SUSTAINABLE INFRASTRUCTURE MATERIAL DESIGN

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ABSTRACT

Traditionally, the foremost concern among transportation engineers has been the safety and reliability of major infrastructure components. Until recently, sustainability has not been included in most infrastructure systems on any level. However, the engineering community, along with society as a whole, is realizing the importance of sustainability-oriented infrastructure systems. Yet incorporating these concepts into the design procedure as a primary goal remains unclear to many engineers. This research seeks to provide a platform for future sustainable engineering of civil infrastructure systems linking the micron-length scale of material microstructural tailoring to the meter-length scale of structural design. In the present study, a high performance fiber reinforced cementitious composite called ECC is evaluated, tailored for "greener" performance, and applied to an infrastructure application for increased sustainability.

1. INTRODUCTION

The impact of the United States transportation infrastructure system on the economic development of the US over the past 60 years is unarguable. Annually, this extensive network of roads and bridges transports over 75% of goods nationwide (US DOT 2004), accounting for over 30% of US Gross Domestic Product (US DOC 2004). Without this critical support system for nationwide shipping and travel, nearly all business would quickly cease due to a lack of raw materials, essential wares, or merchandise. The need for sustaining this vital system is obvious for national and global economic prosperity.

As the US economy annually expands, nearly tripling in size over the past 20 years (US DOC 2005), the importance of national infrastructure only looks to increase in the future. Therefore, the need for sustainable development of this system is essential. Consuming 33.2 million tons of cement each year (PCA 2005), road and bridge construction poses significant sustainability challenges in the U.S. and around the world (van Oss and Padovani 2003). In order to maintain current levels of prosperity, great strides must be made in the sustainability of transportation systems.

One approach to help achieve higher infrastructure sustainability is the development and use of new materials, deliberately designed with sustainability as a primary goal, in terms of improved social well being, increasing economic prosperity, and reduced environmental impact. This can be accomplished through many methods, such as the replacement of dwindling raw materials with suitable waste products, the development of improved materials to replace less sustainable materials, or the use of new materials to extend infrastructure service life. Sustainability of transportation infrastructure systems can be accomplished through deliberate design and incorporation of sustainable infrastructure materials.

2. MATERIAL DESIGN METHODOLOGY

2.1 Integrated Structural and Material Design for Sustainable Infrastructures

Historically, the design methodology behind materials development has been very compartmentalized. Little cooperation has existed between engineers developing new materials and designers who will ultimately use them in practice, with virtually no sustainability considerations. It has been assumed that the toughest, lightest, strongest material would always be more beneficial to structural designers. Therefore, materials were developed independent of their intended use for optimal material performance rather than optimal structural or life cycle performance. This limited design philosophy often results in materials that over-perform in some respects, resulting in higher costs, and under-perform in other respects, requiring the use of additional material and once again increasing cost. This inability of materials to meet proper performance objectives for their intended use ultimately results in massive inflations in costs in terms of economics, energy demand, and raw materials resources. Because of the vastness of typical transportation systems, the magnitude of environmental impact cannot be overestimated.

To achieve more cooperation among materials developers and structural designers who use their materials, Li and Fischer (2002) proposed the integrated materials and structural design (ISMD) paradigm shown in Figure 1. This methodology links material scientists and engineers working on the micro-structural scale with structural designers working on the macro-structural scale through the design values which are common in both fields, the material mechanical properties. Material engineers develop new materials for specific mechanical performance such as compressive strength, or tensile ductility, and structural designers use these composite material properties in the design of structural members. By facilitating cooperation at this level between these two communities, materials can be engineered to closely match the expected structural demands, thus increasing the efficiency of the overall material-structure system.

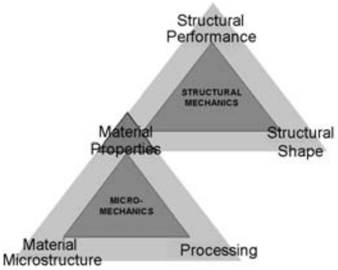

Figure 1. ISMD Paradigm

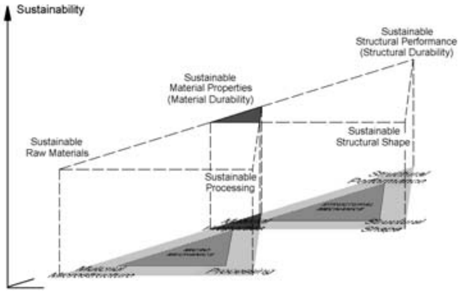

Figure 2. ISMD-SI Paradigm

Yet material sustainability is not captured in the traditional 2-D ISMD paradigm. Sustainability must be incorporated within each apex of the ISMD scheme as a third dimension, as shown in the ISMD for Sustainable Infrastructures (ISMD-SI) proposed in Figure 2. Within this expanded paradigm, sustainability goals are incorporated into each level of materials development. At the microstructural apex this is through replacement of virgin raw materials with recycled wastes. The material properties and structural performance levels are related to material durability (i.e. freeze-thaw resistance) and structural durability (i.e. tight crack widths in reinforced concrete), respectively. Finally, sustainable structural shapes can include the design of reusable building components, while sustainable processing techniques may incorporate extruded materials, which produce little waste. Through the use of this expanded paradigm, the development and use of sustainable materials can be realized, ranging from microscale tailoring up to structural design.

2.2 Sustainable Materials Design Framework

While the ISMD-SI paradigm serves as a useful guide for integrating all the components of sustainable infrastructure design, proper evaluation of new materials for sustainable performance is essential. Without performing a complete analysis of the new system life cycle, claims of sustainability remain unsubstantiated. Further, feedback information regarding the sustainability of the selected infrastructure application allows for further optimization. To provide this level of analysis, a collaborative framework (Figure 3) has been established linking material design, structural application, and sustainability modeling (Keoleian et al 2004).

This framework is the working realization of the ISMD-SI methodology. Within Process Loop “A”, current virgin material components are evaluated and appropriate waste material substitutes are identified. These substitutes are then tailored using micromechanical principles to achieve desired mechanical properties such as tensile strain capacity or strength. The properties of this green material must match with the demands of the infrastructure application for which the material is developed. Loop “B” starts with this application, and a complete life-cycle modeling of the modified infrastructure system is performed to examine the effect of the new green material on infrastructure system sustainability. Finally, these results are used as feedback for the selection of different substitution materials for another iteration. The linking of the two process loops (which forms the figure ‘8’ in Figure 3) underlies the collaborative framework that embodies a complete optimization procedure for the development and implementation of sustainable infrastructure materials and systems.

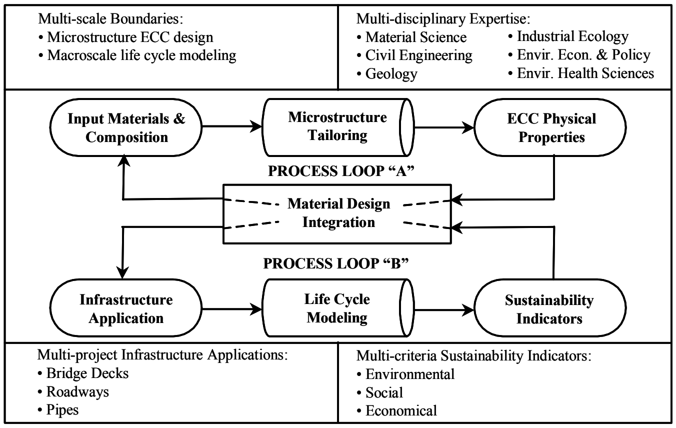

Figure 3. Sustainable Materials Design Framework

2.3 Microscale Materials Development

To further examine the process of sustainable materials development, a closer look at Process Loop "A" is helpful. This is shown schematically below in Figure 4. This procedure begins with the assembly of a pool of potential material substitutes. At this stage, no potential materials are excluded. The substitutes within this pool are then run through a preliminary screening in which three factors are evaluated; mechanical properties, chemical properties, and environmental sustainability. Mechanical properties include the strength or stiffness of the material. Preliminary chemical analysis accounts for any adverse reactions the replacement materials may have with other components or the intended use environment. Environmental sustainability is evaluated through Material Sustainability Indices (MSI). MSI values represent such environmental indicators as CO_2 production, water used, or energy intensity in material production, without regard for the application, and allow for comparison of different green materials on per volume basis. MSI values are also used in the development of sustainable material selection charts.

Following preliminary screening, more advanced analysis of each remaining substitute is undertaken to determine its effect on the composite. In the case of fiber reinforced cement composites, substitute materials may be considered a portion of the binder (cement replacement), filler (sand replacement), or fiber. Specific requirements for each portion are established. This further reduces the number of potential substitutes eligible for microstructural tailoring.

The relatively small number of substitute materials which remain after screening are then subjected to a micromechanical design procedure in which micromechanical principles (Li et al 2001) are used to tailor the various components of the composite at the microstructural level to achieve the exact material performance desired (i.e. strength, ductility, etc.). Following the microstructural tailoring procedure, the highly engineered green material is then matched with an infrastructure application requiring its exact mechanical performance. This is accomplished through the material selection charts mentioned above, and shown in Figure 5. These charts, similar to those developed by Ashby (1992), plot the MSI values versus mechanical performance. This allows designers to select the version of a green material, which meets the mechanical requirements of the structure, while maximizing material sustainability.

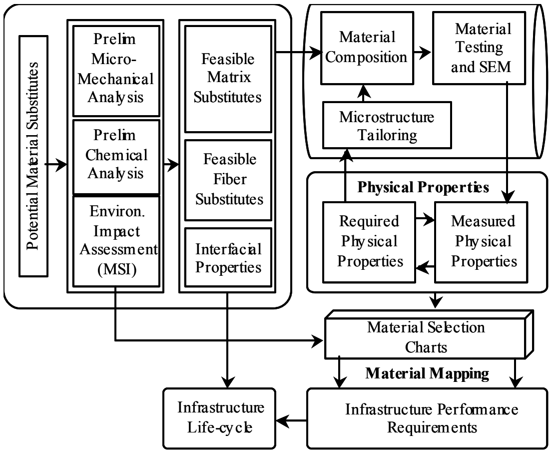

Figure 4. Process Loop "A"

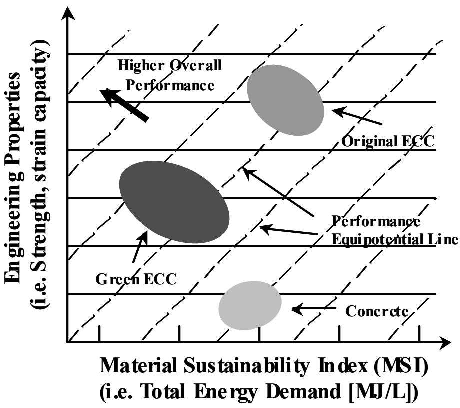

Figure 5. Sample Material Selection Chart

As mentioned previously, once the material and infrastructure application are selected, a complete life-cycle model (Keoleian et al, 2004) is used to evaluate overall system sustainability. These results are used to further optimize the material. This analysis will be not be discussed within this paper.

3. ENGINEERED CEMENTITIOUS COMPOSITES

The material presented in this study is a class of high performance fiber reinforced cementitious composites (HPFRCCs) called Engineered Cementitious Composites (ECC). Recent research on ECC has shown it to be highly durable and well suited for infrastructure applications (Li 2003). The reason for this performance is the ability of ECC to strain harden under uniaxial tension while forming many microcracks up to an ultimate strain capacity typically near 4%, as shown in Figure 6. This large strain capacity is over 400 times that of normal concrete. However, unlike many cement composites, this high tensile strain does not result in large cracks. Typically, cracks within ECC open to a maximum of between 50 – 70μm during early strain hardening (i.e. <1% tensile strain) and remain at that width under additional tensile strain up to failure (Figure 6). The components of a standard ECC mix (M45) are shown in Table 1, along with those of a green ECC utilizing low cement content and replacing virgin sand with waste foundry sand.

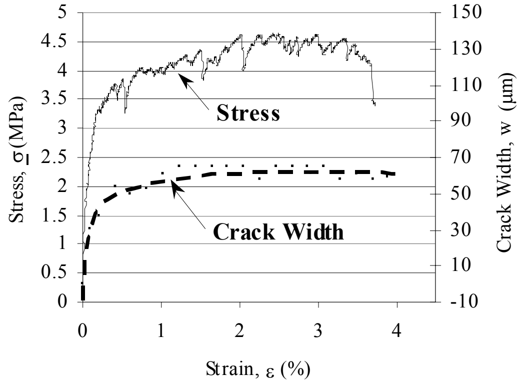

Figure 6. ECC M45 Stress-strain Curve

Table 1. ECC M45 and M45-Green Mix Proportions

	Weight (kg per m^3)	
Component	**M45**	**M45-Green**
Cement	578	318
Fly Ash	693	693
Sand	462	462*
Water	319	319
Superplasticizer	7.5	7.5
PVA Fiber	26	26

* Denotes waste foundry sand

The unique mechanical properties of ECC material can be attributed to deliberate micromechanical tailoring performed on the three phases within the composite; fiber, matrix, and fiber/matrix interface. This tailoring is dependent upon the microscale mechanical relationships between these three phases. At the core of this micromechanical theory is the condition for strain hardening behavior (Li 2003). By carefully controlling the fiber, matrix, and interfacial properties within the composite, the intended performance can be deliberately engineered into ECC material.

However, the incorporation of waste materials can easily upset the delicate balance among fiber, matrix, and fiber-matrix interface, which satisfies the strain-hardening criteria. By understanding the phenomena behind strain hardening performance, there exists an opportunity to deliberately combine or alter potential substitutions to meet the micromechancial conditions discussed above, and therefore engineer a green material with mechanical performance equal to materials which use virgin components.

4. MATERIAL DEVELOPMENT

4.1 Preliminary Screening

A large pool of initial substitutions was considered in this project (summarized in Table 2). Preliminary screening parameters for cement replacements included grain size distribution, low hydration, small material flows, and low MSI values. Parameters for sand replacements included adverse chemical effects (ASR), grain size distribution, small material flows, and low MSI values. Screening parameters for fiber replacements included fiber strength, fiber modulus, maximum elongation, fiber diameter, fiber length, and small material flows, and low MSI values.

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 Municiple 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-consumerCarpet Fiber	Fiber	Passed	Micromechanical Synergy
Banana Fiber	Fiber	Failed	Low Strength

4.2 Micromechanical Tailoring

Once complete, screening yielded a small number of substitutions worthy of further investigation. One such material, which will be discussed within this paper, is waste green sand from a foundry operated by General Motors Corporation in Saginaw, Michigan. This material met all preliminary requirements, yet when tested, the composite (M45-Green) showed a large loss of tensile strain capacity over the conventional ECC mixture (Figure 6). After further micromechanical investigation, this was found to be due to residue on the green sand particles.

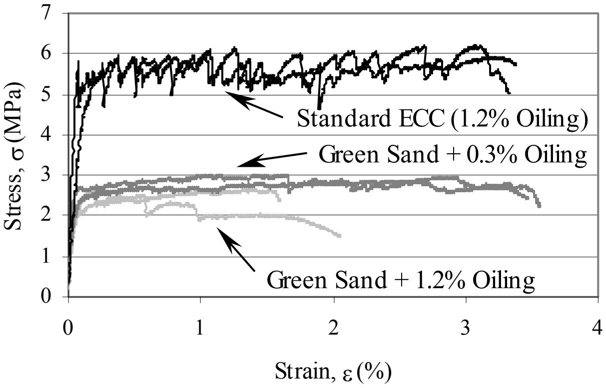

Figure 6. Effect of excess carbon and oiling content on tensile strain capacity

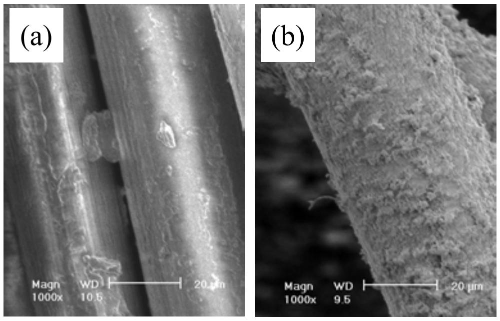

Figure 7. (a) Virgin PVA fiber and (b) PVA with carbon residue coating

To be used in the sand casting process, virgin sand is coated with finely ground coal to produce a smoother casting finish. However, when mixed into ECC material, the excess carbon on the sand surface accumulates on the fibers, as shown in Figure 7. This excess carbon effectively acts as a sleeve, preventing the necessary bond between fiber and matrix from forming. This violates the strain hardening condition discussed above, and decreases composite strain capacity.

To combat this, a unique material solution was proposed. During the original development of ECC material, it was discovered that the strong bond between PVA fibers and the cement matrix was preventing strain hardening (Li et al 2002). Therefore, the fiber surface was oiled to decrease the bond and improve the tensile response. Using the oiled fibers along with the foundry sand, the bond is too weak. Currently, PVA fibers used in ECC have 1.2% (by volume) oiling content on the fiber surface. By reducing this to 0.3%, and thereby restoring the proper bond, the green ECC material utilizing the waste sand shows ductility performance equivalent to standard ECC (Figure 6). The substantial loss of tensile strength is due to lower matrix toughness as a result of incorporating the carbon coated sand particles. Only strain capacity was considered in this work.

To evaluate the overall improvement in sustainability of the green ECC, the MSI values for the standard ECC mix design and the green ECC were compared. For all indicators examined, the green ECC shows improved material sustainability over conventional ECC mixes. These results are shown in Table 3. From this type of study, material selection charts have been developed containing various versions of green ECC incorporating different substitute materials. One such chart, which displays tensile strain capacity versus carbon dioxide production is shown in Figure 8. From this type of selection chart, structural designers can select a version of green ECC material, which meets mechanical requirements, while maximizing material sustainability.

Table 3. Material Sustainability Indices For M45 and M45-Green ECC

Waste Product (per L of Material)	**M45**	**M45-Green**
Total Primary Energy	5.95 MJ	4.32 MJ
Water Used	0.97 L	0.82 L
Carbon Dioxide	632.5 g	374.8 g
NO_x	3.01 g	2.30 g
SO_x	1.53 g	0.99 g
PM 10	4.53 μg	2.21 μg

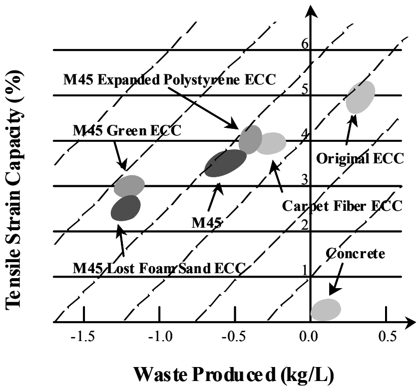

Figure 8. Sample Material Selection Chart for Various Green ECC Versions

5. CONCLUSION

This study exhibits a complete design methodology for developing sustainable infrastructure materials. At its core is the integrated structural and materials design paradigm for sustainable infrastructures (ISMD-SI). This design platform links together the varying scales involved with infrastructure materials design and implementation, ranging from microscale researchers to macroscale designers. Also presented is a materials design framework which outlines the development of sustainable infrastructure materials, and fully integrates life cycle modeling into the materials design paradigm, allowing for iterative optimization of sustainable materials.

The specific material within this study, ECC, represents a new class of materials for future infrastructure. Developed using micromechanics, ECC permits incorporation of substitute waste materials while allowing for tailoring of the interactions between them, guaranteeing mechanical performance equivalent to conventional ECC. This was demonstrated though the design of a green ECC utilizing waste foundry sand. In this case, significant reductions were realized for all sustainability indicators, with no accompanying decrease in mechanical performance. In a related study, Keoleian et al 2004 applies life cycle modeling of alternative bridge deck designs: one with mechanical expansion joints and the other with ECC link slab, which demonstrates sustainability assessment for a specific infrastructure application. While the solutions within this study are unique to ECC, the sustainable material design methodology proposed has potential for widespread application within civil engineering and beyond.

ACKNOWLEDGEMENTS

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