Life-Cycle Benefits of Recycled Material in Highway Construction

Kelly Del Ponte, Bharat Madras Natarajan, Angela Pakes Ahlman, Andrew Baker, Erik Elliott, and Tuncer B. Edil

The use of recycled materials in highway construction can achieve significant benefits affecting the triple bottom line (environment, prosperity, and society). Although state departments of transportation have been at the forefront of introducing recycled materials, they have been unable to clearly convey the benefits in a quantitative and transparent manner using easily understood metrics. Information on sustainability assessment characteristics—that is, energy and water consumption—is lacking. To determine the benefits of using recycled materials for six member state departments of transportation in a pooled fund, the Recycled Materials Resource Center at the University of Wisconsin–Madison was tasked with a project that would quantify the environmental and economic life-cycle benefits associated with the incorporation of recycled materials and industrial by-products in highway construction. An analysis of the environmental benefits (i.e., carbon dioxide emissions, energy consumption, and water consumption) associated with the substitution of recycled materials for conventional virgin materials in highway construction was conducted using the pavement life-cycle assessment tool for environmental and economic effects, a tool developed with the sponsorship of the Recycled Materials Resource Center. An economic impact analysis was conducted by comparing the unit prices of virgin and recycled materials. The analysis showed significant environmental and economic savings in all member states. Total environmental savings from use of recycled materials were approximately equal to the energy consumption of 110,000 U.S. households per year, 9,300 bathtubs of water, and the carbon dioxide emissions produced by 58,000 cars per year. Total systemwide economic savings from use of recycled materials was estimated to be $62.5 million.

More than 26,000 km (163,000 mi) of highways in the National Highway System form the backbone of the 6-million-km (4-million-mi) public road network in the United States. These highways are continuously being constructed and rehabilitated, requiring large amounts of natural raw materials, producing waste, consuming energy, and emitting greenhouse gases (*1, 2*). To reduce the economic and environmental costs, state departments of transportation (DOTs) have been using recycled materials in highway construction.

K. Del Ponte and B. Madras Natarajan, Geological Engineering Program, and A. Baker and E. Elliott, Civil and Environmental Engineering, 2243 Engineering Hall, and A. Pakes Ahlman, 2204 Engineering Hall, and T. B. Edil, 2258 Engineering Hall, Geological Engineering Program and Recycled Materials Resource Center, University of Wisconsin–Madison, 1415 Engineering Drive, Madison, WI 53706. Corresponding author: A. Pakes Ahlman, angela.pakes@wisc.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2628, 2017, pp. 1–11.
http://dx.doi.org/10.3141/2628-01

The Recycled Materials Resource Center (RMRC, http://rmrc.wisc.edu) at the University of Wisconsin–Madison and many governmental agencies have developed fact sheets on various recycled materials and industrial by-products for use in highway construction applications. These fact sheets typically address the engineering properties and environmental suitability issues relevant to various applications and, in some cases, incorporate design guidelines and construction specifications. However, direct information on sustainability assessment characteristics, such as greenhouse gas emissions, energy and water consumption, and life-cycle cost benefits, is not yet readily available. State agencies may track yearly use of quantities of major recycled materials such as fly ash in concrete, recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), and so on, but they have not yet calculated the life-cycle and cost benefits accrued by substituting these materials for conventional materials. Project-by-project tracking of recycled materials with postbid award information has been a challenge. Lacking information or an easy way to track recycled material use, DOTs have not been able to clearly convey the benefits in a quantitative and easily understood manner.

The RMRC submitted a report based on the preliminary analysis and findings of its study to the Geo-Chicago 2016 conference (*3*). This paper expands upon those preliminary findings.

OBJECTIVES

The objective of this study was to quantify the environmental and economic life-cycle benefits associated with the incorporation of recycled materials and industrial by-products into highway pavement construction. These benefits were realistically quantified by collecting and analyzing data from 2013 on the quantities of recycled materials used by each state DOT that is a member of the RMRC pooled fund. Analysis was carried out by using a life-cycle assessment (LCA) tool, the pavement life-cycle assessment tool for environmental and economic effects, or PaLATE. DOTs from the following RMRC member states provided 2013 data for this study: Georgia, Illinois, Minnesota, Pennsylvania, Virginia, and Wisconsin.

DATA COLLECTION

Recycled Materials Used in 2013

To determine recycled material use, RMRC member state DOTs (Georgia, Illinois, Minnesota, Pennsylvania, Virginia, and Wisconsin) were asked to report quantities of recycled materials used for the calendar or fiscal year 2013. Although most of the DOTs were not tracking the quantities of recycled materials used, information was available on as-bid items for projects within the time period for each state. Calculating the quantities of recycled materials from as-bid material quantities required a set of assumptions about average design specifications for each state DOT [e.g., percentage replacement of cement with fly ash, percentage RAP in hot-mix asphalt (HMA), pavement dimensional specifications]. These assumptions were determined through interviews of and correspondence with engineers from each member state. These assumptions and averages were then used to calculate the amounts of recycled materials used in HMA, fly ash in concrete mixes, and recycled aggregates in base course layers.

Average Material Cost

After data on the quantity of recycled materials used in 2013 by RMRC member states were collected, a second phase of data collection began to determine the average unit price of both recycled materials and virgin (conventional, nonrecycled) materials. In general, an average unit price (dollars per ton of material) of each recycled material was found by surveying providers, pavement associations, and various material associations in each state. Because this was a systemwide study, the unit cost of each material did not include transportation costs to the mix plant or to the construction site. However, for a specific project basis analysis, transportation costs could be incorporated, and they can be significant (*3*).

The unit cost of equivalent volumes of virgin materials was estimated by using a weighted average of *Engineering News-Record* (ENR) (*4*) historic material price indices. ENR tracks on a monthly basis the price of raw paving materials of 20 cities including Atlanta, Georgia; Baltimore, Maryland; Chicago, Illinois; Minneapolis, Minnesota; and Philadelphia and Pittsburgh, Pennsylvania. The monthly prices from July 2012 through January 2014 were averaged to determine the average price of aggregate, base course materials, and cement in each city. The individual city price averages were then averaged with the average price of all the cities to normalize any prices that were skewed high or low. Because most state DOTs track the price of liquid asphalt more frequently than ENR does, these indices were used instead of ENR estimates. ENR does not track material prices in any Wisconsin cities: therefore, local pavement associations and material providers were asked to provide estimated savings from using recycled materials, expressed as a unit cost.

ANALYSIS

PaLATE Life-Cycle Assessment

PaLATE LCA Overview

The first step in quantifying the environmental benefits of using recycled materials was to examine existing publicly available pavement LCA tools. LCA can assist in gaining a better understanding of the environmental impacts of materials and processes throughout the product life cycle (cradle to grave) and provide relevant data for use in making informed decisions (*5*). The ISO 14040 series provides general principles and a framework for an LCA study, detailing four phases of an LCA: (*a*) definition of goals and scope, (*b*) inventory analysis, (*c*) impact assessment, and (*d*) interpretation. In general, LCAs should have defined system boundaries, functioning units, and inputs and outputs. For most pavement LCAs, the defined system boundaries are materials, transportation of materials, construction, use, maintenance, and end of life (*6*).

The goal of using LCA for this study was to calculate the environmental benefits of using recycled materials and industrial by-products in highway pavement. To achieve this goal, the LCA tool, PaLATE, was chosen. The other publicly available LCA tools researched for this study are discussed in Pakes Ahlman et al. (*7*). PaLATE, developed for the RMRC, follows the production of materials, transportation of materials, construction, maintenance, and end-of-life processes (*8*). Initial material inputs are analyzed on the basis of the equipment used to produce and transport them to the construction site. Emissions attributable to construction, transportation, maintenance, and production are calculated from the equipment used in all processes. Many PaLATE outputs are based on the volume 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 producing information not only on greenhouse gases emissions, but also on energy use, water consumption, particulate matter, waste generation, and human toxicity potentials. The first version of PaLATE was developed in 2004, and while the range of environmental outputs of PaLATE is wide, these are limited by databases that may be out of date. The PaLATE databases were therefore updated, in part, to ensure that this analysis would reflect the industry conditions in 2013. The details of this update can be found in Pakes Ahlman et al. (*7*).

Assumptions and Parameters

Determining specific design parameters (such as pavement thickness and fly ash replacement of concrete) for every DOT project over the annual period was unfeasible, so certain standard practice assumptions were made (G. Whited, personal communication, 2014). The general assumptions made for the LCA analysis in PaLATE included the following:

1. The replacement volume of virgin materials with recycled materials, despite the known varying mechanical properties, was assumed to be 1:1.
2. All materials were assumed to be used in initial construction operations.
3. Both cement and fly ash were assumed to be delivered by cement trucks over a one-way distance of 320 km (200 mi) from the processing site to the concrete mix plant.
4. All RAP and RCA were assumed to be processed and reused on site with a transportation distance of zero.
5. All other materials included in HMA, ready-mix concrete, and the base course were assumed to be delivered by truck over a one-way distance of 40 km (25 mi) from the processing site to the asphalt or concrete mix plant.
6. All equipment was assumed to be the default equipment type for each process in PaLATE.
7. All densities of materials were assumed to be the listed densities in PaLATE.

It should be noted, these assumptions are general assumptions about the recycled materials reported by each state. More specific assumptions can be found in the final RMRC project report, *State DOT Life Cycle Benefits of Recycled Material in Road Construction* (*3*).

Approach to PaLATE Analysis

The quantities of recycled materials used by each member state were analyzed in PaLATE to determine the environmental impacts and benefits of using recycled materials. These environmental impacts and resulting benefits were analyzed comparatively by using an equivalent volume of virgin materials. Three environmental impact factors, carbon dioxide (CO_2) emissions, energy consumption, and water consumption, were deemed sufficient for evaluation of the state materials. PaLATE determines the environmental impacts on the basis of three categories: material production, material transportation, and construction processes (equipment). Material production includes the processes associated with extracting or generating the materials, such as milling RAP and quarrying virgin aggregate. 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 materials, such as paving, placing, and compaction.

The first step in conducting the PaLATE analysis was to compile the collected recycled materials data for all the member states and to convert the quantities from weight to volume by using the given densities in PaLATE. Then, equivalent virgin material volumes 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 in terms of production, transportation, and processes was determined. Finally, the environmental impact of recycled versus virgin material was analyzed.

Economic Impact Analysis

Parameters and Assumptions

Because of the nature of the collected data, a true life-cycle cost analysis could not be performed without making some significant and perhaps unreasonable assumptions. Given only material quantities and broad assumptions as to how each material was applied to a highway, a life-cycle cost analysis could not be performed to a reasonable degree of accuracy. Instead, the cost savings realized by each state in 2013 were estimated by comparing the prices of recycled and virgin materials.

The general cost assumptions made in the analysis are listed below. Included in these assumptions are the assumptions used to calculate the total quantities of recycled materials used in 2013.

1. The cost of hauling, either to the mixing plant or to the construction site, was not included in the unit price of each material.
2. Materials were assumed to be purchased individually and not as part of a mixture; that is, no distinction was made between the paving contractor and state agency.

Approach to Economic Impact Analysis

As previously mentioned, the economic savings were estimated by comparing the prices of recycled materials and virgin materials per ton of material. Because of the many factors involved in calculating the price of materials, for the purposes of this study, the average purchase price per ton of both recycled materials and virgin materials was determined without including the cost of transportation. As was done for the environmental analysis, the recycled and virgin materials were converted to equivalent volumes and then to corresponding weights. These weights were then used to calculate the cost of recycled materials and virgin materials used. Total savings and unit savings per ton of recycled material could then be estimated for each state; a full analysis can be found in the final RMRC project report, *Life Cycle Benefits of Recycled Material in State DOT Road Construction* (*7*). The estimated unit cost savings in 2013 for the recycled material are shown in Table 1.

These savings are meant to be a conservative estimate of the potential economic savings of using recycled materials. The true economic impact of using recycled materials cannot be determined unless all aspects are known of how both recycled materials and their equivalent virgin materials are priced and applied in construction.

RESULTS AND TRENDS ACROSS STATES

Quantities of Recycled Materials Used

All six member state DOTs used RAP in HMA and fly ash, while at least four member state DOTs used recycled asphalt shingles (RAS) and RCA. Figure 1 shows the tonnage of each major recycled material used per state in the LCA and economic analyses. Although crumb rubber and ground granulated furnace slag were used by many states, they are not presented.

RAP in HMA was used the most by weight and volume across all states, although use varied significantly with geography. In the southern states (Georgia and Virginia) HMA pavement is more widely used than in the northern states (Illinois, Minnesota, and Wisconsin). Northern states tend to use portland cement concrete pavement for their major highways. These characteristics are reflected in the recycled material use for each state. The northern states, where portland cement concrete is more common, use more RCA, and the southern states, where HMA is widely used, use more RAP, particularly in HMA.

TABLE 1 Estimated 2013 Unit Cost Savings per Ton of Recycled Material

Material	Georgia ($)	Illinois ($)	Minnesota ($)	Pennsylvania ($)	Virginia ($)	Wisconsin ($)
RAP in HMA	6.62	6.64	14.72	7.37	16.26	5.72
RAS	67.65	55.02	na	na	82.18	98.00
Fly ash	4.33	43.36	28.61	8.97	66.18	30.00
RCA	1.03	–0.01	1.03	na	na	4.50
RAP in base	na	na	na	1.46	na	4.00

NOTE: na = not applicable.

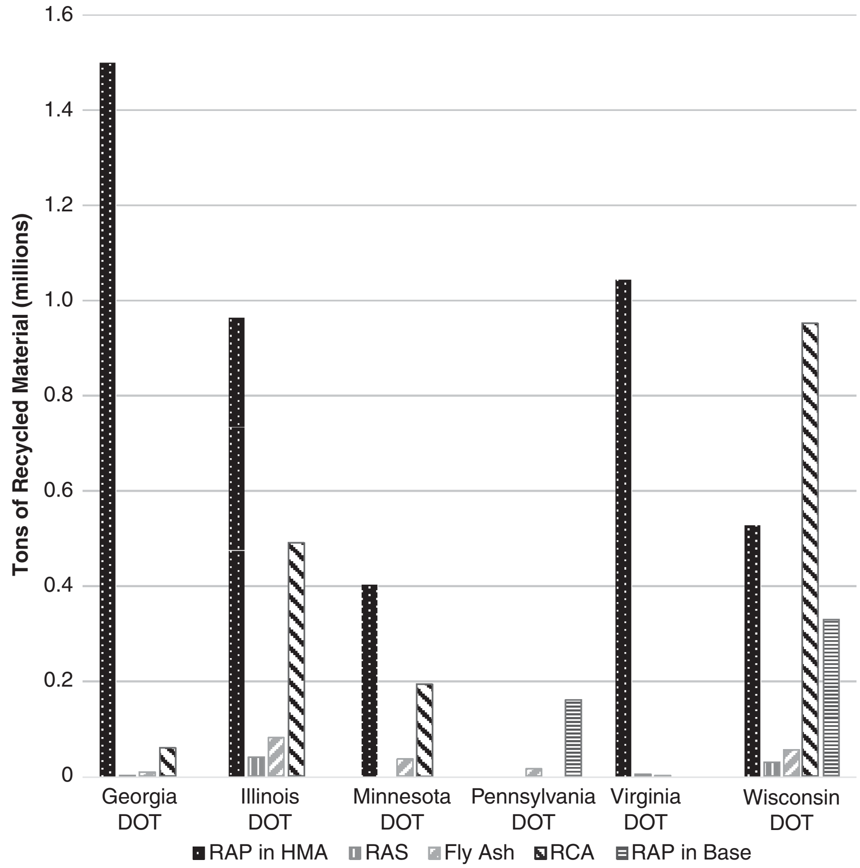

FIGURE 1 Total recycled material used in 2013.

The Illinois DOT used above average quantities of all four widely used recycled materials (RAP in HMA, RAS, fly ash, and RCA), while the Wisconsin DOT used more RAS, fly ash, and RCA. The Georgia and Virginia DOTs used above average amounts of RAP in HMA, and the Minnesota DOT used proportionately greater amounts of fly ash. As shown in Figure 2, the Wisconsin DOT used the most recycled materials, approximately 1.9 million tons, followed closely by the Illinois and Georgia DOTs, approximately 1.6 million tons each. The Virginia DOT used slightly more than half of the quantity of recycled material that the Wisconsin DOT used, while the Minnesota and Pennsylvania DOTs used about one third of the quantity used by the Wisconsin DOT. The total tonnage of the Illinois DOT includes those materials not used in the LCA or economic analysis.

Figure 2 shows that member state DOTs with a higher highway budget then other DOTs usually had a lower use of recycled materials, while those member state DOTs with a lower budget then other DOTs had a higher use of recycled materials. The Pennsylvania and Virginia DOTs had the highest budgets but used fewer recycled materials than the Georgia, Illinois, and Wisconsin DOTs. An exception to this finding is the Minnesota DOT, which had a comparable budget to that of the Georgia, Illinois, and Wisconsin DOTs, but whose tonnage of recycled materials was comparable to that of the Pennsylvania DOT.

Environmental Results and Discussion

Environmental impacts of roadway construction were quantified through CO_2 emissions, energy consumption, and water consumption. The environmental savings from using recycled materials was calculated as the difference between the impact categories for the recycled materials and their virgin equivalents at a 1:1 replacement ratio. These environmental savings are shown in Figure 3.

There were significant savings for all states in every environmental factor. CO_2 savings spanned from 20,975 to 70,178 Mg, energy savings ranged from 344 to 1,171 TJ, while savings in water consumption ranged from 122,287 to 402,829 kg. Additionally, the trends for all the environmental savings were very similar. The Georgia DOT was found to have the highest environmental savings across the board, with the Illinois DOT having the second highest savings. The Virginia and Wisconsin DOTs had similar results for all environmental factors. The Minnesota and Pennsylvania DOTs were found to have lower environmental savings in all categories. From Figure 3 it was determined that all environmental categories had similar trends. Thus, CO_2 emissions savings were used to represent all environmental categories (energy consumption, water consumption, and CO_2 emissions), and the trends noted between CO_2 emissions savings and recycled material use hold true for the other environmental categories.

Figure 4 displays the tons of each recycled material used and the CO_2 emissions saved in every state. Figure 4 demonstrates that states that use more recycled materials should expect greater CO_2 emissions savings. The Minnesota and Pennsylvania DOTs used the least amount of recycled material and are shown to save the least in CO_2 emissions. However, not all states followed this trend because some materials have a greater CO_2 emissions saving capacity than others. For example, the Wisconsin DOT used the most recycled

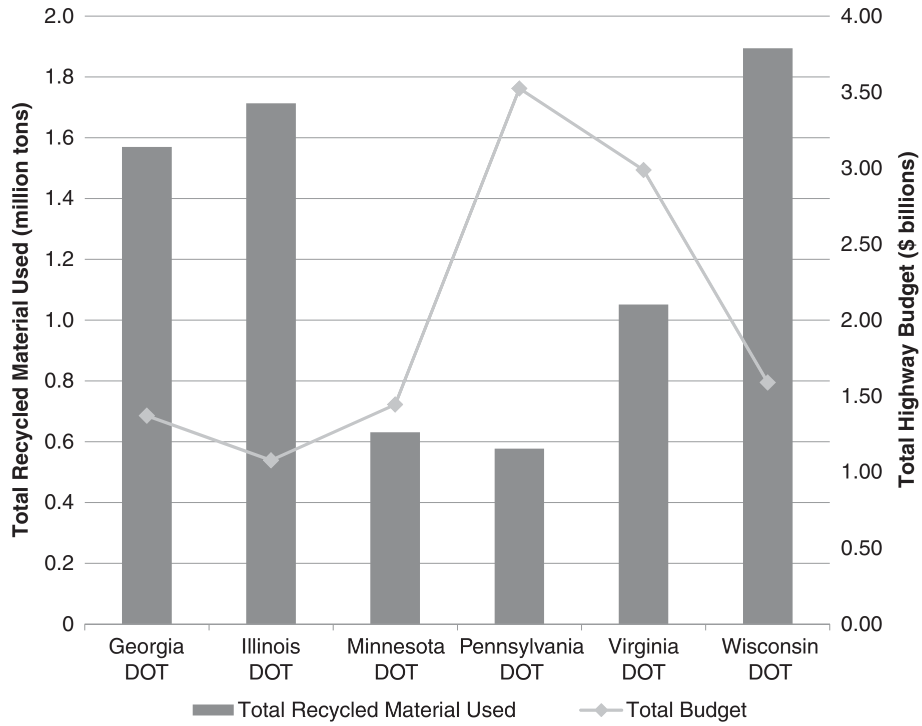

FIGURE 2 Recycled material and total highway budget for FY 2013.

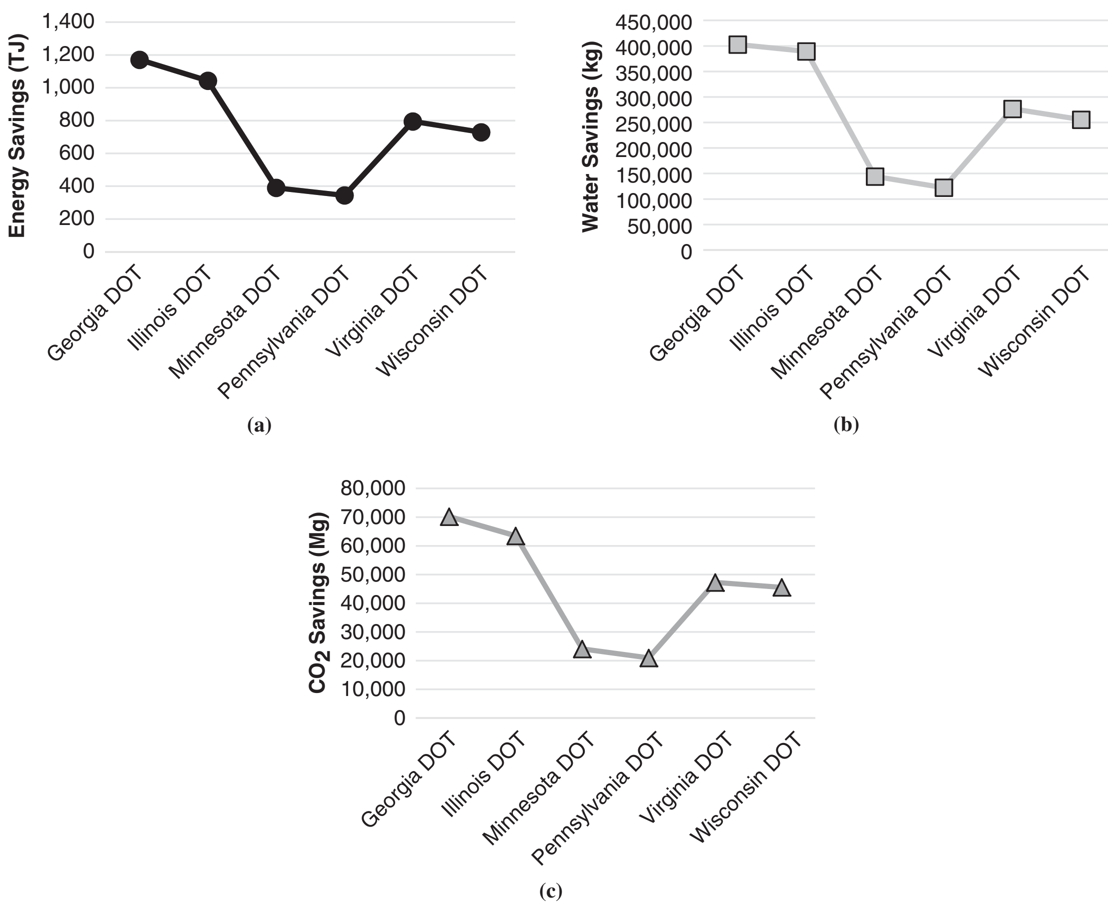

FIGURE 3 Environmental savings comparison for (*a*) energy consumption, (*b*) water consumption, and (*c*) CO_2 emissions.

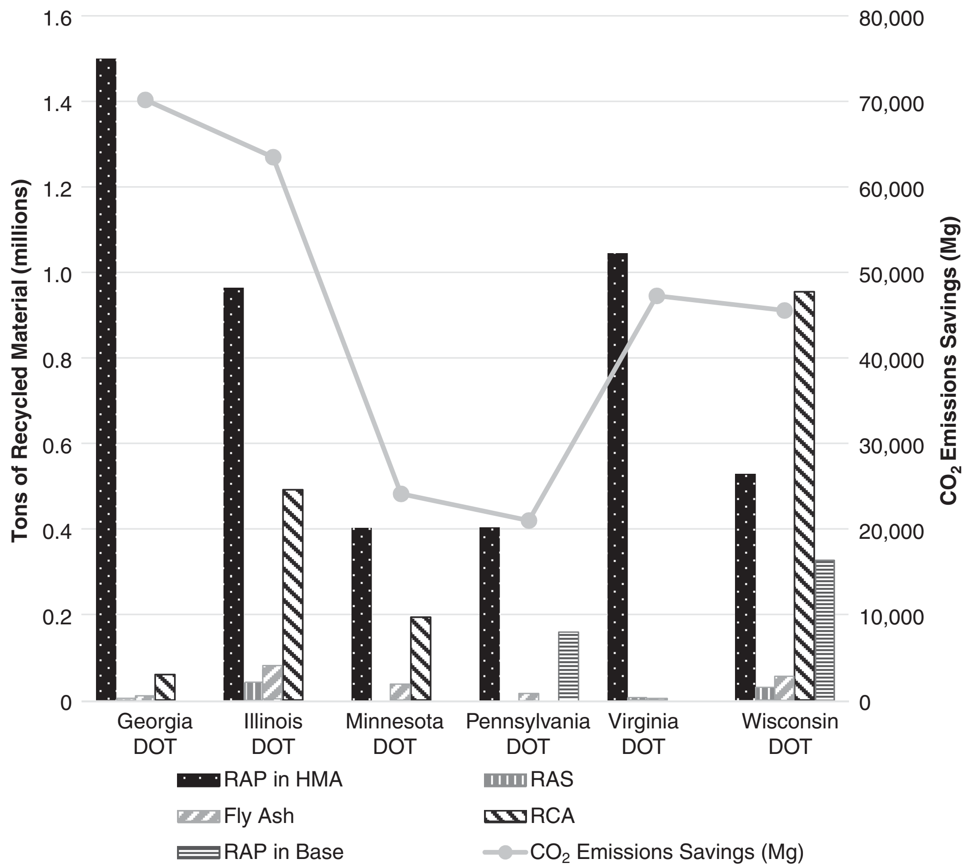

FIGURE 4 Tonnage of recycled materials and CO_2 emissions savings.

material but did not see higher CO_2 emissions savings than the Georgia and Illinois DOTs. A trend between CO_2 emissions savings and RAP in HMA was observed: states that used large amounts of RAP in HMA saw high environmental savings. RAP in HMA was the most widely used recycled material, accounting for about 66% of the total recycled materials used by the six states studied. Therefore, the CO_2 emissions savings reflected for each state were largely influenced by the amount of RAP in HMA the state used.

However, total use of recycled materials has a significant effect as well. This balance can be seen by comparing the Wisconsin, Minnesota, and Pennsylvania DOTs. These three states used a comparable amount of RAP in HMA, but the Wisconsin DOT had a significantly higher CO_2 emissions savings because of a much higher use of total recycled materials. Another example of the balance between RAP in HMA used and total recycled materials used was found when comparing the Wisconsin and Virginia DOTs. Both states saw comparable CO_2 emissions savings despite differences in the amounts and types of recycled material used. The Virginia DOT used about 1 million tons of recycled material mainly consisting of RAP in HMA, while the Wisconsin DOT used about 1.9 million tons of a larger variety of recycled materials. Given the effect of RAP in HMA on CO_2 emissions, it was unsurprising that Wisconsin DOT had lower CO_2 emissions savings.

The large effect of RAP in HMA on CO_2 emissions savings is further illustrated in Figure 5, which shows each recycled material used as a percentage of total recycled materials for each state and CO_2 emissions savings per ton of total recycled material for each state. (Unlike Figure 4, Figure 5 does not consider the total amount of recycled material used.) This figure allows for a clearer view into which recycled material has the highest potential for environmental savings. The Georgia and Virginia DOTs used the largest amount of RAP in HMA as a percentage of the total of recycled material used (both more than 90%) and saw the highest CO_2 emissions savings per ton of recycled materials. This correlation can also be seen with the Wisconsin DOT, which had the lowest RAP in HMA as a percentage of the total recycled materials used and the lowest CO_2 emissions savings per ton. This study found that RAP in HMA has a significant influence on CO_2 emissions savings. One explanation for this finding is that when RAP is used in HMA, it acts partially as a binder replacement. Producing the binder for a pavement is an extremely energy- and emissions-intensive process, thus using RAP in HMA reduced the need for the asphalt binder and the associated environmental impacts (*7*). RAS and fly ash, both binder replacements for their respective pavement types, would likely have the same influence on environmental savings. However, they were not recycled to the extent that RAP in HMA was during the period covered in this study; therefore, their potential environmental savings were not evaluated.

Figure 6 shows the percentage reductions in environmental factors for each state attributable to a 1:1 replacement of virgin materials with recycled materials. High percentage savings were seen for all environmental factors, with water consumption savings being the highest (94% to 99%) and energy savings being the lowest (78% to 83%). Despite energy consumption showing the lowest percentage savings of the three environmental factors, a reduction of at least 78% in energy needed for road construction because of the use of recycled materials is significant.

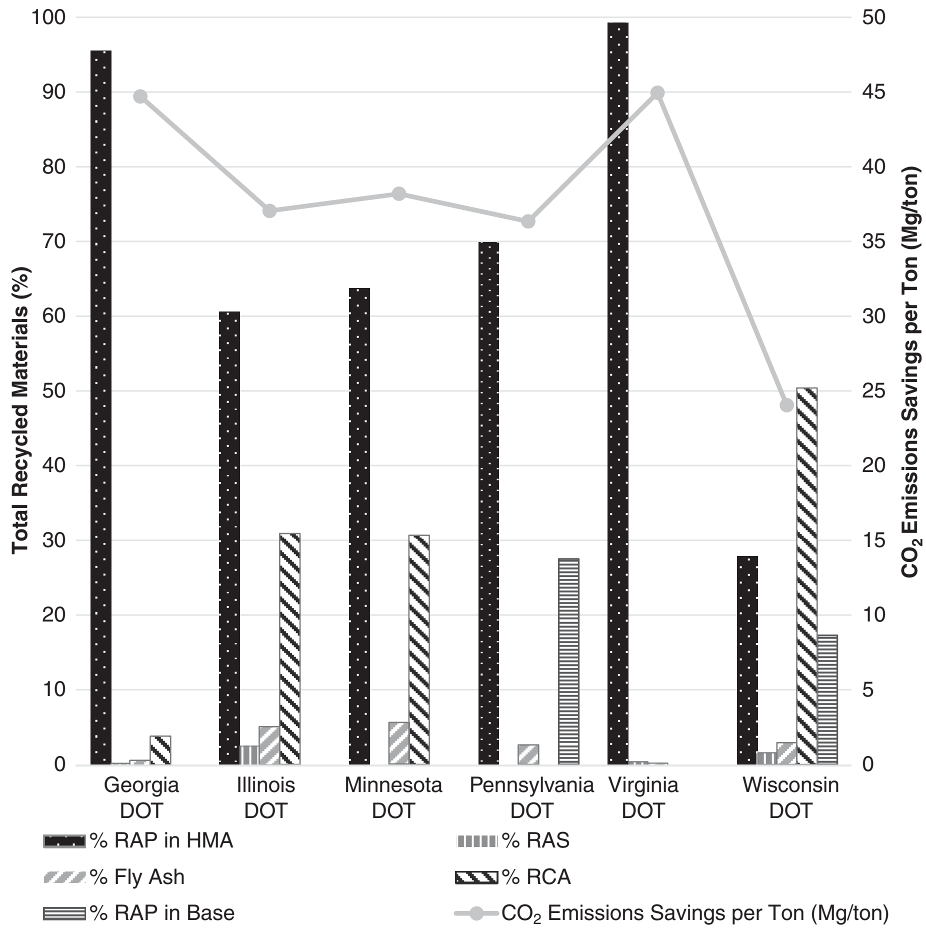

FIGURE 5 Percentage of material and CO_2 emissions savings per ton.

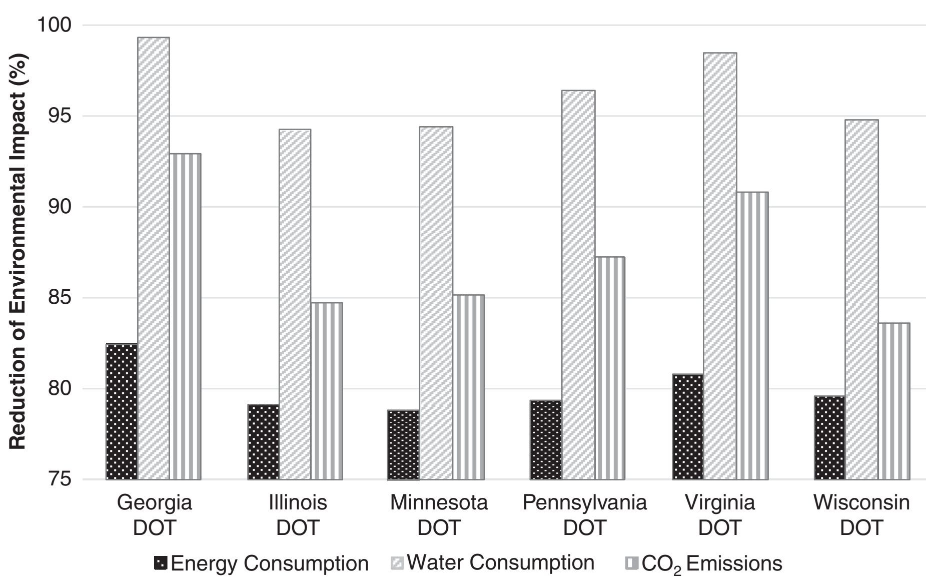

FIGURE 6 Percent reductions of environmental impact.

Economic Results and Discussion

The estimated cost savings of each state ranged from $3 billion to $17.5 billion, as shown in Figure 7. Using RAP in HMA as a binder and aggregate replacement had the highest economic savings of any recycled material used in this study mainly because of the large quantities of RAP in HMA used, but also because of the high costs of virgin asphalt binder. Similar results were seen for RAS and fly ash. These three recycled materials all replace a percentage of virgin materials that act as binders. Binder for asphalt mixes had an average price of about $500/ton, and cement had an average price of about $110/ton; these two materials were the most expensive materials in this study. The price of materials that replaced aggregates was generally much lower: between $10 and $20 per ton, and thus did not have as much of an impact on total cost savings. The Georgia and Illinois DOTs both used similar quantities of recycled material; however, the Illinois DOT saved about $2 million more than the Georgia DOT. This difference can be attributed to the fact that the Illinois DOT recycled more binder replacements other than RAP in HMA, specifically RAS and fly ash, compared with the Georgia DOT.

Variability in cost savings per material may account for some of the differences in total savings, but does not account for the disproportionately higher savings realized by the Virginia DOT, shown in Figure 7. The Virginia DOT used only the fourth largest amount of recycled materials but exceeded the savings of each other state by an average of about $8.4 million. A possible explanation for this incongruity is the differences in local cost structure (ENR average prices for virgin material in and around the city of Baltimore were much higher than in the other cities in this study).

Cost savings per ton of recycled material and their correlation with the total savings realized is shown in Figure 8. Binder replacement materials—RAS, RAP, and fly ash—were found to have the greatest savings per ton in each state. As previously discussed, materials replacing expensive virgin materials had a large impact on total cost savings. Savings varied depending on quantity and type of recycled materials used, but greater use of recycled materials generally led to higher total savings. For example, the Virginia DOT used an average total tonnage of recycled material compared with other states but realized the greatest total savings. In Virginia, the savings per ton of RAP in HMA was slightly higher than in the other states. This

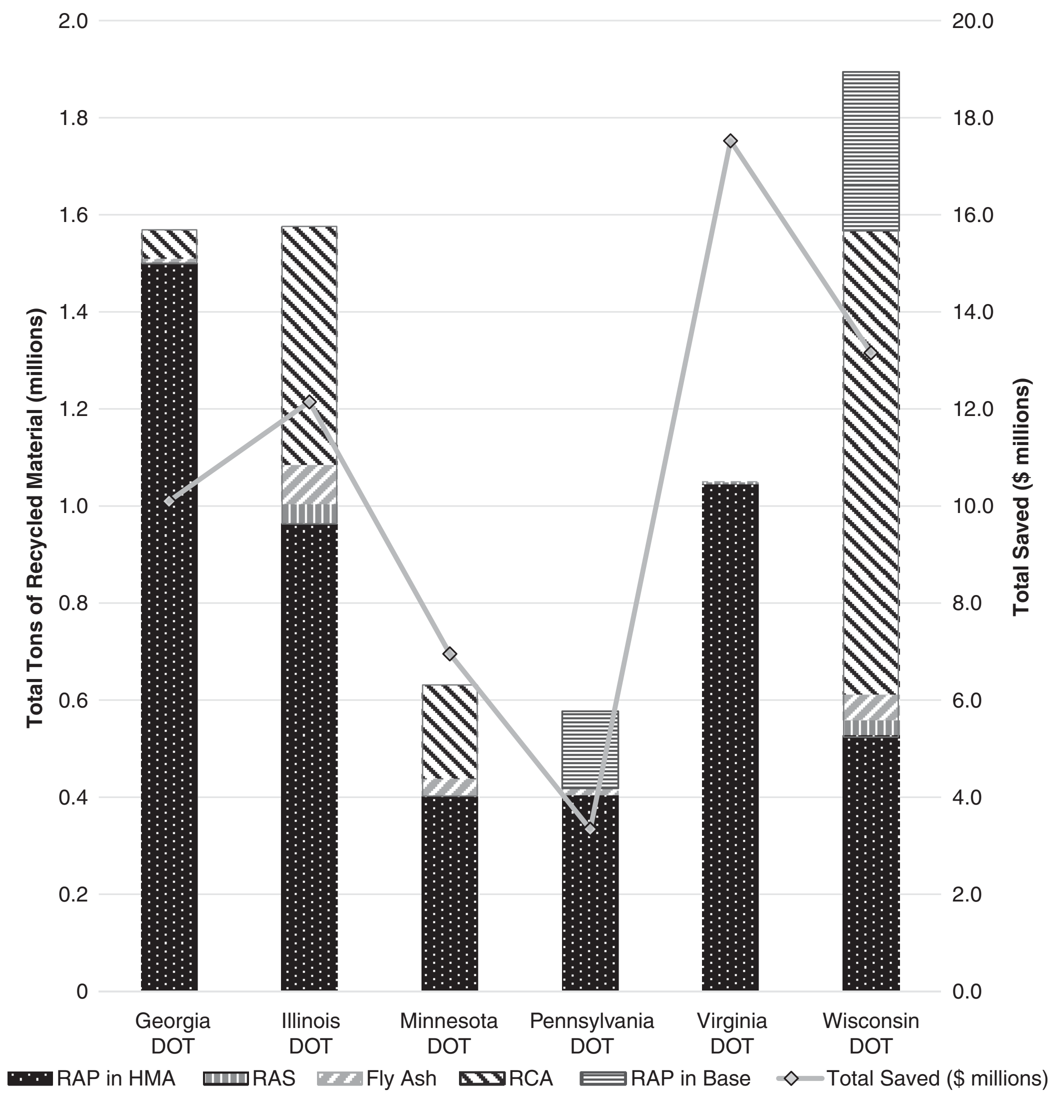

FIGURE 7 Cost savings from use of recycled material.

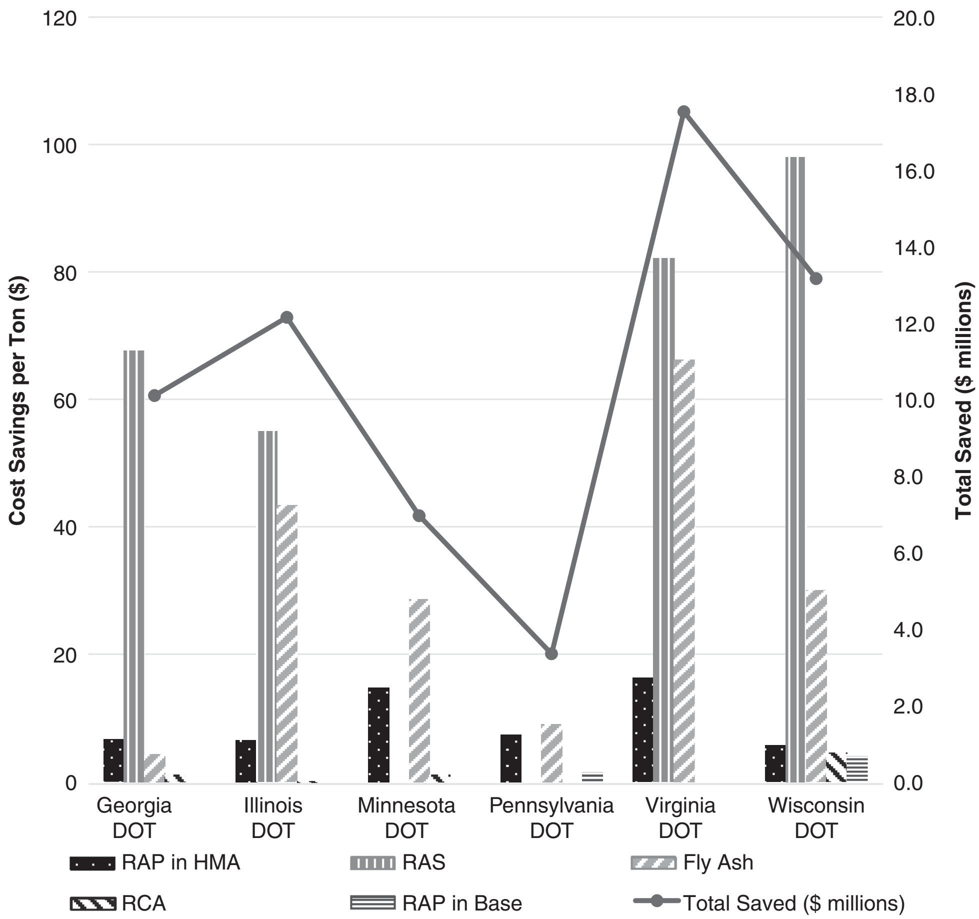

FIGURE 8 Dollar savings per ton of recycled material.

fact, coupled with the high tonnage of RAP in HMA used by the Virginia DOT, explains the significantly higher total savings realized in this state.

Figure 9 shows a comparison of average savings, total tons of recycled material used, and total cost savings. In general, the economic impact realized through the use of recycled materials was found to be dependent on both the type and quantity of recycled materials as well as the local price structure. The Georgia, Illinois, and Wisconsin DOTs all had lower average savings per ton of recycled material but a higher total use of recycled material. As a result, those states had intermediate total cost savings compared with the other states. On the other hand, the Virginia DOT realized the highest average savings per ton of recycled material and intermediate total tons of recycled material used compared with the other states, and its total cost savings were found to be the highest.

CONCLUSIONS

Using the data collected from the six member state DOTs of the RMRC, the environmental and economic benefits associated with the use of recycled materials were quantified. The updated LCA tool PaLATE was used for the analysis of environmental benefits. The economic benefits were calculated by a comparison of the average price of virgin materials and recycled materials by using the cost structure in each state.

The total environmental savings from recycled materials used across all member states are estimated to be 4,500 TJ of energy, 1.6 million kg of water, and 49,000 Mg of CO_2. These totals approximately equate to the energy consumption of 110,000 U.S. households per year, 9,300 bathtubs of water, and the CO_2 emissions produced by 58,000 cars per year (*9–11*). RAP in HMA was the most widely used recycled material and resulted in the greatest environmental benefits compared with the other recycled materials examined in this study. However, the overall environmental benefits resulting from the use of recycled materials in roads are a combination of both the amount of material and the type of materials used.

The total economic savings realized from recycled material use across all member states are estimated to be $62.5 million. Materials used as a partial replacement for traditional binders, such as RAP, RAS and fly ash, had higher cost savings compared with recycled materials used in substitution of aggregates, such as RAP and RCA. Total cost savings are dependent on the usage rate of each recycled material, as well as the cost structure in the location where the material is being sourced.

The research outlined in this paper not only quantifies the environmental benefits of using recycled materials in highway pavement construction but also draws attention to the considerable economic benefits of using these materials. Each member state DOT saw large reductions in the measured environmental outputs and positive total monetary savings as a result of using recycled materials and industrial byproducts in highways in 2013.

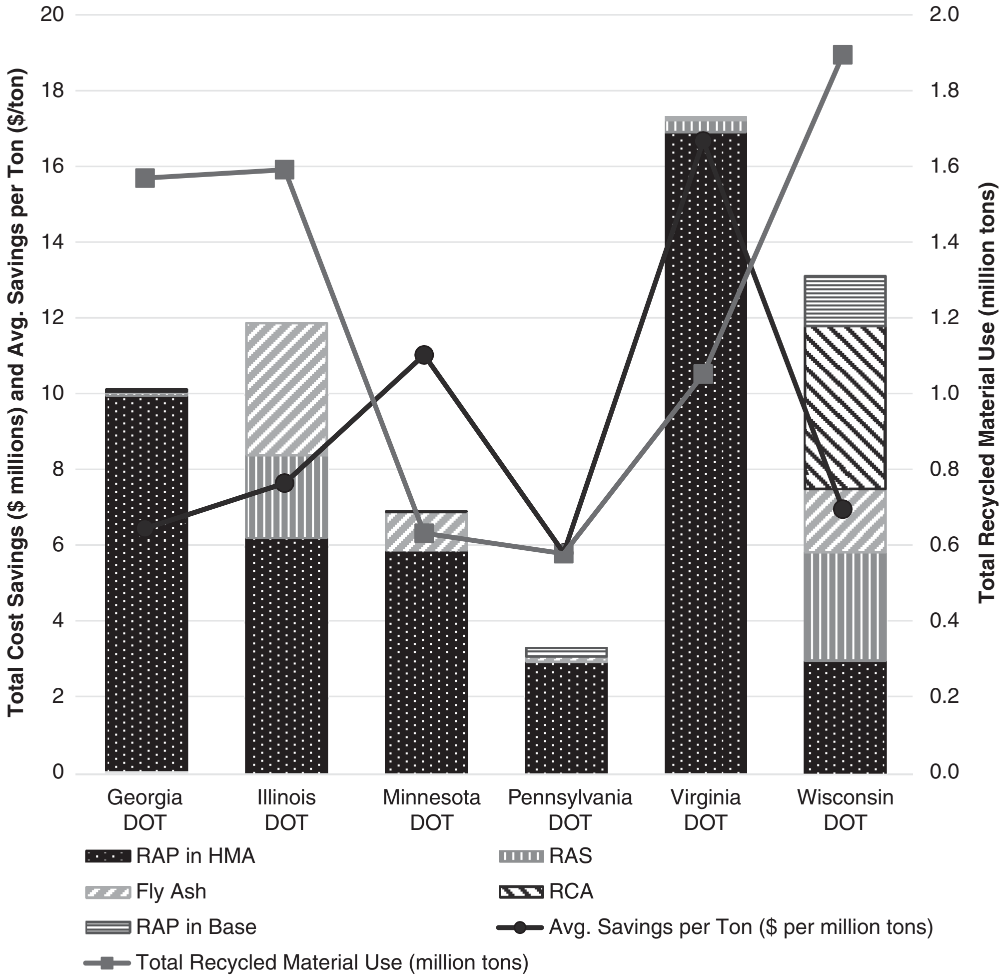

FIGURE 9 Total savings, average savings, and total use of recycled materials.

FUTURE RESEARCH AND RECOMMENDATIONS

Future research into sustainability assessment measurements should consider real-time collection of the data, particularly in relation to material prices. All the data used in this study were collected in 2014 and 2015, which meant some assumptions had to be made for the calculation of quantities of recycled material and average material unit prices as well as for using the LCA in PaLATE for each member state DOT. Because PaLATE was used as the LCA tool in this research, any limitations associated with PaLATE must be considered. If PaLATE is used for future analyses and research, updating its databases should be considered.

The conclusions of this study reflect the positive practices each member state should undertake to realize the life-cycle benefits estimated in this study. The first key takeaway for each member state DOT is the importance of tracking use of recycled materials. This practice will decrease the number of assumptions currently needed to perform an annual life-cycle benefit analysis of the use of recycled materials and also increase the accuracy of future analyses.

As the number of change regulations and initiatives and the amount of social awareness increase, particularly in regard to greenhouse gas emissions, DOTs will need to implement LCA in their pavement management systems and initial construction operations along with any life-cycle cost analysis systems already in place. This type of system would allow for greater environmental impact percentage reductions and cost savings per mile by optimizing an annual budget considering both factors, rather than just economics.

Another practice suggested by the findings of this study that member state DOTs can consider is balancing their use of recycled materials in terms of type of recycled material, as is currently the practice of the Wisconsin DOT. The Wisconsin DOT was able to recycle large quantities of five materials, which affected both the environmental and economic analyses performed.

ACKNOWLEDGMENTS

The pool fund supporting the Recycled Materials Resource Center provided funding for this project. The contributions of engineers from each member state DOT who provided the required material data and reviewed the various assumptions—Steve Krebs, Winnie Okello, Gerard Geib, Edward Wallingford, Mike Fitch, Mathew Mueller, Sheila Beshears, Richard Douds, and Peter Wu—are acknowledged. Various material suppliers and state pavement associations provided cost data. Gary Whited of the University of Wisconsin–Madison and formerly of the Wisconsin DOT aided in data collection and interpretation for this research; his contributions are greatly appreciated.

Within the Recycled Materials Resource Center, Eleanor Bloom and Aaron Canton assisted with data collection and analysis. Greg Horstmeier of the University of Wisconsin–Madison assisted in data collection. Julia Wilcots of Princeton University also assisted with preliminary data collection.

REFERENCES

1. *Primer on Transportation and Climate Change.* Publication PCRT-1. AASHTO, Washington, D.C., 2008.
2. Gambatese, J., and S. Rajendran. Sustainable Roadway Construction: Energy Consumption and Material Waste Generation of Roadways. Presented at the Construction Research Congress, San Diego, Calif., 2005. 10.1061/40754(183)21.
3. Bloom, E., K. Del Ponte, B. Madras Natarajan, A. Pakes Ahlman, T. Edil, and G. Whited. State DOT Life Cycle Benefits of Recycled Material in Road Construction. In *Geo-Chicago 2016: Sustainability and Resiliency in Geotechnical Engineering* (D. Zekkos, A. Farid, A. De, K. R. Reddy, and N. Yesiller, eds.), ASCE, 2016, pp. 693–703. doi: 10.1061/9780784480120.070.
4. Historical Cost Indices from 1978–2012. In *Engineering News-Record.* New York, McGraw-Hill, 1917, p. 140.
5. *Environmental Management–Life Cycle Assessment–Principles and Framework.* Publication 14040:2006. International Organization for Standardization, Geneva, 2006.
6. Santero, N., A. Loijos, M. Akbarian, and J. Ochsendorf. *Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle.* Massachusetts Institute of Technology, Cambridge, 2011. http://www.greenconcrete.info/downloads/MITPavementLCAreport.pdf.
7. Pakes Ahlman, A., T. Edil, and K. Del Ponte. Life Cycle Benefits of Recycled Material in State DOT Road Construction. Final Report, 2016 (forthcoming).
8. Horvath, A. PaLATE: Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects. Consortium of Green Design and Manufacturing, University of California. Berkeley, 2004. http://www.ce.berkeley.edu/~horvath/palate.html.
9. U.S. Energy Information Administration. Frequently Asked Questions: How Much Electricity Does an American Home Use? U.S. Department of Energy, Oct. 21, 2015. https://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3.
10. Portland Water Bureau. *Shower and Bath Fact Sheet.* Portland, Ore., 2016. http://www.portlandoregon.gov/water/article/305153.
11. U.S. Environmental Protection Agency. *Average Annual Emission and Fuel Consumption for Gasoline-Fueled Passenger Cars and Light Trucks.* Publication EPA420-F-08-024. 2008. https://www3.epa.gov/otaq/consumer/420f08024.pdf.

The Standing Committee on Resource Conservation and Recovery peer-reviewed this paper.