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Design of Green Engineered Cementitious Composites for Improved Sustainability

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The sustainability of the built environment is increasingly coming to the forefront of infrastructure design and maintenance decisions. To address this, development of a new class of more sustainable cement-based materials is needed. These materials should be developed with respect to the final application in which they will be used. Neglecting the connection between material development, structural design, and sustainability objectives can lead to shorter-lived, costly, and resource-intensive structures that require greater maintenance. Within this study, a green materials design framework is presented and used to complete a case study in the design of green materials for a specific infrastructure application. Through deliberate control of composite constituents and the interactions among them, cement-based composites have been developed that incorporate industrial waste streams while not sacrificing critical material properties.

Keywords: engineered cementitious composite (ECC); green chemistry; green materials; sustainability; sustainable infrastructure.

INTRODUCTION AND CURRENT CONCRETE PRACTICE

Sustainability initiatives can be traced back to the environmental movement of the 1960s and the energy crisis of the 1970s. Globally, there are a number of academic, industrial, and government initiatives actively improving the sustainability of built environments.[1-3] These efforts focus on green materials development and procurement, design for low-energy demand, and construction methods that produce less waste, use fewer resources, and require less energy.

One approach to reducing the environmental impact (that is, "greening") of concrete has been the use of fly ash and blast-furnace slag as supplementary cementitious materials (SCMs). A by-product of coal-fired power generation and used since the mid-1970s, fly ash replaces cement while increasing workability through improved particle gradations and decreasing environmental impacts by reducing land-filling and replacing energy-intensive cement.[4,5] Improvements in the durability of concrete have also been found.[6-8] This has been attributed to the densified matrix and accompanying lower transport.[9] Recently, Wang and Li[10] successfully used high volumes of fly ash in strain-hardening cementitious materials.

Blast-furnace slag, a pozzolanic by-product of steel blast furnaces, can also be used as a cement substitute for lowering environmental impact.[11] Benefits from using fly ash or ground-granulated blast-furnace slag include reductions in energy consumption, greenhouse gas releases, and other pollutant emissions from initial mining of limestone, calcination, and grinding.[12] Successful industry acceptance of both fly ash and blast-furnace slag is noted by respective ASTM standards (ASTM C618 and ASTM C989).

Recycled aggregates and industrial wastes have also been introduced as alternatives with lower environmental impacts. In many developed countries, the availability of high-quality aggregates is decreasing. By reclaiming aggregates, the supply can be extended. Unlike fly ash and blast-furnace slag, however, recycled aggregate concretes have met resistance, particularly by departments of transportation concerned with lower strength and durability.[13] Nontraditional waste streams have also been explored to reduce impact. These include shredded waste automobile tires,[14] municipal solid waste ash,[15,16] rice husk ash,[17] ground waste glass,[18,19] and reclaimed harbor dredging waste.[19]

While industrial wastes can reduce the environmental impact of concrete per volume, this is not a sufficient indicator of overall sustainability. Effects of material changes on the larger system must be considered. Keoleian et al.[20] found that due to the long service life of concrete infrastructure, the influence of material durability on the overall sustainability (economic, environmental, and social) is large. If incorporating industrial wastes lowers durability, more frequent maintenance, repair, and replacement of infrastructure are required. Keoleian et al. found that bridges incorporating conventional materials with lower initial environmental impact but poorer durability consumed greater volumes of material throughout their total life cycle. This greater consumption ultimately lowered the sustainability of these systems while using materials originally thought to be more sustainable.

New approach: engineered cementitious composites

Material durability plays a central role in sustainable concrete infrastructure. Therefore, adverse effects of industrial waste on durability should be controlled. Engineered cementitious composite (ECC) was identified as a candidate for material greening with the overall goal of improving sustainability. ECC is a high-performance fiber-reinforced cementitious composite (HPFRCC) designed to resist large tensile and shear forces while remaining compatible with ordinary concrete in almost all other respects such as compressive strength and thermal properties.[21] As noted by Lepech and Li,[22] ECC materials are highly durable in a number of harsh environments. This durability results from unique pseudo strain-hardening ductility and distributed microcracking behavior in tension.

To achieve tensile ductility and distributed microcracking, ECC is designed using a well-defined toolbox of micromechanical models. These models characterize crack formation and fiber bridging within the loaded composite.[23,24] The tensile response and microcracking behavior of ECC are

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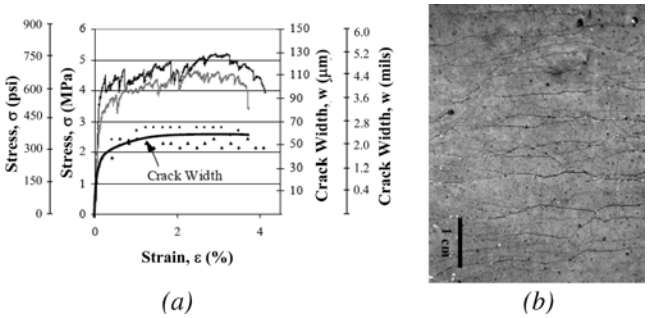

Fig. 1—Composite response in uniaxial tension for ECC material: (a) stress-strain and crack width development characterization; and (b) microcracking behavior.

shown (Fig. 1 with mixture design in Table 1). Key to this response are microcracks that widen to 60 μ (0.002 in.) at 1% tensile strain, and remain at this width as deformation increases (Fig. 1(a)). During this process, further deformation is accommodated by additional microcracks saturating the ECC (Fig. 1(b)) before localization. This tight crack width is essential to durability because preloaded ECC continues to exhibit water permeability equal to sound ECC or concrete even at 3% deformation.[25]

The objective of this work is the development of a new framework for green infrastructure materials design. By validating this framework, low-environmental-impact material substitutes are identified, and a new version of green ECC that incorporates a number of industrial wastes is designed for use in bridge infrastructure.

RESEARCH SIGNIFICANCE

Concrete is the most used anthropogenic material worldwide.[26] The enormous concrete material flows cause significant societal and environmental impacts.[26] Cement production accounts for 5% of global greenhouse gases[27,28] and significant levels of NO_x, particulates, and other pollutants.[29-31] Developing countries require infrastructure expansion; however, the unsustainable interaction between built and natural environments is increasingly a global concern. The establishment of a framework for systematic screening and design of materials, which reduces environmental impact through the introduction of low-impact material streams while maintaining high material performance, provides a foundation for more sustainable infrastructure design.

Table 1—Mixture proportions and fresh flowability results for ECC material (mixture designation M45) along with green ECC mixture proportions (ECC with green foundry sand, ECC with bag house calcinator sand)

Mixture proportions, *high-range water reducer	M45	M45G	M45 Calcin
Cement	1	1	1
F-110 sand	0.8	—	—
Green sand	—	0.8	—
Calcinator sand	—	—	0.8
Fly ash	1.2	1.2	1.2
Water	0.58	0.57	0.58
*High-range water reducer	0.013	0.03	0.013
PVA fiber	0.02	0.02	0.02
Fresh properties			
Average diameter, mm (in.)	885 (34.8) ± 73 (2.9)	915 (36.0) ± 87 (3.4)	960 (37.8) ± 63 (2.5)
Γ	3.4 ± 0.4	3.6 ± 0.4	3.8 ± 0.3
Material sustainability indexes			
Solid waste, kg/L	–0.49	–0.96	–0.96
Carbon dioxide, kg/L	662.7	660.8	660.8
PM_{10}, g/L	5.8×10^{-4}	4.0×10^{-6}	4.0×10^{-6}
Primary energy, MJ/L	6.64	6.63	6.63

MATERIAL DESIGN METHODOLOGY

Material design framework and preliminary screening and assessment

The development process for green ECC comprises a number of stages (Fig. 2). This process is part of a larger sustainable concrete infrastructure paradigm proposed by Keoleian et. al.[32] This paradigm (Fig. 3) integrates materials design with infrastructure service life evaluation and life cycle analysis. Specifically, Fig. 2 details the "Input Materials and Composition," "Microstructure Tailoring," "Material Physical Properties," and "Infrastructure Application" portions of Fig. 3. The iterative design of materials, evaluation of structural performance, assessment of life cycle impacts, and the redesign of materials provides for integration between engineering and life cycle analyses.

To begin material design, a pool of candidate substitute materials is gathered with no potential materials excluded. While industrial wastes have high potential due to low cost and large material flows, any material with comparatively low environmental impacts, including recycled cementitious materials or aggregate, can be evaluated. Development begins with preliminary screening designed to limit the number of substitutes, which undergo rigorous investigation.

Preliminary screening focuses on three factors: mechanical properties, chemical properties, and material environmental sustainability. Mechanical properties may include the strength or stiffness of various substitutes. Preliminary chemical analysis evaluates adverse chemical interactions that replacements may have with other constituents or the intended application environment (that is, the presence of chlorides or corrosives). Environmental sustainability is evaluated through material sustainability indexes (MSI). MSI values capture environmental indicators such as global warming potential, water used, or energy intensity in material production, without regard for the application, and allow for comparison of green materials on a per volume basis. These are calculated using life cycle assessment techniques that provide a comprehensive accounting for all energy and

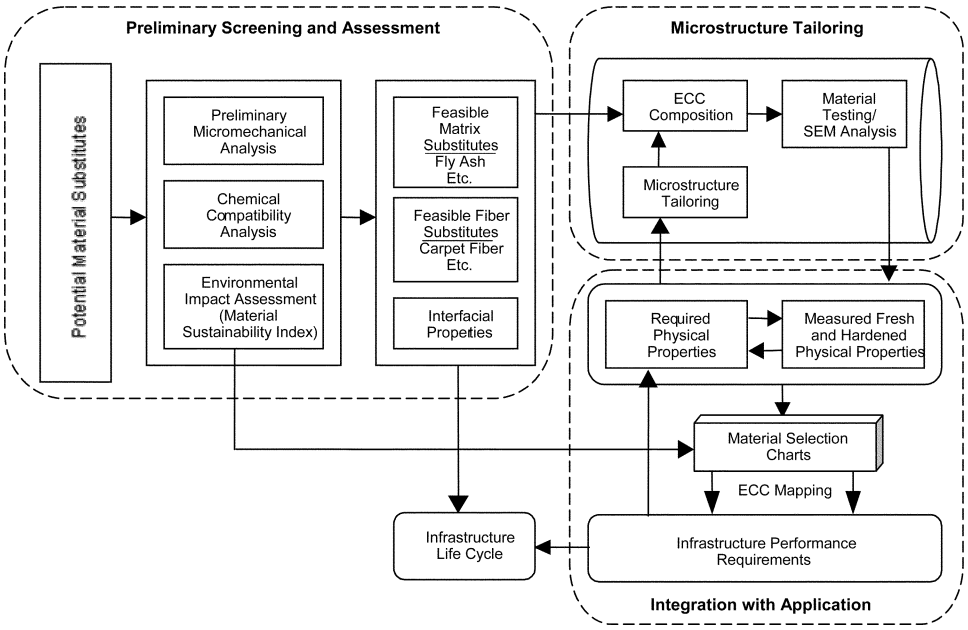

Fig. 2—Schematic of green ECC materials development framework.

material inputs, along with emissions and wastes generated during material production including raw material extraction and processing.[33] Typical MSI values are shown in Table 1.

A large pool of substitutions is initially considered. For ECC, potential substitutes were grouped into three main groups: binder (cement), filler (sand), and fiber. For each group, mechanical, chemical, and environmental preliminary screening was conducted (left portion of Fig. 2). Preliminary screening parameters for cement replacements included grain size distributions, hydration potential, material flow estimation, and MSI evaluation. Parameters for sand replacements included adverse chemical effects (that is, alkali-silica reaction and chlorides), grain size distribution, material flow estimation, and MSI evaluation. Screening parameters for fiber replacements included fiber strength, modulus, maximum elongation, diameter, length, material flow estimation, and MSI evaluation. Parameters were derived from theoretical limits based on micromechanical tailoring (that is, grain size distribution and fiber strength)[34] or practical limits of processing or procurement (that is, fiber length and material availability).

Reductions in MSI values captured the lower environmental impacts of the entire composite (per L) by incorporating wastes or using low-impact virgin substitutes. Building from a life cycle inventory of ECC constituents,[32,33] MSI values could include primary energy consumption (MJ/L), carbon dioxide equivalent release (equivalent grams of CO_2/L), PM_{10} release (grams of PM_{10}/L), biological oxygen demand (grams of BOD/L), along with solid waste generated (kg/L) (Table 1). While most ECC environmental impacts stem from cement production, MSI values can be used as a preliminary guide to material greening by eliminating substitute wastes with large environmental impact (due to excessive processing or toxicity) from being considered.

Material mapping and integration with application

As discussed, durability is an important element in materials design for sustainable infrastructure. Design for durability is closely linked with an understanding of specific structural

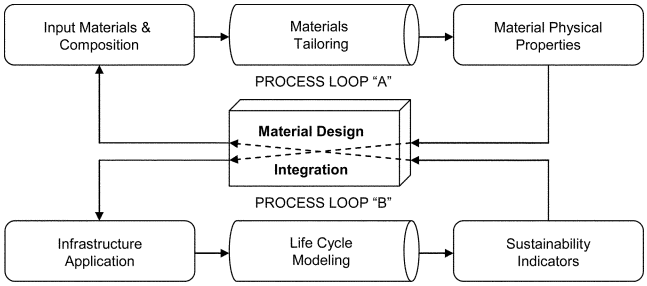

Fig. 3—Interactive design framework for sustainable infrastructure systems.

demands and associated material requirements. This linking of material design with a specific infrastructure application (lower right portion of Fig. 2) was made up of three distinct steps. First, independent of materials development, an infrastructure application was targeted, and sources of failure with existing technologies were identified. These sources were application-specific, and could range from steel corrosion caused by leaking bridge joints to fatigue failure and reflective cracking in rigid pavement overlays.

Second, these performance requirements were linked through structural modeling to required material properties. In the case of bridge joints, these could be replaced by ductile "link slabs," which replace joints with a strip of ECC, allowing for thermal expansion and contraction of bridge spans while creating a continuous, impermeable deck.[35] Within the link slab, ECC tensile ductility coupled with tight crack widths were the most critical elements to structural durability. In this regard, ECC materials were not intended to be a replacement for all concrete infrastructure materials. Rather, ECC was intended for strategic application within concrete infrastructure in circumstances where the brittle behavior of concrete specifically limited structural, durability, or environmental performance (that is, replacement of expansion joints).

Third, the required material properties were compared with actual physical properties (that is, tensile ductility,

Table 2—Potential substitute materials and preliminary evaluation results

Material	Substituting material	Outcome	Reason
Fly ash	Cement	Passed	—
Cement kiln dust	Cement	Passed	—
Granulated blast-furnace slag	Cement	Failed	Poor grain size distribution
Rice husk ash	Cement	Failed	Poor hydration
Solid municipal waste ash	Cement	Failed	Inconsistent chemistry
Foundry green sand	Sand	Passed	—
Waste water sludge	Sand	Failed	Inconsistent chemistry
Expanded polystyrene beads	Sand	Passed	Micromechanical synergy
Pot lining	Sand	Failed	Chemical incompatibility
Post-consumer carpet fiber	Fiber	Passed	Micromechanical synergy
Banana fiber	Fiber	Failed	Low strength

maximum crack widths and tensile strength) of the new material. If actual properties did not meet requirements, the material was re-engineered using the micromechanical tools described in the following. This tight linking of material with structural design and application offered a high degree of efficiency in material consumption and energy use by maximizing industrial waste contents while not sacrificing overall structural performance.

Materials tailoring—grain size distribution

Building from the pool of screened substitutes and using material goals set by the final application, the iterative materials tailoring process began (upper right portion of Fig. 2). Grain size distribution of sand substitutes was critical to meet ECC workability requirements. In addition to restricting maximum particle size, Fischer et al.[36] and Lepech and Li[37] proposed a set of ECC design procedures for processing. Grain size distributions of the various ECC components were designed to produce a free-flowing mixture during mixing, and a self-consolidating material during casting. Relying on control of combined grain-size distributions to achieve a highly dense and closely packed matrix, this approach was analogous to densely packed soils that were subject to liquefaction in earthquakes. In particular, the Alfred grain size distribution curve was proven successful (Eq. (1))[38]

$$f_d = 100\left(\frac{D^q - D_s^q}{D_L^q - D_s^q}\right) \quad (1)$$

where f_d is the cumulative percent of particles finer than D; D is the size of any particle, in mm; D_s is the diameter of smallest particle in distribution, in mm; D_L is the diameter of largest particle in distribution, in mm; and q is the distribution modulus.

To quantify the effects of particle size distribution, a flowability testing follows procedures outlined by Kong et al.[39] A standard concrete slump cone is filled with fresh ECC and discharged onto a level Plexiglas or glass plate. Following discharge, two orthogonal diameters of the ECC "pancake" are averaged, and a characteristic flowability factor, denoted by Γ, is calculated using Eq. (2)

$$\Gamma = \frac{(D_1 - D_0)}{D_0} \quad (2)$$

where Γ is the fresh ECC deformability factor; D_1 is the average of two orthogonal "pancake" diameters, in mm; and D_0 is the diameter of bottom of original slump cone, in mm.

Materials tailoring—micromechanics

Ductility is the cornerstone of ECC mechanisms that improve structural durability. The fundamental micromechanics that govern this ductile behavior through the formation of multiple microcracks provide an additional tool for composite design. The basis of multiple cracking and strain hardening within ECC is the propagation of steady-state cracks, first characterized by Marshall and Cox[40] for continuous aligned fiber-reinforced ceramics, and extended to fiber-reinforced cementitious composites by Li and Leung[41] and Lin et al.[42] The formation of multiple steady-state cracks is governed by the bridging stress versus crack width opening relation and fracture toughness of the mortar matrix. To achieve strain hardening, the inequality shown in Eq. (3) must be satisfied

$$J_b' = \sigma_0\delta_0 - \int_0^{\delta_0}\sigma(\delta)d\delta \geq J_{tip} \approx \frac{K_m^2}{E_m} \quad (3)$$

where J_b' is the complimentary energy; σ_0 and δ_0 are the maximum crack bridging stress and corresponding crack opening, respectively; J_{tip} is the fracture energy of the mortar matrix crack tip; K_m is the fracture toughness of the mortar matrix; and E_m is the elastic modulus of the mortar matrix.

In addition to this energy criterion, a strength criterion (Eq. (4)) must be satisfied

$$\sigma_0 > \sigma_{cs} \quad (4)$$

where σ_0 is the maximum crack bridging stress, and σ_{cs} is the cracking strength of the mortar.

Both σ_0 and σ_{cs} may vary from one crack plane to another. For saturated multiple cracking, Li et al.[34] found that Eq. (4) must be satisfied when a crack initiates at σ_{cs}, and σ_{cs} must be below the values of σ_0 of each the existing multiple cracks.

LABORATORY INVESTIGATION

Preliminary assessment results

The results of the preliminary screening are shown in Table 2. Both fly ash and cement kiln dust passed as cement replacements for further micromechanical analysis and tailoring. This is due to favorable grain size distributions (Fig. 4), good hydration potential, large material flows, and favorable MSI values. Granulated blast-furnace slag was rejected due to large particle size (greater than 300 μ [0.012 in.]) and high particle porosity that significantly increases water requirements. While Kim et al.[43] demonstrated that ground-granulated blast-furnace slag, with an average particle diameter of 11 μ (0.0004 in.), can be used within green ECC and produce uniaxial tension strain capacities over 2.5%, this investigation excluded materials that require further processing and additional energy. Slag particles produced directly from the blast furnace are over 300 μ (0.012 in.) in

average diameter. The use of energy-intensive processes, such as grinding, to refine the waste stream deteriorates composite MSI values.

Rice husk ash and solid municipal waste ash were rejected due to chemical incompatibilities. While the chemical composition of the rice husk ash tested met requirements for ASTM C618 chemical composition of SiO_2, Al_2O_3, and Fe_2O_3, the water requirement (ASTM C618) was nearly 110% and resulted in poor fiber dispersion and fresh properties. Solid municipal waste ash was eliminated due to a high chemical variability. Additionally, Mangialardi et al.[16] found that the levels of combined SiO_2, Al_2O_3, and Fe_2O_3 within most municipal solid waste fail to meet required limits within ASTM C618 without additional processing of the ash. Mangialardi et al. found a propensity for accidental retention of heavy metals from illegal waste disposal. Future leaching of these metals is a concern.

A number of sand replacements were considered, including a variety of waste foundry materials, industrial waste water sludge, pot lining from aluminum casting, and waste-expanded polystyrene (EPS) beads from lost foam metal casting. Three separate waste foundry streams were examined. Preliminary mechanical screening for sand replacements focused on grain size distribution. Building from steady state flat crack theory, the maximum particle size within ECC must be below roughly 200 μ (0.008 in.) to keep the fracture toughness J_{tip} of the matrix low, and to prevent large matrix particles from dominating fiber dispersion.[34]

Three separate foundry sand waste streams were examined, which are referred to as "bag house sand from calcinators," "foundry green sand," and "corbitz." Bag house sand from calcinators is captured by foundry dust collection systems. Due to vacuum collection, particle sizes are small and very consistent (Fig. 4), and are nearly identical in appearance and mechanical properties to virgin sand currently used for ECC. Green foundry sand is waste from lost foam metal casting. While the size distribution is larger than virgin sand, the green sand grain size distribution ranging up to 300 μ (0.012 in.) was within range of the 200 μ (0.008 in.) grain size limit to warrant further investigation and, unlike blast-furnace slag, did not exhibit high porosity. Corbitz is a by-product from chemically bonded lost foam sand casting, and often contains cobble-sized pieces. While these can be sieved, the chemically bonded corbitz sand adsorbs a number of hazardous chemicals, including high levels of phenols, trichloroethene, and toluene, which coat the sand after casting.[44] As with municipal solid waste ash, chemical hazards rule out the use of corbitz as a substitute.

Dried wastewater sludge from foundry wastewater treatment was also examined. This material contained many particles larger than 400 μ (0.016 in.)—too large for ECC. Expanded polystyrene beads, a by-product from lost foam casting, were also too large for sand replacement, with most on the order of 1 to 2 mm (0.04 to 0.08 in.) in diameter.

Waste fibers were considered as replacements for polyvinyl alcohol (PVA) fibers. Li et al.[34] found that fibers within ECC must have a minimum tensile strength of 1000 MPa (145 ksi), an inelastic failure strain greater than 5%, and a fiber diameter between 30 and 50 μ (0.001 and 0.002 in.). Banana fibers and post-consumer carpet fibers (nylon and polypropylene) were considered. All fiber replacements fail to meet minimum values (Table 3). Physical properties for PVA and PE (polyethylene) fibers successfully used in ECC are also shown.

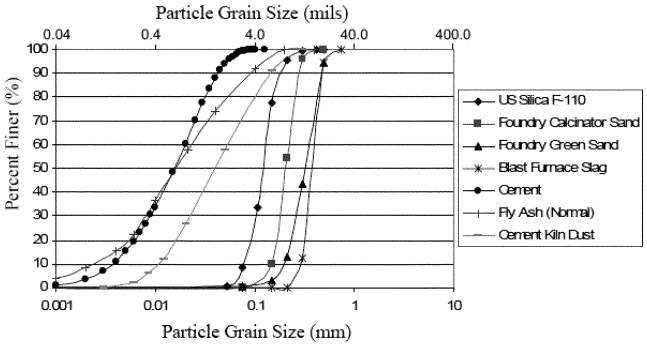

Fig. 4—Virgin and waste material grain size distributions.

Table 3—Physical properties of current and potential ECC fiber replacements

Fiber type	Strength, MPa (ksi)	Minimum elongation, %	Diameter, mm (mils)
PVA REC-15[33]	1620 (235)	6	39 (1.5)
PE[33]	1660 (241)	6	14 (0.55)
Nylon[50]	100 to 750 (14.5 to 109)	10 to 35	50 (2.0)
PP[49]	200 to 600 (29 to 87)	20+	120 to 250 (4.7 to 9.8)
Banana[50]	700 to 800 (102 to 116)	1 to 2	15 to 30 (0.59 to 1.2)

Overall, a small number of green substitutes passed preliminary screening (Table 2). This, however, does not exclude failed substitutes from further examination. Recently, Wang and Li[45] found that artificial flaws embedded within the mortar matrix of ECC can significantly increase crack saturation within ECC. This results in increased material robustness and ductility. Wang and Li[45] suggested that such flaws have a diameter of approximately 3 to 4 mm (0.12 to 0.16 in.) and be inert to act as voids or flaws within the matrix. EPS beads may be used in future studies to meet these requirements because they showed preliminary success in initiating cracks. This use, however, will not be explored in this article.

In addition to the waste substitutes described previously, virgin components used in both the control ECC and green materials (Table 1) used in this study included Type I ordinary portland cement, virgin silica sand consisting of a gradation curve with 50% particles finer than 110 μ (0.004 in.) and a maximum grain size of 300 μ (0.012 in.) (Fig. 4), ASTM C618 Class F fly ash with particle size of 10 to 20 μ (0.0004 to 0.0008 in.) (Fig. 4), ASTM C1017 Type 1 high-range water-reducer, and polyvinyl alcohol (PVA) fibers with a fiber diameter of 39 μ (0.0016 in.) and a length of 8 mm (0.3 in.). The fiber strength was 1620 MPa (235 ksi), with a tensile elastic modulus of 40 GPa (5800 ksi) (Table 3).

Infrastructure application integration

Following Fig. 2, preliminary screening was carried out parallel with evaluation of application demands. Minimum required material properties, such as strength, ductility, or permeability, served as goals for iterative tailoring. As a case study, a bridge link slab was chosen for a green ECC structural application. Large-scale implementation of this material design philosophy and the bridge link slab case study are detailed by Lepech and Li.[37]

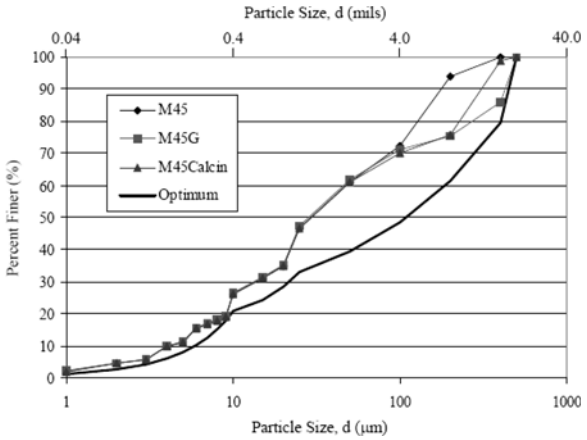

Fig. 5—Grain size distribution of ECC M45, green sand ECC (M45G), bag house ECC (M45Calcin), and optimal Alfred grain size distribution.

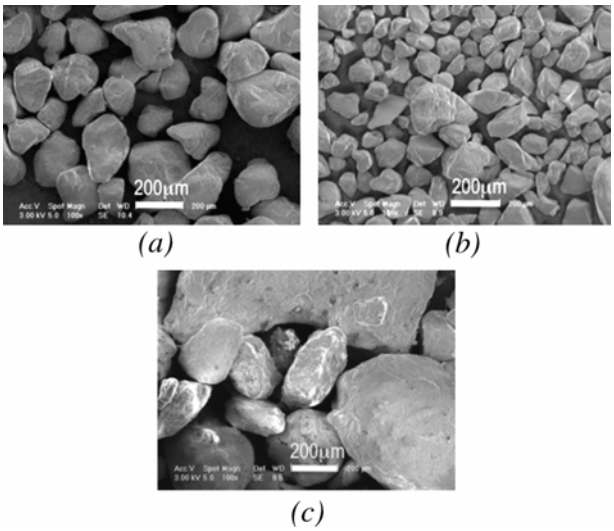

Fig. 6—100× magnification of: (a) bag house sand from calcinator; (b) virgin silica sand; and (c) green foundry sand.

To successfully replace bridge expansion joints with a strip of ECC, Kim et al.[35] determined through analytical structural analysis that a minimum of 1.6% tensile ductility was necessary within the ECC link slab. A maximum crack width of 100 μ (0.004 in.) was required for durability. A minimum compressive strength of 35 MPa (500 psi) was required for traffic. No minimum tensile strength was required. (For this application, tensile strength lower than the concrete in the bridge decks adjacent to the ECC link slab was, in fact, favorable to the designed function of the link slab.) Additionally, the green ECC would have to exhibit flowable fresh properties for on-site casting. These requirements established a target for the materials' tailoring process.

Materials tailoring—grain size distribution

ECC M45 mixture proportions (Table 1) had an overall grain size distribution slightly smaller than the optimal Alfred distribution (Fig. 5). This was most prevalent at larger grain sizes. Mixture proportioning using waste foundry sands (bag house sand from calcinator and green foundry sand) focused on reducing separation between the original distribution and the Alfred curve while still meeting micromechanical requirements.

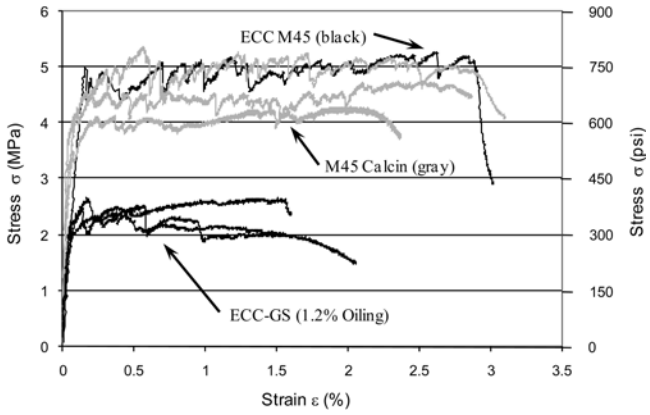

Fig. 7—Typical stress-strain response of ECC M45 and ECC bag house sand from calcinator, and green sand ECC (1.2% fiber oiling content).

Proportioning to match the Alfred curve, the cumulative error between the new mixture designs and the optimal Alfred curve was reduced by roughly 25% over ECC M45, leading to a more flowable fresh state. Mixture proportions are shown in Table 1. Results of flowability tests confirm that new green materials showed improved flowability in the fresh state, as predicted by gradation curves (Table 1). In addition to providing a preliminary tool for evaluation, grain size distribution analysis represents a structured methodology for determining mixture proportions incorporating a number of waste streams (though not attempted in this study). In this case, both foundry sands exhibited improvements over virgin sand for ECC flowability.

Materials tailoring—micromechanics

Waste foundry sand from the calcinator bag house was introduced into ECC with little difficulty. With a grain size distribution (Fig. 4) and physical characteristics close to virgin sand (Fig. 6(a) and (b)), virtually no change was observed following complete replacement of virgin sand (Fig. 7). This ECC material exhibited an average compressive strength of 64.8 MPa (9400 psi), an average crack width of 45 μ (0.002 in.), and a maximum crack width of 75 μ (0.003 in.). The average tensile strain capacity was 2.6%. Because these met required values, no further tailoring was necessary. This was possibly a unique case in which an industrial waste possessed all of the properties to succeed as a virgin material replacement without re-engineering the material to account for the substitution.

The introduction of most wastes is accompanied by a decrease in performance due to an imbalance of carefully controlled fiber, matrix, and fiber-matrix properties. This was observed with foundry green sand. Following replacement of virgin sand, the average tensile strain capacity dropped to 1.3%, below the 1.6% application minimum (Fig. 7). Average crack widths increased to 76 μ (0.003 in.), maximum crack widths increased to 112 μ (0.004 in.), and compressive strength dropped to 60.7 MPa (8800 psi).

This decrease in performance was traced to the metal casting process. Foundry green sand is waste from lost foam metal casting. Within this process, a replica of the desired casting is created through pre-expansion of polystyrene (EPS) into a foam pattern using a pentane blowing agent. This form is then surrounded by compacted sand. Molten metal is poured

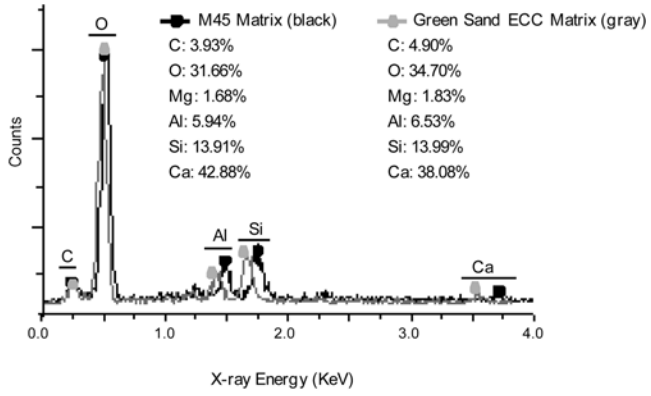

Fig. 8—Chemical composition of: (a) ECC matrix; and (b) ECC fiber-matrix interface for both M45 and green sand ECC (100% green sand replacement).

into the foam mold. As the molten metal melts the foam, it produces a casting identical to the destroyed EPS form.[46,47]

Using clean, virgin sand, the lost foam process produces low-grade finishes that require further machining. To counteract this, treated sands are used for smoother finishes. Treated sand is a combination of dune sand, water, finely ground coal, and clay. Fine coal is used to create a smooth finished surface. As molten metal contacts the treated sand, it burns the coal, creating a thin gas layer between the sand and molten metal. This layer creates a smooth surface. Unburned coal, however, remains on the sand particles after discard and results in a black coloring.

The reduction in strain capacity and increased crack width in ECC containing green sand result from changes within the matrix and fiber-matrix interface due to unburned coal. During mixing, PVA fibers collect coal residue on their surface and exhibit a black coloring that is identical to green sand grains. This residue was verified through XEDS analysis, which found only slightly higher carbon content within green sand matrixes compared with ECC M45 (Fig. 8(a)). This contrasts with the significantly increased carbon content immediately surrounding fibers within the green sand ECC as compared with fiber in ECC M45 matrix (Fig. 8(b)). This points toward a concentration of carbon particles accumulating at the interface of PVA fibers and matrix.

To assess the impact of these changes on strain hardening (characterized by Eq. (3) and (4)), single fiber pullout and matrix fracture toughness tests were conducted. Single fiber pullout tests determine fiber pullout load versus pullout displacement

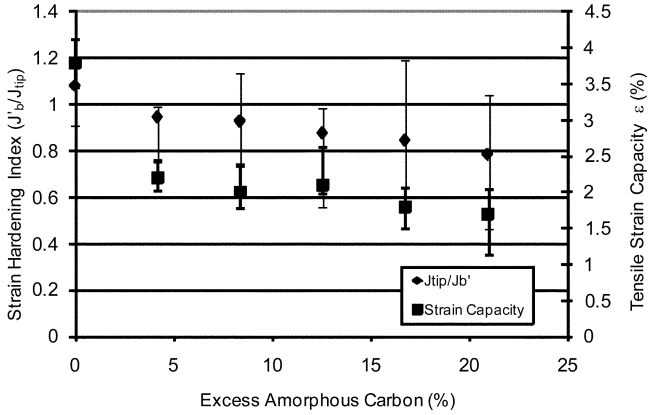

Fig. 9—Strain-hardening index and tensile strain capacity versus excess amorphous carbon content in green sand ECC.

curves (p-δ). This testing follows experimental method procedures detailed by Redon et al.,[48] with ECC material variability summarized by Lepech and Li.[37] The p-δ curve is a precursor to the composite σ-δ relation, used to calculate composite complimentary energy J_b' (Eq. (3)). This calculation follows the theory described in Li and Leung[23] The determination of matrix cracking energy of the green sand matrix was performed using notched beam tests. The matrix toughness K_m was calculated using the appropriate geometric calibration.

The effect of additional carbon on the critical strain-hardening index, J_b'/J_{tip}, which must remain above unity for strain-hardening behavior (Eq. (3)), is twofold. First, excess carbon coating the sand particles reduces matrix toughness. The increase in excess amorphous carbon within the ECC matrix from 0 to 9% resulted in a 30% reduction in matrix toughness, from 0.73 to 0.5 MPa $m^{1/2}$ (0.66 to 0.45 ksi $in.^{1/2}$). Further addition of excess amorphous carbon resulted in a decrease in matrix toughness to 0.41 MPa $m^{1/2}$ (0.37 ksi $in.^{1/2}$). While reducing toughness is desirable to decrease J_{tip}, this reduction was coupled with a second phenomenon. A reduction in complimentary energy J_b' was seen as the carbon particles formed a "sleeve" through which fibers easily slipped out of the matrix and absorbed little energy. Combining these two effects, the strain-hardening ratio (J_b'/J_{tip}) fell below unity. The associated drop in strain capacity is shown in Fig. 9.

Initial development of virgin ECC using PVA fibers showed they performed poorly in cement matrixes due to the hydrophilic nature of PVA.[34] This was due to excessively strong bond that caused fiber rupture during pullout. To reduce bonding, a hydrophobic oiling agent was applied to the fiber surface to reduce rupture failures and increase performance. The application of 1.2% oiling agent (by mass) to the fiber surface was sufficient to lower interfacial bond and yield excellent composite ductility.

However, the combination of 1.2% oiled fibers with the sleeving action provided by excess carbon accumulation results in too little bonding between fiber and matrix. This effect was counteracted by systematically reducing the fiber oiling content to achieve a composites σ-δ curve similar to M45 ECC. Through systematic reductions in oiling content from 1.2 to 0.3%, an increase in the strain hardening index (J_b'/J_{tip}) above unity was seen (Fig. 10) along with an associated increase in tensile strain capacity, reaching a maximum at 0.3% oiling content (by mass) within a matrix that contained compared with 21% excess amorphous carbon.

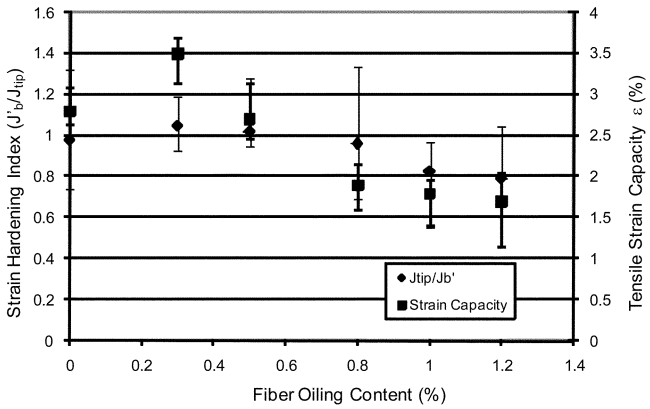

Fig. 10—Strain-hardening index and tensile strain capacity versus fiber oiling content (21% excess amorphous carbon).

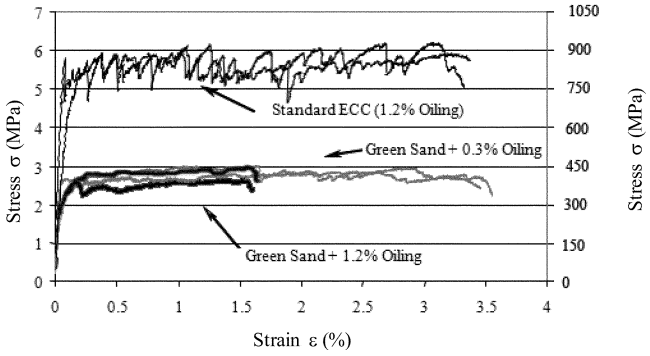

Fig. 11—Typical tensile stress-strain response of green sand ECC with 1.2 and 0.3% fiber oiling content compared with standard ECC M45 with virgin sand.

The combined effect of reducing J_{tip} and the retention of J_b' resulted in an increase in the strain-hardening index to approximately 1.05. This resulted in higher ductility in green sand ECC. As shown in Fig. 11, ECC M45 routinely exhibits 3 to 4% tensile strain capacity. After tailoring, green ECC material exhibits a similar tensile strain capacity (Fig. 11). The average compressive strength of green sand ECC was 61.3 MPa (8890 psi), average tensile crack width was 63 μ (0.0025 in.), and maximum tensile crack width was 85 μ (0.003 in.). All values meet required link slab application limits. Tensile strength, however, due to the lower matrix fracture toughness, dropped significantly. Had a minimum value for this material property been required, further material design iterations would have been undertaken.

The overall effectiveness of these substitutions was verified by comparing MSI values of ECC M45 with ECC using bag house sand from calcinator and green foundry sand. The calculation of MSI values, detailed in Kendall et al.,[33] relies 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. Based on this comprehensive environmental assessment, the introduction of foundry sands resulted in the replacement of an additional 22% of virgin ECC materials, whereas solid waste diverted from landfills increased 93%. Additional small reductions in environmental impact were seen in primary energy consumption, carbon dioxide emissions, and criteria pollutant emissions.

CONCLUSIONS

Materials engineering for increased sustainability is possible through the application of the proposed green materials design framework that combines preliminary analysis techniques, infrastructure application requirements, and micromechanical materials tailoring tools. A large preliminary set of potential substitutes, including industrial wastes, was assessed to gauge their potential within ECC materials. These found that green foundry sand, cement kiln dust, and fly ash served as good potential substitutes. Using an existing micromechanical materials tailoring toolbox, these waste materials were used to replace virgin raw materials within ECC composites.

Following this preliminary assessment, this study focused specifically on the addition of green foundry sand, which was found to reduce green ECC tensile strain capacity by over 50% as compared with virgin materials. This reduction forced ECC material properties below the minimum limits imposed by the bridge deck link slab application identified for green ECC materials. Characterization of the matrix fracture properties and fiber pullout behavior show that, while carbon residue on green foundry sand particles reduces matrix fracture toughness by nearly 40%, a corresponding 80% drop in bridging stress complementary energy eliminates multiple cracking and strain-hardening potential. Re-engineering of the fiber matrix interface to counteract the sleeving action of carbon residue on embedded fibers restored both multiple cracking behavior and strain-hardening potential. compared with previous versions of ECC material, the introduction of foundry sands resulted in significant environmental improvement in virgin material requirements and landfill waste reduction.

Through the use of the integrated materials design process, in which material properties and processing techniques were tailored to meet a specific structural demand, the links between microstructure and structural performance were further clarified. Although this approach focused primarily on the development of ECC materials, the application of micromechanics to tailor material properties and achieve sustainable infrastructure performance can be broadly applied within the civil engineering and materials design communities.

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