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Tensile Rate Effects in High Strength-High Ductility Concrete

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ABSTRACT

Researchers at the University of Michigan have recently developed a new class of concrete, named High Strength-High Ductility Concrete (HSHDC), which possesses exceptional combination of compressive strength (>150 MPa) and tensile ductility (>3%) under quasi-static loads. The structural applications of HSHDC for withstanding extreme events, such as hurricanes, earthquakes, impacts, and blasts, require an understanding of its dynamic behavior at high strain rates. This research experimentally investigates the effects of strain rate (from 10^{-4}/s to 10/s) on the composite tensile properties and the micro-scale fiber/matrix interaction properties of HSHDC. A micromechanics-based scale-linking model is used to analytically explain the composite-scale rate effects based on the micro-scale rate effects. Due to the unique interactions between the Polyethylene fibers and densely packed ultra-high strength matrix of HSHDC, novel rate effects are revealed, which are expected to be foundational for the future development of this class of materials for improving infrastructure resilience.

1. Introduction

A new fiber-reinforced cementitious composite (FRCC), named High Strength-High Ductility Concrete (HSHDC) [1,2], has been recently developed at the University of Michigan in collaboration with the Engineer Research and Development Center (ERDC) of the US Army Corps of Engineers. Under quasi-static loads, HSHDC exhibits a unique combination of ultra-high compressive strength (greater than 150 MPa) and ultra-high tensile ductility (greater than 3% under direct tension). Such properties point toward the potential of utilizing HSHDC in structures subjected to high-energy dynamic loadings, such as impacts, blasts, hurricanes, and earthquakes; however, the behavior of HSHDC at high strain rates is so far unknown, which is the motivation behind this study.

The effects of load/strain rate on the mechanical properties, particularly strength and modulus, of normal and high-strength concretes have been widely reported in the literature [3–14]. The rate of increase in the dynamic strength of concrete with strain rate under tension is almost 2–3 times that of under compression. These observed rate effects are typically formulated as bilinear functions similar to that given in the CEB-FIP code [15]. Although a similar bilinear trend of increase in the dynamic strength with the logarithm of strain rate is observed for high strength concretes, the rates of increase are smaller in high strength concretes than that of normal concrete [16,17].

Significant research exists on investigating the plausible causes of the rate effects in concrete at various length scales. The macroscopic explanation of the rate sensitivity of concrete properties is based on comparing the crack propagation velocity with the Rayleigh wave velocity, and its implications on the apparent fracture toughness [18–20]. The meso-scale (size of aggregate) explanation is based on the observations of cracks cutting through the aggregates, instead of meandering around them along the weak aggregate-hardened cement paste interface [21–23], at high strain rates. This occurs due to both high stresses in the material at high strain rates and the inertia of the material elements besides the surface of the rapidly growing crack [21]. Greater toughness of the aggregates than the interface leads to higher material toughness and, therefore, larger dynamic strength. At nano-/micro-scales, the crack growth is considered as breakage of bonds between two particles governed by thermodynamics. At high strain rates, the material shows higher resistance to crack propagation as it fails to respond thermodynamically as fast as the strain change (thermal inertia) [24]. Each of the above theories explaining the rate sensitivity of concrete's properties is applicable over a limited range of strain rates, and it is plausibly the combined effect of some or all of these theories that leads to the observed change in the mechanical properties, particularly strength and modulus, of concrete with the strain rate.

The presence of fibers in FRCCs adds more degrees of complexity to the material behavior at high strain rates, particularly under tension [25,26]. The hydrophilic polymer fibers in FRCCs form both chemical and frictional bonds with the cementitious matrix. The chemical bond between the fibers and the cementitious matrix is highly rate-sensitive and significantly increases at high strain-rates, which influences the tensile ductility and other composite mechanical properties [27–29]. Compared to the chemical bond, the frictional

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bond between the fibers and the cementitious matrix is less sensitive to strain rate [30–32]. Steel fibers and hydrophobic polymer fibers only form a frictional bond with the FRCC's cementitious matrix and, therefore, the rate effects on the fiber-bridging are less severe in such composites. However, the increase in fiber/matrix frictional bond can be significant for very high volume fraction of fibers (>10%) [33]. In addition to the interfacial bond, the rate effects on the fiber properties also influence the rate effects on the composite properties. For instance, while the polymer fibers are highly rate-sensitive due to their viscoelastic behavior, steel fibers are largely insensitive to strain rate [34,35]. Thus, the composite-scale rate effects on the tensile properties of FRCCs are greatly influenced by the micro-scale rate effects on the fiber/matrix bond and fiber properties, in addition to the rate effects on the matrix fracture toughness [27].

HSHDC, investigated in this study, is a strain-hardening FRCC containing an ultra-high strength cementitious matrix and hydrophobic ultra-high molecular weight polyethylene (UHMWPE) fibers; henceforth, referred as PE fibers. The objectives of the research presented in this paper are: (1) to investigate the influence of strain rates (from 10^{-4}/s to 10/s) on the composite-scale direct tension behavior of HSHDC. (The influence of strain rate on the compressive behavior of HSHDC is beyond the scope of this paper, and it will be investigated in a future study.), (2) to determine the influence of strain rate on the micro-scale fiber/matrix interaction properties and matrix fracture toughness of HSHDC, and (3) to investigate whether the micro-scale rate effects explain the composite-scale rate effects through analytical investigation of the fiber-bridging behavior.

In the following sections, first, the details of the experimental investigations, for determining the rate effects on the composite and micro-scale properties of HSHDC, are presented. While the direct tension tests on dogbone-shaped specimens are used to determine the composite tensile behavior of HSHDC at various strain rates, single fiber pullout tests, in combination with the micromechanics-based analytical models, are used to determine the micro-scale fiber/matrix interaction properties and fiber properties at the corresponding displacement rates. Statistical scale-linking model, taking into account the randomness in fiber distribution and fiber embedment lengths, are then used to predict the composite-scale rate effects based on the observed micro-scale rate effects. The predicted rate effects are finally compared with the experimentally observed rate effects at the composite scale, thus providing crucial insights into the material behavior at both these length-scales under dynamic loads.

2. Research significance

Besides adding significantly to the limited knowledge of the tensile rate effects in strain-hardening FRCCs, this research specifically provides insights into the influence of strain rate on the bond between polyethylene fibers and a cementitious matrix. Although other polymer fibers and steel fibers have been investigated in a limited number of studies, the rate effects on a PE fiber-reinforced FRCC, particularly with such ultra-high strength matrix, have never been examined before this study. The micro-scale rate effects on the bond between the PE fiber and the cementitious matrix, along with the rate effects on the fiber and matrix properties, uniquely influence the composite tensile properties of HSHDC at high strain rates, and this scale linkage is clearly illuminated in this study through analytical modeling. While the experimental data on the composite behavior of HSHDC at high strain rates generated in this study is useful for exploring its structural applications, the micro-scale properties of HSHDC at high rates provide crucial guidance for continued micromechanics-based tailoring of this material for achieving the desired structural performance.

3. Experimental investigation

3.1. Materials and specimens

Similar to other high performance concretes, HSHDC consists of cementitious materials (cement and silica fume), fine aggregates, water, and a High-Range Water-Reducing Admixture (HRWRA), along with the PE fibers. The mix proportions along with the particle size and weights of constituents per unit volume of the composite are given in Table 1. Further details about the constituent materials are given by Ranade et al. [1].

Three types of specimens were cast in this study: (1) planar dogbone specimens made of HSHDC composite, (2) single fiber pullout specimens with PE fibers embedded in HSHDC matrix, and (3) beam specimens (notched after curing) of HSHDC matrix (without fibers) for fracture toughness measurement. The geometry and preparation of the dogbone specimens of HSHDC are described by Ranade et al. [1], and that of the single fiber pullout specimens and the beam specimens for matrix fracture toughness measurements are described by Ranade et al. [2]. In this study, six dogbone specimens, twenty-five single fiber pullout specimens, and four notched beams were tested for each strain rate to reliably determine the average properties and their variations at composite- and micro-scales. All specimens were cured following the *HSHDC curing procedure* described by Ranade et al. [1].

Out of the twenty-five single fiber pullout specimens cast in this study for each strain rate, ten specimens were cast with fibers aligned with the loading direction to measure the interfacial bond properties, whereas five specimens were cast with fibers inclined at 27° [$\tan^{-1}(1/2)$] and another five with fibers inclined at 45° ($\tan^{-1}1$) to quantify the effects of snubbing and inclination hardening on the inclined fibers. The remaining five specimens were cast with embedment lengths exceeding 15 mm to determine the PE fiber's in-situ strength and modulus. Further details regarding the choice of angles and number of specimens are given by Ranade et al. [2].

3.2. Experimental procedures

The direct tension tests on the dogbone specimens were performed at six different tensile strain rates: 10^{-4} s^{-1}, 10^{-3} s^{-1}, 10^{-2} s^{-1}, 10^{-1} s^{-1}, 1 s^{-1}, and 10 s^{-1} by applying controlled tensile displacement rates (gauge length of 90 mm) of 9 μm/s, 90 μm/s, 0.9 mm/s, 9 mm/s, 90 mm/s, and 0.9 m/s, respectively. These tests were performed on an electro-mechanical tensile test system with the maximum load capacity of 10 kN. The test setup for the direct tension tests is shown in Fig. 1a. A lost motion grip assembly was used for all the tests conducted at displacement rates greater than 1 mm/s. The 'gap' shown in this assembly (Fig. 1b) is set such that the actuator of the tensile test system achieves the desired displacement rate before engaging the specimen. While the built-in dynamic load cell (with range of 25 kN) of the test system was used to determine the tensile stress from the measured tensile force, the corresponding tensile strain in a dogbone specimen was determined from the average of the displacements measured by the two LVDTs mounted on either side of the specimen. The data (both tensile force

Table 1
Mix proportions of HSHDC.

Constituent	Particle size (μm)	Weight relative to cement	Weight per unit volume, kg/m^3
Class H cement	30–80	1	907
Silica fume	0.1–1	0.389	353
Silica flour	5–100	0.277	251
Silica sand	100–600	0.700	635
Tap water	–	0.208 w/cm = 0.15	189
HRWRA	–	0.018	16
PE fiber	–	0.0214	19