System Wide Life Cycle Benefits of Recycled Material in Road Construction

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ABSTRACT: The use of recycled materials in highway construction has the potential to achieve significant benefits affecting the triple-bottom line (environment, prosperity and society). Although state departments of transportation (DOTs) have been in the forefront of introducing recycled materials, they have not been able to clearly convey the benefits in a quantitative and transparent manner using easily understood metrics. What is lacking is direct information on sustainability assessment characteristics, i.e. greenhouse gas emissions, energy and water consumption, and waste generation. To determine the benefits of using recycled materials for DOTs, the Recycled Materials Resource Center (RMRC) is undertaking a project with the objective of providing a tool to quantitatively analyze and report the environmental and life cycle benefits of using recycled materials in highway construction. Subsequently, an analysis of the environmental benefits was conducted using PaLATE, a life cycle assessment (LCA) tool developed with RMRC sponsorship. The LCA analysis of four environmental parameters (energy use, water consumption, carbon dioxide emissions, and hazardous waste generation) showed significant environmental benefits when states used recycled industrial byproducts such as fly ash and recycled roadway materials such as recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP).

INTRODUCTION

Roadways around the US are continuously being constructed and rehabilitated, requiring large amounts of natural raw materials, producing waste, and consuming energy (AASHTO 2008, Gambatese 2005). In order to reduce these economic and environmental costs, state Departments of Transportations (DOTs) have been reusing highway construction materials in various DOT projects.

The Recycled Materials Resource Center (RMRC, http://rmrc.wisc.edu), located at the University of Wisconsin-Madison, and many governmental agencies have developed fact sheets on various recycled materials and industrial byproducts for their use in highway construction applications. These fact sheets typically have addressed the engineering properties and environmental suitability issues relevant to various applications, and in some cases have incorporated design guidelines and construction specifications. However, direct information on sustainability assessment characteristics, i.e., greenhouse gas (GHG) emissions, energy and water consumption, and life cycle cost benefits is not yet readily available. Agencies may track system-wide use of quantities for major recycled materials such as fly ash in concrete, recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), etc., but they have not yet calculated the benefits accrued by substitution of these materials for conventional materials. Project by project tracking of recycled materials use post-bid award has been a challenge as well. Although state DOTs have been in the forefront of introducing recycled materials, they have not been able to clearly convey the benefits in a quantitative and easily understood manner.

The objective of this study is to develop a tool by which the state system-wide material use quantities can be used to calculate the life cycle benefits associated with the incorporation of these recycled materials and industrial byproducts to highway pavement construction. In order to realistically quantify the output of such a tool, data on the recycled materials quantities used by each RMRC member state DOT was collected and analyzed. The RMRC member state DOTs that have provided data for this study are: Georgia (GDOT), Illinois (IDOT), Minnesota (MnDOT), Pennsylvania (PennDOT), Virginia (VDOT), and Wisconsin (WisDOT).

EVALUATION OF LCA TOOLS

Life Cycle Assessment Tool Methodology

The first step in developing a quantitative benefit assessment tool was to examine existing publically available pavement life cycle assessment (LCA) tools. An LCA can assist in a better understanding of the environmental impacts of products throughout their life cycle, cradle-to-grave, and provide relevant data in order to make informed decisions (ISO 2006). The International Organization for Standardization (ISO) 14040 series provides general principles and a framework for an LCA study, detailing four phases of an LCA: (i) definition of goals and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation. In general, LCAs should have defined system boundaries, functioning units, and inputs/outputs. For most pavement LCAs, the defined system boundaries are materials, construction, use, maintenance, and end-of-life (Santero 2011). For the purpose of this study, we examined four existing publically available LCA tools (Table 1), focusing on the scope of each tool, including the system boundaries and environmental impacts. The four tools were selected based on their availability to the public and the locations where they were developed.

ABLE 1. LCA tools researched for this project, based on Table 1.2 from Santero, et al., 2011 (AASHTO 2010, Horvath 2004, MTU 2011, Santero 2011, TRL 2011)

Tool	***Developer***	***Interface***	***Pavement Types***
asPECT	Transport Research Library	GUI	asphalt only
GreenDOT	AASHTO	spreadsheet	all
PE-2	Michigan Technological University	web-based	all
PaLATE	UC-Berkeley, RMRC	spreadsheet	all

Overview of LCA Tools

Each LCA tool assessed for this study follows the four phases of an LCA defined by the ISO. The goal of using LCA for this study is to calculate the environmental impacts of using recycled materials or industrial by-products in highway pavement. Ideally, the chosen assessment's impacts would include GHG emissions and energy use at a minimum. Additionally, the chosen tool should be able to analyze as many of the DOTs reported recycled materials as possible. The following section discusses and compares each of the tools.

asPECT: The Transportation Research Laboratory (2011) developed the Asphalt Pavement Embodied Carbon Tool to follow the material used in asphaltic pavement from raw material acquisition through the end of life processes of disposing of or recycling the pavement materials. The main goal of asPECT is to calculate GHG emissions based on ten life cycle stages for a road from user inputs such as materials, fuels, transportation modes and distances, and energy use. While this would be advantageous for an individual project, the tool was too specific for the purposes of a system-wide study. Another major disadvantage is asPECT is only capable of analyzing asphaltic pavements, which does not allow for a complete analysis.

PE-2: PE-2, developed by Michigan Technological University (2011), estimates the life cycle emissions associated with construction, maintenance, and roadway use. Unique to this tool, PE-2 has a web-based interface and takes into account the costs of traffic delay caused by construction operations. PE-2 was designed solely for projects based in Michigan and is limited by pre-defined construction operations and fewer materials in its database. While PE-2 was found to be a good tool to use for a quick estimate of environmental costs, it was not considered to be capable of a more in-depth analyses needed for this project.

GreenDOT: GreenDOT, described by AASHTO (2010), was specifically developed for state DOTs to calculate CO_2 emissions from operations, construction, and maintenance projects. GreenDOT includes emissions based on four categories: electricity, materials, on-road vehicles, and off-road vehicles. GreenDOT is able to calculate project-specific or system-wide emissions. GreenDOT is also unique in that it calculates emissions of the electrical components of a highway, for instance, traffic signals. Overall, GreenDOT was found to be user friendly, but limited in the amount of materials and equipment in its databases.

PaLATE: PaLATE, developed at UC-Berkeley for the RMRC (Horvath 2004), follows the production of materials, construction, maintenance, and end-of-life processes. Initial material inputs are analyzed based on the equipment used to produce and transport them to the construction site. Emissions due to construction, maintenance, and production are calculated from the equipment used in all processes. Many of the outputs of PaLATE are based upon the volumes or weight of materials used and the parameters of equipment used, such as the productivity and fuel consumption of each machine. PaLATE furthers its impact assessment by outputting not only GHG emissions, but also energy use, water consumption, particulate matter, waste generation, and human toxicity potentials. The first and only version of PaLATE was developed in 2004 (Horvath 2004), and while the range of environmental outputs of PaLATE is wide, these are limited by potential out-of-date databases. However, PaLATE can be updated with relative ease, unlike the other LCA tools. Based on the limitations and advantages of each LCA tool, PaLATE was found to be the best suited to accommodate the objectives of this project.

MATERIALS ANALYSES ASSUMPTIONS AND APPROACH

Survey Results

In the first phase (2013) of data collection, a survey was conducted with RMRC six-member state DOTs (GA, IL, MN, PA, VA and WI) in order to determine the degree to which recycled materials were used and tracked by member states. The survey results showed that while many DOTs use commonly recycled materials, most track neither the breakdown of recycled materials used per each pavement layer nor the total annual quantities used. Overall, the six member states agreed that the availability of a recycled materials tracking tool would be useful.

In the second phase of data collection, RMRC member state DOTs were asked to report quantities of recycled materials for the calendar or fiscal year of 2013.The only DOT required to report by law the amount of recycled materials being used is IDOT. Although recycled materials use quantities could not be tracked effectively by most of the DOTs, information on as-let items for projects within the time period for each state was available. In order to calculate the quantities of recycled materials from as-let material quantities, a set of assumptions regarding average design specifications needed to be determined for each state DOT. This was established through interviews and correspondence with engineers from each member state. These assumptions and averages were then used to calculate the amounts of recycled materials used in hot mix asphalt (HMA), concrete mixes, and base course layers.

Assumptions

Because determining specific design parameters (such as pavement thicknesses and fly ash replacement of concrete) for every DOT project over the annual period was challenging, certain standard practice assumptions were made. Table 2 lists the assumptions made in order to calculate the quantities of fly ash used by each member DOT. General assumptions made when running the LCA analysis in PaLATE included:

1. A 1:1 replacement volume or mass of virgin with recycled material was assumed, despite the known varying mechanical properties.
2. Both cement and fly ash were assumed to be delivered by cement trucks over a one-way distance of 200 miles (Gary Whited, personal communication, July 7, 2015).
3. All RAP and RCA was assumed to be processes and reused on site with a transportation distance of zero miles.
4. All other materials, including HMA and ready-mix concrete, were assumed to be delivered by trucks over a one-way distance of 25 miles.
5. For all RAP used in HMA pavement, 6% was assumed to be used as asphalt replacement with the remaining 94% used as aggregate in the mix.
6. For all RAS used in HMA pavement, 20% was assumed to be used as asphalt replacement with the remaining 80% used as aggregate in the mix.
7. Any RAP used in HMA was equated into virgin aggregate and asphalt. However, the RAP specifically identified for base course material was equated only into virgin aggregate.
8. All RCA was assumed to be used in base course, and therefore used as a replacement to virgin aggregate.

TABLE 2. Fly ash assumptions, and the time period for which the data was used

State	***Material***	***Calculation Assumptions***	***Year of Data***
IDOT	Fly Ash	All fly ash used as cement replacement	Calendar Year 2013
WisDOT	Fly Ash	For Concrete Pavements and Driveways: Pavement thickness is 25.4 cm (10 in) Unit quantity of fly ash in concrete is 101 kg/m^3 (170 lbs/CY)	Fiscal Year 2013
MnDOT	Fly Ash	Unit quantity of fly ash in concrete is 101 kg/m^3 (170 lbs/CY)	Calendar Year 2013
PennDOT	Fly Ash	Fly ash replacement in cement was 15% Pavement thickness is 25.4 cm (10 in)	Calendar Year 2013
GDOT	Fly Ash	All reported fly ash quantity was used in HMA and none in concrete pavement.	Calendar Year 2013
VDOT	Fly Ash	20% of half the total cementitious material used	Calendar Year 2013

Approach to PaLATE Analysis

The quantities of recycled material used by each member state were analyzed in PaLATE to determine environmental impacts and benefits of the recycled material use. These environmental impacts and resulting benefits were analyzed comparatively by using the same exact volume of virgin material. Four environmental impact factors: energy, water consumption, CO_2 emissions, and RCRA hazardous waste generation were deemed sufficient for evaluation of the state materials. RCRA Hazardous Waste, as stated by the U.S. EPA, is a waste with properties that make it dangerous or potentially harmful to human health or the environment (U.S. EPA 2015). PaLATE determines the environmental impacts based on three categories: material production, material transportation, and processes (equipment). Material production includes the processes associated with extracting or generating the materials, such as RAP milling and virgin aggregate quarrying. Material transportation incorporates the impacts associated with transporting each material the specified distance in the chosen vehicle. Processes (equipment) consist of the impacts associated with installing the material, such as paving, placing, and compaction.

The first step in conducting the PaLATE analysis was to compile the collected recycled material data for all states. Then, equivalent virgin material amounts were calculated for their recycled counterpart. Both the recycled and virgin material quantities were input into a PaLATE sheet, from which the specific environmental impact for each material's production, transportation, and processes were determined. Finally, the environmental impact of recycled versus virgin material was analyzed.

RESULTS

The recycled materials used by all RMRC member-states and analyzed in PaLATE include RAP, RAS, RCA, fly ash, blast furnace slag, and rubber. These recycled materials could be equated to four virgin materials: virgin aggregate in pavement mixes (HMA and concrete), asphalt, cement, and base course aggregate. The distribution of recycled materials is shown in cled material in some capacity.
. 7.7 million tons of recycled material was used in 2013. It is evident that RAP is the most widely used recycled material, followed by RCA and then fly ash.

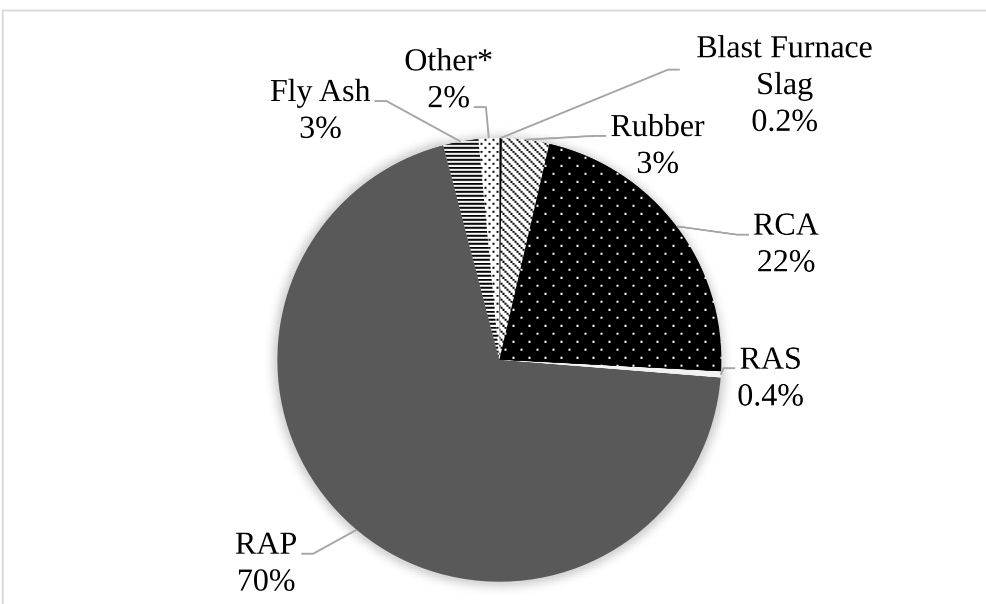

FIG. 1. Distribution of recycled material tracked and reported by all RMRC member states

Of all the recycled materials used by the six states during the one year period, only fly ash and RAP were used and tracked by all states. Most states track RAS and RCA as well. One state, Illinois, tracked several other recycled materials including steel slag, by-product lime, glass beads, microsilica, dowel bars, rebar, and welded wire reinforcement, designated by the "Other" category in cled material in some capacity. . Because they are only used by one state, comprise 1% of the total recycled materials usage, and are not included in PaLATE databases, the "Other" materials were not incorporated in this analysis. It is important to note that even though the states may not be tracking a certain material for the purpose of this study that does not necessarily indicate the state has not used the recycled material in some capacity.

Each state DOT's data was collected and analyzed separately and the results were combined to determine the total savings due to the use of recycled material. A summary of the environmental impact results are listed in Table 3 and are further demonstrated by Figure 2. In general, the use of recycled material significantly reduced the environmental impact in all four factors: energy, water consumption, CO_2 emissions and RCRA hazardous waste.

TABLE 3. Summary of environmental benefits as a results of participating six DOTs use of recycled material

Impact Category	Virgin	Recycled	Savings	% Redux
Energy (TJ)	6,390	1,180	5,210	82%
Water consumption (kg)	1,990,000	59,000	1,931,000	97%
CO_2 (Mg)	355,00	52,600	302,400	85%
RCRA Hazardous Waste (Mg)	68,900	2,180	66,720	97%

Figure 2 aids in the visualization of how the impacts may have been different had virgin materials been used instead of reclaimed recycled materials. The largest reductions by percent are seen in water use reductions. By using recycled materials, state DOTs saved 1.9 million liters of water over a one-year period. This amount would be enough water to fill over 14,000 bathtubs during the one-year period (USGS 2015). The next largest reduction is RCRA hazardous waste, followed by CO_2 emissions. The DOTs reduced their RCRA Hazardous waste generation by almost 67,000 megagrams and saved over 300,000 megagrams of CO_2. This is equivalent to the CO_2 emitted by 64,400 cars in one year (U.S. EPA, 2014). Regarding energy savings, the use of recycled material avoided using 5,210 terajoules of energy, equivalent to the average energy consumption of 133,000 U.S. households in one year (U.S. EIA, 2015).

The results of all participating DOTs recycled material use can be compared based on the type of pavement layers: HMA pavement, concrete pavement, and base course. The greatest savings are associated with HMA. The two main reasons for this are that the most widely tracked/used recycled material is RAP, and asphalt production is environmentally impact-intensive. Although cement is also nearly as environmentally impactful, less fly ash is being used by states compared to RAP. Therefore, we see the majority of the savings stem from the replacement of virgin asphalt and aggregates in HMA mix designs. Base course resulted in the smallest savings, as the equivalent virgin base aggregate impact is not as great compared to impact associated with the pavement surface layers.

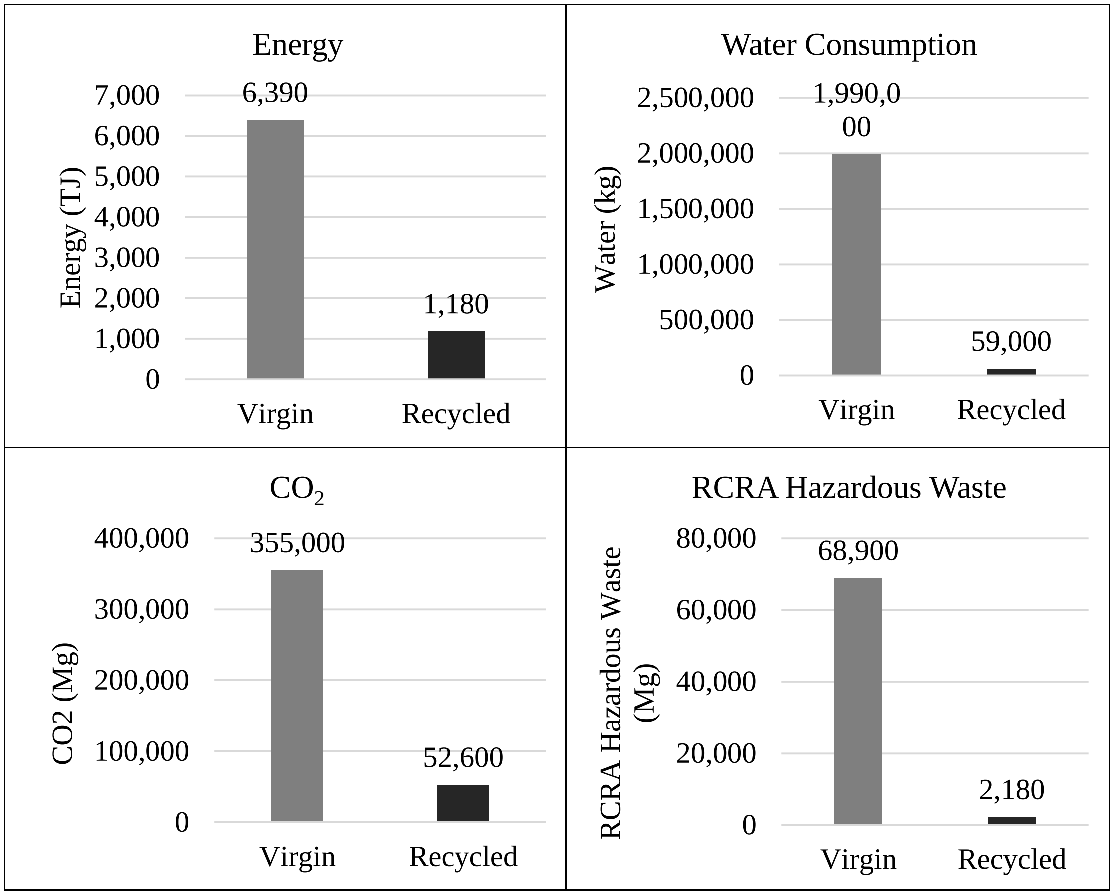

FIG 2. Difference in environmental impact for recycled versus virgin material for all states

The results may also be analyzed in terms of PaLATE assessment categories: materials production, transportation, and processes (equipment). The largest savings are seen in the materials production category, particularly water consumption. Many of the recycled materials require little to no water in their production. Virgin materials, however, require a significant amount of water for processing, particularly asphalt and cement. There are reductions in the transportation category are due in large to the zero-mile transportation distance of material recycled from existing roadways (RAP, RCA).

There is a small (less than 10%) increase in environmental impact due to the processes associated with constructing the roadway. While the paving processes remain the same whether recycled or virgin materials are used, the difference is attributed to placement of base aggregate. In PaLATE's database, recycled base aggregates, mainly RAP and RCA, have a slightly greater density than conventional granular base. Since there is a greater weight of RAP and RCA, more activity and fuel consumption is required for installation. Therefore, the recycled aggregate has a larger impact for the processes category than its virgin counterpart.

DISCUSSION

The four LCA tools researched for this project all had unique advantages and disadvantages. The vast number of materials, equipment, and environmental outputs in the PaLATE database led to it being the LCA tool to be used and further developed in this study. The only version of PaLATE was developed in 2004, making its databases 10 years old at the start of this project. However, the databases could be easily updated as needed.

Six member states (GA, IL, MN, PA, VA and WI) provided the quantities of recycled material used throughout the system over a one-year period. The environmental effects of using recycled material in pavement construction were then analyzed using the LCA tool PaLATE and compared to a reference analysis in which the total volume of recycled material was replaced by an equal volume of virgin material. Overwhelmingly, the use of recycled material in pavement construction decreased the environmental impacts in all four parameters (energy, water consumption, CO_2 emissions, RCRA hazardous waste), showing average environmental impacts savings between 80-97%.

In the future, the RMRC is developing a recycled material tracking tool for member state DOTs, allowing for more accurate reporting of recycled materials use and environmental benefits. The RMRC also hopes to estimate the economic savings associated with the use of recycled material by conducting a life cycle cost analysis. Additionally, the team will complete an update of the environmental, material, cost, and equipment databases within PaLATE so that RMRC member states and users of PaLATE will have up to date data analyses.

CONCLUSIONS

Using the life cycle assessment tool PaLATE, this study has established the quantitative environmental benefits of using major recycled materials. The environmental impact parameters of energy, water consumption, CO_2 emissions, and RCRA hazardous waste indicated a large increase in environmental benefits. Quantifying these benefits may serve as motivation for more DOTs to actively use and track recycled materials in highway applications. The Recycled Materials Resource Center, with the help of six member DOTs (GA, IL, MN, PA, VA and WI), is working to understand how DOTs can better track recycled materials in order to calculate the life cycle benefits associated with the incorporation of recycled materials and industrial byproducts into highway pavement construction.

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