Quantitative Assessment of Environmental and Economic Benefits of Recycled Materials in Highway Construction

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The benefits of using recycled materials in highway pavements was assessed quantitatively by conducting life-cycle analysis and life-cycle cost analysis on pavements consisting of conventional and recycled materials for a highway construction project in Wisconsin. Results of the analysis indicate that using recycled materials in the base and subbase layers of a pavement can result in reductions in global warming potential (20%), energy consumption (16%), water consumption (11%), and hazardous waste generation (11%) while also extending the service life of the pavement. In addition, using recycled materials in the base and subbase layers can result in a life-cycle cost savings of 21%. The savings are even greater if landfill avoidance costs are considered for the recycled materials incorporated in the pavement. Extrapolation of the benefits to conditions nationwide indicates that modest changes in pavement design to incorporate recycled materials can contribute substantially to the emission reductions required to stabilize greenhouse gas emissions at current levels.

New construction and rehabilitation of the roadway system in the United States occurs continuously to meet the nation's transportation needs. These activities consume large amounts of natural materials and energy, produce wastes, and generate greenhouse gas emissions (*1, 2*). Thus any regional or national sustainability plan in the United States must account for roadway construction and rehabilitation.

A sustainable approach to material consumption begins with design and planning that reuses and incorporates suitable by-products that would otherwise be disposed. Ideally, products can be designed so that recycling and reuse occur at all stages of the life-cycle, resulting in limited waste generation. For road construction, Gambatese and Rajendran (*1*) and Kibert (*3*) show that reuse and recycling can significantly contribute to more sustainable road construction practices. However, lack of comparative analysis methods, examples, and protocols for actual construction projects hinders the ability to quantify tangible environmental and economic benefits that can be achieved through reuse and recycling in pavement design and construction.

Carpenter et al. (*4*) illustrate how a life-cycle assessment (LCA) approach can be used to quantify the environmental impacts of using recycled materials in lieu of conventional construction materials and remark on the economic benefit that can be accrued using recycled materials in roadway construction. However, their analysis does not include rehabilitation activities, which are some of the most energy-intensive phases in the roadway life cycle. They also do not quantify the economic benefits from using recycled materials. In the context of sustainability, direct comparisons of the life-cycle cost using recycled materials instead of conventional materials are important.

In this study, comparative environmental and economic life-cycle analyses were conducted to quantify the environmental and economic benefits that could be accrued by using recycled materials when constructing a 4.7-km-long section of the Burlington Bypass in southeastern Wisconsin. Rehabilitation activities were explicitly included in the life-cycle analysis using the international roughness index (IRI) as a metric to define when rehabilitation would be required, as suggested by FHWA (*5*). The benefits illustrated in this quantitative analysis are expected to encourage wider adoption of recycled materials in roadway construction and rehabilitation.

EVALUATION OF THE BURLINGTON BYPASS

A comparative life-cycle analysis was conducted for construction of a section of Wisconsin State Highway 36/83 near Burlington, Wisconsin (the Burlington Bypass), assuming that the pavement would be constructed with conventional or recycled materials. The Burlington Bypass consists of 17.7 km of highway that routes traffic on WIS-11 and WIS-36/83 around the City of Burlington, Wisconsin. The bypass is intended to improve safety, reduce delays, and to provide an efficient travel pattern that reduces truck traffic in the downtown area of the city of Burlington (*6*). The western portion of the bypass is being constructed between spring 2008 and fall 2010. A 4.7-km-long section of the western portion of the bypass was analyzed in this study.

A flowchart for the evaluation procedure is shown in Figure 1. The steps include creating pavement designs using conventional and recycled materials, predicting the service life of each design, identifying rehabilitation strategies, and conducting LCA and life-cycle cost analysis (LCCA). LCCA is a financial-based decision-making

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tool for long-term assessment of construction projects that can be used to systematically determine costs attributable to each alternative course of action over a life-cycle period and to make economic comparisons between competing designs (*7, 8*).

Environmental analysis of the conventional and alternative pavements was conducted with LCA. Four environmental variables were considered in the assessment: energy consumption, greenhouse gas emissions, water consumption, and generation of hazardous wastes, as defined by the U.S. Resource Conservation and Recovery Act (RCRA).

The two potential pavement designs considered in the analysis are shown in Figure 2, a conventional pavement design proposed by the Wisconsin Department of Transportation (WisDOT) and an alternative pavement design employing recycled pavement material stabilized with fly ash as the base course and foundry sand as the subbase. Recycled materials can also be used in hot-mix asphalt (HMA) and in other elements in the right-of-way (e.g., pipes, guide rails, barriers, etc.); in this study, however, recycled materials were only used in the base and subbase layers of the pavement.

The same layer thicknesses were used in the conventional and alternative designs and the structural capacity of both pavements was determined using the same procedure. However, the recycled materials have different engineering properties than the conventional materials, which resulted in differences in the calculated service life. Design parameters for the recycled materials were obtained from recommendations made by Geo Engineering Consulting (*9*), which are based on research findings reported by Li et al. (*10*) and Tanyu et al. (*11, 12*).

The pavements were assumed to be serviceable until the IRI reached 2.7 m/km, as recommended by FHWA (*5*). Once this IRI was reached, the pavement was assumed to require rehabilitation. The IRI was predicted using the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) *Version 1.0* (*13*). MEPDG primarily uses three key variables in the analysis: (a) traffic data, (b) climate conditions, and (c) material properties.

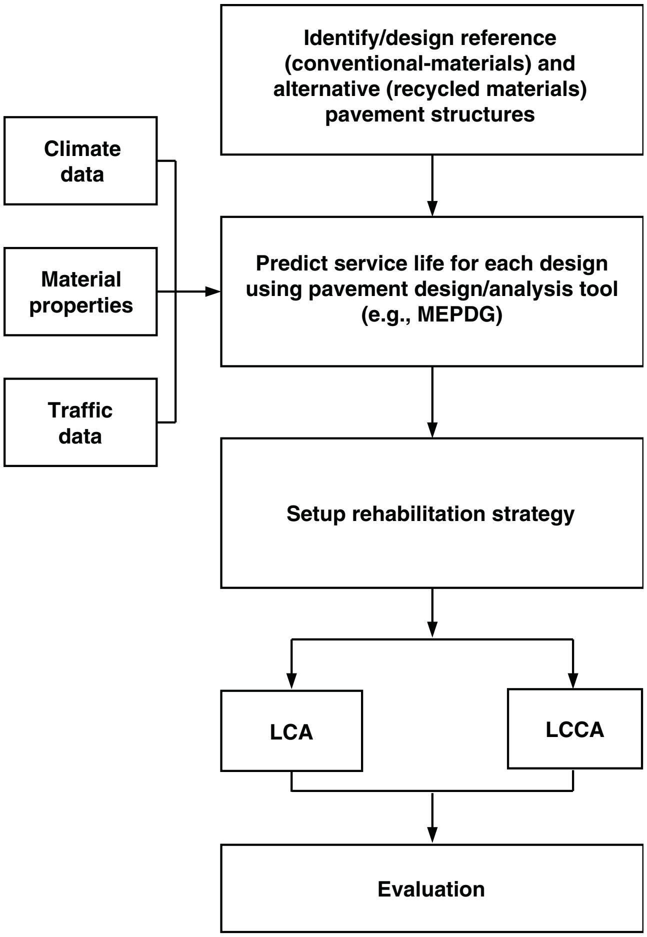

FIGURE 1 Flowchart for comparative life-cycle analysis of conventional and alternative pavement designs.

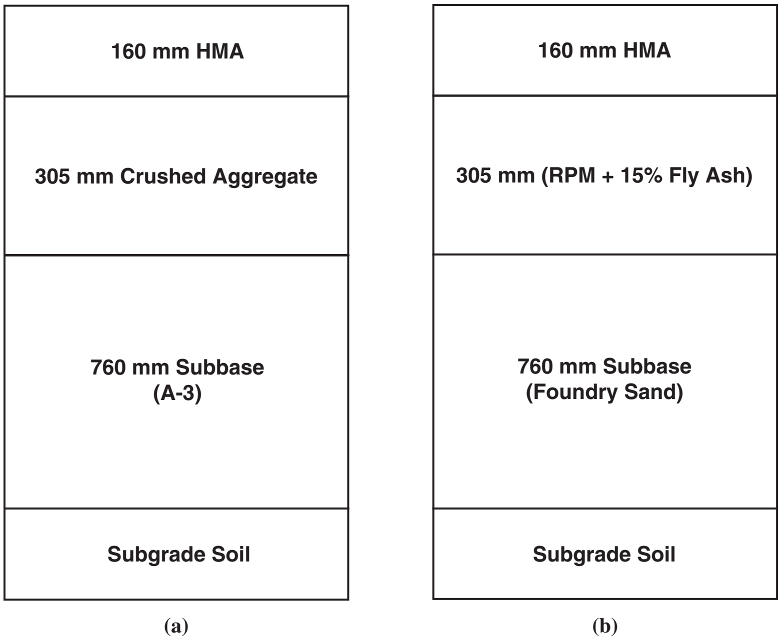

FIGURE 2 Schematic of two pavement designs: (*a*) reference (conventional) materials and (*b*) alternative (recycled) material.

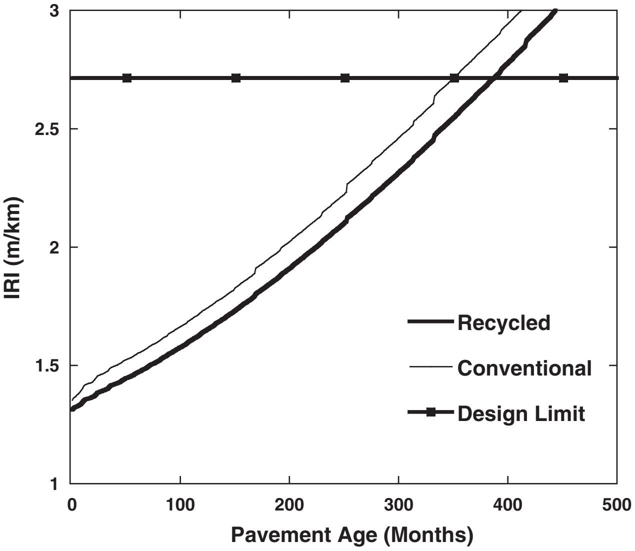

FIGURE 3 IRI as a function of pavement age for pavements constructed with conventional and recycled materials as predicted using MEPDG.

Predictions of the IRI for the conventional and recycled designs are shown in Figure 3. The conventional and recycled material designs reach their terminal serviceability at 29 and 32 years, respectively. The service life for the pavement using recycled materials is 3 years longer because of the superior properties of the recycled materials relative to the conventional materials.

LIFE-CYCLE ASSESSMENT

The LCA was conducted using the spreadsheet program PaLATE Version 2.0 (*14*). PaLATE was used because it includes information on a variety of recycled materials, including the fly ash and foundry sand used in the base and subbase in this study. PaLATE employs reference factors to calculate environmental impacts for a project. For example, PaLATE uses CO_2 emission factors for construction equipment from U.S. Environmental Protection Agency inventory data (*15*) to compute emissions from construction for a project. Total effects are computed as the product of unit reference factors and the quantity of an activity or material in the project.

PaLATE employs economic input–output (EIO) LCA, which permits an assessment of environmental impacts of the entire supply chain associated with conventional and recycled construction materials. EIO-LCA uses economic input–output data (e.g., data from the U.S. Department of Commerce) as well as resource input data and environmental output data to analyze both the direct impact and supply chain effects (*16*). More details of the LCA approach used in PaLATE can be found in *Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects* (*14*).

The LCA was conducted for a 50-year period, which is the standard practice employed by WisDOT. This analysis included one rehabilitation of the pavement at 29 or 32 years, as noted previously. Energy use and global warming potential (reported in carbon dioxide equivalents, CO_2e) reported by PaLATE were used for comparing the environmental attributes of the pavements constructed with conventional and recycled materials. Generation of RCRA hazardous waste and water consumption during construction was also considered in the environmental assessment.

The LCCA was conducted using the spreadsheet program RealCost Version 2.5 (*17*). As with the LCA, the LCCA was conducted for a 50-year period. Agency costs and work zone user costs were included in the LCCA. The user costs include delay costs (cost of delay time spent in work zones) and crash costs associated with construction and rehabilitation.

RESULTS AND ANALYSIS

Results of the LCA are shown in Table 1 for material production, transportation, and construction (placement of the materials in the roadway). The column labeled "difference" corresponds to the total percent change in the environmental metric by using recycled materials in lieu of conventional materials. For both cases, the HMA component dominated the energy and water usage, CO_2 emissions, and hazardous waste generated. Thus the overall benefits of using recycled materials in the base and subbase course are modest. Using recycled materials in the HMA (or an alternative asphalt construction process) and in other elements of the right-of-way (e.g., pipes, guide rails, barriers, signage) in the alternative design would further enhance the environmental benefits. However, as illustrated subsequently, using recycled materials only in the base and subbase layers results in significant environmental and economic benefits.

Greenhouse Gas Emissions

The quantities in Table 1 indicate that a 20% reduction in global warming potential (CO_2e) can be achieved in this case study using

TABLE 1 LCA Predictions for Pavements Using Conventional and Recycled Materials

	Conventional Materials			Recycled Materials			
Environmental Metric	Material Production	Transportation	Construction	Material Production	Transportation	Construction	Difference (%)
CO_2 (Mg)	3,630	323	111	3,028	163	54	−20
Energy (GJ)	66,680	4,318	1,476	58,023	2,187	723	−16
RCRA hazardous waste (Mg)	629	31	9	611	16	4	−6
Water (L)	17,185	735	144	15,637	372	70	−11

NOTE: GJ = gigajoules = 0.001 terajoules (TJ); Mg = megagrams.

recycled materials. Most of the reduction in CO_2e (74%) is from reduced emissions during material production. Heavy equipment operation is the main source of CO_2e emissions during material production. Most recycled materials are available as a by-product from another operation (e.g., fly ash is a by-product of electric power production) and therefore do not require mining, crushing, and so forth. Consequently, production of recycled materials requires less usage of heavy equipment relative to conventional materials, which results in a reduction in CO_2e emissions.

To stabilize greenhouse gas emissions at current levels, the construction industry worldwide must reduce emissions by 22.7 billion Mg-CO_2e over the next 50 years (*18*). Highway construction accounts for 6.8% of total construction (*19*). Accordingly, the highway construction industry must reduce emissions by 1.54 billion Mg-CO_2e over 50 years. The LCA for this case study indicates that a reduction of 819 Mg-CO_2e could be achieved using recycled materials in the 4.7-km portion of the Burlington Bypass considered in this study, or 174 Mg-CO_2e/km. The United States alone is projected to construct 6 million kilometers of roadway over the next 40 years (*4*). Based on this construction rate and the emissions reductions computed in this study, using recycled materials in roadway construction could achieve an emissions reduction of 1.30 billion Mg-CO_2e over 50 years using the relatively modest changes in pavement design illustrated in this example. Thus, with other modest changes to pavement designs, reducing emissions by 1.54 billion Mg-CO_2e over 50 years in roadway construction appears practical.

Energy Savings

The quantities in Table 1 indicate that approximately 13% of the total energy savings obtained using recycled materials is associated with material production. These energy savings are analogous to the reductions in emissions associated with material production and are associated with the heavy equipment used to mine and process conventional construction materials. Use of recycled pavement materials in situ also reduces the energy associated with transportation (e.g., transport to a landfill for disposal and transport of new materials to the construction site).

The total energy savings (16%) using recycled materials for the 4.7-km section is 11.5 terajoules (TJ), or 2.4 TJ/km, which corresponds to the annual energy consumed by 115 average households in the United States (based on 2005 energy use statistics) (*20*). Similar application of recycled materials on a nationwide basis [assuming 150,000 km of construction annually, based on Carpenter et al. (*4*)] corresponds to an energy savings of 360,000 TJ in the United States annually, which is equal to the energy consumed by 3,600,000 average homes (e.g., a city the size of New York or Los Angeles). Thus substantial energy savings can be accrued on a nationwide basis using recycled materials in roadway construction.

Other Environmental Impacts

Using recycled materials in the pavement design also reduced the amount of hazardous waste produced and the amount of water consumed. The reduction in hazardous wastes results in lower management costs (*21*). The reduction in water use is substantial. The use of recycled materials results in a savings of 1,985 L of water (11% or 422 L/km) for the 4.7-km section considered in the analysis. Similar application of recycled materials on a nationwide basis [assuming 150,000 km of construction annually, based on Carpenter et al. (*4*)] could potentially result in an annual reduction of 1.2 million megagrams of hazardous waste and a savings of 63 million liters of water nationwide.

TABLE 2 Life-Cycle Costs for Pavement Designs Using Conventional and Recycled Materials

Category	Reference	Alternative	Saving
Agency cost ($)	9,044,570	7,107,230	1,937,340 (21%)
User cost ($)	10,570	8,380	2,190 (21%)
Total ($)	9,055,140	7,115,610	1,939,530 (21%)

Life-Cycle Cost

The life-cycle costs and the cost savings using recycled materials are summarized in Table 2. These cost savings include avoidance of landfill disposal of the recycled materials based on an average landfill tipping fee of $40/Mg (Wisconsin Department of Natural Resources, *22*). As shown in Table 2, total life-cycle costs can be reduced 21% by using recycled materials in lieu of conventional materials.

CONCLUSION

The potential benefits of using recycled materials and industrial by-products instead of conventional materials in a highway construction project in Wisconsin have been described. LCA and LCCA were used to evaluate environmental and economic benefits. The analyses indicate that using recycled materials in the base and subbase layers of a highway pavement can result in reductions in global warming potential (20%), energy consumption (16%), water consumption (11%), and hazardous waste generation (6%). Overall, use of recycled materials in the base and subbase has a potential life-cycle cost savings of 21% while providing a longer service life.

When extrapolated to a nationwide scale, using recycled materials in roadway construction has the potential to provide the reductions in greenhouse gas emissions needed to maintain emissions by the highway construction industry at current levels. In addition, energy savings commensurate with the annual energy consumption of households in a U.S. city comparable in size to New York or Los Angeles can be achieved by using recycled materials in roadway construction on a nationwide basis.

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