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# Driving infrastructure sustainability with Strain Hardening Cementitious Composites (SHCC)

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ABSTRACT: Infrastructure sustainability has become increasingly important globally as concerns about infrastructure decay and environmental deterioration rise. This paper poses the thesis that Strain Hardening Cementitious Composites (SHCC) has many characteristics that positively contribute to infrastructure sustainability; recent advances in durability studies, material greening, as well as current developments in smart self-healing and self-sensing functionalities in SHCC are highlighted. The paper also identifies additional research needed to realize the promise of SHCC as an enabling technology for infrastructure sustainability.

## 1 INTRODUCTION

Many nations, developing or developed, are experiencing increasing pressures resulting from extreme weather patterns, energy and water scarcity, and civil infrastructure decay. While these large societal challenges of the 21st century initially appear unrelated to one another, they may in fact be coupled in one way or another. For example, concrete is the most used engineered material, exceeding 12 billion t/year and amounting to about 2 ton per person per year (van Oss and Padovani, 2002) on average globally for civil infrastructure construction and repair. Accompanied with the large material flow is the high-energy intensity of cement, about ten times that of the averaged economy in the US (WBCSD 2002). Cement production is also responsible for about 5% of anthropogenic carbon dioxide and significant levels of $SO_2$, $NOx$, particulate matter and other pollutants (USEPA 2000); it contributes disproportionately to the global warming potential when compared with other human activities. It is now the 3rd $CO_2$ polluter worldwide, after fossil fuels and deforestation. About a third of the drinking water in the US never reaches consumers due to leakage in our aging water infrastructure. And about 40% of the energy in the US is consumed in buildings (ASCE 2009). The intertwining relationship between the built and the natural environment is becoming increasingly evident.

Infrastructure decay has significant impact on the environment. In 2009, the American Society of Civil Engineers prescribed an average grade of D to civil infrastructure in the US (ASCE 2009). In the category of bridges, for example, nearly 20% of bridges are rated as "structurally deficient or functionally obsolete." It is estimated that $100 billion is needed to repair and rehabilitate the over 100,000 miles of aging levees many of which are over 50 years old. Energy infrastructure is severely lacking behind demand, which has grown 25% since 1990. The concern does not stop at aging infrastructure with substandard performance affecting public safety. The economic cost of returning them to an acceptable level has been quoted at US$ 2.2 trillion. This financial burden on the US economy is obvious. Less known to the public is the fact that as much as 50% of field repair fails and require re-repair for concrete infrastructure (Vaysburd et al, 2004). In each repair, more material is consumed, with attendant energy consumption and pollution emissions. Poor automobile fuel economy and traffic delays on inferior roadways induced energy waste and tailpipe emissions. The impact of infrastructure decay and maintenance needs on the natural environment represent a major concern to governments, industries and general citizens.

It may be argued that greener concrete with enhanced durability for new and repaired infrastructure provides the best solution to the infrastructure decay problem, while assisting in mitigating environmental concerns. Given the well known fact that cracking in brittle concrete is a major cause of infrastructure deterioration, this makes the case for a future generation of concrete that is more damage tolerant, and which suppresses the deterioration mechanisms commonly experienced in infrastructure, such as corrosion of reinforcing steel. Strain-hardening Cementitious Composites (SHCC) is a class of relatively new concrete material that possesses many of the qualities required. Its development in the last decade has been rapid and significant. There is evidence that with further research and development, SHCC may provide a material solution to many problems stressing our built and natural environments.

This paper overviews the characteristics of SHCC that pertains to addressing infrastructure decay and associated environmental concerns. It also describes some on-going and future additional research necessary to fulfill its promise as a preferred concrete of the next generation intelligent infrastructure. It poses the thesis that infrastructure sustainability can be advanced through deliberate materials engineering of SHCC.

## 2 INFRASTRUCTURE SUSTAINABILITY

### 2.1 *Defining sustainable infrastructure engineering*

The World Commission on Environment and Development (WCED 1987) defined sustainable development as development that "meets the needs of the present generation without compromising the ability of future generations to meet their needs." Infrastructure sustainability needs to incorporate the concepts of life-cycle analysis, carbon and energy footprints, new and renewed infrastructures, and material selection for sustainability. Clearly a range of civil engineering disciplines contributes to infrastructure sustainability, including materials engineering, structural design, and construction and maintenance management. Each discipline may dominate over others at different phases of an infrastructure system's life. From a sustainability viewpoint, however, it is necessary to consider all phases of a structure's life cycle holistically; the economic, social and environmental impacts of each phase are typically dependent on each other. To illustrate, a green construction material that has low environmental impact in the material production phase may end up contributing to a large life cycle carbon and energy footprint if repeated repairs are required during the use phase of the built infrastructure. In this example, it is clear that considering sustainability from a green materials engineering viewpoint only is inadequate in addressing infrastructure sustainability. Thus, a working definition of sustainable infrastructure engineering is the integrated material development, structural design and construction, and infrastructure management that are consistent with the principles of sustainable development.

### 2.2 *The SIMSS design approach to infrastructure sustainability*

A useful approach for deliberate driving of infrastructure sustainability was offered by Lepech (2006, 2009). The Sustainable Infrastructure Materials, Structures, and Systems (SIMSS) design approach integrates the materials development, structural design and infrastructure system operations stages with life cycle evaluation (figure 1). This integration emphasizes the interdependencies of the different phases of the life cycle of a structure in their contributions to sustainability indicators, and encourages a more holistic approach in attaining infrastructure sustainability. In SIMSS, scale linkage occurs naturally. For example, the nanometer scale coating on fibres used in an SHCC can be linked to scheduling of repair maintenance for a fleet of kilometer scale bridges in assessing the life cycle carbon and energy footprints of an SHCC bridge system.

At the "System" scale, maintenance for serviceability of an infrastructure dominates the resource input and emissions output. At the "Structure" scale, durability under combined mechanical and environmental loads dictates the time scale of deterioration and repair needs. At the "Material" scale, composite properties, often beyond the elastic stage, determine local mechanisms of physical and chemical response to load and fluid transport. The three scales are connected through sharing of the materials and structural properties apex (figure 1). It is exactly because of these connectivities that materials with properly designed microstructure and production methodology exerts its influence on infrastructure sustainability throughout the three materials, structure and system scales.

The "Evaluation" module in figure 1 embodies the tools of life cycle analysis (LCA) and economic modeling of a given infrastructure system. This module accounts for energy and raw material input and emissions output at each phase of the life cycle, including material production and transport, construction, operation and maintenance, and end-of-life.

Implementation of SIMSS has been performed on bridge, pavement and pipe infrastructure,

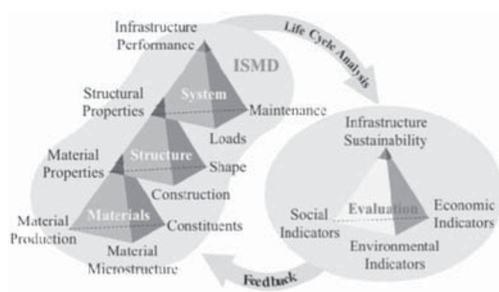


Figure 1. Sustainable Infrastructure Materials, Structures, and Systems (SIMSS) Design Approach (Lepech, 2006; 2009).

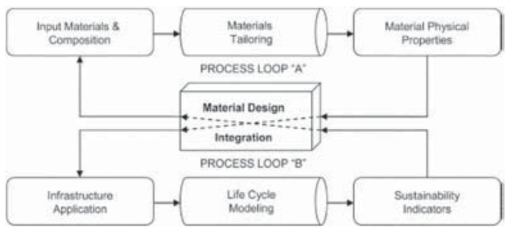


Figure 2. Interactive design framework for sustainable infrastructure systems (Keoleian et al, 2005).

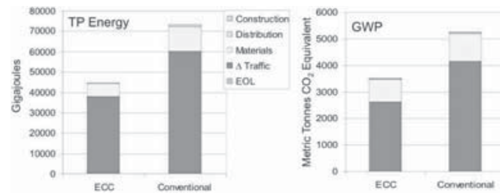


Figure 3. Life cycle analysis results for a R/C bridge deck with ECC link slab versus one with conventional expansion joint (Keoleian et al, 2005).

adopting the iterative methodology of Keoleian et al (2005). Figure 2 shows the iterative looping between materials tailoring (Process Loop "A") and life cycle analyses (Process Loop "B"). In Loop "A", micromechanics is used as the analytic tool to guide the tailoring of material ingredients in the deliberate selection of chemical type, the geometric dimensions, and weight proportions (Li et al, 2001) in order to attain target composite properties. In the case of SHCC, the most important target property would be the tensile strain capacity. This composite property is then translated into infrastructure performance. For sustainability consideration, the structural durability gain as a result of the unique property characteristics of SHCC becomes the focus in linking the materials tailoring loop to the life cycle analyses loop. An infrastructure deterioration model is necessary to make contact between structural durability and system maintenance scheduling (Lepech, 2006). A life cycle model is then used as the analytic tool in Loop "B" to translate alterations in system maintenance scheduling for the use phase into sustainability indicators, and added to contributions from other phases. Finally, the sustainability metric provides insights into avenues of greening of SHCC through selective adoption of industrial waste streams, without compromising the composite properties necessary to maintain high structural durability. This looping can iterate indefinitely for maximum infrastructure sustainability with the greenest SHCC.

Figure 3 shows the first iteration results of the SIMSS approach applied to a conventional bridge deck and one retrofitted with an SHCC link slab (Lepech and Li, 2009; Keoleian et al, 2005). In this case, the deck with the SHCC link slab shows a reduction in total primary energy (TP Energy) usage 40% lower than that of the conventional deck. A similar level of reduction is found in global warming potential (GWP) measured in equivalent $CO_2$ emissions. This figure also shows that the major contribution to the energy and carbon footprints occurs in the use phase due to traffic flow alteration (D Traffic) as a result of repair and reconstruction activities. The second most important contribution occurs in the material production phase. This finding emphasizes the importance of structural durability to reducing maintenance requirement, while acknowledging that greening of construction material is necessary to achieve infrastructure sustainability.

## 3 SHCC MATERIALS AND STRUCTURAL DURABILITY

The durability of many reinforced concrete structures is negatively impacted by the tendency of concrete to crack in tension; tensile stress may be due to live load, restrained shrinkage or thermal loads. Past experiences have demonstrated that cracking and crack widths are difficult to control using steel reinforcements in the field. Given these facts, it would seem natural to look to SHCC for enhancement in structural durability. The tensile ductility characteristics of SHCC should suppress brittle fracture and lead to enhanced structural durability. There is currently only limited field experience (Li and Lepech, 2004; Kunieda & Rokugo, 2006) to support this contention, since SHCC is a relatively new construction material. However, the rapidly increasing volume of laboratory data suggest overwhelmingly that SHCC will contribute to durability of concrete structures, see for example, the State of the Art Report by the RILEM TC HFC (2009). Here we highlight succinctly the material and structural durability of SHCC in the context of prolonging infrastructure service life, reduction in maintenance frequency and enhancement of sustainability.

As a new construction material, SHCC must be carefully scrutinized for its durability in typical infrastructure environments, which may involve a combination of mechanical and environmental loadings. A unique feature of SHCC distinctive from normal or high performance concrete is its tensile strain-hardening behavior. During strain-hardening, the material undergoes controlled multiple microcracking. The strain-hardening stage is expected to be utilized in SHCC infrastructure during service conditions. It is reasonable, therefore, to raise concerns of durability given the expected much higher number of cracks in an SHCC structure in comparison to a normal concrete structure, despite the much tighter crack width in SHCC. Hence it is necessary to experimentally evaluate the durability of SHCC in the elastic state as well as in the strain-hardening state—i.e. when the material has already been loaded to the multiple microcracked state. Further, the potential for changes in transport properties due to the presence of microcracks dictates the need to evaluate structural durability, especially the effect on steel corrosion.

In the following, we highlight durability study results for an Engineered Cementitious Composites (ECC) studied at the University of Michigan and elsewhere. Material durability in the uncracked state under various exposure environments is first summarized. Durability of ECC in the strain-hardening state is then overviewed. Finally, the contribution of ECC to structural durability is highlighted. A typical mix of ECC, labeled M45, is given in table 1. The mix ingredient selection—in terms of ingredient type, proportion, and geometric size—is governed by micromechanical models (Li et al, 2001; Li and Leung, 1992). Specifically, the poly-vinyl-alcohol (PVA) microfibre was coated with a proprietary nanometer scale surface coating to facilitate fibre slippage prior to reaching rupture threshold. Figure 4 shows a typical stress-strain curve of ECC-M45. A tensile strain capacity of 3% can be attained.

Of most importance to the present discussion on durability during the strain-hardening stage is the unique nature of crack development in ECC. Beyond first cracking at about 0.01–0.02%, the number and width of cracks increases with deformation. This continues until the deformation reaches about 1%. Beyond this stage, further deformation is accompanied by increase in crack number but almost constant crack width (figure 4). This constant crack width, termed steady state crack width, is a property of the ECC, analogous to other properties like Young's modulus or compressive strength. In other words, the steady state crack

Table 1. Typical mix proportion of ECC material.

| Cement | Water | Sand | Fly ash | HRWR | Fibre (Vol. %) |
|---|---|---|---|---|---|
| 1.00 | 0.58 | 0.80 | 1.20 | 0.013 | 2.00 |

HRWR = High range water reducer; all ingredients proportions by weight except for fibre.

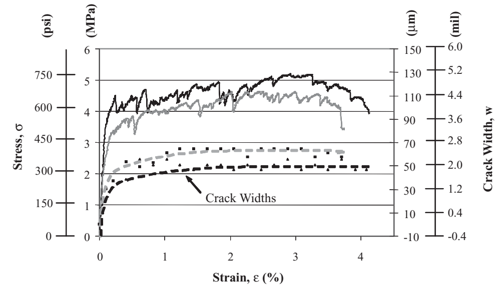


Figure 4. Typical stress-strain-crack width relations of an ECC.

width is independent of specimen or structural size (Lepech and Li, 2004), and is also independent of re-bar size and reinforcement ratio.

### 3.1 *Durability in the uncracked state*

Freeze-thaw testing in accordance with ASTM C666, Procedure A, was performed on ECC prism specimens (Li and Lepech, 2004). The dynamic modulus was recorded as a function of freeze-thaw cycles. ECC specimens survived the test duration of 300 cycles with no degradation of dynamic modulus or surface appearance. In addition, ECC coupon specimens after subjected to 300 freeze-thaw cycles were found to retain a tensile strain capacity of about 3%. The observed frost durability of ECC, despite having no deliberate air entrainment, is due to the increase of larger pore volume, and intrinsically high tensile ductility and strength due to the presence of micro PVA fibres (Sahmaran and Li, 2007).

Salt scaling resistance of ECC was evaluated (Şahmaran and Li, 2007) in accordance with ASTM C672. After 50 freeze-thaw cycles in the presence of de-icing salt, the surface condition visual rating and total mass of the scaling residue for ECC prism specimens remain within acceptable limits of ASTM C672. In addition, ECC coupon specimens exposed to freeze-thaw cycles in the presence of de-icing salts for 50 cycles were found to exhibit negligible loss of ductility, and retained a tensile strain capacity of more than 3%. These results confirm that ECC remains durable despite exposure to freeze-thaw cycles in the presence of de-icing salts.

In contrast to freeze-thaw tests designed to simulate temperature changes in winter conditions, hot water immersion tests were conducted to simulate the long-term effects of hot and humid environments (Li et al, 2004). The tensile strain capacity of ECC dropped from 3% at 28 days to 2.75% after 26 weeks of hot water immersion.

Table 2. Durability of uncracked ECC.

| Test | Exposure condition | Specimen | Test result | Ref. |
|---|---|---|---|---|
| ASTM C666, Proc A | Freeze-thaw (300 cycles) | P | Dynamic Modulus retained 100% | Li & Lepech, 2004 |
| Uniaxial tension | Freeze-thaw (300 cycles) | C | Strain capacity retained 3% | Li & Lepech, 2004 |
| ASTM C672 | Salt scaling resistance (50 cycles) | P | Visual rating & total mass of scaling residue remain within limits of ASTM C672 | Şahmaran & Li, 2007 |
| Uniaxial tension | Salt scaling resistance (50 cycles) | C | Strain capacity retained 3% | Şahmaran & Li, 2007 |
| JIS | Hot water immersion (26 weeks) | C | Strain capacity retained 2.75% | Li et al, 2004 |
| ASTM C1260 | High alkaline (NaOH) immersion | B | Expansion within ASTM C1260 limit | Sahmaran & Li, 2008 |

Specimen Type: P = prisms; C = coupons; B = bars.

While accelerated hot weather testing does result in lower strain capacity of ECC, the strain capacity exhibited after 26 weeks remains over 250 times that of normal concrete.

Another environment that could affect the microstructure and composite properties of ECC is a high alkaline environment. Since ECC has high fly ash content, alkali-silicate reaction (ASR) performance of ECC is expected to be satisfactory. Results of ASTM C1260 test (Sahmaran and Li, 2008) showed no damaging expansion.

Table 2 shows a summary of durability test results for uncracked ECC in a variety of exposure environments.

### 3.2 *Durability in the microcracked strain-hardening state*

Many of the same tests conducted on ECC uncracked specimens were also performed on ECC cracked specimens. For example, prism specimens from beams preloaded to as much as 2 mm (equivalent to 1.5% strain on tension side) and then subjected to salt scaling tests in accordance to ASTM C672 showed negligible surface scaling (Sahmaran and Li, 2007). Similarly, preloaded (to 2% strain) coupon specimens retained the same 3% tensile strain capacity after exposure to 50 freeze-thaw cycles in the presence of de-icing salt (Sahmaran and Li, 2007). Exposure of precracked coupon specimens to an alkaline environment (Sahmaran and Li, 2008) up to 3 months at 38°C showed a slight loss of ductility and tensile strength, but retained a strain capacity of more than 2%.

Transport properties of precracked ECC, including permeation, absorption, and chloride ion diffusion, have been measured. Lepech and Li (2008) showed that the tight crack width of less than 100 micron of preloaded (to 3%) ECC maintained its permeability to a level similar to that of normal sound concrete. Based on ponding tests of precracked specimens under high imposed bending deformation, Sahmaran et al (2007) found that the effective chloride diffusion coefficient was linearly proportional to the number of cracks in ECC, whereas the effective diffusion coefficient of reinforced mortar was proportional to the square of the crack width. Therefore, the effect of crack width on chloride transport was more pronounced when compared with that of crack number. This study concludes that controlling crack width is more important than controlling crack number for structural durability associated with chloride ion penetration.

Paradoxically, the tight crack width of SHCC may result in undesirably high water absorption due to capillary suction. Sorptivity test on pre-cracked ECC specimens (Sahmaran and Li, 2009a) indicated that water absorption increased exponentially with the number of surface cracks. Even so, the sorptivity values of pre-loaded ECC specimens up to a 1.5% strain on the exposed tensile face is not particularly high when compared to that of normal concrete. Moreover, in the same study, the addition of water repellent admixture in the ECC mix easily inhibited the sorptivity for the pre-cracked ECC (Sahmaran and Li, 2009a; Martinola et al, 2004).

Table 3 shows a summary of durability test results for pre-cracked ECC in a variety of exposure environments.

### 3.3 *Structural durability*

Reinforcing steel bars in concrete structures can be depassivated resulting in corrosion initiation when the chloride concentration reaches threshold levels on the rebar surface (Tuutti 1982). By preserving low chloride ion diffusion rate after cracking as

Table 3. Durability of pre-cracked ECC.

| Test | Expo. Condition | Specimen | Test result | Ref |
|---|---|---|---|---|
| ASTM C672 | Salt scaling resist. (50 cycles) | P, Preloaded to 1.5% strain on tension side | Visual rating & total mass of scaling residue within limits of ASTM C672 | Sahmaran & Li, 2007 |
| Uniaxial tension | Salt scaling resist. (50 cycles) | C, Pre-loaded to 2% strain | Strain capacity retained 3% | Sahmaran & Li, 2007 |
| ASTM C1260 | High alkaline (3 mos at 38°C) | C, Pre-loaded to 2% strain | Strain capacity retained >2% | Sahmaran & Li, 2008 |
| Falling head perm. test | Hydrau. head | C, Pre-loaded to 3% strain | Permeability ($8.90 \times 10^{-12}$ m/sec) similar to sound concrete | Lepech & Li, 2008 |
| AASHTO T259-80.24 Chloride ion diffusion | Salt ponding | P, Pre-loaded to 1.5% strain | Effective chloride diffusion coef. linearly proportional to crack nos. | Sahmaran et al, 2007 |
| ASTM C642 & ASTM C1585 | Water Absorption & sorption | P, Pre-loaded to 1.5% strain | Water absorption increased exponentially with number of surface cracks | Sahmaran & Li, 2009 |

Specimen Type: P = prisms; C = coupons.

discussed above, ECC material reduces chloride intrusion to effectively protect reinforcement from corrosion (Sahmaran et al, 2007). Miyazato and Hiraishi (2005) experimentally confirmed that the corrosion rate of steel rebars in preloaded ECC beams was orders of magnitude lower compared with those in similarly preloaded concrete beams, when these beams were exposed to wet (saltwater shower 90% RH for 2 days)—dry (60% RH for 5 days) cycles of an accelerated chloride environment.

A second level of protection against steel corrosion is the anti-spalling ability of ductile ECC to withstand expansive force generated by steel corrosion, if this ever occurs. In accelerated corrosion tests in which the embedded steel was forced to corrode by an imposed electro-chemical cell, ECC did not exhibit the severe distress observed

Table 4. Durability of R/ECC in Corrosive Environment.

| Test | Exposure condition | Specimen | Test result | Ref. |
|---|---|---|---|---|
| Macro & Microcell | Wet-dry cycles of accelerated chloride | R/ECC beams pre-cracked | Corrosion rate < 0.001 mm/yr in ECC; 0.008 mm/yr in R/C | Miyazato & Hiraishi, 2005 |
| Anti-spalling under accellerated corrosion | Impressed current (30 V DC) with specimen in salt bath | Cylinders with embedded steel bar (lollipop) | No spalling in ECC after 300 hrs; Spalling at 90 hrs for R/mortar | Sahmaran et al, 2008 |
| Corroded steel mass loss | Impressed current (30 V DC) with specimen in salt bath | Cylinders with embedded steel bar (lollipop) | 1% loss in ECC, 12% in concrete specimen; after 75 hrs | Sahmaran et al, 2008 |
| Residual flexural strength | Impressed current (30 V DC) with specimen in salt bath | ECC prisms with embedded steel bar | 100% in R/ECC, 20% in R/mortar; after 50 hrs | Sahmaran et al, 2008 |

in conventional mortar specimens. Expansion of corroding steel reinforcement was absorbed by the inelastic tensile deformation of the surrounding ECC. Corrosion related distress in mortar beams resulted in the reduction of the flexural strength and such reduction was not observed in the ECC beams (Sahmaran et al, 2008).

Finally, it should be pointed out that in many structures, steel reinforcements are used to control concrete crack width. Such reinforcements may be completely eliminated when ECC replaces concrete since the crack width in ECC is self-controlled. The elimination of steel reinforcement renders the corrosion related durability issues moot since corrosion cannot occur without the steel reinforcement present.

Table 4 summarizes the durability test results of reinforced ECC under accelerated corrosive environment.

## 4 ENGINEERING MATERIALS GREENNESS IN SHCC

One of the shortcomings of SHCC is the environmental penalty in higher energy and carbon footprints on a unit volume basis, associated with the incorporation of fibres and a typically higher cement content in SHCC compared with normal concrete. The higher cement content in SHCC results from the deliberate elimination of coarse aggregates used as filler material in normal concrete. Figure 5 shows a comparison of the compositions of a typical ECC formulation and a concrete formulation. Figure 6 shows a comparison of the energy consumption per cubic meter of the corresponding formulations (Kandall, 2007). Hence, on a unit volume basis, the primary energy consumption of ECC is a major concern. In the investigation of life-cycle primary energy consumption and equivalent carbon dioxide emission for a bridge deck, Keoleian et al (2005) identified material production as the second largest contributor to these sustainability indicators, behind traffic alterations due to maintenance and reconstruction events. Thus it is important to consider approaches in greening SHCC, even though the enhanced durability of SHCC as discussed in the previous section should drastically reduce repair needs and therefore enhance infrastructure sustainability.

The greening of ECC can target replacement of the virgin fibre and/or the matrix materials with industrial waste stream materials. ECC is optimized for tensile ductility with a minimum amount of fibres. Even so, the typical amount of fibre used is 2% by volume. Attempts at using natural fibre or recycled fibre (e.g. carpet fibre) in SHCC have met with limited success, given the requirement of strong fibre bridges in maintaining composite tensile ductility (Li et al, 2001). However, the greening of the matrix material is promising. We highlight here a few successful cases where Portland cement and silica sand have been replaced by industrial wastes.

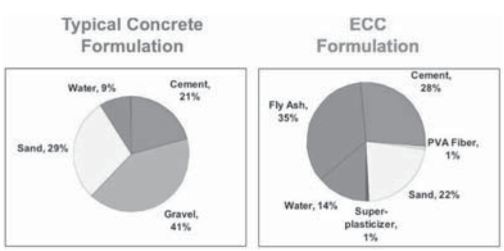


Figure 5. Composition comparison between a typical ECC formulation and a concrete formulation, showing weight percent.

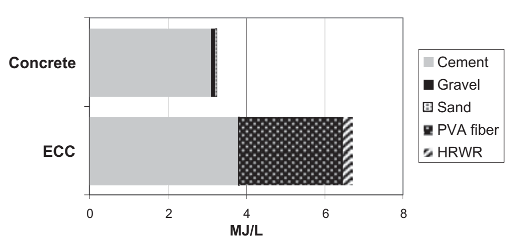


Figure 6. Material energy intensity for ECC and conventional concrete (Kendall, 2007).

Yang et al (2007) investigated green ECCs with Class F fly ash from coal based electric power plants. The "standard" ECC (table 1) already incorporates a relatively high fly ash content of FA/C = 1.2. In the very high fly ash content ECC (HFA-ECC) studied by Yang et al (2007), a FA to cement ratio up to 5.6 was adopted. It was found that at FA/C = 2.8, a 28 day compressive strength of 35 MPa and a 28 day tensile ductility of 3% can be retained. Beyond this FA/C ratio, the compressive strength loss may not be acceptable for many applications, and there may also be durability concerns. Sahmaran and Li (2009b) studied the durability (based on water sorptivity, chloride penetration and accelerated aging tests) of ECC containing FA/C = 2.2, and found that the durability of such HFA-ECC even in the microcracked state to be satisfactory. The use of fly ash actually enhanced composite performance, including reduced shrinkage strain and crack width, and more robust tensile strain capacity (Yang et al, 2007). The improvements in tensile ductility and crack width were attributed to a reduction in chemical bond and an increase in frictional bond due to the presence of the spherical fly ash particles in the interfacial transition zone, thus favoring conditions for tensile strain hardening.

Material sustainability indicators were computed based on life cycle assessment of all material and energy consumption along with water and emission generation associated with raw material extraction and production of ECC and its constituents. For this green ECC, a gain in solid waste reduction (diverting from waste stream) was achieved. With a large amount of cement replaced, this ECC with FA/C = 2.8 now generates a similar amount of $CO_2$ when compared with normal concrete. Even so, the total energy consumption remains about twice that of normal concrete due to the fibre content.

Another case of successful green ECC development was afforded by Lepech et al (2008), based on replacement of virgin manufactured silica sand by industrial waste sand. The waste foundry sand from the calcinator bag house and green foundry sand from lost foam metal casting were found to have the appropriate particle size distribution as dictated by micromechanics and for rheological control of ECCs. While the bag house sand resulted in an ECC with no loss of performance, the adoption of green sand did lead to a loss of tensile strength and ductility in the composite. It was determined that the fibre/matrix interfacial frictional bond was drastically decreased due to agglomeration of carbon nano-particles that are residuals accompanying the green sand in the loss foam casting process. An oiling agent was originally applied on the PVA fibres to reduce the strong hydrophilicity of the fibre and the excessively strong chemical bond to cement. A reduction of fibre surface oiling agent successfully restored the composite tensile ductility although the tensile strength was still substantially lowered.

Kendall et al (2008) computed material sustainability indicators for the two mixes involving foundry sands. The introduction of foundry sands was found to result in the replacement of an additional 22% of virgin ECC materials, whereas solid waste diverted from landfills increased 93%, when compared with a standard ECC (table 1, see also figure 5).

## 5 SMART SHCC FOR SUSTAINABLE INFRASTRUCTURE

While durability of SHCC will contribute to longer service life, deterioration of infrastructure will inevitably occur over time, especially in an aggressive environment such as that typical of coastal regions. Two recent advances in SHCC technology should be helpful in this regard—the endowment of self-healing and self-sensing functionalities in SHCC. Some preliminary findings of these functionalities based on ECC material are highlighted below.

Self-healing in an SHCC structure during service can have a profound effect on infrastructure sustainability. Since SHCC are designed to operate in the strain-hardening stage, it is expected that microcracks will be present during normal service conditions. While proven durable as discussed earlier, it is nevertheless advantageous if the material can reheal itself. Self-healing is defined here as the recovery of the undamaged mechanical and transport properties, without external intervention. Recovery of mechanical properties includes the assurance of uncracked tensile and compressive strength and stiffness, and tensile ductility. Recovery of transport properties implies a self-sealing function that prevents intrusion of aggressive agents. Such recoveries suggest a reverse deterioration process over the lifetime of the structure. While mechanical and environmental loading may cause continuous deterioration, self-healing autonomically reverses such deterioration and restores structural health. Ultimately, as structural durability improves and infrastructure maintenance needs are lowered due to self-healing of SHCC materials, the sustainability indicators will also decrease. Within the SIMSS approach (figure 1), self-healing links material properties to structural properties and infrastructure sustainability performance.

Preliminary studies of self-healing in ECC (Li and Yang, 2007; Yang et al, 2009a) suggest a promising approach towards virtually "crack-free" concrete. The self-healing behavior of ECC has been found to persist in a variety of environments typical of civil infrastructures, including cycles of rain and sunshine (Yang et al, 2009a,b), under continuous water immersion (Yang et al, 2009a,b), under a hydraulic gradient (Lepech and Li, 2008), and in the presence of salt or strong alkali (Sahmaran et al, 2007; Sahmaran and Li, 2008). Self-healing occurs for both young (3 days) (Yang et al, 2009b) and in more mature specimens (6 months) (Yang et al, 2009a). Several characteristics of ECC lend themselves to robust self-healing. Self-healing utilizes unhydrated cement grains in the material for further hydration and for calcium carbonate formation on contact with water and air. This implies that the self-healing process can take place wherever damage occurs since unhydrated cement grains are ubiquitous in the material. The ability of ECC to withstand multiple damage events and to still recover its virgin properties after each self-healing event is less obvious. This issue is currently under investigation at the University of Michigan. Figure 7 shows the full recovery of tensile strength and ductility (3%) and stiffness of an ECC specimen after a 2% damaging tensile pre-load. However, for a specimen with a 3% damaging pre-load, the recovery was incomplete. The material suffered from a reduced first cracking strength. Additional studies of failure mode details and strengthening

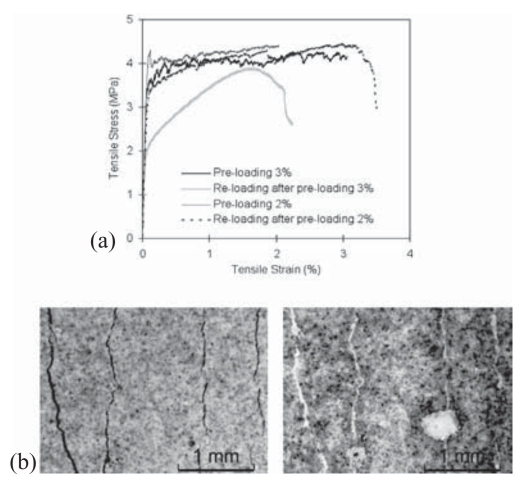


Figure 7. Self-Healing of ECC (a) Recovery of Tensile Properties and (b) Cracks filled with reheal products (Yang et al, 2009a,b).

of the rehealed cracks are needed to advance the concept of "crack-free" concrete.

The current practice of maintenance scheduling for bridges assumes deterioration rates that are based on empirical data of deterioration from similar structures, traffic and environmental exposure conditions. This practice may result in maintenance events that may not be warranted due to better-than-expected performance of the structure, or that may be overdue due to worse-than-expected performance of the structure. An optimized maintenance schedule should be one that is just in time; this would require intimate knowledge of the in-situ surface and internal damage the structure has experienced in real time. An economically feasible technology needed to accomplish this does not currently exist. However, it may be expected that just in time maintenance scheduling can lead to significant savings in materials and reduces unnecessary traffic delays due to minimized reconstruction events. As a result, infrastructure health condition and life cycle sustainability indicators can be significantly and simultaneously improved.

One potential enabling technology to allow real-time in-situ structural health monitoring is a self-sensing SHCC. A self-sensing SHCC will serve both as a structural load-bearing damage tolerant material by virtual of its tensile ductility, while at the same time, be able to self-measure its strain state and crack width. By coupling with wireless communication technologies and cyber infrastructure, it is possible to report to remote monitoring stations the condition of any part of the structure in real time. Such a technology is currently being researched at the University of Michigan (Lynch et al, 2009).

Self-sensing SHCC for structural health monitoring fits seamlessly with the SIMSS design approach (figure 1). Preliminary investigation (Hou and Lynch, 2005) demonstrated that ECC exhibited piezoresistive properties. Specifically, changes in material deformation, especially in the inelastic stage, are accompanied by changes in electrical resistivity (figure 8). At the materials level, manipulation of the piezoresistive sensitivity can be attained by control of the composite ingredients, such as doping the composite with carbon nanotubes or carbon blacks. At the structural scale, strategic location of electrodes within the structure allows current injection and voltage measurements from which data a spatial damage map can be extracted via electrical impedance tomographic approaches (Hou and Lynch, 2009). Unlike other sensing approaches, self-sensing ECC provides direct damage sensing. System scale deterioration information is communicated via a cyber-network to structural health monitoring stations where the

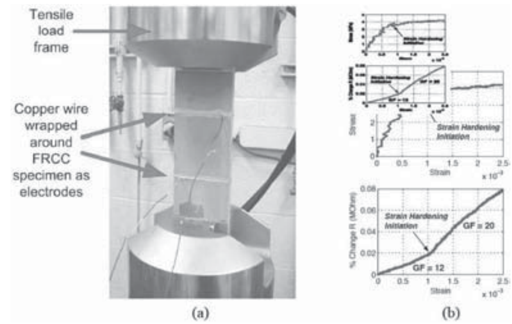


Figure 8. (a) ECC plate element loaded in unaxial tension as resistivity is measured by two-point probing, and (b) Resistivity versus strain plots (Hou and Lynch, 2005).

data can be assimilated with risk and life cycle analyses tools. In this scheme, data collection is autonomous and low cost, and the data is objective. The result is optimized maintenance decision-making with regard to when, what and where repairs should be performed. While attractive, there remain many technical challenges that need to be overcome to turn this concept into a deployable technology. A multi-disciplinary team involving specialists in wireless sensors, materials design, power harvesting, radio technology, cyber infrastructure, structural analyses, human-structure interaction, and industrial ecologists have been assembled (Lynch et al, 2009) to tackle this complex problem.

## 6 CLOSURE

In this paper, SHCC is depicted as a new class of concrete materials that can drive the environmental sustainability of the next generation of reinforced concrete structures. The most direct contribution to infrastructure sustainability comes from the enhanced durability through the unique tensile ductility and tight crack width control of SHCC. These properties assist in suppressing many common deterioration mechanisms of current reinforced concrete structures. As a result, prolonged service life and reduction of maintenance needs substantially curtail energy input and carbon dioxide output over the life cycle of an infrastructure. It should be noted that even though the energy and carbon footprints are emphasized in this paper, other resource input (e.g. water) and emission output (e.g. NOx and SOx) will also be positively impacted by replacing concrete with SHCC. Further, the magnitude of reduction in environmental burden is infrastructure and geographically dependent. Transportation infrastructure such as bridges and roads that suffers rapid deterioration especially in cold weather or coastal regions will likely have the best gain in environmental sustainability with the use of SHCC.

The greening of SHCC has made important advances in recent years. It appears that green SHCC with carbon footprint similar to that of normal concrete is on the horizon, although higher energy content is almost inevitable due to the use of fibres. However, as suggested in the case study result shown in figure 3, the total primary energy and global warming potential over the service life of the bridge deck due to materials are actually lower than that of a deck built with normal concrete. This is so because the total volume of materials used over the life cycle is lessened due to the reduced maintenance events when SHCC is adopted. In that example, the calculation was done with a standard ECC (table 1). With a greener version of ECC adopting a high volume of fly ash partially replacing cement and recycled industrial sand replacing virgin silica sand, the improvements in sustainability indicators should be even more favorable.

While green and durable SHCC have been demonstrated, its self-healing and self-sensing functionalities hold an even more significant amount of untapped potential for major gains in infrastructure sustainability. Self-sensing of SHCC provides a means to continuously track not only material and structural damage, but also the amount of self-healing that takes place over time. Further research will lead to intelligent infrastructure with abilities to monitor its own health in real time, and also self diagnose its recovery should damage occur; or provide meaningful information to responsible agencies for repair assistance. While substantial technical challenges remain, the worldwide efforts in multi-functional SHCC development and field-testing offer infrastructure sustainability a promising future.

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