b. specimen geometry
c. magnitude and type of preloading

k. Thermal stress prediction in mass structures
l. Reinforcement considerations
  a. Development length
  b. Minimum clear cover
m. 3-D numerical code development for structural simulation
n. Full scale tests
o. Marine applications of HPFRCC

6.0 CONCLUSION

The discussions in this TG overlap significantly with those in other TGs, especially TG A on Standards for Materials and Testing and TG B on Durability. These TGs share common interests in the idealization of the tensile stress-strain response, and its connection to SLS and ULS design in structural use. Much research remains to be undertaken, despite the significant number of advances in HPFRCC materials and applications in recent years. The pathway toward development of structural design codes, along with the type of design code, remain topics deserving focused attention. However, it is hoped that the discussions and conclusions drawn from this TG provide meaningful input to the planning and efforts of the three subcommittees on Testing, Durability and Design under the umbrella of RILEM TC HFC.

7.0 ACKNOWLEDGEMENT

M. Lepech took detailed notes of the discussion and conclusion sessions of this TG which greatly aided in putting together this summary.

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GENERAL DESIGN ASSUMPTIONS FOR ENGINEERED CEMENTITIOUS COMPOSITES (ECC)

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Abstract

The use of Engineered Cementitious Composites (ECC) for structural design requires a number of assumptions of the material, some of which can be drastically different from those suitable for normal concrete and tension-softening fiber reinforced concrete. This contribution focuses on design assumptions of the constitutive models of ECC in tension and compression. Specifically, while the tensile strength of the concrete is typically neglected in axial and flexural calculations of reinforced concrete, the tensile load carrying capability of ECC during inelastic straining is explicitly accounted for. Assumptions regarding the shape of the tensile stress-strain relation, usable tensile and compressive strains, and bond between steel reinforcement and ECC will be addressed. In addition, assumptions concerning crack width with respect to serviceablilty limit states will also be discussed. Application of these design assumptions in reinforced flexural ECC elements will be used to illustrate the differences between R/C and R/ECC design. For this purpose, an ECC link-slab designed for combined axial tension and flexure will serve as a case study.

1. INTRODUCTION

With the advent of new materials, there is a constant need for designers to find innovative ways to incorporate these materials into new applications. For instance, the increased use of plastics has allowed designers unparalleled opportunities in the design of aircraft, automobiles, and consumer goods. The field of civil engineering is currently at a crossroads of equal significance with the development of new materials termed high performance fiber reinforced cementitious composites (HPFRCC). These materials, with tensile performance magnitudes higher than reinforced concrete (R/C), allow designers to create structures previously impossible due to limitations of minimum reinforcement, minimum clear cover, or excessive cracking in R/C. Yet the acceptance of HPFRCCs into design has been exceedingly slow, mainly due to the lack of proper codes and design assumptions which characterize these materials in a simple yet accurate fashion for design calculations. Until these characterizations are formulated for HPFRCCs, similar to those for concrete within the ACI building code, these materials will continue to go unrecognised and underutilized.

While there are no current provisions within the ACI building code, there exists an opportunity for engineers to use HPFRCC materials in structural designs. The 2002 edition of the ACI Building Code [1] (hereafter ACI-318-02) Section 1.4 allows for the "approval of special systems of design or construction" by local building authorities. Under this provision, designers are allowed to use new materials and construction techniques within the code, provided that they are consistent with the overall intent of the authors, and approved by the building official. This approval can be time consuming and costly and therefore is rarely used. Further, without a simple design procedure based upon simplified design assumptions, engineers find such deviations from the status quo both complex and intimidating. There exists an immediate need for HPFRCC material characterizations and design guidelines.

2. IDEALIZATION OF ECC STRESS-STRAIN RELATIONS

2.1 Stress-strain Relations of ECC

Within HPFRCCs, a class of cementitious materials called Engineered Cementitious Composites (ECC), has undergone recent development to exhibit ultra-high tensile ductility, similar to metals [2,3]. The most distinctive characteristic separating ECC from other concrete materials is an ultimate strain capacity between 3% and 5%. This strain capacity is realized through the formation of many closely spaced microcracks, allowing for a strain capacity over 300 times that of normal concrete. These cracks, which carry increasing load after formation, allow the material to exhibit *strain hardening*, similar to many ductile metals, as seen in a typical experimental uniaxial tensile stress-strain curve (Figure 1).

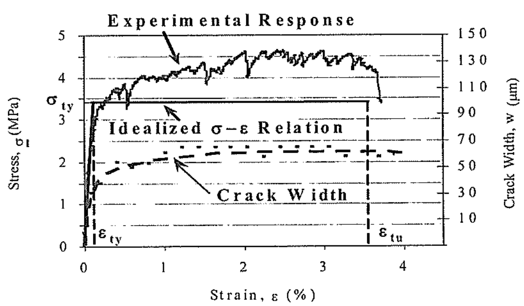

Figure 1. Tensile Stress-Strain Response of ECC along with Development of Crack Width and Idealized $\sigma-\varepsilon$ Relation

Table 1. Typical Mix Proprotions for ECC Material

Component	Proportion
Cement	1.0
Fly Ash	1.2
Sand	0.8
Water	0.58
Superplasticizer	0.013
Fiber (vol%)	0.02

While ECC components are similar to fiber reinforced concrete (FRC) (see Table 1), the distinctive strain hardening through microcracking is achieved through micromechanical tailoring of the components (i.e. cement, sand, and fibers), along with controlled interfacial properties between these components. In this mix design, synthetic poly-vinyl-alcohol (PVA) fiber is used. A unique version of this fiber (PVA REC-15) has been developed for optimal performance within ECC to meet specific micromechanical requirements. Coarse aggregates are not used due to their adverse effects on fiber dispersion and overall performance. While most HPFRCCs rely on high fiber volume for high performance, ECC uses low amounts, typically 2% by volume, of short, discontinuous fiber. This low fiber volume, along with the common components, allows for ECC mixing in conventional equipment. Many HPFRCCs with high fiber content cannot conform to conventional mixing practices.

The overall tensile response begins with an elastic pre-cracking portion followed by a nearly plastic (or mildly strain-hardening) post-cracking performance. A number of versions have been developed including lightweight ECC (LwECC) [4], and "green" ECC (GrECC) [5], specifically developed for low environmental impacts. Regardless of the exact version of ECC, each exhibits this nearly elastic-plastic response in tension. Through this commonality among all ECC materials, a reasonable idealization of the design tensile performance can be proposed. Likewise idealizations can be sought for the compressive response as well.

2.2 Idealized Stress-Strain Relations and Material Parameters

Within ACI-318-02 (Sections 10.2.5, 10.2.6, 10.2.7) [1] an idealized stress-strain relation for concrete is given for the design of R/C members. These sections outline a simple, yet accurate constitutive model for design. Within Section 10.2.5, it is recommended to neglect the concrete tensile strength in both bending and axial loading. Within Section 10.2.6, a rectangle commonly called "Whitney's Stress Block", is suggested for the concrete compressive response, greatly simplifying the complex quasi-parabolic compressive response. Such simple models are needed for both the tensile and compressive response of ECC.

For simple design, an elastic-plastic tensile response may be assumed for nearly all versions of ECC (as shown in Figure 1). Within this model, three parametric values must be assumed; the tensile yield strain (ε_{ty}), tensile "yield" strength (σ_{ty}), and ultimate allowable tensile strain (ε_{tu}). The first two parameters, ε_{ty} and σ_{ty}, may be partially derived from, or used to determine, the tensile elastic modulus (E_t). The ultimate tensile yield strain, ε_{tu}, may be a function of allowable crack width. In most FRC and HPFRCC materials, crack widths grow with increasing tensile deformation. However, this is not the case with ECC. As shown in Figure 1, ECC exhibits a self-controlled crack width, independent of deformation, with a maximum width of approximately 60 μm. ACI 1995 Section 10.6.4 [6] suggests a maximum 330μm crack width for exterior exposure to maintain durable material performance. A similar limit may be set for maximum strain once a relation between tensile strain and crack width has been established. Further, many researchers have found a crack width of 100μm suitable for limiting permeability of cracked HPFRCCs, suggesting even tighter limits than those suggested by ACI may be appropriate for material durability [7]. For any HPFRCC, durability of the material strained to ε_{tu} under service conditions should be assured.

Unlike concrete, in which most work has investigated the compressive response, relatively little work has been done on ECC in compression. However, due to the similar shape of compression loading curves of ECC and well-confined concrete, the adoption of a rectangular stress block (as mentioned earlier) may be appropriate. With this assumption, a suitable maximum compressive strength (σ_{cu}) and allowable ultimate compressive strain (ε_{cu}) must be set. Currently, ACI-318-02 Section 10.2.3 [1] sets the maximum allowable compressive strain of concrete at 0.003. This value is likely too low for ductile materials such as ECC, and should be a function of the compressive strength of the material. Further, study may also show that a more complex model which more accurately represents the material is necessary.

Within ACI-318-02, Section 8.5.1 [1] guides the determination of elastic modulus for concrete. Two equations are given. One equation may be used for normal or lightweight concrete and is a function of unit weight and compressive strength, while the other is a simplified version for only normal weight concrete. While acceptable for concrete, their use for HPFRCCs is questionable and their application to ECC inappropriate. For use in design, an alternate equation may be developed based on compressive strength. However, due to the direct relation between elastic modulus, tensile yield stress (σ_{ty}), and yield strain (ε_{ty}), these may also be used to identify elastic modulus. Any possible difference in modulus in tension versus compression must also be considered and verified through experimental investigations.

3. BASIC FLEXURAL DESIGN ASSUMPTIONS

Section 10.2.1 of ACI-318-02 [1] establishes the basic theoretical assumptions used in flexural design. These assumptions serve as the basis for all calculations, and establish limits for the design equations. Within this section, there are three basic design assumptions. The assumptions of plane sections remaining plane, and a linear strain distribution across the section are commonplace within the design community and hold true in the design of R/C and R/ECC members. However, the assumption of compatible strain between concrete and steel reinforcement in members may be even more sensible in R/ECC members. It is known that under extreme loads, bond splitting cracks form in R/C along the surface of the rebar creating a strain discontinuity. For ECC, in which fracture is suppressed, these bond splitting cracks do not develop. This unique strain compatibility will be discussed further. Ultimately, the application of these well-known and commonly accepted design assumptions should lead to a more rapid acceptance of the design procedures for all HPFRCC materials similar to ECC.

4. REINFORCEMENT CONSIDERATIONS

A large body of research has examined the performance of steel reinforcing in R/C. Past researchers have examined bonding between concrete and deformed rebar, developed models to predict its behavior, and created methods to improve its

performance. Additionally, other reinforcing materials have been investigated such as fiber reinforced plastics, and carbon fiber bars. Prior to design of members using ECC, or any HPFRCC materials, the interaction between reinforcement and the surrounding matrix must be understood and modeled.

4.1 Development Length of Reinforcing Bars

Within ACI-318-02 [1], the development of reinforcement in concrete is addressed in Chapter 12. The basic equation used for development length is a function of steel yield strength, concrete compressive strength, reinforcing bar diameter, concrete cover thickness, transverse reinforcement ratio, bar surface coatings, and the location of steel within the R/C member. Of note within this equation is the inclusion of cover thickness. For small cover thicknesses, the development length increases. This is attributed to splitting failures when there is little cover for confinement. With the addition of cover, the development length may be decreased due to the increased likelihood of pullout failures. However, with ECC this consideration may be excluded as the high toughness of the material eliminates the fracture-based failure phenomenon associated with splitting failures, causing any reinforcement failure to occur through pullout. Further work is needed in this area of research.

4.2 Compatible Deformation of ECC with Reinforcing Bars

In addition, the performance of reinforcement within ECC is drastically different than concrete. Due to its brittle nature, concrete cracks under tensile load resulting in all tensile stresses being transferred to the reinforcement (Figure 2b) [8]. Due to unloading on the concrete crack plane, large shear stresses develop at the steel/concrete interface on either side of the crack. To effectively transfer these stresses, high interfacial bond strengths are required. These high stresses often exceed the bond strength, particularly in high amplitude reversed cyclic loadings common in seismic events, resulting in bond splitting cracks, debonding of the reinforcement, loss of member tensile capacity, and structural failure.

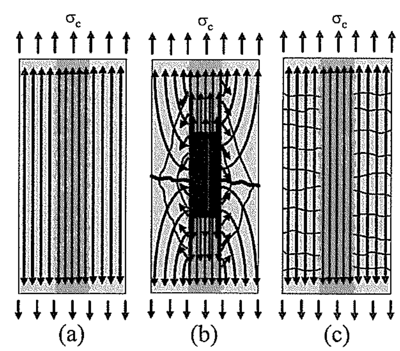

Figure 2. (a) Composite before matrix craching (b) R/C after cracking (c) R/ECC afer cracking

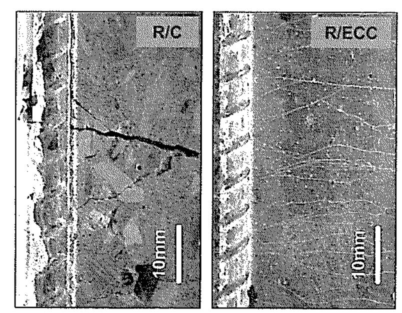

Figure 3. Performance of Reinforcing Steel in R/C and R/ECC

Due to the ductility ECC, this brittle failure mode does not exist. Steel reinforced ECC (R/ECC) under tension initially distributes tensile stress across the entire uncracked section, as does concrete (Figure 2a). However, once cracked the ECC continues to carry increasing tension and does not transfer this load to the reinforcing bars (Figure 2c). This continues until the tensile strain capacity of the ECC is exhausted, on of the order of 4%. At this high strain, most structural members fail to meet serviceability requirements such as deflection or drift limits, designating the member as "failed" not by structural failure but rather by serviceability. Further, since ECC continues to carry tension after cracking and does not transfer loads to the reinforcement, very little shear stress is developed at the reinforcement/ECC interface. This results in no cracking or debonding along the rebar, even at high deformation. The lack of cracking may be construed as a high bond between steel and ECC. However, this is not necessarily the case. As there is no load transfer, the interfacial shear stress is low. Through compatible deformation with the steel reinforcement (Figure 3), ECC is capable of eliminating brittle bond splitting failures, changing the way reinforcing steel performs. In addition, the fundamental assumption of compatible deformation between steel reinforcement and concrete for flexural member design holds better in ECC even for large deflection.

4.3 Crack Control Reinforcement

One major reason for reinforcement within concrete, aside from load capacity, is reduction or elimination of cracking. Through adequate, well-spaced reinforcement, concrete cracking can be kept under good control. Section 7.12 within ACI-318-02 [1] recommends minimum reinforcement for shrinkage and temperature crack control. A minimum reinforcement ratio between 0.0014 and 0.002 is required, depending upon the steel grade. To further control cracking, ACI recommends minimum spacing between reinforcing bars in Section 10.6.4. This limit is a function of the calculated stress in the reinforcement and concrete cover depth.

Due to the remarkably small crack widths of ECC, crack control reinforcement may be redundant. As shown in Figure 1, even at high deformation levels (i.e. 4% tensile strain) ECC crack widths remain at approximately 60 μm. This crack width is far below those typically seen in R/C, and substantially below the 300 μm outdoor exposure limit recommended by previous versions of the ACI [6] and AASHTO codes [9]. Other research has found that the tight crack widths in ECC improve durability as well [10], further suggesting the redundancy of crack control reinforcement. Additionally, this reinforcement may unintentionally over-stiffen concrete structural members and alter performance under heavy or seismic loading.

5.0 LINK SLAB DESIGN ILLUSTRATION

A serious concern facing DOTs is the maintenance and repair of bridge expansion joints. While necessary to accommodate thermal deformations, these joints often deteriorate and leak. This leaking frequently causes damage, allowing water and corrosives to penetrate the deck and corrode the beams. To construct a continuous deck without reconstruction of the entire bridge, an excellent alternative is a bridge deck link

slab [11]. This slab forms a connector between two adjacent simple spans, creating a continuous deck to prevent leaking, while absorbing the thermal deformations which are typically accommodated by an expansion joint. The loading of the link slab is primarily a combination of bending and uniaxial tension.

The design procedure for an ECC link slab, including calculation equations, has been published elsewhere [12]. A simple review of the procedure sheds good insight into the practical use of ECC as a viable infrastructure material. The procedure can be condensed into a series of simple steps which develop an iterative design procedure for determining the steel reinforcing ratio within the ECC link slab, along with a series of checks on the ability of the ECC to properly perform under combined mechanical and environmental loads (Table 2).

Table 2. Summarized Design Procedure for ECC Link Slab

Step	Activity
1.	Determine length of link slab (approximately 10% of brige deck length)
2.	Determine end rotations of link slab due to adjacent span deflection
3.	Determine uncracked link slab moment of inertia from geometry
4.	Determine moment demand induced into link slab by end rotations (from step 2)
5.	Using linear strain profile and force balance, determine neutral axis with assumed reinforcement ratio
6.	Using appropriate stress distribution, determine moment resistance of section
7.	Check that resistance exceeds demand, if not increase reinforcement and repeat steps 5 - 6
8.	Determine required bars and spacing to meet calculated reinforcement ratio
9.	Check that compressive and tensile strains do not exceed limit of ECC material

Initially, this procedure follows closely the design of typical R/C members. It begins with preliminary sizing and determination of mechanical loads and moment demand using mechanics and geometry. However, the computation of moment resistance deviates from typical R/C design. Rather than simply assuming no tensile capacity, the assumed elastic-plastic constitutive law is imposed within the tension region. Within the compression zone, a linear elastic response is used since the strain remains below the liner elastic limit in compression. An initial reinforcement ratio is assumed and the resistance is computed using non-linear sectional analysis. The calculated resistance is compared to demand, and if too low the reinforcement is increased and the process is repeated. Finally, checks are performed to ensure that the material can withstand all imposed compressive and tensile strains.

The procedure described above further assumes a maximum of 40% of steel yield stress in the reinforcement, consistent with that used by Zia [11] for concrete link slabs to ensure durability. Currently, this conservative working stress design has been approved and used by the Michigan Department of Transportation in the completed design of an ECC link slab to be constructed in July 2005 in southeastern Michigan. The willingness of engineers to incorporate this material and use this procedure exhibits a readiness within the community to accept such innovations into practice, provided they are accompanied by adequate design equations and provisions for their safe use. The authors suggest that complete provisions for HPFRCC materials, such as ECC, be incorporated into design codes in the near future to meet this readiness among professionals and begin to positively impact society at large.

6.0 RESEARCH NEEDS

However, before introduction into codes a number of research needs must be met. Chief among these is the identification of robust testing methods of material properties. It is essential that these methods be simple, and allow researchers to easily distinguish between material and testing failures. Tests are needed for determination of tensile yield strain, ε_{ty}, tensile yield stress, σ_{ty}, assumed tensile σ–ε response, tensile elastic modulus, E_t, compressive strain limits, ε_{cu}, assumed compressive σ–ε response, and compressive elastic modulus, E_c. Exhaustive investigation into these parameters will allow for development of rational, reliable material constitutive laws serving as a basis for structural designs using these new materials.

In addition to mechanical properties, research must be performed on material durability. This includes the relation of crack width to durability to aid in setting maximum allowable tensile strain along with an appropriate relation between strain and crack width, if the two are not independent as in the case of ECC. Further, the sulfate resistance of ECC has yet to be investigated. Also of interest are appropriate parameters for minimum clear cover for protection of reinforcement. Recall that materials such as ECC can have a profound effect on the mechanical behavior of steel reinforcement. Drastically different transport properties and deformation capacities of ECC with respect to concrete, particularly after cracking, may also have an impact on the behavior of steel reinforcement.

Other research interests may include the performance and characterization of ECC materials under high strain rates, such as in impact loads or seismic conditions, and the material σ–ε response in tension and compression on shear behavior. Further work must also be done on the processing of ECC material for robust performance, exhibiting a predictable σ–ε response for all test specimens regardless of which version of ECC is examined. This also applies to the processing of ECC materials on large scales for viable commercialization.

7.0 CONCLUSION

Currently, while ACI-318-02 [1] allows for new materials and structural systems, the inability of engineers to make use of these materials along with the high cost of demonstrating them to building officials, severely limits their incorporation into mainstream construction. Therefore it is essential to provide code writing bodies with appropriate test results, material characterizations, and design procedures for development of provisions within the code for new materials such as ECC. Such information includes idealizations of stress-strain relations both in tension and compression, simple material parameters to characterize σ–ε relations, basic design assumptions, and considerations of reinforcement/ECC interaction. Finally, example design procedures such as the link slab illustration, provide code writers and designers the tools and direction necessary for full implementation of such materials.

While substantial research needs exist regarding the characterization and performance of new construction materials, current knowledge has formed a "critical mass" which serves to launch these materials into design codes and widespread use. This is aided by the readiness of engineers demonstrated through the construction of an ECC link slab in Michigan, amongst other full scale applications elsewhere [13]. Broad extensions of these exciting initiatives rest on the development of general design assumptions for new materials, such as ECC.

8.0 ACKNOWLEDGEMENTS

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