BOTH HIGH STRENGTH AND HIGH DUCTILITY ACHIEVED WITH CONCRETE

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ABSTRACT

A new cement-based composite material, High-Strength, High-Ductility Concrete (HSHDC), has been recently developed and overcomes the brittle limitations of most concretes and cementitious materials. The material exhibits very high compressive strength relative to other types of concrete, with values exceeding 160 MPa compared with 20-40 MPa for standard concretes. The main advantage of HSHDC is the capability for elongation and strain hardening in tension, with tensile strain capacity nearing 3.5%. HSHDC, developed through a collaborative research effort between the University of Michigan and the U.S. Army Engineer Research and Development Center, provides unique material properties with broad implications for high deflection, cyclic, and impact loadings. An overview of the micro-mechanics-based design principles and formulations of the new materials is presented. Other topics discussed are material characterization techniques and results, proposed applications and uses, and a comparison of the energy absorption capacity of HSHDC to other cement-based composites.

1. INTRODUCTION

1.1 Overview

As with most materials, portland cement concretes generally exhibit increasing brittleness as greater strength is developed. Two independent thrusts have been ongoing over the past three decades, one to impart higher strength to concrete and another to engineer ductility or strain capacity into concrete. These efforts introduced new technologies into concrete materials and yielded very high strength concretes and, separately, ductile or bendable concretes. The purpose of the research reported herein was to combine the design principles used to develop high-strength concretes and high-ductility concretes with a goal of creating a new class of portland cement concretes demonstrating both high strength and high ductility. The result of this study is the introduction of a new portland-cement-based composite material with unique property combinations: high-strength, high-ductility concrete (HSHDC).

1.2 Background

1.2.1 High-strength concrete

High-strength portland-cement-based concrete was achieved by restricting the particle size of the constituents (typical diameter < 1 mm) and carefully controlling the particle-size distributions to achieve dense packing. Also, large amounts of cement are incorporated, and chemical additives are employed to reduce the requisite water content; the low water-to-cement ratio (w/c ~ 0.2) further improves strength. Additionally, high-temperature curing is often used to further augment the strength of these advanced concretes. The benchmark property of hardened concrete is the unconfined compressive strength as measured by ASTM C39 [1]. While traditional concretes exhibit unconfined compressive strengths in the range 20-40 MPa, high-strength concretes commonly achieve 190 MPa, and unconfined compressive strengths upwards of 300 MPa were obtained by using variations on the basic approach outlined above. A general name for concrete having unconfined compressive strength greater than 140 MPa is very high-strength concrete (VHSC) [2-4].

VHSC was utilized in structural members where size efficiency was needed, in architectural applications where fine detail was desired, in aggressive environments where its dense nature provided low permeability, and in protective structures. In most engineering applications, the utility of VHSC was limited by its brittleness (aside from cost). Many attempts at alleviating the brittle tendency employed reinforcing fibers of various compositions and sizes. Incorporation of well-dispersed fibers into high-strength concrete is common and successfully arrests cracking at various length scales to some extent. Some long-range ductility was achieved with VHSC by using fibrous reinforcement, but improvement in the approach is still needed.

1.2.2 High-ductility concrete

Many approaches have been explored to impart ductility to concrete-type materials, usually based on the addition of fibers as tensile reinforcement. One approach has been particularly successful and has led to a class of concrete composites known as engineered cementitious composites, or ECC [5-7]. The approach is micromechanics-based and relies on small synthetic fibers, particularly polyvinyl alcohol (PVA) fibers, to control cracking and crack propagation. Microcracks are allowed to form and are then bridged by well-dispersed, small PVA fibers. The fiber matrix interface is designed such that the bridged crack has greater load-carrying capacity in tension than the concrete matrix. The crack is arrested at a width of approximately 50 µm, and the crack tip propagates through the material without the further opening of the crack at its origin. This results in flat crack growth rather than more typical Griffith-type crack growth, in which a crack continues to open as the tip progresses. By design, multiple flat cracks form throughout the material but are restrained to the tens of microns in width. The cracks are distributed and parallel and do not coalesce. Each microcracking event produces a small degree of strain before the crack is arrested. When many of these cracks form along the specimen perpendicular to the tensile stress, the global effect is that the specimen strains. Figure 1 provides an illustration of the multiple-flat-cracking phenomenon as well as fibers bridging a microcrack.

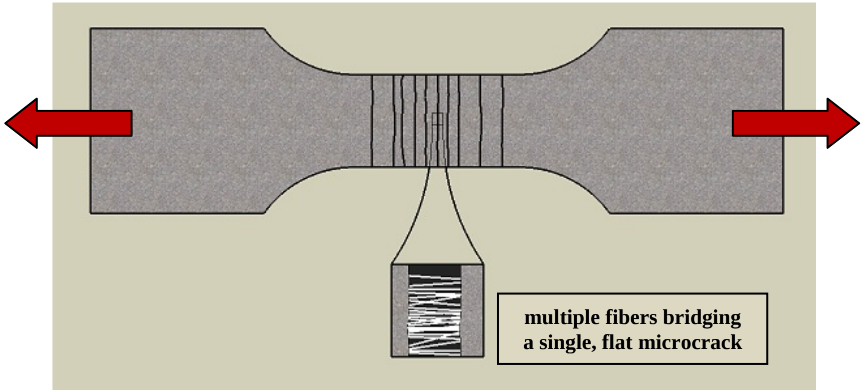

Figure 1. Illustration of distributed parallel microcracking within the gauge length of an ECC dogbone in tension.

Since the fiber-bridged microcrack carries greater load than the uncracked matrix, the strained, and thus cracked, material becomes stronger than the pristine material, resulting in a composite strain-hardening effect. ECC strain hardens in tension much like a metal, until finally the tensile stress exceeds the capacity of the bridged crack, the microcrack opens into a macrocrack, and failure occurs in the specimen. ECC routinely demonstrated an ability to undergo 3-6 % strain in tension before ultimate failure. This is at least an order of magnitude more ductile than VHSC, even when the VHSC was reinforced with steel fibers, as is the case with most formulations. In general, concretes normally are very weak and brittle in tension with strain capacities ranging from 0.01 to 0.1 %.

Another advantage of the ECC design is that much of the strain in the elastic and strain-hardening regions is recoverable. Upon unloading, the ECC recovered 40-50 % of its strain, making this a relatively resilient material even under cyclic loading. It was used in various structural applications, especially those where cyclic loads were expected, such as in earthquake-resistant structures. The microscopic cracks in ECC are small enough to resist moisture ingress, so the material can remain in service after strain is experienced.

Though many of the properties of ECC are remarkable, it was not designed to have very high unconfined compressive strength, which limits its use in some applications for which VHSC would be suited. ECC formulations vary in compressive strength, with most materials yielding at about 30 MPa and with the upper limit being about 70 MPa. Thus, the compressive strength of VHSC is three to four times that of ECC.

1.2.3 High-strength and high-ductility concrete

Though the concept of combining the properties of VHSC and ECC may seem obvious, the materials were designed to function by different, and nearly opposite, mechanisms. VHSC achieves high strength by the elimination of flaws and voids that would lead to matrix crack initiation. This is accomplished using carefully sized fine particles that were processed for uniformity and purity. ECC, on the other hand, functions by allowing matrix cracks to initiate, then bridging the cracks before they open to a detrimental extent. The bridged crack is stronger than the uncracked matrix, unlike VHSC, which relies on resistance to initial cracking but carries no appreciable tensile load after crack formation.

The development of HSHDC began with a full characterization of VHSC to understand the mechanisms of failure. The matrix properties of VHSC were input into the micromechanics-based design principles of ECC to determine the fiber and interface properties required for composite strain hardening. The micromechanics approach balances the effects of three basic characteristics – matrix properties, fiber properties, and fiber-matrix interface properties. Each of these can be controlled to some extent. In order to develop HSHDC, the VHSC formulation was modified to yield the matrix properties required by the micromechanical design; consequently, the compressive strength was reduced somewhat relative to the original VHSC but still remained much greater than that of ECC. Several fiber materials were tested before high density polyethylene (HDPE) was selected based on experimentally determined properties, and the fiber-matrix interface was tailored as well. The result of the micromechanics-based developmental efforts was the HSHDC material [8,9].

HSHDC was produced in laboratories at both the University of Michigan, Department of Civil and Environmental Engineering, and the US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory. The unconfined compressive strength is reproducible from about 150 to 170 MPa. Flexural and tensile testing demonstrated a strain capacity averaging about 3.5%. The compressive strength is somewhat reduced compared to that of VHSC, and the ductility is lower than that of ECC, but the combination of these magnitudes of strength and ductility in a single cement-based composite material is a unique accomplishment.

Other cementitious materials of note were designed for both strength and ductility with some success. Ultra High Performance – Strain Hardening Cementitious Composite (UHP-SHCC) was reported to have a compressive strength of 96 MPa and a tensile strain capacity of 3.3 % [10]. Another material, Ultra High Performance – Fiber Reinforced Composite (UHP-FRC), was reported to have a compressive strength of 200 MPa and a tensile strain capacity of 0.6% [11].

1.3 Scope

This paper presents an overview of the design premises and properties of the new composite material high-strength, high-ductility concrete (HSHDC). Reported results include unconfined compressive strength, splitting tensile strength (indirect tension), and relative hardness. These properties are compared to those of VHSC. The details of the micromechanics-based design principles are not detailed here but are available in the provided references [5-9].

2. EXPERIMENTATION

2.1 Materials

The HSHDC was prepared using constituent materials that are common to many high-performance concretes. The fine aggregates were silica sand with a nominal particle size of about 300 μm, and finely ground quartz powder ranging in size from 5-100 μm. The cementing materials were portland cement and silica fume that range in size of 0.1-1 μm. Water was standard tap water; and a high-range water-reducing admixture (HRWRA), a polycarboxylate chemical additive, was also included so that a low water-to-cement ratio (w/c ~ 0.2) could be maintained. Finally, HDPE fibers with a nominal length of 13 mm and diameter of 40 μm were included.

2.2 Methods

The experimental methods included material processing and sample preparation as well as sample testing. The HSHDC material was prepared by blending the dry components for five minutes in an eleven-liter planetary food mixer, then adding the combined wet components. The mixture was mixed at low speed for approximately 15 min until a homogeneous paste-like consistency was obtained. The chopped fibers were then gradually added under low-speed mixing until completely incorporated and dispersed.

Once the fresh concrete/fiber mixture was prepared, specimens of various geometries were prepared by mechanically transferring and pressing the material into prepared metal molds. A very small degree of vibration was applied to aid in filling the molds and consolidating the material. Cubes, cylinders, and beams of standard test sizes were all prepared from the HSHDC material.

The freshly molded specimens were stored immediately in a controlled environment at 100% humidity and 23°C, de-molded after hardening (about 36 hrs), and kept in this environment until seven-days age. They were then submerged in a water bath at 90°C and held for four days. Finally, they were dried in an oven at 90°C for two days, after which time curing was considered to be complete.

Unconfined compression testing was performed on 50-mm-cube samples according to ASTM C39 [1]. Cylindrical specimens 50 mm in diameter and 100 mm long were prepared for testing by grinding the ends until they were parallel and flat, as is common practice in the art. Tensile strength was measured indirectly by the splitting tensile method, ASTM C496 [12], in which the cylinder is turned on its side and compressed along its edges, causing tensile failure along the axis of the specimen.

Hardness testing was performed on the interior surface created by slicing through a specimen. Each cut face was polished lightly and then tested using an EMCO-TEST Model N3D hardness tester, configured with a 1.6-mm-diam spherical indenter and a 60-kg preload. Hardness testing is not common for concrete because traditional concretes are highly heterogeneous at the applicable length scale. However, owing to the fine particle size, UHPC is relatively homogeneous, and Rockwell hardness B-scale was chosen to provide a relative indication of hardness. The 60-kg preload was selected because higher preloads caused lower-strength specimens to crack upon testing.

3. RESULTS

3.1 Unconfined Compressive Strength

A goal of engineering HSHDC was to obtain high strength by utilizing the design principles of VHSC. The benchmark property for concrete strength is the unconfined compressive strength. While traditional concrete is typically evaluated by testing 150- by 300-mm cylinders, VHSC and other concretes that include only fine particles can be evaluated by using smaller specimens.

The 50-mm cubes prepared from HSHDC were tested in compression, and the results are listed in Table 1 along with similarly obtained compressive strengths of VHSC samples [13].

Table 1. Unconfined compressive strength results (VHSC results obtained from Ref 13).

	Mean (MPa)	Maximum (MPa)	Minimum (MPa)	Number of measurements	Std dev (MPa)	Coefficient of variation
HSHDC	154	160	149	9	4.1	2.7 %
VHSC reinforced with steel fibers	194	221	164	12	15	7.9 %
VHSC unreinforced	180	201	163	10	11	6.1 %

An examination of the results in Table 1 indicates that the HSHDC prepared for the present study did not reach fully the compressive strength of VHSC. For comparison, data were provided for VHSC in both a steel-fiber-reinforced and an unreinforced formulation. An HSHDC material achieving equivalent strength to that of unreinforced VHSC would be considered ideal; however, the HSHDC provided about 85 % of the compressive strength of the unreinforced VHSC, which is a major success considering that the VHSC cube failed in a catastrophic, almost explosive manner, while the HSHDC cubes maintained their general structure and were still capable of supporting a residual load after the peak load was exceeded, as shown in Figure 2.

For comparative purposes, data for VHSC reinforced with steel fibers were included. The peak load-carrying capability of these cubes significantly exceeded that of the HSHDC material. However, because the steel fibers were much larger, cracking was more isolated; and the cubes failed at much lower strain conditions than the HSHDC material. Steel-reinforced VHSC was very brittle, and cracking and spalling yielded badly damaged samples beyond peak loading with severe strain softening after the peak.

Figure 2. Photographs of 50-mm-cube specimens of HSHDC that failed in unconfined compression.

3.2 Splitting Tensile Strength

Direct measurement of the tensile strength of concrete, like many brittle materials, is a very difficult challenge to which much effort has been given. The present study was limited to measuring the tensile strength of HSHDC using the indirect standardized method of the splitting tensile test, ASTM C496 [12]. In this method, cylinders of the material were placed on their side between two platens and loaded vertically in compression, creating an indirect tension field perpendicular to the loading direction, thus splitting the cylinder at failure.

Results from the indirect tension method are listed in Table 2 for HSHDC along with similar results for a steel-fiber-reinforced and an unreinforced VHSC. A known weakness with concrete, both normal and high strength, and other brittle materials is inadequate tensile strength. The data indicate that the unreinforced VHSC had much lower tensile strength than either of the fiber-containing composite materials. The HDPE-reinforced HSHDC material demonstrated virtually equivalent tensile strength to that of the steel-reinforced VHSC. Recalling that the VHSC material was stronger in compression than HSHDC, this is a remarkable result. An important goal in developing HSDHC and other high-performance concrete composites was to improve the tensile properties. The advantages provided by HSHDC in tension outpace its still impressive compression performance, lending it to many applications where concrete was limited in use.

Table 2. Splitting tensile strength results (VHSC results taken from Ref 13).

	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Mean (MPa)
HSHDC	26.7	20.3	24.8	23.9
VHSC reinforced with steel fibers	26.6	23.8	25.2	25.2
VHSC unreinforced	9.2	10.1	11.4	10.2

Figure 3 depicts photographs of HSHDC cylinders that were tested to failure in the splitting tensile mode. The photographs do not capture the distributed microcracking that occurred before ultimate failure, since the cylinders were loaded far beyond their peak capacity before being examined. However, many fibers were observed in the open crack region, and the cylinders retained some load-carrying capacity at this point. The key advantage of HSHDC over the steel-fiber-reinforced VHSC was the strain capacity: the HSHDC cylinders reached their peaks at far greater displacements than the reinforced VHSC, and damage was not as severe after failure.

Figure 3. Photographs of 50- by 100-mm cylinder specimens of HSHDC that failed in indirect tension (splitting tensile test).

3.3 Hardness

The hardness test was performed using an adapted Rockwell method not customarily used for these types of materials. The Rockwell B scale provided values that allowed a relative comparison of the surface characteristic of HSHDC with that of a very high strength concrete lacking fiber reinforcement. The results listed in Table 3 indicate that the maximum hardness value was the same for the two materials; however, much greater variability was observed in the measurements obtained on the HSHDC surface. The presence of the small HDPE fibers in HSHDC likely resulted in softer domains within the harder continuous phase. The concrete phase, in which no fibers were detected with the probe, demonstrated equivalent hardness to that of the VHSC. The fibers influenced some indentations, resulting in increased data scatter on the low end.

Table 3. Hardness test results (relative measurements only, not quantitative).

	Mean value	Maximum value	Minimum value	Number of measurements	Standard deviation	Coefficient of variation
HSHDC	89	109	70	40	12	14 %
VHSC	103	109	98	106	2.5	2.4 %

3.4 Microscopy

After completion of the unconfined compression testing, a single 50-mm cube was selected for optical microscopy to explore residual fiber bridging of the cracks formed during fracture. Figure 4 depicts images taken of the same surface at magnifications of (a) 4.7, (b) 10.6, and (c) 94.0. In Figure 4(a), distributed cracking is seen, and many of the cracks have not coalesced. Globally, the cube was able to deform prior to peak loading, and strain hardened to some extent as microscopic parallel cracks formed and were bridged and arrested by the HDPE fibers. Eventually the peak stress capacity of the cube was exceeded as cracks widened beyond the fibers’ ability to restrain them. Figure 4(b) is a closer view of one of the wider cracks where multiple fibers can be seen in a bridging function. Figure 4(c) is a much closer view of a wide crack section. The fibers, regardless of their original orientation, were functioning in a tension mode, holding the cracked surfaces in close proximity. Though not perfect, fiber distribution was generally good, a critical condition for strain hardening behavior. Also, it is clear in Figure 4(c) that some dislodged particles from the concrete matrix remained bonded to the fibers. The fiber surfaces were probably abraded by the debonding and slipping mechanisms of energy dissipation.

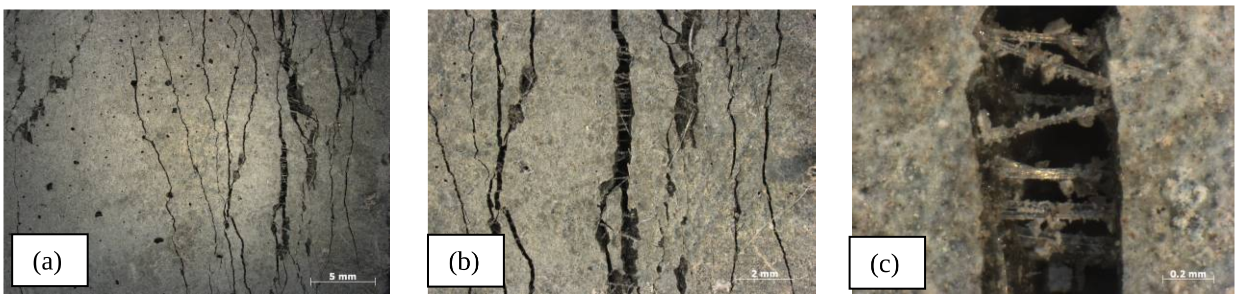

Figure 4. Optical images of the damaged surface of a 50-mm cube that failed in unconfined compression at magnifications of (a) 4.7, (b) 10.6, and (c) 94.0.

4. CONCLUSIONS

A new portland-cement-based composite material was developed that possesses a combination of high strength and high ductility that is unmatched for materials in this class. The unconfined compressive strength is about 25 % lower than strengths that are commonly obtained with other very high strength concretes, but the strength is much higher than that of other ductile concretes. The tensile strength of the new material is equivalent to that of very high strength concretes.

The unique combination of strength and ductility makes this material well suited for many structural applications where other concretes would be inadequate. Structural sections could be made smaller due to the higher strength, and the materials could be subjected to small and cyclic strains, even in tensile conditions. More research is needed to refine the processing techniques of the composite material and to scale up production so that precast or field emplacement is possible.

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