Assessment of Life Cycle Energy Saving and Carbon Reduction of Using Reclaimed Asphalt Concrete

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Outline

• Introduction
• Objectives & Methodology
• Analysis tool and Data Collection
• Sensitivity study of RAP performance
• Conclusions
• Reclaimed asphalt pavement (RAP)
  – has been considered a good recycled material from both economic and environmental perspectives because of its low cost and wide availability (Aravind and Das, 2007)
  – using RAP asphalt concrete causes less environmental impact than using virgin asphalt concrete does, since adding RAP in hot asphalt mixtures (HMA) reduces the usage of natural materials (Chiu et al., 2008; Lin, 2010; Chowdhury et al., 2010).
However….

– Producing RAP mixtures requires extra energy & increasing gas emission
– The performance of RAP may be different from virgin asphalt concrete

➢ the service lives of test sections with RAP may be shorter than that of the sections without RAP, because cracking and potholes occur more easily (Chiang, 2002)

➢ the service life of RAP overlays is 30% to 60% shorter than that of the virgin overlays (Aguiar-Moya et al., 2011)
Material flow diagram of producing HMA mixture

- **Raw RAP**
  - Crush
  - Store
  - Sieve
  - RAP (ready to use)

- **Virgin aggregates**
  - Directly heat
  - Store (with heater)

- **Dry virgin aggregates**
  - Store
  - Weigh
  - Sieve

- **Dry mixed aggregates**
  - Dry mix

- **Aggregate mixture**
  - Wet mix

- **Virgin binder**
  - Directly heat
  - Store (with heater)
  - Add recycling agents (optional)

- **Binder with recycling agents (if used)**
  - Spray

- **Dry RAP**
  - Weigh
  - Feed
  - Indirectly heat

- **Gas emission**
  - Remove odor

- **Extra Energy Needed**
Objectives & Methodology

• evaluate the **cradle-to-gate and life-cycle environmental benefits** of using RAP mixture

• Issues discussed in this study:
  – energy consumption & CO$_2$ emission /ton mixtures
  – environmental benefit of using RAP asphalt concrete from lifecycle approach
  – variability of RAP mixture performance
Analysis Tool and Data

1. The PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects)
   - developed by the Consortium on Green Design and Manufacturing and the Recycled Materials Resource Center (RMRC) at University of California at Berkeley
   - Uses database built on literature review
   - Includes the environmental impact and cost information for several types of materials and processes commonly used in pavement construction

2. Information collected from Taiwan asphalt paving industry
Calculation of Energy Consumption and CO$_2$ Emission

\[
EC_{i\%} = EC_{i\%, VA} + EC_{i\%, VB} + EC_{i\%, pp}
\]

\[
C_{i\%} = C_{i\%, VA} + C_{i\%, VB} + C_{i\%, pp}
\]

EC$_{i\%}$: Energy consumption of mixture with i% RAP content, (MJ)

C$_{i\%}$: Carbon emission of mixture with i% RAP content, (kg-eCO$_2$)

VA: Virgin Aggregate; VB: Virgin Binder; PP: Plant Process
<table>
<thead>
<tr>
<th></th>
<th>Energy Consumption (MJ/m³)</th>
<th>(%)</th>
<th>CO₂ Emission (kg-eCO₂/m³)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Virgin mixture</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregates</td>
<td>234.15</td>
<td>10.83</td>
<td>16.58</td>
<td>15.25</td>
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<tr>
<td>Asphalt binder</td>
<td>1564.89</td>
<td>72.41</td>
<td>88.87</td>
<td>81.75</td>
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<tr>
<td>Batch plant process</td>
<td>362.16</td>
<td>16.76</td>
<td>3.26</td>
<td>3.00</td>
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<tr>
<td><strong>Total</strong></td>
<td>2161.20</td>
<td>100</td>
<td>108.71</td>
<td>100</td>
</tr>
<tr>
<td><strong>30% RAP mixture</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregates</td>
<td>182.55</td>
<td>9.79</td>
<td>12.93</td>
<td>14.81</td>
</tr>
<tr>
<td>Asphalt binder</td>
<td>1230.69</td>
<td>66.03</td>
<td>69.89</td>
<td>80.07</td>
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<tr>
<td>Batch plant process</td>
<td>403.97</td>
<td>21.67</td>
<td>3.64</td>
<td>4.17</td>
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<tr>
<td>RAP preparation</td>
<td>46.74</td>
<td>2.51</td>
<td>0.83</td>
<td>0.95</td>
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<tr>
<td><strong>Total</strong></td>
<td>1863.95</td>
<td>100.00</td>
<td>87.29</td>
<td>100.00</td>
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</table>
**Energy Saving and Emission Reduction**

Energy Saving (%)

\[
\text{Energy Saving}(\%) = \frac{(\text{EC}_{0\%} - \text{EC}_{i\%})}{\text{EC}_{0\%}}
\]

CO₂ Reduction (%)

\[
\text{CO}_2\text{ Reduction}(\%) = \frac{(\text{C}_{0\%} - \text{C}_{i\%})}{\text{C}_{0\%}}
\]

ECₐ%: Energy consumption of mixture with i% RAP (MJ/m³)

Cₐ%: the carbon emission of mixture with i% RAP (kg-eCO₂/m³)
## Categorized by Aggregate, Asphalt Binder, and Plant Process

<table>
<thead>
<tr>
<th>RAP Content (%)</th>
<th>Aggregate</th>
<th>Asphalt Binder</th>
<th>Plant Process*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy Saved (MJ/m³)</td>
<td>Saving percentage</td>
<td>Energy Saved (MJ/m³)</td>
</tr>
<tr>
<td>10</td>
<td>16.70</td>
<td>7.13</td>
<td>98.14</td>
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<tr>
<td>20</td>
<td>33.18</td>
<td>14.17</td>
<td>209.54</td>
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<tr>
<td>30</td>
<td>51.61</td>
<td>22.04</td>
<td>334.20</td>
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<tr>
<td>40</td>
<td>71.88</td>
<td>30.70</td>
<td>472.12</td>
</tr>
<tr>
<td></td>
<td>Carbon Reduced (kg-eCO₂/m³)</td>
<td>%</td>
<td>Carbon Reduced (kg-eCO₂/m³)</td>
</tr>
<tr>
<td>10</td>
<td>1.18</td>
<td>7.13</td>
<td>5.57</td>
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<tr>
<td>20</td>
<td>2.35</td>
<td>14.17</td>
<td>11.90</td>
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<tr>
<td>30</td>
<td>3.65</td>
<td>22.04</td>
<td>18.98</td>
</tr>
<tr>
<td>40</td>
<td>5.09</td>
<td>30.37</td>
<td>26.81</td>
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</tbody>
</table>

*Includes the environmental impact due to RAP preparation.
Benefits of using RAP

Environmental Benefits (%)

Energy Saving

CO2 Reduction

20.47%

13.75%
Performance of RAP vs. Virgin Materials

Good!
resistance to permanent deformations is improved

Tao and Mallick, 2009;
West et al., 2009;
Maupin et al, 2009;
Wang, 2009;
Hajj et al., 2010;
Aurangzeb et al., 2012)

Not so good...
cracking and potholes occur more easily

Li et al., 2008;
Chiang, 2002;
Aguiar-Moya et al., 2011;
Apeagyei et al. 2011;
Nash et al., 2012

How the performance of RAP compares with the
virgin asphalt concrete has no firm answer.
Ratio of Service Life

- Use the ratio of service life \((SLR_{i\%})\) of pavement containing RAP to that of virgin pavement to express their difference in performance.

\[
SLR_{i\%} = \frac{\text{service life of pavement containing } i\% \text{ RAP}}{\text{service life of pavement without RAP}}
\]

\[
MR_{i\%} = \frac{\text{No. of major maintenance containing } i\% \text{ RAP}}{\text{No. of major maintenance without RAP}}
\]
## Energy Saving Ratio and CO$_2$ Reduction Ratio

If RAP’s performance = Virgin Mat’l

<table>
<thead>
<tr>
<th>RAP Content (%)</th>
<th>Energy Consumption* (MJ/m$^3$)</th>
<th>ER$_i$%</th>
<th>Carbon Emission* (kg-eCO$_2$/ m$^3$)</th>
<th>CR$_i$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2111.1898</td>
<td>0.9599</td>
<td>104.8528</td>
<td>0.9431</td>
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<td>20</td>
<td>2016.3270</td>
<td>0.9167</td>
<td>97.8738</td>
<td>0.8804</td>
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<tr>
<td>30</td>
<td>1906.5286</td>
<td>0.8668</td>
<td>90.0295</td>
<td>0.8098</td>
</tr>
<tr>
<td>40</td>
<td>1781.7236</td>
<td>0.8101</td>
<td>81.3125</td>
<td>0.7314</td>
</tr>
</tbody>
</table>

*Includes the environmental impact of a 50-km-long transportation from the plant to the site.

LCES$_i$% & LCCR$_i$%: life cycle energy saving & CO$_2$ reduction of i% RAP mixtures relative to the virgin mixture
Life cycle energy saving of using RAP mixtures

\[ \text{LCES}_{i\%} = 1 - \frac{\text{SLR}_{i\%}}{} \]

Graph showing the comparison between 0% RAP and 30% RAP with 13.75% Saving and LCES\(_{30\%} = 1 - 0.8668/0.8 = 8.35\%\)
Life cycle energy saving of using RAP mixtures

\[ \text{LCCR}_{i\%} = 1 - \frac{\text{CR}_{i\%}}{\text{SLR}_{i\%}} \]
Life cycle carbon reduction of using RAP mixtures

\[ \text{LCES}_{i\%} = 1 - \frac{\text{ER}_{i\%}}{\text{SLR}_{i\%}} \]
Conclusions

- RAP asphalt mixtures indeed causes less environmental impact than virgin asphalt mixtures. The higher the RAP content, the greater environmental benefits can be obtained from material production.

- Adding 30% of RAP into the HMA saves about 14% energy and reduces 20% carbon emission if there is no difference of RAP performance.

- The lower the RAP content, the longer its service life is required in order to gain the environmental benefits. 30% RAP mixture needs service life longer than 87% of virgin mixture’s to obtained environmental benefit.