ON HIGH PERFORMANCE FIBER REINFORCED CEMENTITIOUS COMPOSITES

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ABSTRACT: This paper presents the evaluation basis of performance of HPFRCC designed for structural applications. The material performance most relevant to infrastructure sustainability is discussed and translated into materials properties that can be experimentally characterized. The need of developing robust uniaxial tension test and proper material characterization are then highlighted. Comparisons of the properties of various HPFRCCs to the extent reported in the literature reveals that few materials in fact possess balanced performances that meet the demands. This article is a summary of a keynote lecture given in the JCI Symposium on Cementitious Composite Materials, Dec., 2003.
KEYWORDS: HPFRCC, strain hardening, evaluation basis, property comparison

1. INTRODUCTION

Over the last ten years, there have been rapid advances in the development of High Performance Fiber Reinforced Cementitious Composites (HPFRCC). These advances have taken place in various forms. Basic research has produced improved understanding of the connections between microstructure and composite performance, and these understanding have been utilized in tailoring the fiber, matrix and interface. Processing techniques have also been refined by improved rheology control of the fresh mix. The properties of HPFRCC have seen significant advances in strength and ductility. These property enhancements are particularly noteworthy especially in light of the lower fiber content employed compared to HPFRCC in its earlier days. The lower fiber content combined with processing ease makes it economically and technically feasible to translate material performance to structural performance in the field. While there remain technical challenges to be resolved, there is little doubt that HPFRCC is a material ready to be exploited in the field. Indeed, commercial developments have already begun.

This paper presents the evaluation basis of HPFRCC performance. In so doing, it also clarifies the need for developing robust direct uniaxial tension test, and the needed material characterization with a view towards structural use of HPFRCC. To the extent reported in the literature, comparisons of the properties of various HPFRCCs are presented. Finally, the connection between HPFRCC and infrastructure sustainability is described. Infrastructure sustainability is the ultimate challenge to HPFRCC development.

While the information contained in this paper has largely derived from recent research projects directed by the first author, some of the ideas discussed here have been stimulated by discussions with colleagues in HPFRCC conferences and workshops (see particularly ref. [1] and [2]).

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2. THE MEANING OF HIGH PERFORMANCE

"High performance" can mean different things to different people. For high performance concrete, "high performance" has taken on meanings of high strength, high processability (self-consolidating or self-compacting), and high durability. Different aspects of high performance have been emphasized in different countries and at different times. There should be little disagreement that the most desirable high performance will be attained if all of these characteristics – mechanical properties, processability and durability – can be combined in a single material.

For HPFRCC, the qualification for high performance was first described by Naaman and Reinhardt [3]. In that paper, a high performance fiber reinforced concrete was distinguished from an ordinary fiber reinforced concrete (FRC) by the unique uniaxial tensile stress strain curve. For a HPFRCC, a strain-hardening branch after first cracking must exist. The presence of this branch, and especially with a large tensile strain capacity, makes an HPFRCC different from an FRC. From this definition, high performance in HPFRCC means high tensile ductility.

For practical application of HPFRCC, the material must be economically feasible and processable into structural members. While the definition of high performance in HPFRCC to mean high tensile ductility has largely been accepted by the research community, this definition does not address the technology behind how high ductility can be achieved or optimized. Indeed, HPFRCC have been attained in the 1970's when Allen [4] reported a cement laminate reinforced with 6.7% random discontinuous glass fiber mat which achieved a tensile strain capacity of 1%. In addition, Krenchel and Stang [5] realized tensile strain capacities up to 3% with 6-13% continuous polypropylene fiber. While the mechanical aspect of high performance has been met, the translation of these materials into field applications has little success due to the difficulty in processing these materials and the high cost associated with high fiber content. (The development of these early HPFRCC is important, however, as they demonstrated experimentally the possibility of converting a brittle matrix into a ductile composite by fiber reinforcement, and provided a basis for understanding the mechanisms behind.) If HPFRCC were to make an important impact on infrastructures, the issue of cost and processability must be taken into account.

The durability of a structure is of utmost concern. It is well-known that during strain-hardening in HPFRCC, the matrix undergoes multiple cracking. Multiple cracking provides a means to delay fracture localization as in the case of normal concrete and FRC. Controlling the width of these multiple cracks is important as the material is expected to be used into the strain-hardening stage. The presence of cracks and their crack width may compromise the durability of the material itself, and may also allow the penetration of aggressive agents through the "HPFRCC-cover", and negatively influence the rate of corrosion of the reinforcing steel bars in the structure. There are reasons to believe that the tensile ductility of an HPFRCC should contribute to structural durability. However, this expectation is predicated on the assumption that the crack width during strain-hardening is tightly controlled.

From the above discussion, it appears that a truly high performing HPFRCC must possess at least the following characteristics:

a. High tensile strain capacity,
b. Minimized fiber content, and
c. Limited crack width

These characteristics should ensure high performance in the sense of high ductility, processability, economic feasibility, and durability. It should be noted that while high strain capacity is emphasized as a high performance characteristics of HPFRCC, it does not imply that other mechanical properties are not important. Rather, the high strain capacity is generally recognized as the most unique advantage of HPFRCC compared to other cementitious materials. For example, high compressive strength has been achieved in high strength concrete without the need for fiber reinforcement. High tensile strength up to 68 MPa has been achieved in densified cementitious materials [6] again without fiber reinforcement.

Research on achieving high strength or high strain capacity has so far received the most attention. Work on minimizing fiber content for processability, and crack width control for material and structural durability, has only just begun.

3. TOUGHNESS INDICES AND DEFLECTION HARDENING

Toughness indices [7,8] based on flexural load-deflection tests have long been proposed as parameters characterizing the toughness of fiber reinforced cementitious composites. However, it has been recognized that the toughness indices cannot uniquely characterize the material behavior (see, e.g. [9]). That is, materials with very different load-deflection curves may have the same toughness index value. Thus, the validity of toughness indices for HPFRCC characterization is questionable.

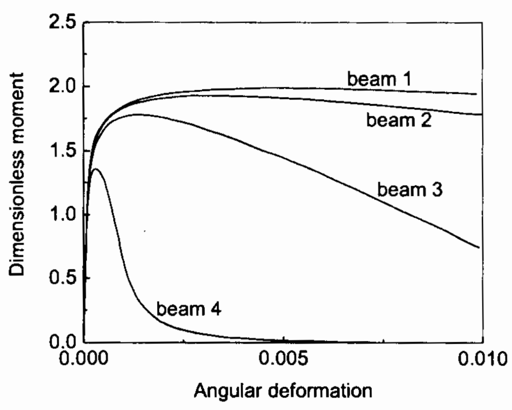

Figure 1. The influence of scale on the angular deformation – dimensionless moment relationship when the FRC beam height is changed from 100 mm (beam 1) to 200 mm (beam 2), 800 mm (beam 3), and 10000 mm (beam 4) [11].

In recent years, the concept of deflection hardening has also been introduced [10] to classify the performance level of fiber reinforced concrete. Unfortunately, deflection hardening for material classification suffers from the phenomenon of size dependencies. It has been known that the load-deflection curve from a bending test depends on the beam height. This issue was revisited recently in an article by Stang [11] who concluded "The hardening behavior of the moment-angular deformation or moment-curvature relation in a tension softening material is strongly scale dependent." In that work, he showed without a doubt that the shape of the load-deflection curve in general, and the presence of hardening or softening in particular, are functions of both the material behavior and the beam height. Figure 1 reproduces a plot from Stang [11] showing the calculated relationship between dimensionless moment and angular deformation for a given tension-softening FRC in beams with beam heights ranging from 100 mm to 10000 mm. Clearly, Beam 4 (10,000 mm beam height) exhibits deflection softening, while Beam 1 (100 mm beam height) exhibits deflection hardening.

Beams used in laboratory testing with smaller beam heights will tend to promote deflection-hardening, while the large size beams in an actual structure will tend to experience deflection-softening. Hence, classification of a material as deflection hardening or not is conceptually unacceptable when this behavior is strongly dependent on the beam height.

To determine whether a material is an HPFRCC possessing high ductility, or whether the material is a regular FRC by a bending test is even more problematic. An ordinary FRC combined with a suitably thin (small height) specimen can always generate a deflection-hardening phenomenon. It has sometimes been argued that the observation of multiple cracking in a flexural specimen is justification of strain-hardening characteristics. This argument ignores the fact that multiple cracking under bending load simply reflects that cracks generated on the tensile side of the beam can be stabilized by the presence of a compressive stress field as they propagate up the beam height, allowing other defect sites to initiate additional cracks. Multiple cracking under bending load therefore does not guarantee multiple cracking under direct tensile load. Tensile strain determined from a standard beam test has questionable validity as tensile property of the material.

The uniaxial tensile stress-strain relation can be used as a basis for developing material constitutive laws useful for analysis of structures subjected to multi-axial stress states. The facts that bending test is easier to carry out compared to direct tensile test, and that many structural members are loaded in bending have been used to justify FRC characterization using beam test. Both arguments are true, and bending test with a beam height equal to that in field use would avoid the size effect problem. However, this should be regarded as structural characterization, rather than material characterization. When the material is used in members subjected to shear, for example at the base of a column or in a shear panel, direct tensile behavior of HPFRCC is needed for structural design. Uniaxial tension test is needed for proper material characterization of HPFRCC.

4. UNIAXIAL TENSION TEST AND HPFRCC CHARACTERIZATION

Uniaxial tension test, while simple in concept, requires attention to many test details. Amongst these are specimen alignment, and post-crack stability. The latter concern makes testing of concrete or tension-softening FRC particularly challenging, and a variety of methods of stiffening the machine and load-trains have been proposed. However, and at least in this respect, the use of uniaxial tension test for characterizing the properties of HPFRCC is much easier, since these specimens do not unload after first cracking, but rather strain-hardens. As a result, no sudden release of energy, and no loss of stability, occurs during the strain-hardening stage up to peak load.

The purpose of characterizing the tensile stress-strain behavior of HPFRCC is to obtain constitutive relations of the material that can be utilized by structural engineers for structural design. For structural elements under simple stress-states such as in a bending beam, the uniaxial tensile stress-strain curve can be used directly. For more complicated structural geometry or loading configurations, it will be necessary to generalize the experimentally obtained uniaxial stress-strain curve into multi-axial stress-strain constitutive relations. Such attempts have been quite successfully illustrated in the work of Kabele [12].

In quasi-brittle concrete or FRC, the proper characterization of the post-cracking behavior is in terms of stress versus crack-opening relationships [13], since the deformation is indeed localized onto a crack plane. For truly strain-hardening HPFRCC, the proper characterization of the post-cracking behavior is in terms of stress-strain relationship, as the microcracks appear as inelastic damage spread over a volume of material, at least during the strain-hardening stage. This assumes, naturally, that the strain gage is long enough compared with the spacing between adjacent microcracks. The "strain" measured would then be interpreted as the smeared and averaged elongation over the gage length. Thus, a minimum requirement for proper strain-measurement in HPFRCC property characterization would be a gage length at least several (say, five times) the averaged crack spacing between adjacent microcracks. Otherwise, the measured stress-strain curve will not be representative of the material behavior. Indeed, if this requirement were not met, it would be doubtful whether the material qualifies as a HPFRCC or is simply a regular FRC. For this reason, it is proposed that the crack pattern should be recorded during testing. At the least, the crack pattern and crack spacing at or beyond peak load, and the gage length used, should be reported in uniaxial tension test of HPFRCC.

For ensuring material and structural durability, it is desirable that only a portion of the stress-strain curve be allowed for use in structural design. The cut-off strain value should correspond to an averaged crack width that ensures durability. The relationship between durability and crack width in HPFRCC is a subject urgently requiring research efforts.

To summarize, uniaxial tension test appears to be the most appropriate method of material characterization of HPFRCC. For the uniaxial stress-strain curve to be valid and useful for structural design, it is recommended that at least the following information be included in a test report:

a. Complete stress-strain curve
b. Crack pattern and crack spacing at or beyond peak load, and gage length
c. Crack opening (averaged over several cracks) during strain-hardening

Because of potential loading rate sensitivity, it is also recommended that the loading rate applied be reported as is commonly done. In addition, the specimen size must be large enough in relation to the fiber length to ensure random orientation of the fibers. The loading boundary condition (pin or fixed) may also have an influence on the material properties measured. These and other considerations are being taken up by committees on standardized testing of HPFRCC set up by professional societies.

5. PERFORMANCE COMPARISONS OF VARIOUS HPFRCCs

A variety of HPFRCCs have been reported in the literature. This section summarizes information on uniaxial tensile properties of HPFRCCs (Table 1), but limiting the scope to those containing discontinuous fibers only. In view of the proper material characterization procedures discussed above, apart from mechanical properties, data on fiber content (V_f) and length (L_f), specimen dimensions (x-sect), crack spacing (cs), and gage length (gl) are included, whenever reported. For some materials, results reported from different research groups or tests conducted on different specimen geometries are also included for comparison. There are more materials claimed as HPFRCC beyond those included in Table 1. Subjective judgment was used in determining which material to be included. This table can be expanded and/or updated as data become available.

Table 1 includes eight HPFRCC materials. A useful guide to reading Table 1 is to first consider fiber orientation in the column labeled "fo". The fiber orientation (fo) is deduced from the fiber length and the specimen section dimensions unless it is explicitly described in the original reference. Fiber orientation is considered 2-D random if the specimen dimensions in one plane are at least three times the fiber length, and 3-D random if the specimen dimensions in two perpendicular planes are at least

Table 1 Properties of HPFRCCs

Material	σ_f (MPa)	σ_u (MPa)	ε_u (%)	E (GPa)	σ_c (MPa)	ε_c (%)	MC ?	cs (mm)	gl (mm)	w (μm)	V_f (%)	d_f (μm)	L_f (mm)	Specimen shape	x-sect (mm x mm)	fo	Processing Route	Ref
Cardifrc	NR	10-15	NR	50	207	NR	NR	NR	NR	NR	6	160	6 (5% V_f) 13 (1% V_f)	Dog bone	100 x 35 *a	3D	Casting	[14, 15]
Densit-CRC	6-7	14	0.08 *b	46	140	NR	NR	NR	NR	NR	6	400	12	Notched dumbbell	Dia. 40	3D	Casting	[16, 17]
Ductal	11.5	12.2	0.06 *c	58.0	160-240	0.39	Y	NR	150	NR	2.0	200	13-15	Prism	70 x 70	3D	Casting	[18, 19]
Ductal (Taiheiyo)	10.3	13.6	0.3 *d	NR	>200	NR	Y	NR	100	NR	2.0	200	15	Dog bone	50 x 10	1.5D	Casting, cured at 90 °C	[20]
PE-ECC	4.5	6.0	3.8	22	80	0.5	Y	4.1	120	150	1.5	39	19	Dog bone	78 x 43	2.5D	Normal casting	[21]
PVA-ECC	3.5	6.5	4.0	23	78	0.45	Y	1.0	180	60	2.0	40	12	Plate	76 x 13	2D	Self-compacting	[22]
	4.5	7.0	6.7	NR	NR	NR	Y	NR	80	NR	2.0	40	12	Dumbbell	30 x 13	1.5D	Normal casting	[23]
	2.8	4.2	2.1	14.6	31.5	0.47	Y	NR	100	NR	1.9	40	12	Prism	100 x 100	3D	Normal casting	[24]
	3.0	4.8	4.1	19.4	47.7	0.45	Y	NR	80	NR	2.0	40	12	Dog bone	30 x 13	1.5D	Sprayed	[25]
SIFCON	7	14	1.3 *e	26.9	60-210	0.7-2.6	N	-	113	No MC	7	500	50	Dog bone	51 x 19	1.5D *f	Slurry infiltration	[26]
	NR	15.6	1.25	45.8	56-120	0.8-1.5	NR	NR	152.4	NR	12	500	30	Dog bone	76 x 38	1.5D *f		[27, 28]
SIMCON	NR	16.0	1.12	20.4	NR	NR	Y	NR	108	NR	5.4	334	241	Plate	76 x 32	1-1.5 D		[29]
Torex-HPFRC	2.5	13.4	1.3	NR	84	NR	Y	7.7	75	NR	2.0	300	30	Dog bone	25 x 25	1-1.5 D	Casting	[30, 31]
	2.5	11.7	0.46	NR	84	NR	Y	9.0	200	NR	2.0	300	30	Plate	50 x 12.5	1.5 D		

σ_f = first crack strength, σ_u = ultimate tensile strength, ε_u = ultimate tensile strain, E = Young's modulus, σ_c = compressive strength, ε_c = compressive strain, MC = multiple cracking, cs = crack spacing, gl = gage-length, w = crack width at peak load, V_f= fiber content, L_f = fiber length, x-sect = specimen cross-section, fo = fiber orientation; NR = not reported, Y = yes, N = no, D = dimension.

Note

*a. Estimated from Fig. 6 of Ref 15.

*b. Calculated from load-displacement results obtained from notched specimens.

*c. Failure occurred at the concrete-adhesive interface.

*d. Estimated. Actual value may be lower since ε_u includes deformation from cracks occurring outside the gauge length.

*e. Depends on the gage location and length since only one crack was observed.

three times the fiber length. fo equals to 1.5 denotes the situation when the fiber orientation is expected to be between 1-D and 2-D. Similarly, fo equals to 2.5 denotes the situation when the fiber orientation is expected to be between 2-D and 3-D. These situations are common when at least one dimension of the specimen is somewhere between one to three times the fiber length. Since fiber orientation has a strong influence on the composite properties, specimens tested in 1-D or 1.5-D is expected to have properties artificially boosted up in comparison to the true properties of the material when used in a structural member with much larger dimensions. Testing with small cross-section size specimens, in which fibers tend to be oriented favorable to loading direction, typically yields higher tensile strength and strain capacity. The fast drop of ductility with specimen size has been documented for some materials, when fo < 3-D.

For interpretation of the tensile strain capacity (ε_u), the columns labeled "cs" and "gl" and "MC?" (referring to whether multiple cracking is observed), are particularly useful. Tensile strain capacity is not meaningful, even when reported, if no multiple cracking occurs in the specimen. Similarly, a "strain" measurement is meaningful only if gl $\geq 5 \times$ cs, as a general rule of thumb. Unfortunately, the crack spacing is almost seldom reported.

The incompleteness of the HPFRCCs' characteristic properties reported in the literature imparts difficulty to conduct comparison on a uniform basis. For some materials, such as Cardifrc and Densit-CRC, multiple cracking under uniaxial tension has not been reported in published literature. Although it does not necessarily mean multiple cracking does not exist for these materials, the lack of the key information makes it difficult to judge the materials. For SIFCON, only one large crack was reportedly observed under uniaxial tension loading, which makes the measurement of tensile strain questionable as it depends on the gage length and gage location.

While controlling crack width is essential for durability design as discussed in Section 4 above, crack width (w) is almost never reported.

Meaningful comparison can be made between different HPFRCCs for the performance measured under similar conditions. Cardifrc, Densit-CRC, and SIFCON will be excluded from the comparison due to lack of multiple cracking information or no multiple cracking observed under uniaxial tension. (It is interesting to notice that all three materials contain high fiber content.) Although multiple cracking is observed in SIMCON, it will also be excluded from comparison because the long fiber length (241 mm) and strong fiber orientation (60-70% of fibers are aligned to loading direction while remaining 30 to 40% of fibers lay at an angle of up to 50 deg. to loading direction) make it more like a continuous fiber reinforced composite (close to 1-D). For the data set with 2.5-D to 3-D fiber orientation (fo=2.5 to 3-D), two groups of materials emerge, namely Ductal and ECCs. Both containing 2% fiber by volume, these two materials in fact represent two distinct categories of HPFRCCs, one featuring high strength but low ductility, and the other one exhibiting relatively moderate strength but high ductility (Figure 2a). While the strength of Ductal is about 2-3 times and 2-5 times that of ECC in tension and compression respectively, the strain capacity of ECC is at least one order of magnitude higher than that of Ductal. These mechanical performance difference reflects contrasting design approach of Ductal and ECC. For Ductal, tight particle packing for high strength underlies the design philosophy following the pioneering research by Bache [32]. For ECC, synergistic interaction between fiber, matrix and interface is the key for high ductility [33]. For the data set with 1.5-D fiber orientation (fo=1.5), three materials emerge, namely Ductal, ECC and Torex-HPFRC (Figure 2b). Again, both Ductal and Torex-HPFRC show high strength, while the ECC shows very high ductility. The tensile strength and strain capacity for the materials in each of these data sets are summarized in Figure 3. It is sometimes suggested that the area under the stress-strain curve up to peak load is a good performance measure of energy absorption. These values are also indicated for the various materials in Figure 3.

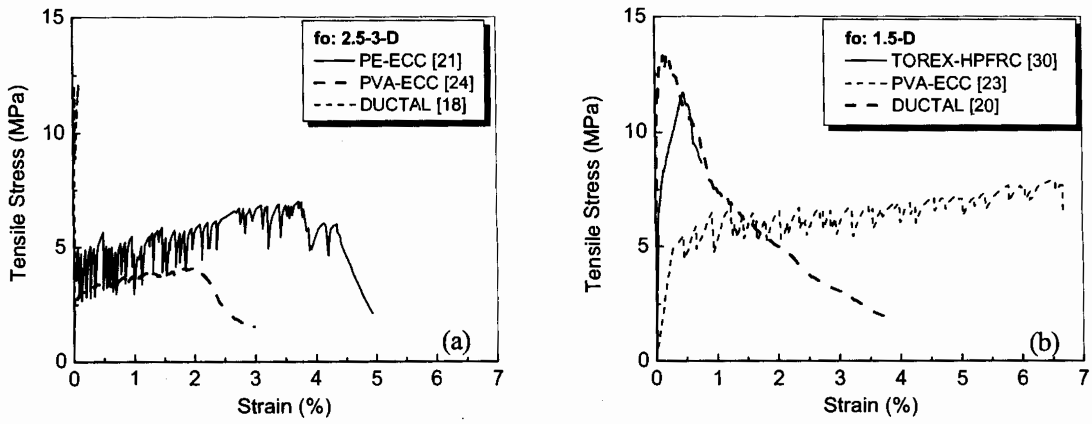

Figure 2. Typical tensile stress-strain relationships of HPFRCCs: (a) fo = 2.5 – 3-D, (b) fo = 1.5-D. Numbers in brackets are the reference numbers.

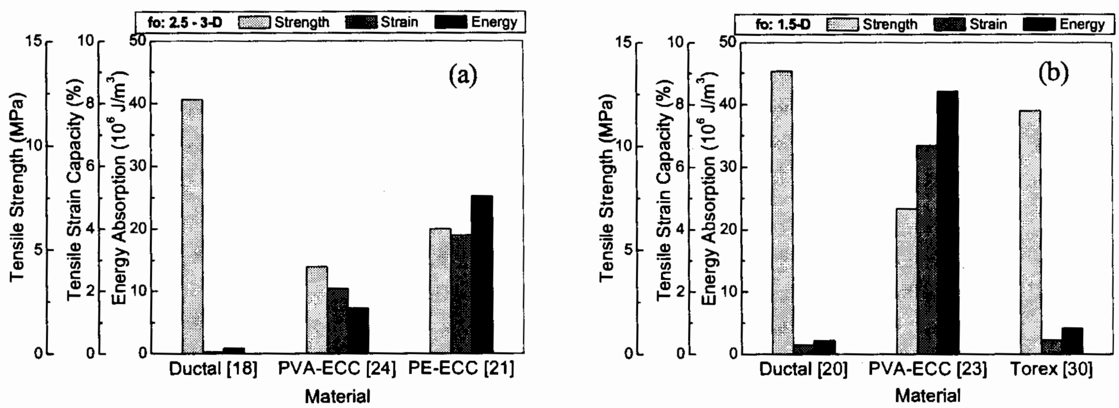

Figure 3. Tensile strength, strain capacity, and energy absorption of HPFRCCs: (a) fo = 2.5 – 3-D, (b) fo = 1.5-D. Number in brackets are the reference numbers.

The advantage of the material in each category has to be appreciated in the context of particular applications. For example, Ductal may be more suitable in situations demanding high load carrying capacity and stiffness with all parts of the structure remaining in the elastic state, while ECCs excel in applications where large deformation demand is placed on the structural elements. RC–steel beam connection designed for seismic load and bridge link slab are some examples of such application, where tensile strain capacity exceeding 1% is often required. As high strength concrete has failed to demonstrate high structural performance in many cases due to its brittleness (see e.g. [34]), it is gradually being recognized that material ductility is a key property to deliver superior structural load carrying capacity and durability. The load carrying capacity of a structural member is often not dictated by the strength of the material it is made of, but rather the ductility. A number of experiments [35] have demonstrated this point.

The column on processing route in Table 1 indicates that a variety of special processes are required/available for different HPFRCCs, including normal casting, casting with high frequency vibration, casting and curing at high temperature, casting with self-compaction, spraying, and slurry infiltration. Selection of an HPFRCC for actual construction will likely include the consideration of the ease and flexibility of processing routes.

6. HPFRCC AND INFRASTRUCTURE SUSTAINABILITY

The sustainability of our infrastructure systems, including buildings and transportation facilities, has received increasing amount of attention in recent years, and in various contexts. The 2003 ASCE report cards [36] on the condition of infrastructures of the US have reiterated the lack of durability of these systems, mainly resulting from material deterioration over time. More and more agencies have employed life-cycle cost (LCC) methods to evaluate alternative infrastructure systems/materials. The American Concrete Institute and a number of cement producers have focused attention on concrete sustainability, particularly in relation to the CO_2 emission of the cement production process. These concerns can be grouped under the roof of infrastructure sustainability, encompassing the dimensions of social, environmental and economics, from raw material resource extraction, to concrete material production, to infrastructure construction, usage and maintenance, to end of life demolition/recycling.

Very little research has been conducted on how HPFRCC may alter infrastructure sustainability. Initial cost and energy consumption in the making of HPFRCC due to fiber addition will likely put a penalty on HPFRCC compared with regular concrete in terms of sustainability indices. However, the reduction of maintenance requirement and reduced risk of failure under severe loading conditions, should lead to more sustainable infrastructure systems. Approaches in lowering the environmental burden, and quantification of how HPFRCC contribute to infrastructure sustainability needs to be developed.

7. CONCLUSIONS

A high performance fiber reinforced cementitious composite should have high tensile ductility, high durability (material and structural), and high processability, while contributing to infrastructure sustainability. These requirements can be roughly translated into high tensile strain capacity, small crack width, and low fiber content. Very few HPFRCC at present can meet all these demands. However, definite progress has been made over the last ten years, as can be seen in Table 1.

To properly evaluate HPFRCC, robust testing methodology for the uniaxial tensile response is urgently needed. Equally important, relevant information such as the crack pattern, crack spacing and crack width should be recorded in addition to the stress-strain curve.

ACKNOWLEDGEMENT

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