2nd International RILEM Conference on Strain Hardening Cementitious Composites
12-14 December 2011, Rio de Janeiro, Brazil

# DEVELOPMENT OF HIGH STRENGTH HIGH DUCTILITY CONCRETE

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## Abstract

The development of a new material, High Strength High Ductility Concrete (HSHDC), and its unique composite properties are reported in this paper. HSHDC attains an average compressive strength of 160 MPa (23 ksi) and average tensile strain capacity of 3.5%. The micromechanics-based design approach, which guided the development of HSHDC, is highlighted. A comparison of the specific energy absorption under direct tension of HSHDC with other concretes of this class is also presented.

## 1. INTRODUCTION

Over the last three decades, high compressive strength concretes and high tensile ductility concretes have emerged as two distinct classes of concrete. Materials at the frontiers of both of these classes include Very High Strength Concrete (VHSC) [1,2] (compressive strength ≈ 200 MPa) and Engineered Cementitious Composites (ECC) [3,4] (tensile ductility ≈ 3-6%). The development of these two concretes was based on two different design philosophies that targeted two different structural performances. VHSC and similar high strength concretes (RPC, Ductal, MDF, and DSP) were designed to achieve size efficiency in structural members for very large structures and to provide additional strength safety margin for strategically critical and protective structures [1,2]. On the other hand, ECC and similar high performance fiber reinforced cementitious composites (HPFRCCs) were developed to ensure ductility of structural elements and massive energy absorption in the face of extreme load/displacement events such as earthquakes [5]. However, the decoupled development of VHSC and ECC resulted in mutual exclusion of each other's desirable properties. VHSC is an order of magnitude less ductile than ECC, whereas the compressive strength of ECC is 3 to 4 times less than VHSC. A combination of high strength and high ductility in one concrete material is highly desirable to ensure resiliency of critical structures under extraordinary loads/displacements, which is the motivation for the present study.

Recently, there have been a few notable investigations on combining high compressive strength and high tensile ductility in one concrete with limited success. The mechanical test results of Ultra High Performance – Strain Hardening Cementitious Composites (UHP-SHCC) were reported in Kamal et al [6]. The best performing UHP-SHCC has average compressive strength of 96 MPa and tensile ductility of 3.3% at 14 days after casting (longer age data are not reported in this reference). The development of another such material, Ultra High Performance – Fiber Reinforced Composite (UHP-FRC), is presented in Wille et al [7]. UHP-FRC has compressive strength of about 200 MPa and tensile ductility of 0.6%. Although both of these materials attempt to combine tensile ductility and compressive strength in one concrete, UHP-SHCC has a compressive strength (96 MPa) that is only about half that of VHSC (200 MPa), and UHP-FRC has tensile ductility of only 0.6%, which is at least 5 times smaller than ECC.

In this paper, the ongoing development of a new composite material, High Strength-High Ductility Concrete (HSHDC), and its unique composite properties are presented. In HSHDC, both the desirable properties of high compressive strength (similar to VHSC) and high tensile ductility (similar to ECC) are integrated into a single material. This results in higher specific energy absorption (or composite toughness) in HSHDC as compared to any other material in the class of high performance cementitious composites. The micromechanics-based principles that guide the design of ECC, combined with a VHSC matrix, led to the development of HSHDC. These micromechanics principles and their application to HSHDC development are outlined in the next section.

## 2. HSHDC DESIGN APPROACH

The central approach to the HSHDC design was inducing tensile ductility in VHSC by applying the micromechanics-based design principles [3,4,8] for multiple microcracking. Guided by these principles, adjustments were made in the material ingredients to maintain the high composite compressive strength.

The starting material towards HSHDC design was a VHSC developed at ERDC [2]. Its composite properties, especially the behavior under direct uniaxial tension, were experimentally determined. The average ultimate tensile strength of VHSC was 10 MPa, and its average tensile strain capacity was 0.2% [9]. Thus, in spite of its very high compressive strength (≈ 200 MPa), the tensile ductility of VHSC is about an order of magnitude smaller than ECC.

As a first step, the micro-scale properties of VHSC were investigated to determine the reasons for such a lack of tensile ductility. VHSC contains hooked steel fibers with lengths of 30 mm and diameters of 0.55 mm at a fiber/composite volume fraction of 3.6%. Single fiber pullout tests of the steel fibers embedded in the VHSC matrix were performed to determine the fiber-matrix interfacial properties which were in turn used to determine the crack bridging (σ-δ) relation. The σ-δ relation determines whether a fiber reinforced composite will exhibit multiple steady-state cracking based on two necessary conditions of micromechanics. It was found that, although the VHSC's σ-δ relation satisfied the crack initiation condition, it violated the crack propagation condition [9]. The complimentary energy ($J_b'$) of crack-bridging in VHSC was insufficient to overcome the crack tip toughness ($J_{tip}$) thereby hindering the steady-state crack propagation and tensile ductility.

With the objective of increasing the complimentary energy ($J_b'$) of crack bridging, different fiber alternatives were investigated. The matrix composition was kept almost constant for preserving its high compressive strength. Due to more flexibility in the selection of properties in polymer fibers than steel fibers, the former were considered for further investigations. Anticipating high interfacial frictional bond due to the dense VHSC matrix on fibers, only high strength polymer fibers were considered for HSHDC to ensure crack bridging without extensive fiber rupture.

Of the wide variety of commercially available high strength polymer fibers, a fiber appropriate for use in HSHDC was selected. The commercially available high strength polymer fibers can be classified based on their affinity to water as hydrophilic (e.g. Aromatic Polyesters and Polyamides) or hydrophobic (e.g. Polyethylene). Hydrophobic fibers were preferred to hydrophilic fibers for use in HSHDC in order to minimize the chemical bond formation. Low chemical bond not only increases the complimentary energy ($J_b'$) but also decreases the rate effect on the interfacial bond [10]. Rate independence is important to maintain the mechanical performance under unpredictable dynamic loading. Hydrophilic fibers also increase water demand of the mix by adsorbing water through hydrogen bond formation, which can potentially deteriorate the compressive strength and also lead to poor fiber dispersion. Thus, the ultra-high molecular weight Polyethylene (PE) fiber was selected for use in HSHDC due to its hydrophobic nature and high strength.

The geometry and volume fraction of the PE fibers in the first version of HSHDC reported in this paper were based on the past experience of the authors with the tailoring of ECC and in consideration of the workability of the mix in the fresh state. Similar to PVA fibers in ECC [4] (diameter = 39 μm, length = 12 mm, and volume fraction = 2%), PE fibers with diameters of 38 μm and lengths of 12.7 mm (0.5 inch) were used in HSHDC at 2% fiber volume fraction.

The high range water reducing admixture (HRWRA) content in the VHSC matrix was modified to accommodate the PE fibers. In spite of their hydrophobic nature, the PE fibers adsorbed a certain amount of mix water, which was more than that adsorbed by steel fibers in VHSC. If the water and HRWRA contents are left unchanged, the reduction of mix water by the PE fibers can adversely affect the fresh properties of the mix leading to non-homogenous fiber dispersion. A study was conducted to determine the appropriate dosage of the HRWRA for more homogenous fiber dispersion (as measured by the fiber dispersion coefficient [11]) without adversely affecting the compressive strength. It was found that raising the HRWRA content by up to 80% (of that used with steel fibers in VHSC) improved the fiber dispersion proportionately without substantially reducing the compressive strength. Beyond 80%, the compressive strength starts to degrade substantially (more than 20% of VHSC's compressive strength) without significant gain in fiber dispersion. Thus, the HRWRA to cementitious material ratio was increased to 1.10% for PE fibers in HSHDC, as compared to 0.62% for steel fibers in VHSC.

The first version of HSHDC was created using the mix developed above, and its mechanical performance under tension and compression loading was experimentally determined. The experimental investigation and the results are reported and discussed in the remainder of this paper.

## 3. EXPERIMENTAL INVESTIGATION

### 3.1 Materials **and mix proportions**

The mix proportions of HSHDC and the properties of the PE fibers are given in Tables 1 and 2, respectively. Similar to other high performance concretes, it consists of cementitious materials, fine aggregates, fibers, water, and HRWRA.

Table 1: Mix Proportions of HSHDC

| Class H Cement | Microsilica | Ground Silica | Silica Sand | Tap Water | HRWRA | PE Fiber |
|---|---|---|---|---|---|---|
| 1.000 | 0.389 | 0.277 | 0.967 | 0.208 | 0.0153 | 0.0234 |

Table 2: Geometry and Mechanical/Physical Properties of the PE Fiber

| Diameter | Length | Volume Fraction | Nominal Strength | Young's Modulus | Specific Gravity | Melting Temp. |
|---|---|---|---|---|---|---|
| 38 μm | 12.7 mm | 2% | 3000 MPa | 100 GPa | 0.97 | 150 °C |

The cementitious materials used in HSHDC matrix were Class H cement and silica fume. Class H cement (also called "oil-well cement") is characterized by low calcium aluminate content and coarse particle size (mean diameter is 70-100 μm and Blaine fineness is 200-260 $m^2$/kg). Compared to other chemically similar cements of finer size, the larger particle size in Class H cement exerts lower water demand, which results in a denser and less porous microstructure. Silica fume was used as a highly reactive supplementary cementitious material to promote the formation of secondary hydration products, thereby maximizing the calcium silicate hydrate (CSH) content. A polycarboxylate-based high range water reducing admixture (HRWRA) was used to maintain flow-ability and rheology of the mix at the very low water-cementitious material ratio (w/cm) of 0.15 used in HSHDC. The cementitious materials in HSHDC were selected to reduce the water demand, increase the formation of CSH, and promote homogeneity of the mix, all of which contribute to the high compressive strength performance.

The aggregates or fillers used in the HSHDC matrix are primarily fine silica sand and ground silica supplemented by unreacted silica fume particles. Fine silica sand with a mean diameter of about 270 μm (maximum aggregate size of 600 μm) was used. Using such a small aggregate size reduces the size of the weak interfacial perimeter. Smaller aggregate also reduces the fracture toughness of the matrix (due to reduced aggregate interlock) for crack initiation and fracture work during steady state crack propagation (due to reduced tortuosity of crack path), both of which are desirable effects for composite ductility according to micromechanics. Fine particles of silica fume (0.1-1 μm) and ground silica (5-100 μm) increase the density of the matrix and interface by filling the larger voids. Thus, the aggregates or fillers in the HSHDC matrix are intended to increase particle packing density, strengthen the aggregate-cement paste interface, and reduce matrix fracture toughness.

### 3.2 Specimen preparation

The specimens for tensile testing of HSHDC used in this research were dogbone-shaped specimens recommended by Japan Society of Civil Engineers (JSCE) [12] for standardized testing of HPFRCCs with multiple fine cracks. The specimen geometry is shown in Figure 1. The dogbone geometry forces most of the cracks to occur in the gage region due to its smaller area thus allowing reliable measurement of the tensile strain.

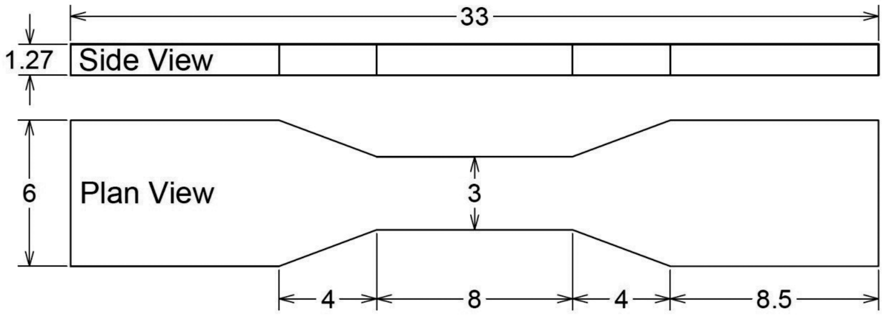


Figure 1: Dogbone specimen geometry for tensile testing of HSHDC (JSCE) [12].
(All dimensions in cm)

Elevated temperature curing was used for accelerating the curing of HSHDC specimens. The HSHDC mix in its fresh plastic state was poured at the middle of the dogbone specimen mold on a vibration table. The material slowly flowed towards the gripping ends while under moderate vibration for about 3 minutes. The molds were then sealed by plastic sheets and cured for 1 day at room temperature. Subsequently, the hardened specimens were removed from the molds and kept in a water tank for curing at room temperature (23±3°C) for 7 days. This was followed by elevated temperature curing for 4 days in water at 90°C and for 2 days in air at 90°C. The purpose of the elevated temperature curing was mainly to accelerate the primary and secondary hydration reactions. The temperatures below 100°C are generally not enough to initiate significant morphological changes to the microstructure of hydration products of oil well cement with low calcium aluminate contents [13]. The HSHDC (like VHSC) attained close to its maximum compressive strength in 13 days (7-4-2), instead of 90 days of curing at ambient temperature, using the aforementioned curing procedure.

The uniaxial compressive strength of HSHDC was measured using three 2 in. (50 mm) cubes of HSHDC that were subjected to the same curing procedure as above.

### 3.3 Experiment setup and procedure

The dogbones and cubes prepared as above were tested under quasi-static uniaxial tension and compression, respectively. The dogbone specimens were gripped using wedge action on their slanting edges. Sufficient degrees of freedom were provided in the grips to ensure the application of almost pure uniaxial tension along the longitudinal axis. The tensile tests on dogbones were conducted at 5 μm/s using a displacement controlled closed loop test system with a maximum load capacity of 100 kN. The strain was computed from the extension of the specimen measured by two ultra-precision LVDTs mounted parallel to the two side edges of the dogbone specimen. The compression tests were performed at a stress rate of 0.34±0.07 MPa/s (50±10 psi/s) using a force controlled compression testing machine with maximum load capacity of 2200 kN (500 kips). The results of these experiments are discussed in the next section.

## 4. RESULTS AND DISCUSSION

The results of four dogbone specimens tested under direct uniaxial tension and three 2-in. cubes tested under direct uniaxial compression of a batch of HSHDC (mix proportions in

Table 1) are presented here. The tensile stress-strain curves are shown in Figure 2. Specimen 1 showed the best performance with an ultimate tensile strength of 14.1 MPa (2.0 ksi) and corresponding tensile strain of 5.0%. The average ultimate tensile stress capacity of the 4 specimens was 11.8 MPa (1.7 ksi) with coefficient of variation (CV) of 16%. The ultimate tensile stress capacity is governed by the minimum of the peak bridging capacities at various cracks, which is further dependent on the interfacial bond and fiber dispersion. The average tensile strain capacity was 3.5% with a rather large CV of 40%. Such high variability in tensile ductility is due to unsaturated cracking in Specimens 2 and 3, which in turn is a result of inadequate flaws in the desired size range to initiate cracks. Nevertheless, the minimum tensile strain capacity was 1.9% (Specimen 2), that is about an order of magnitude higher than that of Very High Strength Concrete (VHSC). The average of first crack strengths of the 4 specimens was 5.7 MPa, and the average secant modulus was 43 GPa. The average crack width observed during testing was about 75 μm, and the average residual crack width observed after testing was about 60 μm. The average compressive strength of three 2-in. cubes of HSHDC was 160 MPa with a CV of 6%. Thus, the HSHDC was shown to simultaneously exhibit high tensile ductility (3.5%) and high compressive strength (160 MPa) similar to that of ECC and VHSC, respectively.

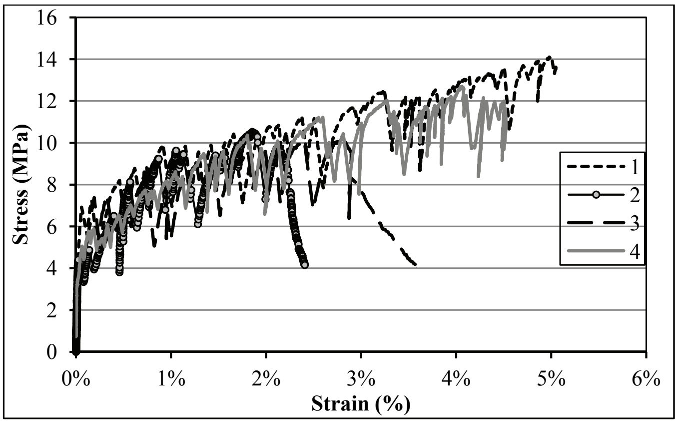


Figure 2: HSHDC tensile stress-strain behavior

The tensile stress-strain behavior of HSHDC can be explained by the process of multiple steady-state cracking similar to ECC, where each crack obeys the crack bridging (σ-δ) relation. Cracks initiate from preexisting flaws (often due to air voids) at stresses determined by the Irwin's fracture criterion. In Figure 2, it can be seen that the stress-strain curve is almost linear-elastic until the stress reaches the first crack strength of the matrix. The stress drops at this point signifying crack formation at the largest flaw and steady-state propagation through the matrix. However, the peak bridging capacity of the fibers is not exceeded, and the stress is regained as more strain is applied. This increase in stress opens the crack in accordance with the σ-δ relation. The stress continues to rise until it reaches the initiation stress level for the next largest flaw, and the process is repeated until the stress is below the peak bridging capacity of the least bridged crack. Beyond this, the damage is localized, and the least bridged crack opens with decreasing stress (softening) corresponding to its σ-δ relation. Due to such controlled cracking enabled by the micromechanical tailoring of the composite material, HSHDC exhibits high tensile ductility in spite of a high strength brittle matrix.

Specific energy (or composite toughness) of HSHDC, which is calculated as the area under the stress-strain curve before attaining ultimate stress capacity, is shown in Table 3. A comparison of other composite properties of HSHDC with other similar high performance concrete materials is also shown in Table 3. It can be observed that the specific energy of HSHDC is the largest among all the materials presented, which is a result of the combination of high tensile strength and high tensile ductility.

Table 3: Comparison of mechanical properties of HSHDC and other materials

| Material | Comp. Strength $f_c'$ (MPa) | First Crack Strength $\sigma_{fc}$ (MPa) | Ultimate Strength $\sigma_u$ (MPa) | Ultimate Strain* $\varepsilon_u$ (%) | Elastic Modulus E (GPa) | Specific Energy SE (kJ/m$^3$) |
|---|---|---|---|---|---|---|
| VHSC | 200 | 8.0 | 10.0 | 0.2 | 50 | 17 |
| ECC | 45 | 3.5 | 5.0 | 3.5 | 20 | 148 |
| HSHDC | 160 | 5.7 | 11.8 | 3.5 | 43 | 305 |
| UHP-FRC | 200 | 6.1 | 14.9 | 0.6 | 53 | 63 |
| UHP-SHCC | 96 | 6.0 | 11.0 | 2.7 | 32 | 228 |

* Ultimate strain $\varepsilon_u$ = strain at ultimate tensile strength $\sigma_u$

## 5. CONCLUSIONS AND FUTURE WORK

This paper demonstrates that, by employing the principles of micromechanics, it is possible to achieve a combination of high compressive strength and tensile ductility in one concrete material, HSHDC. Such material behavior leads to high energy absorption, which is critical for structures to withstand extreme loading conditions.

The micromechanics-based tailoring of HSHDC will be continued in the future to improve its composite performance and consistency of properties. Special attention will be given to the matrix, which was almost unmodified (as compared to the VHSC matrix) in this version of HSHDC. High rate testing and tuning of the material mix thereof is expected to ultimately result in a high performance concrete for resilient infrastructure systems.

## ACKNOWLEDGMENTS

This research at the University of Michigan was supported by a research grant (W912HZ-08-C-0056) from the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, Mississippi. Helpful discussions with Thomas Slawson (ERDC) and Toney Cummins (ERDC) are gratefully acknowledged. The authors greatly appreciate the support of Lafarge (cement), US Silica (sand and ground silica), Elkem (microsilica), WR Grace (HRWRA), and Honeywell (PE fiber) for providing material samples for this research.

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