

Sustainable Design and Manufacturing of Prefabricated Durable Infrastructure

1 Motivating Engineering and Business Problem

Around the globe, nations struggle with increasing problems of unsustainable development¹. The consequences of this struggle, visible in both highly developed and still developing nations, are closely linked with pressures for economic progress². The backbone of much economic activity, infrastructure in the form of highways, bridges, buildings, and aqueous systems supports critical trade and societal needs while encouraging growth^{3,4,5}. While essential for development, the construction, maintenance, and demolition of infrastructure requires large material flows, high energy demands, and creates irreversible impacts^{1,6}. This proposed cross disciplinary study introduces a new design framework for sustainable infrastructure examining the economic impacts of new prefabrication and construction technologies, the environmental impacts of adopting “green” construction materials and processes, and the social impacts, such as unemployment, of changing the structure of the cement and concrete product industry.

1.1 The Sustainable Concrete Construction Dilemma

The preferred material for construction worldwide is concrete, exceeding 12 billion tons used annually. Concrete is currently the most used anthropogenic material, and the second most utilized material behind water⁷. The huge material flows related to concrete production alone cause significant societal and environmental impacts⁶. Cement production accounts for 5% of global greenhouse gas emissions^{8,9} and significant levels of NO_x, particulates, and other pollutants^{10,11,12}. China currently has the world’s second longest expressway system, accounting for 35% of global cement consumption¹³. Cement production, dependent on coal energy, contributes 6%-8% of China’s CO₂ and 40% of PM₁₀ emissions^{9,10}. Countries undergoing rapid development require infrastructure expansion; however the unsustainable interaction between built and natural environments is increasingly a global concern.

Aside from material production, negative impacts accompanying concrete construction or reconstruction can also be large. This is due to the long duration and high energy intensity associated with the one-of-a-kind nature of construction and the jobsite focus of cast-in-place concrete infrastructure. Recent research on highway bridge applications found that a majority of social and economic impacts accrue during the construction and maintenance phases when traffic is interrupted, resulting in lost wages and increased vehicle emissions^{14,15,16}. In addition, the \$20 billion annual concrete repair business in the US alone attests to the magnitude of the concrete structure deterioration problem¹⁷. Therefore, it is critical to both shorten infrastructure “downtime” due to construction/maintenance activities, while extending infrastructure durability to minimize future maintenance and reconstruction.

The unsustainable nature of concrete extends to end-of-life stages. Currently, only 60% of cement materials are recycled after demolition, while the remaining is landfilled amounting to 3 million metric tons of waste annually¹⁸. Such concerns increase as large portions of post-WWII infrastructure in developed countries, such as the U.S. and in Europe, simultaneously meets the end of design life^{19,20}.

Regardless of such disadvantages, the cement and concrete product manufacturing industry remains vital to the US economy along with those of developing nations. Domestically, this sector employs over 218,000 people producing \$44 billion of products annually²¹. Coupled with the concrete construction industry which employs 1.5 million people performing \$195 billion in work annually, any radical shifts in industry structure to improve sustainability may result in increased unemployment, falling production, and a lag on US economic growth. Such tradeoffs, whether temporary or permanent, embody the inherent dilemma in changing industries business practices toward sustainability and must be carefully weighed.

2 Theoretical and Practical Point of Departure

Recently, a new Sustainable Integrated Materials-Structures-System (SIMSS) paradigm for sustainable infrastructure has been proposed²². Building upon “cradle to cradle” concepts suggested by McDonough et al²³, it can be used to guide sustainable infrastructure design, construction, operation, maintenance, and end-of-life. Shown in Figure 1, the paradigm ranges from nanometer-scale materials development to kilometer-scale infrastructure life cycle assessment. Based on the work of Keoleian et al.^{15,16}, the complete iterative design framework takes advantage of the multi-scale nature of the SIMSS paradigm, linking it with life cycle models to evaluate sustainable design efforts and provide detailed feedback for improving sustainability at all length scales (i.e. materials, structure, system).

Beginning with “Materials”, industrial wastes and concrete demolition debris are incorporated into “green”

materials designed and produced for a specific set of

material properties. Within “Structure”, green materials are constructed into specific structural shapes using sustainable construction techniques to achieve more sustainable structural properties, such as high durability and fatigue resistance. Within “System”, these properties are elevated to enhanced service life under combined mechanical/environmental loads, based on long-term materials/structures behavior and maintenance regimes, thus resulting in higher sustainable performance for the entire system, from cradle (material and structural design) to cradle (recycling of industrial waste streams and demolition waste).

Within “Evaluation”, life cycle analysis and economic modeling of a specific application ranges from raw material acquisition, through construction, use, and end-of-life, to produce a set of environmental, social, and economic sustainability indicators. These indicators allow for evaluation of overall infrastructure sustainability and serve as feedback to redesign material inputs (i.e. greener) and material properties (i.e. stronger) through an iterative design loop. This framework relies on the collaboration of numerous disciplines such as material science, civil engineering, geology, industrial ecology, environmental economics and policy, and environmental health science.

Using this collaborative materials-based approach to sustainable infrastructure, Keoleian et al.^{15,16} have shown significant improvements in the sustainability of conventional infrastructure systems using new advanced materials. Performing a comparative life cycle analysis on a conventional bridge deck and a newly implemented bridge deck built with a ductile concrete recently developed at UM, life cycle agency costs were reduced by 27%, user costs reduced by 14%, and environmental impact costs reduced by 28%¹⁶. In addition to cost savings, significant reductions were realized in life cycle primary energy

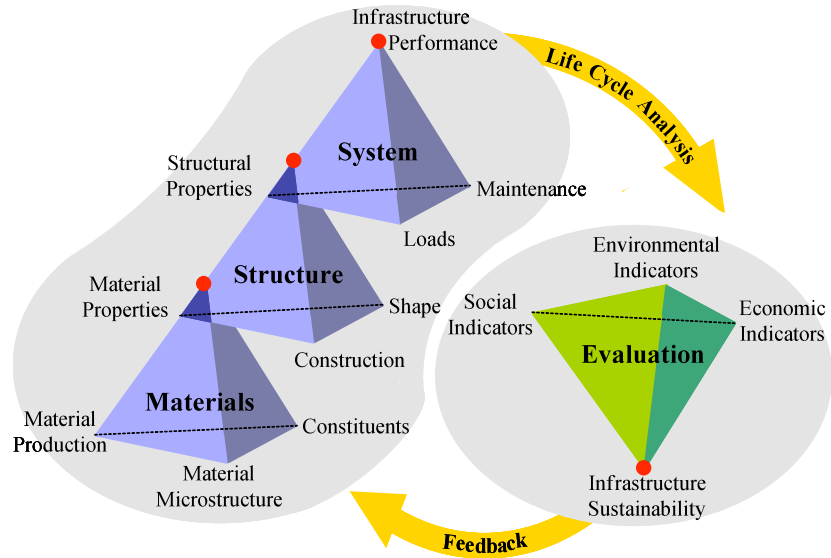


Figure 1. SIMMS Design Paradigm

consumption, along with CO₂, NO_x, SO_x, and PM₁₀ emissions¹⁵. Such results are highly suggestive of the ability of new materials to significantly elevate the sustainability of concrete infrastructure systems.

2.1 Problem Statement

Within the sustainable development community, large concrete infrastructure systems are typically seen as inherently unsustainable and responsible for automobile pollution, urban sprawl, and supporting increased consumption. Within the US specifically, the rapidly deteriorating and highly unsustainable concrete infrastructure system currently in use is reaching the end of service life, but remains essential in maintaining present living standards and economic vitality. Yet replacing this existing system using 60 year old techniques simply sentences the next generation to increasingly outdated and unsustainable infrastructure. Using the proper cradle-to-cradle mindset, infrastructure systems can be designed, built, operated, maintained, reconfigured, and recycled in a highly sustainable fashion. Through adoption of an integrated design framework for sustainable infrastructure, durable prefabricated elements can become an important element of highly sustainable infrastructure systems.

In the context of President Obama's recent focus on "green industries" and infrastructure renewal to stimulate the US economy, the development of construction techniques, materials, and design methods for more sustainable infrastructure are highly pertinent to the broader construction industry. More specifically, this work fits into research being conducted by CII Research Team 250 (Sustainable Design and Construction) and CII Research Team 265 (How do we use industrial engineering/manufacturing techniques for enhancing construction project performance?)

3 Methods and Framework

3.1 Prefabricated Durable Infrastructure - A Sustainable Concrete Solution

A number of recent advances in the diverse fields of cementitious materials development, structural engineering, manufacturing, construction engineering and management, and infrastructure life cycle assessment are being brought together to provide a more sustainable solution to infrastructure design, construction, operation, maintenance, and end-of-life management. The fast, on-site assembly of manufactured infrastructure components which are durable, environmentally friendly, and reusable looks to be a watershed in the challenge to develop sustainable infrastructure systems.

The success of durable prefabricated infrastructure components will be rooted in the development of Engineered Cementitious Composites (ECC), a unique class of highly ductile cement-based materials developed by PI Lepech at Stanford^{24,25} (Figure 2). Unlike concrete, ECC reveals an elastic-plastic stress-strain curve in tension, similar to that of ductile metal, and demonstrates a strain capacity 500-600 times greater than normal concrete. The constituent materials in ECC are similar to normal fiber-reinforced concrete (i.e. cement, sand, water, fibers, and chemical additives)²⁶ but are tailored in type, size and content to act synergistically under load to suppress brittle fracture²⁷. Due to its ductility, ECC has shown to be more durable than traditional concrete²⁸, and has incorporated numerous industrial wastes such as fly ash²⁹, waste foundry sand³⁰, and cement kiln dust²² to improve material sustainability while not sacrificing performance.

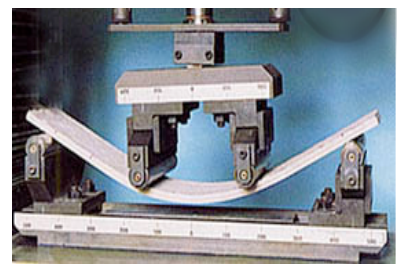


Figure 2: ECC under bending load

The Federal Highway Administration has introduced a nationwide initiative towards prefabrication of infrastructure components for faster, higher quality construction and diminished impact on motorists³¹. By taking advantage of prefabricated construction techniques, the construction and operational sustainability of other infrastructure systems can also be increased^{32,33}. Figure 3 exhibits precast concrete

construction techniques already in use for highway systems. ECC materials are especially suited for such applications. Due to their high ductility, ECC components can be bolted together³⁴, similar to metal components, greatly accelerating construction and allowing for reuse of structural pieces not possible with cast in place or precast concrete elements which must be cemented together due to their brittle nature. Additionally, the versatility of ECC which can be self-consolidating for casting³⁵, spraying^{36,37}, or extrusion³⁸ allows for adoption of highly efficient manufacturing practices of even thin walled structural members.

The overall framework used to tie together the diverse disciplines and research efforts within this work is shown in Figure 1. Different from previous work however, manufacturing and construction of prefabricated elements will be considered, along with associated logistical concerns. Additionally, social impacts related to changes in cement and construction industry structures will be evaluated, providing a more comprehensive assessment of the sustainability of the proposed system. Based upon the design loop shown in Figure 1, efforts will progress toward sustainable infrastructure through an iterative process relying on feedback from the overall infrastructure sustainability assessment to guide the multi-scale engineering design. Using SIMSS, all pieces of the proposed work are neatly integrated in a collaborative multi-scale framework allowing for efficient and productive efforts of each research area.

The overall research will be led by PI Lepech, and due to limited time and resources, a single concrete infrastructure application will be modeled. While the sustainable infrastructure design framework is broadly applicable to any infrastructure system, the scope of this project will focus on a section of concrete interstate highway with two concrete overpasses, one for local vehicle traffic and one for rail (Figure 5). Making up nearly 25% of the cement market, analysis of public construction such as roads and bridges, will be a significant indicator of trends throughout the cement and concrete product manufacturing sector³⁹. Within this boundary, all inflows and outflows will be monitored along with transportation of goods and people across system boundaries to fully capture economic, environmental, and social impacts of the proposed system.

3.2 Development of Green ECC Material with Prefabrication Functionality

While reinforced concrete can be either cast-in-place in the field or precast in large molds, ECC is uniquely suited for prefabrication due to a variety of potential processing methods. Such processes can significantly improve the speed and efficiency of prefabrication, thereby enhancing sustainability through



Figure 6: Extruded ECC Pipe

shorter construction times and less waste. Kong et al.³⁵ has demonstrated self-compacting ECC, eliminating the need for energy intensive and noise-polluting vibration. Kim et al.^{36,37} has demonstrated sprayable ECC, improving construction speed and allowing for intricate prefabrication. Stang et al.³⁸ has extruded ECC water pipes, eliminating much of the waste associated with casting (Figure 6). While this research focuses on transportation infrastructure elements, pipes are shown for illustration.

However, each of these technologies has been demonstrated for ECC containing virgin materials. Green ECC mixes incorporating wastes such as waste carbon nano-particles have yet to be developed with this variety of processing functionality. Initial research will focus on imparting such versatility on green ECC while not sacrificing the unique material properties (i.e. tensile ductility, etc.) necessary for durable infrastructure. Additionally, preferred



Figure 3: Precast highway bridge construction

prefabrication methods will be identified based on minimum ecological impacts, while still meeting production demands and quality assurances.

3.3 Development and Testing of Jointed Prefabricated ECC Elements

As mentioned previously, the use of ECC for prefabricated infrastructure opens up a wide range of construction options not possible with cast-in-place or precast concrete. Concrete elements must be cast monolithically or cemented together rather than bolted like metal. This is due to concrete's brittle nature when in direct contact with steel members, such as bolts. Ductile ECC has been shown to withstand bolting forces without brittle failure, even under earthquake loads³⁴, allowing for faster construction and easier assembly. Most exciting is the possibility to reuse basic elements after disassembly, resulting in virtually no waste at end-of-life. Such reuse is not possible with traditional concrete due to the permanence of cast-in-place or precast concrete. Research will focus on the design of interlocking or bolted prefabricated ECC elements, along with load testing of joints to validate safe design.

Within the selected system this includes the development of roadway pavement slabs out of green ECC material that are not only resistant to cracking due to improved tensile characteristics, but if damaged can be replaced in cost-effective modular sections. In this case, overnight construction of roads could virtually eliminate traffic congestion due to daytime pavement reconstruction events⁴⁰.

3.4 Prefabricated Construction and Operations Modeling

To demonstrate the advantages and quantify the impact of the proposed prefabricated construction techniques on sustainability, the research team will: a) document the sequence of construction operations required to erect a structure using traditional cast-in-place techniques; b) design and verify the soundness of construction operations and resulting constructability of a structure using prefabricated construction techniques; and c) quantify the impacts on construction (i.e. time of construction, fuel consumption, construction waste generation, length of traffic closures, etc.) when constructing a structure designed using prefabricated elements. The design and comparison of alternate construction techniques and measurement of their impact on sustainability will be performed using discrete-event simulation.

Discrete-event simulation (DES) is a powerful objective function evaluator well suited for the comparison of alternate construction methods⁴¹. For each method, process models that describe the construction operations required to erect the structure will be created. These models consider the different resources required to carry out construction, the rules under which different operations tasks are performed, the managerial decisions made, and the stochastic nature of events. The modeled operations will then be digitally simulated and the statistical measures of operational performance studied.

The results will include the cost and time of construction as well as resource utilization rates, waiting time and length at queues, service interruption times, etc. The results will allow for verification of the construction techniques to be used with prefabricated concrete elements and will allow for objective comparison and demonstration of impacts on sustainability. Simulation results will also point out important parts of the operations with potential for improvements that may result in cost or timesavings.

3.5 Life-cycle modeling and Economic Analysis

The prefabricated infrastructure life cycle system consists of material production, prefabrication, construction, use, repair/reconfiguration, and end-of-life, all of which are defined by specific material inputs and infrastructure applications. The ECC material composition and prefabrication method also determine material mechanical properties that ultimately influence system performance and service life. The sustainability of the system will be assessed using environmental, economic and social indicators.

Environmental impacts for each infrastructure system will be evaluated using LCA methods in accordance with ISO 14040⁴². Application of a newly created model for traditional infrastructure

construction¹⁴ has recently identified numerous environmental improvements that can be made throughout the service life of large infrastructure systems. Although some elements of the current model are applicable to new infrastructure materials and prefabricated construction, additional development is required to evaluate materials and construction techniques considered in the proposed work.

The economic impacts will include comparison of the current decision-making approaches of agencies in charge of selecting materials with a life-cycle approach including all external costs. The latter approach provides more comprehensive information for social decision-making. Current approaches may lead to biased decisions because of emphasis on short-run factors and lack of consideration of externalities.

Additionally, economic impacts on the entire cement and concrete products manufacturing sector, along with the construction industry as a whole, will be considered. The proposed move toward prefabricated building may result in radical changes to this industry structure, shifting it closer to manufacturing in terms of material flows and supply chain. Such industry restructuring will undoubtedly result in numerous economic impacts related to private investment, the relationships between suppliers and customers, and the role of public agencies that are often the owner of transportation systems.

Infrastructure systems are associated with many social impacts, including delays and productivity losses, disruption of public services, traffic and worker safety, noise, and social equity. These impacts will be addressed using both aggregated and scenario-specific approaches. Delays and productivity impacts due to construction and maintenance of highways and bridges, will be estimated using traffic routing models⁴³. Major social impacts which arise from the industry restructuring mentioned previously will also be studied, most notably employment variations due to changes in strategy or operating location.

4 Relationship to CIFE Goals

Specifically, this effort meets the stated CIFE goal of increasing the *sustainability of building systems*, the *integration of specialized models developed from distinctive perspectives*, and the *automation of project activities* by:

1. Fostering development of materials and the constructed facilities in which they are used in an integrated fashion – realizing that material properties (i.e. crack resistance, ductility, etc.) can be tailored to improve construction efficiency, cost, and sustainability.
2. Bringing together a number of models including material science models, industrial operations models, industrial ecology models, and economic models to solve a complicated design, construction, and operation problem.
3. Allowing for improved automation and prefabrication of complex infrastructure facilities using extruded elements, precast elements, and directly bolted cement-based elements.

5 Industry Involvement

A number of industry partners, including current CIFE members, have agreed to support this work in a number of ways.

- *Walt Disney Imagineering* – As an integrated building designer, contractor, owner, and user, WDI has expressed interest in the use of these materials and other prefabrication elements. While Discussions with Ben Schwegler have yet to realize any finalized project involvement, the use of such materials for prefabrication is being explored.
- *Federal Highway Administration* - In its recent workshop on the Use of Nanotechnology in Infrastructure the Federal Highway Administration (FHWA) pointed to the use of nano-

technology to tailor materials for improved construction approaches (“get in and get out”) as a major early stage research initiative. The proposed work fits well within this large goal through the use of waste carbon-nanoparticles to tailor materials specifically for improved prefabrication performance.

6 Research Tasks and Deliverables

6.1 Green ECC Materials Technology Development

Using micromechanical models developed for ECC material modeling by PI Lepech and others, a number of waste materials will be incorporated into ECC specifically for the improvement of prefabrication processes (i.e. castability, extrudability, finishing). A series of material mix designs and accompanying performance metrics will be developed.

6.2. Prefabricated Infrastructure Testing

Using the ECC mix designs developed in section 6.2, a small number of meso-scale structural elements will be fabricated to test the performance of bolted ECC elements in monotonic and fatigue loading scenarios. This will serve as a validation of the proposed concept for large scale prefabrication of pavement sections, structural infrastructure sections, and facility components. These performance characteristics will lead directly into operations and life cycle assessment models.

6.3 Construction and Operations Modeling

Discrete-event simulation will be used as an initial evaluation technique for comparison of alternate construction methods for traditional construction and prefabricated construction techniques using ECC bolted elements⁴⁴. For each method, process models that describe the construction operations required to erect the structure will be created. The results will allow for verification of the construction techniques to be used with prefabricated concrete elements and will allow for objective comparison and demonstration of impacts on sustainability.

6.4 Life Cycle Modeling and Economic Analysis

Environmental impacts for each infrastructure system will be evaluated using LCA methods in accordance with ISO 14040⁴⁵. Application of a newly created model for traditional infrastructure construction¹⁴ has recently identified numerous environmental improvements that can be made throughout the service life of large infrastructure systems. Although some elements of the current model are applicable to new infrastructure materials and prefabricated construction, additional development is required to evaluate materials and construction techniques considered in the proposed work.

6.5 Research Schedule and Milestones

Activity	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1. Material Modeling Activities												
1.1 ECC Performance Verification	■	■										
1.2 Green ECC Material Development		■	■	■								
2. Experimental Testing of Prefabricated Elements												
2.1 Fabrication of Test Setups				■	■							
2.2 Experimental Testing of Bolted Infrastructure Elements					■	■	■	■				
3. Construction and Operations Modeling												
3.1 Assembly of Construction Process Models in VDC Model								■	■	■		
3.2 Construction of DES model										■	■	
4. Life Cycle Assessment												
4.1 Life Cycle Inventory									■	■	■	■
4.2 Life Cycle Impact Assessment of Individual Systems											■	■

Research Milestones

- Month 4 – Completion of Green ECC Mix Designs with Prefabrication Functionality
- Month 8 – Completion of Bolted Infrastructure Element Experimental Testing
- Month 10 – Initial Running of Construction and Operations Model
- Month 12 – Development of life cycle assessment model and impact assessment profile

6.5 Deliverables

- A green ECC mix design procedure and associated material properties that are tailored to work with prefabrication processes.
- Bolt-together ECC prefabricated element test data and fabrication specifications.
- Complete life cycle assessment comparison and toolbox for designers, contractors, and facility owners to fully evaluate the economic, social, and environmental costs of such a new prefabrication system.

6.6 Research Risks and Management

A number of risks are associated with the completion of this research. These include:

- The inability to procure adequate industrial waste streams for ECC materials development due to environmental regulation or occupational safety.
- Inability to construct realistic construction/assembly timelines due to low industry involvement.
- Inability to construct an accurate life cycle inventory due to lack of supply chain or life cycle dataset availability.
- Difficulty in integrating the large number of modeling tools and software platforms that are needed to support this work.

To better mitigate these risks, and allow for simultaneous research progress, the tasks have been compartmentalized as much as possible. If necessary all elements of the research can proceed without related research by using surrogate models or substitute materials. The results of individual work segments will still comprise a unique contribution to academic literature and industry practice. By

compartmentalizing risk, we are able to improve the likelihood that valuable output from this project will be realized.

7 Next Steps

Numerous funding opportunities exist for large-scale infrastructure research projects based on the proposed work. A fully developed sustainable infrastructure program could involve transportation, building, or water distribution systems. Potential funding organizations include:

- *Federal Highway Administration (FHWA)* – Prefabricated bridge elements and systems are listed as one of FHWA’s “Priorities, Market-Ready Technologies, and Innovations”³¹. While current precast concrete construction is seen as a large improvement upon cast-in-place technology, the advantages of prefabricated ECC components are expected to be superior to precast concrete.
- *National Science Foundation (NSF)* – NSF has recently emphasized sustainable infrastructure systems both in its Bioengineering and Environmental Systems Division and its Civil and Mechanical Systems Division. In the current engineering directorate reorganization, sustainability has received increased prominence and the contribution this project will serve as a competitive research direction both in the new Civil, Mechanical, and Manufacturing Innovation Division, as well as in the sustainability program within Chemical, Bioengineering, Environmental, and Transport Systems division.
- *World Bank* - While having less tradition in supporting fundamental engineering/sciences research than NSF, the World Bank can serve as a partner in later stages of this project, especially in support of field trials for ECC technologies with promise to improve economic and environmental sustainability of developing countries. With such contacts established, ECC technology can permeate the World Bank’s technical assistance function in applications such as structures, roadways, and water systems. This can be an important vehicle for diffusing ECC technologies into the mainstream.
- *Ministry of Transportation, Beijing, China* – This ministry is responsible for research and design of next generation transportation infrastructure in China. Initial contacts have established high interest in ECC with potential collaborative R&D efforts for the Chinese market. China also offers enormous opportunities for demonstration in a country where harmonious co-existence between the expanding built environment and fragile natural environment is increasingly critical.

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