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Effect of high strain rate on compressive behavior of strain-hardening cement composite in comparison to that of ordinary fiber-reinforced concrete

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HIGHLIGHTS

- Compressive strength of SHCC and FRHSC increases with strain rate.
- SHCC is less sensitive to high strain rate than FRHSC of similar compressive strength.
- Damage of SHCC is less severe than FRHSC at a given high strain rate.
- *DIF* is lower for SHCC and FRHSC of higher compressive strength.
- Code equations overestimate *DIF* of SHCC and FRHSC beyond transition strain rate.

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ABSTRACT

This paper presents an experimental study on the effect of high strain rate on the compressive behavior of two strain-hardening cement-based composites (SHCCs), compared to that of fiber-reinforced high-strength concretes (FRHSCs) with similar compressive strengths. One of the SHCCs was reinforced with 2% of polyvinyl alcohol (PVA) fibers by volume (SHCC-PVA) and had a compressive strength of 64 MPa. The other was reinforced with 0.5% of steel plus 1.5% of polyethylene (PE) fibers by volume (SHCC-ST+PE) and had a compressive strength of 83 MPa.

Split Hopkinson pressure bar and hydraulic machine experiments were conducted to determine the behavior of the SHCC and FRHSC at strain rates from 30 to 300 and 10^{-4} to 10^{-1} s^{-1}, respectively. The Dynamic Increase Factor (DIF_{fc}), the ratio of the material strength under dynamic loading to that under static loading, was determined for the materials considered. The fracture patterns of the specimens, matrix, and fibers were carefully examined. The results indicate that the fiber content has a significant effect on the DIF_{fc} values. In addition, it is shown that the equations in CEB-FIP 1990 and *fib* 2010 codes are not applicable for SHCC and FRHSC beyond a transition strain rate of 30 s^{-1}.

1. Introduction

There is an increasing interest in properties of construction materials and structures under severe loading conditions such as impact and blast. Effects of high strain rate on the compressive properties of ordinary concrete [1], fiber-reinforced concrete [2,3], and ultra-high performance cementitious composites [4], have been studied and reported in the literature. The compressive strengths of these materials generally increase with the strain rate.

During the last few decades, a type of material commonly known as strain-hardening cement-based composite (SHCC) or Engineered Cementitious Composite (ECC) was developed [5] and investigated [6–12]. The SHCC consists of specially designed cement paste or mortar matrices and one or two types of fibers. When subjected to tensile loading, it shows a pronounced strain-hardening behavior and fails with multiple cracks. Compared to ordinary fiber-reinforced concrete, this enhanced behavior of SHCC indicates a superior energy absorption capacity, and thus has potential applications in protective structures [13].

However, most studies on SHCC focus on its tensile properties under quasi-static condition [5,14]. Some studies investigated the tensile properties at intermediate strain rates up to about 10^{-1} s^{-1} using hydraulic machine tests [6–8,10]. The results indicate that the tensile strengths of SHCCs increase with strain rate. However, there is no consensus with regards to the strain rate effect on

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the strain capacity and strain-hardening behavior of different SHCCs, which can be attributed to different mix proportions, fiber types, experimental set-ups and specimen geometrical details. Reports on the quasi-static compressive behavior of SHCC are limited, and the available data [7,12] do not show a significant difference between SHCC and ordinary concrete with regards to their compressive strengths and shapes of stress-strain curve. However, SHCC generally has a lower Young's modulus because of the absence of coarse aggregate.

Only limited information on the properties of SHCC at high strain rates beyond 10 s^{-1} is available. For example, Mechtcherine et al. [9] investigated the tensile properties of a SHCC reinforced with polyvinyl alcohol (PVA) fibers at strain rates from 140 to 180 s^{-1} using a split Hopkinson pressure bar (SHPB) in a spallation configuration. They found significant strain rate effect on the tensile strength of the SHCC and reported a Dynamic Increase Factor (DIF, defined as the ratio of a dynamic property to the corresponding static property) of 6.7, which was higher than those of ordinary concrete, high performance concrete, and ultra-high performance concrete (UHPC). The strain rate sensitivity of the SHCC was attributed to the development of a greater number of micro-cracks parallel and orthogonal to the loading direction, as well as to extensive plastic deformations of the PVA fibers prior to and during fiber pullout. The parallel cracking along the loading direction, which consumes a large quantity of energy, was not observed for the UHPC. Using the SHPB tests, Chen et al. [12] studied the dynamic compressive properties of SHCC reinforced with PVA fibers and containing various amounts of Ground Granulated Blast-Furnace Slag (GGBFS) at strain rates from 85 to 185 s^{-1}. Their results show a significant increase in the compressive strength and a slight decrease in the critical strain (strain corresponding to peak stress) as strain rate increases. In addition, a higher GGBFS content leads to a smaller increase in the dynamic strength.

Relevant literature review indicates that the properties of SHCC, which is a promising construction material for protective structures, are still largely unknown at higher strain rates in compression, beyond the quasi-static condition. None of the studies in published literature has reported on the strain rate sensitivity of SHCCs ranging from quasi static to a few hundreds per second. There is also concern as to whether the most comprehensive and widely accepted models for the strain rate effect on the compressive strength of concrete given in CEB-FIP Model Code 1990 [15] and *fib* model code 2010 [16] are applicable to SHCC. CEB-FIP 1990 defines the Dynamic Increase Factor (DIF_{fc}), which is the ratio of the impact strength to the static strength, as a function of the strain rate and the static compressive strength of concrete, given by

$$DIF_{fc} = \frac{f_{c,imp}}{f_{cm}} = \begin{cases} (\dot{\varepsilon}_c/\dot{\varepsilon}_{co})^{1.026\alpha_s} & \text{For } \dot{\varepsilon}_c \le 30\,s^{-1} \\ \gamma_s(\dot{\varepsilon}_c/\dot{\varepsilon}_{co})^{1/3} & \text{For } \dot{\varepsilon}_c > 30\,s^{-1} \end{cases} \quad (1)$$

where $f_{c,imp}$ and f_{cm} are the impact and static compressive strengths, respectively; $\dot{\varepsilon}_c$ is the strain rate (s^{-1}) ranging from 3×10^{-6} to 300 s^{-1}; $\dot{\varepsilon}_{co}$ is the quasi-static strain rate taken as -30×10^{-6} s^{-1}; and $\log \gamma_s = 6.156\alpha_s - 2$, in which $\alpha_s = 1/(5 + 9f_{cm}/f_{cmo})$ with f_{cmo} as a reference strength of 10 MPa. On the other hand, *fib* 2010 neglects the effect of the concrete strength as can be seen from the equation

$$DIF_{fc} = \frac{f_{c,imp}}{f_{cm}} = \begin{cases} (\dot{\varepsilon}_c/\dot{\varepsilon}_{co})^{0.014} & \text{For } \dot{\varepsilon}_c \le 30\,s^{-1} \\ 0.012(\dot{\varepsilon}_c/\dot{\varepsilon}_{co})^{1/3} & \text{For } \dot{\varepsilon}_c > 30\,s^{-1} \end{cases} \quad (2)$$

This paper presents the findings of an experimental study with regards to the effect of strain rate on the compressive behavior of two types of SHCCs, compared to that of fiber-reinforced high-strength concretes (FRHSC) with similar compressive strengths. One of the SHCCs is a revised mix based on a study by Wang and Li [14], with 2% of PVA fibers by volume (SHCC-PVA) and achieves a 28-day compressive strength of about 60 MPa. The other mix, developed by Maalej et al. [7], is reinforced with 0.5% of steel fibers plus 1.5% of polyethylene (PE) fibers by volume (SHCC-ST+PE) and has a 28-day compressive strength of about 80 MPa. An SHPB equipment was used to determine their behavior at high strain rates from about 30 to 300 s^{-1}, and a hydraulic material testing system (MTS) was used to determine their properties at intermediate strain rates from 10^{-4} to 10^{-1} s^{-1}. This study contributes to the understanding, and also expands the available database, on the dynamic properties of SHCCs at high strain rates compared to those of ordinary fiber-reinforced concretes. The results provide useful information for the design of structures with such materials against impact and blast loadings, as well as for material modelling in numerical simulations.

2. Experimental details

2.1. Materials

ASTM Type I normal Portland cement was used for all the mixtures. Sieved sand with a maximum size of 0.25 mm was used in SHCC-PVA, in contrast to SHCC-ST+PE, which does not require any sand. No coarse aggregate was used in both SHCCs. For the FRHSC mixtures, crushed granite coarse aggregate with a nominal maximum size of 10 mm and natural sand were used. The grading of the coarse and fine aggregates used in the two FRHSCs satisfies the ASTM C 136 requirements, with specific gravities of 2.65 and 2.63 respectively.

A naphthalene-based superplasticizer[1] with a specific gravity of 1.2 was used in all mixes to increase the workability. Mineral admixtures were used in some of the mixtures. Silica fume was used in the SHCC-ST+PE, whereas fly ash was used in the SHCC-PVA. Viscosity modifying admixture[2] was used in the SHCC-PVA fresh mix in order to disperse the fibers properly [17] and to prevent bleeding of the fresh matrix, according to Mindess et al. [18].

Straight steel fibers,[3] PE fibers,[4] and PVA[5] fibers were used, and their properties are summarized in Table 1. The elongation of PE fibers is 3.6–3.9%. The steel fibers have a higher elastic modulus but of similar tensile strength compared to PE fibers. Both the tensile strength and elastic modulus of PVA fibers are lower than those of PE fibers. The PE fibers and the PVA fibers are of similar sizes, with a much higher aspect ratio than steel fibers (similar length but with smaller diameters). To reduce the interfacial bond with cement paste matrix, the manufacturer treated the surfaces of the PVA fibers with 1.2% oil coating.

2.2. Mix proportions

The mix proportions of the SHCCs and FRHSCs are given in Table 2.

The two SHCCs have the same water/cementitious material ratio (w/cm) and total volume of fibers. The SHCC-ST+PE contains 0.5% steel fibers and 1.5% PE fibers, whereas the SHCC-PVA is solely reinforced with 2% PVA fibers. Silica fume was used in the SHCC-ST +PE to replace 10% of cement. In order to achieve the strain-hardening behavior, high content of fly ash was introduced in the SHCC-PVA mix to reduce the interface bond and to modify the matrix properties to control the crack width.

[1] Daracem 100, W. R. Grace Singapore Pet, Ltd.
[2] Methocel™ Cellulose Ethers, The Dow Chemical Company.
[3] Dramix@, Bekaert, Belgium Pte, Ltd.
[4] SPECTRA fiber 900, Honeywell.
[5] Kuraray Co., Ltd.