Cement & Concrete Composites 45 (2014) 186–200

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

High strain rate effects on direct tensile behavior of high performance fiber reinforced cementitious composites

Tuan Kiet Tran, Dong Joo Kim *

Sejong University, Department of Civil and Environmental Engineering, 143-747 Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 24 January 2013
Received in revised form 2 August 2013
Accepted 4 October 2013
Available online 12 October 2013

Keywords:
Strain energy impact test system
High strain rates
High performance fiber reinforced cementitious composites
Dynamic increase factor
Strain rate effect

ABSTRACT

Direct tensile behavior of high performance fiber reinforced cementitious composites (HPFRCCs) at high strain rates between 10 s^{-1} and 30 s^{-1} was investigated using strain energy frame impact machine (SEFIM) built by authors. Six series of HPFRCC combining three variables including two types of fiber, hooked (H) and twisted (T) steel fiber, two fiber volume contents, 1% and 1.5%, and two matrix strengths, 56 MPa and 81 MPa, were investigated. The influence of these three variables on the high strain rate effects on the direct tensile behavior of HPFRCCs was analyzed based on the test results. All series of HPFRCCs showed strongly sensitive tensile behavior at high strain rates, i.e., much higher post cracking strength, strain capacity, and energy absorption capacity at high strain rates than at static rate. However, the enhancement was different according to the types of fiber, fiber volume content and matrix strength: HPFRCCs with T-fibers produced higher impact resistance than those with H-fibers; and matrix strength was more influential, than fiber contents, for the high strain rate sensitivity. In addition, an attempt to predict the dynamic increase factor (DIF) of post cracking strength for HPFRCCs considering the influences of fiber type and matrix strength was made.

1. Introduction

High performance fiber reinforced cement composites (HPFRCCs) are characterized with high tensile resistance and energy absorption capacity due to their unique strain hardening behavior [1]. Based on the high tensile resistance and energy absorption capacity of HPFRCCs, in comparison with concrete or normal fiber reinforced concrete (FRC), the resistance of civil infrastructure under high rate loads is expected to be enhanced by applying HPFRCCs. However, the mechanical response of these structures using HPFRCCs under high rate loads such as impact or blast is not predictable using the mechanical properties tested at static strain rate [2]. Thus, the mechanical response of HPFRCCs in wide range of strain rates should be clearly understood to enhance the resistance of civil infrastructure at high rate loads.

The impact and blast resistance of civil infrastructure is important when considering the possibility of extreme events, including those due to terrorism. Understanding the behavior of HPFRCCs at the high strain rates and dynamic loading will be helpful in the enhancement of the resistance of civil infrastructure under extreme loadings, including projectile impact and blast, for HPFRCCs to be applied in potentially vulnerable structures, such as skyscrapers, nuclear reactor containment vessels, and offshore platforms.

Although much research has been performed on the direct tensile behavior for cement-based material, the investigated strain rates were mostly lower than seismic strain rates [3–7]. Fig. 1 presents a schematic diagram of the range of strain rates including the meaning of seismic strain rates that are typically of interest to material scientists [8]. There are very few studies concerning with the direct tensile behavior at high strain rates, especially for HPFRCCs using high strength deformed steel fibers. Recently, Cadoni et al. [9] studied tensile behavior of FRC reinforced with two different types of fiber, PVA and steel, at high strain rates from 50 s^{-1} to 200 s^{-1} using a modified Hopkinson bar (MHB). They reported that the tensile strength of FRC with steel fibers was significantly enhanced with increasing strain rate while that of FRC with PVA fibers showed less rate sensitivity. Caverzan et al. [10] also used the MHB to investigate the tensile behavior FRC with high carbon straight steel fiber at high strain rates up to 300 s^{-1}.

Mechtcherine et al. [11] investigated, by using high rate MTS hydraulic testing machine, the tensile behavior of strain-hardening cement-based composites (SHCC) reinforced by PVA fibers at rates ranging up to 50 s^{-1}. SHCC with PVA fibers showed a considerable increase in both tensile strength and strain capacity at high strain rates. Zhu et al. [12], also using the hydraulic testing machine, investigated the Young's modulus, tensile strength, maximum strain, and toughness of the AR-glass fabric–cement composite at wide strain rate between 2.2×10^{-5} and 24 s^{-1}.

* Corresponding author. Tel.: +82 2 3408 3820.
E-mail address: djkim75@sejong.ac.kr (D.J. Kim).

0958-9465/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cemconcomp.2013.10.005

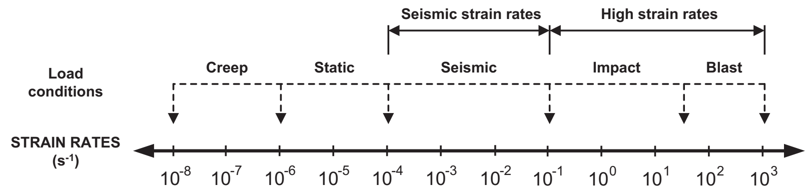

Fig. 1. Strain rate regimes.

The main reason for the lack of studies on the direct tensile behavior of material at high rate loading is the complete absence of a standardized tensile test set-up at high strain rates [2]. In addition, the relatively large size specimen for HPFRCCs can be the other reason because HPFRCCs require large size specimens enough to represent reasonably the behavior of composite materials containing fibers. However, the large-size specimen produces a considerable inertia effect due to gravity, if the test set-up was vertically installed, on the estimation of pure material response. Even though both MHB and high rate hydraulic machine may resolve the problem, they still require very high cost and large space to be installed.

To resolve the limitations of current impact test systems above mentioned, including restriction of inertia effect and reduction of cost, a new impact test set-up named strain energy frame impact machine (SEFIM), which has ability of testing large size specimens with a relatively small device, was built by authors [13], as shown in Fig. 2. Unlike current impact test techniques, SEFIM utilizes a strain energy storage frame to generate high rate impact pulse. The use of energy frame instead of bar not only reduces the size of system leading to the reduction of cost and installation space, but also delivers a higher rate tensile stress wave. Moreover, the machine was designed in horizontal direction, thereby can remove the gravity effect due to the large-size specimen as mentioned above. In particular, since the transmitter bar is connected directly to specimen, the stress wave from specimen will propagate directly to transmitter bar without any distortion. Thus, the signal that obtaining from the strain gauges attached on transmitter bar, in this case, reflects pure material resistance. Finally, this machine can test the specimen with the size and boundary condition as same as static test.

By using this machine, Tran and Kim [14] recently reported how to obtain the direct tensile stress versus strain response of HPFRCCs at high strain rates between 10 s^{-1} and 40 s^{-1}. They also discussed that the interfacial bond strength between fiber and matrix was a key factor for the rate sensitive behavior of HPFRCCs.

However, the previous research performed by authors did not focus on the influencing parameters for rate sensitive tensile behavior of HPFRCCs. The role of fiber type, fiber volume content and matrix strength on the rate sensitive behavior of HPFRCCs is not clearly understood yet. This research is initiated toward a deeper understanding of the strain rate effects on direct tensile behavior of HPFRCCs using high strength deformed steel fibers, with a focus on the effect of matrix, fiber type and volume content. Specific objectives are to (1) investigate the high strain rate effects on tensile behavior of HPFRCCs using SEFIM, (2) evaluate the effect of fiber type, fiber volume content and matrix strength on the rate sensitivity of HPFRCCs, and (3) propose an equation to predict the DIF of post cracking strength of HPFRCCs.

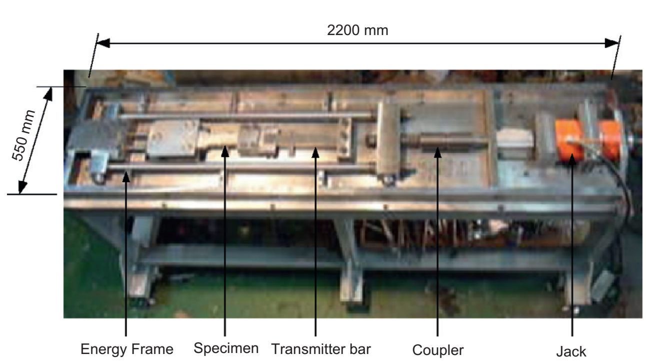

Fig. 2. Strain Energy Frame Impact Machine (SEFIM).

2. Experimental program

An experimental program including six series of tensile specimen was designed to investigate the role of matrix, fiber type and fiber volume content in the rate sensitive behavior of HPFRCCs using deformed steel fibers as shown in Table 3. A flowchart summarizing this experimental program and test series is described in Fig. 3. A universal test machine was applied for the static test at the strain rate of $\dot{\varepsilon} = 0.000167\ s^{-1}$ for tensile specimens with 100 mm gauge length while SEFIM was used for the impact tests at higher strain rates between 10 s^{-1} and 30 s^{-1}. The detail procedure for obtaining tensile stress versus strain response at the higher strain rates was recently reported by authors [12,13].

2.1. Material and specimen preparation

Two deformed steel (H- and T-) fibers, two fiber volume, (1% and 1.5 %) contents and two matrixes (Ma and Mb for 56 and 81 MPa compressive strength) were investigated. The matrix compositions are provided in Table 1 while the properties of fibers are given in Table 2.

Sand, cement, fly ash and silica fume (for Mb only) were first mixed in dry condition for 3 min. And, water was added to the dry mixture slowly three times with 2 min intervals. Then, super-plasticizer was gradually added until the mortar mixture showed adequate workability and viscosity for uniform fiber distribution. Fibers were distributed by hand during the mixing. A visual attention of the mortar mixture during adding fiber should be paid to ensure the uniform distribution of fibers in the mixture. It should be noticed that excessive water or super-plasticizer would lead to the segregation of fibers, and, as a result, the mechanical resistance of HPFRCCs would decrease. Thus, the workability and viscosity of mortar mixture was strictly controlled by investigating the slump flow test to avoid fibers' gravitation or segregation. The slump flow of HPFRCCs with steel fibers was kept as about 600 mm; and there was no visible segregation of fibers. The mortar mixture with fibers was then poured into molds. The specimens after casting were covered by plastic sheet and stored in a laboratory at room temperature. After 24 h, all specimens were demolded and placed in a water tank with temperature of 23 ± 2°C for curing in additional 14 days. Finally, the specimens were removed and dried in the laboratory for 3 days before spraying three layers of thin polyurethane for cracks detection. All specimens stored in laboratory at room temperature about 3 months until testing.