the total aggregate. Mixes with RAP content below 30% are considered low ratio recycled cold mixes, and mixes with RAP content above that are considered high ratio recycled cold mixes. While this classification is not strictly scientific, the two categories are differentiated for reasons of (a) mix characteristics, (b) applications and (c) associated levels of risks. Generally, low ratio cold mixes are considered to match all characteristics of regular cold mixes and are used in the same applications, whereas high ratio cold mixes may have characteristics that are different from the regular cold mixes, such as flow and workability, and are generally considered to pose a higher risk of failure due to durability concerns.

Cold mixes – low ratio: RAP that has been crushed to a specified gradation and blended at low ratios with new aggregate can be processed to produce cold mixes using standard process. The cutter in the cutback will tend to soften the asphalt in the RAP, improving the workability and compaction. This new cold mix may set up quicker than regular mixes because the fines in RAP will absorb some of the cutter. Similarly, in emulsions, the water in the mix will improve workability and compaction, but the fines in RAP will cause the emulsion to break quicker.

Cold mixes – high ratio: Processed RAP blended at high ratio with new aggregate can be used to produce cold mixes using standard processes. At high ratios, a rejuvenator will likely be required to improve workability. This material should be used immediately after mixing and should not be stockpiled.

8.2 HOT AND WARM MIXES

Hot and warm mixes – low ratio: Hot mixes with RAP ratios below 30% can be used for the same applications as virgin hot mixes. From an economic point of view, it makes the most sense to use these mixes as pavement material for intermediate and surface layers.

A recent survey has shown that in the US, due to performance concerns, transportation agencies tend to have a restricted use of hot mixes with RAP in surface layers, with less than 5 states allowing up to 29% RAP in the surface course as compared to 10 states allowing the same RAP content in the intermediate layers. Generally, it was determined that states allow 10% to 20% of RAP in the surface courses.
for medium and heavy traffic roads (meaning 3 to over 30 million ESALs for a 20-year design). A comment was made that even in states allowing usage of higher RAP percentages, contractors typically did not submit mix designs with RAP content above 25% (Copeland 2011). The Ontario Ministry of Transportation uses 20% to 50% RAP content for base and binder courses.

Hot and warm mixes – high ratio: 30 - 100% RAP mixes, although not generally used on main highways, are being implemented in urban and residential applications such as driveways, parking lots and small to medium size road repairs. The hot in-place 100% RAP mixes are suitable for pothole patching, utility cut repairs, curbing, railway crossing repairs, all-winter patching jobs, etc. (Bagela).

100% RAP mixes have been successfully used on shoulders and could be used in alleys. Hot mixes with RAP ratios above 30% can be used for the same applications as virgin mixes on lower pavement surface lifts, but are not recommended as a surface course where some ravel or pick-out is not acceptable. A surface flush, seal or slurry seal can be used to protect the surface in traffic areas.

Whereas low ratio hot and cold mixes have been extensively used throughout North America and are fairly well-studied, high ratio hot and cold mixes are rarely used and are not normally recommended for areas where performance is a priority.

8.3 GRANULAR BASE

According to a recent survey, RAP content of up to 29% in the base course of a conventional road design is used by 10 transportation agencies, with over 20 more considering it (Copeland 2011). In Canada, the City of Hamilton allows the use of up to 30% RAP in its base course (Appendix S3).

While the conventional way of incorporating RAP into base courses is by blending RAP aggregate with virgin aggregate (see Section 6), there is the full-depth reclamation process, consisting of breaking and crushing the existing AC road surface and underlying granular base layers up to a typical depth of 100 mm (and up to a maximum depth of 200 mm) and mixing them (FHWA 1). Other sources suggest, for low volume roads, a mixing depth of up to 300 mm (Koch). Increasing the mixing depth decreases the RAP % and vice versa.

Conventional granular aggregates do not bond well with RAP or blended granular material containing RAP. Consequently, raveling can occur if thin layers of conventional base are placed over material containing RAP (FHWA 1). Construction methods are similar to
conventional base course, although using little or no water improves compaction (FHWA 1). Performance is expected to be equivalent to that of conventional base material.

**Portland cement addition:** Portland cement can be added to base aggregates with high RAP content in order to improve its bearing strength. According to research performed at the University of Texas, the optimum Portland cement content for base course containing 100, 75 and 50% RAP is, respectively, 4, 3 and 2% (Yuan et al). This will produce a semi-rigid layer that will act like soil cement (see Section 6). An increase in cement content results in higher structure rigidity and shrinkage cracking.

**Asphalt-treated bases (ATB):** the stabilization of the base course containing 50% RAP material with asphalt materials is commonly used in Alaska as an alternative to the scarce granular base material. The base can be treated with (i) hot asphalt, (ii) emulsified asphalt and (iii) foamed asphalt. This treatment was found to be most effective with hot asphalt; however, the emulsified asphalt treatment, a cold mix technique, was found to be almost as effective (Li et al).

Recent research indicates that RAP aggregate properties such as stability and gradation can be improved by adding sawdust ash when using it as a subbase or base material (Osinubi et al).

### 8.4 SHOULDER BASE

To prepare shoulder base, RAP is put through a plant at a 100% reclaim ratio and laid on shoulders as opposed to shoulder base. All engineering properties for shoulder base are the same as for regular base (see Section 8.3). Also, a high ratio recycled mix can be used on shoulders.

In Ontario, the Ministry of Transportation allows 100% RAP in shoulder aggregate material (OHMPA).

### 8.5 FILL

US states with similar climate to Saskatchewan, such as Montana, are using reclaim asphalt as an embankment additive, with reported satisfactory results. The design requirements for RAP in embankment construction are the same as for similar sized soil-aggregate blends, conventional aggregates, or shot rock fill. When used as an embankment or fill material, the undersize portion of crushed and screened RAP, typically less than 50 mm (2 in), may be blended with soil and/or finely graded aggregate or used unblended (FHWA 1). The Ontario Hot Mix Producers Association claims that RAP fill stabilizes soft subgrade (OHMPA); this property may be very useful in
Saskatchewan conditions, where plastic clays and tills constitute much of the subgrade.

The City of Regina successfully uses RAP as trench backfill (Kosolofski). The City of Saskatoon uses RAP as a bound or unbound base to backfill utility cuts, as well as utility cut surfacing wet spring conditions, and finds it to be more durable than regular aggregate (Prang). RAP can be also used as a pipe bedding material and culvert backfill.

Where pieces of broken asphalt pavement are used as embankment base, size and placement restrictions should apply in the same manner as for boulders and cobbles (NYSDOT). Due to the bituminous content, asphalt millings are not considered clean fill and should not be used in sensitive areas.

**8.6 DUST CONTROL ON GRAVEL ROADS**

A 2010 study (Koch et al) assessed the performance of RAP aggregate as means of dust control on gravel roads. The study has found that RAP aggregate, when blended with virgin aggregate used as traffic gravel, decreases dust loss. The study also recommends:

- Blending the RAP and virgin aggregates in a pugmill rather than in place to avoid segregation;
- Compacting the blend with a roller to improve serviceability; and
- Adding CaCl to the RAP and virgin aggregate blend to further improve dust control properties (Koch et al).

The fines generated from processing RAP can be used in this application as they are not used in recycled mixes.

**8.7 SLURRY SEALSA ND CHIP SEALS**

A number of cities and transportation agencies are implementing 100% RAP chip seals and slurry seals. The Cities of Duartre (Missouri Petroleum) and Colton (Udelhofen) in California are successfully using the slurry seal material on roadway rehabilitation projects. For City of Duartre slurry specifications, see Appendix S5, p. 3 and the graphic insert on previous page for elaboration.

The use of RAP in slurry seals provides another application for RAP fines. The incorporation of fines in slurry seals is likely more beneficial from an economic perspective than their use for the purpose of dust control (Section 8.6) as it makes better use of the binder.
8.8 BACKFILL FOR TEMPORARY EARTH WALLS

Mechanically stabilized earth walls are vertical retaining walls built with the use of face panels, engineered horizontal reinforcement systems, and backfill. The backfill is usually made of common fill earth which is free-draining, well-graded and has high frictional strength. Clayey and other cohesive types of soil are not desirable as a backfill due to their swelling potential and poor drainage properties (Rathje et al). These materials are far more common in Saskatchewan than free-draining soils.

Several test sections with RAP backfill that were built in Texas have performed well. However, due to the creep potential in RAP, especially for higher binder contents, it is recommended that RAP not be used in permanent retaining walls. However, RAP use as a backfill is possible in temporary walls with a service life no longer than a few years (Rathje et al).

8.9 OTHER

Parking lots
Parking lots are increasingly being built and resurfaced using hot and cold mixes with reclaim asphalt. Successful examples include the Baylor Hospital parking lot in Dallas, Texas, the Las Vegas Motor Speedway parking lot (LVMS), and Lot 4 of the Dallas Cowboys Stadium (Swaner). The City of Regina has also had success using 100% RAP laid as gravel surface in a number of its parking lots.

Driveways
Paving new or repaving old driveways with RAP is a growing application of reclaim asphalt, with the main driving force behind it being the high and increasing cost of new asphalt concrete. In North America, a number of private companies are offering the service of repaving an old driveway or constructing a new driveway with 100% RAP aggregate.

There are two general approaches to laying the 100% RAP driveway:

- Gravel-type driveway: the RAP aggregate is installed on a graded, compacted subgrade with the use of graders, compactors or pavers. Optionally, the surface can be seal-coated. This type of surface is more stable than conventional gravel surfaces and constitutes a good base for an AC surface to be installed at a later date (CreativeAsphalt).

- 100% RAP asphalt concrete pavement surface: a conventional cold-mix or hot-mix process using a 100% RAP aggregate is
Some companies suggest a 75 mm final AC thickness placed in two lifts (CreativeAsphalt).

RAP has also been used as base under paving stones with only enough sand placed on top to provide a smooth surface for laying the stones.

**Bicycle paths and walking trails**

A feasibility study for incorporating RAP materials into the trail program (City of San Jose, 2007) concluded that RAP materials are suitable for this application both as base and hot mix. The same study states that Caltrans currently limits the fraction of RAP in base materials to 50% and the fraction of RAP in hot mixes to 30%. In Ontario, bicycle paths and trails can be built using hot mix asphalt containing 30% reclaim asphalt material (OHMPA). However, the use of higher proportions of RAP both in the base course and as a hot mix on trails and bicycle paths is becoming increasingly common. See insert on page 25 for details.
9. PROCESS AND EQUIPMENT

Asphalt recycling processes are generally divided into two major groups: central plant processes necessitating the haul of reclaimed asphalt offsite and its processing at a central facility, and in-place processes, consisting of reclaiming, processing and placing the asphalt concrete material at the construction site using mobile equipment. There are three general in-place recycling processes: cold in-place recycling, hot in-place recycling and full-depth reclamation (Stroup-Gardiner).

In order to choose the suitable type of treatment, the road surface condition and type of damage must be identified. Refer to Appendix S6, Table 6 on p.7, for guidance on choosing the correct type of treatment based on type of pavement distress.

9.1 CENTRAL PLANT MIX PROCESS

This process is used where (i) high rates of production are required, and/or (ii) the quality control of the output mix is very tight. This process is suited for the production of hot, warm and cold asphalt mixes for the use in the surface and intermediate layers of asphalt concrete pavement.

Regular drum mix plants can be used to produce RAP mixes. Typically, the RAP material is fed in at mid drum in order to keep it away from the flame and prevent the further oxidation of the binder.

Double drum plants work well with RAP and allow higher amounts of RAP while maintaining temperatures. Continuous flow or batch plants can utilize RAP which is fed into the pugmill without going through the drum. These plants typically accommodate only low RAP ratios. The use of a 15 m test section is recommended when implementing any recycling mix, but especially for central plant process (NIBS).

The cold mix is stabilized with the following materials (Kandhal et al, 1997, chap. 12):

- Emulsified asphalt, with optional additives:
  - Hydrated lime; or
  - Portland cement.

  Emulsified asphalt cold mix recycling should be performed at temperatures above 10°C (Kandhal et al, 1997, chap. 12).

- Cutbacks can be effective in rejuvenating RAP as the cutter tends to soften the aged binder. However, there has been a decrease in the use of cutbacks as additives to asphalt mixes,
mainly due to the environmental concerns related to high VOC issues.

Following is the step-by-step central plant cold mix process:

1. **Prepare the existing area** by implementing traffic controls, cleaning it, removing debris, etc.
2. **Pulverize the road surface** to the specified depth. This can be achieved through the following means:
   a. *Ripping, loading and hauling the material to the plant where it is crushed:* this approach results in better control of aggregate gradation.
   b. *Ripping, breaking and pulverizing in-place, then loading and hauling it to a central plant:* this method requires highly specialized equipment and stringent traffic controls. It does not provide for good control over the aggregate size, often resulting in oversized lumps.
   c. *Milling in place, then loading and hauling the RAP material to a central plant:* this is a very common way of producing RAP; it is fast and efficient, but provides less control over the aggregate size than option (a).

   Step 2 is optional (unless the roadway is strictly inadequate), as a road surface does not necessarily have to be pulverized before placing a (previously stockpiled) cold mix course on it (Kandhal et al, 1997, chap. 12).

3. **Crushing and stockpiling:** a crushing and screening plant is used to create the aggregate gradation desired. A RAP stockpile must be limited in height as RAP will stick together under excessive pressure and moisture.

4. **Mixing:** the process of mixing the RAP, aggregate and binder can be done as a batch, drum and continuous process. The proportions of new aggregate, RAP and binder are controlled by the feed rates. The option of adding water, modifiers or rejuvenating agents to the mix is useful (Kandhal et al, 1997, chap. 12). The coating of the mix is not always 100%, which is acceptable as further coating will be achieved during the placement of the mix on the road. For particles passing US sieve #4 (<4.75 mm), the coating should be 100% (NIBS).

5. **Laydown, aeration and compaction:** the process is similar to the one used with conventional hot mix asphalt, and uses similar equipment (Kandhal et al, 1997, chap. 12).
   Construction should avoid rainfall periods. Densely graded mixes should be placed in lifts no thicker than 75 mm, whereas open-graded mixes should be placed in lifts not exceeding 100 mm; two to four days curing time should be allowed between lifts.
The equipment used in central plant cold mix processes varies by the phase of the process.

Pulverizing of the surface (step 2) is done by milling equipment. There are milling attachments suitable for use with motorgraders and excavators, self-contained milling machines and tow-type machines. See graphic insert to the right for example.

The crushing of the material to the required size and gradation is done at a central plant facility and involves conventional crushers, screening plants and auxiliary equipment such as conveyors. This process is reviewed in detail in Section 4.

Central plant mixing is done with the use of a pugmill or an asphalt plant. Cold mix plants are lower cost, lower emission, and easier to set up than hot mix plants; the output material can be stockpiled (AEMA). The material produced by a central plant is a bituminous asphalt concrete material suitable for intermediate and surface layers on low traffic roads, shoulder base (Section 8.4) parking lots and driveways (Section 8.9). See graphic inset to the left for an example of a cold mix plant.

The laydown, aeration and compaction step uses motorgraders and compactors. The motorgrader is used to place mixed material into windrow to aerate, then spread onto road. Aeration is done prior to spreading and compaction to decrease the water content. Three general types of compactors are used: the vibratory roller type, used in the initial compaction step; the pneumatic tire type; and the static steel wheel type, used for final compaction.

9.2 IN-PLACE RECYCLING
In-place recycling includes a number of hot and cold processes which optimize the reuse of materials, haul distances, construction times, disruption to traffic, as well as minimizes the number of construction vehicles and other truck traffic (Stroup-Gardiner).

Cold in-place recycling is a self-contained, continuous train operation that includes ripping or scarifying, processing (screening and sizing/crushing unit), mixing of the milled RAP, and the addition of liquid rejuvenators. The output material of this process is a cold bituminous mix which serves as asphalt pavement surface. For cold in-place recycling, the pavement is removed by cold planing to a depth of 75-100 mm. The material is then pulverized, sized, and mixed with an additive. Virgin aggregate may be added to modify RAP characteristics. An asphalt emulsion or a recycling agent is added. Once the gradation and asphalt content meet specifications, the
material is placed and compacted. For low volume roads, an additional layer is optional, such as a chip seal or 25-75 mm of hot-mix asphalt on top. A 3-piece “train” may be used. This consists of a cold-planing machine, a screening and crushing unit, a mixing device, and conventional lay down and rolling equipment. This train occupies only one lane, thus maximizing traffic flow (Koch et al). Cold in-place recycling can be used for repaving low volume roads, as well as parking lots and driveways (Section 8.9).

Special asphalt-derived products such as cationic, anionic, and polymer modified emulsions, rejuvenators and recycling agents have been developed especially for CIR processes. These hydrocarbon materials are sometimes, but not always, used to soften or lower the viscosity of the residual asphalt binder in the RAP material so that it is compatible with the newly added binder (FHWA 1). CIR addresses distress in the upper 50-100 mm of road surface (Stroup-Gardiner).

Hot in-place recycling includes three general processes: resurfacing, repaving and remixing, and addresses shallow distress at the surface of the pavement. As of 2011, 43 US state transportation agencies were using HIR, with many of them implementing all three processes (Stroup-Gardiner). The output material of a HIR process is an improved asphalt pavement surface. This process can be applied as a preservation or maintenance treatment for any asphalt pavement surfaces exhibiting shallow distress.

The following equipment types are used for in-place recycling processes: cold planers, a mobile screening and crushing unit, a cold mobile or in-place mixing unit for CIR processes and a hot mobile mixing unit for HIR processes. Alternatively, the mobile screening and crushing unit can be replaced with milling equipment (see Section 4), and the mixing of the pulverized aggregate with new binder can be achieved through the use of spreaders.

In addition, for HIR processes, heater-scarifiers can be employed for the following applications (also see insert on the previous page):

- As a surface treatment without additives to reprofile the road;
- As a surface treatment with additives for resurfacing; and
- As a treatment applied prior to an integral overlay to produce a repaved asphalt pavement surface.
9.3 FULL DEPTH RECLAMATION

Full-depth reclamation is a process of recycling or remixing the existing asphalt concrete surface into a stabilized layer which may then be overlaid with new asphalt concrete. The output material of an FDR process is a base material, which may or may not be stabilized (see Section 8.3). FDR equipment consists of a miller or grinder capable of grinding the existing asphalt concrete mat to a depth of 200 mm or deeper. The equipment has the capability of injecting emulsion, rejuvenator, foamed asphalt and water into the mixing area.

The process typically results in the grinding of the existing AC mat with a portion of the underlying granular base layer. The depth of treatment is dependent on the distress being treated, the mat thickness, the underlying base thickness and the expected final surface. A thickness and mix design is established and the amount of new binder or rejuvenator is determined. Virgin aggregate or additional RAP can be spread over the existing surface to be milled into the existing material and modify the gradation.

Generally, if an emulsion is used, cement or lime is added in order to reduce the liquid content and aid compaction. The finished surface is compacted and flushed, then allowed to cure for several months prior to placing a new wearing surface.

The equipment used in full depth reclamation processes includes a rotomixer (see Section 4), a grader and a compactor. For stabilized base, a spreader (see Section 9.2) can be used to spread binder, ash, cement, or other material as determined by the mix design.

9.4 RECYCLERS

There are a number of recyclers or recycling attachments available to use with reclaim. Most are pulvi-type mixers or grinders that can break up the reclaim blocks or millings to workable size. The equipment is then used to mix an emulsion, cutback or rejuvenator into the reclaim which is then loaded and hauled to site for placement using conventional equipment.

Other equipment types have the capability to heat up the reclaim to a temperature where it becomes workable so that new material or rejuvenators can be added.
10. ASSESSMENT OF BEST PRACTICES

10.1 ECONOMIC BENEFITS FOR USING COLD MIXES AND COLD IN-PLACE RECYCLED MATERIALS

From an economic point of view, using RAP to replace the most expensive commodity possible makes the most sense. Generally, it is advisable to use RAP as a source of specialized aggregate or asphalt mix. The rising price of bitumen makes RAP an attractive source of bitumen. However, the increasing scarcity of aggregate sources in Saskatchewan is turning RAP into an attractive source of this commodity, both because of its availability and closeness to roads.

Generally, substituting RAP for asphalt and aggregate introduces cost savings, as RAP is often already owned by the agency reusing it. However, there are cases where the incorporation of RAP into construction materials increases the final price of commodity and is done for reasons other than economical (see Section 10.2). For example, there are generally increased energy costs when producing recycled hot-mix asphalt because it requires more heat to incorporate the recycled material (City of San Jose, 2007).

Cold in-place recycling processes save 20 to 40% of the costs when compared to conventional cold mixing techniques; if compared to hot asphalt pavement processes, the savings are around 40 to 50% (Davio). In areas with aggregate shortages or long hauls, RAP can be used in place of new aggregate, reducing costs.

Base course: the cost of 100% virgin aggregate base averages at $14/ton; the cost of base course containing 50% and 100% RAP material is, respectively, $12.50/ton and $11.50/ton (City of San Jose, 2007). This represents a reduction in cost of 11% and 18%, respectively. The City of Saskatoon “green streets” infrastructure program evaluation suggests savings of 40-50% for base with at least 30% improvement in the mechanistic material properties than virgin source counterparts (Berthelot et al).

Fill: This application of RAP does not represent the most effective use for RAP. RAP as an embankment base may be a practical alternative for material stockpiled for a considerable time period, or that has been commingled from several project sources (Davio).

Dust control: Using RAP blends for dust control on gravel roads has also proven cost-effective, with estimated cost savings of about 50% when compared to conventional gravel/MgCl treatment (Koch et al). Using the fines portion of processed RAP may further reduce costs.
**Driveways:** It is estimated that 100% RAP driveways are 50% cheaper than conventional asphalt concrete driveways (CreativeAsphalt).

**Use of RAS:** According to the Colorado Asphalt Pavement Association, the savings generated by the reuse of asphalt shingles in asphalt concrete mixes constitute $4.80-$6.80 per ton of binder where binder costs are $400-600 per ton (CAPA).

### 10.2 OTHER CONSIDERATIONS

**Aggregate scarcity:** In Saskatchewan, gravel pits are rapidly becoming depleted, with the price of this commodity increasing more than three times over the last three decades, and with the hauling distances increasing to over 100 km in some instances. Reclaimed asphalt, composed of over 90% of aggregate per volume, is conveniently located either directly at the construction site in the case of in-place technologies, or nearby in stockpiles.

**Reduction in damage to haul roads:** an indirect benefit of using reclaimed asphalt is that there is less damage to haul roads due to reduced hauling distances. This can be considered both as direct cost savings as well as indirect societal benefit due to improved quality of service.

**Rising bitumen costs:** The increase in the price of petroleum products has been a main reason behind the rising costs of infrastructure construction and maintenance. Reclaiming asphalt from RAP, containing up to 5.5% per volume of bitumen, and RAS, containing 19-30% of the same, can be a significant source of savings.

**Sustainability:** Both aggregate and bitumen are non-renewable resources. Various environmental incentives such as environmental credits in Ontario (OHMPA) or LEED credits in US (APA) can be earned for RAP or RAS processes.

**Energy use:** processes involving the recycling of reclaimed asphalt vary in their energy consumption needs. As discussed in the previous section, the energy use in the production of hot mix with RAP is higher than that of conventional hot mix. However, both cold and hot in-place processes generally have lower energy requirements than other conventional techniques to produce similar products.
11. AREAS OF FUTURE RESEARCH

While reclaimed asphalt has been used in pavement design for many decades, no comprehensive design methodology exists to date, with the current state-of-practice largely based on empirical knowledge and field implementation. However, due to virgin aggregate scarcity and increasing asphalt prices, RAP and other reclaimed asphalt is increasingly regarded as a valuable resource, with a growing research effort around it. The research areas related to reclaimed asphalt which need to be followed are listed below:

1. Determine the long-term performance, and high volume roads performance (NYSDOT), especially for mixes containing high RAP percentages, as applied to Saskatchewan.
2. Investigate the use of RAP and, specifically, the use of RAP fines, as means of dust control on gravel roads.
3. Study the use of RAP in temporary and permanent retaining walls (Rathje et al) and its potential applications in Saskatchewan.
4. A body of research suggests that RAP is not leachable. Develop procedures and standards regarding storing reclaimed asphalt in areas where groundwater or surface water contamination may be an issue (FHWA 1).
5. Investigate the use of RAP in slurry seals or as a seal aggregate under Saskatchewan conditions.
6. The effect of sawdust ash addition to RAP mixes has shown potential to improve the mix properties such as stability and gradation (Osinubi et al). In Saskatchewan, cogeneration projects could be a source of sawdust ash. It is recommended to further study the effect of adding this material to RAP mixes.
7. Investigate warm mix technology to determine:
   a. The potential to incorporate more RAP into mixes; and
   b. Which warm mix products may be used in high ratio recycling of RAP.
8. Research shows that hot mixes with RAP content up to 50% can be designed under SuperPave specifications, and can perform very well, provided the RAP properties are properly accounted for in the material selection and mix design process (McDaniel et al, 2002). Modifications to the Marshall Method and other design approaches have been published to allow for the incorporation of RAP materials both in hot and cold mixes (see Oliver et al, 2004). One of the main challenges related to the applicability of mix design methods to the RAP mixes is the accurate determination of aged binder content that has
been reincorporated into the mix. Currently, there are multiple efforts to redefine the available mix design procedures to effectively incorporate RAP into the mixes. Investigate the current research to determine the most suitable RAP mix design method under Saskatchewan conditions.

9. In order to encourage information sharing between urban centres and municipalities, as well as to take advantage of the province-wide experience, it is recommended to develop approved product lists for such items as rejuvenators and equipment.
12. TRAINING

The relevant competencies and respective training needs regarding reclaimed asphalt uses, processes and equipment are dependent on the individual’s role in the municipal organization. Three distinct functions can be identified within a municipal authority, which have impact on the implementation of reclaimed asphalt applications in the organizational practices:

- **Planning:** senior management involved with strategic planning and development should be knowledgeable about reclaimed asphalt applications, extent of available resources, design and cost considerations.
- **The construction and maintenance managers must be competent in matters of process implementation and requirements, as well as structural design using reclaim asphalt material. Individuals assuming this role should also determine detailed training requirements for their crews, technicians and operators both in terms of salvaging RAP and reusing it.**
- **Construction and maintenance crews, lab technicians and equipment operators must be adequately trained in matters of implementing specific processes assigned to them. Crews need to know how to salvage and stockpile RAP, as well as handle and place processed RAP in various applications; lab technicians should be trained in all pertinent testing and mix design procedures.**

It is advisable to develop training packages suitable for each group and provide, on a periodic basis, general workshops with the purpose of reviewing the entire process in addition to specialized training for each of the identified functions.
13. CONCLUSIONS AND RECOMMENDATIONS

It is recommended that reclaimed asphalt material is used to replace the most expensive commodity that it is suitable for.

Applications: Reclaimed asphalt can be incorporated in cold mixes, warm mixes, hot mixes, in-place recycling and central plant cold processes for the following uses:

- High and low RAP ratio cold asphalt concrete mixes are recommended for surfacing of roads with low traffic volumes. To accommodate the maximum size of the aggregate in RAP cold mixes while ensuring their proper compaction and interlocking, it is recommended that the wearing course thickness be in excess of 25 mm. Other uses of cold asphalt concrete mixes include paving of cycling lanes, parking lots and driveways.

- Wearing courses made of cold mix with RAP tend to rut, especially when their thickness exceeds 35 mm. Therefore it is recommended that:
  - In areas where performance is a priority, the layer thickness be limited to 30-40 mm; and/or
  - Cold mixes with RAP be placed in areas with low truck traffic or where some rutting can be accepted.

- Low ratio asphalt concrete hot mixes with RAP content up to 30% can be used as surface wearing course for all road classifications. Where performance concerns exist, the use of RAP can be restricted to bottom and middle lifts.

- High ratio asphalt concrete hot mixes with RAP content between 30 and 100% generally are not used for roads with high traffic; their typical applications include surface courses for driveways, parking lots and small to medium size road repairs.

- 100% RAP hot mixes are suitable for pothole patching, utility cut repairs, curbing, railway crossing repairs and all-winter patching applications.

- RAP aggregate is suitable for use as granular base for the base and subbase layers of the road structures. RAP bases are credited with equal or higher strength and durability as compared to virgin aggregate bases. The granular material can be prepared either using central plant or full-depth reclamation processes.
• Portland cement, ash and various cold binders can be added to bases with RAP to improve its engineering properties such as gradation, strength, durability and cohesion.
• Base mixes with RAP content up to 100% can be used for shoulder base on all roads. Central plant processes work best for this application.
• The undersized portion of RAP, containing higher percentages of binder, has limited applications as aggregate, but can be successfully used as a stabilizer for subbase and subgrade. Other suitable applications include trench backfill and utility cut surfacing during wet spring conditions.
• Mixes of RAP and virgin aggregates can be used for dust control on gravel roads and are cheaper than conventional methods. RAP and virgin aggregate mixes can be prepared either using central plant processes or by in-place rotomixing.
• It is recommended that RAP be tested as an aggregate for slurry seals and chip seals tested in pilot projects to assess performance in Saskatchewan climate. To ensure the best quality control in the testing stage, it is recommended that central plant processes are used for the mix preparation.
• RAP aggregate can be used as backfill for temporary earth walls. It is recommended that the use of RAP aggregate mixes be tested in pilot projects to assess performance in Saskatchewan conditions.

A chart of processes involving reclaimed asphalt uses is provided on page 39.

Historically, reclaimed asphalt materials has shown to have different stockpiling requirements as compared to conventional aggregate. These differences stem from the fact that the asphalt fraction, especially in the presence of moisture, binds the aggregate. Following is a summary of stockpiling recommendations (from Davio):

• Avoid low, horizontal RAP piles, which have a tendency to hold water. Large cone-shaped stockpiles, originally thought to cause re-agglomeration, are now thought to be better.
• Experience has proven that RAP tends to form a crust over the exterior that is 20-25 cm thick. Avoid driving front-end loaders and bulldozers directly on RAP stockpiles to minimize compaction.
• Cover RAP stockpiles when feasible because RAP doesn’t shed water or drain like other aggregates. However, tarps should not be used because they cause condensation.
• Place RAP on a solid paved surface to improve drainage and reduce soil contamination during loading.
Asphalt Reclaim Sources:

- **RAP:** 90%+ aggregate, up to 5.5% bitumen (v/v)
- **RAS:** 19-30% bitumen (v/v)

Storage:
- Store RAP in large, cone-shaped stockpiles.
- Avoid driving heavy equipment onto RAP stockpiles.
- If possible, cover RAP stockpiles to prevent water from entering. Do not use tarps to avoid condensation.
- Place RAP stockpiles onto a paved surface.

Processing:
- **In Place**
- **Cold Mix Plant**
- **Hot Mix Plant** not covered in the Guidelines

Blends

Structural Design:

- **AASHTO Guide for Design of Pavement Structures**

Applications:

- **Recycled Cold Mix:**
  - RAP % 0-100
  - Applied as road wearing course or bottom lifts
  - Not recommended as wearing course for roads with high traffic

- **Recycled Hot and Warm Mix:**
  - For RAP % = 100%, used as wearing course on parking lots, driveways, small to medium size road repairs
  - For RAP <30%, used as wearing course on all roadways

- **Granular Base:**
  - For RAP % < 30%, used as base for all roadways
  - Portland cement addition increases bearing strength
  - Hot asphalt, foamed asphalt or emulsions stabilize 50% RAP base material

- **Shoulder Base:**
  - RAP % = up to 100%

- **Fill:**
  - For base and subbase, the undersized fraction for RAP (<50mm) can be mixed in at any proportion
  - For subgrade, the RAP fines are reported to improve stability
  - 100% RAP used as trench backfill, utility cut backfill.

- **Dust Control on Gravel Roads:**
  - Blended with virgin aggregate and CaCl (optional)

- **Slurry Seal/Chip Seal:**
  - 100% RAP
  - For chip seal, use the larger RAP aggregate fraction (3/8” to 1/4”)
  - For slurry seal, use the undersized fraction

Mix Design:

- **Hot Mix Design** not covered in the Guidelines
- **Cold Mix Design** For CIR and central plant processes

- **Modified SuperPave**
- **Modified Hveem**
- **Asphalt Institute Design Method**
- **Oregon Estimation**
- **Chevron Mix**
REFERENCES


Bagela(R) pavementrecyclers.com accessed April 2012.


Kosolofski, Trevor, Manager of Asphalt Services, City of Regina, tkosolofski@regina.ca, personal contact April 2012.


Las Vegas Motor Speedway (LVMS) “Pieces of McCarran airfield recycled into LVMS parking lot” April 30, 2008.

Main Street Materials and Western Emulsions “Case Study: Caltrans Innovates a Sustainable, Low-cost Wearing Course Using RAP & PASS® Emulsion” 2010.


New Jersey Department of Environmental Protection (NJ DEP) “Asphalt Millings Guidance Document”.

New York State Department of Transportation (NYSDOT) “Cold In-Place Recycling” Federal Highway Administration National Review close out meeting, July 14, 2005.


Prang, C., City of Saskatoon, colin.prang@saskatoon.ca personal contact April-May 2012.


Udelhofen, G. “Using RAP in Slurry Seals”  

Shanghai Shibang Machinery Co., Ltd (SBM), “Impact Crusher”  


Swaner, K. “Dallas Cowboys Go Green with Warm Mix Asphalt” Texas Asphalt Magazine Fall 2009.

Thurston County, WA “Reclaimed Asphalt Pavement User Guideline”  
http://www.co.thurston.wa.us/planning/asphalt/notebook/section1/1.5%20RECLAIMED%20ASPHALT%20PAVEMENT.pdf accessed April 2012.


Waste and Resource Action Programme, UK (WRAP)  

PHOTO CREDITS:

Cover page: RAP central plant crushing operations, courtesy of City of Saskatoon, 2012.


Section 4: pictures of Wirtgen W2200 cold milling machine and Wirtgen 2200 CR cold recycler reproduced from www.wirtgen.de.

Section 4: pictures of the Asphalt Zipper (R) FDR attachment, attached to a frontloader, reproduced from www.asphaltzipper.com.

Section 8.8: 3 pictures of RAP chip/slurry dust and two pictures of RAP chip seal and RAP slurry seal application reprinted from Ford.

Section 8.8: Mechanically stabilized earth wall, reproduced from Rathje et al, p. 9.

Section 8.9: Lot No. 4 of the Cowboys Stadium in Dallas, Texas. Reproduced from Swaner, p. 3.

Section 9.1: 3 pictures of Maddock milling machines (Maddock AM24, Maddock VT325 and Maddock 84E) reproduced from www.maddockcorp.com.


Section 9.2: picture of CIR on Marquis Drive in Saskatoon, Saskatchewan, courtesy City of Saskatoon.

Section 9.3: 2 pictures of FDR with addition of emulsion on Kenderline Road in Saskatoon, Saskatchewan, courtesy of City of Saskatoon, 2009.

APPENDICES

Appendices 24, 25 and 26 are available on the CD attachment only.