Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration

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Abstract: Pavement systems provide critical infrastructure services to society but also pose significant impacts related to large material consumption, energy inputs, and capital investment. A life-cycle model was developed to estimate environmental impacts resulting from material production and distribution, overlay construction and preservation, construction-related traffic congestion, overlay usage, and end of life management. To improve sustainability in pavement design, a promising alternative material, engineered cementitious composites (ECC) was explored. Compared to conventional concrete and hot-mixed asphalt overlay systems, the ECC overlay system reduces life-cycle energy consumption by 15 and 72%, greenhouse gas emissions by 32 and 37%, and costs by 40 and 47%, respectively. Material, construction-related traffic congestion, and pavement surface roughness effects were identified as the greatest contributors to environmental impacts throughout the overlay life cycle. The sensitivity analysis indicated that traffic growth has much greater impact on the life-cycle energy consumption and environmental impacts of overlay systems compared to fuel economy improvements.

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Introduction

While pavements are the central elements of automobile transportation systems, they are significantly deficient in the United States. ASCE report card assigns the U.S. roads a grade of D which means a poor condition. This poor road condition costs U.S. motorists $54 billion a year in repairing and operating costs. An estimated $375.5 billion in highway money is needed over the next 5 years to maintain and improve current conditions (ASCE 2006).

As the pavements age and deteriorate, maintenance and rehabilitation are required to provide a high level of safety and service (Huang 2004). For pavements subjected to heavy traffic, one of the most prevalent rehabilitation strategies is the placement of an overlay on top of the existing pavement (DOT 1989). An overlay provides protection to the pavement structure, reduces the rate of pavement deterioration, corrects surface deficiencies, and adds some strength to the existing pavement structure. Depending on the type of overlay and existing pavement, two possible designs are generally used: an unbonded concrete overlay or a hot-mixed asphalt (HMA) overlay. An unbonded concrete overlay is typically placed over a pavement which is badly cracked. A separation layer, usually consisting of asphalt less than 50 mm thick, is placed between the new concrete overlay and the cleaned existing pavement to prevent reflective cracking [American Concrete Pavement Association (ACPA) 1990]. An HMA overlay usually has several layers with the different mixes of HMA (Huang 2004). Concrete and asphalt are the most common materials used in the construction of pavement and overlay systems. Nearly 57% of the mileage of interstate highways and other freeways is either concrete surface or concrete base, while other highways, rural roads, or urban streets are asphalt surface [Horvath and Hendrickson 1998; Federal Highway Administration (FHWA) 2007]. The use of both concrete and asphalt pose significant environmental challenges. The worldwide production of cement, a key constituent in concrete, releases more than 1.6 billion metric tons of CO_2 annually, accounting for over 8% of total CO_2 emissions from all human activities (Wilson 1993), and significant levels of other pollutants, such as particulate matter and sulfur oxides (Estakhri and Saylak 2005). Asphalt, a petroleum by-product, is energy intensive which contains 7,613 MJ of feedstock energy per cubic meter (The Athena Institute 2006). Asphalt is also a large source

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of volatile organic compounds (VOCs) accounting for 200,000 t of VOC emissions each year in the United States from asphalt pavement construction (Spivey 2000). Additionally, concrete and asphalt have some physical limitations that contribute to durability concerns, which increase the likelihood of pavement failure and preservation (maintenance and rehabilitation) frequency. Consequently, alternative materials are being developed to improve road performance. Part of the process to introduce new materials into application includes evaluation of the environmental impacts at each stage of the material life cycle from resource extraction through manufacturing, transportation, construction, and final disposal.

Life-cycle assessment (LCA) is an analytical technique for assessing these potential environmental burdens and impacts. LCA provides metrics that can be used to measure progress toward environmental sustainability (Keoleian and Spitzley 2006).

Two approaches have been used in previous LCA studies of pavement. One approach uses a process level LCA method to trace the energy consumption and related environmental impact of the system (Zapata and Gambatese 2005). The other approach is the economic input-output analysis-based life-cycle analysis (EIO-LCA) method, developed by Carnegie Mellon University's Green Design Initiative. This method traces the various economic transactions for various sectors and uses an economic input-output matrix of the U.S. economy to evaluate resource requirements and environmental emissions (Horvath and Hendrickson 1998).

A number of researchers and practitioners have applied life-cycle analysis to study pavement. The University of Texas at Austin performed a life-cycle cost assessment which is an engineering-economic analysis tool used to quantify the differential costs of alternative investment options for a given project, to evaluate concrete pavement (Wilde et al. 2001). Horvath and Hendrickson used the EIO-LCA model to study the environmental impacts of asphalt and steel-reinforced concrete pavements. Few researchers evaluated the impacts of maintenance activity and pavement surface roughness on highway users. The Swedish Environmental Research Institute conducted an LCA of concrete and asphalt pavements based on process flows, including pavement construction, maintenance, and operation (Stripple 2001). Athena Institute incorporated pavement roughness in the evaluation of concrete and asphalt pavements performance (The Athena Institute 2006). This research did not address the changes in roughness over time due to deterioration and the related dynamic effects on highway users' fuel consumption and environmental impacts.

The life-cycle model in this study was developed to simulate and evaluate the life-cycle energy consumption and environmental impacts of pavement overlay systems. This model was applied to an alternative material, engineered cementitious composites (ECC), to analyze its environmental sustainability performance.

ECC is a unique fiber-reinforced composite developed using a microstructural design technique guided by micromechanical principles. ECC is deliberately designed as a fiber-reinforced cementitious material with a deformation behavior analogous to that of metals (Li and Fischer 2002). Experimental testing of ECC overlays reveals significant improvements in load-carrying capacity and system ductility compared to concrete or steel fiber-reinforced concrete overlays (Li et al. 2008). Thereby, ECC can decrease common overlay system failures such as reflective cracking (Li 2003). Since the introduction of this material a decade ago, ECC has undergone a major evolution both in the academic and industrial communities (Li 2002). ECC is a promising candidate material for road repairs, pavement overlays (Li 2003), and bridge deck rehabilitation (Gilani 2001). A demonstration bridge project was constructed in the fall of 2005 to provide performance data on ECC field applications. In this demonstration project, an ECC link slab was applied to substitute the conventional steel expansion joint between two steel-reinforced concrete bridge decks. The project site is Grove Street over Interstate 94 (S02 of 81063) in Ypsilanti, Michigan. An LCA model for this ECC bridge link slab application has been constructed (Keoleian et al. 2005).

The objective of this research is to develop an LCA model to enhance pavement overlay design and evaluate the long-term environmental performance of overlay systems by simulating the impacts of users, construction, and roadway deterioration. In the following section, the system boundary is defined and the LCA models are described. Subsequently, the life-cycle model is applied to evaluate the potential environmental impacts of ECC overlay system. To consider the potential benefit of the ECC overlay system, conventional unbonded concrete and hot-mixed asphalt overlay systems are also evaluated as a benchmark. Finally, sensitivity analysis is performed for different traffic growth rates and fuel economy improvement scenarios.

Methodology

To evaluate environmental performance of an overlay system from raw material acquisition to overlay disposal, an LCA model has been created. The LCA model is divided into six modules: material production, construction, distribution, traffic congestion, usage, and end of life (EOL). Environmental impact categories include energy and material resource consumption, air and water pollutant emissions, and solid waste generation. The environmental impacts of the existing pavement, a severely deteriorated concrete pavement, are excluded from this study because they are common to each system compared.

System Definition

The overlay designs analyzed in this study are constructed upon an existing reinforced concrete pavement originally built by the Michigan DOT (MDOT). The overlay system is modeled as 10 km long and four lanes wide (two lanes in each direction). The thickness of ECC overlay is 100 mm and designed service life is 40 years. This design is based on the results from an experimental study conducted by University of Michigan's Department of Civil and Environmental Engineering (Qian 2007). The ECC overlay is designed for ultrahigh ductility and damage tolerance, resulting in a thin and durable overlay. With a tensile stress-strain curve which resembles that of ductile metal, this approach directly builds in a mechanically autoadaptive behavior in which the ECC steps down in material stiffness by undergoing an elastic-inelastic transition when overstressed in tension/bending, but without giving up the load-carrying capacity. This proposed solution exploits the ultra ductility and high damage tolerance of ECC, without relying on stress relieving interlayer (Qian 2007). Under fatigue loading test, ECC shows great enhancement in fatigue stress-fatigue life relation when compared with concrete currently used by MDOT. Under the same fatigue stress level, the fatigue life of ECC is at least nine orders of magnitude higher when compared with concrete. This test indicated that the introduction of ECC will greatly enhance the service life of concrete pavement overlay. The fatigue life of pavement overlay is then converted to

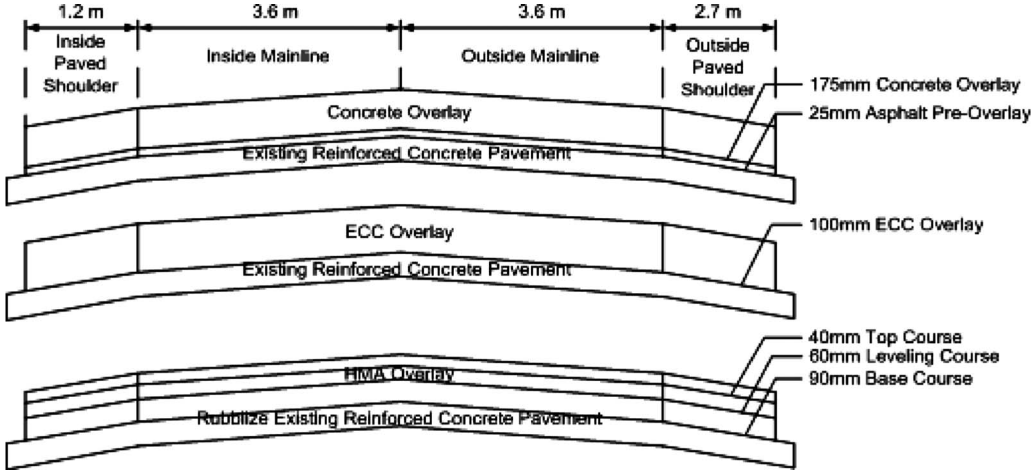

Fig. 1. Overlay structure and thickness in one direction

equivalent single-axle load (ESAL) assuming 70,000 annual average daily traffic (AADT) with 8% heavy duty trucks and up to 5% annual growth rate. For this case, the total number of ESAL derived is 8×10^7 for a 40 year service life ECC overlay (Qian 2007). Other aspects of ECC material properties including thermal stress can be found in Qian (2007). A 200-mm-unbonded concrete overlay and 190-mm HMA overlay with 20-year service life is also studied in this research for comparison with ECC overlay. The thickness and service life design of these conventional overlay systems are based on the MDOT pavement design manual [Michigan DOT (MDOT) 2005]. Fig. 1 illustrates the structures of the different types of the overlay systems in one direction including the thickness of different layers.

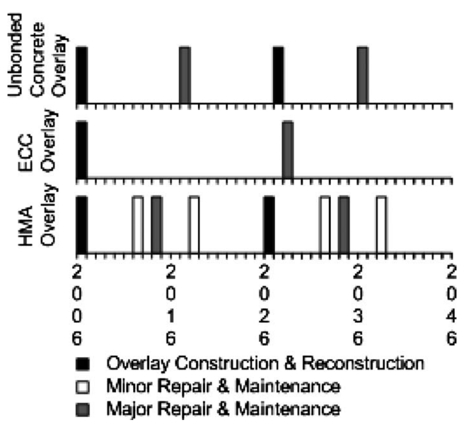

Fig. 2. Timeline and maintenance schedule for construction activities

Fig. 2 shows the construction and preservation schedule for the three overlay systems. The base case assumes that all construction and preservation event are conducted during daytime. The construction and preservation schedule for concrete and HMA overlay systems were developed based on MDOT service life models and previous analysis results [Michigan DOT (MDOT) 2005]. For ECC overlay, the preservation schedule assumes a single repair event in the middle of its service life. This result is based on the fact that ECC prevents commonly observed overlay failure modes, such as reflective cracking (Li 2003). The reflective cracking resistance mechanism of ECC overlay has been experimentally confirmed and is reported by Qian (2007). A demonstration bridge deck link slab in Michigan and a completely jointless ECC/steel composite bridge deck in Japan also support this mechanism (Lepech 2006). More details on the development of the preservation schedule for ECC overlay can be found in Qian (2007). The total material consumption over the entire life cycle for the three systems is provided in Table 1, along with the energy intensity of each material and the source of life-cycle inventory data for each material.

Table 1. Total Material Consumption in Each Overlay System and Associated Data Sources

Material	Concrete overlay (Mt)	ECC overlay (Mt)	HMA overlay (Mt)	Energy intensity (MJ/kg)	Sources
Portland cement	26,789	15,749	0	4.5–6.6	Portland Cement Association (PCA) 2002
Gravel	88,605	0	0	0.11	SimaPro 6.0
Sand	66,861	12,616	39,292	0.11	SimaPro 6.0
Fly ash	4,042	19,299	0	0	Fly ash is a by-product of power plant, so no energy intensity is allocated in this study
PVA fiber	0	702	0	101	Keoleian and Kendall 2005
Super plasticizer	0	473	0	35.2	Keoleian and Kendall 2005
Asphalt	900	0	15,112	14.5	SimaPro 6.0
Crushed aggregate	9,986	0	167,630	0.21	SimaPro 6.0
Limestone	623	0	10,462	0.08	SimaPro 6.0

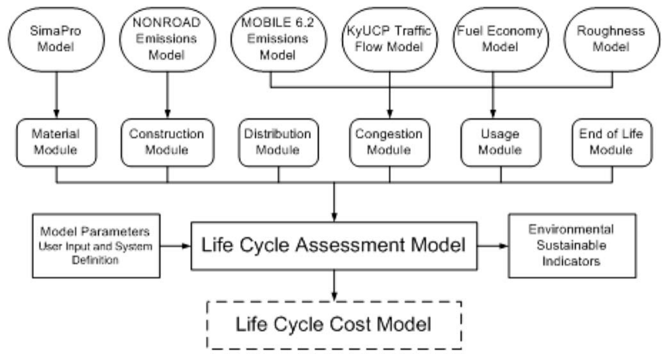

Fig. 3. Logic relationship between LCA component

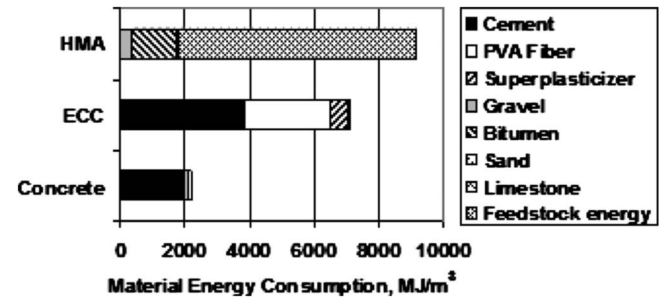

Fig. 4. Primary energy consumption per volume of each material

Life-Cycle Assessment Model

To simulate the service life of pavement overlay systems, an LCA model is developed. As shown in Fig. 3, The LCA model is divided into six modules: material production, consisting of the acquisition and processing of raw materials; construction, including all construction processes, preservation activities, and related construction machine usage; distribution, accounting for transport of materials and equipment to and from the construction site; traffic congestion, which models all construction and maintenance related traffic congestion; usage, including overlay roughness effects on vehicular travel and fuel consumption during normal traffic flow; and EOL, which models demolition of the overlay and processing of the materials.

The material consumption phase is modeled using data sets from various sources including the Portland Cement Association, the Athena Institute, and the SimaPro 6.0 life-cycle database. The data fields supplied by the manufacture are total primary energy consumption, carbon dioxide emissions, NO_x emissions, SO_x emissions, VOC, biological oxygen demand (BOD) discharge, chemical oxygen demand (COD) discharge, and waterborne suspended matter. The modeled material compositions of concrete, HMA, and ECC are shown in Table 2.

The total primary energy contribution per volume for each material constituent is shown in Fig. 4. The primary energy consumption for concrete, ECC, and HMA is 2,212, 7,103, and 9,142 MJ/m^3, respectively. In the case of HMA, although the asphalt is only 7% of HMA by volume, the feedstock energy (7,613 MJ/m^3 HMA) contained in the asphalt binder accounts for 80% of the total energy consumed in HMA production. However, the feedstock energy contained in the asphalt binder is a by-product from petroleum refinery and is hardly used in other applications. In comparing ECC and concrete, ECC contains a large amount of fly ash (34% of ECC by volume compared to 2.0% of concrete), which is a by-product of coal consumption. Consequently, there is no environmental burden or energy consumption from coal consumption allocated to this substitute. Fly ash typically comes from coal-fired electricity generation plants in remote locations. The impact of fly ash transportation is modeled in the distribution module. Fly ash was not considered for wide use in conventional concrete due to code restrictions in Michigan policy regarding concrete used in pavements. The particular ECC mix used in this study contains twice as much cement per volume compared to concrete (28% compared to 14%), which accounts for the higher energy intensity for ECC. Additionally, poly-vinyl-alcohol (PVA) fiber (1.2% of ECC by volume) also contributes to a major portion of energy in the production of ECC (36% of total energy consumption).

The distribution module is closely linked to the material and EOL modules. All the materials, equipment, and wastes are transported by a combination of roadway, railway, and waterway.

Table 2. Material Composition of Concrete, ECC, and HMA (per Unit Volume)

	Concrete (%)	ECC (%)	HMA (%)
Cement	14	28	
Fly ash	2.0	34	
Gravel	45		71
Sand	32	22	17
PVA Fiber		1.2	
Superplasticizer		0.8	
Bitumen			7
Limestone			5
Water	7.0	14	

Table 3. Distribution Distance and Assumptions

Materials	km	Truck (%)	Train (%)	Tanker (%)	Assumptions
Cement plant to concrete mixer	42	100	0	0	Local
Concrete mixer to site	10	100	0	0	Local
Sand source to site	80	100	0	0	Local
Gravel source to site	80	100	0	0	Local
Water source to site	5	100	0	0	Local
Fly ash source to site	2,333	5	95	0	From San Antonio, Texas to Ann Arbor, Mich.
PVA fiber source to site	12,427	2	27	71	From west coast to Michigan
Bitumen source to site	40	100	0	0	Local
Site to landfill	34	100	0	0	From Ann Arbor, Mich. to Northville, Michigan

Table 4. Total Equipment Usage during Construction Activities in Hours

Equipment	Power (kW)	Concrete system	ECC system	HMA system
Crawler-mounted hydraulic excavator	320	256	128	256
Air compressor	260	128	64	128
Dumper	17	336	192	288
Hydraulic hammer	75	160	64	128
Motor grader	123	32	32	32
Water truck	335	64	64	64
Vacuum truck	132	64	64	64
Wheeled front-end loader	175	416	192	384
Signal boards	4	65,338	35,404	79,401
Concrete paver	186	662	435	0
Concrete truck	223	662	435	0
Resonant breaker	447	0	0	200
Asphalt paver	150	56	0	902
Asphalt roller	93	16	0	310
Asphalt truck	223	56	0	843

Table 3 shows the distribution distance and assumptions. The environmental impacts for distribution include both fuel production for transportation vehicles and their emissions.

In the construction module, the operating time of the equipment during construction events is estimated by using previous construction project documents from MDOT and the production rate of each machine. The fuel-related emissions from this equipment are assessed using the U.S. EPA NONROAD2005 model of diesel engine emissions for Michigan (U.S. EPA 2005). The equipment used in this study is presented in Table 4. Fuel usage is obtained from the NONROAD2005 model and the upstream process impacts for this fuel are calculated by using SimaPro 6.0 fuel production data.

The traffic congestion considered in this study is caused only by the construction and preservation activities. The changes in traffic flow and congestion are estimated using the KyUCP model [Kentucky Transportation Center (KTC) 2002]. The delays are calculated using model input parameters such as AADT, work zone speed limits, lane capacity, detour distance, and the number of lane closures during construction. The AADT is approximately 70,000 vehicles with 8% heavy duty trucks [Michigan DOT (MDOT) 1997]. In the baseline scenario, the annual traffic growth rate is 0%. To facilitate partial-width construction, only one lane in each direction will be closed during all construction events. Speed limit is reduced from 105 km/h to a work zone speed of 65 km/h. In this scenario, 12% of drivers are assumed to self-detour 2.5 km on nonhighway roads, thus resulting in slower travel speeds (65 km/h) and longer travel distances (Keoleian et al. 2005).

Once vehicle delay and congestion due to construction and maintenance events are calculated, these results are coupled with fuel consumption and vehicle emissions to measure environmental impacts. Fuel consumption is determined using fuel economy estimated by city and highway drive cycles. The city drive cycle is used to estimate the fuel consumption during congestion and detour modes. Likewise, the highway drive cycle is used to model the normal traffic flow during free flowing traffic periods. Vehicle fuel economy is taken from the U.S. EPA fuel economy guide (U.S. EPA 2006). Carbon dioxide (CO_2) emissions are derived using fuel consumption, carbon content, and engine efficiency. Other vehicle emissions are calculated using U.S. EPA's MOBILE 6.2 software at varying traffic speeds. MOBILE 6.2 is used to predict the tailpipe emissions and evaporative emissions on a per year basis through 2050 (U.S. EPA 2002). Four localized MOBILE 6.2 data inputs for the winter and summer seasons used in this study include annually temperature range, Reid vapor pressure, age distribution of the vehicle fleet, and average vehicle miles traveled data [Southeast Michigan Council of Governments (SEMCOG) 2006]. The output results of fuel consumption and vehicle emissions in the LCA model are calculated using Eq. (1) based on the difference between traffic flow during construction periods and traffic flow during normal conditions. VMT_x represents the total vehicle miles traveled under normal, highway, work zone, detour, and queue conditions. Y_x represents the marginal change for different environmental indicators, such as emission values (g/km) and fuel usage (L/km)

$$\begin{aligned} Y_{\mathrm{Total}} &= \mathrm{VMT}_{\mathrm{Highway}} \times Y_{\mathrm{Highway}} + \mathrm{VMT}_{\mathrm{Queue}} \times Y_{\mathrm{Queue}} \\ &\quad + \mathrm{VMT}_{\mathrm{Work\ zone}} \times Y_{\mathrm{Work\ zone}} + \mathrm{VMT}_{\mathrm{Detour}} \times Y_{\mathrm{Detour}} \\ &\quad - \mathrm{VMT}_{\mathrm{Normal}} \times Y_{\mathrm{Normal}} \end{aligned} \tag{1}$$

For pavement infrastructure with a long service life cycle, the output results are highly dependent on future changes in fuel economy and annual traffic growth rate. This effect will be discussed in the scenario analysis section.

The traffic congestion module predicts how construction activities affect traffic flow and emissions. The usage module describes the effects on traffic during normal operation of the overlay section, and this module is significantly more complex than the other modules. There are two primary factors which effect fuel consumption and vehicle emissions: fuel economy changes and pavement roughness changes over time.

In this model, the fuel economy of a heavy duty truck combining cost-effective conventional improvements with hybridization is predicted to save 32% of total energy consumption over a 20-year period (Langer 2004). This is described by Eq. (2)

$$\mathrm{FE}_n = \mathrm{FE}_{\mathrm{base}} \times (1+r)^n \tag{2}$$

FE_n=heavy duty truck fuel economy factor for nth year and $\mathrm{FE}_{\mathrm{base}}$=2003 baseline heavy duty truck fuel economy factor which is presented in the Vision model [U.S. DOE 2004]. The Vision model is developed by U.S. DOE to provide estimates of the potential energy use, oil use, and carbon emission impacts to 2050 of advanced light and heavy duty vehicle technologies and alternative fuels. The value r=annual fuel economy improvement, estimated at 1.5% fuel consumption savings per year due to increased boosting, improved combustion control and other design changes.

For passenger cars and other light duty vehicles, there are two methods to estimate future fuel economy trends. The first method is also described by Eq. (2). In this case, $\mathrm{FE}_{\mathrm{base}}$ is the 2003 baseline car and light duty vehicle fuel economy. The value r is estimated at 1% fuel consumption savings per year (Davis and Diegel 2002), based on fuel economy trends from 1995–2005. The second method is based on a model of future performance of the internal combustion engine over a 30-year time horizon (Heywood et al. 2004) shown as Eq. (3). The time period is extrapolated to 40 years to match the service life of the three overlay system. In this equation, n_0 and n are the initial year and the nth year of this project, respectively

$$\begin{aligned} \mathrm{FE}_n &= -4.96 \times 10^{-4} \times (n-n_0)^3 + 4.08 \times 10^{-2} \times (n-n_0)^2 - 2.28 \\ &\quad \times 10^{-1} \times (n-n_0) + 1.88 \times 10^{-1} + \mathrm{FE}_{\mathrm{base}} \end{aligned} \tag{3}$$

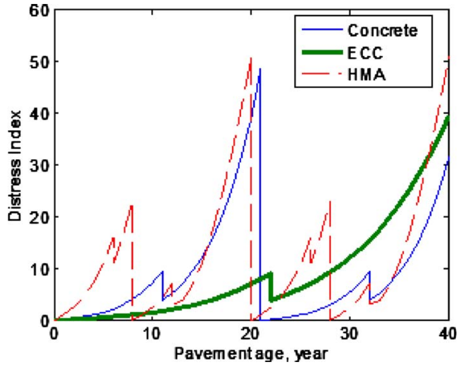

Fig. 5. Distress index of each pavement

Due to surface deterioration, the overlay surface roughness increases continuously over time. Roughness is generally defined as an expression of road surface irregularity which affects the operation of a vehicle, including speed of travel, fuel economy, emissions, and safety. Hence, it also impacts vehicle operation costs and maintenance costs. Roughness is often measured using the international roughness index (IRI), which was developed by the World Bank in the 1980s (Sayers et al. 1986). The IRI is a ratio of a standard vehicle's accumulated suspension motion (in millimeters, inches, etc.) divided by vehicle distance traveled during the measurement (kilometers, miles, etc.). The commonly recommended unit of IRI is meters per kilometer (m/km) (Sayers and Karamihas 1995). The IRI describes a linear scale of roughness beginning with 0 m/km for a perfectly flat surface and no theoretical upper limit, although IRI values above 8 m/km means driving uncomfortably and reducing the speed. (Archonodo-Callao 1999).

The pavement deterioration trend of the concrete and HMA overlays was derived from MDOT pavement design manual [Michigan DOT (MDOT) 2005]. Currently, there is no deterioration data of full-scale field test of the ECC overlay. By suppressing reflective cracking, modeling indicates that the ECC overlay deteriorates two times slower than the concrete overlay (Qian 2007). In Michigan, a distress index (DI) is used to gauge pavement conditions including surface roughness and deterioration. A set of plots showing the evolution of DI for each overlay over time is shown in Fig. 5. As can be seen, the distress of overlay decreases from individual maintenance activities (Fig. 2).

DI does not have a direct impact on vehicle energy consumption and environmental impacts. Thus, the relationship between DI and IRI for the concrete and HMA overlays was established through Eq. (4) and Eq. (5), respectively (Lee et al. 2002). An extremely conservative assumption is made based on the fatigue loading tests and FEM simulations that the IRI and DI of the ECC overlay has the same relationship as the concrete overlay (Qian 2007)

$$\mathrm{IRI} = \left(\frac{16.44\mathrm{DI}}{35 - \mathrm{DI}}\right)^{0.30} \tag{4}$$

$$\mathrm{IRI} = \left(\frac{26.84\mathrm{DI}}{35 - \mathrm{DI}}\right)^{0.308} \tag{5}$$

The WesTrack project has tested the impact of roadway roughness on the fuel consumption of heavy duty trucks (Epps et al. 1999). The result showed that the fuel economy decreased from 4.4 to 4.2 mpg while the IRI increased from 1.2 to 2.4 m/km. Based on this result, a linear equation is developed to represent the relationship between fuel consumption and road surface roughness. A sensitivity analysis was conducted in the following section to address the uncertainty of the relationship of fuel consumption and IRI

$$\mathrm{FCF} = 0.0397 * \mathrm{IRI} + 0.9524 \tag{6}$$

where FCF = fuel consumption factor (greater than 1.0).

Using this fuel consumption factor (FCF), the total fuel consumption can be assessed by multiplying the ideal fuel consumption on a perfectly smooth overlay by the FCF. The final result is expressed as the difference between fuel consumed during vehicle operation on a rough overlay and on an ideally smooth overlay.

To estimate effect of roughness on emissions, both driving behavior and engine load are considered. Most drivers slow down when driving on a rough road. The World Bank classifies "comfortable riding conditions" as up to 80–95 km/h when the IRI is 3.5–4.5 m/km (Archonodo-Callao 1999). The speed adjustment factor S based on average running speed and IRI is described by Eq. (7) (Wilde et al. 2001)

$$S = 4.3065e^{(0.52 - 0.26\mathrm{IRI})^{0.0928}} \tag{7}$$

Roughness changes affect highway capacity due to speed reduction. Highway capacity decreases approximately 150 passenger car units per hour per lane as IRI increases by 1 m/km (Chandra 2004). This lane capacity change directly determines queue formation and detour selection assessed through the KyUCP model. Operating emissions for a vehicle traveling on a rough overlay versus on a smooth overlay are calculated using the speed adjustment factor and the lane capacity change factor.

Another source of increased vehicle emissions is engine load changes owing to increased friction and vertical acceleration of the vehicle body caused by additional roughness. To estimate emissions produced by engine load change a typical torque curve for an engine (Tunnell and Brewster 2005) was used. Within the region of maximum torque, there is an area designated the not-to-exceed (NTE) zone. The U.S. EPA defines the NTE zone to control heavy-duty engine emissions over the full range of speed and load combinations commonly experienced during vehicle operation. Inside this zone, under the maximum torque curve of an engine the emissions must not exceed a specified value for any of the regulated pollutants.

Because of the constraints imposed by NTE limits, a constant emission rate (in grams of emission per liter of fuel burned) is assumed for a typical speed of operation (90–105 km/h) of a truck (Tunnell and Brewster 2005). Any additional emissions produced as a result of engine load increasing can be estimated as proportional to the fuel consumption increase calculated by Eq. (6).

In the EOL module, the base case assumes that all material is deposited in a landfill. The concrete pavement is not widely recycled. Only 3 million metric tons of concrete pavements are reclaimed annually because that concrete pavements are often rubbleized or cracked in the construction site and used as a base for a new asphalt overlay (Horvath and Hendrickson 1998). Reclaimed concrete material (RCM) can be used as coarse or fine aggregate in concrete pavements. However, incorporating more than 10–20% fine RCM aggregates into the concrete mix can decrease the quality of concrete because of the high amount of water required to maintain adequate workability of the concrete mix [Federal Highway Administration (FHWA) 2008]. Asphalt can be recycled around 80% into highway applications (Horvath and Hendrickson 1998). Reclaimed asphalt pavement (RAP) is now routinely accepted in asphalt paving mixtures as an aggre-

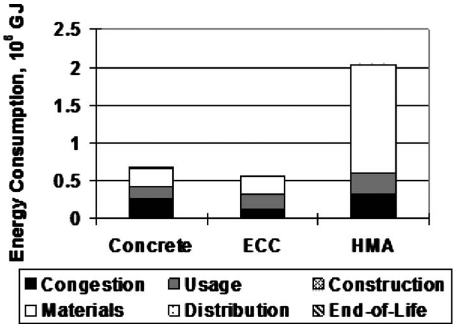

Fig. 6. Total primary energy consumption by life-cycle phase

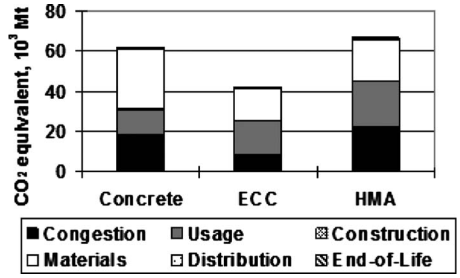

Fig. 7. Greenhouse gas emission by life-cycle phase

gate substitute and as a portion of the binder. Substitution rates ranges from 10 to 50% or more, depending on state specifications. However, asphalt mixes incorporating more than about 20% RAP can suffer a reduction in quality. Additionally, the application of RAP requires special processing equipments and quality control procedures [Federal Highway Administration (FHWA) 2008]. In the future, an LCA model is necessary to evaluate the environmental impacts of possible recycle procedures of concrete and asphalt materials. Information detailing the demolition process was obtained from professional construction contractor, including machinery and construction process requirements. ECC material with the PVA fiber in it follows the same recycle procedure as other plastic fiber-reinforced concrete. The disposal materials transported from the construction site to landfill site are modeled in the same method as the distribution module.

Life-Cycle Environmental Impacts

Total life-cycle results represent the environmental inventory and impacts from the material module, construction module, distribution module, traffic congestion module, usage module, and EOL module over the 40-year life cycle. The environmental indicators in this study include energy consumption, global warming potential, air pollutant emissions, and water pollutant emissions.

Energy Consumption

Primary energy consumptions for 10 km of the concrete overlay, ECC overlay and HMA overlay are 6.8×10^5, 5.8×10^5, and 2.1×10^6 GJ, respectively. The primary energy consumption by stage is shown in Fig. 6. The life-cycle energy consumption for three systems is dominated by material production energy, traffic congestion related energy, and roughness related energy. Roughness related energy has not been previously studied using LCA. Without considering the roughness effects, the life-cycle energy consumptions of concrete, ECC, and HMA overlay systems will decrease 23, 36, and 14%, respectively.

Due to the superior material properties of ECC which can double its service life compared to the other overlay materials, the simulation result shows that ECC overlay uses about 15 and 72% less energy than the concrete overlay and the HMA overlay, respectively. The high energy consumption for the HMA overlay is caused by the high feedstock energy contained in asphalt which accounts for 30% of the total life-cycle primary energy consumption for the HMA overlay system. Athena Institute reported that the inclusion of 20% RAP in the asphalt mix can reduce 5.0–7.5% of embodied primary energy usage of HMA pavement (The Athena Institute 2006). While this reduction decreases the energy use of HMA pavement, the gap between HMA and other materials are still significant.

Greenhouse Gas Emissions

Greenhouse gas (GHG) emissions inventoried in this study include CO_2, methane, and nitrous oxide. The global warming impact is characterized by GHG emissions in metric tons of CO_2 equivalent. This is calculated by multiplying the mass of each GHG emission by its global warming potential (GWP), where GWP is 1 for CO_2, 23 for methane, and 296 for nitrous oxide (Houghton 2001). Fig. 7 shows the global warming impact of each overlay system.

CO_2 emissions significantly dominate the contribution to global warming impact. In the concrete overlay system CO_2 represents 99.2% of total life-cycle GWP, in the ECC system CO_2 represents 99.4% of total life-cycle GWP, and in the HMA system CO_2 represents 94.4% of total life-cycle GWP. The ECC system reduces GHG emissions by 32 and 37% compared to the concrete overlay system and HMA overlay system, respectively. Generally, CO_2 emission reflects energy consumption; however, cement production releases CO_2 during calcination of limestone. Additionally, a large amount of primary energy consumption in the HMA overlay system is the feedstock energy. Carbon embodied in the material is fixed and does not generate CO_2 unless it is burned. This relationship is evident in the comparison of Figs. 6 and 7 wherein the CO_2 emissions of the HMA overlay system are not significantly higher than the other two systems.

Air Pollutant Emissions

Other air pollutant emissions in addition to the GHG emissions in this analysis include nitrogen oxides (NO_x), sulfur oxides (SO_x), nonmethane hydrocarbons (NMHC), particulate matter ($PM_{2.5}$), carbon monoxide (CO), and VOCs. Fig. 8 presents these air pollutant emissions by life-cycle stage.

In most cases, material phase related emissions dominate total pollutant emissions. The emissions of NO_x and CO show negative values for the traffic congestion module and usage module for all systems resulting from NO_x and CO production being greater at high speeds than at low speeds. While most pollutants increase with congestion and overlay deterioration, NO_x and CO emissions decrease (Sher 1998). The large VOC emissions associated with the HMA overlay system result from the evaporation of petroleum distillate solvent, or diluent, used to liquefy the asphalt cement during construction and maintenance events. VOC emissions occur at both the construction site and the mixing plant. The road surface emissions at the construction site are the largest source of

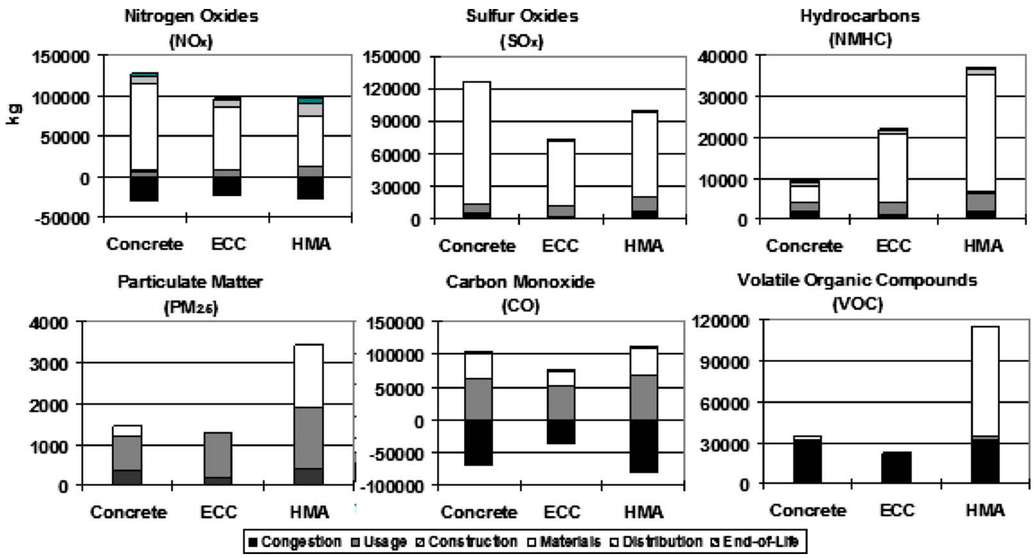

Fig. 8. Air emissions by life-cycle phase

emissions and an emission which can last for 4 months (USEPA 2001). In this study, these emissions are assumed as an instantaneous emission which is grouped within liquefied asphalt emissions.

Water Pollutant Emissions

Water pollutant emissions including BOD, ammonia, phosphate emissions, and dissolved matter as a function of life cycle are shown in Fig. 9.

For both BOD and ammonia emissions, the use phase has a significant effect on total emissions. However, the PVA fiber used in ECC overlay system and asphalt used in the HMA overlay system are also responsible for large BOD emissions and ammonia emissions, respectively. For phosphate and dissolved matter emissions, the material phase overwhelmingly dominates the total emissions.

Table 5 summarizes the life-cycle inventory results. The environmental impacts of the ECC overlay system are listed in the

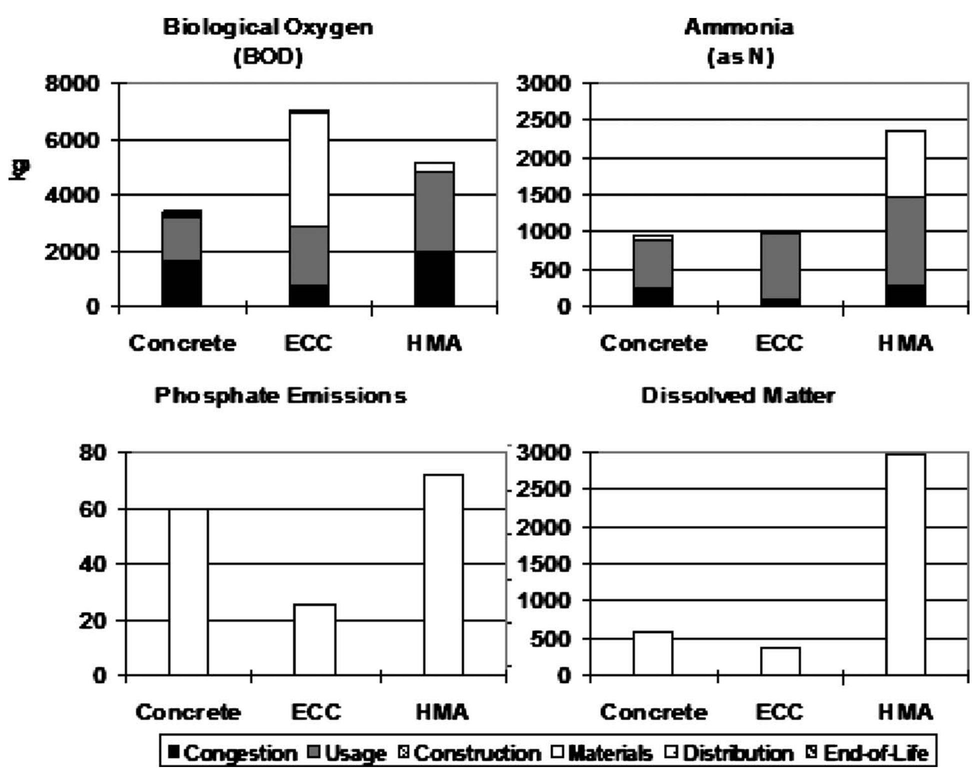

Fig. 9. Water pollutant emissions by life-cycle phase

Table 5. Summary of Life-Cycle Inventory and Impact Results

Item	ECC	Concrete (%)	HMA (%)
Total primary energy consumption (GJ)	5.8×10^5	−15	−72
GHG (mt)	4.2×10^4	−32	−37
Carbon monoxide (kg)	4.2×10^4	+19	+30
VOC (kg)	2.2×10^4	−34	−81
NMHC (kg)	2.2×10^4	+137	−41
$PM_{2.5}$ (kg)	1.3×10^3	−11	−63
NO_x (kg)	7.3×10^4	−26	+6
SO_x (kg)	7.3×10^4	−42	−27
Ammonia (kg)	1.0×10^3	+5	−58
BOD (kg)	7.0×10^3	+102	+36
Dissolved matter (kg)	3.8×10^2	−36	−87
Phosphates (kg)	25.5	−57	−64

table along with percentage changes relative to concrete and HMA overlay systems.

Sensitivity Analysis

The LCA model was applied to simulate the service life of concrete, ECC, and HMA overlay systems. Several assumptions and generalizations were made regarding preservation schedule, traffic pattern, and overlay surface deterioration. Thus, significant level of uncertainty was introduced into the model. Sensitivity analysis was performed on several key assumptions.

The results discussed above assume a baseline scenario which has no traffic flow growth or fuel economy improvements over time. Traffic growth will affect traffic related energy consumption and pollutant emissions by increasing total vehicle miles traveled and congestion. Fig. 10 shows that the traffic related energy consumption (traffic congestion and roughness effects) increases significantly when the annual traffic growth rate increases from 0 to 2%. At 2% traffic growth, traffic related energy consumption increases to more than 3.4, 3.1, and 3.7 times compared to the 0% growth levels for the concrete, ECC, and HMA overlay systems, respectively. However, under a 2% growth rate, the congestion queue increases significantly (longer than 15 km) due to high traffic volume in year 2046. This unrealistic queue length is a product of the inability of the model to account for the potential increase of highway capacity. Nevertheless, this analysis shows

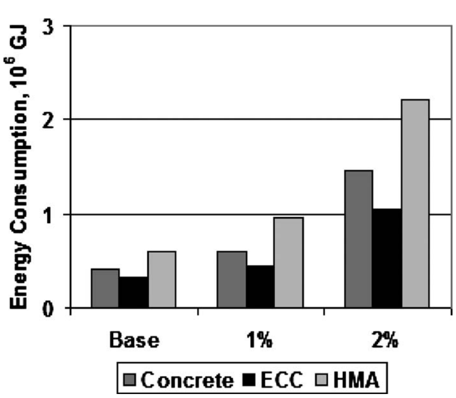

Fig. 10. Sensitivity of traffic related energy consumption to changes in annual traffic growth rate

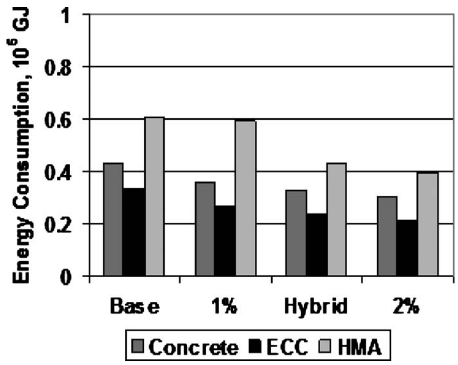

Fig. 11. Total primary energy consumption based on different fuel economy improvement scenario

that the model result is very sensitive to the traffic congestion component and could increase significantly under high traffic growth scenario.

If traffic flow increases over time, the ECC overlay system will save even more energy than the concrete overlay system. When the assumed traffic growth rate is 2%, the ECC overlay system will save an additional 20% energy over concrete when compared with the baseline scenario.

Fuel economy improvements will affect traffic related energy consumption and pollutant emissions. The impact of hybrid vehicle technology diffusion forecasted by Heywood was also studied (Heywood et al. 2004). Fig. 11 shows the traffic related energy consumption based on different fuel economy improvement scenarios. At 2% fuel economy improvement, traffic related energy consumption decreases more than 29, 37, and 35% compared to the baseline fuel economy levels for the concrete, ECC, and HMA overlay systems, respectively.

Considering that the average traffic growth rate in the United States has been estimated at 2.4% since 1994 (Davis and Diegel 2002), traffic growth has a greater effect on traffic related energy consumption than improving the fuel economy of vehicles on the road. In the baseline scenario, the overlay usage phase which accounts for the overlay surface roughness effects is identified as one of the greatest contributors to the life-cycle energy consumption. A key parameter for roughness effects is the surface roughness change (IRI). If IRI increases 2% faster than the baseline scenario, the total life-cycle energy consumption will increase 3.5, 1.9, and 0.5% for concrete, ECC, and HMA overlay systems, respectively. At 5% IRI growth rate, the total life-cycle energy consumption will increase 5.7, 4.8, and 1.0% for concrete, ECC, and HMA overlay systems, respectively.

Conclusions

This study developed an LCA model and a set of environmental metrics to simulate and evaluate the environmental performance of new material application in pavement overlay system over the entire service life. In addition to agency cost and material properties which currently guide the selection of materials and designs for infrastructure applications, broader environmental and social indicators are addressed in this study. This study extends previous modeling efforts by incorporating and evaluating the impacts of construction-related traffic congestion and pavement surface roughness effects on highway users. Traffic congestion, roughness effects, and material consumption were identified as the life-cycle stages with greatest environmental impacts throughout an overlay system life cycle. This result enables highway agencies to explore a variety of preservation strategies to improve the environmental sustainability performance of long-term infrastructure systems.

Improvement in material selection criteria is important for enhancing the sustainability of infrastructure. The ECC overlay system showed improved performance compared to the conventional concrete and HMA overlay systems over a 40-year service life due to a reduced maintenance and rehabilitation frequency for the ECC overlay system. From an environmental sustainability perspective, the ECC overlay system consumed less energy and nonrenewable resources, and emitted fewer GHG and other pollutants. From a social sustainability perspective, such as user time delay caused by preservation activities related traffic congestion, the ECC overlay system also performed better than concrete and HMA overlay systems.

The modeling results established environmental sustainability performance criteria for a novel material and can be used to inform the design and the other development of new materials for pavement application. While the assumption of longer service life of the ECC overlay system is supported by results of experimental tests, FEM simulations, and bridge deck applications, it is necessary to verify the result with the actual application of ECC material in an overlay system and observation of its performance over time.

Another uncertainty in this model comes from the modeling of traffic. Sensitivity analysis focused on the traffic phase showed that a growing traffic flow significantly increased traffic related energy consumption and air emissions. Even with improvements in vehicle fuel economy, a growing traffic volume overwhelms benefits derived from fuel economy improvements and still results in an increase in user time delay due to preservation activities.

The analysis also showed the potential of environmentally preferable mixtures which use industrial by-products to substitute for energy intensive or environmentally harmful materials, such as waste fly ash for portland cement in the ECC overlay system. This substitution results in significantly reduced raw material and energy consumption and decreased environmental burdens while maintaining or improving overlay mechanical properties.

The LCA model outlined in this paper shows that the applications of advanced materials and designs, even if they have higher initial energy and environmental burdens, can result in lower life-cycle energy consumption and environmental impacts over the long-term perspective. The LCA model can be applied to other States pavement systems by substituting the traffic parameters using local data. Additionally, other sustainability indicators can be incorporated into the model, such as heat island effect and noise. The LCA model and results developed in this research can serve as a foundation of a life-cycle cost model and life-cycle optimization model to enhance infrastructure sustainability and pavement asset management decisions.

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