Influence of Fiber Type on the Tensile Behavior of Strain-Hardening Cement-Based Composites (SHCC) Under Impact Loading

Iurie Curosu[1(✉)], Viktor Mechtcherine[1], Daniele Forni[2], and Ezio Cadoni[2]

[1] Institute of Construction Materials, Technische Universität Dresden, Dresden, Germany
iurie.curosu@tu-dresden.de
[2] DynaMat Laboratory, University of Applied Sciences of Southern Switzerland, Canobbio, Switzerland

Abstract. Two different types of strain-hardening cement-based composites (SHCC) were investigated under uniaxial quasi-static and impact tensile loading. The normal-strength matrix was combined with polyvinyl-alcohol (PVA) fiber in one composite and with high-density polyethylene (HDPE) fiber in another. A modified Hopkinson bar was used to assess the impact resistance of SHCC in terms of stress–strain relationships at strain rates of up to 120 s^{-1}.

SHCC reinforced with PVA fiber, the composite with considerable ductility under quasi-static loading, performed much worse under impact loading than SHCC made with HDPE fiber. This could be traced back to the peculiar alteration of the fiber-matrix interaction depending on the type of fiber and corresponding bond properties, i.e. chemical bond in case of PVA fiber versus frictional bond in case of HDPE fiber.

Keywords: Cementitious composites · Multiple cracking · Impact · Tensile loading · Polymer fiber

1 Introduction

Strain-hardening cement-based composites (SHCC) (also ECC, Engineered Cementitious Composites) consist of finely grained cementitious matrices and short, high-performance polymer micro-fibers. The post-elastic tensile behavior of SHCC is characterized by the formation of multiple, fine cracks under increasing loading up to failure localization, after which softening occurs (Li 2003). Such behavior implies several very positive mechanical features; the most distinguished being the very high strain capacity in combination with the limited crack width.

SHCCs' ability to undergo extensive inelastic deformations without losing load-bearing capacity makes them suitable both as main material and as reinforcing layers in structural members that might be subject to sudden mechanical loading, such as impact. However, due to the possible negative effects of increasing strain rates on the quasi-ductility of SHCC, a high energy dissipation capacity under impact loading can

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be ensured only by targeted material design. The current knowledge regarding the effect of increasing strain rates on the tensile behavior of SHCC is mainly limited to lower strain rates, being very scarce in the case of impact loading. Thus, there is need for a reliable quantitative basis that could enable the formulation of material design recommendations with respect to high loading rates.

The previous investigations by the authors in spall experiments provided valuable insight into the effects of high strain rates on the tensile behavior of SHCC (Curosu et al. 2016, Mechtcherine et al. 2011a). The energy dissipation capacity of SHCC was found to be several times higher than that of ultra-high performance concrete (UHPC) reinforced with steel fibers. However, two important limitations were encountered in these investigations. The first one was that the testing configuration applied did not enable measurement of the stress, strain, and crack-opening time histories. The second limitation was that the physical limits of the Hopkinson bar used in the spall configuration were reached when testing highly ductile SHCC. Despite the extremely high energy input, complete fracture was only achieved in the tests on notched specimens.

In this work the normal strength SHCC reinforced with PVA and HDPE fibers as presented in (Curosu et al. 2016; Mechtcherine et al. 2011a) were investigated with a modified Hopkinson tension bar at strain rates of up to 120 s^{-1}. The actual dynamic testing setup enabled an accurate recording of the stress–strain relationships and in turn a detailed quantitative assessment of the strain rate sensitivity of SHCC depending on fiber type and matrix composition.

2 Materials and Testing Methods

2.1 SHCC Compositions and Specimens Preparation

The PVA fibers investigated are Kuralon REC-15 fibers produced by Kuraray, Japan, with a diameter of 40 μm and a cut length of 12 mm. According to Kuraray, they have a tensile Young's modulus of 40 GPa and a tensile strength of 1600 MPa. The HDPE fibers are produced by DSM, the Netherlands, under the product name Dyneema SK62. They have a tensile strength of 2500 MPa and a Young's modulus of 80 GPa according to the manufacturer. Their cut-length is also 12 mm but the diameter is just 20 μm, half the diameter of the PVA fiber.

The PVA fibers are strongly hydrophilic, which results in a pronounced chemical bond with the cementitious matrices. An excessively strong interfacial bond may lead to premature fiber rupture if no interfacial delamination occurs during crack opening. Such a scenario leads to the brittle fracture of the composite. The cementitious matrix was specifically designed with respect to the PVA fibers used. To ensure optimal bond strength, the strength and density of the cementitious matrix were limited by a high content of fly ash and a relatively high water-to-binder ratio; see Table 1.

As opposed to PVA, the HDPE fibers are hydrophobic. This results in a much weaker frictional bond with the cementitious matrix. The combination of this cementitious matrix with HDPE fibers (SHCC-PE) was described in (Curosu et al. 2016) where it was investigated to highlight the influence of matrix composition and fiber type on the tensile behavior of SHCC under impact loading. The matrix was not

Table 1. Mixture compositions of the SHCC under investigation.

	SHCC-PVA	SHCC-PE
CEM I 42.5R-HS	505	
fly ash	621	
quartz sand 0.06 - 0.2 mm	536	
viscosity modifying agent	4.8	
Water	338	
high-range water reducing agent	10	
PVA fibers (2.00% by volume)	26	-
HDPE fibers (2.06% by volume)	-	20

adapted to the thinner and hydrophobic HDPE fibers, which had a negative effect both on its fresh state properties and on the tensile behavior under quasi-static loading. However, the performance of SHCC-PE under dynamic loading was superior to that observed for SHCC-PVA.

The dynamic testing setup imposed a cylindrical specimen geometry with a diameter of 20 mm. The specimens were core-drilled out of prismatic beams with a length of 280 mm and side dimensions of 75 mm. The testing age of 14 days was chosen to enable an easier comparison with the results obtained in the previous study (Curosu et al. 2016). The gauge lengths of the specimens in both the quasi-static and dynamic testing setups were 50 mm.

2.2 Quasi-Static Experimental Setup

In order to conduct a consistent experimental series with comparable results in both loading regimes, an adjustable fixing device for cylindrical specimens was built for the quasi-static tensile experiments. The specimens were glued at both ends in 12.5 mm thick steel rings. Subsequently the rings were bolted to special steel stamps and rigidly connected to the testing machine with steel rods, ensuring non-rotatable boundary conditions. A circular frame with an adjustable height was fixed around the embedment rings, on which two Linear Variable Differential Transformers (LVDT) were installed to measure axial deformations.

2.3 Modified Hopkinson Bar

The high-speed experiments were performed in collaboration with the DynaMat laboratory at SUPSI, Switzerland, where the Modified Hopkinson Bar (MHB) is installed. The setup consists of an input bar of length 9 m and of an output bar 6 m long, both bars being made of aluminum and having a diameter of 20 mm (Cadoni 2010). The first 6 meters of the input bar are used as a pre-tensioned bar for generating the tensile loading pulse; see Fig. 1.

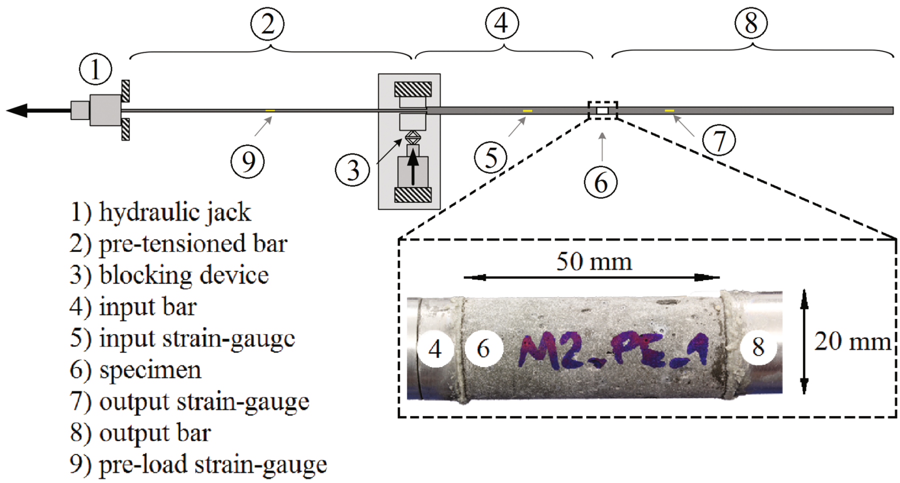

Fig. 1. Modified Hopkinson bar setup with an SHCC specimen.

The specimens were loaded by a tensile wave of trapezoidal shape of 2.4 ms duration and with a rise-time of about 30 µs. In the present investigation, the target maximum displacement speed was 6 m/s. The generated pulse propagates along the input bar with the velocity C_0 of the elastic wave with its shape remaining constant. When the incident pulse ε_I reaches the specimen, part ε_R of it is reflected by the specimen due to the different impedances of the specimen material and aluminum, whereas another part, ε_T, passes through the specimen and propagates into the output bar. The relative amplitudes of the incident, reflected, and transmitted pulses depend on the mechanical properties of the specimen. Strain gauges glued to the input and output bars of the device are used to measure as a function of time the elastic deformation created on both bars by said incident, reflected, and transmitted pulses. The application of the elastic, uniaxial stress wave propagation theory to the Hopkinson bar system allows calculation of the forces F_1 and F_2 and the displacements δ_1 and δ_2 acting on the two faces of the specimen in contact with the input and output bars, respectively. The calculations are based on the recorded strains ε_I, ε_R, ε_T of the elastic input and output bars (Cadoni 2010).

3 Results and Discussion

3.1 Quasi-Static Tension Experiments

Figure 2 presents the stress-strain curves obtained from the SHCC specimens in quasi-static tension tests. The curves are quantitatively very similar to those presented by the authors in previous works on much larger cylindrical specimens 75 mm in diameter, 250 mm effective length and 70 mm gauge length (Curosu et al. 2016; Mechtcherine et al. 2011a). The first-crack stress for SHCC-PVA is higher than that of SHCC-PE. This demonstrates the effect of the strong chemical bond between the PVA

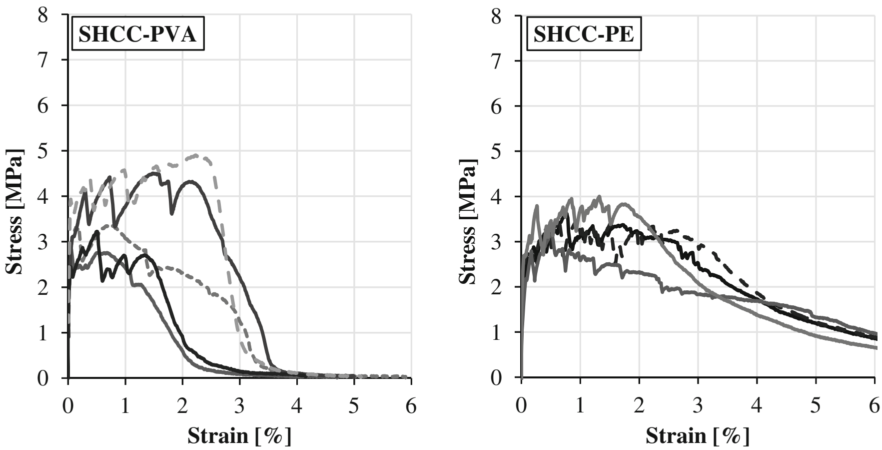

Fig. 2. Stress-strain curves of the SHCC under investigation as obtained in quasi-static tension tests.

fibers and the cementitious matrix, which involves the fibers' hindering the propagation of micro-cracks before the formation of a larger crack recognizable by the first stress drop in the stress–strain curve. The hydrophobicity of the HDPE fibers leads to a weak frictional bond with the normal-strength cementitious matrix, meaning that the fibers are activated only after crack formation. The fiber-matrix interfaces act as micro-defects in this case, reducing the first-crack stress of the composite compared to the tensile strength of the constitutive cementitious matrix. Another reason could be a worse fiber distribution in this composite, as judged by the poor fresh state properties.

The composites reached average tensile stresses of 3.8 MPa (SHCC-PVA) and 3.6 MPa (SHCC-PE); see Table 2. The fracture surfaces of SHCC-PVA exhibited a very pronounced fiber rupture, the maximum protruding length of the fibers being less than 2 mm, much less than half of fiber length. This was caused not only by the strong interfacial bond, but also by the slip-hardening pullout behavior of the PVA fibers from the cementitious matrix under low strain rates (Boshoff et al. 2009; Curosu et al. 2016). In this case the tensile strength of the composite was chiefly limited by the tensile strength of the PVA fibers. In contrast to SHCC-PVA, the fracture surfaces of SHCC-PE showed complete fiber pullout since neither a chemical bond nor a dense and uniform surrounding matrix enabled a proper fiber anchorage; this explains the lowest tensile strength.

The strain capacity of SHCC-PVA was lower compared to SHCC-PE. An important reason for such behavior was poor multiple cracking due to the excessively strong fiber-matrix interfacial bond, causing rupture of a considerable part of crack bridging fibers during crack formation already.

Table 2 presents the work-to-fracture of the SHCC investigated. Work-to-fracture was calculated as the area under the stress-strain curves up to failure localization (softening). The average valued of work-to-fracture of the investigated SHCC were very similar – 52.7 kJ/m^3 for SHCC-PVA and 53.5 kJ/m^3 for SHCC-PE.

Table 2. Average values of the mechanical properties of SHCC obtained from quasi-static tension tests, standard deviations are given in parentheses.

SHCC type and specimen geometry	SHCC-PVA	SHCC-PE
First-crack stress (MPa)	3.1 (0.5)	2.4 (0.3)
Tensile strength (MPa)	3.8 (0.9)	3.6 (0.4)
Ultimate strain (%)	1.5 (0.8)	1.7 (0.8)
Average crack spacing (mm)	15.3 (6.6)	9.3 (1.4)
Work-to-fracture (up to softening) (kJ/m^3)	52.7 (35.3)	53.5 (24.8)

3.2 Tension Experiments at High Strain Rates

The recorded responses of the specimens are presented in Fig. 3. They show an initial force peak, which is much higher than the forces associated to subsequent deformations and multiple cracking in the specimen. This stronger initial response is a result of the structural inertia caused by the increasing strain rates, i.e. high accelerations in the initial loading phase.

After the initial loading phases, the specimens were subjected to relatively constant strain rates; see Fig. 3. Under these conditions the structural inertia is negligible and the peak crack bridging stresses measured can be considered as the true, dynamic tensile strength of SHCC. The stress oscillations observed in Fig. 3 are caused by the damage induced in the deforming specimens, crack formations at the first place, but possibly also other phenomena such as fiber dislocations.

Table 3 summarizes the average values of the dynamic tensile strength of the SHCC tested, and the corresponding Dynamic Increase Facors (DIFs). SHCC-PVA yielded the lowest average tensile strength of just 6.4 MPa (DIF = 1.7). Only one SHCC-PVA specimen showed strain-hardening and multiple cracking (curve marked with an arrow); the other two specimens exhibited strain-softening. Interestingly, the

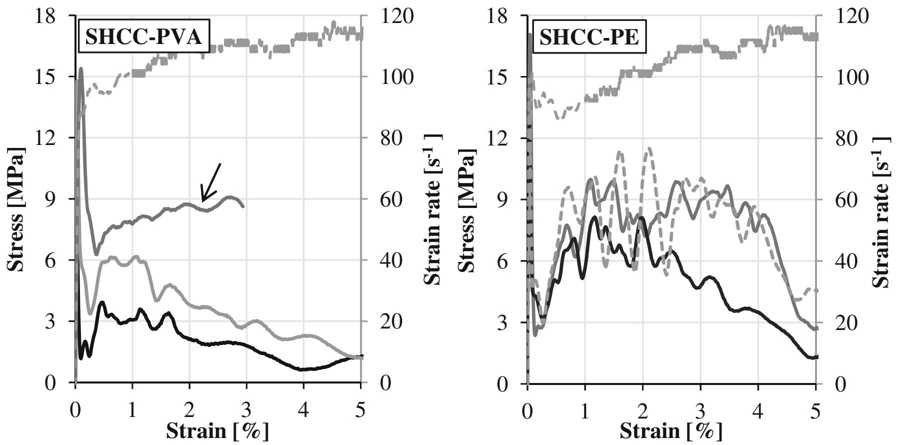

Fig. 3. Stress-strain and representative strain rate–strain curves obtained from high-speed tension tests.

Table 3. Dynamic mechanical properties of the analyzed SHCC; average values, standard deviations are given in parentheses, and the corresponding Dynamic Increase Factors (DIFs).

SHCC type and specimen geometry	SHCC-PVA	SHCC-PE
Peak crack bridging stress (MPa)	6.4 (2.6)	9.9 (1.7)
Ultimate strain (%)	1.6 (0.9)	3.3 (1.2)
Average crack spacing (mm)	11.0 (6.5)	3.3 (0.3)
Work-to-fracture (up to localization) (kJ/m^3)	90.0 (23.8)	413.8 (114.2)
DIF of peak crack bridging stress	1.7	2.8
DIF of ultimate strain	1.1	2.9
DIF of work-to-fracture	1.7	5.3

specimen that yielded strain-hardening failed at the glue connection with the input bar without reaching failure localization. The change of the failure mode of M1-PVA when subjected to high-speed tensile loading was reported before in (Mechtcherine et al. 2011a, b). The failed specimens developed few cracks in the vicinity of the fracture zone, while the fracture surfaces showed a complete fiber pullout. Curosu et al. (2016) showed with the help of single-fiber tension tests at low displacement rates that the dynamic increase of the tensile strength of the PVA fibers is higher compared to that of HDPE. This indicates that the pronounced pullout of the PVA fibers out of the SHCC specimens loaded at high strain rates is a result of a pronounced increase in fiber tensile strength in combination with a moderate enhancement of the bond strength. The reason for such a low dynamic enhancement of the fiber-matrix bond in PVA-SHCC at high strain rates is a matter of further investigations.

The average tensile strength of SHCC-PE is 9.9 MPa, with a DIF of 2.8, yielding a much higher increase. Such an enhancement of the crack bridging capacity indicates a pronounced increase in interfacial bond strength. This is in good agreement with the single-fiber pullout investigations presented in (Curosu et al. 2016), in which the frictional interaction between the HDPE fibers and the normal-strength cementitious matrix was the most strain rate sensitive among the other fiber-matrix combinations. The pronounced enhancement of the interfacial bond strength had a beneficial influence on the dynamic strain capacity of SHCC-PE as well. Considering the very weak fiber-matrix interaction under quasi-static loading, the average ultimate strain of SHCC-PE increased from 1.7% under quasi-static loading to 3.3% under dynamic loading. The high speed video recordings and the subsequent analysis of the specimens showed a very pronounced multiple cracking.

Figure 4 presents the averaged stress–strain curves of the SHCC obtained both under a quasi-static loading regime (continuous lines) and during high-speed tensile tests (dashed lines). SHCC-PVA shows the lowest increase in tensile strength and a negative influence of high strain rate on the strain capacity when considering the strain-softening behavior of two out of three tested specimens. Nevertheless, the average work-to-fracture increased from 52.7 to 90 kJ/m^3. The enhanced tensile behaviour of SHCC-PE under dynamic loading resulted in a significant increase in the work-to-fracture from 53.5 kJ/m^3 (quasi-static) to 413.8 kJ/m^3 (dynamic).

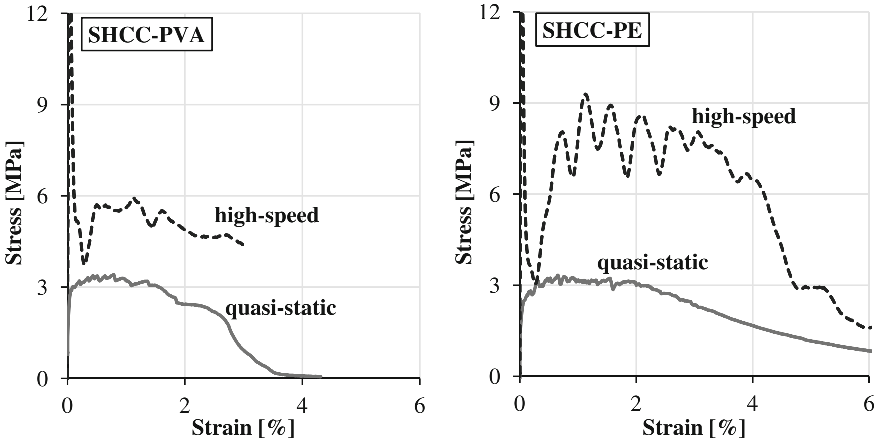

Fig. 4. Average tensile stress-strain curves of the SHCC obtained from quasi-static tests (continuous lines) and high-speed experiments (dashed lines).

4 Summary and Conclusions

Two different types of SHCC were investigated under quasi-static and impact tensile loading, consisting of identical normal-strength cementitious matrices, one being reinforced with polyvinyl-alcohol (PVA) fibers while the other with high-density polyethylene (HDPE) fibers. With the help of the modified Hopkinson bar, displacement rates of 6 m/s were achieved, corresponding to strain rates approximately 100 s^{-1}. The main findings from the presented experimental investigation can be summarized as follows:

- The strain rate sensitivity of the fiber-matrix interface depends strongly on the fiber type;
- When subject to high strain rates, the strong chemical bond between PVA fibers and the normal-strength cementitious matrix suffers a peculiar alteration, leading to a reduced dynamic composite cracking strength and to a strain-softening behavior of the composite.
- Contrarily, while the frictional bond between the HDPE fibers and the normal-strength matrix is very weak under quasi-static conditions, it yields a pronounced enhancement when subject to high strain rates. This leads to a considerable increase in composite cracking strength and to a much more pronounced multiple cracking in comparison to its behavior under quasi-static loading.

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