Outline

- Recycling Background
- Hot Central Plant
- Cold In-Place
- Hot In-Place
- Life Cycle Cost Analysis

Outline

- Recycling Background
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Recycling Initiative

- Conservation
  - Materials (aggregate and asphalt binder)
  - Energy (burner fuel and trucking)
- Preservation
  - Environment
  - Existing materials
  - Pavement geometrics
- Economics
  - First cost (structural design and materials)
  - Life cycle cost
  - Reduced user costs (user delays)
  - Margins

Social Responsibility

- Good Environmental Stewards
  - Landfill Diversion
  - Recycling
  - Air Quality – Green House Gases
  - Reduced consumption of virgin materials
- Increased pavement recycling 30-percent
  - 65-million barrels of oil saved

Recycling Quantities and Rates

- Domestic Waste¹
  - 18M tons Paper and Paperboard (25%)
  - 4.2M tons Yard Waste (12%)
  - 0.3M tons Plastic (2%)
  - 2.6M tons Glass (20%)
  - 0.4M tons Tires (17%)
  - 25.5M tons
- Steel Recycling²
  - 76M tons Steel (74%) – US and abroad
- Asphalt Pavement Recycling¹
  - 80M tons Asphalt Pavement (80%)
¹Ref: FHWA and EPA 1993
²Ref: Steel Recycling Institute
Recycling Methods

- Asphalt Pavement Recycling
  - Hot Central Plant
  - Hot In-Place
  - Cold In-Place
  - Recycled Aggregate Base
- Portland Cement Concrete Recycling
  - Recycled Base
  - Aggregate for PCC
  - Aggregate for HMA
  - Aggregate for Chip Seals

Why is Cement and Asphalt Binder Consumption so Important?

Historical Price Increases

Note: Costs assume 9-in for each material, concrete does not include reinforcing steel and joints.

(FHWA)
Why is Energy Consumption so Important?

Historical Crude Oil Prices

(US Dept. of Energy)

Allowable %RAP by Pavement Course

<table>
<thead>
<tr>
<th>State</th>
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E = Engineer – Maximum value determined by the Engineer.
PS = Project Specifications – Maximum value stated in the project specifications.
### Allowable %RAP by Pavement Course

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---

### Allowable RAP by Pavement Course

#### Surface Course Allowable %RAP

- 43% of State DOTs Allow 15% RAP in Surface Course HMA
- 75% of State DOTs Allow 10% RAP in Surface Course HMA
Outline
- Recycling Background
- Hot Central Plant
- Cold In-Place
- Hot In-Place
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RAP Sources
- Cold Milling
- Full Depth Reclamation
- Plant Waste/Reject

RECYCLED CONCRETE & AC ONLY
LOADS MUST BE INSPECTED AND FEES PAID AT ASPHALT PLANT BEFORE UNLOADING.
VIOLATORS WILL BE PROSECUTED.
Can We Do It?

QC/QA Plan
- RAP Processing
- Mix Design
- HMA Production
  - Virgin asphalt binder
  - Virgin aggregate
  - RAP asphalt binder (higher RAP %)
  - RAP aggregate
- Field Construction
- Performance

Processing RAP
- Scalp +2in material
- RAP breakers can be used
- Crusher
  - Horizontal impact
  - Hammermill impact
  - Jaw/roll
- Fractionating (~>15% RAP)
RAP Processing

Stockpiling
- Separate based on sources/mix types
- Avoid consolidation
- No loaders, dozers or trucks on stockpile
- Protect from moisture intrusion
- Protect from contamination

Stockpiling RAP
- Large, conical stockpiles preferred
- RAP does not re-compact
- Forms “crust” (200-250 mm) 8-10 inches
- Crust sheds water and easily broken
- RAP under crust easy to manage
Disadvantage of Horizontal RAP Stockpiles

- More crust develops
- May require re-crushing
- Slows production
- Drainage poor
- Increase drying costs

Processed RAP

Feeding RAP after Rainfall

- Remove wet part of open face and set aside to dry
- Keeps RAP percentage up and drying costs down, ensures adequate drying of RAP
Feeding RAP

- “Trickle feed” RAP bin when charging bin with loader
  - RAP more prone to bridging than fine aggregates
  - Ensures uniform and consistent feed of RAP

Feeding RAP

- Unload RAP bin each night and after one hour down time
  - Helps keep feed uniform, especially on hot humid days
  - Do not fill RAP bin completely
    - Material may bridge
  - Do not use vibrators to counteract bridging
    - Material tends to pack

Plant Temperatures

- Virgin aggregate temperature dependent upon:
  - RAP moisture content
  - RAP content
  - Desired HMA plant discharge temperature
### Batch Plants

- **Plant Variations**
  - RAP feed into weigh hopper
  - RAP feed into pugmill
  - RAP feed into elevator
  - RAP dried in separate dryer
  - RAP heated conductively
  - Practical RAP limit – 30%

### RAP Fed into Weigh Hopper

---

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Assume 10°F loss from dryer to pugmill; 20°F outside air temperature.
**RAP Fed into Weigh Hopper**
- RAP added to weigh hopper
- Weighed as additional material
- Mixed with virgin materials
- Conductive heat transfer
- Significant steam release

**Adding RAP into Weigh Hopper**
- Cold, wet RAP into weigh hopper
- Mixed with superheated materials
- RAP heated conductively
- Significant steam release
- 25 to 30% RAP typical
- Exit gas temperature may limit % RAP

**RAP Fed into Weigh Hopper**
- Balancing steam release difficult
- Tower typically ducted with butterfly damper to primary
- Over-drafting dryer helps balance air flow imbalance
- 25-30% maximum
- 10-15% practical
RAP Fed into Weigh Hopper

- Watch build-up in duct and duct transition areas, especially horizontal ducts
- Monitor lowering of inlet baghouse temperature and $\text{H}_2\text{O}$ condensation on bags
- These factors can limit RAP percentages possible

RAP Fed into a Bin which Discharges Directly into the Pugmill

- Separate RAP weigh hopper can be used
- Slightly shorter batch cycle time
- Chute, slinger or screw conveyor used to transport RAP from RAP hopper to pugmill
Adding RAP into Pugmill

- Separate weigh hopper
- RAP added to pugmill
- Otherwise same as weigh bucket technique

RAP Fed into Pugmill

- Shortens cycle times, increases production
- Ducting for steam release easier to fit to tower
- Balancing steam release easier – can draft continuous-can draft to dryer as option
- 20-25% easier to achieve (limited by heat transfer not steam management)

RAP Fed into Pugmill

- Watch build-up in duct and duct transition areas
- DO NOT design duct too large or horizontal
- Attempt to design duct for downward flow
- DO NOT over-draft pugmill area during idle times (RAP not being produced)
RAP Fed into Boot of Hot Elevator

- Easier to fit to plant
- Steam management easy
- Trip up elevator short, and no agitation = low RAP %’s
- 10-20% possible
- 5-10% practical
- % impacted by whether using screens or not & size/screens

RAP Fed into Bucket Elevator

- RAP will buildup in hot bins on side wall – requires cleanout
- Watch screen blinding
- Monitor tower for “sweating” – RAP not drying in elevator
- DO NOT push percentages too high (no agitation in drying RAP in bucket elevator)
Drum Plants

- Plant Variations
  - Parallel-flow
    - Emissions limits RAP percent
  - Counter-flow
    - Can reduce gas emissions
    - RAP must be shielded from burner
  - Practical RAP limit – 30 to 50%

RAP Feed to Parallel-Flow Drum Mixer

Adding RAP Parallel Flow

- RAP collar most common
- RAP heated convectively
- Emissions limit RAP to 50 percent
- Variations
  - Isolated mixing area
  - External mixing device
  - Primary dust collector usually added
**RAP Collar**
- Aggregate heated convectively
- RAP heated convectively
- RAP added at mid-drum
- Emission requirements limit RAP percentage

**RAP Feed to Parallel-Flow Dryer and Continuous Mixer**

**RAP Collar with Mixer**
- RAP added at mid-drum
- Virgin binder added in mixer
  - Reduces hydrocarbons in gases
- Requires primary dust collector
  - Fines returned to mixer
**RAP Feed to Parallel-Flow Dryer with Isolated Mixing Area**

Diagram of RAP feed system to parallel-flow dryer with isolated mixing area.

**RAP Collar with Isolated Mixer**

- Similar to separate mixer
- Mixer integral to dryer
- Convective RAP heating
- Requires primary dust collector
  - Fines returned to mixer

**Parallel-Flow Dryer with RAP Feed to Continuous Mixer**

Diagram of parallel-flow dryer with RAP feed system to continuous mixer.
Counter-Flow Dryer with RAP Feed to Continuous Mixer

Counter-Flow Dryer in Mixer
- Counter-flow reduces gas exit temperatures
- Cool, wet aggregates cool gas
- RAP heated conductively in mixer
- Percent RAP affected by mixing space
- Gases from mixer back to dryer

RAP Feed to Counter-Flow Drum Mixer
**Counter-Flow Mixer RAP Collar**
- Burner extended into drum
- Virgin aggregate heated convectively
- RAP heated conductively
- Virgin binder added in mixing section
- Gasses in dryer

**Placement of Recycled HMA**
- Potential for lower temperature production
- Less compaction time
- May be easier to compact than conventional HMA

**Materials Evaluation**
Mix Design

- Level 1
  - Small quantities of RAP (<10 to 15%)
- Level 2
  - Greater than approximately 15% RAP

Virgin Asphalt Considerations (FHWA)

- 0 to 15% no change in binder grade
- 16 to 25% one temperature grade lower
- Greater than 25% use blending charts

Level 1 Mix Design

- Gradation of RAP (asphalt free)
- Gradation of new aggregate
- Combined gradation
- Trial mix design
Mix Design Procedure

- Combine Districts
- Aggregate for Cement
- Heat Aggregate
- Add NAIR at Preliminary Point
- Heat NAIR and Aggregate
- Add single blend in a Neutral Context

Level 2 Mix Design

- Level 1
- Plus binder grading & blending

Blending Charts

- Desire a high temperature grade of 64°C
- Failure temperature of 58.8°C or greater for virgin asphalt binder
- Desire a high temperature grade of 64°C
Importance of Blending Charts

Temperature, °C

What Happens During Mixing with RAP?

Looking at the Asphalt Films
Importance of Material Variability

![Importance of Material Variability graph]

Aggregate Considerations
- Shape
- Surface texture
- Specific gravity
- Friction
- Other properties

QC from RAP (Asphalt Free Gradations)

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Standard Deviation: 0.31 0.0 0.9 2.1 3.4 2.9 1.9 1.1
Mix Design Procedure

Mix Considerations
- Volumetrics
- Gradation
- Asphalt binder
- Engineering properties
Plant Verification

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<td>Hot Sample</td>
<td>Process</td>
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<td>Hot Sample</td>
<td>Process</td>
<td>100.0</td>
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</tr>
</tbody>
</table>

Performance

Hot Central Plant Recycling
**RAP Field Performance**

- Widespread use began in mid-1970's
- High RAP contents allowed by some agencies (>40%)
- Results in higher stabilities, but prone to longitudinal, transverse and reflective cracking
- Agencies applied conventional mix design policies to RAP designs

**Published Field Performance of RAP Mixtures**

- Washington DOT
  - 24 recycled HMA pavements prior to 1985
  - RAP content: 8 to 79%
  - Performance was equivalent to conventional HMA
  - Predicted service life: 9 to 16 years
- Texas SPS-5 section
  - RAP content: 30%
  - Visual condition survey: 10 years after const.
  - No significant distresses

- Connecticut - Route 4
  - RAP content: 30%
  - Visual condition survey: 6 years after const.
  - No permanent deformation
  - Transverse cracking similar to conventional HMA
  - Longitudinal cracking greater than conventional HMA
- Louisiana DOT
  - 10 sections
  - RAP content: 25 to 20%
  - Visual condition survey: every year for 5 years
  - Comparable performance
Published Field Performance of RAP Mixtures

- Kansas DOT – Reflective Cracking
  - RAP content: 50 to 70%
  - Visual condition survey: 3 years after const.
  - Comparable performance: <1% reflective cracking

- Utah DOT
  - 5 test sections
  - RAP content: 40 to 60%
  - Visual condition survey: 3 years after const.
  - Control section showed greater trans cracking than test sections

- Utah DOT
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  - RAP content: 40 to 60%
  - Visual condition survey: 3 years after const.
  - Control section showed greater trans cracking than test sections

- Utah DOT
  - 5 test sections
  - RAP content: 40 to 60%
  - Visual condition survey: 3 years after const.
  - Control section showed greater trans cracking than test sections

Published Field Performance of RAP Mixtures

- Georgia
  - 5 test sections
  - RAP content: 15 to 25%
  - Visual condition survey: 2 years after const.
  - No difference in rutting, raveling and fatigue

- Kansas DOT – US 56
  - RAP content: 50%
  - Visual condition survey: 11 years after const.
  - More trans. and long. cracking than conventional HMA
  - 12 year service life

Unpublished Field Performance of RAP Mixtures

- Arizona DOT
  - Mix designs based on conventional HMA designs
  - Considers recovered asphalt binder properties

- Florida DOT
  - Comparable performance
  - Established specs for sampling and controlling RAP

- Minnesota DOT
  - 1 test section: full depth AC
  - Comparable performance: 15 years
**Unpublished Field Performance of RAP Mixtures**

- Massachusetts DPW
  - 1 test section
  - RAP content: 35%
  - Visual condition survey: 11 years after const.
  - No trans, long, or reflective cracking
- New Jersey DOT
  - 1 test section
  - RAP content: 50%
  - Visual condition survey: 3 years after const.
  - Control section showed more significant reflective cracking

**Performance - Arizona SPS-5**

<table>
<thead>
<tr>
<th>Section ID</th>
<th>Start of Section (m)</th>
<th>End of Section (m)</th>
<th>Section Length (m)</th>
<th>RAP Content (%)</th>
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<tr>
<td>14-0502</td>
<td>1397</td>
<td>1790</td>
<td>193</td>
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<td>14-0503</td>
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<td>622</td>
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<td>14-0504</td>
<td>235</td>
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<td>14-0505</td>
<td>2024</td>
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<td>156</td>
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<td>14-0508</td>
<td>1165</td>
<td>137</td>
<td>152</td>
<td>30</td>
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</table>

2.4-in Conventional HMA

2.7-in Conventional HMA

2.6-in Recycled HMA

4.1-in Recycled HMA

0.7-m Coarse Agg

1.0-m Coarse Agg

Section 507

Section 508
Performance - Arizona SPS-5

PCI

Fatigue Cracking

Transverse/Longitudinal Cracking
Cold in Place Recycle

Cold In-Place Recycling: Advantages
- Significant Structural Improvements
- Most Pavement Distress Treated
- Ride Quality Improved
- Hauling Costs Minimized
- Minimal Air Quality Problems
- Pavement Widening Possible

Partial vs. Full Depth

Old HMA Surface
Old Base Course
Subgrade
Soil
Problem Areas

- Depth of removal
- Degree of pulverization
- Uniformity of mixing
- In-place density
- Curing
- Protection from traffic

Tale of the Tape

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy, Btu/yd²</th>
<th>Cost, $/yd²</th>
<th>Estimated Service Life w/o Routine Maint., Yrs</th>
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<tbody>
<tr>
<td>HMA Asphalt Concrete</td>
<td>29,068</td>
<td>0.74</td>
<td>10</td>
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<td>HMA Milling</td>
<td>1,080</td>
<td>0.65</td>
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<tr>
<td>CIPR Cold In-Place Recycling – Full Depth</td>
<td>17,948</td>
<td>0.65</td>
<td>15</td>
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<tr>
<td>CIPR Cold In-Place Recycling – Partial Depth</td>
<td>12,024</td>
<td>0.64</td>
<td>15</td>
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</tbody>
</table>

Outline

- Recycling Background
- Hot Central Plant
- Cold In-Place
- Hot In-Place
- Life Cycle Cost Analysis
Hot In-Place Recycling: Advantages

- Surface Cracks Eliminated
- Ruts, Shoves, Bumps Corrected
- Aged Asphalt is Rejuvenated
- Aggregate Gradation and Asphalt Content Can be Modified
- Reduced Traffic Interruption During Construction
- Hauling Cost Minimized

Hot In-Place Recycling: Advantages

- Pavement Geometrics Preserved
- Corrects Surface Distresses Not Caused by Structural Inadequacy
- Can Modify Existing Surface Mix
- Can Improve Surface Frictional Resistance
- Relatively Cheap
- Needs Minimal Traffic Control

Project Considerations

- Uniformity
- Depth of HMA
- Presence of Chip Seals
- Asphalt Content (Bleeding)
- Aggregate Gradation
- Asphalt Properties
- Traffic
- Type of Pavement Distress
Project Considerations

- Modifiers or additives
- Mix design
- Sampling and testing

Equipment Development and Typical Use

- Early concerns
  - In-place air voids
  - Overheating
  - Air quality
  - Safety
  - Depth
  - Production / cost
  - Vegetation

Equipment Development and Typical Use

- Developments in the late 1980s, early 1990s
  - Greater depths
  - Uniformity and control
  - Air quality
  - Production
HIR Processes

- Surface Recycling
- Repaving
- Remixing

Two Stage Remixing

New Mix

Heater, Miller and Mixer

Tale of the Tape

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy, Btu/yd² in</th>
<th>Cost, $/yd²</th>
<th>Estimated Service Life w/o Routine Maint, Yrs</th>
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</thead>
<tbody>
<tr>
<td>HMA Asphalt Concrete</td>
<td>30,000</td>
<td>3.00</td>
<td>20</td>
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<tr>
<td>HMA Hot-in-Place Recycling - Repaving</td>
<td>30,000</td>
<td>2.50</td>
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<tr>
<td>HIPR Hot-in-Place Recycling - Repaving</td>
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<td>2.50</td>
<td>10</td>
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<td>HIPR Hot-in-Place Recycling - Surface Recycling</td>
<td>40,000</td>
<td>1.50</td>
<td>8</td>
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</table>
Outline

- Recycling Background
- Hot Central Plant
- Cold In-Place
- Hot In-Place
- Life Cycle Cost Analysis

Life Cycle Cost Analysis

- An economic analysis
- Compare design/rehabilitation alternatives
- Considers all significant costs
- Evaluates the alternatives over the same analysis period

Significance of Life Cycle Cost

- HMA
- PCC – Remove and Replace
- PCC – Rubbilize and Overlay

IC = Initial Cost
CS = Crack Seal
M&F = Mill & Fill
R&R = Remove & Replace
Rub & OL = Rubbilize & Overlay
Salvage

Salvage
Scenario A - Hypothetical Roadway

1,000,000 ESALs

Ex. collector roadways

Scenario A - Construction/Material Alternatives

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Initial Rehabilitation</th>
<th>Rehabilitation</th>
<th>Year(s) of Rehab</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>4.5-in Overlay</td>
<td>1.5-in Overlay</td>
<td>11 / 22 / 33</td>
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<tr>
<td>A2</td>
<td>2-in M&amp;F, 2.5-in Overlay</td>
<td>2-in M&amp;F, 1.5-in Overlay</td>
<td>14 / 28</td>
</tr>
<tr>
<td>A3</td>
<td>2-in CMR - Partial Depth, 4.5-in Overlay</td>
<td>1.5-in Overlay</td>
<td>14 / 28</td>
</tr>
<tr>
<td>A4</td>
<td>2-in CPR - Full Depth, 6-in Overlay</td>
<td>1.5-in Overlay</td>
<td>15 / 23</td>
</tr>
<tr>
<td>A5</td>
<td>2-in HIPR, 2.75-in Overlay</td>
<td>1.5-in Overlay</td>
<td>16 / 26</td>
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</table>

Scenario A - Construction/Material Alts (per yd²*)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Energy for Initial Construction, BTU/yd²*</th>
<th>Energy over 40 Years, BTU/yd²*</th>
<th>Asphalt Binder Consumed, lbs/yd²*</th>
<th>First Cost, $/yd²*</th>
<th>NPV 4.0, $/yd²*</th>
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<tbody>
<tr>
<td>A1 (Overlay)</td>
<td>114,000</td>
<td>278,369</td>
<td>0.011</td>
<td>14.03</td>
<td>25.11</td>
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<tr>
<td>A2 (M&amp;F)</td>
<td>119,500</td>
<td>274,289</td>
<td>0.012</td>
<td>13.56</td>
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<td>A3 (CMR - Partial)</td>
<td>143,500</td>
<td>278,924</td>
<td>0.014</td>
<td>13.25</td>
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<td>A4 (CPR - Full)</td>
<td>234,000</td>
<td>448,166</td>
<td>0.017</td>
<td>16.15</td>
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<td>A5 (HIPR)</td>
<td>193,700</td>
<td>289,860</td>
<td>0.012</td>
<td>11.80</td>
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Scenario A – Percent Savings (per yd²*)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Energy for Initial Construction % Savings, BTU/yd²***</th>
<th>Energy over 40 Years % Savings, BTU/yd²***</th>
<th>Asphalt Binder Consumed % Savings, lbf/yd²*</th>
<th>First Cost % Savings, $/yd²*</th>
<th>NPV 4.5 % Savings, $/yd²*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (Overlay)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>A2 (HIPR)</td>
<td>13.25</td>
<td>6.16</td>
<td>11.76</td>
<td>56.73</td>
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<tr>
<td>A3 (CIPR - Partial)</td>
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<td>9.38</td>
<td>13.66</td>
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<td>A4 (CIPR – Full)</td>
<td>(96.11)</td>
<td>(22.43)</td>
<td>0.66</td>
<td>(13.39)</td>
<td>9.56</td>
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<td>A5 (HIPR)</td>
<td>17.70</td>
<td>24.32</td>
<td>23.47</td>
<td>13.34</td>
<td>22.44</td>
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Benefits Recycling Offers*

<table>
<thead>
<tr>
<th></th>
<th>Initial Construction**</th>
<th>Life Cycle of Pavement**</th>
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<tbody>
<tr>
<td>Cost savings</td>
<td>3 to 21%</td>
<td>4 to 19%</td>
</tr>
<tr>
<td>Asphalt Binder savings</td>
<td>3 to 40%</td>
<td>10 to 36%</td>
</tr>
<tr>
<td>Energy savings</td>
<td>8 to 21%</td>
<td>10 to 25%</td>
</tr>
</tbody>
</table>

*Percent reduction in comparison to conventional alternative
**Savings dependent upon recycling activity

Questions