Sustainable Concrete Infrastructure Materials and Systems: Developing an Integrated Life Cycle Design Framework

1 Background and Problem Statement

1.1 Materials, Infrastructure and Sustainability: Research Frontiers Traditionally, materials engineering has focused on the interplay between material microstructure, physical properties, processing and performance[1]. Using this paradigm, Li successfully developed a ductile cementitious composite reinforced with fiber, known as engineered cementitious composites (ECC)[2]. He employed micromechanics as the analytical tool to guide microstructure tailoring of ECC. While this approach delivered favorable physical characteristics, such as extreme ductility and durability, it did not address the new material's impacts on infrastructure sustainability. To address this shortcoming, a materials engineering methodology must be developed that incorporates social, economic, and environmental indicators – the three dimensions of sustainability. The proposed research will accomplish this task and provide a critical tool for use across a broad class of materials and infrastructure applications.

1.2 Concrete Infrastructure: Performance and Impacts Global output of construction-related concrete exceeds 12 billion tons per year[3]. This enormous volume represents huge flows of material between natural and human systems, which is expected to increase significantly as world population urbanizes[4]. Environmental, economic, and social performance of current infrastructure systems is deficient[5,6]. Cement production is very energy intensive and accounts for 5% of global anthropogenic CO_2 emissions[7,8] and significant levels of SO_2, NO_x, particulate matter and other pollutants[9-11]. Its brittleness and limited durability lead to significant infrastructure failure and repair. One-third of US roadways are in poor condition[5], burdening society with large capital investments and construction-related impacts such as congestion[12].

1.3 Alternative Infrastructure Material: Engineered Cementitious Composites (ECC) ECC is a unique fiber-reinforced material with a microstructure design driven by micromechanical principles[13,14]. Unlike other concrete materials, ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates a strain capacity 500-600 times greater than normal concrete[14]. Other characteristics of ECC include a fracture toughness like that of aluminum alloys[15], extreme damage tolerance[16] and ductility under severe shear loading conditions[17]. ECC contains ingredients similar to those in fiber-reinforced concrete (e.g., water, cement, sand, fiber and chemical additives); coarse aggregates are notably absent in ECC. The amount of fiber (e.g., polyvinyl alcohol and polyethylene) in ECC is generally 2% or less by volume. Potential infrastructure applications include building frames[18], bridge piers[19], bridge deck repair[20], extruded pipes[21] and roadway repairs.

1.4 Problem Statement: Sustainable Design of New Infrastructure Materials Currently, only functional performance and financial cost guide the design of new infrastructure materials. A new life cycle framework to integrate broader social, environmental and economic issues into the R&D and application of new materials is critical for achieving sustainable infrastructure; this is the focus of our research. The diverse nature of impacts, the range in scale (nanometers in materials science to kilometers in the geological sciences), the long-lived nature and consequences of infrastructure systems, and institutional barriers for implementing new materials, highlight the complexity of this project. Our framework will be developed and tested using ECC to enhance the sustainability of public infrastructure. It will be transferable to the design of other emergent materials and complex systems.

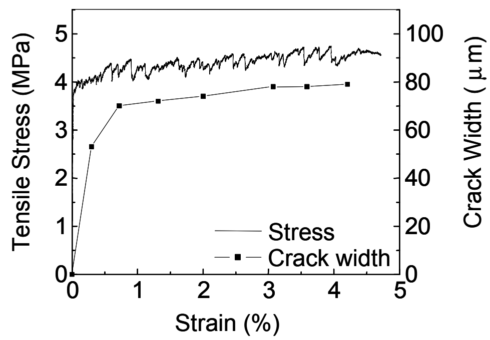
2 Results of Prior NSF Support

CMS-0223971 $110,000 Sept. 2002 to Aug. 2003
PIs: G.A. Keoleian, V.C. Li, S.E. Kesler, R. E. Robertson, S. A. Batterman, M.R. Moore
Project Title: "Sustainable Infrastructure Materials and Systems: Integration of microstructure tailoring and life cycle analysis of engineered cementitious composites (ECC)"

During the period from September 2002 – February 2003, the six principal investigators conducted exploratory research for this proposal, convened a series of six workshops[22-27] and established partnerships with government and industry that have led to the formation of an Advisory Group (Section 8). A "microscale" team tested new formulations of ECC while a "macroscale" team developed a life cycle model to compare the current ECC mix with conventional concrete for application to a bridge deck. Year one research provided valuable training for ten students and two research staff and contributed to the thesis work of two students on the macroscale and microscale teams[28,29]. Preliminary results will be presented at the 2003 International Society of Industrial Ecology, 2nd Annual Conference in June 2003[30].

2.1 Microscale Research and Preliminary Development of Green ECC Microscale research activities focused on: 1) determining the required mechanical properties of link-slabs to prevent cracking and leakage of concrete bridge decks, 2) establishing an industrial waste materials database for use as possible substitution materials for "green" (environmentally preferable) ECCs, and 3) assessing properties of ECCs containing fly ash, calcium sulfoaluminate (CSA) cement, or recycled carpet fibers. Structural mechanics analysis revealed that the most important properties required for link-slabs are tensile strain capacity (ductility) and crack width control for durability, while also considering compressive strength and freeze-thaw resistance. The minimum ductility required to withstand temperature/drying shrinkage induced movement and live-loads was found to be 1.4%, while the crack width should be below 100 μm to minimize water/chloride penetration. These requirements are difficult if not impossible to attain for normal concrete, but easily achievable with the current ECC mix. The macroscale team determined that the polymeric fiber together with the high content of portland cement account for the majority of the material production energy necessary for the current ECC mix. Hence, our investigation of materials design for sustainable infrastructure focused on substituting materials to improve the environmental performance.

One solution is to replace fiber, cement and other components in the current ECC mix with industrial by-products, provided that the physical properties of the resulting "green" ECC would still fulfill the requirements prescribed by a particular application. For example, recycled carpet fiber leads to lower tensile strain capacity ECC that may still be acceptable for link-slab applications. Initial cement substitution tests, which vary the amount and type of fly ash and bottom ash used, indicated that the resulting ECC mixtures exhibit a tensile strain capacity of 2-5%. Figure 1 shows that the strain capacity and crack width satisfy the performance requirements for link-slab application exceedingly well for a green ECC mixture with 45% less cement than the current ECC mix. The use of post-consumer carpet fiber in the current ECC mix reduced the strain capacity to 1% when 40 M% (M = mass) of virgin PVA fiber was replaced, but showed little negative effect at 10 M% replacement. At higher replacement percentage, micrographs of the fracture surface indicated severe entangling of the carpet fibers that may act as large defects and limit the composite performance. Some of the microscale test results showing stress/strain performance are presented in Table 1.



Materials Tested	Compressive Strength (MPa)	Tensile Strain Capacity (%)
Conventional Concrete	35.0	0.02
Current ECC mix	65.0	5.0
High Fly Ash ECC mix	33.0	3.8
ECC with Carpet Fiber	55.0	2.1

Fig. 1 Tensile stress-strain curve of ECC with high fly ash content, at 28 days – exceeds the properties required for link-slab applications (portland cement 318 kg/m^3, class F fly ash 701 kg/m^3, sand 701 kg/m^3, water 289 kg/m^3, PVA fiber 26 kg/m^3). **Table 1. Microscale test results of conventional concrete and various ECC mixtures.**

The overall conclusion from Year One investigations is that the development of greener ECC, based on sustainability indices, such as energy consumption, is feasible. The deteriorated properties, due to the use of low quality substitutions, can be offset by micromechanical tailoring of the ingredients. Performance reduction in infrastructure applications is expected to be minimal, while sustainability indices are greatly enhanced.

2.2 Macroscale Modeling Results For Bridge Deck Simulation A life cycle model was created to evaluate environmental, economic and social indicators for a bridge with either conventional concrete joints or ECC link slabs. Life cycle inventory modules were constructed using data from the Portland Cement Association, the Michigan Department of Transportation, a local bridge contractor, the Kentucky Transportation Center's KyUCP model[31], US EPA's MOBILE6.2[32] program, and other sources. The scope of the analysis covered a 60-year time horizon and incorporated projected changes in several model parameters (e.g. vehicle miles traveled, fuel economy). Figure 2 below presents preliminary results for life cycle energy consumption, CO_2 emissions, and solid waste production. ECC shows a significant advantage over the conventional system. While ECC is more energy and carbon intensive on a per volume basis than conventional concrete, its longer expected service life extends the bridge deck life, resulting in lower total life cycle emissions and energy consumption. The cost model tracks agency and social costs for all life cycle stages. Agency costs include the costs of material production and distribution, construction (e.g. equipment, labor, fuel) and end-of-life (equipment, fuel and labor needed for demolition and disposal/recycling). Social costs include costs related to fatalities and injuries, productivity losses (personal and freight), vehicle operation, vehicle congestion, and emissions-related environmental health impacts. The total agency costs are \$770,000 and \$910,000 for the ECC and the conventional concrete systems, respectively. Total social costs amounted to \$1.1 million for the ECC system and \$1.4 million for the conventional concrete system demonstrating the magnitude of social costs and importance of life cycle modeling.

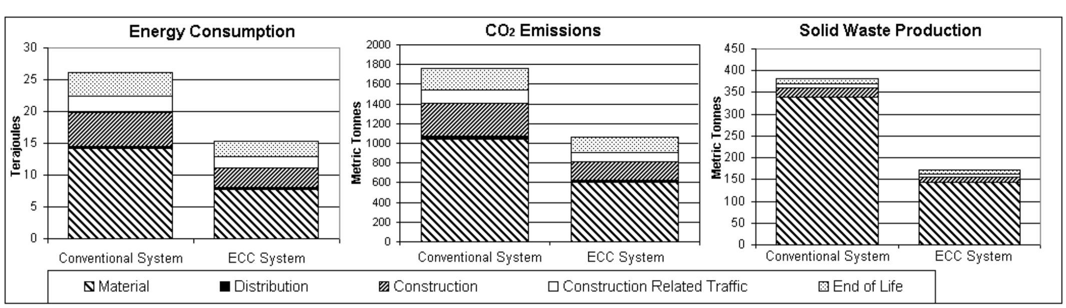


Figure 2: Preliminary Life Cycle Inventory Results for the Conventional Concrete System and the ECC System over a 60-year time horizon.

3 Objectives and Broader Impacts

3.1 Project Objectives Building upon current research, the multi-disciplinary team from civil engineering, materials science, industrial ecology, environmental economics and policy, geology, and environmental health sciences has developed the following set of project objectives:

- *Develop a novel material design framework that integrates microstructure tailoring and macroscale life cycle modeling*. This framework will enable the design and implementation of new infrastructure materials that address environmental, social, and economic performance objectives including resource use, human and environmental health, and agency and social costs.
- *Apply this framework to the design of ECC formulations that enhance sustainability of bridge deck, roadway and pipe infrastructure*. Life cycle performance of ECC will be evaluated relative to conventional concrete to improve its design. A range of alternative inputs that include industrial and municipal wastes and bio-based feedstocks will be characterized and tested.
- *Examine material flow implications of ECC use in infrastructure and the effects of mining operations (superquarries vs. smaller mines) and infrastructure location (urban vs. rural / U.S. vs. China) on sustainability performance.* Geospatial factors will be studied to inform material sourcing strategies and the design of specific ECC formulations. Material budgets for alternative ECC input materials will be evaluated.
- *Provide policy recommendations that incorporate life cycle analysis into major design and construction decisions.* Recommendations to overcome institutional barriers that hinder the use of more sustainable materials, such as ECC, will be developed to enhance decision-making for stakeholders (e.g., materials scientists, public works engineers, government budget specialists).
- *Advance scholastic and professional education in sustainable infrastructure materials.* Educational goals will be met by student training through laboratory research and life cycle modeling, seminars and team workshops, and by creating an educational resource compendium.

3.2 Expected Significance and Broader Impacts Meeting the project objectives will provide more sustainable alternatives for the U.S. and other developed countries to employ as they rebuild their aging infrastructure. Also, developing countries can particularly benefit from these alternatives as they rapidly expand their infrastructure in the coming decades. Broader impacts include:

- A novel, integrated life cycle design framework that can be applied to the design of ECC and other new materials.
- A new set of ECC formulations that incorporate industrial/municipal by-products and bio-based materials. These formulations will extend infrastructure service life, minimize agency and social costs, reduce traffic congestion/productivity losses, and improve human/environmental health.
- The development of life cycle material flow diagrams for cement. These will compare the current base case using conventional concrete against various scenarios of ECC substitution. Results will guide decisions about raw materials, such as whether to acquire them from superquarries or from smaller, more distributed mines.
- Increased opportunities for interdisciplinary education and research training for postdoctoral, doctoral, undergraduate and minority high school students.
- A new generation of civil engineers, materials scientists, and environmental and social scientists who are competent in life cycle modeling techniques and can further advance the knowledge base and practice of sustainable infrastructure design.
- An expanded network of national and international collaborators from academia, government agencies and labs, business and industrial associations, and NGO’s (Sections 7 and 8).

4 Research Methodology

4.1 Conceptual Framework A conceptual framework will facilitate research across the four main areas of complexity highlighted by Figure 3. *Multi-scale boundaries* range from nanometers in materials science and engineering (e.g., ECC design and testing) to kilometers in the geological and environmental sciences (e.g., life cycle modeling and evaluation). *Multi-disciplinary expertise* reflects the need for contributions from diverse academic disciplines, and collaboration with industry and government experts (Sections 7 and 8). *Multi-criteria sustainability indicators* encompass performance and evaluative criteria for judging design decisions (e.g., material durability, structural integrity, life cycle emissions and energy consumption, land use, human health impacts, and social and agency costs). *Multi-project infrastructure applications* including bridge decks, roadways and pipes pose unique challenges for sustainable design.

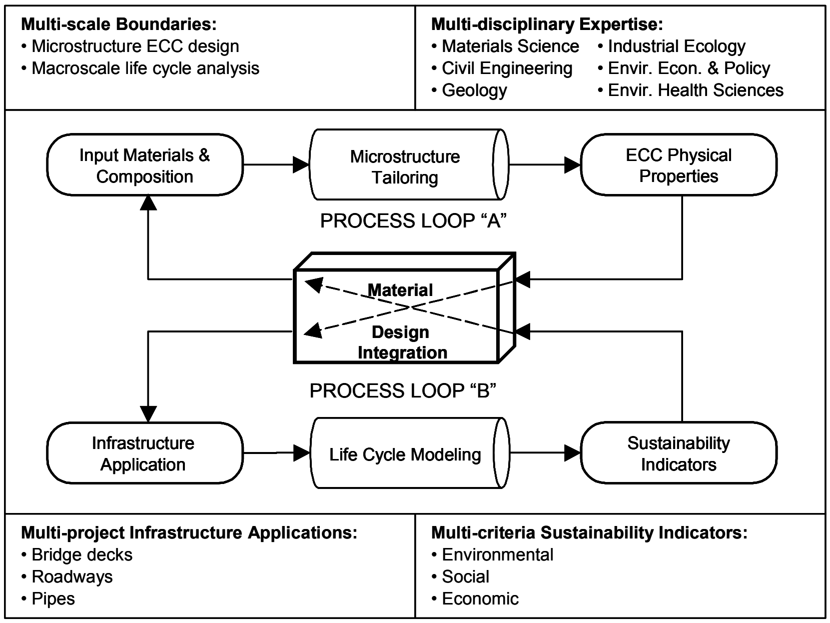


Figure 3. Integrated Materials Design Framework for Sustainable Infrastructure

Figure 3 demonstrates the challenge of sustainable design within these dimensions of complexity. Traditionally, process loops "A" and "B" have existed separately. Materials scientists and engineers have focused on a limited set of performance criteria in design activities within loop "A," while industrial ecologists, economists and geologists have maintained a macro-level perspective for analyzing the life cycle of infrastructure systems within loop "B." Prior to this work, no meaningful link has existed between these two loops.

The proposed framework will ensure regular flows of information between these two loops, shown as "Material Design Integration" in Figure 3. ECC formulations developed in loop "A" are translated into material and energy inputs for life cycle analysis in loop "B." The environmental, social and economic performance indicators developed throughout this process can be used to guide changes in material design in order to optimize system performance. This iterative design, evaluation, and re-design sequence fully addresses the four complexity dimensions, and it can be repeated until satisfactory solutions are reached.

4.2 Disciplinary Contributions

4.2.1 Civil Engineering and Materials Science: Expanding Design Requirements Infrastructure design has traditionally optimized structural shape and dimensions with given material properties to meet structural performance requirements. Prescriptive structural design codes are gradually giving way to performance-based design codes that permit greater choice in material and shape, provided structural performance requirements are met. Significant innovation is achieved by integrating structural design and materials engineering. Adding life cycle environmental, social and economic analysis to this "integrated structure-materials design approach"[33]provides the essential elements of sustainable infrastructure design.

4.2.2 Industrial Ecology: A Scientific Basis for Assessing Infrastructure Sustainability Industrial ecology is the systematic analysis of global, regional and local material and energy flows associated with products, processes, economic sectors and other complex systems[34-36]. Life cycle assessment (LCA) quantifies these flows and evaluates impacts that occur during materials production, manufacturing, use, and end-of-life stages [37-39]. The proposed research differs from previous LCA studies of infrastructure and building applications[40-45] by addressing material design and implementation, and by using economic and social indicators. This work builds upon the PI's previous life cycle design research that integrates environmental, performance and cost requirements into product development [46-51].

4.2.3 Environmental Economics: Assessing Infrastructure's Full Social Costs and Benefits Standard accounting for construction projects emphasizes the initial cost of materials, labor and equipment, and ignores the total cost. Life cycle costing methods account for maintenance and repair costs[52,53], but rarely account for external social costs. Environmental economics methods incorporate externalities[54,55], which can be very extensive for infrastructure. These include pollution costs[56,57], traffic congestion from construction and repair, and increased fuel use, emissions and travel time[12,31]. Failure to consider these costs results in sub-optimal decisions and lower net social benefits.

4.2.4 Economic Geology: Reserves, Mining and Environmental Implications Cement is the largest volume of material used in construction, with about 85 million tons of cement produced annually in the U.S. from about 150 million tons of rock material[3,58]. Another 150 million tons of sand, gravel or crushed stone is mined for the >50% aggregate in concrete, the form in which most cement is used[59], making it one of the largest agents of land disturbance. The location of these disturbances is strongly affected by geology and transportation. The distribution of rock suitable for cement raw materials and aggregate is highly variable. Because they are relatively low value materials, long transport distances, particularly by land, add greatly to cost. Thus, inefficiencies in locating mines, kilns and associated operations can greatly increase burdens. As population and urban sprawl grows, many good deposits will become inaccessible. These and other factors constrain the areas that are desirable or suitable for cement and concrete production, compounding costs and impacts.

4.2.5 Environmental Health Sciences: Impact Assessment Many methods are used to assess environmental and health impacts. Epidemiological studies have examined historical health outcomes, such as respiratory symptoms, in communities near cement kilns[60-62]. General ISO14040 indicators[37] and the traditional and expanded cumulative environmental impact analysis framework, encompassing scoping, assessment and evaluation phases, have been extensively used[63]. LCA inventories combined with damage functions can estimate costs of emissions. Aggregated modeling/ranking procedures, e.g., using fugacity models, estimate concentrations in environmental compartments for comparison to guideline limits. More detailed risk assessment methods can account for spatial and temporal factors and nonlinear dose-responses by simulating pollutant emissions, migration and fate, estimating exposure using demographics and activity factors, and assessing risks using pharmacokinetics and toxicology[64-69]. These methods can be data intensive and scenario-specific, involving trade-offs between model realism, data requirements and uncertainty[70-72]. Intermediate level methods using spatially explicit modeling and dose-fraction approaches are also available[73].

5 Research Plan

5.1 Research Scope The integrated life cycle design framework and ECC formulations will be developed, tested, and refined by investigating a range of materials (see Figure 4), three infrastructure applications, and three geographic scopes as indicated below:

Infrastructure Applications	Geographic Scope
▪ Bridge Decks	▪ Population Density: Urban / Rural
▪ Roadways	▪ Regional: Mid-West / Mid-Atlantic
▪ Pipes	▪ International: U.S. / China

5.1.1 Infrastructure Systems: Applications and Geographic Scope Bridges, roadways, and pipes are some of the most appropriate applications for ECC technology. ECC link slabs in bridge decks can eliminate deteriorating expansion joints, and ductile ECC strips within roadways can prevent cracking and vastly extend structural life. Maintenance and expansion of the nation's aging water/sewer infrastructure is of great concern. The ductility of ECC pipes allows them to carry loads more effectively without cracking/fracture failure, substantially limiting the loss of drinking water or transport of contaminants into the environment through leakage of wastewater. Given the impact of construction site location on sustainability performance, we will examine infrastructure applications at both urban and rural sites. Material production impacts related to the distribution of concrete mineral resources and material sourcing strategies will be studied for Mid-Atlantic and Mid-West regions. The life cycle model for roadways will be adopted to study infrastructure design for select sites in China. The exponential growth of infrastructure in China represents tremendous opportunities for enhancing infrastructure systems.

5.1.2 Alternative Infrastructure Materials ECC will be compared to conventional steel-reinforced concrete, the dominant infrastructure material. Further improvement in concrete performance is hindered by its inherent brittleness. Due to its metal-like ductility, ECC is expected to significantly increase infrastructure service life. ECC is composed primarily of cement, aggregates, and fiber. Fine aggregates, e.g. sand, (< 0.5 mm) are used to achieve uniform fiber distribution and to control matrix fracture toughness. Without coarse aggregates, the current version of ECC uses a higher amount of cement than normal concrete. Fiber (< 2%, typically polymeric, such as PVA) is needed for creating strain-hardening. Cement and fiber are energy-intensive and have large environmental impacts. Consequently, low energy content substitutes, such as industrial by-products or wastes, will be explored.

There is a wide variety of cementitious or pozzolanic by-products, including fly ash from coal combustion, bottom ash, silica fume, granulated blast-furnace slag from the steel industry, rice husk ash, and aluminum manufacturing potlining that can partially substitute for portland cement. Geopolymers[74,75], an inorganic network polymer made by mixing an alkali with reactive sources of silicates and aluminates, may also serve as an alternative binder. Fine aggregates can be replaced by industrial waste sands, such as foundry sand from metal casting industries, or by shredded plastic from disposed office equipment. Because the compressive strength of the current ECC is much higher than that needed for most applications, there is latitude to introduce other types of waste materials into ECC matrix as inert fillers. Possible wastes include waste chalk from the fertilizer industry, lime blended municipal wastewater sludge, municipal solid waste incinerator ash, and processed garbage. Waste polymer fibers from the auto and carpet industries are available as reinforcements. The partial substitution of virgin with recycled fiber and bio-based materials (e.g. banana fiber, sisal) will also be investigated.

5.2 Microscale Research Activities

5.2.1 Overview Figure 4 shows the links between ECC composition, mechanical properties, and infrastructure performance. The microscale research proposed for this project will identify a set of specific green ECC formulations for life cycle modeling (Section 5.3). Microstructure tailoring will be used to adjust the composition of ECC to achieve material properties prescribed by specific applications.

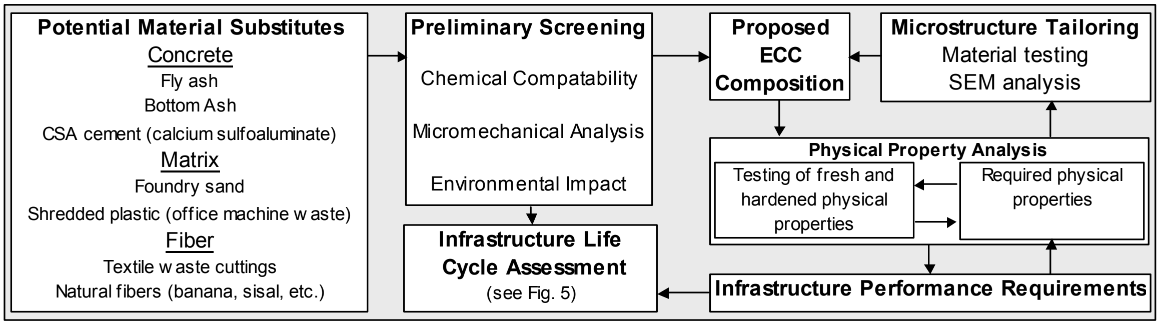


Figure 4. Details of Loop 'A' in Figure 3

5.2.2 Development of Material Screening Methodology This research will focus on the preliminary screening of ECC material compositions for extensive life cycle modeling. Material screening will be based on three criteria: *environmental assessment*– minimize material production burdens; *preliminary micromechanical analysis* –strain-hardening potential; *chemical compatibility analysis* – compatibility between substitute materials and the host matrix avoiding reaction products which lead to composite deterioration over time. To prioritize the large number of potential substitution materials in green ECC development, material sustainability metrics (e.g. material production energy) will be used to compare the environmental impact of different substitution materials. New versions of green ECC with selected substitution materials (a mix design) will then undergo material evaluations to determine the entire effect of these substitutions on engineering performance, such as strength, ductility, and crack width control.

Utilizing both material sustainability metrics and engineering performance of each mix composition, a series of material selection charts will be created similar to those developed by Ashby[76]. Green ECC formulations, as well as other concrete materials and the current version of ECC will occupy a specific space, defining the "bubbles" on Ashby's charts. These charts are used in conjunction with structural member performance index lines to optimally select materials for specific types of structural members (e.g. link-slabs in tension and bending, pavement slabs in tension, etc.) using a "multi-stage" material selection process. Such Ashby charts will be developed and explored for material selection for infrastructure members to achieve optimum structural performance and material sustainability metric. It should be pointed out that Ashby charts, while elegant, remain an initial screening tool in Loop A (Figure 3), since full sustainability assessment (Loop B) accounts for much broader dimensions than can be represented on Ashby charts. However, Ashby charts as described here do link information from Loop B to Loop A to initiate the proposed, much more comprehensive, iterative material design process.

5.2.3 Green ECC Development and Laboratory Testing ECCs are microstructurally designed based on the mechanics of interactions between the fiber, matrix and interface. As examples, the fiber has attributes of length, diameter, strength and elastic modulus; the fiber/matrix interface has chemical and frictional bonds; and the cementitious matrix has toughness, modulus and flaw size that can be controlled within a certain range. The tailoring process selects or otherwise modifies these "micromechanical" parameters so that their combination gives rise to composite tensile ductility, guided by micromechanical models[14]. The principles of micromechanics-based design will be applied to the development of green ECC, in combination with microstructural analyses based on Scanning Electron Microscopy (SEM) and other analytic tools.

Laboratory testing will be conducted at two scales. At the microscale, the interface parameters will be determined with the single fiber pull-out test[77]. In addition, matrix toughness will be characterized via double-torsion fracture testing. Flaw dimensions and size distribution will be quantified with SEM/fluorescent microscopy techniques. This information will be fed into the micromechanical model for checking the satisfaction of the theoretical tensile strain hardening condition. Once a green ECC composition is designed and specimens fabricated, mechanical testing for strain-hardening verification will be conducted. Tensile and compressive strength and strain capacities will be measured and compared with required properties to verify suitability for a specific infrastructure application. In addition, fresh properties will be measured by slump cone tests. Self-consolidation behavior will also be assessed with rheological tests[78].

5.2.4 Structural Testing and End-of-Life Studies The expected performance of infrastructure elements made with green ECC will be validated experimentally. In the case of ECC link-slabs, ongoing tests[79], sponsored by MDOT, will be expanded to include a green ECC link-slab. In addition, a field demonstration of this technology is planned for 2004 on a Michigan bridge. Freeze-thaw resistance, traffic load resistance, and crack development will be monitored. In the case of ECC pipes, a ring test will be conducted[21]. The deformation capacity and water leakage of the pipe will be monitored in buried (under soil) and unburied conditions. In the case of ECC ductile strip in pavements, laboratory testing of strip connectivity and inhibition of concrete cracking will be conducted at Tsinghua U. by our research partner. We will provide the green ECC material mix design and collaborate on data analyses. In addition, ongoing research on precast post-tensioned ECC bridge piers at Stanford U. will be extended to include a green ECC specimen. The recycling of CO_2 into ECC processing will be investigated in collaboration with Tohoku U.[80,81] (Section 7.1).

While much of this research is focused on materials development with ultra-long service life, demolition waste and costs may pose significant environmental, social, and economic burdens. High performance materials may inflate the demolition cost and time dramatically. We will conduct initial investigations on the demolition of ECC structural elements. Using current techniques (e.g. pneumatic hammers), demolition of ECC requires up to 10 times more labor than conventional concrete due to its extreme ductility. To overcome this burden, new techniques will be needed to destroy the ECC at the microscopic level, in effect unraveling the micromechanical tailoring performed in the original design of ECC. This research will focus on three areas: *matrix demolition* – attacking the matrix directly (water jetting / hydro-demolition); *fiber demolition* – attacking the fibers directly through methods such as heat treatment, destruction of the fiber will result in loss of ductility allowing for conventional demolition techniques; and *interface demolition* – attacking the critical interface between the mortar matrix and fibers through chemical processes. This last method changes the ductile ECC into a brittle material similar to concrete, after which conventional demolition methods can be used. A full investigation of demolition techniques will be beyond the scope of this research. However, we plan to develop future end-of-life projects, once concept feasibility is demonstrated for this project.

5.3 Macroscale Research Activities

5.3.1 Life Cycle Modeling of Infrastructure Systems The focus of macroscale life cycle modeling is highlighted in Figure 5. The infrastructure life cycle system consists of material production, construction, use, repair and end-of-life management processes, which are defined by the specific material inputs and infrastructure application. The ECC material composition also determines the material and mechanical properties that ultimately influence system performance and service life.

The sustainability of the infrastructure system will be assessed using environmental, economic and social indicators.

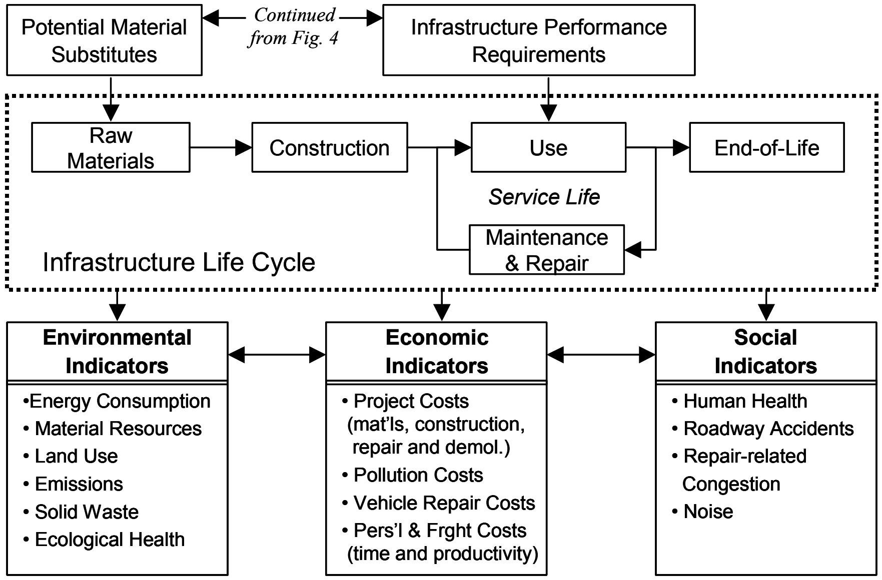


Figure 5. Macro-scale life cycle modeling

Environmental Modeling Using Life Cycle Assessment (LCA) Environmental impacts for each infrastructure system will be evaluated using LCA methods in accordance with ISO 14040 guidelines[37]. A bridge life cycle was modeled in Year One research. The development of this preliminary model has resulted in the identification of numerous improvements and additions that can be made, both to the bridge model and to proposed models for road and water pipe infrastructure. Although some elements of the current model are applicable to other infrastructure materials and systems, significant modeling work, as outlined in the research scope, is required to evaluate each alternative material, process, and application, and to better represent temporal variation.

It was revealed in the initial bridge model that energy consumption and emissions due to construction delays are large and variable. Small changes in the patterns of traffic growth over time result in large fluctuations in this stage of the life cycle. Improving methods for estimating these parameters is an important priority of this research. The long timeframe of the analysis also presents problems of parameter uncertainty, (e.g., in fuel efficiency and emission factors). Consequently, a range of scenarios will be developed to explore changes in consumption patterns and technological innovation. The importance of secondary effects such as vehicle damage and impaired fuel economy due to poor road conditions will be investigated using a life cycle model of a mid-sized vehicle previously developed by the Center for Sustainable Systems[82]. Modeling pipe infrastructure systems poses other unique challenges such as location-specific construction requirements, quantification of water leakage, and infiltration of contaminants. The life cycle inventory model will be designed to link inventory results (e.g., air pollutant emissions) with the social impact model to assess such impacts as human health effects.

Social Impact Modeling Initial analyses for each infrastructure system and case study scenario will use a screening level assessment, similar to that described earlier, but will consider a broader range of impacts, including on-site, local, regional and global scale impacts. Subsequent analyses for critical impacts will utilize intermediate to detailed level environmental and health risk assessment methods that incorporate spatially explicit modeling and dose-fraction approaches, in order to understand effects of locational and geographic factors. For example, changes in air pollutant concentrations assignable to changes in cement production and congestion will be estimated, followed by estimations of exposures, risks, and health outcomes for affected populations. Models and databases for such analyses are generally adequate, although in some cases uncertainties are high. Vehicle emissions and ambient concentrations will be derived using current EPA models, e.g., MOBILE6 for vehicle emissions, and ISC3-ST/LT for peak and annual average concentrations. Changes in morbidity and mortality will be based on latest census and epidemiological studies[8387]. Critical parameters will be identified using sensitivity and uncertainty analyses (Section 5.3.3). For validation, results from screening and intermediate-level models will be compared to predictions from the detailed models.

Infrastructure systems are associated with many other social impacts, including delays and productivity losses, 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 infrastructure reconstruction and maintenance, e.g., highways and bridges, will be estimated using traffic routing models[31]. Traffic and worker safety impacts attributable to infrastructure construction activities, e.g., injuries, deaths, and property damage, will be estimated from national injury statistics, activity types and durations, and other factors[88]. Noise impacts will be predicted by mapping predicted sound levels (accounting for attenuation) onto population distributions of the case study scenarios[89,90]. Infrastructure is known to adversely affect social equity since burdens fall disproportionately on minorities and the poor[91,92]. To assess equity impacts associated with pollutants, environmental health, noise and safety, impacts will be disaggregated by race and income using census data for each case study scenario. Selected urban environmental justice indices will be used to provide summary indicators of equity impacts[93]. Such analyses are sensitive to population density, traffic, rerouting opportunities, season, and other factors, thus, sensitivity and uncertainty analyses, including a range of scenarios, will be used to obtain representative results.

Economic Modeling The economic analysis will include comparison of the current decision-making approaches of agencies in charge of selecting materials with a life-cycle approach including all social costs. The latter approach provides better information for social decision-making, as it reflects all societal costs resulting from the decision. Current approaches may lead to biased decisions because of emphasis on short-run factors and lack of consideration of externalities.

The first phase of this project included a first-order life cycle cost analysis, consisting of two parts: an agency life cycle cost analysis and an externality cost component. Industry and government data were used to develop the materials, construction, maintenance/repair, and end-of-life management costs of the conventional concrete and ECC systems. Externality costs of air pollution were estimated using unit damage costs from the literature[56,57] and were applied to emissions calculated from the LCA model. While the current model provides a basic comparison of the two systems, several aspects would benefit from further economic analysis: 1) examination of different growth scenarios on economic results; 2) further investigation of the damage cost studies available and the implications of valuation method for the results; 3) inclusion of other pollutants, such as mercury and ozone precursors; 4) inclusion of spatial and temporal effects of pollutants; 5) inclusion of ecological effects, effects on property prices and noise costs; 6) examination of potential "rebound" effects (decreased construction might lead to increased vehicle traffic); 7) consideration of increasing scarcity of fuels and raw materials, including effects on price and on substitution of other materials; and 8) determination of how factors will change if this model is to be used in another country (China). Inclusion of these additional factors, to the extent feasible, will enhance the accuracy of the economic analysis and will contribute to the increased efficiency of the decisions on material selection.

5.3.2 Spatial Distribution of Cement Mineral Resources and Size of Mining Operations

Recognition of the pivotal role of cement and aggregate production in overall infrastructure costs has encouraged forward thinking governments to consider the location and suitability of their long-term supplies. Efforts have been largely local and are strongly hampered by lack of communication between governmental jurisdictional areas and areas of consumption or mining[94]. We propose to examine trade-offs between local production from numerous small mines versus production from a few large mines. “Superquarries” for production of aggregate have been developed in the UK and some of this material is shipped to the U.S.[94-96]. As a start, we will confine our comparisons to two large areas of about 100,000 mi^2, one in the Great Lakes area around Chicago and another in the Mid-Atlantic region around Washington, D.C.

Using a GIS approach, surface and bedrock geologic maps will be employed to determine the location of all lithologic or alluvial units most likely to contain cement and aggregate deposits. Limited field reconnaissance and petrographic study will be used to determine whether rocks in these units meet appropriate specifications and contain sufficient reserves. The location of existing cement and aggregate operations, as well as infrastructure and cultural features will then be determined. This information will be used in three ways: 1) to rank the areas in terms of geological favorability for extraction of cement and aggregate, regardless of location, which is expected to reveal whether the most favorable deposits are being used presently; 2) to rank these areas in terms of competing land uses that would limit location of operations based on cultural and infrastructure data; and 3) to predict demand for these products in the two areas for several decadal time periods, based on demographic and historical data, in order to identify areas that might be mined in the future. The location of these areas will then be compared to jurisdictional areas to determine whether land use regulations and policies are appropriate for efficient use of the resources.

5.3.3 Uncertainty Analysis of Life Cycle Sustainability Indicators Investigating uncertainty is an essential aspect of this research given the complexity and scope of the life cycle model, which links environmental, social and economic indicators. While uncertainties in LCA data and modeling techniques have been described[73,97,98], few studies have explicitly addressed them. Monte Carlo analysis has been applied successfully to life cycle inventories of energy systems [99-101], and an exploratory Monte Carlo analysis of our current bridge deck model generated distributions that differed significantly from the deterministic model. In the proposed research, Monte Carlo analysis will be used to identify key (sensitive) micro and macro model parameters, characterize overall uncertainties, and prioritize areas for model improvement, following available guidance[70,102]. Analyses of alternate scenarios will be used to evaluate site factors, e.g., geographic area, climatic zone[103], and other aspects. Finally, verification/validation studies will be used to compare simple and intermediate-level model results to detailed model simulations, as well as to laboratory and literature data. Given the uncertain nature of “real world” behavior of new ECC designs, this full treatment of sensitivity and uncertainty is necessary to ensure that results are sufficiently robust to support decision-making.

5.4 Microscale and Macroscale Integration and Outreach Activities

5.4.1 Design Iterations for Enhancing Sustainability Performance In this research we plan to analyze the physical property requirements of structural elements used in the chosen infrastructure applications (bridge, roadway and pipes) based on expected service life and dead/live loads. Ashby charts (Section 5.2.2) will be used to map each specific ECC composition to an appropriate infrastructure application. With the mapping initiated, life cycle sustainability indicators will be modeled for each ECC material and its corresponding infrastructure application based upon new material components, new construction techniques, and projected service life. From these analyses, the material components posing the largest social, economic, or environmental impacts will be identified. Insights on potential improvements will be recommended to material designers. Using this information, another iteration of materials development begins with modified material components and subsequent micromechanical tailoring. Through this iterative process, depicted in Figure 3, materials developers can create and refine new materials that not only exhibit necessary engineering characteristics, but also enhance life cycle sustainability performance. At least two iterations will be performed for each infrastructure application.

An expected output from this research is a classification of ECC formulations for specific infrastructure applications that yield the highest levels of environmental, social and economic sustainability. Part of this research will be devoted to generalizing the Integrated Materials Design Framework (Figure 3) to a form usable for other types of materials for other industrial sectors.

5.4.2 Material Flow Implications for Widespread Use of ECC Material flow analyses[36,104] for concrete infrastructure in the U.S. will be constructed in collaboration with Hendrik van Oss (cement commodity specialist) using USGS data. Different material substitution scenarios involving ECC will be developed and their effects on the baseline cement material flow analyses will be estimated. Adequacy of the industrial by-product and bio-based material supply for meeting demand for the various material substitution scenarios will be determined.

5.4.3 Development of Policy Recommendations Inflexible codes, failure to consider total life cycle costs, and other institutional barriers hinder the introduction of new infrastructure materials, such as ECC. The research team, in conjunction with professional associations and regulatory agencies, will explore policy options to overcome these barriers. Key stakeholders, including members of the project Advisory Group, American Association of State Highway and Transportation Officials, American Concrete Institute (Committees 122 and 318F), American Society of Civil Engineers, and the Federal Highway Administration, will be consulted. Exploratory research indicated that the Michigan Department of Transportation (MDOT) does not generally consider total life cycle costs in infrastructure material selection decisions. State transportation agencies in the U.S. will be surveyed to investigate policies that support life cycle costing. Policy recommendations will then be developed that better integrate life cycle analysis of economic, social and environmental performance into material selection and construction decisions. This will benefit engineers, urban planners and policymakers who influence infrastructure budgeting and funding decisions.

6 Education Plan

Interdisciplinary education and research training will be facilitated through a web-based educational resource compendium, a MUSES seminar series, regular team workshops, postdoctoral and graduate student fellowships, and undergraduate and high school student research opportunities.

6.1 Educational Resource Compendium and Project Website For a decade, the Center for Sustainable Systems has created Pollution Prevention/Sustainability Educational Resource Compendia for over a dozen disciplines. These offer instructional faculty a broad set of resources for course development that include problem sets, relevant publications with annotated bibliographies, course syllabi, software, and videos. A web-based compendium on sustainable infrastructure will be developed along with a project website for dissemination of education and research outputs.

6.2 MUSES Seminars and Research Training Two MUSES seminars will be held each year with invited speakers drawn from the advisory group and outside experts from relevant fields. Research training will be emphasized through two postdoctoral fellowships, 3-5 graduate student research assistantships, and two undergraduate research positions through the UM Undergraduate Research Opportunities Program and the Marian Sarah Parker Scholars Program, which encourages women undergraduates to continue onto graduate school. In addition, two high school students from the Summer Engineering Academy of the Minority Engineering Program Office will participate in research during summer terms.

7 National and International Collaboration

7.1 Exploratory Collaborative Research with National and International Partners The University of Michigan team is excited about the opportunity to leverage output from the proposed research through the following three collaborations (letters of commitment are attached). The UM International Institute will provide travel funding to support these collaborations. Video conferencing will also aid communications between the UM team and these project participants.

- Dr. Toshiyuki Hashida, Fracture Research Institute, Tohoku University, Japan, is studying the application of waste CO_2 to enhance the mechanical properties of concrete while also using recycled cement from concrete demolition. The objective of the proposed exploratory work is to investigate the use of CO_2 hardening process with a set of green ECC mixes. UM will provide these mixes to Dr. Hashida to test the feasibility of the process with ECC and samples will be returned to UM for mechanical testing.
- Dr. Sarah Billington, Civil and Environmental Engineering, Stanford University, is researching the application of ECC for bridge columns and infill panels for buildings. Dr. Billington has expressed interest in the proposed integrated life cycle design framework and has offered to test the ECC formulations developed in this project.
- Dr. Jun Zhang, Building Material Research Laboratory, Department of Civil Engineering, Tsinghua University, China, will partner with the UM to apply the life cycle models for assessing environmental, social and economic sustainability indicators to select infrastructure systems in China. Dr. Zhang will provide key model parameters for these assessments and results will be compared with infrastructure applications in the U.S.

7.2 Sustainable Infrastructure Materials and ECC Technology Networking A MUSES Sustainable Infrastructure Materials web site will be created to share MUSES seminar presentation slides, research publications, and the Educational Resource Compendium (Section 6.2). It will be linked to the existing ECC Technology Network hosted by UM at www.engineeredcomposites.com. To foster the integration of sustainability concepts and new tools into industrial ecology and traditional disciplines of materials science and civil engineering, at least three special sessions at international conferences will be organized. Potential international conferences where special sessions can be organized include: International Conference on Fracture Mechanics of Concrete and Concrete Structures (Dr. Li is the co-organizer for 2004); American Concrete Institute, Symposiums on fiber reinforced concrete; and the International Society of Industrial Ecology Conferences.

8 Management Plan

The following chart shows the schedule of activities described in Sections 5-7 and the investigators primarily responsible for each research and educational activity. Dr. Keoleian, Co-Director of the Center for Sustainable Systems, will serve as Project Director providing overall project management. Together with Dr. Li, Director of Advanced Civil Engineering Material Research Lab, they will provide team leadership and supervise the two postdoctoral research fellows focusing on microscale and macroscale research. At least two Principal Investigators will supervise each doctoral student research assistant (3-5 students per year). Project activities are highly integrated (e.g., microscale materials are evaluated by macroscale modeling and results used to refine material design) and this interdependency requires precise coordination. Project management software will be used to track progress and ensure that milestones are met. UM will provide networked, shared file storage so that all project staff can access the life cycle models and data. Options for expanding the collaborative file system to outside collaborators will be explored. The entire project team will meet as a group at least six times per year for team workshops, MUSES seminars, and an annual advisory committee meeting. Dr. Keoleian will facilitate collaboration with the Advisory Group and Dr. Li will facilitate research collaboration with Stanford, Tsinghua University, and Tohoku University. A group of experts has committed to serve on an Advisory Group for this project. Its role is to review results and provide guidance on our research direction, which will enable us to make strategic refinements to our research plan including a mid-course evaluation.

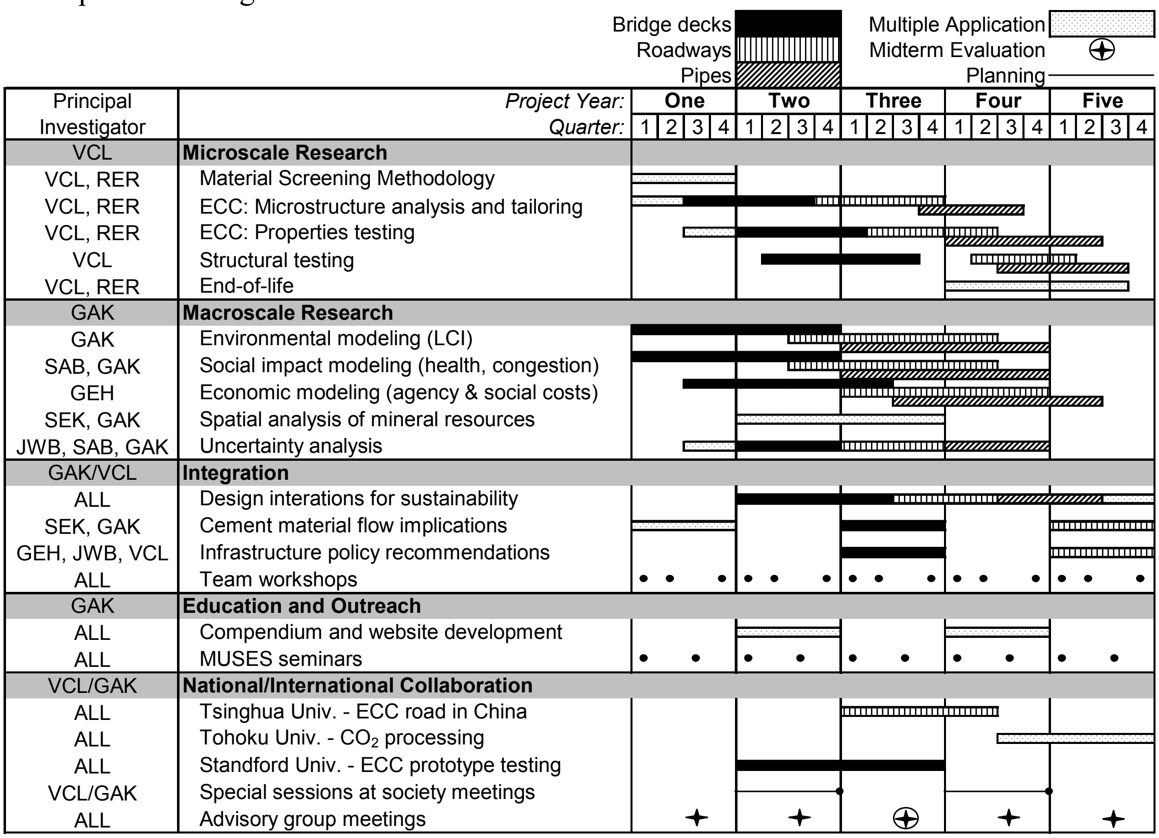


Figure 6. Schedule of Research, Educational and Outreach Activities

Principal investigators:

- Stuart Batterman (SAB) – Envir. Hlth Scs.
- Gloria Helfand (GEH)– Envir. Economics
- Gregory Keoleian (GAK) – Ind. Ecology
- Stephen Kesler (SEK) –Geology
- Victor Li (VCL) – Civil & Environ. Eng.

Senior Personnel:

- Jonathan Bulkley (JWB) –Policy/Civ. Eng.
- Richard Robertson (RER) – Mat. Sciences

Collaborating Units at U. Michigan:

- Adv. Civil Eng. Material Research Lab
- Center for Sustainable Systems
- Civil and Environmental Engineering
- Lit., Sciences, and the Arts – Geology
- Materials Science and Engineering
- School of Natural Resources and Envir.
- School of Public Health
- GIS Lab

Other Project Participants (Section 7.1)

Advisory Group:

- Howard Klee – Sust. Cement Init., World Business Council for Sust. Development
- Al Innis, VP Qual./Assoc. Affairs– Holcim
- Hendrik G. van Oss – Economic Geologist – US Geological Survey
- Barbara Lippiatt – Economist, National Institute of Standards and Technology
- Roger Till – Eng. of Struc. Research, MI Dept. of Transportation
- Joe Malloure, President – C.A. Hull Contractors
- Steve Kosmatka, Managing Director, Res./Tech. Serv. – Portland Cement Assoc.
- 3 other members TBD (including NGO's)