EVALUATING THE SUSTAINABLILITY OF CONSTRUCTION WITH RECYCLED MATERIALS

by

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ABSTRACT

EVALUATING THE SUSTAINABILITY OF CONSTRUCTION WITH RECYCLED MATERIALS

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A lack of data on quantified benefits that can be achieved through the application of sustainability strategies acts as a barrier to the promotion of sustainable movement. For this reason, two frameworks were developed to provide a quantitative methodology for evaluating the benefits of sustainable construction and to rate the relative benefits of construction projects compared to projects using conventional construction concepts: a pairing method of comparative environmental and economic life-cycle analyses for assessing construction; a rating system, the Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways^{TM}.

A pairing method was used to quantify the benefits of using recycled materials in highway pavements by conducting life-cycle assessment 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, energy and water consumption, and hazardous waste generation 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.

The BE^2ST-in-Highways™ system is grounded in quantitative metrics so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. For the system, a method of estimating the number of rehabilitations required during a given analysis period using the international roughness index (IRI) was suggested. The pilot project evaluation indicates that the use of smaller quantities of raw material in highway construction results in a project that consumes less energy and emits less CO_2, thus resulting in higher sustainability scores. The superior material properties of some recycled materials reduce material consumption and also extend the service life of the highway structure, a decisive factor affecting the sustainability rating. The results of this study illustrate design strategies that offer a greater sustainability in two frameworks.

Two frameworks can be used to encourage quantifying the benefits of sustainable construction practices and promoting reuse and recycling of materials, resulting in more sustainable construction and sustainable growth.

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CHAPTER 1

EXECUTIVE SUMMARY

1.1 MOTIVATION AND PROBLEM STATEMENT

There is considerable evidence that sustainable development can be affected directly or indirectly by engineering design and construction methods (Kibert 2002; Horvath 1998; U.S. EPA 2008). The built environment consumes about 40% of all materials extracted annually in the U.S. (Kibert 2002), and the construction industry is one of the top emitters of greenhouse gases, emitting 6% of total U.S. industrial-related greenhouse gases in 2002 (Truitt 2009). These levels of emission and consumption are increasing with global economic growth, resulting in a condition that is unsustainable in the long term (Kelly 2002; U.S. EIA 2010). A path to sustainable construction can be engendered by altering design objectives and selecting alternative methods and materials for construction (Kibert 2002; Truitt 2009). Because of their size and abundance, buildings and roads are ideal targets for sustainable design and construction initiatives.

Highway construction consumes significant amounts of material and energy and produces a large amount of waste (Gambatese 2005; AASHTO 2008). For example, constructing a typical 1-km-long, two-lane road with flexible pavement consumes 7 TJ of energy (Horvath 1998). A sustainable approach to highway construction begins with a plan to reuse and incorporate as much of the material already existing on the site as practical (Gambatese 2005). However, lack of quantitative and comparative analysis methods hinders assessment of economic and environmental benefits that can be achieved using recycled materials in construction.

Historically, the highway construction industry has emphasized three factors: cost, schedule, and quality. These factors do not account explicitly for human demands, environmental impacts, or social responsibility risks (Mendler and Odell 2000). Sustainable design and construction explicitly consider the financial, environmental, and social aspects of a project – the so called triple bottom line (Elkington 1994).

Mendler and Odell (2000) suggest that incorporating environmental and social aspects into design and construction projects requires realignment of the decision strategy from the conventional triangular model balancing cost, schedule, and quality to a pentagon model that also includes social and environmental aspects. ASCE (2007) suggests that engineers transition from designers and builders to leaders responsible for project life-cycle and sustainability. However, lack of analysis methods, examples, and protocols hinders quantification of the benefits associated with sustainable designs and construction methods.

1.2 RESEARCH OBJECTIVES

Environmental and economic benefits that can be achieved through the application of sustainability strategies (e.g., reducing, reusing, and recycling construction materials) to highway construction projects are significant. If the benefits can be expressed quantitatively, project designers will be encouraged to choose strategies that adopt sustainable initiatives in highway construction projects. Thus, the objective of this research is to develop transparent and objective methods for quantitative comparative analysis and rating of sustainable highway construction. The proposed comparative assessment methods and the accompanying rating system may be used for quantitatively evaluating the impacts of construction projects on sustainability, and rewarding accomplishments based on the result of evaluations. In addition, the methods could serve as a merit-creating tool to attract federal funding for highway construction or rehabilitation.

1.3 THESIS OUTLINE

Availability of comparative assessment methods, which can be used to evaluate the benefits of applying sustainable strategies in construction is likely to promote application of more sustainable strategies to construction projects. This thesis is written as a collection of four technical papers about comparative assessment methods developed for quantitative environmental and economic assessment of the sustainability strategies in construction. An executive summary is first presented in Chapter 1 to address the methods employed for this research and the findings and summary of research. Second, a pairing method of LCA and LCCA were developed and presented in Chapter 2. The pairing method was developed to quantitatively assess alternative designs in terms of the environmental and economic impacts of replacing conventional construction materials for highway construction with recycled materials. Rehabilitation activities were explicitly included in life-cycle analysis process. In Chapter 3, a sustainability rating system for highway construction, developed based on the pairing method presented in Chapter 2, is presented. The developed rating system was applied to two highway construction projects (Burlington Bypass and Baraboo Bypass) to evaluate the functionality of the system and variables affecting the sustainability of highway designs. The results of the two case studies are presented in Chapter 4 (Burlington Bypass) and Chapter 5 (Baraboo Bypass), respectively.

A series of appendices are presented at the end of this thesis to provide supplemental information and sensitivity analyses, which were conducted during this study. Additionally, the application of the LCA and LCCA pairing method is presented in Appendix B in a different context to assess the environmental benefits of using coal combustion products (CCPs) as construction materials. Three major areas where CCP are used were considered: fly ash to replace Portland cement, coal ashes to replace conventional aggregate for geotechnical applications, and flue gas desulfurization (FGD) gypsum to replace virgin gypsum for wallboard manufacturing. In this study, a different economic impact analysis method was employed; i.e., environmental benefits were converted to monetary values.

1.4 METHODS

In Chapter 2, a comparative life-cycle analysis was conducted for construction of a section of Wisconsin State Highway (WIS) 36/83 near Burlington, Wisconsin (the Burlington Bypass) assuming that the pavement would be constructed with conventional or recycled materials. A 4.7-km-long section of the western portion of the bypass was analyzed in this study. The steps included creating pavement designs using conventional and recycled materials, predicting the service life of both designs, identifying rehabilitation strategies, and conducting LCA and LCCA. Environmental analysis of the conventional and alternative pavements was conducted using LCA.

Four environmental variables were considered in the assessment: energy consumption, greenhouse gas emissions, water consumption, and hazardous waste generation.

In Chapter 4, the Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^2ST-in-Highways^{TM}) rating system (described in Chapter 3) was applied to a pilot project (the Burlington Bypass project in southeastern Wisconsin) to check the degree of difficulty in obtaining a score in each criterion. The case study consists of a comparative assessment and rating based on a LCA and a LCCA for construction of a section of the Burlington Bypass for the pavement structure constructed with conventional or recycled materials. The steps include creating pavement designs using conventional and recycled materials, predicting the service life of both designs, identifying rehabilitation strategies, conducting LCA and LCCA, scoring, and labeling. The environmental analysis of the conventional and alternative pavements was conducted using LCA. Four environmental criteria were considered in the assessment: energy consumption, GHG emissions, water consumption, and hazardous waste generation, as defined by the U.S. Resource Conservation and Recovery Act (RCRA).

In the fourth paper (Chaper 5), the BE^2ST-in-Highways^{TM} rating system was applied to a pilot project (the Baraboo Bypass in south central Wisconsin) to assess ten alternative design strategies employing recycled material in terms of energy consumption, CO_2 emissions and other environmental factors relative to traditional designs relying on conventional construction materials. The surface layer (rigid or flexible) was kept mechanically equivalent to the surface layer in the original plan for the project (i.e., same hot mix asphalt (HMA) stiffness or Portland cement concrete (PCC) strength) and with the same thickness. The base layer thickness of the flexible pavement in each alternative design was selected so the alternative would have the same structural number as the original design. For rigid pavement, the base layer thickness of each material was calculated using the AASHTO rigid pavement design method. Thickness of the base layer in alternative designs was selected so the composite modulus of subgrade reaction equaled that of the original design. Service life of the flexible or rigid pavements was determined using the method in the Mechanistic-Empirical Pavement Design Guide (M-EPDG) program (NCHRP 2006) based on modulus and thickness of each layer. The surface layer and the subgrade were assumed to be the same for all designs. The base course varied and affected the service life. Service lives of pavements were predicted based on the moduli of the layers following the same procedure used for the initial designs. The required number of surface rehabilitations was computed by dividing the period of analysis of 50 yr, which is the standard practice employed by WisDOT, by the expected service life of a pavement design. Based on the initial construction plan and the rehabilitation strategy, LCA and LCCA were conducted in the judgment phase.

1.5 MAJOR FINDINGS

The first paper (Chapter 2), titled “Quantitative Method for Assessing Green Benefits of Using Recycled Construction Materials in Highway Construction” describes a method of pairing comparative environmental and economic life-cycle analyses for assessing highway construction. The pairing methodology was applied to a specific project for illustrative purposes. The results of the pilot project indicate that 21% of global warming potential can be reduced through the use of recycled materials. An energy savings of 17% and a life-cycle cost savings of 23% can be accomplished through the reduction of virgin material use. There are also additional financial savings that have not been included in the results, such as avoidance of landfilling industrial byproducts.

In the second paper (Chapter 3), the BE^{2}ST-in-Highways^{TM} system is introduced to objectively measure the sustainability of highway construction. A practical application (i.e., using recycled materials in the surface and base layers of highway) indicates that efforts to obtain the highest level of Green Highway certification (i.e., Green Highway-Gold) brings significant environmental and economic benefits: 24% energy saving, 25% reduction of global warming potential, and 29% of life-cycle cost saving through the reduction of virgin material use and landfill of industrial byproducts. These quantified outputs (i.e., environmental and economic benefits) as well as input data (material type and amount, transportation distance, etc.) that are readily accessible provide transparency and objectiveness in rating the environmental and economic sustainability of highway construction. Since the BE^{2}ST-in-Highways^{TM} system provides auditable outputs as a result of sustainability assessment, environmental and economic benefits can be maximized by concentrating on options with higher impact, such as using recycled materials in the base layer. In this perspective, this rating system is expected to encourage more efforts in reusing and recycling of materials, resulting in sustainable construction and sustainable growth without the shortcomings found in point systems like the LEED^{TM} system (e.g., lack of transparency and objectiveness and 'point mongering').

In the third paper (Chapter 4), the potential benefits of using recycled materials and industrial by-products instead of conventional materials in a highway construction project in Wisconsin are described using the BE^{2}ST in-Highways^{TM}

system. The analyses indicate that using recycled materials in the surface, base and subbase layers of a highway pavement can result in reductions in global warming potential (32%), energy consumption (28%), water consumption (29%), and hazardous waste generation (25%). Overall, 92% use of recycled materials in the surface, base and subbase layers has a potential life-cycle cost savings of 23%, while also providing a longer service life. The case study showed that the maximum total score (12 points) can be achieved in the rating system using a carefully selected alternative design, thus resulting in the best label of sustainable highway construction.

In the fourth paper (Chapter 5), evaluation of variables affecting sustainable highway design using the BE^{2}ST-in-Highways^{TM} system reveals many benefits of employing recycled materials in place of conventional materials in a highway construction project. The superior material properties of some recycled materials (e.g., the high resilient modulus of fly ash-stabilized recycled pavement material) reduce the amount of material consumption and also extend the service life of the highway structure; therefore, environmental impacts are reduced and economic savings are obtained. The result of a sensitivity analysis (Appendix A) also reveals that the service life of the highway structure is a decisive factor affecting the sustainability score. Major conclusions of the study include:

- The results of a pilot project evaluation indicate that use of recycled material in lieu of conventional material in highway construction can improve sustainability considerably: 27% reduction in global warming potential, 26% reduction in energy, and 27% reduction in water use.
- Reductions in CO_2 emissions, energy use, and water consumption are largely due to reductions in the material production phase (e.g., mining and processing) achieved by substituting recycled materials for conventional materials. Reductions are also achieved by reducing the thickness of the base layer and the number of rehabilitation events due to longer service life resulting from the superior properties of recycled materials.
- A reduction in life-cycle cost as large as 30% is achieved using recycled materials. The largest reduction in life-cycle cost is obtained using recycled material in the base course because larger material quantities involved in base course.
- Using recycled materials in the surface layer is not the use with highest sustainability value. Using recycled materials in the base course is more advantageous.

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CHAPTER 2

QUANTITATIVE METHOD FOR ASSESSING GREEN BENEFITS OF USING RECYCLED CONSTRUCTION MATERIALS IN HIGHWAY CONSTRUCTION

ABSTRACT: 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 larger 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.

2.1 INTRODUCTION

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 (Gambatese and Rajendran 2005, AASHTO 2008). 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 byproducts that would otherwise be disposed. Ideally, projects 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 (2005) and Kibert (2002) 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. (2007) 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 (1998). The benefits illustrated in this quantitative analysis are expected to encourage wider adoption of recycled materials in roadway construction and rehabilitation.

2.2 EVALUATION OF THE BURLINGTON BYPASS

A comparative life cycle analysis was conducted for construction of a section of Wisconsin State Highway (WIS) 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 (Wisconsin DOT 2009). The western portion of the bypass is being constructed between Spring 2008 to 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 2.1.

The steps include creating pavement designs using conventional and recycled materials, predicting the service life of both designs, identifying rehabilitation strategies, and conducting LCA and lifecycle cost analysis (LCCA). LCCA is a financial-based decision making 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 (Bull 1993, Kirk and Dell'isola 1995).

Environmental analysis of the conventional and alternative pavements was conducted using LCA. Four environmental variables were considered in the

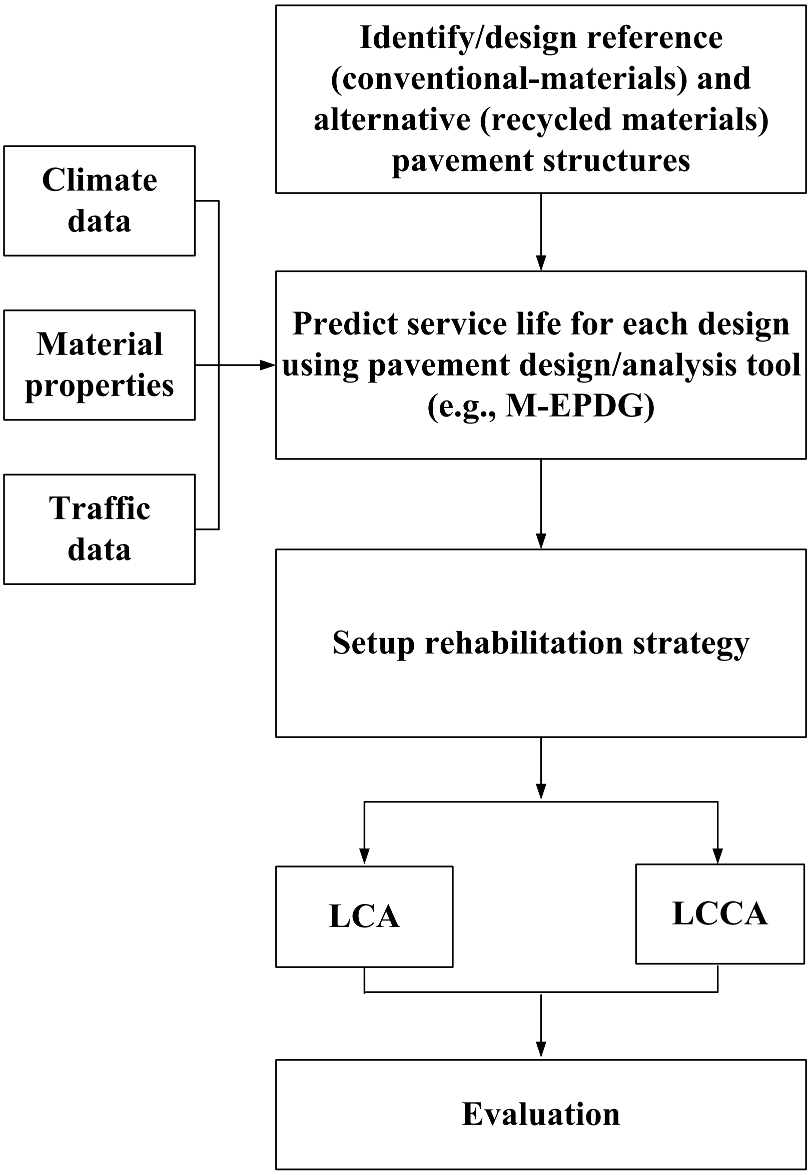

Figure 2.1. Procedure of Comparative Life Cycle Analysis of Two Pavement Designs.

assessment: energy consumption, greenhouse gas emissions, water consumption, and generation of hazardous wastes, as defined by the US Resource Conservation and Recovery Act (RCRA).

The two potential pavement designs considered in the analysis are shown in Figure 2.2, a conventional pavement design proposed by the Wisconsin Department of Transportation (WisDOT) and an alternative pavement design employing recycled pavement material (RPM) 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 (2009), which are based on research findings reported by Li et al. (2008) and Tanyu et al. (2004, 2005).

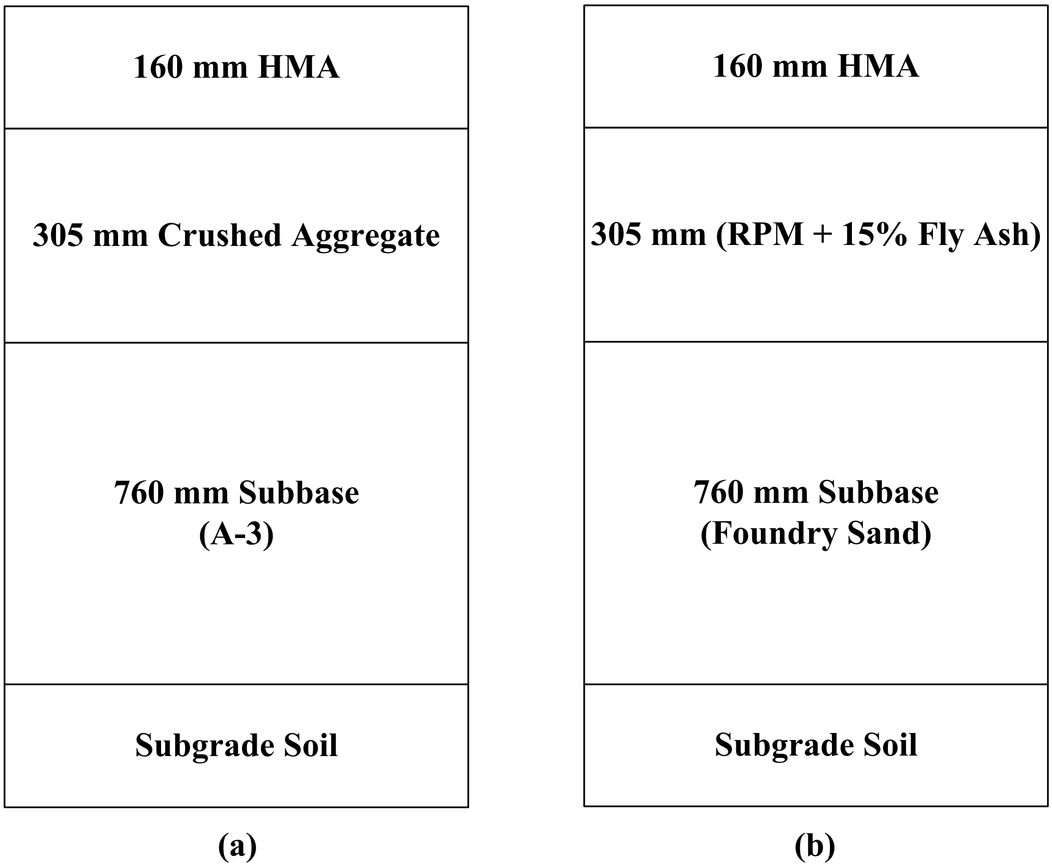

Figure 2.2. Schematic of Two Pavement Designs: (a) Reference-conventional Materials vs. (b) Alternative-recycled Material.

The pavements were assumed to be serviceable until the international roughness index (IRI) reached 2.7 m/km, as recommended in FHWA (1998). Once this IRI was reached, the pavement was assumed to require rehabilitation. The IRI was predicted using the *Mechanistic-Empirical Pavement Design Guide (M-EPDG) Version 1.0* (2009). *M-EPDG* primarily uses three key variables in the analysis: (1) traffic data, (2) climate conditions, and (3) material properties.

Predictions of the IRI for the conventional and recycled designs are shown in Figure 2.3. The conventional and recycled material designs reach their terminal serviceability at 29 and 32 yr, respectively. The service life for the pavement using recycled materials is 3 yr longer because of the superior properties of the recycled materials relative to the conventional materials.

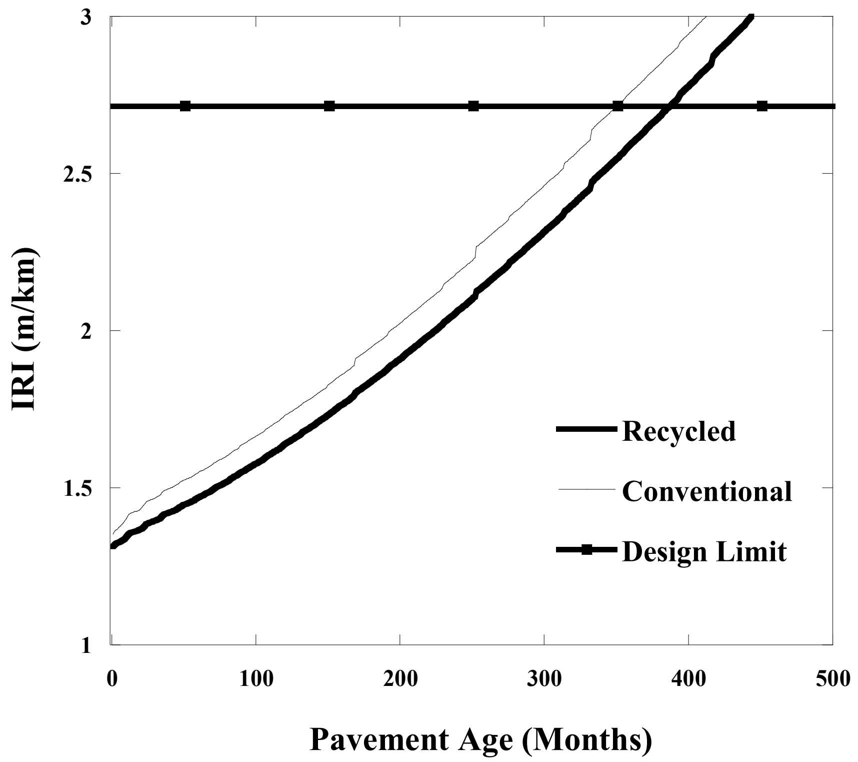

Figure 2.3. IRI as a Function of Pavement Age for Pavements Constructed with Conventional and Recycled Materials as Predicted Using M-EPDG.

2.3 LIFE CYCLE ASSESSMENT

The LCA was conducted using the spreadsheet program, *PaLATE Version 2.0* (RMRC 2009). *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 US Environmental Protection Agency inventory data (U.S. EPA 1996) 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 US Department of Commerce) as well as resource input data and environmental output data to analyze both the direct impact and supply chain effects (Horvath 2003). More detail of the LCA approach used in *PaLATE* can be found in RMRC (2009).

The LCA was conducted for a 50-yr period, which is the standard practice employed by WisDOT. This analysis included one rehabilitation of the pavement at 29 or 32 yrs, 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 (FHWA 2009). As with the LCA, the LCCA was conducted for a 50-yr 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.

2.4 RESULTS AND ANALYSIS

Results of the LCA are shown in Table 2.1 in terms of 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 processes) 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.

2.4.1 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 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 byproduct from another operation (e.g., fly ash is a byproduct of electric power production) and therefore do not require mining, crushing, etc. Consequently production of recycled materials requires less usage of heavy equipment relative to conventional materials, which results in a reduction in CO_2e emissions.

Table 2.1. LCA Predictions for Pavements Using Conventional and Recycled Materials.

Environmen-tal Metric	Conventional Materials			Recycled Materials			Difference
	Material Production	Transpor-tation	Con-struction	Material Production	Transpor-tation	Con-struction	
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%

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 yr (Socolow and Pacala 2006). Highway construction accounts for 6.8% of total construction (U.S. Census Bureau 2005). 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 USA alone is projected to construct 6 million km of roadway over the next 40 years (Carpenter et al. 2007). 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 yr 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 yr in roadway construction appears practical.

2.4.2 Energy Savings

The quantities in Table 2.1 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 US (based on 2005 energy use statistics, U.S. EIA 2009). Similar application of recycled materials on a nationwide basis (assuming 150,000 km of construction annually based on Carpenter et al. 2007) corresponds to an energy savings of 360,000 TJ in the US 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.

2.4.3 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 (U.S. EPA 2009). The reduction in water use is substantial. Using 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. 2007) could potentially result in an annual reduction of 1.2 million Mg of hazardous waste and a savings of 63 million L of water nationwide.

2.4.4 Life Cycle Cost

The life cycle costs and the cost savings using recycled materials are summarized in Table 2.2. These costs 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, 2009). As shown in Table 2.2, total life-cycle costs can be reduced 21% by using recycled materials in lieu of conventional materials.

Table 2.2. Life Cycle Costs for Pavement Designs Using Conventional and Recycled Materials.

Categories	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%)

2.5 CONCLUSION

The potential benefits of using recycled materials and industrial byproducts instead of conventional materials in a highway construction project in Wisconsin have been described. Life-cycle analysis and life-cycle cost analysis 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 US city comparable in size to New York or Los Angeles can be achieved by using recycled materials in roadway construction on a nationwide basis.

2.6 ACKNOWLEDGEMENT

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CHAPTER 3

BUILDING ENVIRONMENTALLY AND ECONOMICALLY SUSTAINABLE TRANSPORTATION INFRASTRUCTURE-HIGHWAYS™: A GREEN HIGHWAY RATING SYSTEM

ABSTRACT

This paper introduces a rating system to assess the environmental and economic sustainability of highway construction projects, namely the Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways™ (BE^{2}ST-in-Highways™) system. BE^{2}ST-in-Highways™ employs economic and environmental life-cycle analysis techniques to provide a quantitative assessment of a highway construction project. Energy and water consumption, greenhouse gas emissions, hazardous waste generation, and life-cycle cost are used as criteria. Based on the score received, a project is assigned a label commensurate with the level of sustainability achieved; e.g., silver, gold, etc.

Analysis of a pilot project shows that relatively modest changes in a highway design that employ recycled materials in lieu of conventional materials can generate significant environmental and economic benefits: 24% energy savings; 25% reduction in global warming potential, and a 29% life-cycle cost savings. The BE^{2}ST-in-Highways™ system can be used to quantify the benefits of sustainable construction

practices and motivate reuse and recycling of materials, resulting in more sustainable construction and sustainable growth.

3.1 INTRODUCTION

There is considerable evidence that sustainable development can be affected directly or indirectly by engineering design and construction methods (Kibert 2002; Horvath 1998; U.S. EPA 2008). The built environment consumes about 40% of all materials extracted annually in the U.S. (Kibert 2002), and the construction industry is one of the top emitters of greenhouse gases, emitting 6% of total U.S. industrial-related greenhouse gases in 2002 (Truitt 2009). These levels of emission and consumption are increasing in response to global economic growth, resulting in a condition that is unsustainable in the long term (Kelly 2002; U.S. EIA 2010). This long term unsustainability can be checked in part by altering design objectives and selecting alternative methods and materials for construction (Kibert 2002; Truitt 2009). Because of their size and abundance, buildings and roads are ideal targets for sustainable design and construction initiatives.

Highway construction consumes significant amounts of material and energy, and produces a large amount of waste (Gambatese 2005; AASHTO 2008). For example, constructing a 1-km length of a typical two-lane road with flexible pavement consumes 7 TJ of energy (Horvath 1998). A sustainable approach to highway construction begins with a plan to reuse and incorporate as much of the material already existing on the site as practical (Gambatese 2005). However, lack of quantitative and comparative analysis methods hinders assessment of economic and environmental benefits that can be achieved using recycled materials in construction.

Historically, the highway construction industry has emphasized three objectives: cost, schedule, and quality. These objectives do not account explicitly for human demands, environmental impacts, or social responsibility risks (Mendler and Odell 2000). In addition to the conventional objectives, sustainable design and construction explicitly consider the financial, environmental, and social aspects of a project – the so called triple bottom line (Elkington 1994).

Mendler and Odell (2000) suggest that incorporating environmental and social aspects into design and construction projects requires realignment of the decision strategy from the conventional triangular model balancing cost, schedule, and quality to a pentagon model that also includes social and environmental aspects (Figure 3.1). ASCE (2007) suggests that engineers transition from designers and builders to leaders responsible for project life-cycle and sustainability. However, lack of analysis methods, examples, and protocols hinders quantification of the benefits associated with sustainable designs and construction methods.

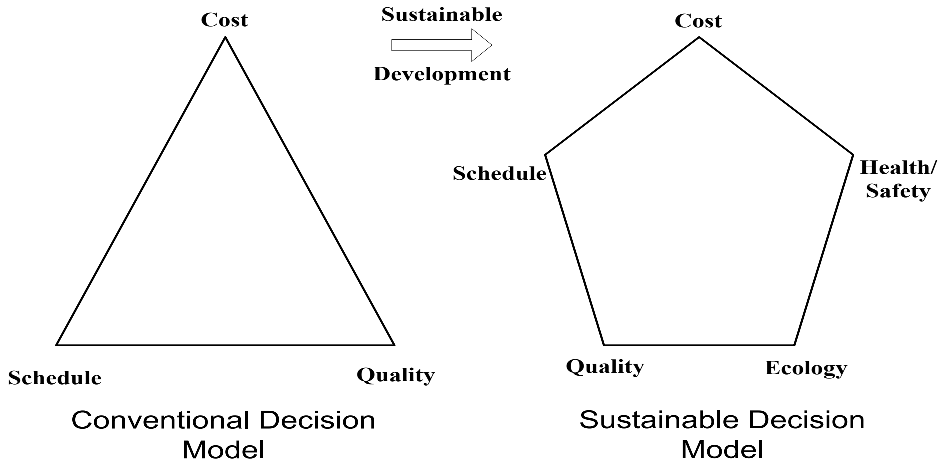


Figure 3.1. Conventional and Sustainable Decision Models for Construction Project (Adapted from Mendler and Odell 2000).

The objective of this study was to develop a transparent and objective method for quantitative comparative analysis and rating of sustainable highway construction. This approach is consistent with the well-known remark by Lord Kelvin: "When you can measure what you are speaking about, and express it in numbers, you know something about it." This system is referred to as Building Environmentally and Economically Sustainable Infrastructure-Highways^{TM} (BE^{2}ST-in-Highways^{TM}).

3.2 BACKGROUND

Sustainability evaluating systems for highway construction are currently being developed in the U.S. and elsewhere. Five rating systems (e.g., GreenLITES, Greenroads, STEED, I-LAST, and IN-VEST) are identified and summarized in Table 3.1.

These rating systems have the same shortcoming as the Leadership in Energy and Environmental Design (LEED) system for buildings, which lacks objectiveness in the criteria selection and weighting process (Schendler and Udall 2005). The rating procedures of the five rating systems (Table 3.1) are not based on standardized performance metrics and, for this reason, the effect of meeting environmental targets in these rating systems cannot be quantified. In some cases, achieving certification or obtaining credits becomes the primary goal in these systems, regardless of whether the target environmental value is achieved.

Carpenter et al. (2007) show how environmental life-cycle analysis approaches can be used to quantify environmental benefits of using recycled materials in lieu of conventional construction materials in highway construction. Their analyses using an environmental life-cycle assessment tool reveal that significant environmental benefits can be accrued from using recycled materials in the road subbase. However, their analyses did not include rehabilitation events which are some of the most energy intensive phases in the highway life-cycle. Carpenter et al. (2007) also did not show how to quantify the economic benefits from using recycled materials.

Lee et al. (2010) introduced pairing of comparative environmental and economic life-cycle analyses for assessing highway construction. Their method explicitly includes rehabilitation in the life-cycle assessment using the international roughness index (IRI) as a metric to define when rehabilitation is required.

Table 3.1. Rating Systems to Evaluate the Sustainability of Road Construction.

Rating System	Attributes
GreenLITES	GreenLITES was developed by New York State DOT to recognize best practices and to measure their performance by evaluating projects incorporating sustainable choices (New York State DOT 2010). There are two certification programs; i.e., a rating program for project designs and a rating program for operations. Highway construction projects are evaluated for sustainable practices based on these programs, and an appropriate certification level (i.e., certified, silver, gold, and evergreen) is assigned based on the total credits received (New York State DOT 2010).
Greenroads	Greenroads is a collection of sustainability best practices that can be applied to roadway construction (Muench 2010). Greenroads consists of required best practices and voluntary best practices. Required best practices should be satisfied as a minimum requirement, whereas voluntary best practices may optionally be considered to enhance sustainability (Muench 2010).
STEED	STEED is a checklist developed by Lochener Inc. to rate sustainable roadways projects (Demich 2010). STEED consists of 21 elements (e.g., air quality, aesthetic and livability, etc.). Points are awarded if applicants provide a description of the elements they select to obtain points and supporting information on how they address the selected elements (Demich 2010).
I-LAST	I-LAST is a rating system and guide developed by Illinois DOT to evaluate the sustainability of highway projects (Knuth and Fortmann 2010). I-LAST consists of over 150 sustainable items. The scoring process of I-LAST consists of three steps: (1) determining the items applicable to a project; (2) evaluating the total points for the achieved items; and (3) scoring by calculating the percentage of achieved points to the total available points (Knuth and Fortmann 2010).
IN-VEST	IN-VEST is a web-based self-evaluation tool developed by FHWA to measure the sustainability of highway construction (Shepherd 2010). IN-VEST consists of 68 criteria based on sustainability best practices. IN-VEST uses other tools (e.g., GreenLITES and Greenroads) as references. The measurement methods are similar to those of the LEED™ rating systems (Shepherd 2010).

Their analyses using a paired tool reveal that using recycled materials in the base and subbase layers of a highway pavement can result in an increase in environmental and economic benefits while providing a longer service life.

3.3 STRUCTURE OF BE^{2}ST-IN-HIGHWAYS^{TM}

The Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^{2}ST-in-Highways^{TM}) system incorporates standardized measurement methods such as life-cycle assessment (LCA) to measure environmental impacts and life-cycle cost analysis (LCCA) to measure the economic aspect. The BE^{2}ST-in-Highways^{TM} system is equipped with a tool to weight sustainability indices using the analytical hierarchy process (AHP) (Saaty 1980) and is embedded in an Excel^{TM} spreadsheet for convenient use. Two elements of the Bellagio Principle (Bell and Morse 2008; Piper 2002) were used as guiding principles when developing BE^{2}ST-in-Highways^{TM}: (1) progress towards sustainable development should be based on measurement of a limited number of indicators based on standardized measurement methods and (2) methods and data employed for assessment of progress should be transparent and accessible. BE^{2}ST-in-Highways^{TM} can be used to evaluate the sustainability metrics for highway construction projects, and the certification label.

Criteria embedded in BE^{2}ST-in-Highways^{TM} were selected by stakeholders (i.e., several agency officers, engineers, and scholars) through three meetings at the Wisconsin DOT, and are summarized in Table 3.2. Each has a specific target. For example:

- The highway construction industry must reduce CO_2emission by 20% over next 50 years (1.3 billion Mg-CO_2e) if global warming potential (GWP) is to remain at the current level [based on Lee et al. (2010)].
- Using fossil fuels to produce energy is directly related to CO_2 emission; thus, the target reduction in energy use is 20%.
- The target for reduction in life-cycle cost is set at 10% based on recommendations in Egan (1998).
- Using recycled material in highway construction results in substantial reductions in energy and emissions by eliminating or reducing mining and processing of construction materials. *In situ* recycling of existing pavement materials also reduces needs for transportation and landfilling. For this reason, *in situ* recycling is separated from total recycled material content in the criteria used in BE^{2}ST-in-Highways^{TM}. Targets for the total recycled material content rate and the *in situ* recycling rate were selected based on the Roadway Standards (Section 460) of

Wisconsin DOT (2009); i.e., no more than 20% of recycled asphalt material (if used alone) can be used in a surface layer. Although up to 40% of recycled asphalt material can be used in other layers (i.e., base and subbase layers) based on the standards, the minimum recycling ratio was selected as a target to address every project type including a pavement resurfacing project. However, targets for these criteria can be adjusted as allowable amounts of recycled material are updated.

- The target for the social cost of carbon (SCC) saving is set at $24,688/km ($39,500/mi), which is commensurate with the average annual salary of an individual American (U.S. Census Bureau 2006). SCC is the cost to recover damages caused by CO_2 released to the atmosphere and can be used by an agency to account for the social benefits (e.g., spending SCC savings to create new jobs) of reducing GWP into a cost-benefit analysis of sustainable construction efforts (U.S. DOE 2010). For 2007, the estimates of the average SCC spanned from US$5 to US$65 per Mg across models' scenarios at different discount rates and the higher than-expected impacts (U.S. DOE 2010). From these values, the worst case scenario (US$65) was used to evaluate SCC saving in this rating system.

Table 3.2. Criteria and Targets in the BE²ST-in-Highways™ System.

Major Criteria	Subcriteria	Target	Intent
Mandatory Screening	Social Requirements Including Regulation & Local Ordinances	Satisfied or unsatisfied	Meeting project needs, public perceptions/demands, local official requests/performance requirements/environmental compliance
Judgment	Greenhouse Gas Emission	20% reduction	1.3 billion Mg of CO_2 in 50 yr
	Energy Use	20% reduction	Reduce energy use by 20%
	Waste Reduction (Including *Ex situ* Materials)	20% reduction	Reduce resource mining up to 20%
	Waste Reduction (Recycling *In situ* Materials)	Utilize *in situ* waste for 20% volume of the structure	Reduce waste to landfill up to 20%
	Water Consumption	10% reduction of water consumption	Reduce water consumption up to 10%
	Hazardous Waste	20% less hazardous waste	Highway construction in hazard-free manner
	Life Cycle Cost	10% reduction by recycling	10% annual reduction of life-cycle cost
	Traffic Noise	0.5 point for HMA	Prerequisite: traffic noise modeling to maintain moderate living condition
		Additional 0.5 point for adapting ideas to reduce noise	
	Social Carbon Cost Saving	Greater than $24,688/km	Average annual salary for 1 person by saving social cost of carbon

- Other targets, such as water saving and hazardous waste reduction, are practical arbitrary numbers, explained by Lee et al. (2010).

If a target is too easy or difficult to achieve, a rating system has no power of discrimination. Therefore, adjustment of the targets may be necessary.

The BE^2ST-in-Highways^{TM} system consists of two layers, a mandatory screening layer and a judgment layer, as suggested by Dasgupta and Tam (2005). Regulatory and project-specific indicators are initially used at the mandatory screening layer to exclude from further assessment some of the alternative designs which do not satisfy given regulatory and social requirements including local ordinances and project specific requirements (e.g., preserving a specific historic site). Alternative pavement designs that satisfy all the requirements at the mandatory screening layer are evaluated further in the judgment layer as shown in Figure 3.2.

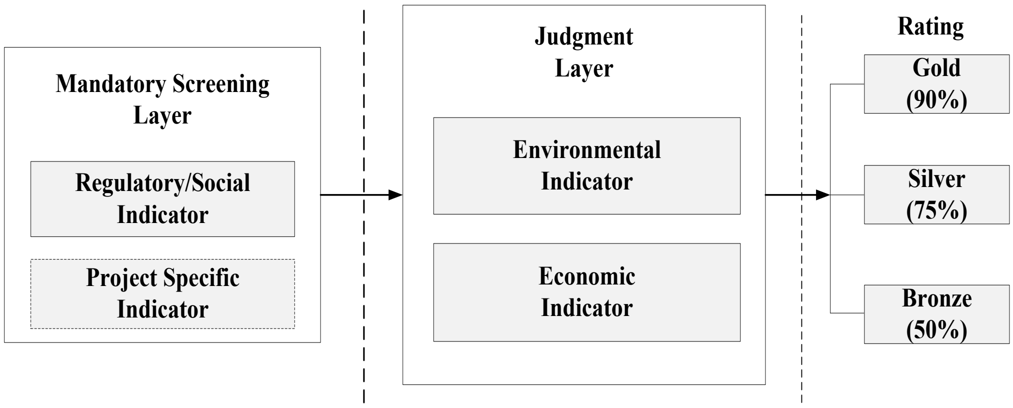


Figure 3.2. Structure of the BE²ST-in-Highways™ System.

3.3.1 Layer 1: Screening

The screening phase is conducted to evaluate mandatory requirements and required prerequisite assessments [i.e., traffic noise and stormwater best management practices (BMPs)]. Regulatory/social indicators and project-specific indicators are used to assess whether the project conforms to a set of laws, regulations, local ordinances, and also project-specific requirements. A regulatory/social indicator encompasses criteria required to meet public perceptions or demands and local official requests or requirements.

Submission of an approved environmental impact statement (EIS) is an example of a satisfied regulatory indicator. An EIS is required to demonstrate conformance with the National Environmental Policy Act (NEPA). A project-specific indicator may address cultural and aesthetic concerns such as preserving a historical site (Dasgupta and Tam 2005). These mandated processes must be satisfied for an assessment to proceed to the judgment indicators.

Screening is conducted based on the official regulatory requirements at the very moment a screening take place. Therefore, the most recent regulatory requirements should be assured before screening is conducted. For example, even though federal officials may not impose strict requirements, local officials can impose stricter requirements on the use of certain recycled materials.

Two prerequisites are incorporated into the BE^2ST-in-Highways™ system; i.e., traffic noise modeling and analysis of stormwater management. Traffic noise modeling is conducted to assess the noise impact of a highway's traffic to residential areas. Noise is usually defined as any unwanted sound. At very high levels, such as 75 to 80 A-weighted decibels [dBA], noise can cause hearing loss (NCHRP 2002). The exterior criterion of equivalent noise level (Leq) in residential areas is 67 dBA (FHWA 2010). For this reason, maintaining the noise below 67 dBA is set as a prerequisite to get credits in this criterion. The TNM-LookUp Table (FHWA 2004) is linked to the BE^2ST-in-Highways system to simulate traffic noise. The TNM-LookUp Table illustrates the effect of noise levels due to changes in traffic volume and construction of noise barriers. If this prerequisite is not satisfied first, assessment of noise mitigation efforts has no meaning.

Assessment of BMPs for stormwater management is the other prerequisite incorporated into the BE^2ST-in-Highways™ system. The effectiveness of BMPs for stormwater management can be assessed with a cost-benefit analysis with respect to control of stormwater volume, total suspended solid (TSS), and their life-cycle costs. (Dreelin et al. 2006). The Minnesota Department of Transportation (2006) developed a metric to evaluate BMPs with respect to these aspects. The metric provides an analysis tool for both the life-cycle cost and the capacity of stormwater volume control. This metric is incorporated into the BE^{2}ST-in-Highways^{TM} system.

3.3.2 Layer 2: Judgment

Once an alternative design satisfies the requirements in the screening layer, up to one point will be awarded to the design based on the achievement calculated using the sustainability indexes in the judgment layer as compared to the reference design. Judgment indicators (i.e., CO_2 emission, energy/water consumption, generation of hazardous waste, life-cycle cost, traffic noise, social cost of carbon, total recycling material content, and *in situ* recycling rate) are used to measure the environmental and economic impacts of an alternative design relative to the target of each issue.

The judgment layer consists of nine metric components to measure the environmental and economic performances of alternative designs by comparison with a reference design. Two major subsystems are incorporated into the BE^{2}ST-in-Highways system; i.e., Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (Horvath 2004) for LCA studies and RealCost (FHWA 2009) for LCCA studies and are shown in Figure 3.3. PaLATE is selected as the LCA tool in the BE^{2}ST-in-Highways system because PaLATE is the only identified LCA model that can be used for analyzing road construction and maintenance. The PaLATE model is a LCA tool that contains environmental and engineering information and data to evaluate the use of conventional and recycled materials in the construction and the maintenance of pavements (Horvath 2004). As shown in Figure 3.3, the user defines the dimensions of each layer in the pavement, the distance between the project site and material sources, and the density of the construction materials. These yield types and volumes of construction materials, sources and hauling distances, and a set of construction and prescribed maintenance activities. From this information, PaLATE calculates cumulative environmental effects such as energy and water consumption as well as atmospheric emissions. Several different sources of information and analysis methods are used in PaLATE to characterize the environmental impact of road construction projects. For this study, the environmentally augmented economic input-output analysis (EIO-LCA), a Leontief general equilibrium model of the entire US economy, was employed. The economy is divided into a square matrix of 480 commodity sectors. The economic model quantifies energy, material, and water use as well as emissions. Because EIO-LCA emission factors are available in metric tons per dollar of sector output, PaLATE uses average US producer prices ($/metric ton, e.g., from Means 1995) to calculate emissions per mass of material used. The databases used in PaLATE are described in Horvath (2004).

RealCost version 2.5 (FHWA 2009) was selected as the main LCCA platform to compute the life-cycle cost of road construction and maintenance for this study. RealCost is a spreadsheet program, which is accompanied by a catalog of individual input parameters. The RealCost model was used because the model automates FHWA's best practice LCCA methodology (FHWA 1998), which is employed by the BE^2ST-in-Highways system. A basic understanding of the FHWA's LCCA methodology (FHWA 1998) is sufficient to operate the software (FHWA 2007). However, the accuracy of subsystem level analysis cannot be warranted by the BE^2ST-in-Highways system. Updates and risks associated with subsystems should be frequently checked and reflected to the subsystem by users.

Two individuals conducting a LCA and a LCCA using PaLATE and RealCost, respectively, are expected to obtain slightly different results because of the subjectivity characteristic of the life-cycle assessment and cost estimating process. Therefore a standardized LCA and cost estimating process is required to provide consistency. For example, the input parameters required for the PaLATE model (e.g., volume of a material, distance of transportation, and type of construction equipment) should be chosen based on users' best judgment, and the same cost source should be used in comparing two designs (i.e., a reference design and an alternative design).

Manuals for PaLATE and RealCost are not provided in the BE^{2}ST-in-Highways system. The BE^{2}ST-in-Highways system was developed with the assumption that users have sufficient knowledge about PaLATE and RealCost. Otherwise, understanding two subsystems is required for users.

Environmental and economic indicators incorporated into the BE^{2}ST-in-Highways^{TM} system are imbedded in or interlinked with Excel^{TM}-based software. Input data may be entered in the appropriate worksheet cells and all of the entered data is stored in Excel^{TM} worksheet cells. Thus, data employed for an assessment of progress can be open and accessible to all; therefore, transparency can be obtained as described in the Bellagio Principle. Data entered into a form's data entry field are automatically transferred to corresponding cells in the appropriate underlying worksheet. For example, the "Rating Summary" worksheet contains the data entered in the form shown in Figure 3.3.

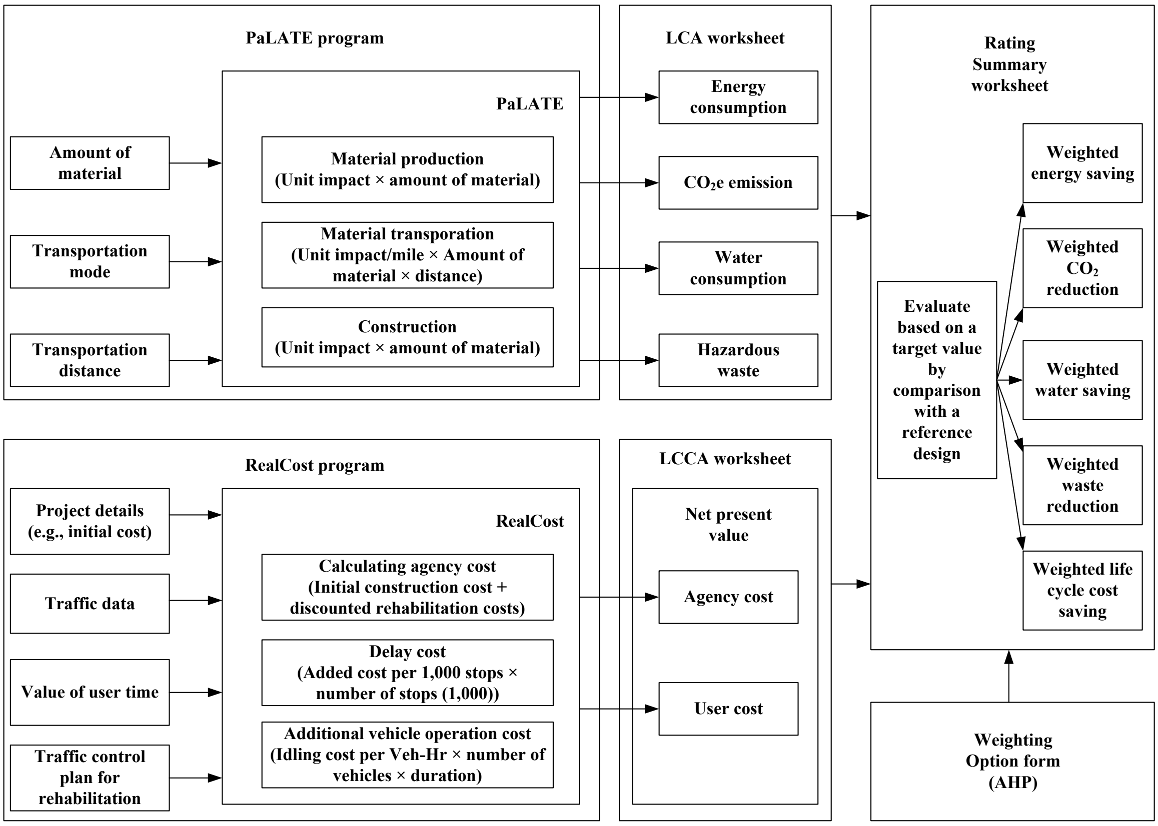


Figure 3.3. Process Diagram in the BE^{2}ST-in-Highways Software (from Input to Output).

3.3.2.1 Life Cycle Assessment

Most of the judgment indicators (i.e., CO_2 emission, energy/water consumption, and generation of hazardous waste) are incorporated into LCA. According to Guinée (2002), LCA is “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life- cycle.” The environmental impact of products and services at all of their life-cycle stages from the production of materials and products, through the use of the product, and recycle of material or final disposal are assessed using LCA.

The BE^2ST-in-Highways^{TM} system employs the PaLATE model Version 2.0 (Horvath 2004), to conduct LCA. PaLATE provides a unique platform to carry out LCAs for highway construction. A variety of recycled material uses are also included in PaLATE (e.g., fly ash, bottom ash, foundry sand, etc.). Energy use, water consumption, and greenhouse gas emission during production, transportation, and construction process of those recycled materials can be simulated using PaLATE data. Since Economic Input-Output LCA approaches were applied to the program, it is possible to simulate environmental impact of a whole supply chain of those materials. PaLATE provides many options of transportation means for materials and construction equipment as well. If a user defines the dimension of each pavement layer, the distance between material sources and the project site, and transportation and construction equipments used for the project, PaLATE calculates cumulative environmental effects (i.e., energy and water consumption as well as atmospheric emissions).

In road construction applications, the PaLATE model considers consumption of energy and water, emission of greenhouse gases, and production of hazardous waste associated with material transportation and placement as well as mining/processing of conventional material. Unit impacts for energy, water, and greenhouse gases were multiplied by the amount of material consumed during a highway construction project.

3.3.2.2 Life Cycle Cost Analysis and Evaluation of Social Cost of Carbon

Two economic sustainability indexes are incorporated into the BE^{2}ST-in-Highways^{TM} system; i.e., LCCA and SCC assessment. The life-cycle cost of a highway incorporates both agency costs and work zone user costs for initial construction and rehabilitation events over its life time. Work zone user costs cover both delay and crash costs. Delay costs are costs of time spent in work zones during highway construction or rehabilitations. Crash costs are costs associated with crashes in work zones. RealCost version 2.1 (FHWA 2004) was used in the BE^{2}ST-in-

Highways^{TM} system for LCCA. RealCost calculates the net present values of two alternative designs' life-cycle cost using input parameters (e.g., initial construction cost, rehabilitation cost, service life, and traffic control plan during initial construction and rehabilitation events) as shown in Figure 3.3.

To evaluate the SCC savings of an alternative design using the BE^{2}ST-in-Highways^{TM} system, the difference in GWP of two designs (i.e., reference design and alternative design) is multiplied by unit SCC (i.e., $69 in 2010 dollar). A local agency (e.g., Wisconsin DOT) can incorporate this amount of saving into cost-benefit analysis. In the BE^{2}ST-in-Highways^{TM} system, alternative designs that save US$39,500 of SCC [equivalent to creating a new job (U.S. Census Bureau 2006)] are set to be given full credit (1 point).

3.3.2.3 Total Recycled Material Content and In Situ Recycling Rate

Two equations are incorporated into the BE^{2}ST-in-Highways^{TM} system to evaluate *in situ* recycling efforts and total recycled material content for a highway construction project. The intention of these criteria is not only reduction of initial waste production *in situ* to reduce transportation and landfilling of old pavement materials but also an enhancement of using recycled materials instead of conventional material to reduce mining of natural resources.

Equation 1 is used to calculate total recycled material content including *ex situ* materials in the BE^2ST-in-Highways™ system. Equation 1 is a modified form of the equation currently being used in the LEED rating system to calculate the recycled rate.

Total recycled material content =

$$\frac{\text{Total construction material used (volume) - Actual material recycled (volume)}}{\text{Total construction material used (volume) - Target material recycled (volume)}}$$

Recycling old pavement materials *in situ* can maximize the benefits of recycling efforts by reducing transportation needs and energy use for recycling plant operation. *In situ* recycling rate is evaluated by comparing the actual amount of material recycled *in situ* with the target amount of material recycled *in situ*, as follows in Equation 2:

In situ recycling rate =

$$\frac{\text{Total construction material used (volume) - Actual } \textit{in situ} \text{ material recycled (volume)}}{\text{Total construction material used (volume) - Target } \textit{in situ} \text{ material recycled (volume)}}$$

3.3.2.4 Traffic Noise

Since TNM-LookUp cannot address the effect of different surface types,

Table 3.3. Average Comparative Noise Levels of Different Surface Types (Adapted from Kandhal 2004).

Pavement Surface Type	dB(A)	Credit
Open-graded Friction Courses (OGFC)	-4	1
Stone Matrix Asphalt (SMA)	-2	
Dense-graded Hot Mix Asphalt (HMA)	0	0.5
Portland Cement Concrete (PCC)	+3	0

mitigation of noise level depends on the selection from the respective surface types shown in Table 3.3. The noise level of rigid pavements is generally 3 dB(A) higher than that of flexible pavements (Kandhal 2004). For this reason, 0.5 point is awarded to flexible pavement. Some states (e.g., Arizona, California, and Texas) have made efforts to mitigate traffic noise (Kandhal 2004). In this context, up to 0.5 point will be awarded to projects that incorporate extra methods of noise mitigation. Mitigation methods include techniques such as placing asphalt rubber, stone matrix asphalt, or open graded friction courses. Points are awarded based on the result of an absolute evaluation.

3.3.3 Labeling

Each of the sustainability metrics in the judgment layer is normalized to provide a sustainability index (Si) between 0 and 1 based on a linear scale between the metric for conventional and target conditions. For example, Equation 3 is used for GWP:

$$S_{GWP} = \frac{GWP_{conventional} - GWP_{achieved}}{GWP_{conventional} - GWP_{target}} \ (>0, <1)$$

$$= 0 \quad \text{if} \quad GWP_{achieved} < GWP_{conventional}$$

$$= 1 \quad \text{if} \quad GWP_{achieved} > GWP_{target}$$

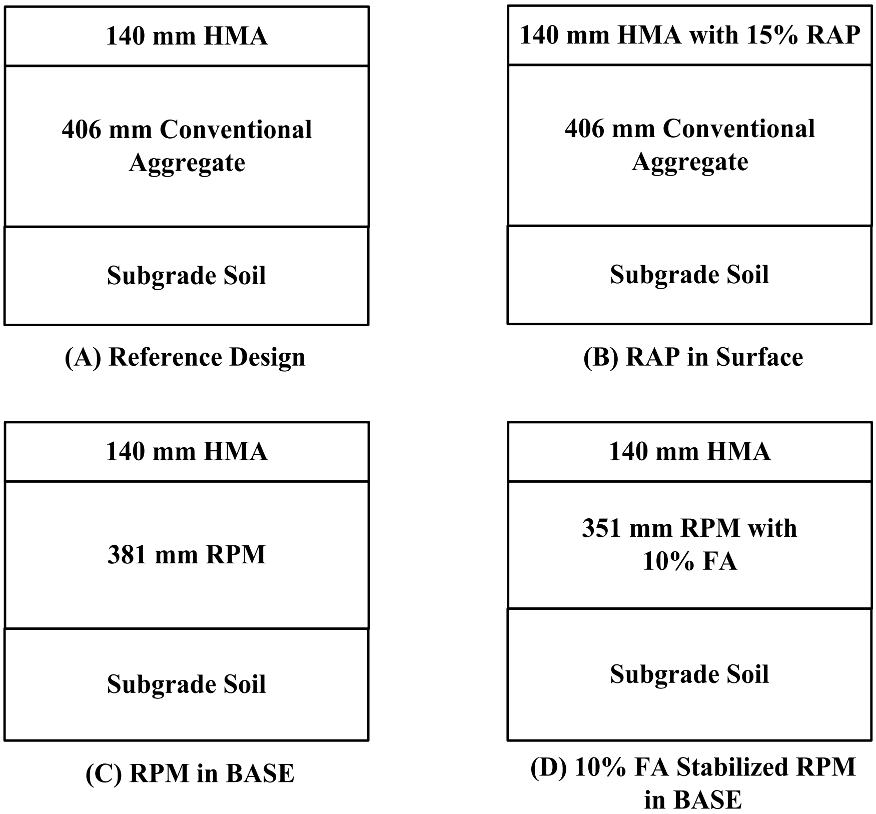
The points of other assessment (e.g., energy use, water use, SCC, and hazardous waste) through the judgment layer are scaled to give a project the full credit (1 point) if the performance of a criterion is equivalent to its target. Therefore, if 50% of the target is accomplished, 0.5 point will be granted to the project. Normalization of assessed performance values is required to better understand the relative magnitude and importance. The final total score is the sum of the points obtained as a fraction of 9 total points. Based on an achieved score, as a result of the assessment, the project can be awarded three different levels of label; i.e., Green Highway-Bronze, Green Highway-Silver, and Green Highway-Gold for the project that achieves a score greater than 50%, 75%, and 90%, respectively.

3.3.4 AMOEBA: Auditable Outputs of the BE^{2}ST-in-Highways^{TM} System

The BE^{2}ST-in-Highways^{TM} system provides auditable outputs using AMOEBA graphs (Bell and Morse 2008). AMOEBA is a Dutch acronym, which stands for “general method for ecosystem description and assessment” (Bell and Morse 2008). The AMOEBA allows a quantitative comparison between the targets of criteria and present values. The AMOEBA approach attempts to reconstruct systems where fundamental targets would be achieved. The AMOEBA graph shows the areas in which they should invest more time and effort. An AMOEBA graph has a strong tendency to create ubiquitous equilibrium in all areas. In other words, “the more the AMOEBA initiates a perfect circle within the equilibrium band, the more the project tends towards sustainability” (Bell and Morse 2008). Based on the shape of the AMOEBA describing the status of progress, more effort to initiate a perfect circle can be made.

3.4 PRACTICAL APPLICATION

To evaluate the environmental and economic benefits accrued using recycled materials, sustainability of a freeway relocation project (Baraboo Bypass), approximately 1km west of existing US-12 near Baraboo, was assessed using the BE^{2}ST-in-Highways^{TM} system. The Baraboo Bypass project consists of sections each with a different surface type (i.e., PCC and HMA). For this study, only four potential pavement designs consisting of a reference design and three alternatives for HMA surface type were considered based on readily available design information of the alternatives for a 1.6-km-long (1 mile) section of the bypass (Figure 3.4), although other alternatives can be added. This project was selected because the project includes 34,681 Mg of flexible pavement (HMA) section and, therefore, sufficient information



Note: RPM = Recycle Pavement Material, RAP = Recycled Asphalt Pavement, FA = Fly Ash

Figure 3.4. Schematic of Reference and Three Alternative Pavement Designs.

about flexible pavement was available from the Wisconsin DOT to conduct an analysis.

The thickness of the surface layer was kept constant and mechanically equivalent to the surface layer in the original plan of the project; i.e., the same HMA stiffness or PCC strength. The base layer thickness was changed in each design to generate the same structural number as in the original design. This was accomplished using the relationship given for layer coefficients and the thickness of conventional (aggregate) and alternative recycled base materials chosen (recycled pavement material, RPM, consisting of full depth reclaimed pavement materials and RPM stabilized with 10% fly ash, FA) in (Ebrahimi et al. 2010). RPM has a slightly higher modulus of 650 MPa than the conventional aggregate modulus of 600 MPa (assumed equivalent to Class 5 aggregate of MNDOT) corresponding to their respective layer thicknesses and thus results in a slightly thinner base layer than the reference design, whereas FA-stabilized RPM has a significantly higher modulus of 845 MPa (independent of layer thickness) and results in a markedly thinner base layer than the reference design.

The service life of flexible pavement structure was determined using the Mechanistic-Empirical Pavement Design Guide (M-EPDG) program (NCHRP 2006) based on modulus and thickness of each layer. The surface layer and subgrade were set to be the same among the alternatives; however, the base course varied and affected the service life. Predicted service lives of each of the four pavement designs are shown in Figure 3.5 in terms of IRI.

All pavement sections degrade steadily (increasing IRI) (Figure 3.5). The service life of the pavement was assumed to end when the IRI exceeded 2.7 m/km (FWHA 1998), thus requiring rehabilitation. At least four (A, B, and C) or three (D) rehabilitation activities are required based on the calculated service lives. For the purpose of this study, common rehabilitation strategies were assumed to include full depth reclamation (FDR) followed with HMA resurfacing.

The required number of surface rehabilitations was computed by dividing the period of analysis of 50 years, which is the standard practice employed by Wisconsin DOT, by the expected service life of a pavement design [i.e., 10.8 yrs (design A, B, C) and 12.6 yrs (design D)]. Design (D) has relatively longer service life (approximately 13 years). Design (D) includes a base layer stabilized with FA to increase stiffness and to prevent development of rutting.

The BE^{2}ST-in-Highways^{TM} software was used for assessing and rating alternative designs for the pavement structure of an actual highway project to

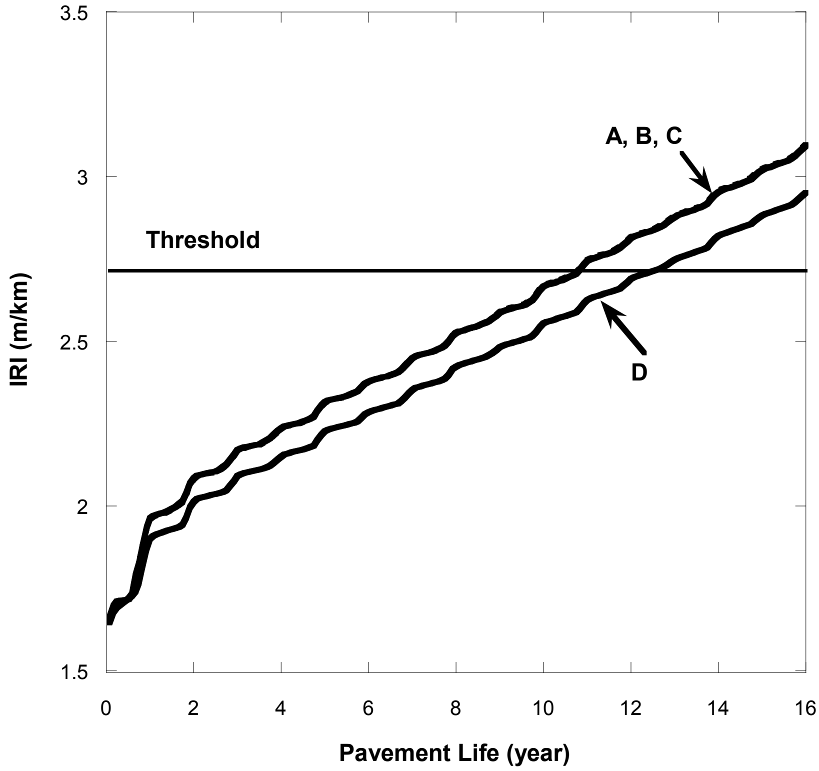


Figure 3.5. International Roughness Index (IRI) of the Alternative Designs Predicted Using M-EPDG (Note: the initial IRI are the default values given in M-EPDG).

demonstrate relative impact of material choices. The alternatives were assessed to conform to all requirements (e.g., laws, project specifications, etc.) and therefore pass the screening phase. For instance, all of the materials including the recycled materials are currently permissible for use. LCA and LCCA were conducted for the judgment phase, as described in (Lee et al. 2010). Other environmental and economical assessment were also conducted using sustainability indexes described earlier. The points that all individual sustainability metrics achieved and the total score that is the sum of the points obtained as a percentage of 9 total points are calculated and summarized in Table 3.4.

The best sustainable alternative (D) of flexible pavement section of the Baraboo Bypass project obtained 94% of the total score. Since projects obtaining greater than 50% or 90% of the total score deserve the Green Highway-Bronze or Green Highway-Gold label, respectively, design (C) was labeled the Green Highway-Bronze and design (D) achieved Green Highway-Gold label.

Seeking more sustainable designs using AMOEBA graphs is shown in Figure 3.6. Even though using recycled material in the surface layer reduces the construction cost significantly (8%), little impacts are made on environmental issues (e.g., 2% reduction in energy use and CO_2 emission).

Table 3.4. Points Obtained and Total Rating Score.

Design	Energy	GWP	Recycled Content	Water	LCC	SCC	Traffic Noise	Hazard Waste	Total Score
B	0.1	0.1	0.4	0.3	0.8	0.1	0.5	0.1	26
C	0.4	0.4	2.0	0.5	1.0	0.4	0.5	0.1	58
D	1.0	1.0	2.0	1.0	1.0	1.0	0.5	1.0	94

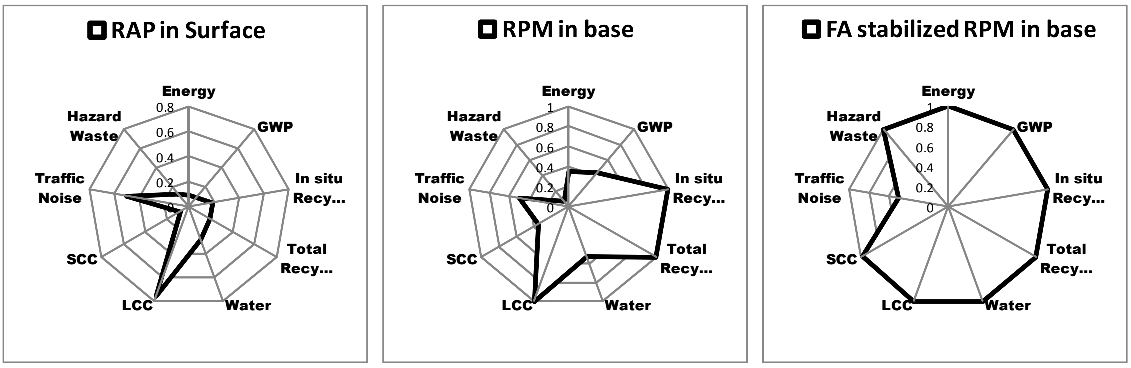


Figure 3.6. Auditable Outputs of BE^{2}ST-in-Highways^{TM} System.

However, using recycled material in the base layer increases the reduction in energy use (7%) and water consumption (5%), while demanding less life-cycle cost (i.e., 24% reduction compared to the reference design). Using FA-stabilized recycled material reduces the thickness of base layer significantly (i.e., from 406 mm to 351 mm), while achieving the same structural number as in the original design. Therefore, the design incorporating the FA-stabilized recycled material into the base layer obtained best sustainability result.

3.5 SUMMARY AND CONCLUSION

A BE^{2}ST-in-Highways^{TM} system to objectively and repeatedly measure the sustainability of highway construction was introduced. To evaluate functionality of the BE^{2}ST-in-Highways^{TM} system, three different alternative designs incorporating sustainable practices were analyzed. The analyses indicate that a significant amount of environmental and economic benefits can be obtained by pursuing Green Highway certification and thus employing green strategies (e.g., reduce, reuse, and recycle).

The result of a practical application (i.e., using recycled materials in the surface and base layers of highway) indicates that efforts to obtain the highest level of Green Highway certification (i.e., Green Highway-Gold) brings significant environmental and economic benefits: 24% energy saving; 25% reduction of global warming potential; and 29% of life-cycle cost saving through the reduction of virgin material use and landfill of industrial byproducts. These quantified outputs (i.e., environmental and economic benefits) as well as input data (material type and amount, transportation distance, etc.) that are readily accessible provide transparency and objectiveness in rating the environmental and economic sustainability of highway construction.

Since the BE^{2}ST-in-Highways^{TM} system provides auditable outputs as a result of sustainability assessment, environmental and economic benefits can be maximized by concentrating on higher potential issues, such as using recycled materials in the base layer. In this perspective, this rating system is expected to encourage more efforts in reusing and recycling of materials, resulting in sustainable construction and sustainable growth without the shortcomings found in point systems like the LEED^{TM} system (e.g., lack of transparency and objectiveness).

3.6 ACKNOWLEDGEMENT

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CHAPTER 4

USE OF BE^{2}ST IN-HIGHWAYS FOR GREEN HIGHWAY CONSTRUCTION RATING IN WISCONSIN

ABSTRACT: This paper describes a green highway construction rating system named Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^{2}ST-in-Highways). BE^{2}ST-in-Highways employs life cycle analysis techniques to provide a quantitative assessment of the impacts associated with a highway construction project. Energy and water consumption, greenhouse gas emissions, service life, and life cycle cost are evaluated in a quantitative framework that can be used to compare alternative construction strategies from a holistic perspective. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for 'gaming' of the rating system. Application of the BE^{2}ST-in-Highways system to a project in Wisconsin is described. Results of the application indicate that using recycled materials in a pavement can result in reductions in global warming potential (32%), energy consumption (28%), water consumption (29%), and hazardous waste generation (25%) as compared to the reference design using conventional materials, while also extending the service life of the pavement. In

addition, using recycled materials in a pavement can result in a life cycle cost savings of 23%. Because of this environmental and economical outperformance of the alternative design using recycled materials compared to the reference design using conventional materials, the maximum total credit (i.e., 12 points) is granted to the project.

4.1 INTRODUCTION

There is considerable research showing that construction projects are directly or indirectly causing adverse environmental impact (Gambatese 2005; Kibert 2002). For example, the built environment accounts for 30% of all primary energy use in the U.S. (Gambatese 2005). Approximately 7.0×10^6 MJ of energy are required to construct a 1-km length of a typical two-lane road with asphalt concrete pavement (AASHTO 2008). Additionally, 6% of the total U.S. industrial greenhouse gas (GHG) emissions was produced by the construction sector in 2002, and 13.4% of that was produced by highway, street, and bridge construction (Kibert 2002).

The U.S. national highway system continuously requires new construction of highways and their periodic improvement to meet growing traffic demand. However, the conventional project value used in the construction industry has primarily emphasized three aspects: cost, schedule, and quality. Using these relatively short-term strategies limits the ability of construction projects to avoid the conflicts between satisfying human demands and abatement of environmental and social responsibility risks. Therefore, availability of procedures to quantify the benefits of sustainable construction practices is a key factor influencing growth in sustainable construction of public infrastructure. For example, the Leadership in Energy and Environmental

Design (LEED) evaluation system has resulted in considerable interest and investment in sustainable building construction. Established evaluation systems similar to LEED are not yet available for highway construction projects, but are currently being developed in the U.S. and elsewhere. However, the majority of criteria and their evaluation procedure for such systems are a result of benchmarking the LEED program. Likewise, those rating systems do not consider the logical connection between their purpose and the surrounding factors. In other words, they lack transparency and objectiveness in the criteria selection and weighting process. At the same time, these rating procedures are not based on a standardized method of performance measurement. For this reason, they may lead to improvements, but the quantitative impact on meeting environmental targets is not known. Consequently, such a point system may lead to point mongering regardless of whether the choices add environmental value (Schendler and Udall 2005). In this study, a rating system that primarily addresses sustainable highway construction, namely Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^{2}ST-in-Highways), is described. The system encompasses a rating tool to score the performance of an alternative design compared to the reference design (conventional design concept) of the pavement structure using standardized measurement methods. Rehabilitation activities are 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 (1998).

The proposed rating system was applied to a pilot project to check the system's actual functionality and the degree of difficulty in obtaining the target value in each criterion. In the pilot project evaluation, the proposed rating system was used 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. The rating system, based on quantitatively measured environmental and economic benefits, is expected to encourage wider adoption of recycled materials in roadway construction and rehabilitation.

4.2 PRINCIPLES OF BE^{2}ST IN-HIGHWAYS

The first step of designing a sustainable highway construction rating system is constructing a broad view of sustainable highway construction consisting of two general components: the criteria and the target value of each criterion. Gambatese (2005) pointed out that sustainable road construction could be accomplished by several factors including use of recycled material and use of the principles of the 4R's (Reduce, Recover, Reuse, and Recycle). Gambatese (2005) claimed that several other factors such as noise levels, GHG emissions, hazardous waste, and workers' safety should also be incorporated into the planning and design process of a project to generate sustainable road construction. Others (e.g., Kibert 2002, Toleman 2008) also suggested similar criteria. The fifth clause of the Bellagio Principles to gauge sustainable development emphasizes that a limited number of criteria should be used (Bell and Morse 1999). Bellagio Principles are the result of a conference held by the International Institute for Sustainable Development in November 1996 to discuss actio n plans for sustainable development. Hence, criteria selection should be based on whether or not standardized measurement is available.

Once the criteria selection is accomplished, the next step is to make decisions about the target of each criterion. Targets are projected numbers, which the system is ultimately trying to achieve. For example, the target for global warming potential (GWP) or GHG emissions reduction could be acquired though a series of calculations based on related theories and information. The 2002 Census results show that road construction is roughly 6.8% of the entire construction industry (U.S. Census Bureau 2005). Thus, if the construction industry is allocated one wedge of the CO_2 stabilization triangle (i.e., 22.7 billion Mg) (Socolow and Pacala 2006), 1.54 billion

Mg-CO_2e will be allocated to the road construction industry over a period of 50 years from the overall allocation to the construction industry. According to Carpenter et al. (2007), the U.S. alone is projected to construct 6 million km of roadway over the next 40 years. At the same time, construction of 1 km of a typical four-lane road and related rehabilitation activities for 50 years releases roughly 865 Mg of CO_2. This results in about 6.5 billion Mg-CO_2e. Therefore, 24% CO_2 (i.e., 1.54 billion Mg-CO_2e) should be mitigated during highway construction and rehabilitation to accomplish the reduction goal of the global warming potential.

According to Bell and Morse (1999), as stated earlier, the first task of building a rating system itself is “to identify and bring together the stakeholders in the project and to gain a clear vision of the sustainability system which is expected to emerge from the project process.” For this purpose, a series of committee meetings was held at the Wisconsin Department of Transportation with stakeholders to move towards consensus on the criteria and the targets. Figure 4.1 depicts a summary of the developed criteria and their targets in this rating system being developed with the participation of the Wisconsin Department of Transportation.

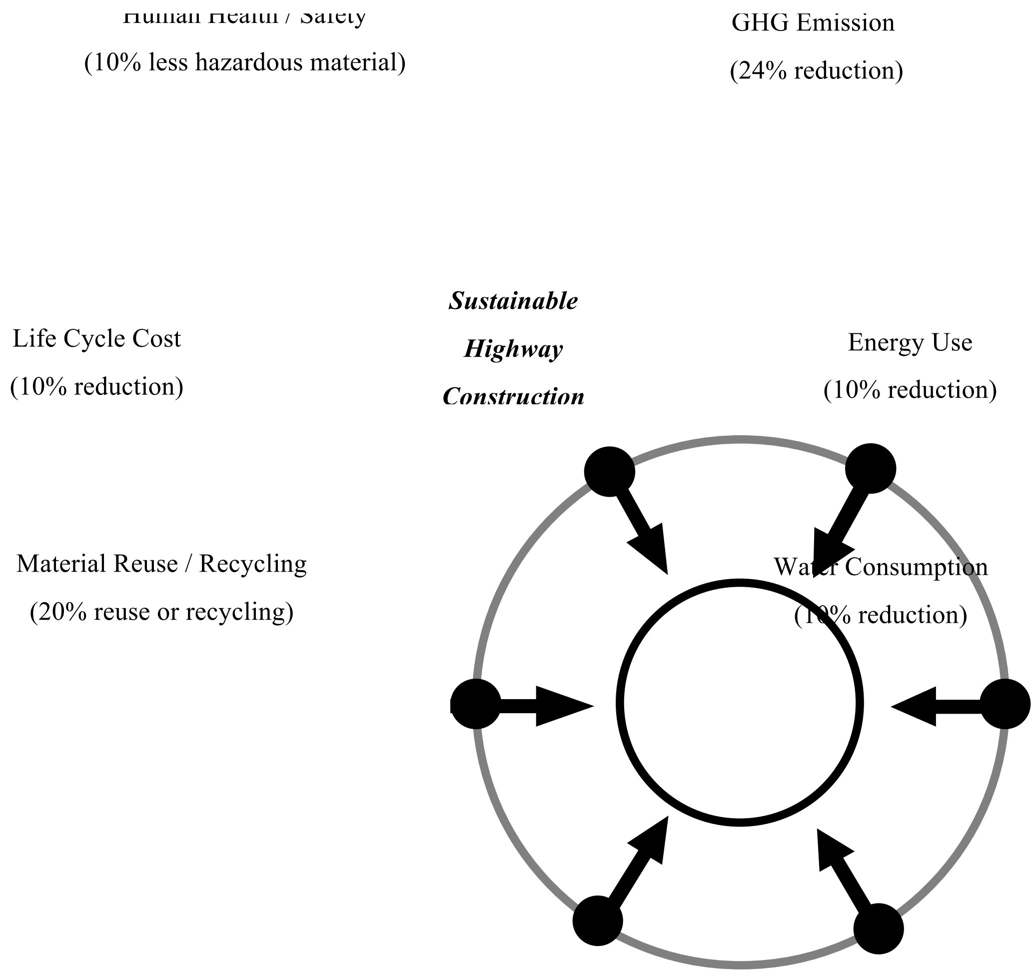

Figure 4.1. General Components of the BE^{2}ST in-Highways System.

Once the big picture (Figure 4.1) of criteria and their targets is drawn, a weighting value should be assigned to each criterion followed with the credit levels of criteria. An equally weighted system consisting of 2 points for each criterion, resulting in 12 total points, was adopted in the BE^{2}ST in-Highways system.

The performance of a construction project should be measured based on standardized measurement methods to have wide acceptance. Availability of a standardized measurement is thus necessary in the criteria selection phase. To satisfy this requirement, standard measurement methods was chosen from the currently available methods or developed if no method was available to measure the performance of a criterion.

Figure 4.2 shows the design procedure of the BE^{2}ST in-Highways system, a comparative quantitative assessment method. This proposed rating system can be used during the process of planning and designing highway construction projects to implement the sustainability goal of the projects (Figure 4.1).

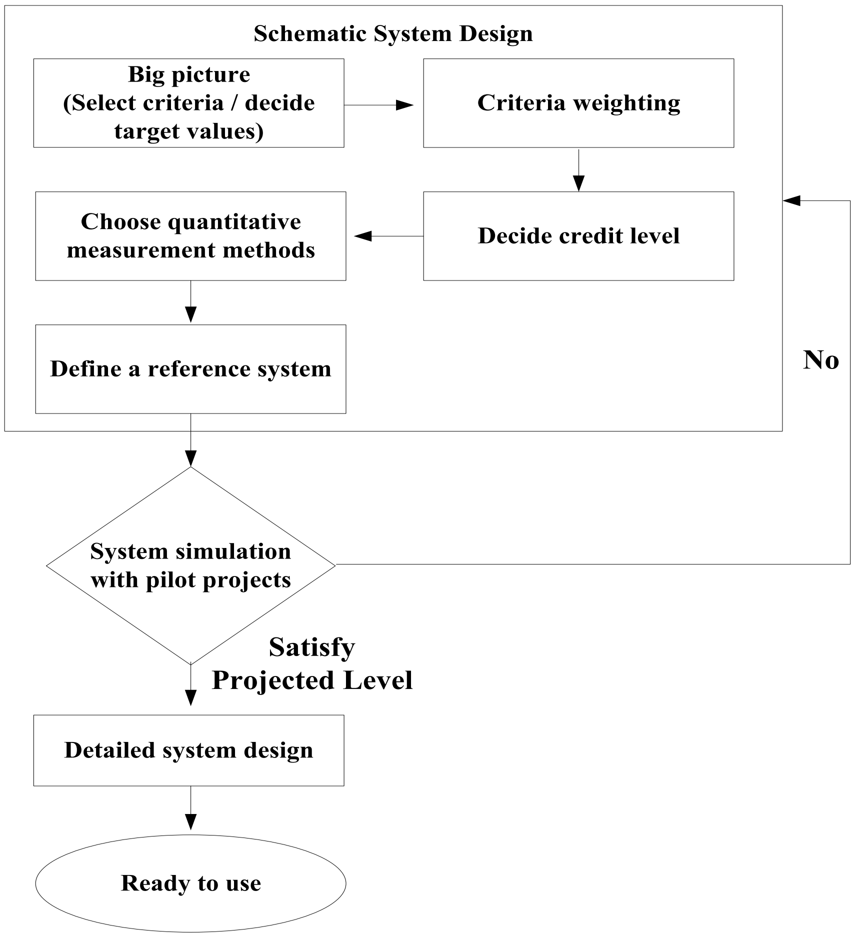

Figure 4.2. The Design Flow Chart of the BE²ST-in-Highways™ System.

4.3 A CASE STUDY: THE BURLINGTON BYPASS PROJECT

A case study was conducted to verify the actual functionality of the BE^{2}ST in-Highways system and to check the degree of difficulty in obtaining a score in each criterion. The case study consists of a comparative assessment and rating based on a life-cycle assessment (LCA) and a life-cycle cost analysis (LCCA) for construction of a section of Wisconsin State Highway (WIS) 36/83 near Burlington, Wisconsin (the Burlington Bypass) for the pavement structure 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 (Wisconsin DOT 2009). The western portion of the bypass was constructed between Spring 2008 to Fall 2010. A 4.7-km-long section of the western portion of the bypass was analyzed in this study.

A flowchart for the system simulation is shown in Figure 4.3. The steps include creating pavement designs using conventional and recycled materials, predicting the service life of both designs, identifying rehabilitation strategies, and conducting LCA and LCCA. The environmental analysis of the conventional and alternative pavements was conducted using LCA. Four environmental criteria were considered in the assessment: energy consumption, GHG emissions, water consumption, and hazardous wastes generation, as defined by the U.S. Resource Conservation and Recovery Act (RCRA).

LCCA is a financially based decision-making 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 (Bull 1993; Kirk and Dell'isola 1995).

Two potential pavement designs considered in the assessment are shown in Figure 4.4, a conventional pavement design proposed by the Wisconsin Department of Transportation (WisDOT) and an alternative pavement design employing hot mix asphalt (HMA) using 15% recycled asphalt pavement (RAP) and 5% reclaimed asphalt shingles (RAS) for surface course, recycled pavement material (RPM) stabilized with fly ash as the base course, and foundry sand as the subbase. Recycled materials can also be used in other elements in the right-of-way (e.g., pipes, guide rails, barriers, etc.); however, in this study, recycled materials were considered only in the surface, base, and subbase layers of the pavement structure.

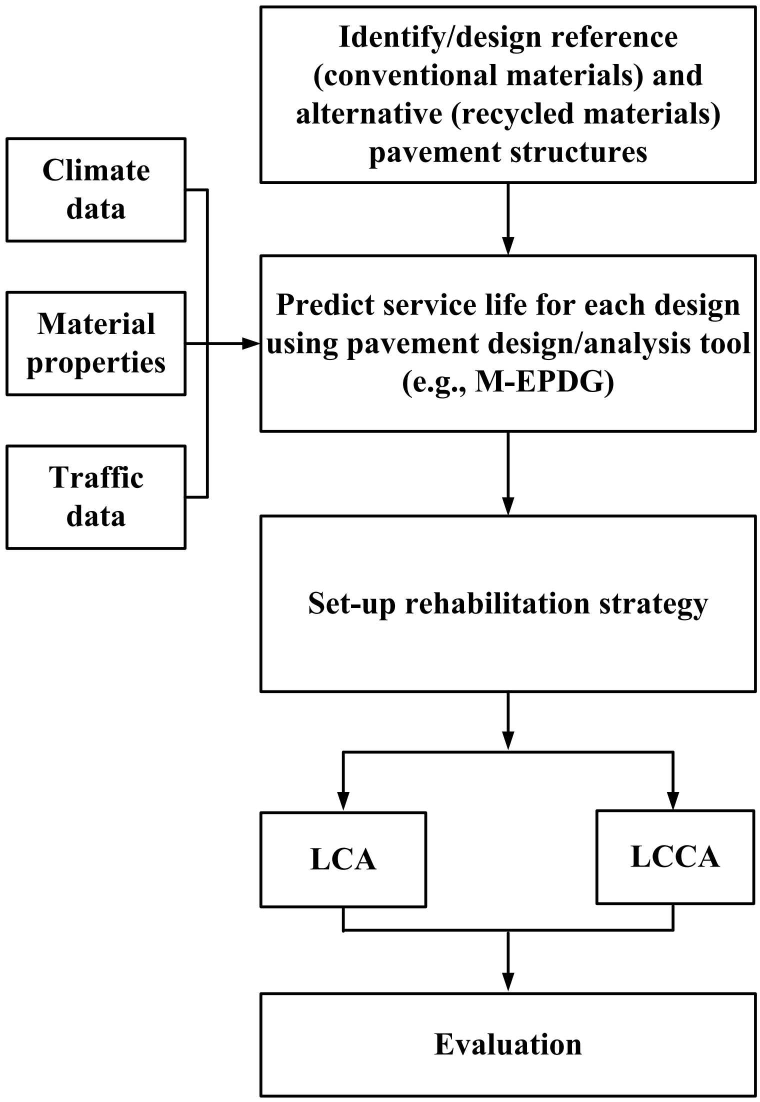

Figure 4.3. Flow Chart for the System Simulation Phase of Figure 4.2 (After Lee et al. 2010).

The same layer thicknesses (i.e., volume of materials) were used in the conventional and the 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 the recommendations made by Geo Engineering Consulting (2009), which are based on research findings reported by Li et al. (2008) and Tanyu et al. (2005).

Pavement systems are assumed to be serviceable until the international roughness index (IRI) reaches 2.7 m/km, as recommended in FHWA (1998). Once this IRI is reached, the pavement is assumed to require rehabilitation. The IRI was predicted using the *Mechanistic-Empirical Pavement Design Guide (M-EPDG) Version 1.0* (NCHRP 2009). *M-EPDG* primarily uses three key variables in the analysis: (1) traffic data, (2) climate conditions, and (3) material properties.

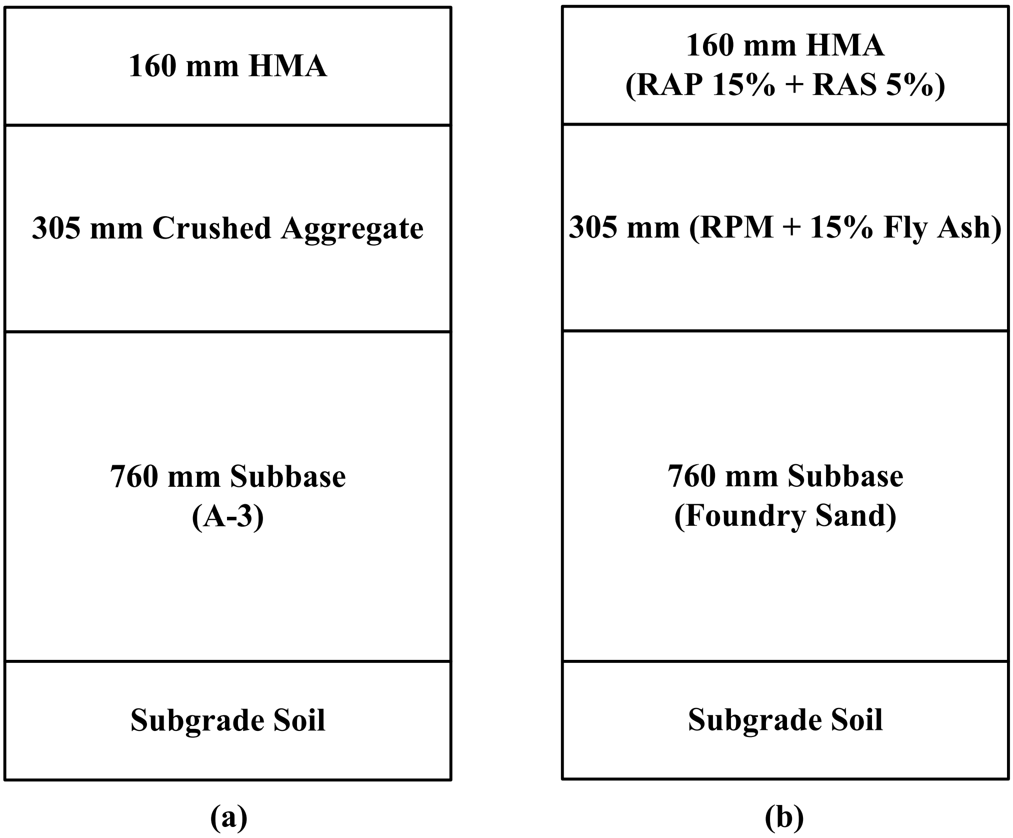

Figure 4.4. Schematic of Two Pavement Designs: (a) Reference-conventional Materials vs. (b) Alternative-recycled Materials.

Predictions of the IRI for the conventional and recycled designs are shown in Figure 4.5. The conventional and recycled material designs reach their terminal serviceability at 29 and 32 yr, respectively. The service life for the pavement using recycled materials is 3 yr longer because of the superior properties of the recycled materials relative to the conventional materials.

4.4 PERFORMANCE MEASUREMENT

The LCA was conducted using the spreadsheet program, *PaLATE Version 2.0* (RMRC 2009). *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 the US Environmental Protection Agency inventory data (U.S. EPA 1996) 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

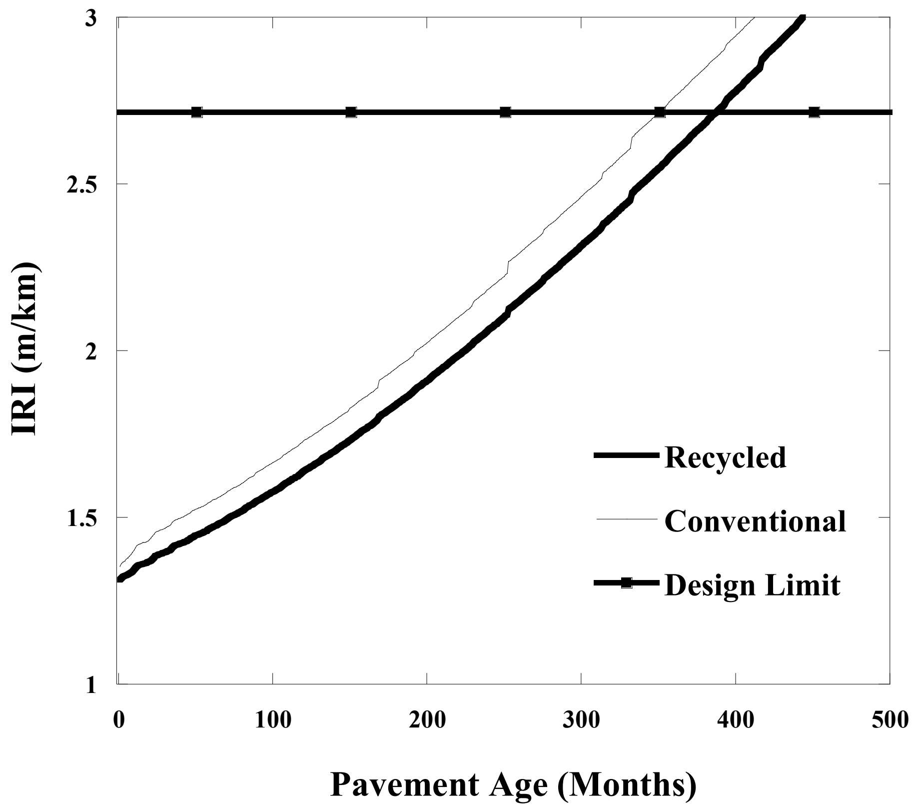

Figure 4.5. IRI as a Function of Pavement Age for Pavements Constructed with Conventional and Recycled Materials as Predicted Using M-EPDG.

conventional and recycled construction materials. EIO-LCA uses economic input-output data (e.g., data from the US Department of Commerce) as well as resource input data and environmental output data to analyze both the direct impact and supply chain effects (Horvath 2003). Additional detail on the LCA approach used in *PaLATE* can be found in (Horvath 2003).

The LCA was conducted for a 50-yr period, which is the standard practice employed by the WisDOT. This analysis included one-time rehabilitation of the pavement at 29 or 32 yr, 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 the conventional and the 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* (FHWA 2009). As with the LCA, the LCCA was conducted for a 50-yr 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.

4.5 RESULTS AND ANALYSIS

Results of the LCA are shown in Table 4.1 in terms of 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 the recycled materials in lieu of the conventional materials. Using recycled materials 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, using recycled materials just in the surface, base, and subbase layers results in significant environmental and economic benefits as illustrated subsequently.

Table 4.2 provides a comparison of the benefits accrued from the surface asphalt layer versus the unbound layers below due to the use of recycled materials. Considering that relatively small amount of recycled materials were incorporated in the surface layer, environmental benefits of using recycled materials in the surface layer are significant. In the case of water savings and RMRC hazardous waste reduction replacing virgin asphalt concrete with concrete that includes RAP and RAS result in even higher percent changes than the base and subbase together. This is a result of higher rates of hazardous wastes production and water use during the asphalt production process than the aggregate production process. Therefore, use of recycled materials in the HMA (or an alternative asphalt construction processes) would enhance the environmental and economic benefits significantly and efficiently.

4.5.1 Greenhouse Gas Emissions

The quantities in Table 4.1 indicate that a 32% reduction in GWP (CO_2e) can be achieved in this case study using recycled materials. Most of the reduction in CO_2e (83%) 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 byproduct from another operation (e.g., fly ash is a byproduct of electric power production) and therefore do not require mining, crushing, etc. Consequently, production of recycled materials requires less usage of heavy equipment relative to conventional materials, which results in a reduction in CO_2e emissions. Similarly, the asphalt content of RAP and RAS in the HMA does not require production of new asphalt.

To stabilize greenhouse gas emissions at current levels, the highway construction industry must reduce emissions by 1.54 billion Mg-CO_2e over 50 yr as indicated above. The LCA for this case study indicates that a reduction of 1,296 Mg-

Table 4.1. LCA Predictions for Pavements Using Conventional and Recycled Materials.

Environ-mental Metric	Conventional Materials			Recycled Materials			Diffe-rence
	Material Production	Trans-portation	Const-ruction	Material Production	Trans-portation	Const-ruction	
CO_2e (Mg)	3,630	323	111	2,551	163	54	-32%
Energy (GJ)	66,680	4,318	1,476	49,630	2,178	723	-28%
RCRA Hazardous Waste (Mg)	629	31	9	480	16	4	-25%
Water (L)	17,185	735	144	12,398	371	70	-29%

Note: GJ = gigajoules = 0.001 terajoules (TJ), Mg = megagrams.

Table 4.2. Comparison of LCA Results of HMA and Other Layers.

	Surface (HMA)	Base and Subbase	Total
CO_2e (Mg)	477 (-12%)	819 (-20%)	1,296 (-32%)
Energy (GJ)	8,401 (-12%)	11,542 (-16%)	19,943 (-28%)
RCRA Hazardous Waste (Mg)	131 (-19%)	38 (-6%)	169 (-25%)
Water (L)	3,241 (-18%)	1,984 (-11%)	5,225 (-29%)

CO_2e could be achieved using recycled materials in the 4.7-km portion of the Burlington Bypass considered in this study, or 276 Mg-CO_2e/km. The U.S. alone is projected to construct 6 million km of roadway over the next 40 yr (Carpenter et al. 2007). 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 2.07 billion Mg-CO_2e over 50 yr using the relatively modest changes in pavement design illustrated in this example. Thus, with other modest changes to pavement design, reducing emissions by 1.54 billion Mg-CO_2e over 50 yr in roadway construction appears achievable.

4.5.2 Energy Savings

The quantities in Table 4.1 indicate that approximately 85% 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* such as RPM 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 (28%) using recycled materials for the 4.7-km section is 17 terajoules (TJ), or 3.6 TJ/km, which corresponds to the annual energy consumed by 170 average households in the U.S. (based on the 2005 energy use statistics, EIA 2009). Similar application of recycled materials on a nationwide basis (assuming 150,000 km of construction annually based on Carpenter et al. 2007) corresponds to an energy savings of 540,000 TJ in the U.S. annually, which is equal to the annual energy consumed by 5.4 million average homes (e.g., a state the size of Illinois or Pennsylvania). Thus, substantial energy savings can be accrued on a nationwide basis using recycled materials in roadway construction assuming that recycled materials are readily available.

4.5.3 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 (U.S. EPA 2009). Using recycled materials results in a savings of 5,225 L of water (29% or 1,112 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. 2007) could potentially result in a savings of 166.8 million L of water nationwide (approximately 10,410 persons' annual water use for shower) and an annual reduction of 5.4 million Mg of hazardous waste.

4.5.4 Life Cycle Cost

The life cycle costs and the cost savings using recycled materials are summarized in Table 4.3. These costs savings also include avoidance of landfill disposal of the recycled materials based on an average landfill tipping fee of $40/Mg (Wisconsin Department of Natural Resources 2009). As shown in Table 4.3, total life cycle costs can be reduced 23% by using recycled materials in lieu of conventional materials.

Based on the performance of a project in each criterion compared to the reference design (i.e., 50% or 100% satisfaction of the target value of a criterion), 1 point or 2 points will be awarded to the project respectively. Because of the superior performance of the alternative design of the Burlington Bypass project (see Table 4.4) compared to its reference design, the maximum total credit (i.e., 12 points) can be granted to the project. The project outperformed the target values by a wide margin in some criteria. For example, 32% reduction of global warming potential passed its

Table 4.3. Life Cycle Costs for Pavement Designs Using Conventional and Recycled Materials.

Categories	Reference	Alternative	Saving
Agency Cost ($)	9,044,570	7,006,830	2,037,740 (-23%)
User Cost ($)	10,570	8,380	2,190 (-21%)
Total ($)	9,055,140	7,115,610	2,039,930 (-23%)

Table 4.4. Rating Results.

Criteria	Target Value	Performance	Score
Global Warming Potential	-24%	-32%	2
Energy Consumption	-10%	-28%	2
RCRA Hazardous Material	-10%	-25%	2
Water Consumption	-10%	-29%	2
Life Cycle Cost	-10%	-23%	2
Reuse / Recycling	20%	92%	2
Total			12/12

target (24%) and the recycling ratio (92%) largely exceeded its goal (20%). Therefore, the targets of the criteria can be adjusted so the rating system is more challenging. If a rating system is too easy, the power of discrimination cannot be achieved.

4.6 SUMMARY AND CONCLUSIONS

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 using a rating system named Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^2ST-in-Highways). Life-cycle analysis and life-cycle cost analysis were used in the rating system to evaluate the environmental and economic benefits. The analyses indicate that using recycled materials in the surface, base and subbase layers of a highway pavement can result in reductions in global warming potential (32%), energy consumption (28%), water consumption (29%), and hazardous waste generation (25%). Overall, 92% use of recycled materials in the surface, base and subbase layers has a potential life-cycle cost savings of 23% while providing a longer service life. For the environmental and economic benefits of using recycled materials, the case study obtained the maximum total score (12 points), thus the best label of sustainable highway construction can be awarded to the project.

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 the emissions by the highway construction industry at the current levels using the suggested strategies. In addition, energy savings commensurate with the annual energy consumption of households in a state comparable in size to Illinois or Pennsylvania can be achieved by using recycled materials in roadway construction on a nationwide basis.

As illustrated in the case study, BE^{2}ST-in-Highways employs life-cycle analysis techniques to provide an overall assessment of the environmental impacts associated with a highway construction project. Energy and water consumption, greenhouse gas emissions, service life, and life-cycle cost are evaluated in a quantitative framework that can be used to compare alternative construction strategies from a holistic perspective. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for ‘gaming’ of the rating system.

4.7 ACKNOWLEDGEMENT

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CHAPTER 5

EVALUATION OF VARIABLES AFFECTING SUSTAINABLE HIGHWAY DESIGN USING THE BE^{2}ST-IN-HIGHWAYS^{TM} SYSTEM

ABSTRACT: The Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^{2}ST-in-Highways^{TM}) sustainability rating system was developed to provide a quantitative methodology for rating the benefits of sustainable highway construction. The methodology is grounded in quantitative metrics so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This rating system can be employed by the highway construction industry and agencies to quantitatively evaluate sustainable practices and to incorporate sustainable elements into projects. To illustrate how BE^{2}ST-in-Highways^{TM} is employed, ten alternative designs were evaluated relative to two reference pavement designs for a pilot project (Baraboo Bypass). The results of this pilot project evaluation indicate that use of recycled materials in lieu of conventional materials in highway construction can improve sustainability considerably: about 27% reduction in global warming potential, energy and water use. Reductions in CO_2 emissions and energy and water consumption are largely due to the reduction of the material production phase (e.g., mining and processing) by substituting existing recycled materials and reducing the thickness of the base layer

and the rehabilitation events due to longer service life resulting from superior properties. Use of recycled material resulted in reductions in the life-cycle cost by as much as 30%. Using recycled materials in surface layer is not the use with highest value. Using recycled materials in the base course is thus more advantageous and has higher value because larger material quantities are involved in the base course with greater potential for cost savings as shown in this case study.

5.1 INTRODUCTION

Sustainable development is defined as the ability to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (U.N. 1987). Elkington (1998) suggests that three equally important elements (i.e., environmental, economic, and social aspects) must be evaluated when assessing sustainability. These aspects are known as the "triple bottom line." Kibert (2002) indicates that the construction industry can play a major role in improving sustainability by greening the built environment (e.g., reduce resource consumption, recycle built environment end-of-life resources, and use recyclable resources). Highway construction projects consume large amounts of energy and natural material, produces waste, and generate greenhouse gases (Gambatese 2005; U.S. EPA 2009). Consequently, there is a growing demand to make highway construction more sustainable without compromising conventional construction goals (i.e., cost, quality, and schedule). Rating systems (e.g., Greenroads (Muench 2010) and GreenLITES (N.Y. DOT 2010)) that evaluate the sustainability of road construction are currently being developed in the U.S. and elsewhere. Most mimic the Leadership in Energy and Environmental Design (LEED) program employed for buildings. They lack transparency and objectiveness in the criteria selection and weighting process and are not based on a standardized methods of performance measurement. As a result, the quantitative impact of these rating systems on meeting environmental targets is unknown.

Efforts also have been made to quantitatively evaluate the sustainability of highway construction projects. For example, Carpenter et al. (2007) showed how life-cycle assessment (LCA) can be applied to quantify the environmental impacts of using recycled materials in roadway construction. Lee et al. (2010) introduced the pairing of comparative environmental and economic life-cycle analyses for assessing highway construction by explicitly including rehabilitation activities in the LCA using the international roughness index (IRI) as a metric to define when rehabilitation is required. The approaches suggested by Capenter et al. (2007) and Lee et al. (2010) were used to create the quantitative sustainability assessment system, Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^2ST-in-Highways^{TM}) for measuring and rating sustainability in highway construction projects (2010). The BE^2ST-in-Highways^{TM} system employs quantitative assessment techniques to assess overall life-cycle performance. Energy, greenhouse gas emissions, and service life are evaluated in a quantitative framework that can be used to compare alternative highway construction strategies from a holistic perspective and in the context of system-wide targets established in a weighted approach defined by stakeholders. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for 'gaming' of the rating system, which is a common problem associated with sustainability rating systems in the building construction industry (Schendler and Udall 2005).

In this study, the BE^2ST-in-Highways^{TM} rating system was applied to a pilot project (the Baraboo Bypass in southcentral Wisconsin) to assess ten alternative design strategies employing recycled material in terms of energy consumption, CO_2 emissions and other environmental factors relative to traditional designs relying on conventional construction materials. The findings in this study are expected to help project designers choose strategies that enhance sustainable initiatives in highway construction.

5.2 BE^2ST-IN-HIGHWAYS^{TM} RATING SYSTEM

Two indicator layers (i.e., mandatory screening and judgment indicators) are used in the BE^2ST-in-Highways^{TM} system (Dasgupta and Tam 2005) (Figure 5.1). Regulatory and project-specific indicators are used in the screening layer to screen alternatives that do not satisfy regulatory, social, or project specific criteria (Dasgupta and Tam 2005). These criteria include characteristics essential to meet project needs and public perceptions or demands.

Local official requests or requirements can be included in regulatory indicators. For instance, a highway project requires an environmental impact statement (EIS) to demonstrate conformance with the National Environmental Policy Act (NEPA) and it must be completed to be eligible for federal funds. Project specific indicators address cultural and aesthetic concerns; e.g., preserving a specific historical site. Pavement design alternatives for a highway project that pass the screening layer are evaluated further in the judgment layer relative to environmental and economic indicators.

A summary of criteria, target values, and objectives in the assessment system is given in Table 5.1. The scope of the system is also defined in Table 5.1. The rating system is restricted to environmental, economic, and social issues related to quantifiable construction materials and processes. The boundary of the system can be expanded in the future as new sustainability indices become available. Targets for each issue are also assigned (e.g., 20% reduction in global warming potential, GWP).

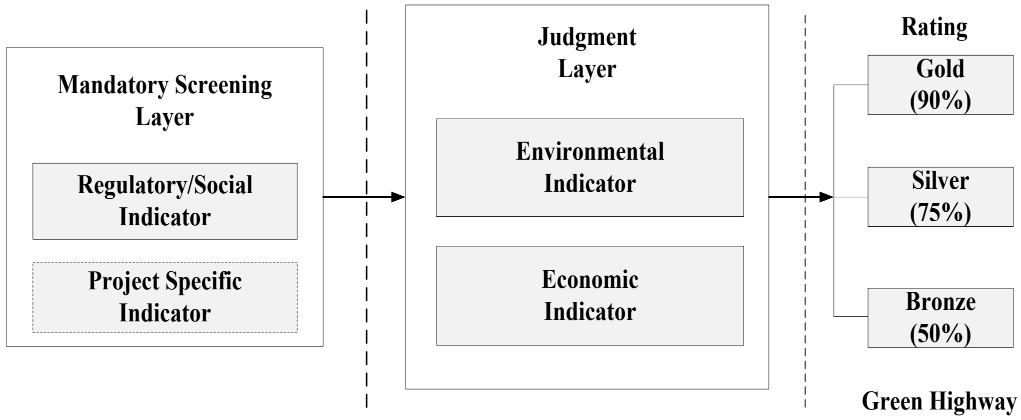


Figure 5.1. Structure of the BE^{2}ST-in-Highways^{TM} System.

These assignments are made by stakeholders or an overseeing agency based on projected systemwide requirements to accomplish the goal for each issue (e.g., reduction of 1.3 billion Mg of CO_2e in next 50 yr by highway construction industry corresponding to 20% reduction from the current levels in each project (Lee et al. 2010; Lee et al. 2010*)*.

Weights can be assigned to each criterion along with points. An equally weighted system consisting of 1 point for each criterion (9 total points) is the default in the BE^2ST-in-Highways™ system and is used here for demonstrative purposes. A project is given full credit (1 point) for an issue if the target is met. If a fraction of the target is accomplished, points are prorated linearly. The total score is the ratio of points awarded to 9 total points multiplied by 100%. Based on scores obtainted, projects are assigned a label; e.g., Green Highway-Bronze, Green Highway-Silver, and Green Highway-Gold, as shown in Figure 5.1.

In an actual application, stakeholders or the agency would select the targets, weights, and points. Weights based on the importance ascribed to each criterion can be assigned based on stakeholder input using the analytical hierarchy process (AHP) (Saaty 1980). A tool for computing the weights with AHP is provided as a separate software package.

Table 5.1. Criteria and Target Values in the Assessment System.

Major Criteria	Subcriteria	Target	Intent
Mandatory Screening	Social Requirements Including Regulation & Local Ordinances	Satisfied or unsatisfied	Meeting project needs, public perceptions/demands, local official requests/performance requirements/environmental compliance
Judgment	Greenhouse Gas Emission	20% reduction	1.3 billion Mg of CO_2 in 50 yr
	Energy Use	20% reduction	Reduce energy use by 20%
	Waste Reduction (Including *Ex situ* Materials)	20% reduction	Reduce resource mining up to 20%
	Waste Reduction (Recycling *In situ* Materials)	Utilize *in situ* waste for 20% volume of the structure	Reduce waste to landfill up to 20%
	Water Consumption	10% reduction of water consumption	Reduce water consumption up to 10%
	Hazardous Waste	20% less hazardous waste	Highway construction in hazard-free manner
	Life Cycle Cost	10% reduction by recycling	10% annual reduction of life cycle cost
	Traffic Noise	0.5 point for HMA	Prerequisite: traffic noise modeling to maintain moderate living condition
		Additional 0.5 point for adapting ideas to reduce noise	
	Social Carbon Cost Saving	Greater than $24,688/km	Average annual salary for 1 person by saving social cost of carbon

Note: 1 point is given if target is achieved or exceeded. For reductions less than the target, linearly prorated fractional points are given. No negative points are assigned.

The BE^2ST-in-Highways™ system evaluates sustainability of a highway project in terms of a quantitative difference between a reference design and proposed alternative design(s). Thus, the reference highway design must be defined realistically. A conventional design approach in which sustainability concepts are not incorporated explicitly can be used as a reference design. The analysis assumes that the service life of conventional and alternative designs can be based on an international roughness index (IRI) prediction made with the Mechanistic Empirical Pavement Design Guide (M-EPDG) program (NCHRP 2006*)* and that rehabilitation occurs at the end of the predicted service life.

A screening phase is conducted to evaluate mandatory requirements and required prerequisite assessments (i.e., traffic noise and stormwater best management practices). After these requirements and prerequisites are satisfied, judgment assessments are conducted (e.g., LCA using PaLATE (Horvath 2004), life-cycle cost analysis (LCCA) using RealCost (FHWA 2004), calculation of recycled material content, and analysis of social cost of carbon (SCC) (U.S. DOE 2010)). A more detailed description of the BE^2ST-in-Highways™ system is given in (Lee et al. 2010; Lee et al. 2010*).*

5.3 PILOT PROJECT

A freeway relocation project (Baraboo Bypass) approximately 1 km west of existing US-12 near Baraboo, Wisconsin, was selected for a pilot evaluation of the BE^{2}ST-in-Highways^{TM} system. The intent was to evaluate the environmental and economic benefits accrued using recycled materials. The project was selected because sufficient information was available from the Wisconsin Department of Transportation to conduct an analysis. The first portion of the project, from I-90/94 south to the existing four-lane roadway at Tarrytown Road (9.2 km), is being constructed in 2009 - 2011(Wisconsin DOT 2006). The project includes 21,703 m^2 of new concrete pavement (PCC) and 34,681 Mg of flexible pavement (HMA), with a budget of $3.7 million.

The Baraboo Bypss project consists of sections with different surfaces (i.e., PCC or HMA). For this study, six potential pavement designs (a reference design and five alternatives) for each surface type were considered for a 1.6-km-long (1 mile) section of the bypass (Table 5.2).

5.3.1 Equivalent Aternative Pavement Design

The surface layer (PCC or HMA) was kept mechanically equivalent to the surface layer in the original plan for the project (i.e., same HMA stiffness or PCC strength) and with the same thickness. The base layer thickness of the flexible pavement in each alternative design was selected so the alternative would have the same structural number as the original design. This was accomplished using the relationship between layer coefficients and thickness in (Ebrahimi et al. 2010) for conventional (aggregate) and the recycled base materials chosen (recycled pavement material (RPM) consisting of full depth reclaimed pavement materials or RPM stabilized with 10% fly ash).

For rigid pavement, the base layer thickness of each material was calculated using the AASHTO rigid pavement design method (Huang 1993). Thickness of the base layer in alternative designs was selected so the composite modulus of subgrade reaction equaled that in the original design (i.e., 91.8 MPa/m). The subgrade soils of the project consisted of silts and silty clays and the typical resilient modulus of the subgrade was assumed to be 34.5 MPa (Huang 1993).

RPM has a slightly higher modulus (250 MPa) than conventional aggregate (225 MPa). Thus, pavements employing RPM have a slightly thinner base layer than the reference design employing conventional aggregate. Fly ash stabilized RPM has significantly higher modulus (845 MPa) than conventional aggregate. Thus, pavements employing fly ash stabilized RPM have markedly thinner base layer than the reference design.

5.3.2 Service Life of Alternative Designs

Service life of the flexible or rigid pavements was determined using the method in the M-EPDG program (NCHRP 2009) based on moduli and thickness of each layer. The surface layer and the subgrade were assumed to be the same for all designs. The base course varied and affected the service life.

Predicted service lives of each of the twelve pavement designs are shown in Figure 5.2 in terms of IRI and are summarized in Table 5.3. Service life of the pavement was assumed to end when the IRI exceeded 2.7 m/km (FHWA 1998). All pavement sections degrade steadily (increasing IRI) (Figure 5.2). The rehabilitation strategy was assumed to include full depth reclamation (FDR) and HMA resurfacing for flexible pavement. For rigid pavement, different strategies were assumed for the first and subsequent rehabilitation events. The first rehabilitation event consisted of rubblizing the concrete pavement and HMA resurfacing. For subsequent rehabilitation events, FDR followed with HMA resurfacing was assumed. Service lives of pavements with FDR and HMA resurfacing and rubblizing with HMA resurfacing (i.e., 10 yr and 12.6 yr, respectively) were predicted based on the moduli of the layers following the same procedure used for the initial designs. The required number of surface rehabilitations was computed by dividing the period of analysis of 50 yr, which is the standard practice employed by WisDOT, by the expected service life of a pavement design (see Table 5.3). Four (F-1, F-2, F-3, F-4, R-1, R-2, R-3, and R-4) or three (F-5, F-6, R-5, and R-6) rehabilitation activities are required based on the predicted service lives. Two designs of each pavement types (F-5, F-6 and R-5, R-6) have relatively longer service lives (approximately 13 and 15 yr, respectively).

Each of these designs includes a base layer stabilized with fly ash to increase stiffness and to prevent development of rutting**.** Although RPM base layer has higher resilient modulus than aggregate base, RPM does not increase the service life of the layer due to accumulation of rutting caused by the higher plastic deformation of RPM compared to conventional aggregate.

5.4 ASSESSMENT

The BE^{2}ST-in-Highways^{TM} software was used for assessing and rating the alternative designs for the Baraboo Bypass. The alternatives were found to conform to all requirements (i.e., laws, project specifications, etc.) and therefore passed the

Table 5.2. Characteristics of Reference and Alternative Pavement Designs.

Design #	Surface type	Recycled material in surface	Thickness of surface (mm)	Base material	Thickness of base (mm)	Recycled material in base
F-1 Reference	HMA	No	140	Conventional Aggregate	406	No
F-2		15% RAP	140	Conventional Aggregate	406	No
F-3		No	140	RPM	381	RPM
F-4		15% RAP	140	RPM	381	RPM
F-5		No	140	RPM with 10% FA	351	RPM with 10% FA
F-6		15% RAP	140	RPM with 10% FA	351	RPM with 10% FA
R-1 Reference	PCC	FA 15%	254	Conventional Aggregate	152	No
R-2		FA 30%	254	Conventional Aggregate	152	No
R-3		FA 15%	254	RPM	150	RPM
R-4		FA 30%	254	RPM	150	RPM
R-5		FA 15%	254	RPM with 10% FA	132	RPM with 10% FA
R-6		FA 30%	254	RPM with 10% FA	132	RPM with 10% FA

Note: RAP = recycle asphalt pavement, RPM = recycled pavement material, FA = fly ash, HMA = hot mix asphalt, PCC = portland cement concrete.

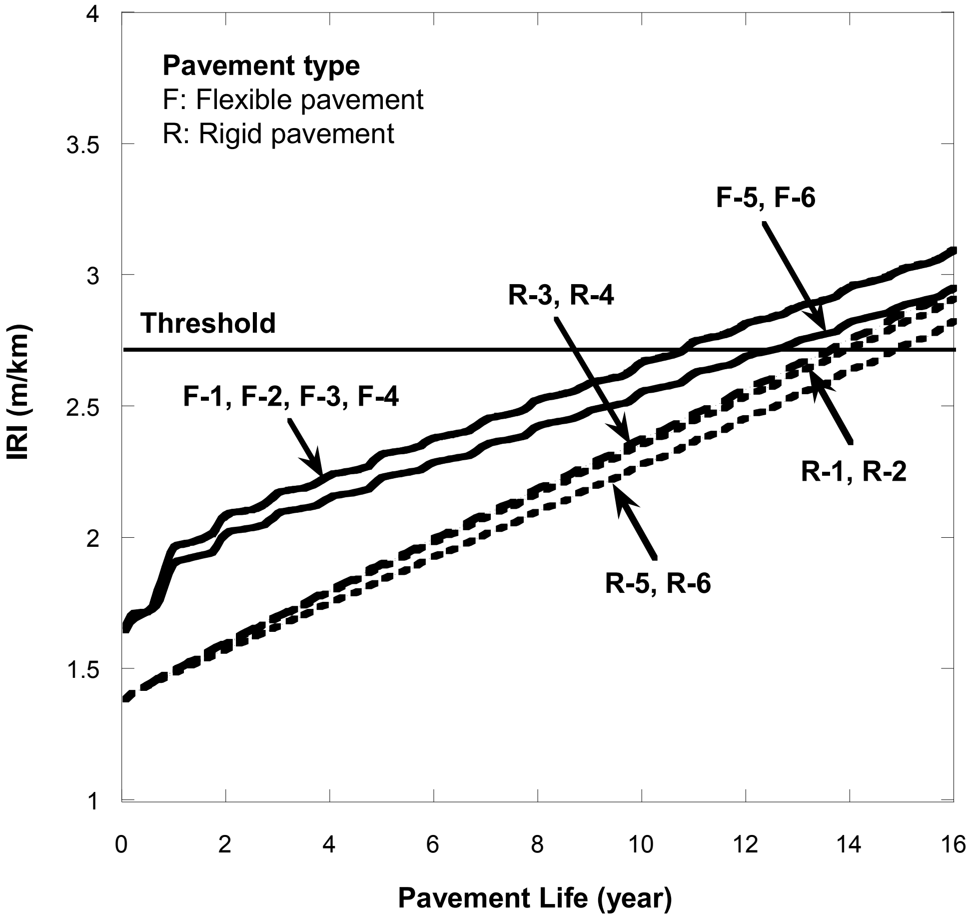


Figure 5.2. International Roughness Index of the Alternative Designs Predicted Using M-EPDG (Note: Initial IRI Set at the Defaults in M-EPDG).

screening phase. For example, all of the conventional and recycled materials are currently permissible for use. Life-cycle assessment and life-cycle cost analysis were conducted in the judgment phase as described in (Lee et al. 2010; Lee et al. 2010).

5.4.1 Life Cycle Assessment

Global warming potential and energy consumption were calculated using the database in PaLATE Version 2.0 (NCHRP 2006) for conventional and recycled materials in construction and maintenance of pavements. PaLATE employs the most comprehensive databases currently available for energy and water consumption and greenhouse gas emissions associated with production, transportation, and placement of a large variety of conventional and recycled materials using commonly available equipment for highway construction.

The user defines the dimensions of each layer in the pavement structure and the compacted density of the construction materials to determine the volume of materials needed as well as the distance between the project site and the material sources.

Table 5.3. Predicted Service Life and Number of Rehabilitations Required over 50 Years.

Design	Service Life (yr)	Number of rehabilitations required over 50 years and rehabilitation methods		
		1st	2nd and 3rd	4th
F-1, F-2	10.8	FDR with HMA resurfacing	FDR with HMA resurfacing	FDR with HMA resurfacing
F-3, F-4	10.8	FDR with HMA resurfacing	FDR with HMA resurfacing	FDR with HMA resurfacing
F-5, F-6	12.6	FDR with HMA Resurfacing	FDR with HMA resurfacing	No
R-1, R-2	13.9	Rubblizing with HMA resurfacing	FDR with HMA resurfacing	FDR with HMA resurfacing
R-3, R-4	13.7	Rubblizing with HMA resurfacing	FDR with HMA resurfacing	FDR with HMA resurfacing
R-5, R-6	14.9	Rubblizing with HMA resurfacing	FDR with HMA resurfacing	No

Note: FDR = full depth reclamation.

Based on this information, and a set of construction activities and prescribed maintenance activities, PaLATE calculates cumulative environmental effects such as energy and water consumption as well as atmospheric emissions associated with the mining and processing, hauling, and placement of these materials.

Recycled materials typically involve no manufacturing (e.g., fly ash) or modest processing (e.g., reclamation and pulverizing of RPM). Fly ash stabilization requires an additional step of blending fly ash into RPM. This process is similar to FDR. Thus, sustainability metrics for fly ash stabilization were assumed to be equal to those of FDR of flexible pavement to account for this additional step in construction.

All sources of construction materials were assumed to be located within 16 km. Recycled asphalt pavement (RAP) was assigned 16 km transportation to an HMA reprocessing site and an additional 16 km transportation back to the construction site. Since the project is being reconstructed along the current alignment, the existing HMA pavement can be recycled and used as RPM on site. Therefore, the transporation distance for RPM used in the base layer material was assumed to be 1.6 km. Densities of three base layer materials (i.e., aggregate, RPM, and RPM stabilized with 10% fly ash) were obtained from (Ebrahimi 2010). Other input parameters were assigned the defaults in PaLATE.

5.4.2 Life Cycle Cost Analysis

RealCost (Horvath 2004) software was used in conjunction with published construction cost data (RS Means 2007) for calculating life cycle costs. The cost of recycled materials was obtained locally from representatives of the recycled materials industry.

5.5 RESULT AND DISCUSSION

The BE^{2}ST-in-Highways^{TM} program was used to compare the LCA and LCCA for the alternative and reference designs (Design F-1 and Design R-1) and to assign ratings based on sustainability metrics (i.e., reductions and savings compared to reference designs) and comparison to stated targets. An example of the rating summary window of the BE^{2}ST-in-Highways^{TM} program is shown in Figure 5.3. The window provides the relative performance of an alternative design compared to reference design for each issue considered, as well as a spider web diagram depicting how well the targets have been accomplished.

Summary of Rating

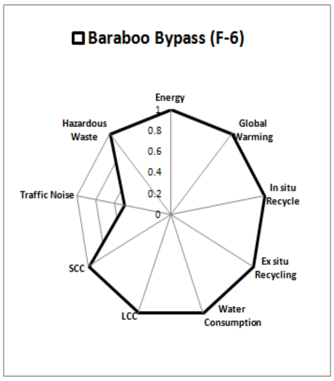
Get a score and label

Project Name:	Baraboo Bypass (F-6)
State Route:	US-12
Length of Analysis (km)	1.6

Criteria	Target Value	Reference	Alternative	Performance
Energy Use (MJ)	>= 20% Reduction (1 pt)	40,729,901	30,185,282	25.89%
GWP (Mg)	>= 20% Reduction (1 pt)	2,257	1,652	26.83%
In Situ Recycling (CY)	>= 20% Recycling Rate (1 pt)	0.00	10040.00	66.50%
Total Recycling (CY)	>= 20% Recycled Content (1 pt)	0.00	11440.00	75.78%
Water Consumption (kg)	>= 10% Reduction (1 pt)	9,945	7,275	26.84%
Life Cycle Cost ($)	>= 10% Reduction (1 pt)	$6,318,767	$4,431,491	29.87%
Social Carbon Cost ($)	>= $24,688/km Saving (1 pt)	$155,758	$113,972	41,786
Traffic Noise (no unit)	HMA (0.5 pt) SMA or OGFC (1 pt)	1	1	1
Hazardous Waste (kg)	>= 20% Reduction (1 pt)	388,157	299,428	22.86%

Accomplished Score	94.44
Awarded Label	Green Highway Gold

AMOEBA(General Method for Ecosystem Description and Assessment)



Title | Rating summary | M-EPDG | Weighting | PaLATE | LCCA | Traffic Noise | Stormwater | Sheet1

Figure 5.3. Screen Shot of the Rating Page for Design F-6 in the BE²ST-in-Highways™ Program.

5.5.1 Global Warming Potential and Energy Consumption

Global warming potential for each design is shown in Figure 5.4 in terms of CO_2 equivalents (CO_2e). Using recycled content in the surface layer (RAP in HMA, fly ash in PCC) results in modest reductions in CO_2 emissions (2-4%) and energy consumption (2-3%) for both the flexible and rigid pavements. Since production of portland cement is a CO_2-intensive manufacturing process, using fly ash in the rigid surface layer in lieu of portland cement was expected to have a high potential to reduce CO_2 emission. However, because the permissible amount of fly ash is limited, using fly ash in the PCC has a minor impact. RAP substitution in HMA also has limited impact. In contrast, using recycled material in the base layer results in larger reductions in CO_2 emissions (up to 27% when fly ash RPM is used, especially for the flexible pavements). Most of the CO_2e (90%) emissions associated with base layer materials are produced by heavy equipment used in mining and crushing materials. Because recycled materials require minimal or no processing, CO_2e emissions are reduced significantly.

Although not shown, impacts on energy consumption are similar. Four of the pavement designs (F-5, F-6, R-5 and R-6) consumed less energy during their entire life cycle (24%, 26%, 19%, and 23%, respectively) relative to the reference designs. These four designs use less material (i.e., thinner base layers) and fewer rehabilitation events due to longer service lives, and therefore less energy is consumed and CO_2e emissions are lower. For example, adding fly ash to RPM used in base increases the RPM modulus by 30%. Thus, the service life of a flexible pavement is extended and the thickness of the base is reduced (406 mm to 351 mm). Since the reference flexible pavement has a thicker base (406 mm) than the reference rigid pavement (152 mm), incorporating RPM stabilized with fly ash in a flexible pavement results in larger reduction in CO_2 emissions and energy use.

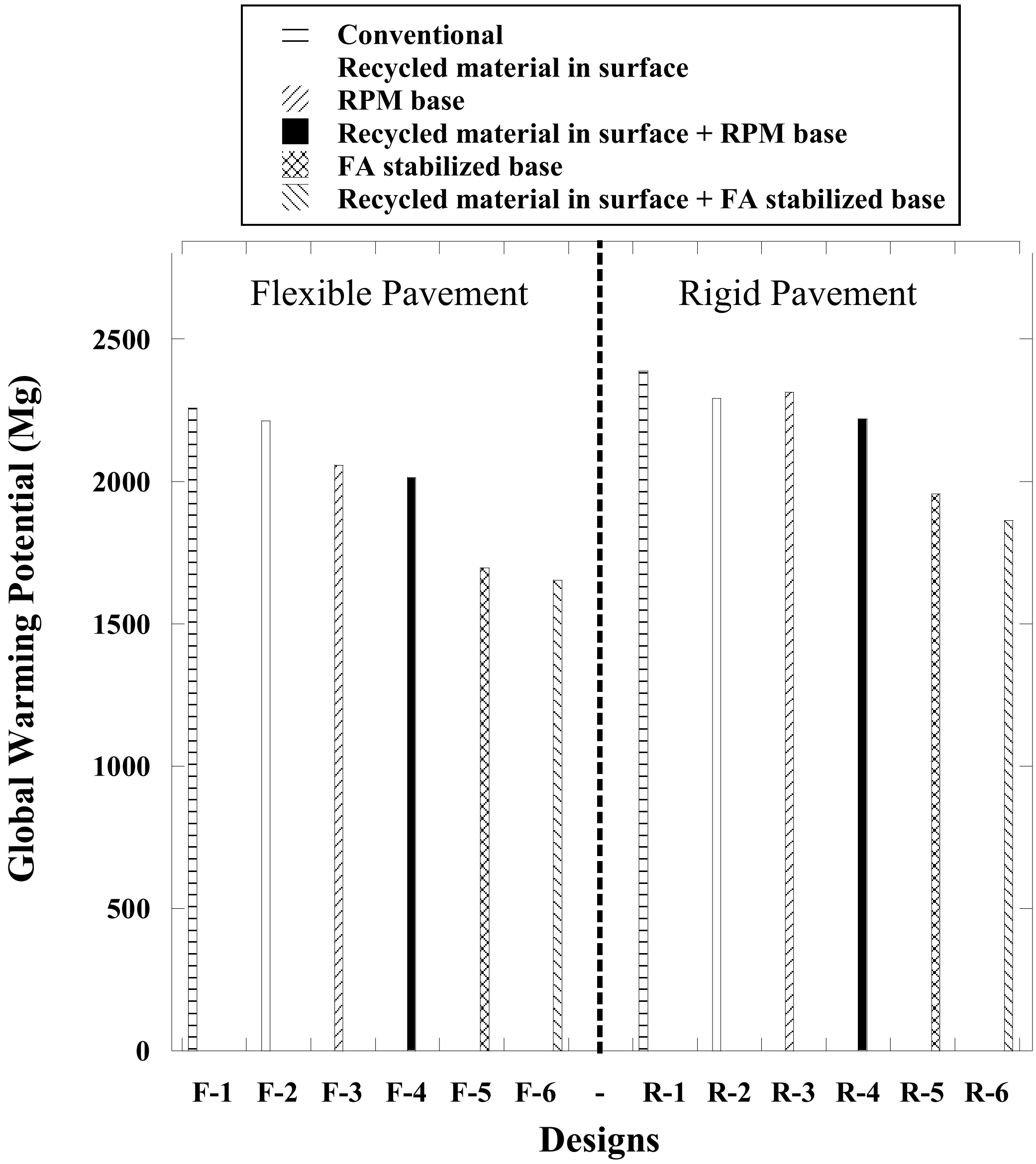


Figure 5.4. Global Warming Potential of the Reference and Alternative Designs.

5.5.2 Water Consumption

Water consumption for the twelve designs is shown in Figure 5.5. Incorporating recycled content into the surface layer results in a small reduction in water consumption (3-5%). A large reduction in water consumption is achieved using recycled materials in the base layer (5-24%), especially for the flexible pavements (24%). For example, designs F-5, F-6, R-5, and R-6 employ thinner layers and require fewer rehabilitations due to longer service lives. Therefore, these designs require less water for material extraction, transportation, and construction.

As shown in Figure 5.5, rigid pavements consume more water than flexible pavements during the entire life cycle due to the water-intensive characteristic of concrete. Reducing the surface thickness of rigid pavement can reduce water consumption modestly. However, greater savings can be accrued by using a thinner base layer constructed with recycled materials. Even larger water saving can be achieved for flexible pavements because the base layer in the reference design is thicker.

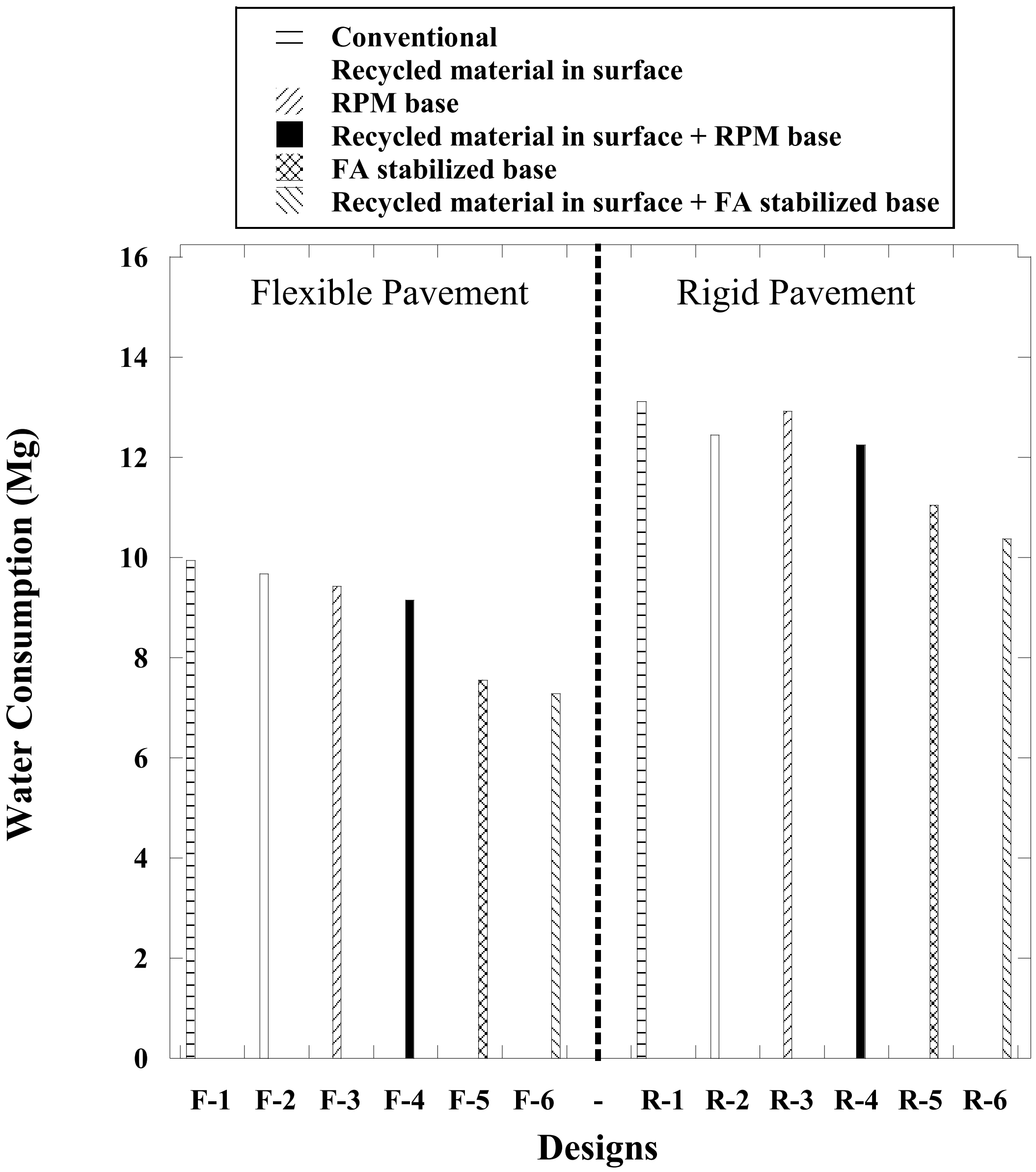


Figure 5.5. Water Consumption for the Reference and Alternative Designs.

5.5.3 Life Cycle Cost

A comparison of life cycle costs for each of the design strategies is shown in Figure 5.6. Including recycled content in the surface layer reduces the life-cycle cost modestly (1-8%). Larger reductions in life cycle cost are achieved by incorporating recycled material in base course (11-28%), especially for flexible pavements (28%). The reference designs using conventional materials (F-1 and R-1) have the highest life cycle cost.

The alternative designs incorporating recycled materials have lower life-cycle cost because the materials have superior properties relative to conventional materials, which extends the service life of the pavement, reduce the frequency of rehabilitation events and therefore the life-cycle costs. Recycled materials are also less costly than conventional materials. Therefore, highway construction with recycled materials of high quality can result in significant financial savings along with the benefits of sustainability.

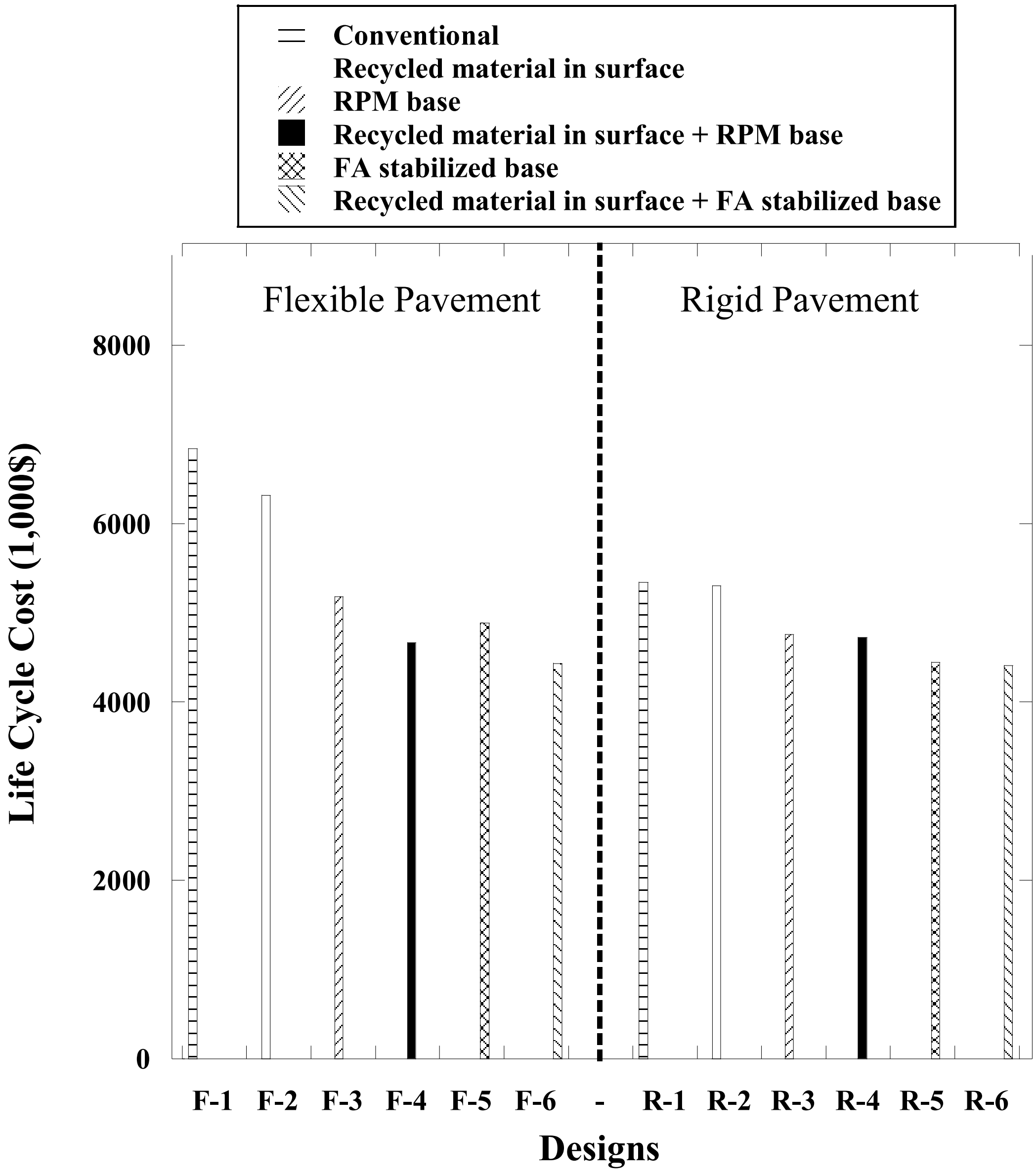


Figure 5.6. Life Cycle Cost of the Reference and Alternative Designs.

5.5.4 Rating

The environmental and economic attributes of the ten alternative designs were normalized to provide a sustainability index between 0 and 1 based on linear scaling between conventional and target conditions using fuzzy logic (Zadeh 1996). Normalization was conducted so that the magnitude of sustainability metric can be evaluated for an alternative design relative to a target condition (Zadeh 1996; Andriantiatsaholiniaina and Phillis 2001). Normalizing sustainability metrics permits understanding of the relative magnitude and importance of these metrics for each alternative under evaluation (Guinée 2002).

Normalization results are tabulated and presented in Table 5.4. Design alternatives F-6 and R-6 achieved the highest scores for almost every criterion and the highest score for each pavement type. For example, compared to the reference design (F-1), F-6 has 26%, 27%, and 27% lower energy, water consumption, and global warming potential, respectively. The life cycle cost was reduced by 30% by replacing 76% of the surface and base construction materials with recycled materials.

A saving of $16,210 in social carbon cost (SCC) can also be achieved per km of highway. The SCC is “an estimate of the monetized damages associated with an incremental increase in carbon emission in a given year” (U.S. DOE 2010). The SCC calculation permits a state agency (e.g., Wisconsin DOT) to incorporate the social benefits of reducing global warming potential into the cost-benefit analyses of sustainable construction efforts (U.S. DOE 2010). Since reducing CO_2 can directly contribute to financial benefits by reallocating resources to other purposes, an increase in SCC can motivate project planners and designers to employ sustainable strategies in designs.

All alternative designs with a HMA surface (i.e., F-2 through F-6) obtained 1 points due to the efforts of mitigating traffic noise. In Design F-6, 76% of construction material is recycled material and 67% of construction material is recycled *in situ* material. Thus, Design F-6 achieved 0.5 point in each criterion (i.e., *in situ* recycling rate and total recycled material content). For Design F-6, hazardous wastes were reduced by 23% due to the reduction in conventional material use and associated reduction in mining and processing equipment use. Therefore, 1 point was awarded to the design in this category.

Table 5.4. Points Assigned to Each Alternative Design and Total Score.

Design	Energy	GWP	Recycled Content	Water	LCC	SCC	Traffic Noise	Hazard Waste	Total Score
F-2	0.1	0.1	0.4	0.3	0.8	0.1	0.5	0.1	25.8
F-3	0.4	0.4	2.0	0.5	1.0	0.4	0.5	0.1	58.2
F-4	0.4	0.5	2.0	0.8	1.0	0.4	0.5	0.2	65.8
F-5	1.0	1.0	2.0	1.0	1.0	1.0	0.5	1.0	94.2
F-6	1.0	1.0	2.0	1.0	1.0	1.0	0.5	1.0	94.4
R-2	0.2	0.2	0.2	0.5	0.1	0.2	0.0	0.0	14.9
R-3	0.2	0.2	2.0	0.1	1.0	0.1	0.0	0.0	39.9
R-4	0.3	0.4	2.0	0.7	1.0	0.3	0.0	0.0	51.5
R-5	1.0	0.9	2.0	1.0	1.0	0.8	0.0	1.0	84.6
R-6	1.0	1.0	2.0	1.0	1.0	0.9	0.0	1.0	88.0

Note: GWP = global warming potential, LCC = life cycle cost, SCC = social cabon cost.

5.6 CONCLUSIONS

The benefits of employing recycled materials in place of conventional materials in a highway construction project have been evaluated and described by evaluating a pilot project using the BE^{2}ST-in-Highways^{TM} system. The superior material properties of some recycled materials (e.g., the high resilient modulus of fly ash-stabilized recycled pavement material) reduce the amount of material consumption and also extend the service life of the highway structure; therefore, environmental impacts are reduced and economic savings are obtained.

Major conclusions of this study include:

- The results of this pilot project evaluation indicate that use of recycled material in lieu of conventional material in highway construction can improve sustainability considerably: 27% reduction in global warming potential, 26% reduction in energy, and 27% reduction in water use.
- Reductions in CO_2 emissions, energy use, and water consumptionare largely due to reductions in the material production phase (e.g., mining and processing) achieved by substituting recycled materials for conventional materials. Reductions are also achieved by reducing the thickness of the base layer and the number of rehabilitation events due to longer service life resulting from the

superior properties of recycled materials.

- A reduction in life-cycle cost as large as 30% is achieved using recycled materials. The largest reduction in life-cycle cost is obtained using recycled material in the base course because larger material quantities involved in base course.
- Using recycled materials in the surface layer is not the use with highest sustainability value. Using recycled materials in the base course is more advantageous.

5.7 ACKNOWLEDGEMENT

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APPENDICES

APPENDIX A

SENSITIVITY ANALYSIS FOR THE BE^{2}ST-IN-HIGHWAYS^{TM} SYSTEM

Stepwise Regression: Score versus Surface Type, Service Life, ...

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Alpha-to-Enter: 0.05  Alpha-to-Remove: 0.05


Response is Score on 6 predictors, with N = 15


Step              1         2
Constant      1.472  -108.992

Service Life   2.92      5.98
T-Value        2.81      8.80
P-Value       0.015     0.000

Surface Type             39.4
T-Value                  6.65
P-Value                 0.000

S              17.2      8.28
R-Sq          37.82     86.72
R-Sq(adj)     33.03     84.51
Mallows Cp     81.9      10.8
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APPENDIX B

A PAIRING METHOD OF COMPARATIVE ENVIRONMENTAL AND ECONOMIC LIFE CYCLE ANALYSES

ABSTRACT: Electric utilities produce more than 118 million Mg of coal combustion products (CCPs) annually. Approximately 45 million Mg are used in a wide variety of applications. This study examines the environmental and cost benefits associated with the most common uses of CCPs in construction activities—replacement of Portland cement in concrete, replacement of gypsum in wallboard, and replacement of granular fill in geotechnical applications. According to the study results based on 2007 data, CCPs use reduced energy consumption by 66.7 petajoules, water consumption by 22.3 billion liters, and GHG emissions by 9.3 million Mg CO_2e. Cost savings ranged from $2.4-7.8 billion. Considering that this study excludes financial benefit due to the saving of material costs and other areas of application (e.g., agricultural application and mine reclamation), removal of the barriers preventing increased use of CCPs can bring enormous additional environmental and economic benefits.

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B-1 INTRODUCTION

The United States Energy Information Administration (EIA) reported that coal combustion generated 33% of the total Btu energy produced in the United States in 2007. Moreover, coal combustion contributed to 50% of the electrical power generating capacity of the nation (EIA 2009). Use of coal as an energy source has steadily increased over the last 30 years and coal will continue to be an important fuel for the foreseeable future. As a result of increased coal use and new air emissions controls, the production of coal combustion products (CCPs) is also steadily increasing (Figure B-1). In 2007, 118.9 million Mg of CCPs were produced in the United States (ACAA 2008). Fly ash (65 million Mg), bottom ash (16.4 million Mg), and gypsum from flue gas desulphurization (FGD) operations (11.2 million Mg) constituted the majority (78%) of the CCPs produced in 2007. Beneficial use in construction and other applications consumed 47% (43.7 million Mg) of the fly ash, bottom ash, and FGD gypsum that was produced in 2007. The remaining 53% (48.9 million Mg) was disposed or stored in impoundments or landfills.

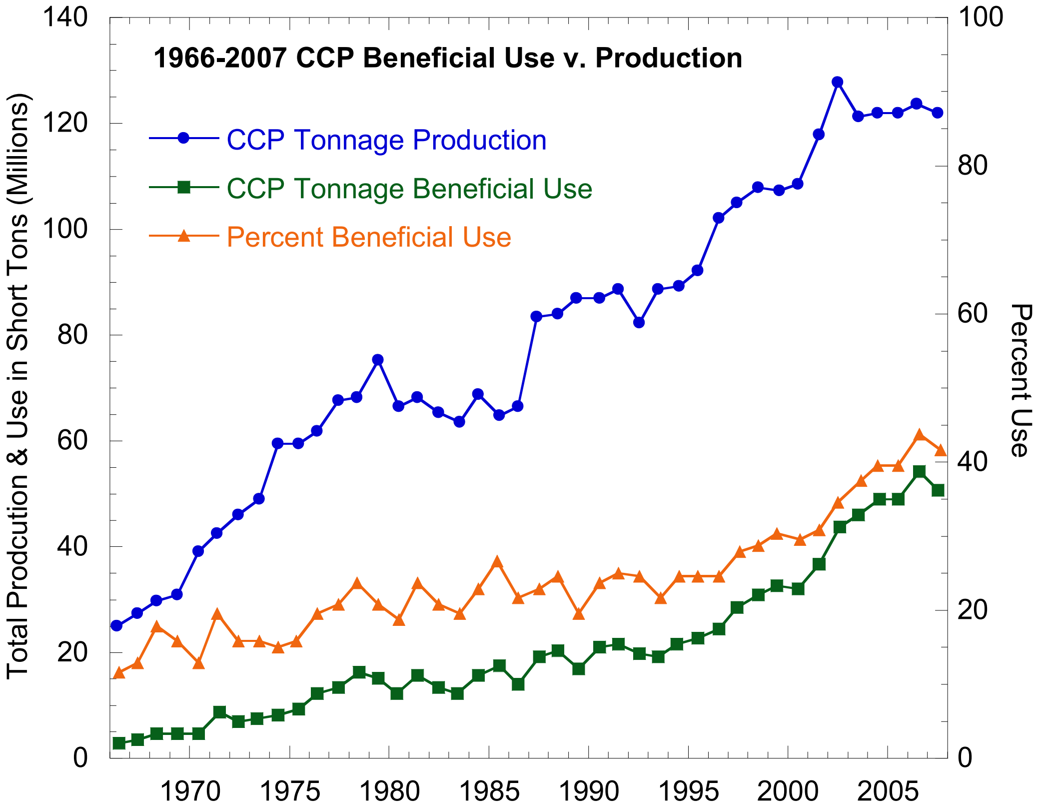

Figure B-1. Historical Production and Use of CCPs (Adapted from ACAA 2009).

Fly ash is a fine powdery material collected from the exhaust of a coal combustion chamber that is pozzolanic and can be cementitious. The majority of fly ash use is associated with cement and concrete (55% of total used in 2007), with partial replacement of Portland cement in concrete being the most common use (43% of total fly ash used) (ACAA 2008). Geotechnical applications, which include roadway base and subbases, subgrade stabilization, and embankments and structural fills, are also significant uses of fly ash (28% of total fly ash used in 2007) (ACAA 2008).

Bottom ash is a coarse granular residue (gravel and/or sand-size particles) from coal combustion that has similar chemical composition as fly ash (EPA 2008; FHWA 2008). Because the particles are larger, bottom ash is used as substitute for conventional aggregates such as sands and gravels, primarily in geotechnical applications (55% of total bottom ash used in 2007) (ACAA 2008).

FGD gypsum is a byproduct of flue gas desulphurization at coal-fired power plants that use wet scrubbers and forced oxidation to reduce SO_2 emissions. The gypsum produced by the desulphurization process is mineralogically identical to natural gypsum ($CaSO_4 \cdot 2H_2O$), making FGD gypsum an ideal replacement for mined gypsum used to manufacture wallboard. In 2007, 75% of FGD gypsum produced was used beneficially, 90% of which was used to produce wallboard. Other significant uses of FGD gypsum include agriculture and cement/concrete production (ACAA 2008).

Use of CCPs in construction materials has been steadily increasing (Figure B-1), and in some applications (e.g., wallboard, Portland cement concrete) CCPs are now considered as standard or required materials in manufacturing and construction. The fraction of CCPs used beneficially is increasing (Figure B-1) due to the desirable attributes of CCPs as construction materials and increased interest in sustainable construction and development. For example, production of Portland cement accounts for 5 to 8% of annual CO_2 emissions worldwide (Anderson 2008; Reiner and Rens 2006). Replacing a portion of the Portland cement with fly ash reduces the CO_2 emissions associated with production of Portland cement proportionally. Energy and water use associated with cement production are also reduced. These savings are accrued because the fly ash is used essentially “as is;” no processing or transformation is required, thereby eliminating emissions and resource consumption associated with creating a construction material.

Although the contribution of CCPs in construction to sustainability is logical, a quantitative assessment of beneficial use of CCPs has not been conducted (past studies focused on one material, such as concrete or wallboard). The study described in this report was conducted to quantify the environmental and economic benefits of using CCPs in each of the major construction applications. The focus was on fly ash, bottom ash, and FGD gypsum because of the preponderance of these CCPs relative to other byproducts of coal combustion. The primary uses of fly ash, bottom ash, and FGD gypsum (2007 data) are shown graphically in Fig. B-2. Geotechnical applications are lumped together in Fig. B-2 and include uses of CCPs for structural fill and embankments and road base/ sub-base soil modification and stabilization. Cement and concrete, geotechnical applications, and wallboard manufacturing consume 72% of the CCPs that are used beneficially. Consequently, this study focused on these three applications for each of the three CCPs considered. The analysis focused on the benefits of using CCPs in terms of reductions in greenhouse gas (GHG) emissions, consumption of energy and water, and economic savings. Avoidance of landfill disposal costs was also considered in the analysis.

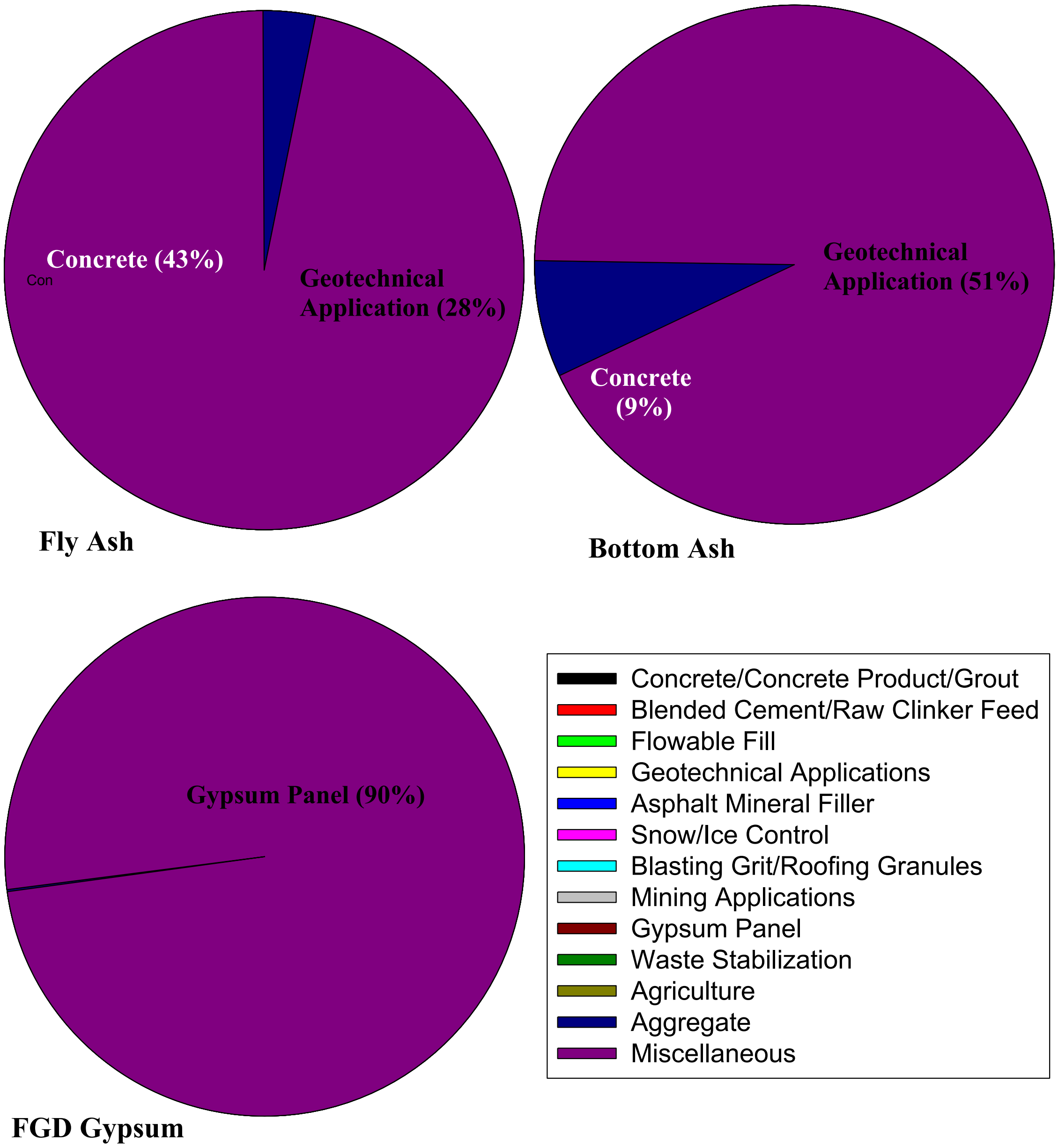

Figure B-2. Uses of Fly Ash, Bottom Ash, and FGD Gypsum by Application.

B-2 METHOD

Environmental benefits of using CCPs in sustainable construction were estimated using life cycle analysis models. Economic benefits were calculated based on the monetary value of the environmental benefit. Unit benefits (e.g., environmental benefits per ton of CCP used in the given application per year) were obtained from predictions made with the Building for Environmental and Economic Sustainability (BEES) (NIST 2007), SimaPro (Pré Consultants 2009), and the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (RMRC 2004) life cycle analysis programs. Predictions with BEES were made by EPA (2008). The BEES predictions were independently verified and updated as part of this study. Predictions using SimaPro and PaLATE were modeled as part of this study. Descriptions of each model are provided in the following sections.

The BEES model was developed by the National Institute of Standards and Technology (NIST 2007) for life-cycle analysis of building construction. BEES 4.0 contains environmental data for over 230 products across a wide range of building elements including beams, columns, wall insulation, ceiling finishes, etc. Environmental data for a variety of concrete products (e.g., concrete columns, walls, slab on grade, and beams) are included. The user can compare the environmental performance data of each of these products using different pre-determined concrete mix-designs, some of which include fly ash. A summary of the databases used to compile the information used in BEES can be found in NIST (2007).

SimaPro is a life cycle analysis program developed by the Dutch company Pré Consultants that can be used to conduct detailed analyses of complex products and processes (Pré Consultants 2009). SimaPro quantifies inflows and outflows of resources, products, emissions, and waste flows during product manufacturing. SimaPro integrates all inputs (resources) and outputs (emissions and waste) by tracing all the references established on process trees from one process stage to another. The computations made by SimaPro rely on information from the EcoInvent database (Pré Consultants 2009) and integrated Swiss databases (e.g. ETH-ESU 96; BUWAL250).

The PaLATE model is a life cycle assessment tool that contains environmental and engineering information and data to evaluate the use of conventional and recycled materials in construction and maintenance of pavements (Horvath 2004). The user defines the dimensions of each layer in the pavement, the distance between the project site and material sources, and the density of the construction materials. These yield types and volumes of construction materials, sources and hauling distances, a set of construction activities, and a set of prescribed maintenance activities. From this information, PaLATE calculates cumulative environmental effects such as energy and water consumption as well as atmospheric emissions. Several different sources of information and analysis methods are used in PaLATE to characterize the environmental impact of road construction projects. For example, the environmentally augmented economic input-output analysis (EIO-LCA), a Leontief general equilibrium model of the entire US economy, was employed.

The environmental and economic benefits of CCP use were quantified by computing differences in energy expenditure, water consumption, and GHG emissions between conventional materials and those produced with CCPs, as predicted by the life-cycle analysis codes, BEES, SimaPro, and PaLATE. Three major applications were considered: concrete, wallboard, and geotechnical applications using fly ash and bottom ash. Unit impacts (environmental impacts per 1 Mg of CCP used in manufacture per year) derived for concrete using BEES was developed from EPA

(2008). Unit impacts resulting from wallboard production were modeled using SimaPro; unit impacts for geotechnical applications were modeled using PaLATE. Total annual benefits for all applications were obtained as the product of unit benefits for energy, water, or GHG emissions and the most recent annual beneficial use quantity (in Mg) provided by ACAA (2008) (Appendix E). Unit financial savings for energy and water were generated using financial data given by the National Propane Gas Association (NPGA 2006) and NUS Consulting (2006). The social cost of carbon (SCC) was used to calculate the financial benefit of the reduction of greenhouse gases (CO_2e) from CCP use as a construction material. The SCC incorporates social benefits of CO_2 reduction into a cost benefit analysis of regulatory actions. The SCC was set at \$5.20 or \$68.00 per metric ton of carbon (2009 US dollars) to reflect low and high cost scenarios based on recommendations in US DOE (2010).

B-3 ANALYSIS OF UNIT IMPACTS

B-3.1 Fly Ash Use in Concrete

Unit benefits of using fly ash as a cement substitute in concrete were obtained from LCA modeling with BEES described in USEPA (2008). The BEES functional unit was 0.76 m^3 (1 yd^3) of structural concrete having a compressive strength of 27.6 MPa (4000 psi) and 75-yr lifespan. System boundaries for the analysis are shown in Figure 5.3. The BEES program incorporates round-trip transportation distances of raw materials from extraction sites (e.g., quarries, power plants, etc.) to ready-mix concrete plants using data provided by NIST (2007). The analysis assumed that 0.24 Mg of cement was required to produce 1 Mg of concrete (Lippiatt 2002). Conventional concrete was assumed to contain no CCPs. For concrete manufactured with CCPs, 15% of the Portland cement was replaced by fly ash at a 1:1 (by weight) substitution ratio. Discussions with representatives in the ready-mix concrete industry indicated that this replacement rate is conservative (i.e., higher rates are common in practice). FHWA (2003) and PCA (2009) also suggest that 15-30% of the Portland cement in concrete can be replaced by fly ash. Use of fly ash or other CCPs in manufacturing cement used in concrete was not incorporated into the analysis.

For concrete production, transport distances for Portland cement and fly ash to the ready-mix plant were both assumed to be 97 km. Therefore no differential in benefits due to differences in raw material transport were considered. A sensitivity analysis was conducted to assess the significance of this assumption as transport distances for fly ash tend to be less than those for Portland cement. Increasing the transport distance for Portland cement to 161 km while keeping fly ash transport distance fixed at 97 km showed that the environmental benefits would increase by only about 4%, suggesting that differences in raw material transport distance can be considered negligible (Appendix C).

Unit benefits of replacing Portland cement with 15% fly ash (benefit/Mg of fly ash) for energy consumption, water consumption, GHG emissions, and their corresponding financial savings are shown in Table B-1. Environmental benefits are primarily obtained by avoiding the process of cement production.

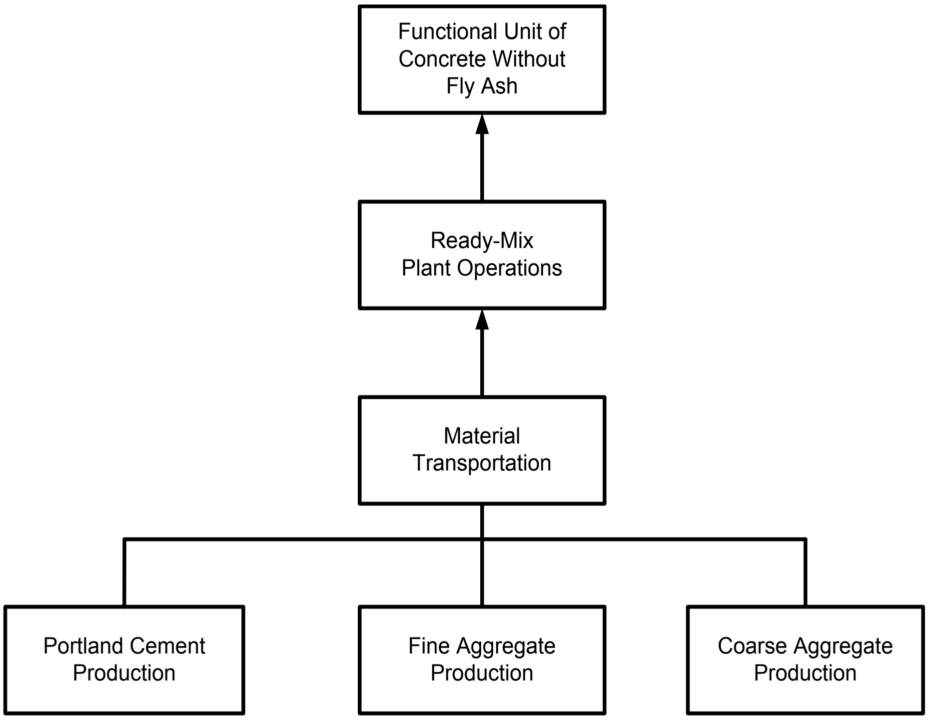

Figure B-3. System Boundary for 27.6 MPa Concrete Production without Fly Ash (Adapted from EPA 2008). Replacement of Cement by Fly Ash Adds an Additional Branch in The Tree Parallel to The Cement Branch.

Table B-1. Benefits Obtained by Replacing 15% of Portland Cement with Fly Ash (adapted from EPA 2008).

Areas of impact		Savings per 1 Mg of fly ash
Energy Savings	Saving (megajoules)	4,259
	Financial Savings (US$)	124
Water Savings	Savings (Liter)	342
	Financial Savings (US$)	0.23
CO_2 Equivalent	Reduction (Megagrams)	0.7
	Financial Saving (US$)	3.4 ~ 47.4

B-3.2 FGD Gypsum in Wallboard Manufacturing

Unit benefits of using FGD gypsum as a substitute for conventional gypsum in wallboard manufacturing were obtained with SimaPro (Appendix D) using the EcoInvent and US LCI (NREL 2000) databases as inputs and the cumulative energy demand (CED) (version 1.07) assessment method for energy consumption and the BEES (version 4.02) assessment method for water consumption and GHG emission. The system boundary for production of stucco (moist gypsum to create wallboard sheet) is shown in Fig. B-4 for virgin and FGD gypsum. Discussions with industry representatives indicated that the resources associated with pre-drying FGD gypsum at the wallboard plant are comparable to or lower than those associated with milling and pre-drying virgin gypsum. Therefore, the resources associated with processing virgin and FGD gypsum at the wallboard plant were conservatively assumed to be equal. Consequently, gypsum mining was the only factor contributing to environmental differences between wallboard manufacturing using virgin gypsum and FGD gypsum (Figure B-4).

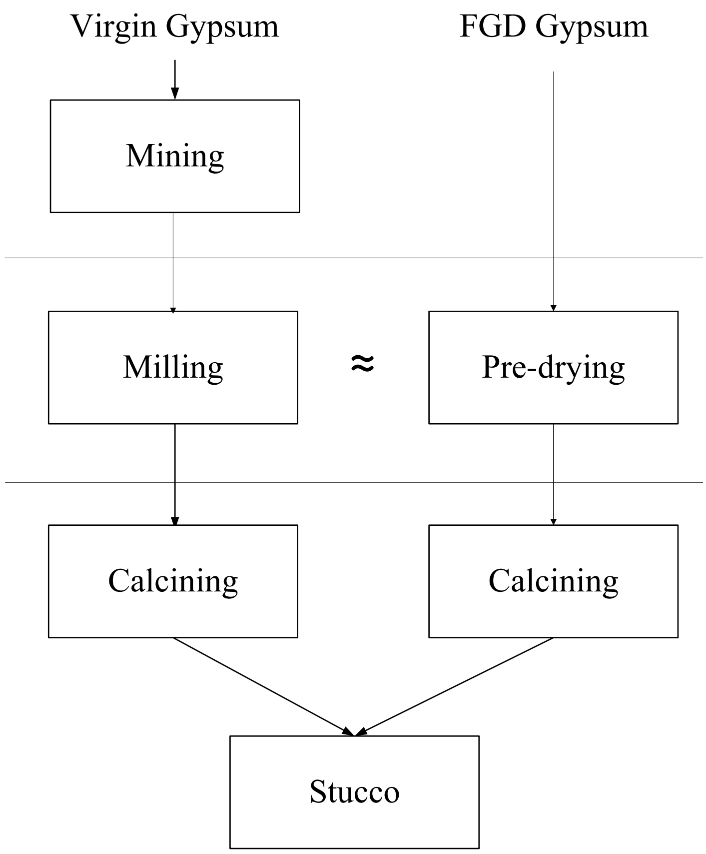

Figure B-4. System Boundary for Stucco Production for Wallboard Manufacture Using Virgin Gypsum or FGD Gypsum.

The EcoInvent database employed by SimaPro uses a Swiss electricity mix. To make the analysis more representative of U.S. conditions, the database was modified using a U.S. electricity mix (NREL 2000).

Transport of natural gypsum can require greater energy and result in increased greenhouse gas emissions compared to FGD gypsum, especially for wallboard manufacturing plants constructed adjacent to coal-fired power plants employing wet scrubbers for FGD. This benefit is difficult to quantify and was not included in the analysis (i.e., transportation energies for virgin gypsum and FGD gypsum were assumed to be identical). This assumption resulted in additional conservatism in the analysis.

Unit benefits in terms of energy consumption, water consumption, and GHG emissions obtained by replacing natural gypsum with FGD gypsum in wallboard (benefits/ton) and the corresponding economic savings are shown in Table B-2. These benefits are achieved by avoiding the water use, energy consumption, and emissions associated with mining virgin gypsum.

Table B-2. Benefits Profile for 100% FGD Gypsum Replacing 100% Virgin Gypsum.

Areas of impact		Savings per 1 Mg of FGD
Energy Savings	Saving (Megajoules)	41.45
	Financial Savings (US$)	1.2
Water Savings	Savings (Liter)	2,400
	Financial Savings (US$)	1.59
CO_2 Euivalent	Reduction (Megagrams)	0.003
	Financial Saving (US$)	0.01 ~ 0.20

B-3.3 Fly Ash and Bottom Ash in Geotechnical Applications

Unit benefits of using fly ash or bottom ash in geotechnical applications were evaluated using PaLATE (RMRC 2004). The analysis considered structural fills as well as roadway applications (bases, subbases, and subgrades).

For structural fills, fly ash and bottom ash were assumed to replace sand and gravel at a 1:1 (volume) replacement ratio. The same equipment and effort was assumed for placement of conventional soils and CCPs. Fly ash and bottom ash were assumed to be placed at a dry unit weight of 1.48 Mg/m^3 (RMRC 2008); conventional soils were assumed to have a dry unit weight of 1.90 Mg/m^3 (Tanyu et al. 2004).

For roadway construction, fly ash was assumed to be used as a stabilizer for subgrades at a 10% dosage in lieu of excavation of soft soil and replacement with crushed rock, as described in Edil et al. (2002). A 10% dosage is conservative because fly ash dosages used for stabilization typically range from 10 to 20%. Bottom ash was assumed to replace sand and gravel used in base and subbase courses at 1:1 replacement (by volume) as suggested by FHWA (2008).

Structural numbers and layer coefficients are used in road designs to determine the necessary layer thickness needed to sustain designed traffic loads. A structural number represents the structural requirement needed for a particular road design. A layer coefficient represents the structural characteristics of a construction material and can be used with the structural number to determine the required road thickness. The PaLATE analysis for fly ash stabilization compared roadway subbase constructed with a structural number of 2.8 and a layer coefficient of 0.18 for conventional construction with crushed rock and 0.13 for fly-ash-stabilized subgrade (Geo Engineering Consulting 2009). As a result, a 0.4-meter-thick layer of crushed rock and a 0.56-meter-thick layer of fly ash stabilized subgrade were analyzed. The difference in energy required for placement was also considered. Stabilized subgrade is constructed using a reclaimer to blend fly ash into the existing subgrade. For crushed rock, the subgrade is removed using an excavator. The dry unit weight of the fly ash stabilized subgrade was assumed to be 1.64 Mg/m^3, as documented by Edil et al. (2002).

Benefits of using bottom ash were computed by comparing roads constructed with a subbase consisting of 100% bottom ash or Wisconsin Grade 2 granular fill (sand or gravel). The two granular layers were designed to have the same structural number (1.6) using a layer coefficient of 0.08 for granular backfill and 0.06 for bottom ash, as suggested by Geo Engineering Consulting (2009). This resulted in a 0.5-meter-thick subbase layer of conventional granular fill and a 0.69-meter-thick layer of bottom ash.

Equipment used to install the Grade 2 granular material and the bottom ash was assumed to be the same. The bottom ash was assumed to have a unit weight of 1.48 Mg/m^3, whereas the granular fill was assumed to have a unit weight of 1.90 Mg/m^3.

Unit benefits of using fly ash or bottom ash in structural fills and embankments are summarized in Tables B-3 (fly ash) and B-4 (bottom ash). Unit benefits of replacing crushed rock with fly-ash-stabilized subgrade are summarized in Table B-5 and unit benefits of replacing conventional granular subbase with bottom ash are summarized in Table B-6.

Table B-3. Benefits Profile for Replacing a 50% Sand and Gravel Mixture with Fly Ash in a Structural Fill.

Areas of impact		Savings per 1 Mg of Fly Ash
Energy Savings	Saving (megajoules)	221
	Financial Savings (US$)	6.38
Water Savings	Savings (Liter)	0.033
	Financial Savings (US$)	0.00002
CO_2 Equivalent	Reduction (grams)	0.011
	Financial Saving (US$)	0.06 ~ 0.75

Table B-4. Benefits Profile for Replacing a 50% Sand and Gravel Mixture with Bottom Ash in a Structural Fill.

Areas of impact		Savings per 1 Mg of Bottom Ash
Energy Savings	Saving (megajoules)	174.0
	Financial Savings (US$)	4.95
Water Savings	Savings (Liter)	0.02
	Financial Savings (US$)	0.0001
CO_2 Equivalent	Reduction (grams)	0.01
	Financial Saving (US$)	0.06 ~ 0.67

Table B-5. Benefits Profile for Replacing Crushed Rock with Fly-Ash-Stabilized Subgrade.

Areas of impact		Savings per 1 Mg of Fly Ash
Energy Savings	Saving (megajoules)	2,093
	Financial Savings (US$)	62.4
Water Savings	Savings (Liter)	0.29
	Financial Savings (US$)	0.0002
CO_2 Equivalent	Reduction (grams)	0.15
	Financial Saving (US$)	0.78 ~ 10.15

Table B-6. Benefits Profile for The Substitution of Bottom Ash for Wisconsin Grade 2 Granular Fill Subbase.

Areas of impact		Savings per 1 Mg of Bottom Ash
Energy Savings	Saving (megajoules)	198
	Financial Savings (US$)	5.82
Water Savings	Savings (Liter)	0.029
	Financial Savings (US$)	0.00002
CO_2 Equivalent	Reduction (grams)	0.01
	Financial Saving (US$)	0.06 ~ 0.67

B-3.4 Benefits of Avoided CCP Disposal

Using CCPs in sustainable construction activities results in additional environmental and economic benefits through avoided landfill disposal. These additional savings were calculated using life cycle inventory (LCI) data for construction, operation, and maintenance costs for Subtitle D (non-hazardous municipal solid waste) landfills in EREF (1999). Environmental impacts associated with construction, operation, and maintenance of Subtitle D landfills were assumed to be similar to that of Subtitle C disposal facilities. Using Subtitle D LCI information is conservative because Subtitle C landfills employ more sophisticated containment systems and additional restrictions on operations, waste acceptance, and disposal that increase emissions as well as consumption of energy and water. The model system boundaries for a landfill life cycle defined by EREF are shown in Figure B-5. The major components are landfill construction, landfill operation, landfill closure, landfill post-closure care, and leachate treatment (leachate treatment costs are normalized over a 100 yr period starting from initial waste placement). Life-cycle inventory data are summarized in Table B-7 through B-11 for each major component of the landfilling process shown in Figure B-5. Any inventory information that was specific to municipal solid waste and not applicable to CCP disposal was excluded. Methane (CH_4) reported in Table B-7 through B-11 is from equipment and processes associated with construction and closure of a MSW landfill and not from waste decomposition

A summary of the LCI information for all landfilling processes is shown in Table B-12. The total economic benefits of avoided landfill disposal are summarized in Table B-13. Economic benefits were derived by multiplying the unit saving by the amount of avoided landfilling (i.e., total amount of fly ash, bottom ash, and FGD currently being beneficially used for concrete, wallboard, and geotechnical applications in 2007). A summary of the unit impacts associated with CCP disposal is shown in Table B-14. The CO_2 equivalence reported in Table B-14 includes CO_2 savings and methane savings, with the latter converted to CO_2e by assuming 1 Mg of CH_4 = 23 Mg CO_2e.

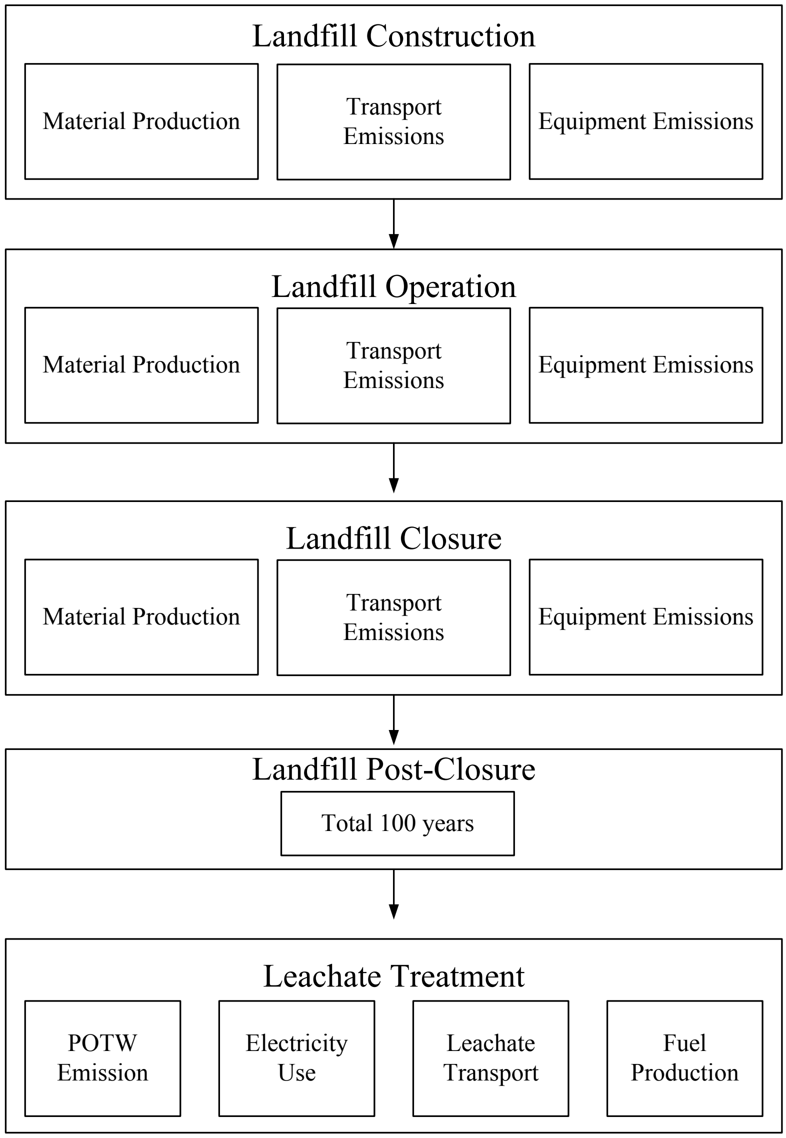

Figure B-5. Life Cycle System Boundaries for Landfilling (Adapted from EREF 1999).

Table B-7. Total LCI Attributable to Landfill Construction (Data from EREF 1999).

Parameters	Material Production	Transport Emissions	Equipment Emissions	Total
Energy (MJ/Mg)	0	31.1	0	31.1
CO_2 (kg/Mg)	0.73	0.13	0.54	1.41
Methane (kg/Mg)	0.005	0.0005	0.002	0.008

Table B-8. Total LCI Attributable to Landfill Operations (Data from EREF 1999).

Parameters	Plastic	Soil	Steel	Fuel	Transport Emission	Equipment	Total
Energy (MJ/Mg)	0.05	1.40	3.11	52.12	0	0	56.68
CO_2 (kg/Mg)	0.0008	0.097	0.24	0.734	0.37	3.08	3.82
Methane (kg/Mg)	7.0E-07	4.0E-05	0.0002	0.002	-	-	0.002

Table B-9. Total LCI Attributable to Landfill Closure (Data from EREF 1999).

Parameters	Material Production	Transport Emissions	Equipment Emissions	Total
Energy (MJ/Mg)	29.06	0	0	29.06
CO_2 (kg/Mg)	1.21	0.29	0.18	1.68
Methane (kg/Mg)	0.0008	-	-	0.0008

Table B-10. Total LCI Attributable to Landfill Post-Closure Care (Data from EREF 1999).

Parameters	Total 100 years
Energy (MJ/Mg)	2.9
CO_2 (kg/Mg)	0.17
Methane (kg/Mg)	0.00008

Table B-11. Total LCI Attributable to Leachate Management for 100 yr (Data from EREF 1999).

Parameters	POTW Emissions	Leachate Treatment	Electricity	Fuel	Total
Energy (MJ/Mg)	0	0	3.11	1.30	4.41
CO_2 (kg/Mg)	0	0.08	0.20	0.009	0.30
Methane (kg/Mg)	0	-	0.0006	0.00005	0.0005

Table B-12. Benefits Due to Avoided Landfilling of Recycled CCPs (Fly Ash, Bottom Ash, and FGD Gypsum).

	Energy (MJ/Mg)	CO_2 (kg/Mg)	Methane (kg/Mg)
Construction	31.07	1.41	0.0008
Operation	56.68	3.82	0.002
Closure	29.06	1.68	0.0008
Post Closure	2.91	0.17	0.0001
Leachate	4.41	0.29	0.0005
Total	124.13	7.37	0.011

Table B-13. Economic Benefits Due to Avoided Landfilling of Fly Ash, Bottom Ash, and FGD Gypsum Currently Used in Sustainable Construction.

	Unit Cost	Quantity	Total
Construction	$74/m^2$	1.55 cumulative million m^2	115 million
Operation	$6.61/Mg	31.4 million Mg	208 million
Closure	$37.1/m^2$	1.55 million m^2	57 million
Post Closure	$3.71/m^2$	1.55 million m^2	6 million
Leachate	$0.01/L	1,192 million cumulative L	12 million
Total			0.4 billion
Commercial Landfills (Average tipping fee for subtitle D = $44/Mg)*			$1.4 billion
Commercial Landfills (Average tipping fee for subtitle C = $165/Mg)**			$5.2 billion

* Wisconsin DNR (2009), ** Benson (2009)

Table B-14. Benefits Profile for Avoided Landfilling of Fly Ash, Bottom Ash, and FGD Gypsum Currently Used in Sustainable Construction.

Benefit		Savings/Mg CCP
Energy	Savings (MJ/Mg CCP)	127.93
	Financial Savings (US$/Mg CCP)	3.71
GHG Emission	CO_2e (Mg/Mg CCP)	0.008
	Financial Savings (US$/Mg CCP)	0.04 ~ 0.52

B-4 CUMULATIVE BENEFITS

Total annual benefits of using CCPs in construction applications are reported in Table B-15 in terms of reductions in energy use, water consumption, and global warming potential (in CO_2e based on BEES global warming potential characterization factors reported in NIST 2007). Total savings for each application were computed as the product of the annual use of each CCP in each use application and the derived unit benefits (Tables B-1 through B-5, B-6, B-13, and B-14).

The largest environmental benefit in sustainable construction is currently accrued by using fly ash in concrete production. Use of fly ash as a cement substitute annually saves more than 58 petajoules of energy and reduces GHG emissions by 8.7 million Mg CO_2e (Table B-15). Using FGD gypsum in wallboard manufacturing results in modest annual energy savings (0.32 petajoules), substantial annual savings in water consumption (17.8 billion liter), and a small annual reduction in GHG emissions (0.03 million Mg CO_2e). Geotechnical applications of CCPs result in moderate annual savings in energy consumption and CO_2 emissions at current usage rates, and modest annual savings in water consumption. Financially, the greatest benefits are obtained using fly ash in concrete, followed by use of CCPs in geotechnical applications, and

Table B-15. National Annual Savings Obtained by Using CCPs in Sustainable Construction.

Resource	Concrete	Wallboard	Geotechnical	Landfill Avoidance
Energy (petajoules)	58	0.3	4.5	3.9
Water (million liter)	4,542	17,791	0.64	Not Known
CO_2e (million Mg)	8.7	0.03	0.3	0.3
Financial (billion $)	2.3	0.02	0.15	0.5-5.3*

*Includes landfill tipping fee (1.e., $0.4 billion ~ $5.2 billion) and environmental costs.

FGD gypsum in wallboard manufacturing. The financial benefits are closely aligned with benefits associated with reductions in energy consumption and GHG emissions.

Reductions in energy use, water consumption, and GHG emissions are obtained by avoiding production of conventional materials. In contrast to the construction materials they replace, CCPs are byproducts of energy generation and are not produced specifically for construction applications. Consequently, the resources embodied in CCP production are accounted for in electricity production and are expended regardless of whether CCPs are used beneficially.

The benefits from avoiding disposal are also shown in Table B-15. Avoided landfilling accounts for a savings of 3.9 petajoules of energy and a reduction of CO_2e emissions by 0.3 million Mg. The combined financial savings ranges considerably, from $0.5 billion annually for a Subtitle D-style landfill operated on site by utilities to $5.3 billion annually for offsite commercial disposal in a Subtitle C landfill. Disposal in an offsite commercial Subtitle D landfill would likely cost $1.4 billion annually. These commercial disposal costs are based on a tipping fee of $44/Mg for a Subtitle D landfill and $165/Mg for a Subtitle C landfill (Wisconsin DNR 2009 and telephone interviews with solid waste industry representatives).

The total annual benefits obtained from using CCPs in sustainable construction applications are summarized in Table B-16. Using CCPs in construction applications results in a reduction in energy consumption of 66.7 petajoules, a reduction in water consumption of 22.3 billion liters, and a reduction in CO_2e emissions of 9.3 million Mg. The financial savings ranges from $2.4–7.8 billion. These benefits may increase markedly in the future given the current interest in creating “greener” concrete by increasing the fly ash content, the increased production of FGD gypsum (and corresponding impacts on wallboard manufacturing) that is anticipated as more power plants employ wet scrubbers, and the increased use of fly ash stabilization to reduce cost and increase the service life of roadways.

Table B-16. Summary of Environmental Savings Achieved by Using Fly Ash, Bottom Ash, and FGD Gypsum in each Major Application.

Material	Application	Energy (petajoules)	Water (million liter)	CO_2e (million Mg)
Fly Ash	Concrete	58	4,542	8.7
	Structural Fill	1.6	0.23	0.07
	Road base	2.3	0.34	0.17
Bottom Ash	Structural Fill	0.4	0.04	0.03
	Road base	0.2	0.04	0.01
FGD Gypsum	Wallboard	0.3	17,791	0.03
Landfilling		3.9	Not Known	0.27
Total		66.7	22,334	9.28

B-5 BENEFITS ANALYSES BASED ON EPA REGIONS

The U.S. EPA compartmentalizes the United States into ten regions to assign the responsibilites for several states and territories. For the measurement of regional differences of CCPs production (Figure B-6) and use, environmental benefits for each of the ten regions are evaluated independently based on the ten regions of EPA.

Figure B-7 summarizes the regional break down of the benefits of replacing conventional construction materials with CCPs. Each EPA region has attained different levels of energy savings. There are big discrepancies in the amount of energy saving among the EPA regions. The result reconfirms that the most obvious ways of energy saving are through the use of fly ash in concrete instead of Portland cement.

An analysis about the correlation between energy saving and the amount of annual production of CCPs was conducted and presented in Figure B-8. The result illustrates that CCPs' production has a statistically significant fit (t stat = 3.2) against energy savings (R^2=0.72). Therefore, the amount of energy savings is considered to be closely aligned with the annual amount of CCPs produced by each EPA region.

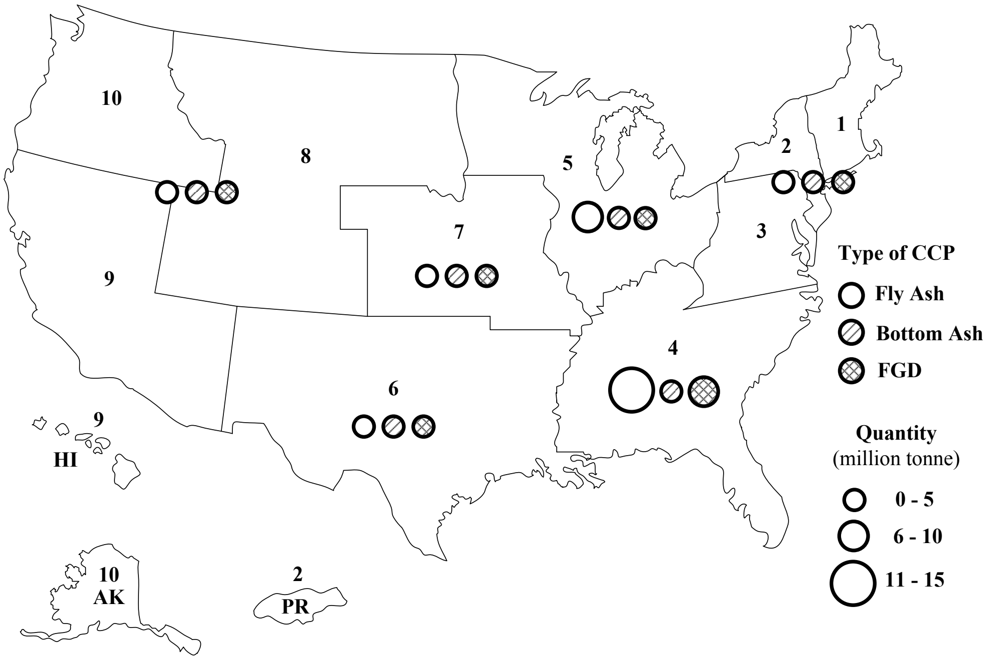

Figure B-6. Regional Distribution of CCPs Generation in 2007.

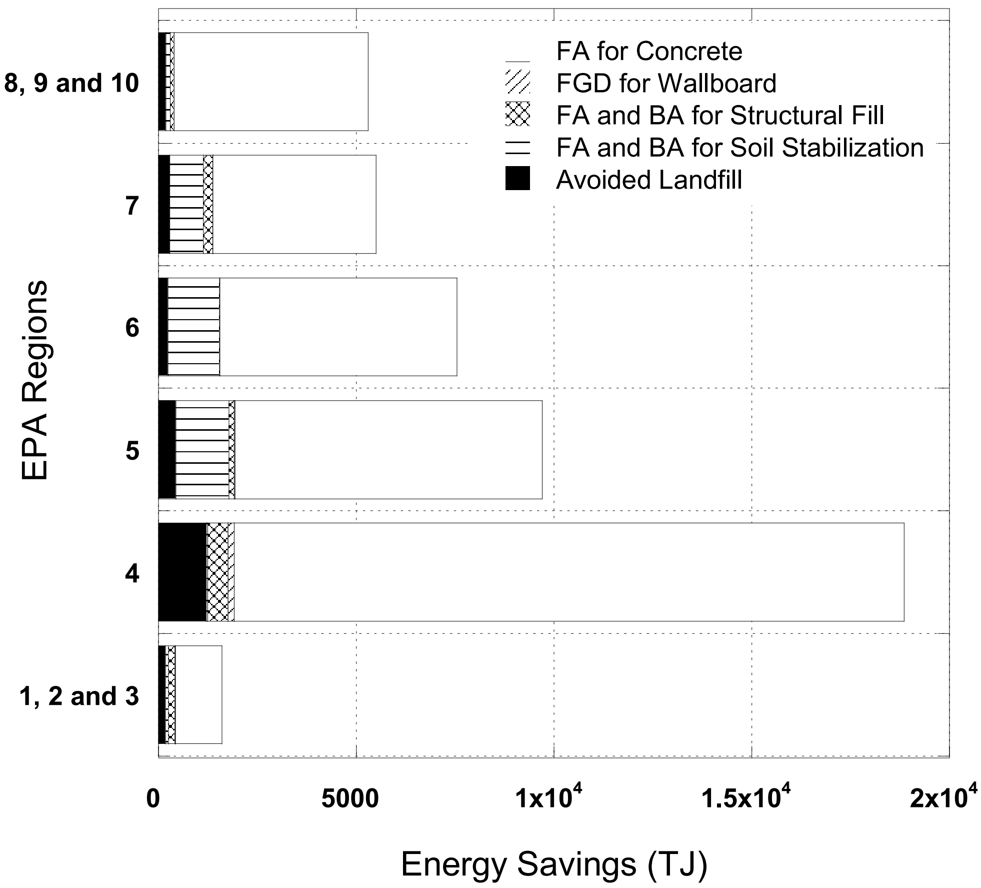

Figure B-7. Regional Comparison of Energy Savings from Beneficial Use of CCPs.

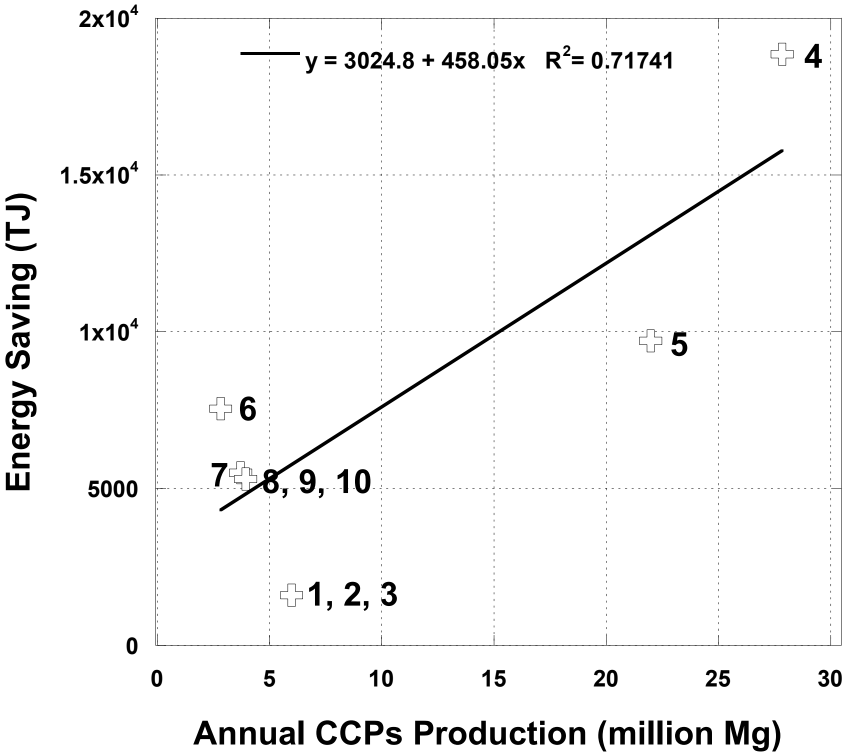

Figure B-8. Energy Savings Compared to the Amount of Annual CCPs Production.

B-6 SUMMARY AND CONCLUSION

This study has quantified the environmental and economic benefits from each major use of fly ash, bottom ash, and FGD in sustainable construction. Savings associated with reductions in energy and water consumption and lower GHG emissions are accrued by offsetting the need for material production (mining and processing). CCPs are byproducts of energy generation and are not produced specifically as a construction material that they can replace. Consequently, the resources embodied in their production are accounted for in electricity production and are expended regardless of whether CCPs are used beneficially.

The total environmental benefits obtained by replacing conventional construction materials with CCPs are remarkable. Annually, approximately 66.7 petajoules of energy is saved, 9.3 million Mg of CO_2e emissions are avoided, and 22.3 billion liters of water are not consumed. These quantities are comparable to the energy used by homeowners in a large US city and the emissions associated with approximately 1.8 million automobiles. The financial savings are large as well - $2.4-7.8 billion is made available for other uses by using CCPs in sustainable construction. These quantities indicate that CCP use in construction contributes significantly to sustainability in the US.

There are many barriers preventing the increased use of CCPs. For example, it is known that concerns about production quality and performance can prevent potential users from using coal ash instead of Portland cement or in concrete products. The concerns are considered to be related more to the conventional terminology than actual performance. The term “recovered mineral content” has a tendency to make some people consider these materials as wastes that are worse in quality than virgin materials (EPA 2008).

The benefit discrepancies in terms of EPA regions could be further evidence indicating the existence of these barriers. As shown in Figure B-8, Region 1, 2, 3, and 5 beneficially used a lower percentage of CCPs. On the contrary, Region 4 and Region 6 used a relatively higher percentage of CCPs. Considering recent efforts by Region 4 to build synthetic gypsum-based wallboard plants near coal-fired power plants, more efforts are required to promote the beneficial use of CCPs in those areas (Region 1,2,3,and 5).

Considering that this study excludes financial benefit due to the saving of material costs and other areas of application (e.g., agricultural application and mine reclamation), removal of the barriers preventing increased use of CCPs can bring enormous additional environmental and economic benefits.

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APPENDIX C

SENSITIVITY ANALYSIS FOR TRANSPORTING CEMENT AND FLY ASH

A sensitivity analysis was conducted to evaluate how differences in transportation distance for cement and fly ash delivery to a ready-mix concrete plant affect energy use and GHG emissions. Transportation distances for cement tend to be longer than those for fly ash due to the more uniform distribution of coal-fired power plants compared to Portland cement productions facilities. The analysis assumed that fly ash was transported 60 mi to the plant and the cement was transported 60 to 100 mi.

The analysis showed that the difference in energy consumption and GHG emissions increases as the transportation difference increases. However, the differences were only approximately 4% at the maximum practical difference in transport distance (100 mi). Thus, the effect of difference in transportation distance was considered negligible relative to other sources of energy use and GHG emissions in this study.

Table C-1. Effect of Difference in Transportation Distance on Energy Consumption When Transporting Cement and Fly Ash to Ready-mix Concrete Plants.

Distance difference = cement – fly ash (mi)	Energy Use (billion Btu)			Energy savings from transportation (%) = (c/49.4) x 100
	Cement (a)	Fly Ash (b)	Difference (c) = a-b	
0	1194.2	1345.9	-151.6	-0.3
10	1393.3	1345.9	47.4	0.1
20	1601.8	1345.9	255.9	0.5
30	1800.8	1345.9	454.9	0.9
40	1999.9	1345.9	654.0	1.3
50	2198.9	1345.9	853.0	1.7
60	2397.9	1345.9	1052.1	2.1
70	2597.0	1345.9	1251.1	2.5
80	2796.0	1345.9	1450.1	2.9
90	2995.0	1345.9	1649.2	3.3
100	3525.8	1345.9	2179.9	4.4

Table C-2. Effect of Difference in Transportation Distance on GHG Emissions When Transporting Cement and Fly Ash to Ready-mix Concrete Plants.

Distance difference = cement – fly ash (mi)	CO_2e Emission (ton)			CO_2e savings from transportation difference (%) = (c/3,270,329 ton) x 10
	Cement (a)	Fly Ash (b)	Difference (c) = a-b	
0	30,166	29,394	772	0.0
10	40,222	29,394	10,828	0.3
20	50,277	29,394	20,883	0.6
30	60,333	29,394	30,939	0.9
40	70,388	29,394	40,994	1.3
50	80,444	29,394	51,050	1.6
60	90,499	29,394	61,105	1.9
70	100,555	29,394	100,555	3.1
80	110,610	29,394	110,610	3.4
90	120,666	29,394	120,666	3.7
100	130,721	29,394	130,721	4.0

APPENDIX D

LCA RESULTS OF GYPSUM MINING

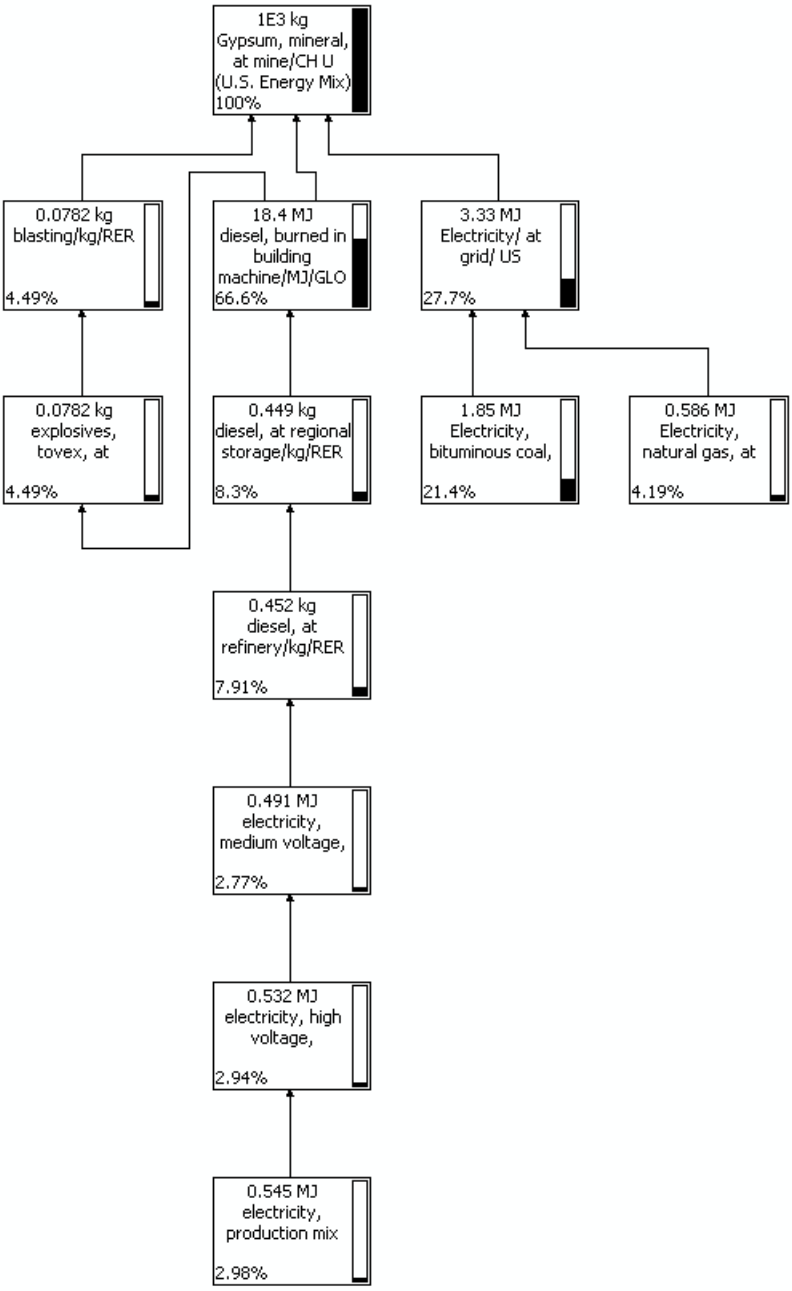

Figure D-1. Network Diagrams for 1,000kg of Gypsum Mining.

Table D-1. The Impact Assessment Result of Energy Consumption.

SimaPro 7.2	Impact assessment	
Project	EPRI	
Title:	Analysing 1E3 kg 'Gypsum, mineral, at mine/CH U (US Energy Mix)'	
Method:	Cumulative Energy Demand V1.07 / Cumulative energy demand	
Indicator:	Characterisation	
Impact category	Unit	Total
Non renewable, fossil	MJ eq	37.0428257
Non-renewable, nuclear	MJ eq	4.032946609
Non-renewable, biomass	MJ eq	9.6449E-05
Renewable, biomass	MJ eq	0.150623664
Renewable, wind, solar, geothermal	MJ eq	0.011947173
Renewable, water	MJ eq	0.261235557

Table D-2. The Impact Assessment of Water Consumption and CO_2e Emission.

SimaPro 7.2	Impact assessment	
Project	EPRI	
Title:	Analysing 1E3 kg 'Gypsum, mineral, at mine/CH U (US Energy Mix)'	
Method:	BEES V4.02	
Indicator:	Characterisation	
Impact category	Unit	Total
Global warming	g CO2 eq	2620.147
Water intake	liters	2400.86

APPENDIX E

CCP PRODUCTION AND USE IN 2007

Table E-1. CCP Production and Use in 2007 (Adapted from ACAA 2008).

Application	Fly Ash	Bottom Ash	FGD Gypsum
	(short ton)	(short ton)	(short ton)
1. Concrete, Concrete Products, Grout	13,704,744	665,756	118,406
2. Blended Cement, Raw Feed for Clinker	3,635,881	608,533	656,885
3. Flowable Fill	112,244	0	0
4. Structural Fills and Embankments	7,724,741	2,570,163	0
5. Road Base/Sub-base Soil Modification and Stabilization	1,234,095	1,116,429	0
6. Mineral Filler in Asphalt	17,223	21,771	0
7. Snow and Ice Control	0	736,979	0
8. Blasting Grit and Roofing Granules	0	71,903	0
9. Mining Applications	1,306,044	165,183	0
10. Gypsum Panel Products	0	0	8,254,849
11. Waste Stabilization and Solidification	2,680,348	7,056	0
12. Agriculture	49,662	2,546	115,304
13. Aggregate	135,331	806,645	70,947
14. Miscellaneous	1,025,724	530,574	11,880
Total CCP Used	**31,626,037**	**7,303,538**	**9,228,271**
Total CCP Produced	**71,700,000**	**18,100,000**	**12,300,000**