Assessing the Life Cycle Benefits of Recycled Material in Road Construction

Eleanor F. Bloom[1]; Gregory J. Horstmeier[2]; Angela Pakes Ahlman[3] P.E., LEED AP; Tuncer B. Edil[4], Ph.D., P.E., D. GE; Gary Whited[5], P.E.

[1]M.S. Student, Geological Engineering Program, University of Wisconsin-Madison, Madison, WI, email: efbloom@wisc.edu
[2]Undergraduate Student, Geological Engineering Program, University of Wisconsin-Madison, Madison, WI, email: ghorstmeier@wisc.edu
[3]Technical Director, Recycled Materials Resource Center, University of Wisconsin–Madison, Madison, WI, email: angela.pakes@wisc.edu
[4]Research Director, Recycled Materials Resource Center, University of Wisconsin–Madison, Madison, WI, email: tbedil@wisc.edu
[5]Senior Administrative Program Specialist, Civil and Environmental Engineering Department, University of Wisconsin–Madison, Madison, WI, email: whited@engr.wisc.edu

ABSTRACT: Life cycle assessments of recycled material use in roadways is currently not well-understood or well-documented. The Recycled Materials Resource Center (RMRC) research is aimed at quantitatively determining the environmental and economic benefits of using recycled material in road construction. Two case studies were performed to analyze the impacts of incorporating recycled material in the reconstruction of two major roadways using life cycle assessment (LCA) and life cycle cost analysis (LCCA) tools. Results from both roads show that the use of recycled materials reduces energy and water consumption, greenhouse gas emissions, and cost. Because typical roadway construction projects do not separately track the extensive use of recycled materials, the RMRC was unable to utilize the LCA and LCCA technology in the first roadway's analysis without making significant assumptions for the inputs. To clarify and verify some of these assumptions, the second roadway project was undertaken. This second case study is being studied to determine a better methodology for data collection with fewer assumptions, in addition to assessing the benefits of recycled material use. The methodology for data collection and analysis developed through the second project can be used to conduct LCAs and LCCA for future highway construction projects with greater confidence.

INTRODUCTION

The sustainable roadway construction has become an increasingly popular topic because of global climate change and rising costs of virgin materials. Buildings and infrastructure utilize 40% of all materials extracted in the U.S. (Kilbert 2002), and the construction industry emits approximately 6% of total U.S. industry-related greenhouse gasses (GHGs) (Truitt 2009). To be sustainable, highways must be designed to reduce their environmental impacts through thoughtful planning, design and constructions, including the reduced use of virgin materials.

The goal of this paper is to quantitatively and accurately determine the environmental and economic benefits of using recycled material through the reconstruction of two roadways, thereby further demonstrating the viability of life cycle analyses in evaluating the advantages of sustainable road construction. Life cycle assessments (LCAs) quantify environmental impacts over the lifetime of a product by using a meticulous evaluation methodology. Life cycle cost analyses (LCCAs) outline cost comparisons among design alternatives, denoting economic benefits (Van Dam et al. 2015). For both studies, the environmental and economic savings are evaluated by comparing the actual road designs with recycled materials, "Actual," to an equivalent design which substitutes conventional virgin materials for all recycled materials, "Reference."

CASE STUDY: INTERSTATE-94

Background

One life cycle tool called Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE^2ST-in-Highways), uses LCA and LCCA techniques to evaluate the overall impact of highway construction projects. A 1.6 km (1 mi) north-south corridor of Interstate 94 (I-94) in Kenosha County was identified by the Wisconsin Department of Transportation (WisDOT) and the RMRC for a BE^2ST-in-Highways analysis. Construction plans outline a multi-year reconstruction, modernization, and expansion of I-94 mainline and ramps, as well as a resurfacing of State Highway (STH) 142 (WisDOT 2015a). Recycled materials used in the project include fly ash, bottom ash, foundry sand, recycled concrete aggregate (RCA), and recycled asphalt pavement (RAP) (N. Schlegal and B. Blum, personal communication, August-January, 2013-2014).

Design of I-94 Reconstruction

There are three portions of the reconstruction: mainline, ramps, and STH 142. The reconstructed mainline is comprised of layers given in Table 1. The ramps and STH 142 have similar layers, but with slightly different dimensions and no asphalt base layer. The embankment was quantified separately in addition to the three portions of the roadway. Embankment was used in various locations with varying thicknesses in order to elevate roads to design specifications in the mainline and the ramps. A total volume of approximately 180,000 cubic meters of embankment was used for this portion of the I-94 construction. STH 142 underwent resurfacing rather than full reconstruction, therefore needed no SCM or embankment. The embankment was comprised of bottom ash from We Energies (70%), on-site native clays (25%), and foundry sand from Rexnord Sand & Gravel (5%).

TABLE 1. Mainline materials by layers with dimensions and distance to source

Layer	Material	Thickness	Distance	Source
Portland Cement Concrete (PCC) Surface Pavement	Fly Ash	30.5 cm (12")	16 km (10 mi)	We Energies
	Cement		1.6 km (1 mi)	Michels Paving
	Aggregates			
	Water			
Asphalt Base – Hot Mix Asphalt (HMA)	Asphalt Binder Virgin Aggregate	7.5 cm (3")	1.6 km (1 mi)	Payne & Dolan
Base Aggregate	Virgin Aggregate	15 cm (6")	28 km (17 mi)	Bartel Aggregate
	RAP (55%)		0	Recycled On-Site
Select Crushed Material (SCM)	Virgin Aggregate	33 cm (13")	48 km (30 mi)	Franklin Aggregates
	RCA (37.5%)		0	Recycled On-Site

Analysis

BE^{2}ST-in-Highways

Lee et al. (2013) describes the life cycle tool used for the I-94 analysis. BE^{2}ST-in-Highways was created as a tool for quantifying how a highway reduces its environmental impact by incorporating recycled materials in its design. Criteria considered by BE^{2}ST-in-Highways, which were recommended by RMRC stakeholders, include: energy use (MJ), global warming potential (GWP) (Mg), water consumption (kg), social carbon cost (SCC) ($), hazardous waste (kg), in situ recycling (m^3) without transporting from off-site, total recycling (m^3), and life cycle cost ($).

BE^{2}ST-in-Highways utilizes the Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) as a support program to assess the environmental effects of pavement and road construction. Because PaLATE was primarily used to conduct the LCA for the second case study, this program will be discussed in the second case study's analysis later in this paper. The expected lifetime (50 years), maintenance schedule, and rehabilitation procedures for I-94 were provided by WisDOT and incorporated in the LCA and LCCA model.

Assumptions

A significant amount of assumptions were required to perform the LCA and LCCA of the Actual and Reference designs. The assumptions are as follows:

- The Reference design dimensions were assumed exactly the same as the Actual design's dimensions. Virgin aggregate or other traditional material was substituted in place of recycled material in the Reference design. In reality, different dimensions or quantities of virgin material may have been required based on the actual properties of the materials involved.
- The quantities of materials used in each layer were proportional to the volume

of the layer as calculated from the design plans. Actual purchased quantities for the reconstruction could not be obtained.

- Ranges of percentages of recycled material used in the base aggregate and SCM layers were provided. The average of these ranges was used to calculate the volume of material in these layers
- The dimensions of roadway fill and embankment could not be accurately quantified from roadway plans. However, the total volume of embankment material volume was provided. This quantity was used in the analysis.
- The amount of individual material within the surface PCC pavement was calculated from the proportions in the PCC mix design used by the pavement supply company.
- No recycled materials were included in the HMA mix for the asphaltic base. Therefore, it was assumed there would be no difference in the asphalt base's environmental impact between the Actual and Reference designs.
- Although the lifetime of the roadway may differ between the Actual and Reference design, the lifetime and maintenance schedule predicted by WisDOT was used for both designs.
- The material required for maintenance procedures was assumed to have the same designs and mixes as the initial reconstruction.
- If the designer did not provide a transportation method, it was assumed that the material was transported via dump truck.
- The transportation distances were based on project-specific data. Transportation distances were calculated from the material suppliers (quarries, pavement mix plants, etc.) to the I-94 reconstruction site.
- The life cycle costs were estimated from average costs of raw materials provided by suppliers, the Wisconsin Concrete Pavement Association (WCPA), and Engineering News-Record (ENR's Dodge Data and Analytics 2015 report). Transportation costs were not available and, therefore, not used in this analysis.

Results

The results of the BE^{2}ST-in-Highways analysis are summarized in Table 2. The criteria gathered from PaLATE include energy use, GWP (equivalent to carbon dioxide, or CO_2, emissions), water consumption, and hazardous waste. The SCC is based on a unit SCC of 69 \$/MJ of CO_2. The 'percent improved' is calculated by the percent increase or decrease in the results of constructing the Actual as compared to the Reference design. For most criteria, a decrease in impact is desired for the Actual. Since the Reference uses no recycled materials, its values for *in situ* recycling and total recycling are zero. The percent improved for the 'recycling criterion' are based on the fraction of recycled materials over total materials used for the reconstruction. The cost savings are calculated from the difference in the cost of actual quantities of fly ash, RAP and RCA base aggregate, bottom ash, and foundry sand versus the cost of hypothetical, equivalent quantities of cement, virgin base aggregate, granular fill, and sand, respectively.

For all criteria, the Actual result in improved environmental impacts. The greatest percent improved is in total recycling. This is, in large, due to the extensive use of bottom ash for embankment and fill material. Only RAP and RCA contributed to the *in situ* recycled material, and therefore, the *in situ* recycling improved by a smaller percentage than total recycling. Although the bottom ash was not recycled on site, it was transported from a coal power plant landfill ten miles from the construction site. The second largest percent improvement is in GWP and SCC, both by 39%. This suggests that the Actual design reduced carbon emissions and the associated social cost for the reconstruction project by over one third. Cost savings were calculated by the reduction in material unit costs from using recycled versus virgin material. The project saved over $770,000. The largest cost savings were attributed to the use of bottom ash (over $410,000 saved) because of the lower unit cost due in large to the close proximity to the site and the large volume of bottom ash used.

TABLE 2. Results of BE2ST-in-Highways

Criteria	Reference	Actual	Percent Improved
Energy Use (TJ)	141,000	89,000	37%
GWP (Mg)	9,500	5,800	39%
Water Consumption (kg)	38,000	28,000	25%
SCC ($)	$ 654,000	$ 398,000	39%
Hazardous Waste (kg)	237,000	151,000	36%
In Situ Recycling (m^3)	0	19,100	7%
Total Recycling (m^3)	0	154,000	57%
Life Cycle Cost Savings [$]:	$771,000		

CASE STUDY: BELTLINE

Background

The Beltline Highway is a multi-lane, urban, and major arterial highway used by a substantial number of local and regional travelers in the Madison, Wisconsin area (WisDOT 2015b). This 2.5-kilometer (1.5-mile) section is a part of the Wisconsin Backbone System (US 151) from Dubuque, IA, to Fond du Lac, WI. Safety and population growth are key reasons the Beltline is being expanded, and increased mobility is crucial to the efficiency of Beltline travelers.

This RMRC analysis focuses on the eastbound half of the Beltline Highway reconstruction from Whitney Way to Seminole Highway, including an expansion from two to three lanes in each direction. This section of highway includes the convergence for major roads: Highways 18/151 and Highways 12/14. The top wearing course was converted from the existing HMA overlay to 28 cm (11”) concrete pavement, at times with an asphaltic base. Six ramps were updated and four were added. Construction on the Beltline began in fall of 2014 and is expected to end in late 2015 for eastbound lanes. Recycled materials used in this project include: RAP, recycled asphalt shingles (RAS), RCA, and fly ash. RAP and RAS were used in HMA pavement. Fly ash was used in concrete. RAP and RCA were recycled both onsite from the existing pavement and offsite at a quarry for embankment/fill, SCM, and base aggregate.

Analysis

In addition to determining the life cycle benefits of recycled materials use as in the I-94 analysis, another objective of this study was to determine a methodology for gathering information such that significant assumptions will not be made regarding the LCA and LCCA.

Data Collection

The RMRC worked directly with WisDOT employees and contractors to collect real-time data for this project. As research progressed, the RMRC contacted sub-contractor representatives from various engineering and construction firms to better refine project details. Key, site-specific WisDOT and sub-contractor files, including IRA spreadsheets, Quality Management Plan (QMP) specifications, concrete and HMA pavement mix designs, site plans, and bid item lists, were used to determine the LCA/LCCA inputs. Such files aided in tracking materials, specifically material type, volume, tonnage, unit cost, equipment/processes for installation, and transportation distance. Weigh tickets were also critical in data collection because they described the material, its origin, and its quantity. Additionally, WisDOT provided a maintenance schedule over the 50-year lifetime of the roadway, including material quantities for the rehabilitation processes.

Omitted from weigh tickets were the RAP and RCA recycled from the existing pavement and used for base aggregate and embankment/fill. To determine the amount of RAP and RCA, the site plans were used to calculate the volume of existing HMA and PCC pavement on the road. The average density of the pavements was then used to calculate the weight of the recycled materials. According to the contractor, this estimation method would be valid because almost all onsite-recycled pavements were used in the reconstruction.

The costs for the actual design were gathered from either Beltline-specific bid item prices, WisDOT average bit item prices, or a personal communication with state or national pavement agencies.

PaLATE

PaLATE is an LCA/LCCA program designed by the Consortium on Green Design and Manufacturing from the University of California, Berkeley and commissioned by the RMRC. For this case study, PaLATE was used directly to conduct the LCA and LCCA. PaLATE can be updated by the user to allow for project specific details, such as adding RAS to the list of materials or updating the equipment specifications. Users input the initial design, initial construction materials and transportation, maintenance materials and transportation, equipment use, and cost for a roadway. Bid item data from WisDOT and contractors was separated by raw materials. For example, typical PCC concrete consists of cement, fly ash, aggregates, and water. For each raw material, a transportation distance and unit price were determined. Environmental outputs include (UC Berkeley 2007): energy consumption (GJ), water consumption (kg), CO_2 emissions (kg), nitrous oxide (NO_x) emissions (kg), particulate matter-10 (PM_{10})

emissions (kg), sulfur dioxide (SO_2) emissions (kg), carbon monoxide (CO) emissions (kg), and leachate information, including Mercury, lead, Resource Conservation and Recovery Act (RCRA) hazardous waste generated, and both cancerous and non-cancerous human toxicity potential (HTP). Economic outputs include the net present value life cycle costs ($) and annualized costs of the net present values ($).

For the PaLATE LCCA, costs associated with the initial construction materials and processes were calculated. Costs of maintenance and repairs were entered in the subsequent years when rehabilitation is expected to occur and brought to present value. Actual bid item costs reflect the use of both recycled and virgin material. To determine cost savings for bid item materials, the cost of 100% virgin material was compared to estimated recycled material prices. Unit prices for virgin aggregate and salvaged asphaltic pavement were gathered from WisDOT's average bid item prices (WisDOT, 2015c). Fly ash, cement, and RCA prices were estimated by the Wisconsin Concrete Pavement Association. The National Asphalt Pavement Association and the Wisconsin Asphalt Pavement Association provided cost data on RAS and RAP in HMA, respectively.

Assumptions

Although the method of data collection was improved compared to I-94 project, a number of assumptions were needed while performing the LCA, as follows:

- Only the eastbound portion of the construction would be analyzed. However, minor construction on both the west- and eastbound sides occurred in fall 2014, carrying into April 2015. Thus, all material quantities from the start of construction until April 1, 2015 were divided in half to estimate materials for only the eastbound highway more accurately.
- Results presented in this paper reflect the material used for the eastbound Beltline construction up to late October, 2015. At that point in time, the eastbound construction was approximately 80% complete.
- Existing roadway dimensions were used to calculate volumes of RAP and RCA. When ranges of widths were provided, the widths were averaged.
- Unless otherwise stated, the assumed transportation vehicle was dump trucks, with the exception of cement trucks for cement/fly ash.
- Virgin material, Reference, was substituted ton-for-ton for recycled material, Actual. In reality, different quantities of virgin material may be required to construct the Reference design road to meet structural support requirements.
- Recycled aggregate from offsite quarries was designated as RCA.
- Only the total volume of the PCC surface material was provided. The amount of raw material was calculated from the proportions in the PCC mixes used by the pavement supply company. The same process was used for HMA pavement raw material calculations
- Costs for the Reference design or recycled materials not found in the project bid items were estimated from averages based on literature or personal communications.

Results

The LCA results of the Beltline analysis are shown in Tables 3a and 3b. In general, reductions were seen in all PaLATE categories. The PaLATE categories are slightly different than BE^2ST-in-Highways, including more parameters that address air and toxic emissions. The greatest reduction is seen in PM_{10} at 21%. Because more recycled material was used with a smaller transportation distance, less vehicles and equipment were used on and off site, resulting in fewer particulate emissions. The reductions in categories reported in BE^2ST-in-Highways indicate reductions or improvements as follows: energy (13%), water consumption (12%), CO_2 emissions (13%), and RCRA hazardous waste (9%).

TABLE 3. PaLATE results of Beltline analysis

	Energy (TJ)	Water Consumption (g)	CO_2 (kg)	NO_x (g)	PM_{10} (g)	SO_2 (g)
Actual	146,000	40,400	10,000	95,200	33,100	386,000
Reference	167,000	45,900	11,500	98,300	41,600	390,000
Reduction	13%	12%	13%	3%	20%	1%

TABLE 3b. PaLATE results of Beltline analysis

	CO (g)	Hg (g)	Pb (g)	RCRA Hazardous Waste (g)	HTP cance r (kg)	HTP non cancer (Mg)
Actual	36,400	163	9,120	823,000	8,980	24,100
Reference	37,400	173	9,960	903,000	8,750	28,900
Reduction	3%	6%	8%	9%	-3%	17%

LCCA savings from the initial construction were estimated to be $34,900 from the use of RAP and RAS in HMA, $130,000 from the use of both onsite and offsite recycled base aggregate and SCM, and $56,000 from the substitution of fly ash for cement concrete pavement. At present value, the savings from maintenance over the roadways lifetime are $27,750. The savings total about $250,000 from the use of all recycled material over the project's lifetime.

DISCUSSION

Comparison of Data Collection Methods

The I-94 and Beltline case studies provided an opportunity to analyze and improve data collection methodology for highway life cycle analyses. The majority of the data for the I-94 analysis was provided post-construction. Post-construction data collection for I-94 led to issues including over-generalization of mix designs and sourcing, averaging market prices for materials, and inability for real-time data collection. Because real-time data was not collected, estimates of material quantities were based on road plan dimensions rather than actual amounts of purchased material. This calculation method was avoided for the Beltline analysis, because data was collected during construction. Favorable timing, resources, and personnel were available for the Beltline data collection. However, the onsite recycled RCA and RAP were calculated from dimensions, as they were not directly weighed and tracked during Beltline construction.

These case studies also demonstrated the different challenges associated with material tracking and evaluation in urban (Beltline) versus rural (I-94) construction. Although urban construction has time and area constraints not seen in rural construction, urban settings generally have greater access to resources, suppliers, and offsite recycled materials. Rural construction is advantageous for recycling existing roadways due to adequate storage room for RAP and RCA onsite, eliminating additional offsite transportation.

Comparison of LCA Tools

Another objective of these two case studies was to explore LCA and LCCA tools. BE^2ST-in-Highways focuses on a few of the impact categories included in the PaLATE analysis that were approved by stakeholders. The variety of categories evaluated by PaLATE can be advantageous when trying to understand the full environmental impact of a roadway. It is important for the public to understand that using recycled materials can improve air quality and reduce waste in addition to more commonly referenced environmental issues such as energy and GHG reduction. PaLATE is also formatted on an unlocked spreadsheet, allowing the user to make adjustments for project specific details. However, adjustments could lead to errors in formulas if the user does not understand the program's complex calculations.

BE^2ST-in-Highways is advantageous because it draws from multiple databases and tools to calculate the environmental and economic benefits of recycled materials. It was created for the RMRC, and therefore addresses the impacts requested by member state departments of transportation. Because the program is locked, it does not allow for adjustments, preventing possible errors in spreadsheet formulas.

Comparison of Results

The two case studies demonstrated the environmental and economic benefits of using recycled materials in road construction. For both roadways, the use of recycled materials led to a decrease in energy and water consumption, CO_2 emissions, and hazardous waste generation. Greater reductions are seen for the I-94 analysis as compared to the Beltline. Reductions in the four, shared categories for I-94 range from 25-39%, while Beltline reductions range from 9-13%. This can be attributed to a greater ratio of recycled to virgin material in the I-94 reconstruction compared to the Beltline. The more recycled materials substituted for virgin, the lower the environmental impact.

CONCLUSION

The two studies promoted a better understanding of DOT methods for material tracking, which assisted in developing an improved methodology for collecting input data needed for life cycle analyses. The reduction of the negative environmental impacts due to recycled materials in highway construction improves the sustainability of roadways. Therefore, using recycled material in road construction, as well as the tracking and assessment of the benefits of recycled materials use, should be made a priority by state DOTs.

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