DEVELOPMENT OF GREEN ENGINEERED CEMENTITIOUS COMPOSITES FOR SUSTAINABLE INFRASTRUCTURE SYSTEMS

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Abstract

Over the last decade, enormous strides have been made in creating engineered cementitious composites (ECC) with extreme tensile ductility, on the order of several hundred times that of normal concrete or fiber reinforced concrete (FRC). Current ECC investigations include load carrying structural members in new infrastructure systems, as well as for repair and retrofitting of existing structures. ECC design has been built on the paradigm of the relationships between material microstructures, processing, material properties, and performance. This paradigm has worked very well in creating various versions of ECC that can be processed by self-consolidated casting, spraying, and extrusion. This paper describes preliminary results of an initial attempt at creating green ECCs, ECCs that maintain the tensile ductility characteristics, but which also incorporate sustainability considerations in the design of these materials for infrastructure applications. Sustainable material design integrates microstructure tailoring with life cycle analysis based on social, environmental, and economic (SEE) indicators. The framework of green ECC development is described. Some preliminary experimental results of the effect of cement substitution and fiber substitution with industrial by-products on the mechanical properties are reported. It is demonstrated that the concept of green ECC for sustainable infrastructures is feasible, although an extensive amount of research remains ahead.

1. Introduction

Materials engineering in recent years has emphasized the inter-relationship between material microstructure, properties, processing and performance (National Research Council 1990). This materials engineering paradigm, while widely adopted and shown to be effective, nonetheless does not take into account sustainability concerns. At the moment, there is no systematic approach in materials design that recognizes the inter-connection between microstructure, properties, processing, performance, and sustainability. The objective of this research is to develop a new materials engineering methodology that explicitly embodies sustainability in the form of SEE indicators. In this paper, this methodology will be briefly introduced. Emphasis will be placed on an initial attempt at creating a green (environmentally preferable) version of an engineered cementitious composite (ECC), which maintains the high tensile ductility characteristics but also incorporates sustainability considerations in the design of these materials for infrastructure applications.

The volume of concrete used in global infrastructure represents huge flows of material between natural systems and human systems. Global use of concrete for construction projects exceeds 12 billion tons per year. To support this amount, cement production in the year 2001 totaled 1.65 billion metric tons (van Oss 2002). Rates, compositions, and spatial distributions of such important flows are major determinants of the degree to which societies are sustainable. While concrete infrastructure continues to grow worldwide, evidence suggests that the performance of current infrastructure systems is deficient in terms of the SEE dimensions of sustainability. Some of the challenging sustainability issues regarding infrastructure include the following:

Social: 32 *percent* of U.S. major roads are in poor and mediocre condition, while 28 percent of US bridges are structurally deficient or functionally obsolete. Roadway improvements would reduce accidents and save lives. Of the 41,821 U.S. traffic fatalities in 2000, 30% have been attributed to inadequate roadway conditions (TRIP 2002). Furthermore, construction causes significant traffic delays. Total urban traffic congestion costs the nation $78 billion in wasted fuel and lost time each year (TRIP 2001).
Environmental: Cement production, an energy intensive process, is responsible for 3% of global greenhouse gas emissions (WBCSD 2002), and significant amounts of NO_x, particulate matter (PM) and other pollutants such as SO_2. The production of 1 ton of cement clinker requires approximately 1.7 tons of non-fuel raw materials and results in the release of 1 ton of CO_2 (van Oss 2002).
Economic: Roads represent one infrastructure system with significant economic impacts. For example, driving on roads in need of repair or improvement costs motorists in the US an average of $222 per driver in extra vehicle operating costs each year, or $41.5 billion total (TRIP 2001). Also, delayed shipments of freight can lead to productivity losses directly impacting business and industry.

The unsustainability of current infrastructure systems, coupled with the anticipated rapid growth of new ones, lead to an obvious need for improvement. Recent research suggests the possibility of substituting concrete with advanced cementitious composites that have superior mechanical performance. Introducing huge volumes of a new material is likely to have profound impacts in each of the three dimensions of sustainability. These impacts occur throughout an infrastructure system's life cycle, which encompasses resource extraction, materials processing, construction, use, maintenance and repair, and end-of-life management. We must understand the nature of these impacts and optimize the overall performance of the new material through intelligent design and application.

Reinforced concrete's limited durability is responsible for significant amounts of infrastructure repair. Its brittleness has caused numerous and catastrophic failures of buildings and bridges in recent earthquake events. Alternative technologies promise to improve the performance of concrete-related materials. One such technology involves the family of engineered cementitious composites (ECC). Given the demand for infrastructure systems worldwide, the potential application of ECC could be enormous.

ECC represents a unique group of short fiber reinforced cementitious composite materials with ultra high ductility. As a successful sample of materials engineering on the paradigm of the relationships between material microstructures, processing, material properties, and performance (Li 1992), the fiber, matrix and interface of ECC are carefully tailored under the guidance of micromechanical models that link the composite ductility to individual phase properties (Li 1998). ECC strain-hardens in tension, accompanied by sequential development of multiple cracking after first cracking. Tensile strain capacity exceeding 5% has been demonstrated on ECC materials reinforced with polyethylene (PE) and polyvinyl alcohol (PVA) fibers (Li 1998; Li et al. 2002.). Closely associated with the strain-hardening and multiple cracking behaviors is the small steady state crack width. Even at a strain of 4-5%, crack widths of ECC remain below 100 μm. Such small crack widths imply a significant improvement in structural durability (Li 2002). Through careful material design, the fiber volume fraction in ECC remains moderate, typically below 2.5%. As a result, unlike many other high performance FRC, ECC can be prepared in standard concrete mixers. With appropriate control of rheology properties, ECCs suitable for self-consolidating casting (Kong 2003), spraying (Kim 2003), and extrusion (Stang and Li 1999) have been developed.

ECC material is emerging from laboratory testing to field applications. With its flexible processing, ECC can be used in either new construction or as repair and retrofitting material. Potential infrastructure applications under investigation include building frames (Fischer and Li 2001), bridge piers (Yoon and Billington 2002), bridge deck repair (Gilani 2001), extruded pipes (Stang and Li 1999), and most recently roadway repairs.

In this paper, an integrated materials design framework for sustainable infrastructure systems is proposed. Two major ingredients of ECC, i.e., the cement and fiber, account for the major part of the environmental impact. As a preliminary attempt, the effects of cement substitution and fiber substitution with industrial by-products on the mechanical properties are experimentally investigated. These findings highlight the feasibility of creating a green ECC material for sustainable infrastructure applications.

2. Integrated Materials Design Framework for Sustainable Infrastructures

A number of wide ranging disciplines must be brought together for life cycle assessment of any complex system. For ECC infrastructure systems, these disciplines include civil engineering, materials engineering, industrial ecology, environmental health, geology, and environmental economics. Such a team, sponsored by the US National Science Foundation, has been assembled at the University of Michigan.

The creation of a well-defined, integrated materials design framework was essential to facilitate cooperation between the various disciplines. For this project, the framework was specifically tailored to infrastructure applications, however it may be readily adapted to development of sustainable materials for other industrial applications. The design framework, which is an iterative process comprised of two loops forming a continuous "figure eight" is pictured in Fig. 1.

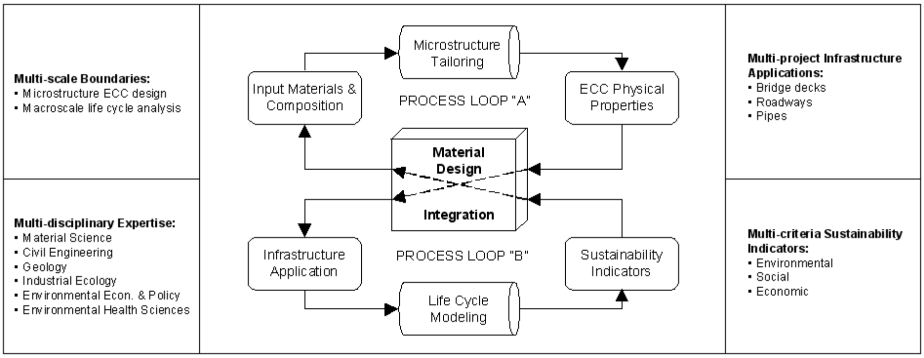

Fig. 1: Integrated materials design framework for sustainable infrastructures

Process loop A involves the microstructure tailoring of ECC. By adjusting the formulation of various input materials, the mechanical properties of the composite are controlled. Process loop B involves the evaluation of an entire infrastructure system using a complete life cycle model. Indicators of environmental, social, and economic sustainability are assessed on a macro-scale. The two loops provide feedback to one another through the central integration box. This box takes input from loop B to inform loop A on viable material compositions with favorable sustainability indicators and mechanical property demands of the particular infrastructure application. In turn loop A informs loop B of properties of ECC suitable for a particular infrastructure application, whose performance (e.g. durability/service life time) is taken into account in the life cycle model. Because of these feedback loops, both mechanical performance and sustainability indicators may be optimized simultaneously for the ECC material and the ECC infrastructure.

The infrastructure application chosen for initial implementation of this design framework is portions of a bridge deck in a simply supported steel-girder bridge. Currently, expansion joints between adjacent bridge spans are used to allow for thermal expansion and contraction of the bridge girders. However, these joints leak, allowing water and other corrosives to deteriorate the deck and girders, requiring replacement of the deck and/or the entire bridge superstructure. To eliminate the problematic joints, a link slab may be used to connect the two spans, creating a continuous deck over the steel girders. However, the link slab must be able to accommodate the high strain demand imposed by thermal length changes and drying shrinkage deformation in the deck along with any structural demand placed by highway traffic. The high strain capacity of ECC, mentioned earlier, make it an ideal material for the link slab application.

The use of the integrated design framework to develop a green ECC material for the link slab application appears promising. In addition to optimizing the ECC material directly using component substitutions and additional microstructure tailoring, the overall life cycle of the bridge system will be greatly impacted. According to the Michigan Department of Transportation, the expected service life of a typical bridge is forty years, while the expected service life of bridge waterproofing membrane is ten years (MDOT 2002). Bridge superstructures typically deteriorate most rapidly near joint regions due to leaking. Using ECC link slabs to prevent deterioration, the expected service life of a typical bridge will almost certainly be extended, but by how much is difficult to estimate. With the use of ECC link slabs, it is quite possible that the bridge will outlast its usefulness. In addition to extending the overall service life of the bridge, the maintenance frequency will almost certainly decrease. The combination of greener ECC materials along with the extended life cycle of the total infrastructure system suggests that the sustainability of highway bridges utilizing ECC link slabs will be far superior to the current concrete infrastructure system.

3. Guidelines for Designing Green ECC

The development of green ECC material is contained within process loop A of the integrated material design framework of Fig. 1. While loop A does not involve complete life cycle analysis, a significant number of sustainability considerations must be taken into account when designing a green version of ECC. To begin the design process, a small set of indicators, referred to as Material Sustainability Indicators (MSI) are chosen as preliminary indicators of overall sustainability. The MSI are selected to be dependent only upon ECC component materials, in order to initiate efficient material evaluation without complete life cycle analysis of the final application. In this study, the environmental indicators of total production energy, solid production waste, carbon dioxide generated during production, and chemically polluted water produced were chosen as the MSI. Values for these MSI are shown in Table 1 for both conventional concrete and a current ECC design (Li et al. 2002). The

MSI have been calculated based on data from MDOT, the Portland Cement Association, a local bridge contractor, Kentucky Transportation Center's KyUCP Model (KTC 2002), US EPA's MOBILE 6.2 program (US EPA 2002), and various material suppliers. A complete life cycle assessment is outside the scope of this paper.

Table 1: Properties and material sustainability indicators (MSI) for concrete and ECC

	Compressive strength (MPa)	Tensile strain capacity (%)	Total energy use (MJ/L)	Solid waste (Kg/L)	Carbon dioxide (g/L)
Concrete	35.0	0.02	2.68	0.152	407.0
ECC	65.0	5.0	8.08	0.373	974.8

As seen in Table 1, concrete and ECC show significant differences in both mechanical properties and MSI. While this version of ECC clearly outperforms concrete in mechanical performance, its production has greater environmental burdens than concrete due to the high cement content of standard ECC, and the inclusion of polymeric fibers. ECC material is only sustainable in terms of solid waste production due to the use of fly ash, an industrial waste from coal-fired power plants. This initial analysis suggests that a reduction in the cement content of ECC, along with reduced use of PVA fibers, may be possible methods of increasing the sustainability of ECC material with respect to concrete.

One natural solution is to replace fiber, cement and other components in the current ECC mix with industrial by-products, provided that the properties of the resulting green ECC would still meet the requirements for a particular application. At least 20 industrial waste materials have been identified as potential cement, virgin fiber, and aggregate substitutes in ECC. Among them, fly ash and bottom ash are of great interest due to their abundance and increasing negative impact on the environment related to their disposal.

Introduction of fly ash into the ECC matrix has an inevitable influence on the microstructure of matrix and interface, and in turn the micromechanical properties governing the fiber bridging behavior and cracking behavior. For PVA fiber reinforced ECC, experimental results from single fiber pullout tests and matrix fracture tests indicate that the interfacial bond strength and matrix fracture toughness decrease with an increase of fly ash content. The interfacial bond strength of PVA fiber in ECC is excessive due to its hydrophilic nature and must be artificially lowered (Li, et al 2002). The presence of fly ash may in fact lead to improved strain-hardening behavior.

The integrated material design framework emphasizes the tailoring of material properties for a specific application, e.g. link-slabs. Structural mechanics analysis reveals that the most important properties required for link-slabs are tensile strain capacity (ductility) and crack width control for durability purposes. The minimum ductility required to withstand temperature and drying shrinkage stress, as well as live loads, was computed to be 1.4% using a factor of safety of two. Furthermore, crack widths should be below 100 μm to minimize water/chloride penetration. These requirements are difficult, if not impossible, to attain for normal concrete, but are easily achievable with current ECC, which has ductility exceeding 3%. There is a rather large buffer in mechanical performance that can be "traded" for material greenness.

4. Experimental Program

This preliminary experimental program involves two sets of investigation, i.e. cement substitution with ashes and fiber substitution with recycled carpet fiber, in which the effect of the individual substitution on the mechanical properties of ECC is independently studied. For lack of space, only the research findings involving cement substitution is reported in this paper.

Mix proportions of five ECC mixes (ECC G0-G4) with high fly ash content are listed in Table 2, along with the reference concrete mix and a reference ECC mix (ECC R0). The cement used in this study is Ordinary Portland cement (OPC). Except for the concrete, which contains both coarse and fine aggregate, the aggregates in ECC mixes solely consists of fine silica sand with an average size of 110 μm. PVA REC15 fiber, specially developed for ECC materials (Li et al. 2002), is used in this study with a fixed volume fraction of 2%. Viscosity agent hydroxypropyl methylcellulose (HPMC) and superplasticizer (SP) are necessary in ECC mixes for achieving adequate workability.

Table 2: Mix proportions of concrete and ECC materials

	Cement (kg/m^3)	Fly ash (kg/m^3)	Aggregates (kg/m^3)	Fiber (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	HPMC (kg/m^3)
Concrete	390	–	1717	–	166	–	–
ECC R0	838	–	838	26 (PVA)	366	17	1.26
ECC G0	583	700 (Class F)	467	26 (PVA)	298	19	0.16
ECC G1	318	509 (Class F) 191 (fine fly ash)	701	26 (PVA)	289	19	0.16
ECC G2	318	701 (Class F)	701	26 (PVA)	289	19	0.16
ECC G3	318	191 (fine fly ash) 250 (Class F) 250 (bottom ash)	701	26 (PVA)	289	19	0.16
ECC G4	318	701 (bottom ash)	701	26 (PVA)	289	19	0.24

Two types of fly ash and one type of bottom ash are investigated. Fine fly ash is a special type Class C fly ash with high calcium content, and particle size (average 2 μm) much smaller than class F fly ash (average 13 μm) and bottom ash (average 50 μm).

The mechanical properties and MSI of mixes are shown in Table 3, where the compressive strength and tensile strain capacity are measured at 28 days. Direct uniaxial tensile test using coupon specimens was employed to characterize the tensile behavior.

5. Results and Discussion

As shown in Table 3, the introduction of a high content of ashes results in little change in composite ductility, while it significantly improves the MSI over current versions of ECC. Although fly ash has been widely used in structural concrete, the ratio of ash to cement (typically 10%-30%) is much lower than in these ECC mixes (ranging from 120% to 220%). Except for ECC G1, which shows a large variability in strain capacity, all other mixes with high ash content demonstrate a high strain capacity exceeding 4%.

Fig. 2 shows the compressive strength development of the green ECCs, where the strength gain rate was, as expected, slightly compromised due to the reduction of cement content. However, compared with conventional structural concrete, the green ECCs show similar early compressive strength and higher long-term strength. The type and the proportion of ash, due to different reactivity and particle sizes, have different influences on the compressive strength. Bottom ash, due to its low pozzolanity, leads to both lower early and long-term (up to the 100 days age for this set of tests) strength in the ECC. In the current calculations of MSI, these three types of ashes are not differentiated. However, their true recycle value is different. This difference will be reflected in future refinements of the model.

The distinguishing characteristics of ECC include its high tensile ductility and small steady state crack widths. Fig. 3 shows a tensile stress-strain curve and accompanying crack width development of ECC G2. The crack width stabilizes after 1% strain and remains below 80 μm until failure. Hereby, the mechanical properties of ECC G2, in terms of strength, ductility, and crack width well satisfy the performance requirements for the link-slab application. One obvious trend among the new greener versions of ECC is the larger amount of total energy used in material production. This high-energy demand is mostly due to the large amount of energy used in PVA fiber production. By using waste fiber substitution, the energy demand will be reduced, and the MSI will be further improved. These results will be reported in a separate paper.

Table 3: Mechanical properties and material sustainability indicators of green ECC

	Compressive strength (MPa)	Tensile strain capacity (%)	Total energy use (MJ/L)	Solid waste (Kg/L)	Carbon dioxide (g/L)
Concrete	35.0	0.02	2.68	0.152	407.0
ECC	65.0	5.0	8.08	0.373	974.8
ECC R0	42.0	4.9	8.79	0.280	957.8
ECC G0	68.0	4.5	7.16	-0.504	702.5
ECC G1	40.8	1.6	5.43	-0.585	440.7
ECC G2	38.6	4.0	5.43	-0.586	440.7
ECC G3	36.5	4.3	5.43	-0.576	440.7
ECC G4	29.1	4.3	5.43	-0.586	440.7

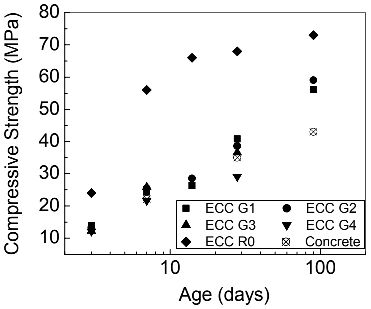

Fig. 2: Compressive strength development

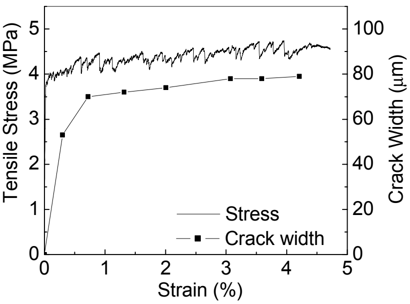

Fig. 3: Crack width vs. strain of green ECC

6. Conclusions

- Development of greener ECC based on consideration of material sustainability indicators (msi) is feasible.
- The generally deteriorated properties due to the use of low-quality substitutions can be offset by micromechanical tailoring of the ingredients.
- Mapping of the green ECC properties to required properties for specific infrastructure applications should lead to minimum performance reduction in the infrastructure, while greatly enhancing the sustainability indices.

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