

Materials design for sustainability through life cycle modeling of engineered cementitious composites

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Abstract Evaluating and enhancing construction material sustainability requires a life cycle perspective of the structures in which they are used, since material properties and durability can have a profound effect on overall infrastructure performance. A framework is proposed to evaluate and enhance the design of “greener” materials that integrates material design, structural design, and life cycle modeling of the built system. This framework is applied to engineered cementitious composite materials, a family of high performance fiber-reinforced composites used as link slabs in a concrete bridge deck. Modeling results show incorporating waste materials, such as fly ash, should be pursued only if the material retains adequate durability for the structural application where it is used. Additionally, traffic congestion

resulting from bridge deck construction and rehabilitation events dominates environmental and economic life cycle results, consuming the most energy, producing the largest amount of pollutants, and generating the greatest life cycle costs.

Keywords Life cycle assessment · Life cycle cost · Fiber-reinforced composites · Bridge design · Environmental impacts · Materials engineering

1 Introduction

Concrete infrastructure, such as bridges and roads, provide essential services to our society and economy. Because of concrete’s long application lifetime and its critical role in transportation, concrete infrastructure performance has ongoing impacts on social, environmental and economic factors, including congestion, safety, pollution, and nonrenewable resource consumption. In addition, concrete presents challenges to sustainability from a materials perspective. Production of cement, concrete’s key binding agent, accounts for 5% of global human-derived carbon dioxide emissions, a greenhouse gas (GHG), and requires large quantities of fossil and mineral resources for its production [1]. A holistic framework for improving material sustainability should integrate material design with a life cycle perspective of the material’s application in civil infrastructure.

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The research presented here describes the application of a novel approach to improving infrastructure sustainability through integration of material design and life cycle modeling. The approach is applied to engineered cementitious composites (ECC), a family of high performance fiber-reinforced cementitious composite materials. In this study ECC materials are used as link slabs in a concrete bridge deck design to replace conventional steel expansion joints. In the integrated framework, life cycle modeling is used to create sustainability indicators for ECC materials based on their predicted performance in an infrastructure application. The indicators are communicated back to material engineers in order to further improve material sustainability. This iterative process of life cycle modeling, sustainability indicator development, and continuous improvement of the material design is part of an explicit framework for improving material sustainability that takes into account the intended infrastructure application of the material.

Life cycle modeling refers to both environmental life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCA is an analytical framework for measuring environmental and social impacts of a product system or technology by evaluating the inputs and outputs of a product or process throughout its life cycle, including raw material acquisition, production, use, final disposal or recycling, and transportation needed between these phases [2]. LCCA is a total cost accounting technique and a complementary methodology to LCA. It uses life cycle principles to augment conventional cost analyses by estimating not just initial costs, but also use and disposal costs. In this study LCCA costs also include estimates of environmental damage costs, an important external cost. External costs refer to those costs or impacts of an economic activity not borne by the individuals or groups that engage in that activity.

This research departs from more typical applications of life cycle modeling in two ways; first, it is applied to improve the material design process, and second, it is applied to road infrastructure. Road infrastructure, such as the concrete bridge deck modeled in this study, lasts decades and requires repair and rehabilitation throughout its life cycle. This life cycle is long-lived and complex when compared with those of most consumer products, a more common application for LCA.

2 Background

The application of life cycle methods and models for enhancing materials and products has evolved over the last two decades. The first well-known applications of LCA were comparative assessments of consumer products. These assessments often examined two similar products made from different materials e.g., paper versus plastic grocery sacks and beverage containers [3, 4]. While results from this kind of LCA provide useful information for choosing between equivalent products, it can only establish the better option between products already in the marketplace. Use of LCA in this manner, to compare existing product alternatives, does not necessarily lead to improvement of product performance.

Life cycle design and design for environment are methods that integrate LCA and other environmental analysis methods into the product development process, shifting the focus from finished product to product design [5–7]. Life cycle design moves life cycle modeling from the final product stage, when products arrive at market, to the product design stage. A shift to life cycle design allows questions of material selection and other aspects of the product life cycle such as improving manufacturing processes or considering disposal or recycling options to be addressed before products arrive at market.

While early applications of LCA typically focused on consumer products, life cycle methods have been applied to building and construction material selection. A large study that created LCAs for a multitude of building materials including steel, wood, plaster, gypsum board and glass was developed by the American Institute of Architects (AIA) with funding from the US Environmental Protection Agency (EPA) more than a decade ago [5]. The National Institute of Standards and Technology has also developed its own computer-based tool, Building for Environmental and Economic Sustainability (BEES), intended to help those involved in building construction make material selection decisions that take into account a life cycle perspective [6]. The AIA study and BEES assess existing building materials and provide standard life cycle material datasets that are widely applicable and useful in making choices between materials when planning and designing structures.



While material selection that accounts for life cycle impacts of materials is a valuable tool for improving building design, this study takes the next step in moving life cycle modeling further upstream; from product or building design to an even earlier phase, material design. By incorporating life cycle modeling and principles at this earliest of phases, additional improvements in sustainability performance can be realized.

2.1 Integrated structures and materials design for sustainable infrastructure

In order to bring life cycle modeling into the material design process, a series of steps must be taken to integrate the two fields of study. Li and Fischer (2002) introduced the concept of integrated structures and materials design [7]. Their method couples structural engineering and materials engineering so that the material design process is done in connection with the structural design process, thereby integrating the design across length scales from micro-scale materials development to meter-scale structural engineering. This differs from the traditional process where materials are developed independent of structural design, and then material selection occurs based on material properties defined by structural requirements. Li and Fischer's method was then enhanced by Lepech and Li (2005) with yet another factor, sustainability, resulting in an integrated structures and materials design for sustainable infrastructure [8]. Figure 1 shows the integrated materials design framework for sustainable infrastructure (IMD-SI). This method is applied using life cycle modeling as the primary tool for sustainability analysis and indicator development [9].

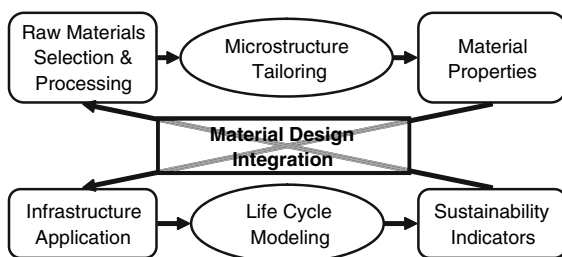


Fig. 1 Integrated materials design framework for sustainable infrastructure

Life cycle modeling creates sustainability indicators that reflect the environmental and economic burdens associated with the infrastructure application analyzed. LCA quantifies the inputs and outputs from the material production, construction, use, and end-of-life phases of the application. This accounting process can then be translated into specific impacts such as global warming potential and energy consumption, or benefits such as the quantity of material diverted from the waste stream if waste materials are incorporated into new materials.

LCCA calculates agency, user, and environmental damage costs over the entire lifetime of the infrastructure application. In general, user and environmental costs are not reflected in conventional costing methods. For infrastructure, conventional costing assesses costs to the funding agency but not costs external to that agency, such as costs incurred by bridge and roadway users, or those people affected by pollution derived from infrastructure construction. Thus, life cycle modeling can assess direct and indirect environmental and cost impacts of infrastructure and material design decisions. This information may then be used to guide the material development stage.

2.2 Previous work in life cycle modeling of highway infrastructure

Research on LCA applied to transportation infrastructure materials, and materials used in bridges particularly, is limited. Horvath and Hendrickson (1998) used economic input–output LCA to compare two alternative materials, steel and steel reinforced concrete, for use as bridge girders [10]. Their study found that in the manufacturing and use phases the steel girders required more inputs and resulted in higher environmental outputs than concrete girders. However, in the end-of-life phase the steel performed better than the concrete design because of Horvath and Hendrickson's assumptions about the likelihood of recycling steel versus concrete. Steel recycling rates are assumed to be very high; whereas, concrete recycling rates very low. The scope of their study did not include traffic-related impacts during use, repair or construction.

Zapata and Gambatese (2005) analyzed roadway pavement materials by comparing the life cycle

energy associated with asphalt versus reinforced concrete pavements [11]. The authors included raw material extraction, material processing, and placement of the pavement. The scope of their study did not include energy associated with the pavements once they were in use, nor their removal and disposal at end-of-life. A key finding from their study relevant to sustainable material development showed the production of cement accounted for the majority of energy used by the concrete pavement system, and substituting industrial waste products, such as fly ash, could greatly reduce energy requirements for concrete pavements.

Keoleian et al. (2005) applied LCA to a concrete bridge deck to compare the performance of a conventional design and an ECC link slab deck design [12]. Findings from this study showed improved performance in the ECC link slab design driven by reduced construction events and related effects. Neither Horvath and Hendrickson's nor Zapata and Gambatese's studies include construction-related traffic, but findings from Keoleian et al. suggest construction-related traffic can be an important element in road infrastructure LCA.

The body of literature available for life cycle costing of bridges and road infrastructure is greater than for LCA. Hastak and Halpin (2000) applied life cycle benefit–cost analysis to construction material selection of composites [13]. Their study accounts for costs beyond simple agency costs, including traffic related costs such as the cost incurred by motorists delayed in construction zones. Hastak and Halpin also applied an analytical hierarchy process to include intangible benefits of materials. Their study did not, however, account for the damage cost associated with environmental pollutants.

Ehlen (1999) examined life cycle costs of a fiber-reinforced polymer (FRP) bridge deck [14]. Ehlen's study compared agency, user, and third party costs of three FRP deck designs to a conventional concrete bridge deck. Here, third party costs refer to environmental impacts of construction and the impact of construction on nearby businesses. Despite acknowledging these costs, the author did not quantify them.

The National Cooperative Highway Research Program and the Office of Applied Economics at the National Institute of Standards and Technology developed life cycle cost models for bridges referred to as *BLCCA* and *BridgeLCC* respectively [15, 16].

Both models calculate user and agency costs. In addition, *BridgeLCC* allows the software user to enter third party cost parameters, and *BLCCA* includes vulnerability costs, which are the expected costs associated with extreme events, such as earthquakes or explosions, that are unlikely but possibly disastrous. While *BridgeLCC* allows the user to input third party costs, it does not provide support for calculating or estimating them.

There has also been evaluation of how improved materials may affect performance of the entire highway infrastructure system in the U.S. The Center for Transportation Research at Argonne National Laboratory examined a number of scenarios for improved materials and evaluated how they would change overall energy consumption by the highway system and its users [17]. The report concludes that increasing road life is the most significant factor for energy savings in highway material improvement, followed by reducing construction delay, when compared with the other scenarios modeled. The study relies entirely on national average data and does not specify which materials could provide improved performance.

This study expands on previous work in life cycle modeling of road infrastructure by combining LCA and LCCA, accounting for traffic related burdens and costs, quantifying the costs of environmental damages, and integration with the material development process.

3 Methods

3.1 Goal and scope

The bridge deck evaluated in this study uses an alternative design that replaces conventional steel expansion joints with ECC link slabs. Figure 2 shows a conventional bridge deck expansion joint and an ECC link slab deck design.

Link slabs are a strategic application of ECC. By replacing the steel expansion joints found in most reinforced concrete bridge decks, the link slabs eliminate key failure modes for bridge deck deterioration. The replacement of expansion joints is possible because of ECC's ultra high ductility, which can accommodate thermal expansion and contraction of the bridge along with bending deformation, and



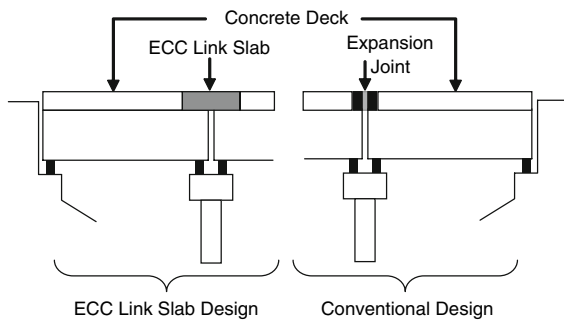


Fig. 2 Engineered cementitious composite link slab deck design

thus eliminate the need for expansion joints. The design procedure and predicted performance of ECC link slabs can be found in Kim and Li (2004) [18]. ECC material engineering is based on the relationships between material microstructures, processing, material properties, and performance [19]. This makes it an excellent candidate for the IMD-SI framework which relies on material processing and microstructure tailoring to achieve desired material performance while varying constituent raw materials.

Previously, LCA and LCCA modeling were applied to compare the ECC link slab deck design with a conventional steel expansion joint design [12, 20]. These analyses showed that the ECC link slab design performed better in terms of the environmental indicators assessed in the LCA model and costs evaluated in the LCCA. The primary driver for improved ECC link slab bridge deck performance was reduced repair and rehabilitation frequency over the life cycle of the deck. Construction-related traffic congestion dominated results for energy consumption, air pollution, and cost. The environmental impacts of construction-related traffic congestion are caused mostly by increased fuel use and related combustion emissions in construction zones. The high cost of congestion results from time lost to private and commercial roadway users while they wait in construction-related congestion.

The previous analyses showed the ECC link slab deck outperformed the conventional design. This study builds on that previous finding by applying the material sustainability framework to develop better performing ECC materials. A number of alternative ECC mix designs have been developed, many of which incorporate industrial waste products or

alternative polymeric fibers in order to reduce the environmental burdens associated with material production. These new ECC mix designs are evaluated and compared to the material modeled in previous applications of the LCA and LCCA models. In this study, the ECC material modeled in previous applications of the LCA and LCCA models is referred to as mix D-1. Mix D-1 is the most studied and tested ECC mix design. The life cycle modeling of alternative ECC mix designs provides sustainability indicators as feedback to material engineers to further improved material designs.

3.2 ECC mix designs

A variety of ECC mixes have been developed, many of which incorporate industrial by-products that displace virgin materials. The objective of incorporating these alternative materials is to improve the environmental performance of these ECC mix designs. D-1 is considered the baseline ECC material, and it too incorporates an industrial by-product, fly ash, into its mix design. Table 1 shows the mix designs developed and their expected lifetime when applied as a bridge deck link slab. Expected lifetimes in Table 1 were calculated using an adapted model from Liu and Weyers and Thoft-Christensen [21, 22]. The expected lifetime of ECC in a bridge deck is governed by the rate of reinforcing steel corrosion within the deck. Using the accepted rate of the oxidation reaction and models adapted from Liu and Thoft-Christensen, the time to end of service life was numerically modeled for concrete and ECC materials [23].

All materials contain cement, water, sand, and polymeric fibers. Additional plasticizers and admixtures are used in most mixes, such as high rate water reducers, and hydropropyl methyl cellulose (HPMC). The polymeric fiber used in all but one mix shown here is a polyvinyl alcohol (PVA) fiber. These PVA fibers are modified by surface oiling required to achieve the right bonding properties with the matrix around them. In one case polyethylene (PE) fibers are used instead. These PE fibers have excellent material properties for ECC design; however, their high cost makes them an unattractive candidate for the ECC link slab application. In three mixes, designated D10,

Table 1 ECC mix designs

Mix design	Material lifetime (years)	Cement content (kg/L)	Fly ash (kg/L)	Virgin sand (kg/L)	HRWR (kg/L)	HPMC (kg/L)	PVA fiber (kg/L)	Alternative constituent materials (kg/L)
D-1	75.1	0.578	0.693	0.462	0.00751	0	0.026	N/A
D-2	93.2	1.266	0	0.633	0.0126	0.00063	0	0.02—virgin polyethylene fibers
D-3	153.3	0.845	0	0.845	0.0169 ^a	0.00127	0.026	N/A
D-4	129.7	0.590	0	0.472	0.01904 ^a	0	0.026	0.708—bottom ash
D-5	103.0	0.322	0	0.709	0.01934 ^a	0.00016	0.026	0.709—fine fly ash
D-6	118.6	0.322	0.258	0.709	0.01934 ^a	0.00016	0.026	0.193—fine fly ash, 0.258 bottom ash
D-7	118.6	0.373	0	0.822	0.02241 ^a	0.00028	0.026	0.448—bottom ash
D-8	83.9	0.578	0.693	0	0.00751	0	0.026	0.462—calcinator sand
D-9	79.5	0.583	0.7	0	0.0175 ^a	0	0.026	0.467—green sand, 0.3% oiling on PVA fiber
D-10	88.5	0.578	0.693	0	0.013	0	0.0234	0.0026—reused woven nylon carpet fiber
D-11	51.8	0.578	0.693	0	0.013	0	0.0234	0.0026—reused single nylon carpet fiber
D-12	51.8	0.578	0.693	0	0.013	0	0.0234	0.0026—reused polypropylene carpet fiber
D-13	6.8	0.444	0.533	0	0.01332 ^a	0	0.026	0.355—green sand, 0.178 bag house
D-14	11.0	0.583	0.7	0	0.0175 ^a	0	0.026	0.467—green sand, 1.2% oiling on PVA fiber
D-15	18.4	0.322	0.516	0.709	0.01934 ^a	0.00016	0.026	0.193—fine fly ash

^a Indicates use of formaldehyde-based HRWR, those without refer to polycarboxylate-based HRWR

D-11, and D-12, the virgin PVA fiber content is reduced by adding post-consumer carpet fibers.

Fly ash is the dominant alternative material in these mixes, and is a common alternative material in conventional concrete as well. Fly ash, bottom ash, and fine fly ash are waste materials created in coal-fired electricity plants. These materials vary by particle size and collection location within the electricity plant emission stack. Their pozzolanic characteristics mean they have some cementitious qualities and can displace a portion of cement. Green sand, bag house residue, and calcinator sand are also industrial waste products, though these are created at foundry plants. The green sand and calcinator sand can be substituted for virgin sand, and bag house residue is used as matrix filler. The green sand and calcinator sand are found to be particularly suitable for inclusion in ECC due to their particle size being compatible with requirements for the tensile ductility designed into ECC.

The green sand surface is covered in carbon nano-particles from the casting process. These carbon nano-particles act as a sleeve or coating on the fibers that reduces bonding between the fibers and the matrix. To counteract the weakened bonding caused by carbon nano-particles, surface oiling on the PVA

fibers is reduced. The two affected mixes, D-9 and D-14, have reduced fiber surface oil contents of 0.3 and 1.2% by weight respectively, compared to 1.8% surface oil content for typical PVA fibers.

3.3 Life cycle modeling datasets and parameters

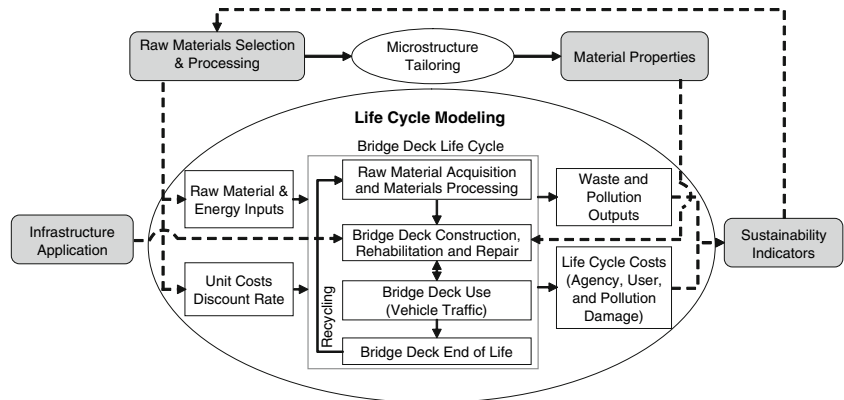
Life cycle assessment accounts for the raw materials and energy used in the bridge deck throughout the bridge deck life cycle. The output from LCA reports the pollution, solid waste, and total resource consumption caused by the system. The LCCA model takes unit cost inputs, including costs to the funding agency, bridge deck users, and pollution damage estimates, and accounts for these costs over the entire life cycle of the deck. Figure 3 shows a schematic for the bridge deck life cycle model used in this analysis and how it fits into the IMD-SI framework.

3.4 Environmental life cycle assessment

The LCA model creates a life cycle inventory (LCI) of all the inputs and outputs from the bridge deck system over its 60-year life. The LCI is used to create



Fig. 3 Life cycle model schematic



environmental sustainability indicators. The LCI also provides data to the LCCA model in order to calculate environmental costs incurred by society due to damaging effects of pollutants.

In order to create the LCI, datasets for materials and transport modes are required, as well as additional simulation tools. Three external models are incorporated into the LCA; MOBILE6.2, a U.S. Environmental Protection Agency (U.S. EPA) vehicle emissions model; Nonroad, a U.S. EPA off-road vehicle emissions model used to model construction equipment; and a traffic delay model developed by the Kentucky Transportation Institute [24–26]. The life cycle inventory datasets were collected from a number of sources. Sources for material LCI datasets are shown in Table 2. All other sources for non-material LCI datasets, such as transportation modes, may be found in Keoleian et al. (2005) [12].

3.5 Life cycle cost analysis

Life cycle cost analysis estimates three types of costs; agency, user, and environmental. Agency costs refer to costs borne by the funding department, usually a regional, state, or federal department of transportation. User costs are imposed on those individuals or commercial enterprises that use the bridge deck system for travel. These costs are calculated based on the time travelers are delayed due to construction-related traffic congestion, increased vehicle operation costs resulting from congestion, and increased risk of accidents in a construction zone. Finally, environmental costs are based on estimates of criteria air pollutants and greenhouse gases. Criteria pollutants directly affect human health, and the cost of

morbidity and mortality is estimated as the damage cost of these pollutants [27, 28]. GHGs indirectly affect human health and economic activity through climate change. The damage cost for GHG emissions is devised based on a cost benefit and cost effectiveness analysis of different possible climate and emissions scenarios [29].

Unlike the materials, energy, and pollution accounted for in the LCA model, the costs in the LCCA model are subject to discount rates. Application of a discount rate is founded in the notion that humans have a time preference when it comes to money; in other words, a dollar today is worth more than a dollar some time in the future. The discount rate used in this model for agency and user costs is 4% and is based on the Office of Management and Budget estimates for publicly funded projects [30]. The discount rate used here is referred to as a real discount rate, since costs in the life cycle model are not inflated in future years. The discount rate for environmental costs, in this study limited to air pollution damage costs, is a slight variation of the 4% discount rate. The environmental cost discount rate falls as time progresses from the near term, to the medium term, and to the distant future. Discount rates for these three periods are 4, 3 and 2% respectively. A falling discount rate is used to account for uncertainty associated with the long term effects of environmental pollution on people and the planet [31].

3.6 Link slab deterioration model and bridge deck service schedule

The bridge deck in this study is based on a highway overpass located in southeast Michigan at the

Table 2 Sources for life cycle inventory material datasets

Material	Source of life cycle inventory information
Cement	Portland Cement Association (Nisbet 2002) and Ecobilan (Ecobilan 2001) cement data
Sand	Portland Cement Association (Nisbet 2002), adjusted with electricity and fuel production from (Ecobilan 2001) and equipment emissions from USEPA's Nonroad (US Environmental Protection Agency 2000)
Polyvinyl alcohol (PVA) fiber	Industry Source and polyethylene data from Association of Plastic Manufacturers in Europe (Bousted 1999)
Polyethylene (PE) fiber	Dataset for high density polyethylene extruded pipes from Association of Plastic Manufacturers in Europe (Bousted 2005). Fibers require extrusion but also a drawing process not included in this inventory dataset, thus the inventory can be considered a lower bound for polyethylene fiber inputs and outputs
High rate water reducer (HRWR), formaldehyde-based	Formaldehyde data as surrogate for super plasticizer (Ecobilan 2001). Primary Ecobilan source: (Swiss Agency for the Environment, Forests and Landscape 1994)
High rate water reducer (HRWR), polycarboxylated polymer-based	Acrylonitrile LCI dataset from the Association of European Plastic Manufacturers (Bousted 2005) used as a surrogate. Acrylonitrile is one of two possible precursors for polycarboxylated polymer (Wu, Embree et al. 2002). This dataset is considered a lower bound for a polycarboxylated polymer LCI
Hydropropyl methyl cellulose (HPMC)	Methyl Ethyl HydroxyEthyl Cellulose (MEHEC) LCI is used as a surrogate dataset (Bermocoll 2002). MEHEC is a similar product, relying on the same cellulose-based backbone, but modified by additional chemicals
Fly ash (class n)	Fly ash is modeled as an industrial by-product diverted from the waste stream, so it is simply considered a solid waste credit. Only distribution-related impacts from transporting it from its source in Texas to the ECC mix site in Michigan is modeled
Bottom ash, fine fly ash, green sand, bag house, and calcinator sand	These products are all treated as a negative solid waste; that is, material diverted from the waste stream and not treated or processed in any other way. Only distribution related impacts are modeled. Materials are all from GM's foundry in Saginaw, MI, and are all assumed to be transported by truck to the mixing site
Reused carpet fiber	Woven nylon, single nylon, and polypropylene carpet fibers are reused directly. These fiber are modeled simply as diverted waste, and are transported from Atlanta, GA to Ann Arbor, MI

intersection of two highways, M-14 and US-23, with an average annual daily traffic (AADT) of 35,000 vehicles in one direction. The bridge is approximately 30 years old and undergoing its first deck replacement, the initial deck replacement is referred to as year 0 in this study. The substructure is expected to last another 60 years; thus, the timeframe for this analysis is 60 years. If the deck is still in good condition at the end of bridge life, no residual value is considered since the entire bridge will be demolished and replaced.

To determine life cycle impacts of ECC link slabs, a link slab deterioration model is required. The deterioration model considers steel rebar corrosion as the key failure mode for link slab deterioration and assumes the worst-case scenario for rebar corrosion—namely that permeation of aggressive chemical agents occurs on the first day of link slab installation

in the deck. Rebar expands as it corrodes; the link slab is able to maintain its performance for some time due to ECC's capacity to absorb strain energy [32]. When the strain capacity of the ECC material is exceeded by the expanding rebar, the link slab fails.

A vital assumption here is that the ECC deck performs like a jointless bridge, since the ECC link slab eliminates the deterioration mechanisms introduced by mechanical expansion joints. The deterioration trends for jointed versus jointless bridges are based on those found in a 1993 article by Yanev and Chen (1993) that compared the performance of jointed and jointless bridges in New York [33]. This deterioration model for jointed and jointless bridges developed by Yanev and Chen is based on the continual assessment of both jointed and jointless bridges according to bridge evaluation metrics and rating schemes detailed by the US



Federal Highway Administration National Bridge Inventory [34]. This model relies on department of transportation inspector evaluations of existing bridge structures to produce numerical structural ratings over time. These changing structural ratings form the basis of the comparative bridge deterioration model. To ensure that the ECC link slab design performs as well or better than the equivalent conventional design, a performance index was created based on the structural deck rating. After establishing an average deck rating using a Michigan Department of Transportation repair schedule for concrete bridge decks, an equivalent repair schedule based on average deck rating was devised for the ECC deck design [32].

The bridge deck link slab design allows the deck to be modeled as a jointless bridge as long as the link slab does not fail. Thus, the link slabs must always be replaced prior to reaching a critically deteriorated state.

3.7 Methodological challenges for developing bridge deck service schedules

The key methodological issue for evaluating green ECC mixes is how to resolve additional construction events associated with the link slab that are not part of accepted repair processes and schedules used by Departments of Transportation. Two approaches can be taken for construction timeline development; a mechanistic approach or a consolidated approach.

The mechanistic approach relies on one simple rule: whenever a link slab reaches a critical state of deterioration it will be replaced without regard to construction events occurring in the years around it. If by chance the link slab replacement coincides exactly with another event, those two construction events will be consolidated, but otherwise the construction events will occur separately.

The consolidated approach seeks to combine and economize construction events over the bridge deck life. The constraint of never exceeding link slab life is maintained, but events occurring in close temporal proximity; that is, within a year or two of each other, will be consolidated into one event that meets the constraint of never exceeding link slab life, which is determined based on the deterioration model described earlier. For example, in a consolidated

rehabilitation schedule if a resurfacing event is expected to take place in year 15, and the link slab replacement is scheduled to occur in year 14, then the resurfacing event and link slab replacement will be consolidated into a single construction event occurring in year 14.

Rather than determine a single method for developing the construction timeline, ECC mixes that require link slab replacement events will be evaluated using both the mechanistic approach to timeline development and the consolidated approach. Those materials whose link slab lives meet or exceed the bridge deck life can be modeled by a standard timeline shown in Table 3, since they do not require additional construction events associated with the link slab. The timelines used for materials that required additional link slab replacement events over the bridge deck life are also shown. Each material requires a consolidated and mechanistic timeline, since the service schedules differ for each approach when the link slab life falls short of the bridge deck lifetime.

4 Results

4.1 Life cycle assessment results

Total primary energy (TPE) is presented as an indicator for environmental performance. TPE includes both the energy consumed directly in material production, vehicle fuel combustion, and other activities associated with the bridge deck system, and also accounts for the upstream energy requirements associated with fuel and electricity production such as raw material extraction, refining, and delivery. Though other indicators are tracked in the LCA model, TPE is often illustrative of overall LCA results, especially in systems like this one where fuel combustion during material production and vehicle use dominate results. On average traffic related energy consumption accounts for about 85% of total life cycle TPE. While the focus of this paper is material sustainability, the dominance of traffic-related energy highlights the importance of maintaining a life cycle perspective when attempting to improve material sustainability performance. Since vehicles mainly combust non-renewable fossil fuels, TPE is also representative of global warming

Table 3 Bridge deck service schedules for mechanistic and consolidated approaches

Mix design	Link slab life	Timeline type	Year																					
			0	6	10	11	13	18	20	22	27	28	30	33	34	36	40	44	46	47	50	51	54	55
D-1–D-10	60 and higher	Standard	1	3				2				3			2				3					
D-11–D12	52	Mechanistic	1	3				2				3			2				3	4				
	52	Combined	1	3				2				3			2				3b					
D-13	7	Mechanistic	1	4	3		4	2b	4		3		4	2b				4	3			4		
	7	Combined	1	3b			3b	2b	3b			3b		2b				3b				3b		
D-14	11	Mechanistic	1	3	4			2	4		3	4		2	4				3			4		
	11	Combined	1	4				2b			4			2b					4					
D-15	18	Mechanistic	1	3			4	2			3			4	2				3			4		
	18	Combined	1	3			2b				3			2b				3				2b		

- 1 = Deck replacement
- 2 = Shallow overlay
- 2b = Shallow overlay with link slab replacement
- 3 = maintenance/pothole patching
- 3b = Link slab replacement and maintenance
- 4 = Link slab replacement

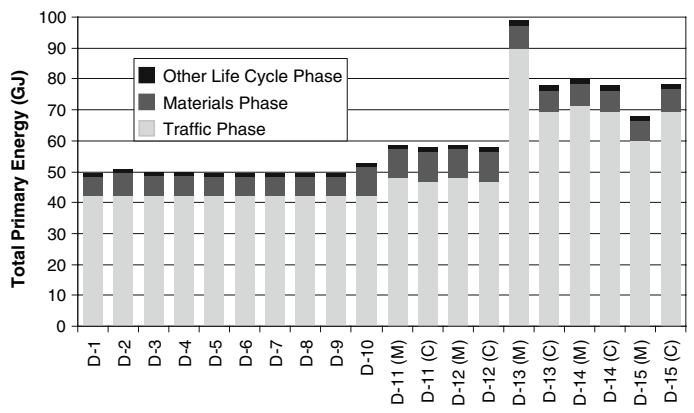
potential, fossil fuel resource depletion, and many criteria air pollutants. The LCA results for TPE for all materials and timelines are shown in Fig. 4, where (C) represents the consolidated approach to the repair and rehabilitation schedule development and (M) the mechanistic approach.

These results illustrate that incorporating green materials into a mix design can lead to increased TPE consumption. In most cases this results from reduced link slab durability when alternative constituent materials are used. At the extreme is mix D-13, which has the lowest material energy intensity (MEI), but performs very poorly from a life cycle energy perspective. This material has a link slab life of only

7 years, requiring many link slab replacements over the bridge deck life. Each replacement causes traffic congestion and requires new materials to be produced and installed, which drives the increase in total life cycle TPE.

A few of the ECC mix designs, such as D-4 and D-9, that meet or exceed bridge deck life and incorporate green materials still perform slightly worse than the reference mix. These materials, as evident in Table 1, have higher cement contents. Despite substituting other constituents with greener materials, the energy intensity of cement production is high enough that the additional green materials do not displace the impacts of higher cement content.

Fig. 4 Life cycle assessment results for total primary energy



A comparison of results in Table 4 for the mechanistic and consolidated approaches to timeline creation reveals that the method which results in lower TPE consumption is case dependent. For three mixes, D-11, D-12 and D-13, the consolidated approach results in reduced TPE. In the remaining two cases, D-14 and D-15, the mechanistic approach is preferable for reducing TPE. Intuitively the consolidated approach seems like it should always result in greater efficiency, since construction events are consolidated and construction time reduced. One explanation for why a consolidated approach may not improve life cycle results is that combining events may lead to a repair event occurring earlier than its optimal time, and in the long run this approach may require an additional repair or reconstruction event. This modeling shows that rehabilitation schedules should be developed on a case-by-case basis when materials with reduced durability are used.

Another way to look at the relationship between materials and life cycle performance is through MEI. MEI is a measure of the energy required to produce a material as well as the energy embodied within a material. Table 4 shows the MEI for each ECC mix

in ascending order, along with the life cycle material phase TPE, and the material phase TPE ranking when compared to all other mixes. The material phase TPE accounts for all materials used in the bridge deck, not just the link slab, and reflects the durability of the ECC material since less durable mixes require more frequent link slab replacements and thus a greater mass of material over the bridge deck life.

D-13, which incorporates both green sand and bag house waste, has the lowest MEI. However, from a life cycle perspective D-13 ranks 10th or 12th compared to the other mix designs depending on the repair schedule used. This highlights the difference between a life cycle perspective and a short term perspective for sustainability. Taking only the initial energy intensity into account, mix D-13 looks preferable; however, life cycle modeling clearly shows that these mixes are less sustainable than many with higher MEIs. ECC mixes D-5 and D-6 perform best overall from a life cycle perspective, though mixes D-13 and D-15 perform best from the strictly materials perspective. The MEI of ECC mixes appears to be less important than ECC durability when life cycle energy consumption is used as an indicator for sustainability. Link slabs are a strategic application of ECC. If ECC were used in a continuous pavement, for example, the results might change since the MEI of a mix would play a larger role in life cycle TPE results.

Table 4 Material energy intensity and material phase life cycle energy

Mix designation	MEI (MJ/L)	Material phase TPE (TJ)	TPE (rank)
D-13 (C)	3.7	7.1	10
D-13 (M)	3.7	7.3	12
D-15 (C)	5.7	7.5	13
D-15 (M)	5.7	6.5	6
D-5	5.8	6.3	1
D-6	5.8	6.3	1
D-7	6.2	6.3	2
D-1	6.7	6.4	4
D-10	6.9	9.4	15
D-11, D-12 (C)	6.9	9.4	16
D-11, D-12 (M)	6.9	9.4	16
D-8	7	6.4	3
D-9	7.3	6.4	5
D-14 (C)	7.3	7.1	9
D-14 (M)	7.3	6.8	10
D-4	7.5	6.5	8
D-3	9.3	6.5	7
D-2	10.8	7.6	14

4.2 Life cycle cost assessment results

As with LCA, a key factor in LCCA material performance is whether the link slab lasts as long as the bridge deck. Shorter link slab life results in increased construction activity which costs the funding agency in material, labor, and equipment; road users in time lost and increased fuel costs; and society at large due to increased environmental damage. Table 5 shows the LCCA results.

Mixes D-11 through D-15 all result in higher life cycle costs when evaluated using either mechanistic or consolidated construction timeline approaches compared with the mixes that use the standard timeline for repair, since these mixes require additional construction and rehabilitation events. D-5, D-6, D-7, and D-8 mixes all perform slightly better than the reference mix due to reduced environmental

Table 5 Life cycle cost results (\$1,000–U.S. \$2003)

Mix designation	Agency	User	Environmental	Total	% Change from D-1
D-1	452	19,256	74	19,783	0
D-2	461	19,256	76	19,793	0
D-3	453	19,256	75	19,784	0
D-4	452	19,256	74	19,783	0
D-5	452	19,237	71	19,761	0
D-6	452	19,237	71	19,761	0
D-7	452	19,256	74	19,783	0
D-8	452	19,256	74	19,782	0
D-9	452	19,256	74	19,782	0
D-10	452	19,256	77	19,785	0
D-11 (M)	461	19,731	78	20,269	2
D-11 (C)	461	19,654	77	20,192	2
D-12 (M)	461	19,731	78	20,269	2
D-12 (C)	461	19,654	77	20,192	2
D-13 (M)	569	25,008	80	25,656	30
D-13 (C)	588	24,403	71	25,062	27
D-14 (M)	586	24,403	71	25,060	27
D-14 (C)	586	24,403	71	25,060	27
D-15 (M)	513	22,265	77	22,855	16
D-15 (C)	545	22,265	77	22,887	16

damage costs. However, the improved performance is so small it is not evident in the percent change column in Table 5 due to rounding. User costs are directly linked to the rehabilitation schedule, so all the ECC mixes with durability that meet or exceed the 60-year timeline have the same rehabilitation schedule and share the same user cost value. This modeling shows that while there may not be a significant cost savings associated with green materials, there are not additional costs associated with green materials when material durability is sufficient.

4.3 Scenario analysis

Scenario analysis was applied to some key modeling parameters. Scenario analysis is necessary because of considerable uncertainties in modeling long lived civil infrastructure applications. Over the estimated 60-year life of the bridge deck, personal transportation trends and vehicle technology will certainly change, but exactly how conditions will change cannot be known. Assumptions about future

conditions can have significant effects on life cycle modeling results, and scenario analysis is one method for testing predictions of future conditions. The scenarios examined here include vehicle fuel economy improvement, increasing AADT and a combination of both these conditions. Scenario 1 is the baseline scenario for this study.

- Scenario 1: No fuel economy improvement and no increase in AADT.
- Scenario 2: Fuel economy improvement over time and no increase in AADT.
- Scenario 3: Fuel economy improvement and AADT growth bounded at 45,000.
- Scenario 4: No fuel economy improvement and AADT growth bounded at 45,000

Fuel economy changes over time are based on a model for hybrid vehicle market penetration over a 30-year time horizon [35]. The results from this model were fit with a third-order polynomial in order to extrapolate to 60 years, the predicted lifetime of the bridge deck. The polynomial has a forced intercept of 22.5 miles per gallon (mpg) at year 0, which reflects real-world estimates of average vehicle



fuel economy, and plateaus at a maximum fleet average fuel economy of approximately 50 mpg.

Average annual daily traffic growth is estimated at 2.4%, which is the national average growth rate for vehicle miles traveled in the U.S. between 1992–2002 [36]. While the growth rate looks relatively small, if it grows unbounded for the 60-year life of the bridge construction zone back-up grows to hundreds of miles. The traffic model used here cannot reasonably model this sort of congestion, nor would drivers wait in such congestion; thus, the AADT is bounded at 45,000 for one-way AADT. At AADT levels slightly higher than this, traffic congestion back-ups grow rapidly.

All those materials with the standard rehabilitation timeline have very similar results, showing an approximate 16% improvement compared to the baseline scenario for traffic related TPE consumption in Scenario 2, where fuel economy improves and AADT remains constant. Improving fuel economy over time reduces the TPE associated with all the mix designs; however, some ECC materials are more affected than others. The most improvement is seen with ECC mixes that require a great number of repair events. For example, mix D-13 shows an improvement of 32% in traffic related TPE consumption for Scenario 2. Since traffic related energy consumption represents close to 85% of total life cycle TPE, fuel economy improvement yields significant improvements in total life cycle TPE results. Increasing AADT has a greater effect on TPE than does fuel economy improvement however. For Scenario 3, where fuel economy improvement and an AADT growth rate are both evaluated, the increase in TPE from AADT growth overwhelms the savings resulting from improved fuel economy.

Scenario analysis also changes life cycle cost results. Scenario 2 resulted in a slight improvement in user and environmental costs, and no change to agency costs. In Scenarios 3 and 4, life cycle costs increase for all mix designs. Most increased are a result of user costs because the scenario analyses only tested traffic-related parameters, however small changes in environmental costs also result from fuel economy improvement, and increases in environmental costs result from fuel consumption with higher AADT.

Results from Scenario 2 show that fuel economy improvements create a moderate savings to user cost

from reduced fuel consumption. User costs are dominated by time lost to drivers delayed in construction-related traffic congestion, thus total user costs only change a small amount since time spent in construction-related traffic is independent of fuel economy. There are environmental cost savings of 6.6% for all the standard timelines in Scenario 2 as well. Because environmental costs comprise less than 1% of total costs, a 6.6% improvement has no significant effect on total cost results.

Results for Scenarios 3, 4, and 5, which include increasing AADT, show increased user and environmental costs and unchanged agency costs. The results for the combined fuel economy improvement and AADT growth, Scenario 3, show that AADT growth has a more significant impact on life cycle costs compared to improving fuel economy. This scenario analysis demonstrates that traffic growth in a region may significantly impact the magnitude of congestion related effects, and offset the energy and cost benefits of improved vehicle fuel economy.

Throughout the traffic parameter scenario analysis, the preferential ranking of ECC mix designs does not change. That is, the mix designs that were ranked by performance as one, two, three, and so forth, remain in the same rank, despite that the four scenarios modeled affect the performance of different ECC mixes to varying degrees. This means that although there is significant uncertainty in modeling long-lived infrastructure applications, uncertainty related to many key parameters is unlikely to affect which materials are preferable from a sustainability perspective.

5 Conclusions and future work

This research applied life cycle modeling as the primary tool for assessing and improving the sustainability of ECC materials used in infrastructure applications within the IMD-SI framework. The sustainability indicators developed using life cycle modeling show that ensuring sufficient material durability is a vital element for maintaining and improving sustainability of ECC materials applied as bridge deck link slabs. Those ECC mix designs that meet or exceed the lifetime of the concrete bridge deck perform on par or superior to the reference material, D-1.

Including industrial waste materials, such as ashes and sands, to displace virgin raw materials yields small improvements in LCA results and has a negligible impact on LCCA results when material durability is sufficient for a link slab life of 60 years. This life cycle modeling reinforces previous conclusions about the primary driver for material performance, namely sufficient durability. The clear message to material developers is that incorporation of waste materials can improve the sustainability of materials, but material durability must meet the infrastructure application durability needs. These conclusions may not extend to other road infrastructure applications, such as pavements, where more ECC material will be used. In this case, ECC was strategically applied in the bridge deck as a link slab, comprising only a portion of the total bridge deck. In pavement applications where ECC may be applied continuously, the incorporation of waste materials may play a much larger role in reducing life cycle energy and other sustainability indicators since more ECC material would be used.

Road infrastructure applications are long lived, and thus future conditions can significantly effect results. Scenario analysis was performed to account for possible changes in traffic volume and vehicle fuel economy. In all scenarios assessed, the categorization of preferable versus inferior ECC mix designs did not change. The preferable materials are still those that last as long as or longer than the life of the bridge deck. Likewise, the poorly performing materials are those that require link slab replacement during the bridge deck life. Scenario analysis also showed that increasing traffic volume had a much greater negative effect on LCA and LCCA sustainability results than the positive effects of improving the fuel economy of vehicles on the road.

Since results were highly dependent on link slab life, or more specifically whether link slab life met or exceeded bridge deck life, future work will include uncertainty modeling and sensitivity analysis to link slab life estimation. Data from laboratory testing combined with variability in the construction process will be used to estimate a range or probability distribution for link slab lifetime. This modeling will be important for choosing the minimum expected link slab life that will ensure, given material and construction variability, the link slab meets or exceeds the life of the bridge deck.

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