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ELEVATING FRC MATERIAL DUCTILITY TO INFRASTRUCTURE DURABILITY

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Abstract

Concrete is a brittle material. The lack of durability of concrete infrastructure has been a recognized concern. Research in fiber reinforced concrete (FRC) often addresses the issue of material brittleness. However, the translation of improved ductility of FRC into infrastructure durability is often overlooked. This paper explores the concept of elevating the ductility of high performance fiber reinforced concretes (HPFRCC) material to the improved durability of reinforced HPFRCC (R/HPFRCC) structural elements. Special focus is placed on two levels of protection of R/HPFRCC elements. The first level involves the control of ingress of aggressive agents through the HPFRCC cover via crack width control, thereby reducing the rate of corrosion of the rebar. The second level involves the resistance to spalling associated with expansion of corroding steel reinforcing bars. Experimental results supporting both levels of protection are presented. It is suggested that the unique characteristics of certain HPFRCC with high ductility several hundred times that of normal concrete can serve to effectively enhance infrastructure durability.

1. Introduction

Our ability to create safe reinforced concrete (R/C) structures has continued to grow with experience. However, the knowledge gap with regard to creating durable infrastructure remains big. For example, the US Federal Highway Administration [1] estimated the annual direct cost of maintenance and replacement of deteriorated R/C bridge structures at over $8 billion. The problem of infrastructure deterioration is not limited to the US alone. In countries like Japan and Korea, the annual outlay for infrastructure maintenance will soon surpass that of new construction. In Europe, it has been estimated that more than 50% of the European infrastructure needs improvements.

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While much research has been conducted on the cause of infrastructure deterioration, solutions to actually solving this problem at the root level have not been forthcoming. This paper proposes and examines the feasibility of a fundamental material solution – the use of the material ductility of HPFRCC to intrinsically control cracking, and hence significantly enhance infrastructure durability. This proposal is grounded on the recognition that much of the deterioration of R/C structures can be traced to the fact that cracking in concrete is inevitable. This cracking due to restrained shrinkage or otherwise, leads to corrosion of the reinforcing steel, which in turn results in potential spalling of the concrete cover and further accelerated damage. In previous studies of steel corrosion in cracked R/C specimens, Ramm and Biscoing [2] found that "with a crack width of 100μm, corrosion was not to be observed in any case." In addition, in a study on chloride ingress in cracked concrete, Paulsson-Tralla and Silfwerbrand [3] concluded that ".... chloride ingress rate associated with a (crack) width of 50μm or less could be considered similar to the ingress rate in uncracked concrete." These experimental data suggest that crack width control may be the most potent strategy in enhancing structural durability. In this paper, we consider evidences of the innate ability of a specific version of HPFRCC in support of this concept.

Although the proposal to replace concrete by HPFRCC may appear to be prohibitive economically, the alternative of maintaining the status quo may be even more expensive. If we factor in life-cycle cost, then the judicious use of HPFRCC can in most cases, be shown to be feasible. Initial research on life-cycle assessment which includes both social and environmental cost in addition to economic cost [4] suggests that infrastructures built with HPFRCC should be much more sustainable. Practical attempts (see, e.g. [5]) in converting the ductility of HPFRCC into structural durability have already been initiated.

In this following, the concept of material ductility as a means of enhancing structural durability is first laid out. It is argued that material ductility, not compressive strength (in association with low concrete porosity/permeability), is the controlling factor for the durability of infrastructures. The HPFRCC strategy – i.e. how HPFRCC enhances durability is then described. Preliminary experimental evidence is given to support the argument. Conclusions are then drawn, with indications of future research directions.

2. The Concept

2.1 Insights from factors governing restrained drying shrinkage crack width

The concept of using material ductility to enhance structural durability is motivated by the connection between toughness and restrained drying shrinkage crack width first shown by Stang and Li [6] in a quasi-brittle material. The simple case of a slab of repair material of length *L* under rigid end constraints (Fig. 1) was considered. For a quasi-brittle material with a simplified strain-softening curve shown in Fig. 2a, a single crack forms (Fig. 2b) when the stress exceeds the tensile strength of the material, or

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$$E(\varepsilon_{sh} - \varepsilon_{cp}) \geq \sigma_t \qquad (1)$$

where ε_{sh} and ε_{cp} are the shrinkage strain and tensile creep strain respectively, E is the Young's modulus and f_t is the tensile strength. Equation (1) can be re-written as

$$\varepsilon_{sh} \geq \varepsilon_e + \varepsilon_{cp} \qquad (2)$$

where $\varepsilon_e = f_t / E$ is the elastic tensile strain capacity of the material. Equations (1) and (2) show the well known fact that high tensile strength and creep strain, low Young's modulus and shrinkage strain are conducive to resisting cracking due to restrained shrinkage. The left hand side of (2) can be thought of as a strain demand due to shrinkage, while the right-hand side of (2) can be thought of as a strain supply. It should be noted that shrinkage and creep are time/stress dependent properties, thus complicating Eqs. (1) and (2).

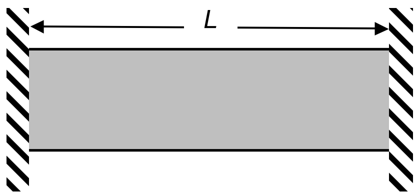

Figure 1: Simple slab of repair material under end constraints

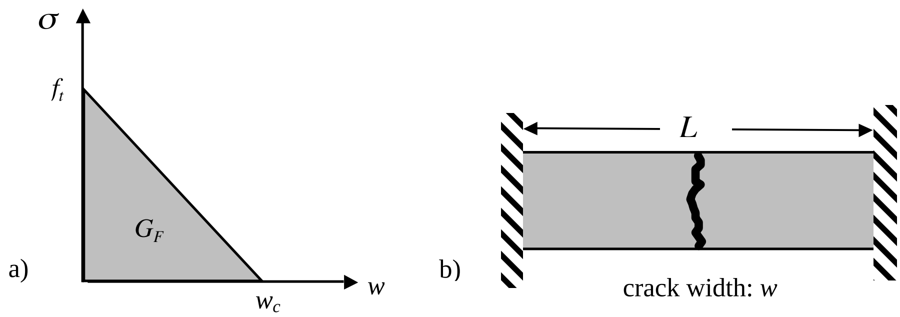

Figure 2: (a) The post-crack tension-softening curve of a quasi-brittle material governing (b) the width w of a single crack

Once condition (1) or (2) is satisfied, a single crack is formed in the slab, with crack width w governed by the degree of brittleness ($1/l_{ch}$) of the slab material [6]:

$$w = \begin{cases} Lp/\left(1 - L/2l_{ch}\right) = Sp & for \;\; \varepsilon_{sh} \leq (w_c/L) + \varepsilon_{cp} \;\; and \;\; L/2l_{ch} < 1 \\ L\left(\varepsilon_{sh} - \varepsilon_{cp}\right) & for \;\; \varepsilon_{sh} > (w_c/L) + \varepsilon_{cp} \;\; or \;\; L/2l_{ch} > 1 \end{cases} \qquad (3)$$

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where the material characteristic length $l_{ch} \equiv EG_F / f_t^2$ and G_F, w_c are the fracture energy and critical crack opening (when traction drops to zero in Fig. 2a), respectively. In Eq. (3), $p \equiv \varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp})$ defines the restrained shrinkage cracking potential, i.e. the excess of strain demand over strain supply.

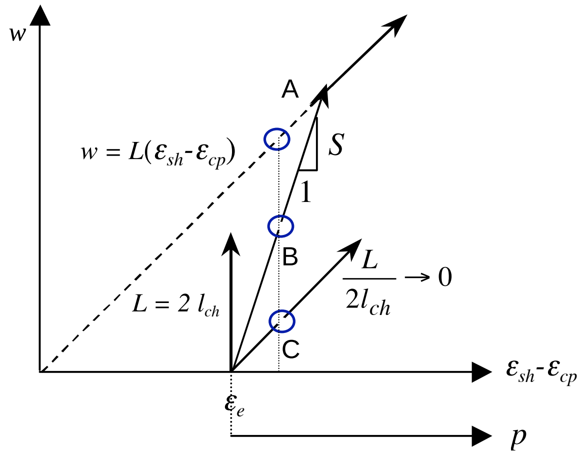

Figure 3: Schematic plot of crack width w as a function of shrinkage strain ε_{sh} or cracking potential p. The crack width development A, B, or C is shown for three materials with different degrees of brittleness.

Equation (3) is illustrated in Fig. 3 as the linear line with slope $S = L/(1 - L/2l_{ch})$, which suggests that the crack width will grow from zero linearly proportional to p. This slope has two limits. When l_{ch} decreases to $L/2$, the slope becomes infinite, and the material behaves like an ideally brittle material. When l_{ch} is lower than $L/2$, the slope becomes negative, and the cracking becomes highly unstable. When l_{ch} becomes large compared to $L/2$, the slope approaches L. The ratio L/l_{ch} is the brittleness number [7]. Figure 3 demonstrates that even for the same cracking potential, a material with low l_{ch} will have larger crack width (e.g. Point A) and the crack development tends to be unstable. A material with high l_{ch} will have the lowest crack width (e.g. Point C) and the crack development tends to be stable. For material with intermediate l_{ch}, the crack width development (Point B) will behave somewhere in between these two limits.

From the above analysis, it is clear that the restrained shrinkage crack width w depends on the cracking potential p, the degree of brittleness $L/2l_{ch}$, and the slab dimension L. It explains that concrete material with a higher toughness, such as FRC, will have smaller crack width than a plain concrete due to a higher value of l_{ch}, assuming all other properties the same. Thus, the cracking potential p may be thought of as the driving force behind large crack width, and the toughness serves as a material resistance to large crack width. In recognition that large crack width is conducive to the transport of

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aggressive agents through the concrete cover, leading to various kinds of structural deterioration, materials with low p and high toughness may be expected to enhance structural durability.

2.2 Strength versus Ductility

In most concrete structure design guidelines and design codes, material performance is expressed in terms of compressive strength. In recent years, this concept has been carried over to structural durability, particularly in view of the fact that high strength concrete (HSC) has lower permeability and should therefore serve as a better concrete cover against the transport of aggressive agents. Recent field experience, however, has not been consistent with this expectation. For example, data collected on high strength concrete bridge decks in the US indicate that these decks have unexpectedly high deterioration rates [8]. This paradox can be understood from the factors governing crack formation due to restrained shrinkage, as described above and further elucidated below.

High strength concrete is made with a lower water/cement ratio than normal concrete. As a result, the degree of autogenous shrinkage, especially at early age, can be much higher than that for normal concrete [9]. This implies that the cracking potential p can be high, resulting in a higher tendency to crack at early age under restrained conditions. In addition, the value of l_{ch} for HSC has been shown to be 40% lower than normal concrete [10] due to the higher value of tensile strength f_t. This implies that S in Eq. (3) is higher for HSC structures, leading to more unstable crack opening and larger crack width once restrained cracking initiates. This observation suggests that high strength, and specifically high compressive strength, does not ensure structural durability.

From the above discussions, it appears that a strategy for designing durable structures would be to adopt materials with low cracking potential, combined with high toughness. One such possibility is high performance fiber reinforced concrete (HPFRCC).

3. The HPFRCC Strategy

3.1 The Low Cracking Potential of HPFRCC

The distinctive characteristic of HPFRCC is that it has a high tensile strain capacity ε_i. One version of HPFRCC, known as Engineered Cementitious Composites or ECC developed at the University of Michigan, has ε_i reaching 2-5%. A typical tensile stress-strain curve of an ECC with composition given in Table 1 is shown in Fig. 4. Besides common ingredients of cementitious composites such as cement, sand, fly ash, water and additives, ECC utilizes short, randomly oriented fibers (e.g. Polyethylene, Polyvinyl Alcohol), which are added during the mixing procedure at low fiber volume fractions (V_f =1.5%–2%). The fiber, matrix and interface between them are tailored according to micromechanical principles for ultra composite ductility [11-13]. Whereas FRC toughens an essentially brittle concrete into a quasi-brittle composite, ECC converts a tension-softening FRC into a ductile metal-like strain-hardening cementitious composite.

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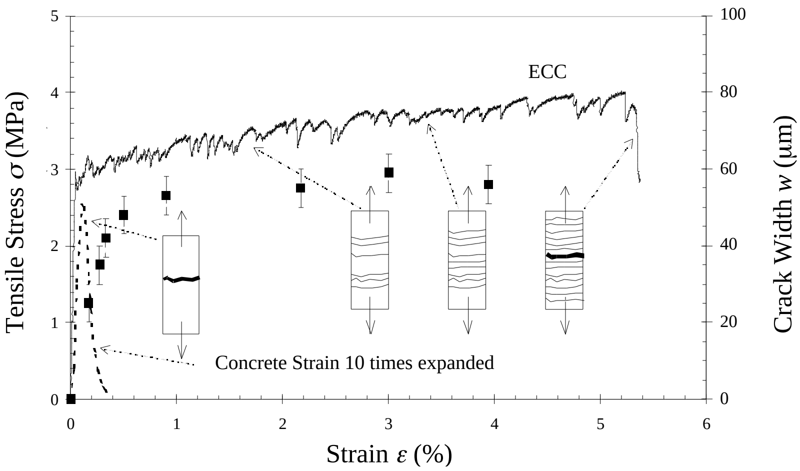

Figure 4: Measured uniaxial tensile stress-strain relation (continuous line) & crack width development (square symbols) of a typical ECC (after [14]).

Table 1: Composition of a typical ECC

Cement	Water	Sand	Fly Ash	SP	V_f (%)
1.0	0.53	0.8	1.2	0.03	2.0

SP = superplasticizer; all ingredients proportion by weight except for fiber

Table 2: Typical properties of ECC and normal concrete

Properties	Normal Concrete	ECC	Reference
ε_e (%)	0.01	0.015	[13]
ε_{sh} (%)	0.04 – 0.1	0.1 – 0.15	[14]
ε_{cp} (%)	0.02-0.06	0.07	[15]
ε_i (%)	0	2-5	[13]
$p = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})$ (%)	(-0.03) to 0.07	(-4.99) to (-1.94)	
w (μm)	40-660*	30-50	See Fig. 5
k (m/s)	1.6 x 10^{-6}	4.0 x10^{-12}	[16]
f_c' (MPa)	30-60	60-70	[17]

*Specimen size-dependent

For such ductile materials, the cracking potential modifies to

$$p = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp}) \quad (4)$$

For realistic values of ε_e, ε_{sh}, and ε_{cp}, all in the order of 10^{-2} to 10^{-1}%, Eq. (4) suggests that p will be small, or even negative for ECC. Hence ECC may be expected to suppress

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fracture induced by restrained shrinkage. Table 2 summarizes experimental data of ECC. Typical properties of normal concrete are also included for comparison purpose.

3.2 Crack Width Control

Despite the fact that HPFRCC can resist fracture failure, material damage in the form of sub-parallel microcracking does occur during strain hardening. These microcracks are closely spaced, one mm or so apart, with crack width tightly constrained to within tens of microns. The crack width development during strain hardening in ECC is also shown in Fig. 4. As tensile strain increases, the crack width increases but then stabilizes to a steady state value about 60 μm when the strain exceeds about 1%. From a durability point of view, it is important that this steady state crack width is small. In composites where the crack width does not reach a steady state or if the steady state crack width is excessively large, the strain capacity ε_i used in structural design must be restricted to account for a crack width consistent with material and structural durability [18].

It should be noted that for quasi-brittle materials, Eq. (3) implies that crack width *w* induced by restrained shrinkage will depend on the structural dimensions (*L* in the above example). For HPFRCC, however, and as long as *p* remains negative, the microcrack width is an intrinsic material property, and will not depend on the structural dimension. A series of simple restrained drying shrinkage tests confirm the size-independency of crack width on specimen dimension (Fig. 5). The data points corresponding to the three largest specimen lengths *L* were obtained from steel ring restrained tests, while the other data points were from plates with end-restrains. This figure shows that for concrete, the crack width *w* increases linearly with specimen length as expected, and is predicted by the second of Eq. (3) when values of ε_{sh} = 0.105% and $\varepsilon_{cp} = 0.55\varepsilon_{sh}$ [19] were used. In contrast, the restrained drying shrinkage induced crack width in ECC remains more or less constant below 50 μm for all specimen dimensions. By virtue of the fact that crack width in ECC is an intrinsic material property, structures built with ECC will have the same small microcrack width no matter the planar dimensions of the structure.

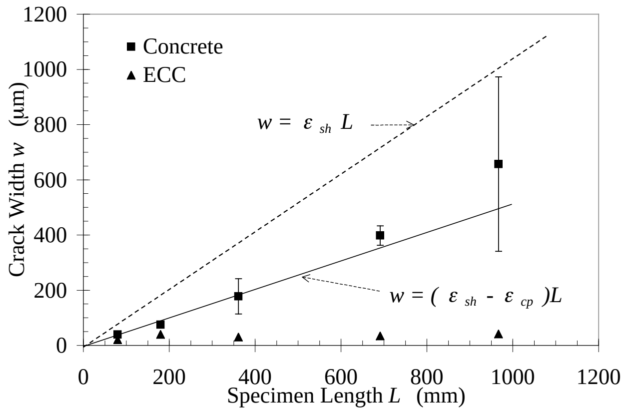

Figure 5: Crack width as a function of specimen dimension for concrete and ECC.

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3.3 Water Transport Property

The water transport properties, including the permeability coefficient, flow rate, and absorption in various cracked cementitious materials, have been studied [20-22]. Wang et al. [20] demonstrated the significance of crack width *w* in controlling the permeability of cracked concrete. The permeability was shown to decrease by seven orders of magnitude (from 10^{-4} to 10^{-11} m/s) as the crack width decreases from 550 μm to zero (Fig. 6). Of particular interest is that the curve in Fig. 6 becomes noticeably flat when *w* drops to below 100 μm. This implies that cracked cementitious materials with crack width restricted to below 100 μm will behave similar to sound concrete as far as water transport property is concerned.

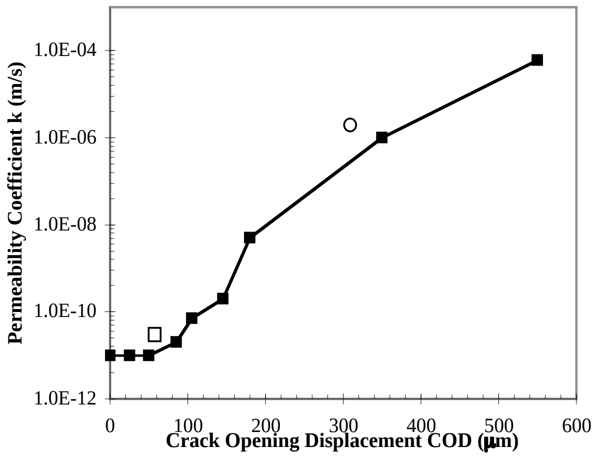

Figure 6: Permeability of cracked concrete versus crack width (black squares, after [20]). The open circle data point is permeability measured for cracked mortar, and the open square data point is permeability measured for cracked ECC [16].

Tsukamoto [21] studied the water flow rate in cracked FRC, and found that the flow rate scales as the third power of *w*. This relationship holds for both plain concrete and FRC, although FRC suppresses the flow rate further compared to plain concrete, for a given *w*. This was attributed to the increased tortuosity of the cracks in the presence of fiber bridging. In all cases, the flow rate becomes negligible when *w* falls below 100 μm.

Preliminary investigations on the influence of cracking on permeability in mortar and ECC have been conducted [16]. Specifically, two types of specimens, reinforced mortar and plain ECC plates, of dimensions 75mm x 180mm x 12mm, were subjected to tensile pre-loading to deformations of 1.5% of the initial specimen length. A high wire mesh reinforcement ratio of 2.9% was chosen for the mortar specimens, in order to limit the crack width to the 300 μm limit (for severe exposure) given by the AASHTO design

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code. This imposed deformation resulted in 10 cracks of approximately 300 μm averaged width in mortar and 50 cracks of 60 μm averaged width in ECC. Subsequently, the permeability of the cracked specimens was determined using a hydraulic head. The constant head method was adopted for the mortar specimen, while the falling head method was used for the ECC specimen for high and low permeability materials [23]. The permeability test was carried out with the preloaded specimens in the unloaded state. A small amount of crack closure occurred on unloading, but was considered small enough to be ignored in this preliminary study. The steady state permeability values of 1.6 x 10^{-6} m/s and 4.0 x 10^{-12} m/s were found for mortar and ECC, respectively on a "per crack" basis. Both values support the anticipated relationships between crack width and permeability of cementitious materials described earlier (Fig. 6). Despite the same magnitude of imposed overall deformation and higher crack density, the ECC reveals a permeability at least five orders of magnitude lower than that of the reinforced concrete because of the tight crack width control.

3.4 Chloride Penetration and Corrosion Rate

Tests on chloride penetration depth and the rate of corrosion of rebar were carried out [24] on both mortar beams and ECC beams. The beams were pre-loaded to the same flexural load of 20kN prior to exposure to a chloride accelerated environment for 28 days. This environment consists of alternate wet-dry cycles. During the wet cycle, the specimens were exposed to a saltwater shower (NaCl 3.1 wt %) at 90% RH for two days. During the dry cycle, the specimens were exposed to 60% RH for five days.

The preload resulted in a single deep crack of 300 to 400 μm width in the mortar beam, while the ECC beam experienced many multiple shallow cracks 100 μm or less in width. These crack widths were maintained during the accelerated environmental exposure.

In the chloride penetration test, the beams after environmental exposure were split and a 0.1mol/l $AgNO_3$ (aq) was sprayed onto the fractured surface after the steel bar was removed. The fractured surface changed to a white color where chloride ion was present. The chloride penetration depth was determined at various locations along the beam, by measuring the depth from the tensile side of the beam surface to the boundary where the color was changed. In the case of the mortar beams, it was found that chloride penetration concentrates at where the pre-crack was located, and the penetration depth was deep, approximately 80-100 mm depending on the w/c ratio of the mix. In the case of the ECC beams, chloride penetration occurs at multiple locations corresponding to where the multiple cracks were formed during the pre-load. However, the penetration depth was much shallower, between 0 and 20 mm depending on the w/c ratio of the mix. While the penetration rate due to a pressure head (permeation) and a concentration gradient (diffusion) is expected to be different, the smaller crack width in the ECC again confirms the advantage in the slowing of chloride ingress in such material.

In the corrosion rate test, macrocell and microcell corrosion rates were separately determined. The microcell corrosion current density was obtained from the

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measurement of the polarization resistance within each steel segment in a specially manufactured rebar consisting of alternate segments of steel and epoxy-resin [24]. These measurements of current densities were then converted into corrosion rates using the conversion ratio of 100 μA/cm^2 to 1.18 mm/year.

The corrosion rate test findings are summarized in Fig. 7. In the case of the mortar beam, the corrosion activity is concentrated at the location of the pre-crack, and has higher macrocell current induced corrosion than microcell current induced corrosion, with a total corrosion rate reaching over .008 mm/year. In the case of the ECC beam, corrosion activities are more spread out, and appear to be controlled by microcell current induced corrosion. The total corrosion rate is much lower, at less than 0.0004 mm/year.

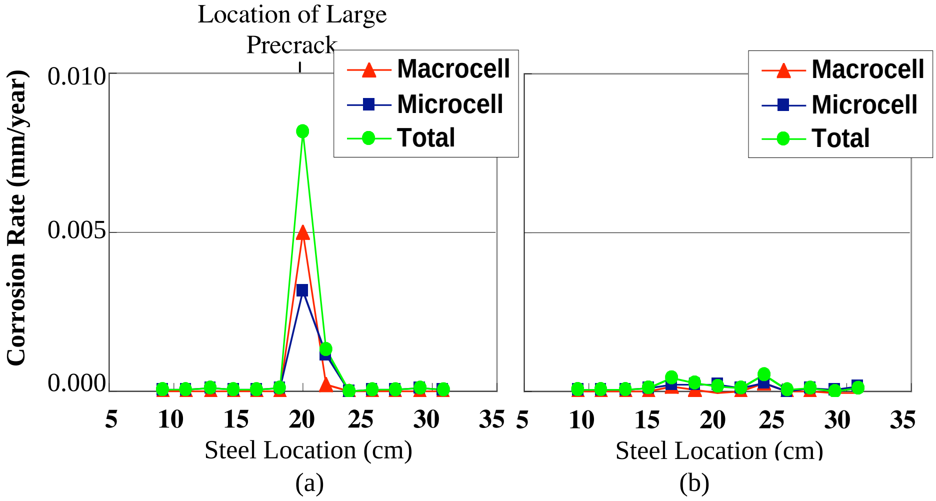

Figure 7: Microcell and macrocell corrosion rate measured for (a) R/C, and (b) R/ECC along the reinforcement bar length (adapted from [24]).

3.5 Spall Resistance

It is well known that once corrosion of the steel reinforcing bar initiates, the corrosion debris can expand against the surrounding concrete, creating a tensile circumferential stress state in the cover concrete. This may lead to tensile radial cracking and subsequent spalling of the cover, resulting in a shortening of the structural service life.

The study of the spall resistance of ECC versus that of normal concrete has been conducted. Rectangular slabs of ECC or concrete with a center hole were cast (Fig. 8a). The dimension of the radial distance from the edge of the hole to the edge of the slab was chosen to simulate the concrete cover thickness recommended by ACI. Each specimen was loaded by forcing a tapered rod into the hole (Fig. 8b) until fracture or softening of the specimens occurred. Fig. 9 plots the applied vertical load P against the

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radial displacement measured by a strain gage at the edge of the hole. Two ECCs were used in this experiment: ECC1 has the same and ECC2 has slightly higher compressive strength than the reference concrete. In both cases, the ECC slab exhibits over three times the load and deformation capacity as the concrete slab. This demonstrates that the improvement in spall resistance derives from the tensile ductility of the material. The material strength is less important. The failure mode of both ECC specimens was via multiple radial microcracking during material strain-hardening. The concrete slab failed with a single crack brittle fracture (Fig. 10). These test results are consistent with those obtained by Kanda et al. [25] who conducted a similar investigation.

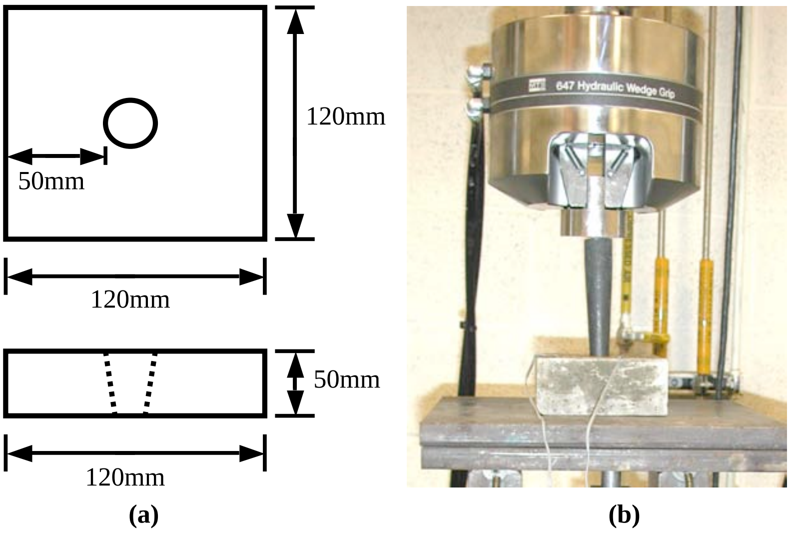

Figure 8: (a) Spall resistance test specimen geometry for simulation of expansive force from steel rebar corrosion, and (b) loading of specimen by tapered rod.

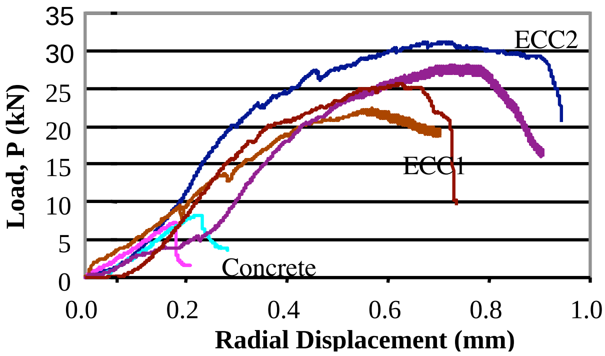

Figure 9: Load-displacement curves of concrete and ECC in spall resistance test.

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(a) (b)

Figure 10: Failure modes of (a) concrete, and (b) ECC

4. Further Discussions and Conclusions

The previous section describes a number of contrasting features between HPFRCC and normal concrete in connection with structural durability, the most important being that HPFRCC features a high tensile strain capacity ε_i, and therefore a low cracking potential p. Although real cracks resulting from restrained shrinkage or mechanical loading are not likely, HPFRCC does experience damage during strain-hardening in the form of micro-cracks. Fortunately these microcracks have crack widths which are self-controlled, i.e. do not rely on steel reinforcement ratios and are independent of structural dimensions, and the crack widths are on the order below 100 μm. Permeability tests indicate that the transport property of the HPFRCC cover material will be several orders of magnitude lower than that of normal cracked concrete, and approaching that of sound concrete. Chloride ion penetration test and accelerated corrosion test suggest that HPFRCC material can serve as an excellent cover protecting the steel reinforcement from harmful aggressive agents. This is the first level of protection offered by HPFRCC when used as the cover material in an R/C member.

If for some reason, corrosion does initiate in the steel reinforcement, the high ductility of HPFRCC can prevent surface spalling, thus providing a second level of protection against structural deterioration. This duo-level protection is expected to support a significantly extended service life of R/C structures even in very aggressive environments.

An early attempt to replace concrete with ECC in the cover of an R/C beam was carried out by Maalej and Li [26] although accelerated corrosion studies were not carried out. The mechanical loading test results, however, do provide evidence of the superior spall

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resistance and the microcrack width control in the cover, even when the beam was loaded to severe failure on the compressive side of the beam.

An additional benefit of the distinctive nature of HPFRCC having self-controlled crack width is that it allows full decoupling between steel reinforcement and crack width control. In certain structures, steel reinforcement is applied only for crack width control. With self-controlled microcrack width, the steel reinforcement can be eliminated, resulting in no possibility of steel corrosion. Steel reinforcement is used only for ensuring adequate load capacity or otherwise, but not for crack width control. An example where this decoupling has been taken advantage of is an ECC link-slab connecting between two bridge deck spans [27]. The link-slab serves as a flexible hinge, allowable rotational and axial movements (mechanical/environmental load induced) of the adjoining decks. The minimization of steel reinforcement serves to enhance the flexible hinge functionality, while the danger of corrosion induced deterioration is precluded.

The crack width independent of structural size implies that HPFRCC can be effective in preserving service live of structures with large exposed surface where restrained drying shrinkage can be difficult to control. The size-independence and reinforcement ratio-independence of the micro-crack width in HPFRCC provides additional degrees of freedom in the designing of durable structures.

The conventional wisdom is that durable R/C can be made with quality concrete (i.e. high strength) and/or with a large cover thickness. With the information described above, especially in relation to the importance of ductility, the classical understanding of "quality" may need to be revised. Certainly, a low porosity high strength concrete may not provide the best results.

In addition to the advantages of HPFRCC described above, the small width of the microcracks is expected to promote self-healing. For example, Edvardsen [28] showed that the dominant factor promoting self-healing in concrete is a small crack width. Preliminary observations of the ECC specimens used in the permeability test show a self-healing tendency. The self-healing may explain the gradual decrease of permeability measured over time [16]. The expected self-healing ability of HPFRCC will further enhance the durability of structures built with such materials.

The concept of elevating material ductility to infrastructure durability described in this paper can be effective only if material durability of the HPFRCC can be assured. This is a largely unexplored area requiring extensive research, especially when the material is exposed to mechanical and environmental loads while in the strain-hardening stage. It is a fundamental requirement that the unique tensile characteristics of HPFRCC, especially the tensile strain capacity ε_i, must be maintained over time. This subject is taken up in a companion paper [18].

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Material and structural durability of HPFRCC depends on the self-controlled tight crack width. Some experimental evidences mentioned in this paper suggest a crack width threshold of 50 μm for chloride diffusion. This appears to be a good target for HPFRCC material design for an upper limit of the intrinsic crack width.

There are at present two communities of researchers, one working on structural durability, and the other working on material toughening. These two communities are generally disconnected. This paper shows preliminary evidence that by elevating material ductility to structural durability, important advances can be made towards fundamentally solving the problem of structural deterioration. However, complete validation and implementation of this concept in practice will require extensive collaborations between these two apparently distinct disciplines.

Finally, it is worth noting that structural durability is an important component of infrastructure sustainability. The economic, social and environmental cost of repeated repairs and service interruptions due to lack of structural durability is enormous. Materials technology can be a powerful tool towards the goal of infrastructure sustainability.

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