LIFE CYCLE ASSESSMENT OF HIGHWAY RECONSTRUCTION: A CASE STUDY

Eleanor Bloom, M.S., EIT
Geological Engineering Program, University of Wisconsin-Madison
2243 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706
Tel: (219) 771-0409; Email: efbloom@wisc.edu

Aaron Canton
Civil and Environmental Engineering Department, University of Wisconsin-Madison
2221 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706
Tel: (781) 698-5275; Email: acanton@wisc.edu

Angela Pakes Ahlman, P.E., LEED AP, Corresponding Author
Geological Engineering Program and Recycled Materials Resource Center, University of Wisconsin-Madison
2204 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706
Tel: (608) 890-4966; Email: angela.pakes@wisc.edu

Tuncer Edil, Ph.D., P.E., D.GE, Dist. M. ASCE
Geological Engineering Program and Recycled Materials Resource Center, University of Wisconsin-Madison
2258 Engineering Hall, 1415 Engineering Drive, Madison, WI 53706
Tel: (608) 262-3225; Email: tbedil@wisc.edu

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ABSTRACT

The use of recycled materials in the reconstruction of an urban highway was quantitatively analyzed to assess the environmental and economic benefits of sustainable road construction. Recycled materials in the reconstruction included fly ash, recycled concrete aggregate, recycled asphalt shingles, and recycled asphalt pavement. In addition to assessing the benefits of recycled material use, this case study was used to evaluate two methodologies for gathering input data for life cycle assessments (LCAs). In past studies on road LCAs conducted post or prior to construction, significant assumptions were made to determine the input data. This project offered a unique opportunity to compare the post-construction, estimated input data with data explicitly collected and tracking while the road construction was on-going. Furthermore, multiple LCA tools were used to conduct, compare, and verify the LCA results. The actual design including recycled materials was compared to a reference design using only virgin materials to determine the reduction in environmental impacts. Results show that use of the recycled materials does reduce impacts in most environmental criteria, including energy consumption (15-25% reduction) and CO₂ emissions (17-24% reduction). Although impact results did differ between LCA tools, the data collection method comparison revealed significant variances in LCA inputs regardless of which tool was used for the impact assessment. Therefore, it is recommended that Departments of Transportation should focus future efforts on material tracking for LCAs when these issues are critical. Overall, the study’s results suggest that incorporating recycled materials improved the sustainability of road construction.

Keywords: Environmental impact, Life cycle assessment, Recycled material, Sustainability
INTRODUCTION
There is interest in determining and validating the environmental benefits of incorporating recycled materials into road construction using life cycle assessments (LCA) tools. However, the process of collecting the necessary data for LCAs from departments of transportation (DOTs) and road construction contractors is not well defined. In previous case studies, LCA data was estimated from planned design and average mix specifications gathered after the road construction was completed. Post construction data led to issues such as over-generalization of mix designs and sourcing and inability for real-time data collection. For this study of a typical urban highway, the Recycled Materials Resource Center (RMRC) was able to work with local engineers and contractors to explicitly track and quantify the material used in construction, identify material sources, and determine transportation distances. This project provided a study of real-time data collection to compare with the results of estimated post-construction LCA data. The goal of this comparison is to determine a data collection precedent for environmental analyses of future projects. Additionally, two prominent LCA tools were used in conducting the LCA and the results were compared.

Background
Sustainable roadway construction has become an increasingly popular topic because of the impacts on climate change and rising costs of virgin, or non-recycled materials in road construction. Buildings and infrastructure utilize 40% of all materials extracted in the U.S. (1), and the construction industry emits approximately 6% of total U.S. industry-related greenhouse gases (GHGs) (2). To be sustainable, environmental impacts of highways must be reduced through thoughtful planning, design and construction. This includes reducing the use of virgin materials (3). Production of common road construction materials, such as crushed rock aggregate or cement, consume significant energy, generate GHG emissions, are increasingly limited in supply, and often incur high transportation costs (4), (5). After demolition, previously used concrete or asphalt pavement is either recycled or sent to a landfill to remain unused (6)–(8). However, sustainable road construction incorporates as much existing material on site as possible. Recycled coal by-products such as fly ash and bottom ash are proven useful alternatives to using virgin material (9), (10). The RMRC studies the viability of fly ash as an alternative binder both in the surface concrete mix and as stabilization in the base course.

For this case study, recycled materials in the reconstruction and expansion of a 2.4 km (1.5-mi) stretch of an urban highway was quantitatively analyzed. Preliminary findings were presented at the 4th international conference in Sustainable Construction Material and Technologies (SCMT4) and Geo-Chicago 2016 (11), (12). Recycled materials used in this reconstruction included: fly ash, blast furnace slag, recycled asphalt shingles (RAS), recycled asphalt pavement (RAP), and recycled concrete aggregate (RCA). Fly ash and blast furnace slag can be used as a partial replacement of Portland cement in the ready-mix concrete (9), (13). RAP was used in both the hot mix asphalt (HMA) pavement as well as a base course material. Properly processed RAP consists of high-quality, well-graded aggregates coated by asphalt cement (14). The aggregated RAP often undergoes a specific gradation process such that it becomes fractionated recycled asphalt pavement (FRAP). In HMA, the asphalt content of RAP can be used as binder, while the aggregate portion can replace virgin aggregates (15). Similarly, RAS was substituted for binder and aggregate material in some HMA mix designs. For this highway, approximately 20% of RAS and 4% of RAP was allowed as binder replacement in the HMA design. RAP was also used with RCA as base aggregate and fill material.
The reconstruction involved expanding from two to three lanes in each direction. The existing HMA surface pavement was replaced with concrete pavement, at times over an asphaltic base. Six ramps were updated and four were added. The reconstruction design chosen for the 2.4 km (1.5-mi) stretch is generally comprised of 28-cm (11-in) Portland cement concrete (PCC) pavement over a 15-cm (6-in) base aggregate over a 41-cm (16-in) subbase of select crushed material (SCM). An 8-cm (3-in) asphaltic base layer appears between the concrete pavement and base course in certain locations.

Life Cycle Assessment

LCAs were conducted to quantify the environmental benefits gained from using recycled materials in reconstruction. LCA quantifies environmental impacts over the lifetime of a product by using a meticulous evaluation methodology (16). According to the FHWA, LCAs provide a comprehensive approach to evaluating the total environmental burden of a particular product or a more complex system of products and processes (17). In the case of pavements, LCAs often evaluate the impacts from the materials and processes used to construct the highway, the transportation of those material, and any rehabilitation processes. Rehabilitation and maintenance can be considered the end-of-life practices for roads. Impacts during the use phase are often not considered, as those impacts are mainly caused by the vehicles on the road rather than the road itself. In this study, two LCA computer tools are used to evaluate the environmental benefits of recycled material use, as discussed in the LCA Methods section.

DATA COLLECTION AND LCA METHODS

Data Collection

Two data collection methodologies were employed to gather the necessary inputs for LCA of the reconstruction: 1) material quantities estimated from designs and specifications as planned prior to construction (referred as Planned), and 2) material quantities explicitly tracked and collected while construction was on-going (referred as Constructed).

Collecting Planned Data

Plans for the reconstruction project were analyzed to estimate LCA input material quantities. Pavement volumes were calculated from cross-sectional drawings using the provided dimensions. The road layers were divided into component materials based on average mix designs and estimated ratios. Also included in the design plans were total material volumes for the concrete bridges and structures. Mix designs for concrete and HMA, as well as estimated recycled-to-virgin aggregate ratios in the base and subbase, were provided by DOT engineers and the project contractors. For this project, all RAP and some RCA in the base was recycled on-site from existing pavements. Some RCA was imported from a near-by aggregate supplier.

To perform a life cycle analysis, materials for future maintenance were required. The DOT provided a maintenance schedule over the 50-year lifetime of the road, including material quantities for the rehabilitation processes (18). Maintenance materials included concrete for two repair and grind rehabilitations and HMA for a 10-cm (4-in) overlay. The mix designs and sourcing for the maintenance materials are estimated based on initial pavement specifications, although they may vary in time.
Collecting Constructed Data

DOT engineers and project managers helped facilitate the collection process while construction was on-going. Contractors and sub-contractors clarified quantities and procedures. Key, site-specific DOT and sub-contractor files, including Item Record Account (IRA) spreadsheets, Quality Management Plan (QMP) specifications, concrete and hot mixed asphalt (HMA) pavement mix designs, weigh tickets, site plans, and bid item lists, were accessed for information on materials. QMP plans kept particularly detailed records of the type and amount of material being used, as well as their sources. QMP specifications are used to verify product acceptance based on contractor’s quality control testing (19). Quality testing must be verified per a certain amount of product used in the road construction. Therefore, QMP plans tracked the quantity of materials, supplier, and date of placement in great detail. Weigh tickets were also critical in data collection because they specified the material, its origin, and its quantity. Weigh tickets were used to track the quantity and supplying quarries for subbase SCM.

Omitted from weigh tickets were pavements recycled in situ, such as RAP and RCA used as base course or fill. To account for these un-weighed materials, the site plans were used to calculate the tonnage of RAP and RCA recycled from the existing road. This estimate was deemed valid because the contractor stated that in the construction, almost all RAP and RCA was immediately used for the new highway as either base or fill.

As the rehabilitation construction will not begin for a number of years, the material used for these processes could not be collected. Therefore, this maintenance data was estimated based upon the requirements for rehabilitation strategies anticipated by the DOT.

Data Input Assumptions

The assumptions made while performing the LCAs are as follows:

- Existing road dimensions were used to calculate volume of RAP and RCA. Average widths were used when ranges were provided.
- Transportation distances were determined from the material origin to either the plant locations or the reconstruction site as appropriate.
- Unless otherwise stated, the assumed transportation vehicles were dump trucks, with the exception of cement trucks for cement/fly ash. Cement was also shipped from the plant via barge.
- To analyze a comparable reference design with no recycled material, conventional virgin material was substituted ton-for-ton for all recycled material used in the project (i.e. cement for fly ash, virgin aggregate for RCA, etc.). In reality, different dimensions or quantities of virgin material may be required to construct the virgin road to meet the structural support requirement. Additionally, the all-virgin design may also result in a different service life or rehabilitation procedures. All quantities, service lives, and rehabilitation schedules were considered equal for the reference, virgin design.

Life Cycle Assessment Tools

Two prominent tools were used to conduct the LCA with the objective of validating LCA result. Both tools provide individual impact assessment parameters, as well mutual impact categories that could be used for a comparison.
PaLATE

The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is an open-source LCA program commissioned by the RMRC and designed by the Consortium on Green Design and Manufacturing (20). It is an LCA tool in spread sheet format specifically developed for highway construction and available in the public domain. Users input the initial construction and maintenance materials and transportation details. PaLATE calculates environmental impacts from material production, materials transportation, and construction processes. Environmental outputs include:

- Energy consumption (GJ)
- Water consumption (kg)
- Carbon dioxide (CO\textsubscript{2}) emissions (Mg)
- Nitrous oxide (NO\textsubscript{x}) emissions (kg)
- Particulate matter 10 (PM\textsubscript{10}) emissions (kg)
- Sulfur dioxide (SO\textsubscript{2}) emissions (kg)
- Carbon monoxide (CO) emissions (kg)
- Mercury (g)
- Lead (g)
- Resource Conservation Recovery Act hazardous waste (Haz Waste) generation (kg)

When comparing the LCAs of two or more products, a relative ranking of alternatives was analyzed as well as the absolute impacts, or the impact magnitudes in a certain category. For this study, the design of the actual roadway that incorporated recycled material (referred to as Recycled) was compared to a reference, hypothetical design comprised of no recycled material (referred to as Virgin). This method demonstrates the impact reduction from the use of recycled material. A Recycled and Virgin design was analyzed for both the Planned and Constructed data.

One challenge of LCAs is comparing absolute impacts of two or more designs across different environmental categories, as each category differs in units. This can be aided by normalization (21). Raw LCA scores are normalized per category and per product as:

\[ \text{LCA}_{n}^{\text{x}} = \frac{\text{LCA}_{\text{raw}}^{\text{x}}}{\text{LCA}_{\text{max}}^{\text{x}}} \]

where \( \text{LCA}_{n}^{\text{x}} \) is the normalized impact per category \( \text{x} \) per design, \( \text{LCA}_{\text{raw}}^{\text{x}} \) is the raw impact per category \( \text{x} \) per design, and \( \text{LCA}_{\text{max}}^{\text{x}} \) is the maximum value across all designs for category \( \text{x} \). The results of normalization provide impacts on a scale of 0 to 1, with 1 being the maximum impact magnitude across the designs.

SimaPro

SimaPro is one of the leading commercial software programs for LCA studies and is employed worldwide (22), (23). It is a professional LCA software used to collect, analyze, and monitor the sustainability performance data of products and services. Unlike PaLATE, SimaPro LCAs are not specific to road construction projects. SimaPro follows the traditional four-step LCA method as described by ISO standard 14040 (16), including inventory analysis and impact assessment procedures.

The inventory analysis includes a compilation, tabulation, and preliminary analysis of all environmental exchanges of the materials and processes of the final product, in this case, the highway (24). The inputs (raw material, energy, etc.) and outputs (waste, emissions, etc.) for some common road construction processes such as concrete material, asphaltic material, rock crushing, stone quarrying, and transportation are readily available in SimaPro. However, some
recycled materials specific to roads are not included (e.g. (F)RAP and bottom ash). To simulate impacts for grinding, milling, and crushing (F)RAP and RAS, the impact for the hypothetical amount of diesel fuel used in these processes was found. This is a similar assessment methodology used in other LCAs, namely PaLATE (20). Concrete recycling was present in SimaPro’s inventory and included the impact from concrete demolition. An additional process of crushing was added to the RCA inventory to simulate grading the demolished concrete into desired aggregate sizes. Also included in SimaPro’s inventory was cement with fly ash and slag replacement.

Many road construction processes were not included in SimaPro’s built-in inventory. However, based on previous LCAs conducted by the RMRC, construction processes had a relatively insignificant (less than 10%) environmental impact as compared to the material production and transportation (25). Therefore, the impacts from these processes were ignored in the SimaPro analysis.

SimaPro’s Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) impact assessment method was selected to calculate the impacts because it was developed by the U.S. EPA specifically for North America using input parameters consistent with U.S. locations (26). TRACI’s impact categories were constructed to represent potential effects in the U.S. and include:

• Ozone depletion (kg chlorofluorocarbon (CFC)\(^{-11}\) equivalents (eq))
• Global warming (kg CO\(_2\) eq)
• Smog (kg ozone (O\(_3\)) eq)
• Acidification (kg SO\(_2\) eq)
• Eutrophication (kg nitrogen (N) eq)
• Carcinogenic (CTUh, a comparative toxic unit for human toxicity impacts)
• Non-carcinogenic (CTUh)
• Respiratory effects (kg in particulate matter 2.5 (PM\(_{2.5}\)) eq)
• Ecotoxicity (CTUe, a comparative toxic unit for aquatic ecotoxicity impacts)
• Fossil fuel depletion (surplus MJ)

Impacts predicted by PaLATE versus SimaPro were compared to validate the LCA results. However, none of the TRACI impacts can be directly compared to PaLATE’s. Additional SimaPro analyses were conducted for single LCA factors similar to PaLATE’s, including energy, CO\(_2\), NO\(_x\), SO\(_2\), CO, and lead. Because construction processes were ignored in the SimaPro analysis, they are also removed from the PaLATE results when comparing the two LCA tools’ impact predictions.

RESULTS
A summary of the Planned and Constructed materials for the highway is shown in Table 1. In general, the Constructed data predicts slightly greater material use as compared to the Planned data. When explicitly tracking the material during construction, a more thorough collection of all of the materials and constructed features was recognized. For example, the designs specified the dimensions of concrete for the road surface alone. However, the Constructed data also include ancillary concrete quantities, which is any concrete item not explicitly part of the pavement such as curbs, gutters, and dividers.

Similarly, only the HMA used in the asphaltic base pavement was included in the designs. More HMA of varying mixes was used in the actual construction as driveways, temporary pavements, shoulders, and tie-ins to existing pavement on the construction ends.
Additionally, a lesser amount of base and subbase materials was specified in the designs as were actually purchased during construction. Likely, some of the recycled pavements were used in embankment fill as well as base courses, thus were not evident from design plans.

TABLE 1. Summary of Initial Construction Material Quantities Found from Planned and Constructed Data Collection Methodologies

<table>
<thead>
<tr>
<th>Material</th>
<th>Planned Volumes (m³)</th>
<th>Constructed Volumes (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>1,880</td>
<td>2,380</td>
</tr>
<tr>
<td>Fly ash</td>
<td>715</td>
<td>567</td>
</tr>
<tr>
<td>Slag</td>
<td>0.00</td>
<td>17.2</td>
</tr>
<tr>
<td>PCC aggregate</td>
<td>15,800</td>
<td>20,100</td>
</tr>
<tr>
<td>PCC mix water</td>
<td>2,720</td>
<td>3,500</td>
</tr>
<tr>
<td><strong>Concrete total</strong></td>
<td><strong>21,100</strong></td>
<td><strong>26,900</strong></td>
</tr>
<tr>
<td>RAP binder</td>
<td>3.15</td>
<td>10.6</td>
</tr>
<tr>
<td>RAS binder</td>
<td>15.4</td>
<td>30.7</td>
</tr>
<tr>
<td>Asphalt binder</td>
<td>55.6</td>
<td>227</td>
</tr>
<tr>
<td>FRAP</td>
<td>206</td>
<td>395</td>
</tr>
<tr>
<td>RAS</td>
<td>44.1</td>
<td>86.9</td>
</tr>
<tr>
<td>HMA aggregate</td>
<td>1,210</td>
<td>1,690</td>
</tr>
<tr>
<td><strong>HMA total</strong></td>
<td><strong>1,550</strong></td>
<td><strong>2,440</strong></td>
</tr>
<tr>
<td>On-site RAP</td>
<td>2,510</td>
<td>7,630</td>
</tr>
<tr>
<td>On-site RCA</td>
<td>2,480</td>
<td>7,550</td>
</tr>
<tr>
<td>Imported RCA</td>
<td>4,230</td>
<td>7,100</td>
</tr>
<tr>
<td>Imported virgin aggregate</td>
<td>1,220</td>
<td>3,010</td>
</tr>
<tr>
<td>SCM subbase</td>
<td>6,980</td>
<td>9,040</td>
</tr>
<tr>
<td>RCA subbase</td>
<td>13,700</td>
<td>12,700</td>
</tr>
</tbody>
</table>

LCA Results

PaLATE Results

The PaLATE results of the LCA are represented by Figure 1. In Figure 1a, the percent reduction was calculated by the difference in impact of the Recycled and Virgin divided by the Virgin’s impact. Across both data collection methods, reductions were seen in most PaLATE categories. Most categories also predicted slightly greater impact reductions for the Planned data as compared to the Constructed data. However, the trends between the two data sets are similar. Many transportation sectors focus on reducing their impacts of CO₂ emissions, energy, and water in particular. The reductions in these three categories range from 15-17% (Planned) and 12-13% (Constructed). These impacts largely stem from the materials’ production. Mining and grading virgin aggregate is more resource intensive than milling and grinding existing pavement. Similarly, milling asphalt pavement and grinding recycled shingles to use in HMA is a less environmentally intensive than producing their virgin counterparts. Because fly ash is a by-product, it is considered to have no impact. In the production of concrete, substituting fly ash for cement results in significant impact reductions.
The results are shown in Figure 1. In Figure 1a, the reductions from the Planned data appear greater than the Constructed data. However, the normalized results in Figure 1b reveal that the absolute impacts predicted from the Planned data are less than the Constructed data. The absolute impact results are related to the total quantity of material inputs. The data estimated from design plans and contractors suggested a smaller quantity of materials than those actually used during construction (see Table 1).

**FIGURE 1. Results of the PaLATE analysis of both the Constructed and Planned data sets represented by (a) percent reduction and (b) normalized absolute impacts**

*SimaPro Results*

The TRACI assessment results for the two data sets are portrayed in Figure 2. There are reductions in most TRACI impact categories for both data sets (Figure 2a). The greatest
reductions are seen in the TRACI results for carcinogens, eutrophication, ecotoxicity, and non-carcinogens. The impact associated with quarrying and crushing the virgin base and subbase aggregate in the Virgin design is contributing to much of the reductions. SimaPro does predict an increase in respiratory effects from the Recycled design, stemming from recycling concrete as compared to the production of virgin aggregate from a quarry. The absolute impacts were also normalized (Figure 2b). SimaPro predicts greater impacts for the Constructed data set as compared to the Planned data for both the Virgin and Recycled designs. This is also consistent with the trends seen in the PaLATE normalized impacts, further suggesting that the greater quantities found with the Contracted data collection method result in greater impacts.
FIGURE 2. Results of SimaPro’s TRACI assessment of both the Constructed and Planned data sets represented by (a) percent reduction and (b) normalized absolute impacts

In addition, those SimaPro categories comparable to PaLATE impacts were included in the impact assessment. The comparable results from both tools are shown in Table 2.
**TABLE 2. Comparable Planned and Constructed Data Results for PaLATE and SimaPro**

<table>
<thead>
<tr>
<th>Data Set, LCA Tool, Design</th>
<th>Energy (GJ)</th>
<th>CO₂ (Mg)</th>
<th>NOₓ (kg)</th>
<th>SO₂ (kg)</th>
<th>CO (kg)</th>
<th>Lead (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planned, PaLATE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycled</td>
<td>76,700</td>
<td>5,380</td>
<td>41,300</td>
<td>16,400</td>
<td>10,300</td>
<td>3,780</td>
</tr>
<tr>
<td>Virgin</td>
<td>99,200</td>
<td>6,980</td>
<td>44,600</td>
<td>20,600</td>
<td>11,500</td>
<td>4,700</td>
</tr>
<tr>
<td>Savings</td>
<td>22,500</td>
<td>1,600</td>
<td>3,300</td>
<td>4,200</td>
<td>1,200</td>
<td>920</td>
</tr>
<tr>
<td>Reduction</td>
<td>23%</td>
<td>23%</td>
<td>7%</td>
<td>20%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Planned, SimaPro</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycled</td>
<td>72,000</td>
<td>4,470</td>
<td>14,200</td>
<td>8,370</td>
<td>8,800</td>
<td>1,190</td>
</tr>
<tr>
<td>Virgin</td>
<td>85,700</td>
<td>5,840</td>
<td>16,800</td>
<td>11,300</td>
<td>12,400</td>
<td>1,890</td>
</tr>
<tr>
<td>Savings</td>
<td>13,700</td>
<td>1,370</td>
<td>2,600</td>
<td>2,930</td>
<td>3,600</td>
<td>700</td>
</tr>
<tr>
<td>Reduction</td>
<td>16%</td>
<td>23%</td>
<td>15%</td>
<td>26%</td>
<td>29%</td>
<td>37%</td>
</tr>
<tr>
<td><strong>Constructed, PaLATE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycled</td>
<td>97,100</td>
<td>6,930</td>
<td>51,400</td>
<td>20,500</td>
<td>13,100</td>
<td>4,760</td>
</tr>
<tr>
<td>Virgin</td>
<td>118,000</td>
<td>8,300</td>
<td>53,700</td>
<td>24,300</td>
<td>14,000</td>
<td>5,560</td>
</tr>
<tr>
<td>Savings</td>
<td>20,900</td>
<td>1,370</td>
<td>2,300</td>
<td>3,800</td>
<td>900</td>
<td>800</td>
</tr>
<tr>
<td>Reduction</td>
<td>18%</td>
<td>17%</td>
<td>4%</td>
<td>16%</td>
<td>6%</td>
<td>14%</td>
</tr>
<tr>
<td><strong>Constructed, SimaPro</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycled</td>
<td>98,500</td>
<td>6,000</td>
<td>22,620</td>
<td>10,600</td>
<td>14,600</td>
<td>1,480</td>
</tr>
<tr>
<td>Virgin</td>
<td>115,000</td>
<td>7,510</td>
<td>22,600</td>
<td>16,800</td>
<td>19,000</td>
<td>2,760</td>
</tr>
<tr>
<td>Savings</td>
<td>16,500</td>
<td>1,510</td>
<td>-20</td>
<td>6,200</td>
<td>4,400</td>
<td>1,280</td>
</tr>
<tr>
<td>Reduction</td>
<td>14%</td>
<td>20%</td>
<td>-0.1%</td>
<td>37%</td>
<td>23%</td>
<td>46%</td>
</tr>
</tbody>
</table>
DISCUSSION

Planned vs. Constructed Data

One goal of this project was to evaluate the two data collection methodologies and their LCA results. PaLATE’s reduction comparison is made in Figure 1a. In the data collection process, the Planned materials often over-generalize the actual materials used in construction. For example, the average concrete pavement mix contained 3% fly ash. However, detailed data collection during construction revealed that some sections of the road were paved with mixes with no fly ash. Because cement in concrete has a large influence in the PaLATE analysis, the ratio of fly ash to cement is significant in recognizing impact reductions. The Planned data predicts a larger ratio of fly ash to cement. Additionally, only the asphaltic base was included in the design plans. From the construction data, it was found that HMA was used in numerous other places such as medians and shoulders. However, there was a larger ratio of RAP substitution in the binder for the Planned data’s HMA as compared to the Constructed data. Therefore, the Planned data’s higher RAP to virgin binder ratio leads to greater reductions. Due to similar recycling ratios, the base materials have little contribution to the percent reduction differences from the two data sets.

Unlike PaLATE, SimaPro predicted greater reductions from the Constructed data (Figure 2a). There are a number of reasons for this inconsistency. The TRACI impact categories are different than PaLATE’s. The same trends we see in PaLATE’s impacts may not be the same in a TRACI analysis. Additionally, SimaPro’s material inventory differs from that included in PaLATE. A more detailed comparison of PaLATE and SimaPro is included later in this discussion.

The normalized results in Figures 1b and 2b also aide in the comparison. All analyses predict greater absolute environmental impacts for the Recycled and Virgin designs from the Constructed data. The greater impacts are due to the greater quantity of materials identified during the construction as compared to the quantities estimated from the designs. Calculating materials from the designs plans caused some details found from the Constructed data to be excluded. When collecting data during construction, it was found that more material quantities were used than depicted in the design plans. For the HMA pavement, this is because the plans only specify the asphaltic base and no other smaller HMA pavement work. For concrete, the difference is likely caused from changes from the plans in the actual construction. For example, ranges of width are provided for certain lanes in the plans, and average widths were used in the design quantities calculation.

The largest difference in material quantities is found in the base course. There is almost a 60% decrease from the Constructed to the Planned base course material predictions. While the ratios of RCA and RAP to virgin aggregate are relatively uniform, the total volume of base calculated from the plans differs significantly from those collected during construction. The Constructed base was gathered mainly from two sources: (1) calculated volumes of existing pavement from design plans and (2) QMP testing of imported material and recycled pavement used in base. All base material, both imported and recycled on site, were tested for their quality and therefore explicitly tracked by DOT personnel. However, a certain amount of recycled pavement was used for embankment fill and not tested or tracked. This is likely the cause for the greater quantity of base material in the Constructed data set, and thus greater overall environmental impact.

Overall, the Planned and Constructed data produced similar results. In particularly important PaLATE categories such as energy and CO2 emissions, the two data sets differed by 7-
8%. In similar TRACI categories such as global warming and fossil fuel depletion, the
Constructed data predicted a 5-6% difference in impacts reductions. Although the normalized
results did show greater impacts from the Constructed data, both data sets’ results are similar,
with no difference between like-design results greater than 30% (PaLATE) to 40% (SimaPro). It
may be concluded that to gain the most accurate understanding of environmental benefits from
road construction, detailed recycled material tracking is necessary. However, should the DOT be
unable to explicit track recycled material use and application, an evaluation of quantities based
on design plans’ estimated quantities and typical mix designs would provide a reasonable
estimate of the benefits.

**SimaPro vs. PaLATE**

Comparing results across multiple LCA tools can be challenging. There has not yet been
an internationally accepted data format for LCAs (27). Different formats lead to different
boundaries within material inventories, i.e. the inputs and outputs of the same material might not
be consistent. Most material inventories are an average of the inputs and outputs of processes and
products. For example, because PaLATE was specifically designed for roads, rock crushing
impacts are calculated for processes included in crushing rock for aggregate in roads. Because
SimaPro is a general LCA tool, its rock crushing process averages impacts of rock crushing for
multiple purposes. Additionally, the location and temporal range of the data within the software
can vary. Most of SimaPro’s inventory is more recent than PaLATE’s. PaLATE’s inventory was
created prior to 2004. SimaPro’s database pulls from multiple LCA inventories including Agri-
footprint 2.0 (28), ecoinvent v3.1 (29), and the USA Input Output, or CEDA (30). SimaPro is an
international software, and therefore has inventory data from multiple nations. While some of the
materials, process, and assessment methods are specifically for the U.S., many inventories are
aggregated from global or developing world averages. PaLATE was created with U.S.-specific
data and designed for state DOTs.

To further evaluate the differences between PaLATE and SimaPro’s LCAs, a course
sensitivity analysis for energy consumption was conducted. For the Recycled designs based on
both the Constructed and Planned data quantities, SimaPro and PaLATE analyses were
conducted while varying broad material quantities. The inputs were varied by: 1) no change in
inputs, 2) doubling base and subbase quantities, 3) doubling surface pavement quantities, i.e.,
concrete and HMA materials, and 4) doubling binder quantities, i.e., cement, fly ash, asphalt, etc.
Doubling the base led to small increases (8-9%) in overall impacts for both PaLATE and
SimaPro. However, doubling the surface material, particularly the binder, led to greater increases
in energy, particularly for PaLATE. Doubling the surface material led to a 74% (Planned) and
75% (Constructed) increase in energy consumption in the PaLATE analysis. From the SimaPro
results, the energy impact increased 34% (Planned) and 54% (Constructed) due to doubling the
surface material. Similar increases are felt when doubling the binder material alone. This trend
indicates that both analysis tools are most sensitive to changes in binder material inputs, but
PaLATE may be more sensitive to the ratio of recycled to virgin binder material as compared to
SimaPro.

With these differences in mind, six common environmental impacts were evaluated
between the two softwares (see Table 2). Figure 3 shows the percent reductions predicted for
both the Constructed and Planned data from PaLATE and SimaPro. The reductions in the energy
and CO₂ impact categories for all analyses are within 10%. There is more variability in the
predictions for NOₓ, SO₂, CO, and lead due to greater differences in each LCAs’ inventories and
assessment methods. For instance, PaLATE calculates larger savings in NO\textsubscript{x}, SO\textsubscript{2}, CO, and lead from fly ash replacement, whereas SimaPro predicts larger savings from recycled pavement replacement in base. The results are related to each software’s estimation of impact reduction per unit of material production. In PaLATE, estimates are based on many EPA emissions standards. Because SimaPro is a proprietary software, the calculation methods and inventory are not readily visible. Therefore, it is not clear how the software estimates its impact reductions.

**FIGURE 3.** Percent reductions from PaLATE and SimaPro analyses of Planned and Constructed data sets

Figure 4 shows the normalized impacts from the Recycled and Virgin designs from both data sets analyzed by the two LCA tools. Again, the Constructed data consistently predicts greater impacts than the Planned data. For the same design (i.e. Recycled) from the same data set (i.e. Constructed), SimaPro and PaLATE predict similar results, particularly in energy, CO\textsubscript{2} emissions, and carbon monoxide. For energy and CO\textsubscript{2} impacts, PaLATE found slightly greater impacts as compared to SimaPro. Overall, these trends indicate that the data collection methods and resulting LCA inputs have a greater influence in environmental impact predictions as compared to analysis tools, particularly for the relevant categories of energy and CO\textsubscript{2} emissions.
FIGURE 4. Absolute impacts from PaLATE (Pa) and SimaPro (S) analyses of Recycled (R) and Virgin (V) designs from Planned (Pl) and Constructed (C) data sets. In the legend, the labels should be read as the initials for: LCA tool (Pa vs. S), Data set (Pl vs. C), Design (R vs. V)

CONCLUSION
This case study indicated that fairly typical recycled material use in highway construction resulted in significant positive environmental impact reductions over the service life of the road. The study evaluated two methods of data collection for the purpose of LCA. Based on the LCAs results, the two data sets provided similar impacts and reductions. However, greater absolute impacts were consistently predicted from the Constructed data (actual data collected during construction). This is directly related to the quantity of materials found by the data collection. The Constructed data was able to capture more applications of material, as well as a greater variety of material types and mix designs. Although the in-depth tracking of material may have resulted in more accurate environmental impact predictions, the Planned data (material quantities estimated from plans and specifications) provided similar enough results to suggest that it could be an acceptable method for estimating impacts should the DOT be unable to explicitly track recycled material use and application. Additionally, results from two separate LCA tools indicated that the environmental impacts for energy consumption and CO₂ emissions were within 7% and 1%, respectively. Although PaLATE and SimaPro LCA results did differ, the data collection method comparison revealed significant variances in LCA inputs regardless of which tool was used for the impact assessment. Therefore, it is recommended that DOTs should focus future efforts on material tracking for the purpose of LCAs when environmental impact issues are critical. Overall, the study’s results suggest that incorporating recycled materials improved the sustainability of road construction.
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