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Comparative experimental investigations on the compressive impact behavior of fiber-reinforced ultra high-performance concretes using split Hopkinson pressure bar

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HIGHLIGHTS

- Investigating compressive behavior of fiber reinforced UHPC (200 MPa) under high strain rates.
- Using and tailoring pulse shaping to achieve satisfying constant strain rate and stress equilibrium.
- Providing dynamic impact factor (DIF) in dependency of the fiber volume fraction.

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ABSTRACT

In this paper the compressive impact behavior of steel fiber reinforced ultra-high performance concrete (UHPC) with compressive strengths in excess of 210 MPa was investigated. Different steel fiber volume fractions were used ranging from 0% to 4%. The tested strain rate ranged from 22 to 110 s^{-1}. Based on the obtained results a general equation was developed expressing the dynamic impact factor (DIF) in dependency of the fiber volume fraction. The impact resistance of all UHPC specimens was investigated using a split Hopkinson pressure bar complemented with pulse shaping disks or a shaped striker bar. All analyzed test results were found to satisfy the requirements of dynamic testing such as stress equilibrium, constant strain rate, and reduced friction to minimize inertial effects. A complementary finite element model was developed to simulate the behavior of UHPC specimens under high strain rates. From the results of the finite element analysis it was concluded that the contribution of friction between a greased specimen and the impact bars on the DIF can be neglected. Additionally, UHPC specimens reinforced with 0.5% volume fraction of steel, basalt, or polyvinyl alcohol fibers were tested under dynamic compressive loading at a strain rate of about 40 s^{-1}. The results showed that the slope of the DIF versus strain rate increased with increasing fiber volume fraction. Moreover, UHPC with polyvinyl alcohol fibers was more strain rate sensitive than UHPC with steel and basalt fibers of the same length and volume fraction.

1. Introduction

The mechanical properties of fiber reinforced cement based materials depend on the type and volume fraction of added fibers due to their different effects on crack development and crack bridging. Since crack propagation and friction between fiber and matrix during fiber pull out are considered strain rate sensitive [1], fiber reinforced cement based composites show strain rate sensitive behavior under impact loads.

This study aims to develop an equation to quantify the effect of fiber volume fraction on the dynamic impact factor (DIF) of ultra-high performance concrete (UHPC) reinforced with steel fibers (SF) with compressive strength in excess of 210 MPa. Research emphasis was placed on obtaining test results satisfying the requirements of dynamic stress equilibrium (SE) on both faces of the specimen and constant strain rate (CSR) during effective test duration. This is challenging to achieve with brittle materials and thus reliable test data at high strain rates are scarce.

Additionally, the ultimate strength of UHPC reinforced with 0.5 vol% of SF, basalt fiber (BF), and polyvinyl alcohol (PVAF) at a high strain rate of about 40 s^{-1} is measured to investigate the effect of fiber type on the impact behavior.

In the current research the length of the fibers is set to 6 mm to accommodate the geometrical restrictions of the specimen, and

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thus, to provide reliable data for the dynamic compressive strength of UHP-FRC.

1.1. SF-UHPC dynamic testing

Extensive research has been carried out on the effect of using mono-fibers in a steel fiber reinforced ultra-high performance concrete (SF-UHPC) and steel fiber high performance concrete (SF-HPC) under different strain rates [2–13]. In [5,7] it is experimentally shown that the dynamic compressive strength of SF-HPC is lower than the quasi-static compressive strength. In [6] it is reported that SF-HPC tends to have higher impact resistance than plain concrete without adding fibers using drop projectiles on SF-HPC panels. Generally, it was widely accepted that fiber reinforced cement-based materials are less strain rate sensitive than plain cement-based materials, using the SHPB. Contrary results were obtained by [8], who tested plain high strength concrete (HSC) and HSC with fiber volume fraction of 2% and 3% of large paddle shape steel fibers (l = 30 mm, Ø = 0.6 mm) while, the other researchers used steel fibers with smaller dimensions (l = 13 mm, Ø = 0.16–0.22 mm) [10]. Developed an equation for the compressive DIF for SF-HPC with a quasi-static compressive strength ranging between 126 MPa and 167 MPa.

Table 1 summarizes past information about dynamic compressive tests of SF-UHPC and SF-HPC.

1.2. BF and PVAF reinforced concrete.

[13] reported the impact response of basalt fiber reinforced concrete with 0.1%, 0.2% and 0.3% using 100 mm diameter SHPB and concluded that the addition of basalt fiber can significantly improve the deformation and energy absorption capacities of geo-polymeric concrete (GC). With an optimum of fiber volume fraction of 0.3% an increase of 8.9% (at 40 s^{-1}) and 13.2% (at 100 s^{-1}) of specific energy absorption was achieved. No remarkable improvement in dynamic compressive strength was attained.

No significant research was found by the authors using PVA fibers in UHPC under impact loading. PVA has a low specific density (1.3 kg/m^3), thus researchers such as [14] used it for lightweight concrete.

1.3. Experimental principle of SHPB

SHPB is a widely used dynamic test method [15] to determine the dynamic stress strain behavior of materials. Fig. 1 shows the schematics of the SHPB and the data acquisition system used in this research. The UHPC and UHP-FRC specimens are sandwiched between the incident and transmitted pressure bar. The impact of the striker bar generates an elastic wave in the incident bar travelling towards the specimen. Due to the low impedance between the incident bar and the specimen a reflective wave travels back into the incident bar and the rest of the wave completes as a transmitted compressive wave. Strain gauge signals from the incident wave (ε_i) and reflected wave (ε_r) in the incident bar, as well as from the transmitted wave (ε_t) in the transmitted bar, are amplified and recorded using an amplifier and an oscilloscope at a frequency of 40 Mhz. Although, SHPB is widely used in obtaining the dynamic behavior of materials, brittle materials such as concrete, rock and ceramics challenge the acquisition of test results satisfying dynamic stress equilibrium (SE) on both faces of the specimen and constant strain rate (CSR) during effective test duration.

In this research emphasis was placed on obtaining test results satisfying the requirements of SE and CSR. This included the optimization of the incident pulse, the reduction of imperfections, the minimization of the frictional effects between specimen and bar, and the reduction of the specimen's lateral inertial effects. Further details about the SHPB limitations and measurements can be found in [16]. The same material and dimensions of the SHPB reported in [14] were used here.

Pulse shaper disks and a shaped striker have been used in this research to tailor the incident stress wave which facilitate CSR and SE in the specimen during testing. In this research increasing the rise time of the incident wave was emphasized to achieve SE and nearly CSR. The rise time was tailored by using thin circular disks made of copper or aluminum with carefully selected dimensions at the interface between the striker bar and the incident bar (Fig. 1). Using a shaped striker bar as shown in Fig. 2 [17] has been another way to tailor the rise time here. The striker bar was designed according to [18] to initiate a half sine waveform in the incident bar.

Axial and lateral inertial effects were first introduced by [19]. In order to reduce the inertia effect they suggested a specimen's

Table 1
Dynamic compressive increase factor of UHP-FRC.

Author	Steel fibers		Quasi-static comp. strength (f_{cs}) [MPa]	Dynamic Test		DIF $\frac{f_c}{f_{cs}}$
	V_f (%)	Dimensions (mm)		Strain rate (s^{-1})	Compressive strength (f_c) [MPa]	
B. Riisgaard (2007) [24]	0	–	160	81–267	187–241	1.17–1.5
Jiao, Sun, Huan, Jiang (2009) [8]	0	L = 30, Ø = 0.6 (paddle end)	118	15–93	91–154	0.77–1.3
	2		138	14–95	90–183	0.65–1.32
	3		154	14–91	91–203	0.59–1.32
Lai, Sun (2009) [7]	0	L = 13, Ø = 0.2 (straight)	143	25–87	138–200	0.96–1.39
	3		186	32–99	147–192	0.79–1.03
	4		204	24–96	150–203	0.73–0.99
Tai (2009) [9]	0	L = 13, Ø = 0.2 (crimped)	173	78–566	178–312	1–1.8
	1		198	104–685	111–309	0.6–1.6
	2		187	131–797	131–294	0.7–1.6
	3		181	234–1240	147–301	0.8–1.7
Ju, Liu, Sheng & Wang (2010) [10]	0	L = 13, Ø = 0.2–0.22 (shear type)	126	21–57	128–158	1.02–1.25
	1		160	35–105	141–175	0.88–1.09
	1.5		162	35–105	160–180	0.99–1.11
	2		165	41–100	164–182	0.99–1.10
	3		167	41–105	137–167	0.82–1.00
Rong, Sun, Zhang (2010) [5]	0	L = 13, Ø = 0.175 (straight)	143	26–83	130–200	0.91–1.4
	3		186	32–93	138–190	0.74–1.02
	4		204	32–93	170–200	0.83–0.98

Note: L is the fiber length, Ø is the fiber diameter, f_c the dynamic compressive strength, f_{cs} the quasi-static compressive strength.