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RESPONSE OF THE ULTRA HIGH PERFORMANCE CONCRETE UNDER DYNAMIC COMPRESSIVE LOADING

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Abstract. Ultra high performance concrete is a modern cementitious material which exhibits excellent mechanical properties such as damage tolerance, fracture toughness and durability. These features make this materials suitable for wide range of applications where is the material subjected to different modes of loading and different loading rates.

This paper deals with measurement of the Ultra high performance concrete reinforced with steel fibres in quasi-static compression mode of deformation and two elevated strain rates using split Hopkinson pressure bar. The results of the measurement show high increase of the mechanical properties with elevated strain rate.

Keywords: Ultra high performance concrete, split Hopkinson pressure bar, scanning electron microscopy, quasi-brittle material, dynamic testing.

1. Introduction

Ultra high performance concrete (UHPC) is a cementitous composite material which can be used in wide range of applications, mostly in civil engineering. Thanks to excellent mechanical properties such as high damage tolerance, fracture toughness and durability, which UHPC exhibits, it can be used in special applications. These applications include for example marine structures, underground spaces, nuclear waste containers, protection of critical infrastructure, mobile anti-vehicle barrier, and national defence and military facilities [1–3].

UHPC is a fine-grained composite material made of high amount of portland cement, supplementary cementitious materials, reactive powders, limestone or quartz flour, fine sand, high-range water reducers,and small amount of water. The UHPC was first introduced in the mid-1990s by de Larrard and Sedran [4] as well as Richard and Cheyrezy [5, 6]. After that UHPC has seen widespread implementation throughout the world.

By including fiber reinforcement, post-cracking retention and a level of ductility can be achieved that cannot be observed in conventional concrete [7, 8].

The material is in this special applications frequently subjected to dynamic loading. Therefore, it is necessary to test this material under wide range of strain rates from quasi-static to high velocity impacts and different loading modes. This paper deals with testing of UHPC in quasi-static compression and dynamic compression in two strain rates.

2. Material and methods

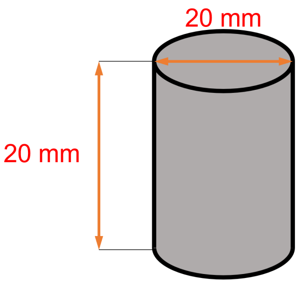
2.1. Ultra high performance concrete samples

The samples used for testing were prepared from UHPC reinforced by steel fibres (UHPFRC). Mixture of the UHPFRC was developed in Klokner Institute and modified in terms of intended use for explosive tests. All dry components were premixed and placed into bags. This preparation made it possible to speed up the whole mixing process. Main characteristics of the mixture are very low water to cement ratio, self compacting character and very high material properties such a compressive strength, flexural strength and also durability. Mixture was reinforced by scattered reinforcement – steel fibres in volume of 1.5 %. Detailed mixture parameters are shown in Table 1.

Material	**UHPFRC** $\left[\mathrm{kg\,m^{-3}}\right]$
Cement 52.5	700
Aggregate 0-2 mm	867
Microfillers (microsilica + slag)	180
Water	175
Superplasticizer	40
Steel fibres 0.2/13 mm	120

Table 1. UHPFRC mixture

The samples were drilled out from big block made of the UHPFRC resulting in the shape of cylinders with diameter approximately 20 mm and height 20 mm, see Figure 1. Samples were prepared from core (middle) of the UHPC block and from the shell (edge) of the block.



(a). Dimensions of the UHPC samples.

(b). UHPC specimen.

Figure 1. UHPC specimen.

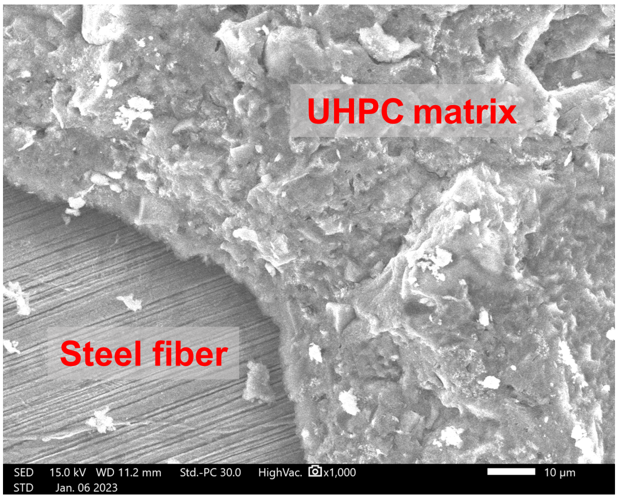


Figure 2. SEM image of the UHPC matrix and fibre reinforcement.

2.2. Scanning electron microscopy

In order to get information about the microstructure and bond between the fibre and matrix, scanning electron microscopy (SEM) was performed using Jeol JSM-IT200 (Jeol, Japan). In Figure 2 is the SEM image of the bond between UHPC matrix and steel fibre. The image was obtained using secondary electron detector with magnification of 1000×.

2.3. Quasi-static experiments

Measurements in quasi-static compression mode were performed using Instron 3382 (Instron, USA) with maximal loading capacity of 100 kN. Displacement of the cross-head and applied force were captured at a 50 Hz frequency. Velocity of the crossbar was set to 1 mm min^{-1}. Figure 3 shows the setup for the quasi-static experiments.

2.4. Dynamic experiments

Split Hopkinson pressure bar in traditional configuration was used for dynamic testing of the samples, see Figure 4. The length of the incident bar was 1600 mm and the length of transmission bar was 2100 mm. The length of the striker bar was 750 mm and the impact velocities were 26 m s^{-1} and 37 m s^{-1}, respectively. The corresponding gas-gun pressure used for lower

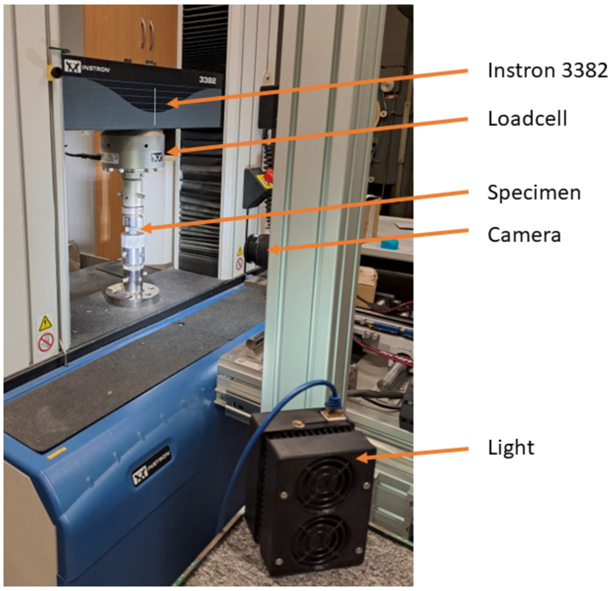


Figure 3. Setup for the quasi-static measurement.

strain rate was 4 bar and for higher strain rate was 8 bar, respectively. All of the used bars had diameter of 20 mm and were manufactured from high-strength aluminium alloy (EN-AW-7075).

Incident bar was instrumented with four foil strain gauges (3/120 LY61, HBM, Mainz, Germany), one pair in the middle of the bar and one pair near the interface between the incident bar and the specimen. One pair of the strain-gauges was mounted at the transmission bar near the interface specimen- transmission bar. All of the strain gauges were connected in the Wheatstone bridge to capture all deformations appearing during the impact. A pair of high-speed cameras (Fastcam SA-Z, Photron, Japan) were used for optical imaging. One high-speed camera was used for the recording of the deformation behaviour of the specimens and the second camera for velocity of the bars measurement. Both cameras recorded the scene with frame rate of 300 kfps with the corresponding resolution of the images 256 × 128 pixels. Figure 4 shows that in the setup is a mirror. The reason is to protect the high speed camera from the X-ray beam because the setup is designed to be used also for X-ray imaging.

The strain pulse was shaped using pulse shaper made from copper in the shape of cylinder with diameter 6 mm and height 1.5 mm to mechanically filter high frequency oscillations caused by wave dispersion effects. Actual velocity of the impact at the boundary of the specimen was lower than the striker velocities 26 m s^{-1} and 37 m s^{-1}, respectively because of the early failure of the specimen during ramp-in period of the strain pulse. Actual impact velocities during compression of the specimen were thus lower and corresponded to approximately 5 m s^{-1} and 10 m s^{-1}, respectively (see Figure 5).

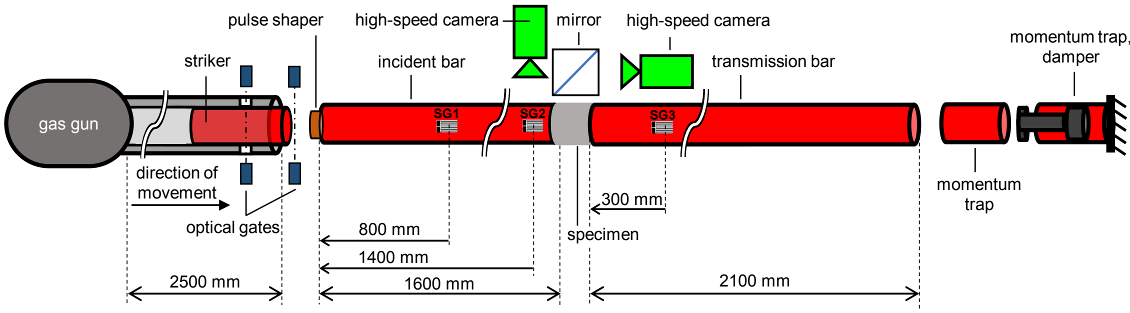
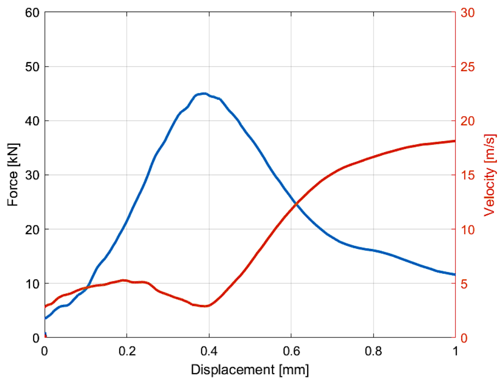
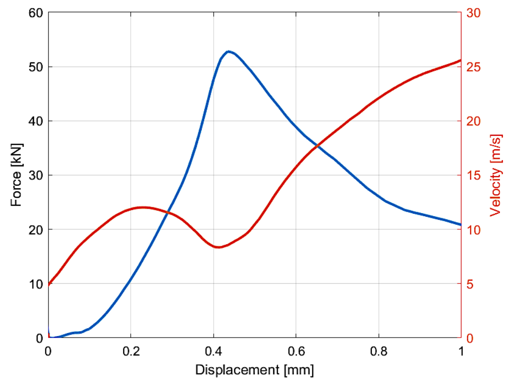


Figure 4. Results from the quasi-static experiments.

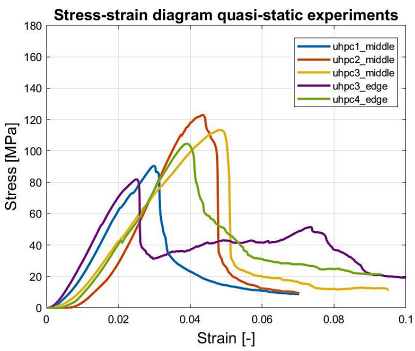


(a). Typical force and velocity histories during low velocity measurement.

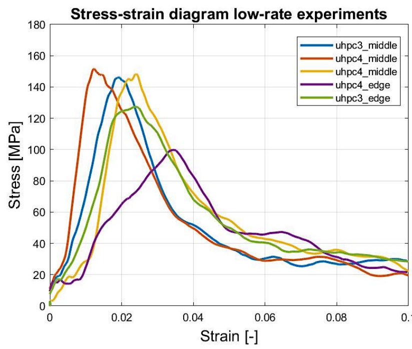


(b). Typical force and velocity histories during high velocity measurement.

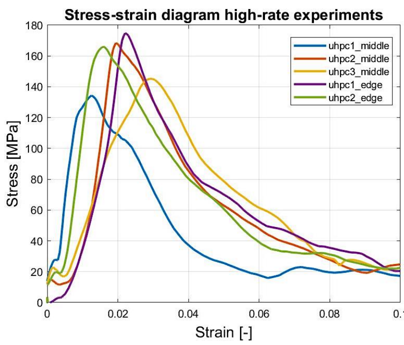
Figure 5. Typical recorded forces and velocities for both strain rates during SHPB experiments.



(a). Results from the quasi-static experiments.



(b). Results from the low velocity experiments.



(c). Results from the high velocity experiments.

Figure 6. Results for each deformation mode.

3. Results

The samples made from UHPFRC were tested in quasi-static compression mode of deformation and in dynamic compression mode of deformation. For each deformation condition were performed 5 measurements.

The Figure 6 are depicted stress-strain diagrams for quasi-static mode (6a), for low velocity mode (6b) and high velocity mode (6c).

From results shown in Figure 6 is obvious that there is no significant difference between deformation behaviour in compression of samples from the core and from the shell of the UHPFRC block. Scattering of the results can be caused by inner imperfections of the samples.

In Figure 7 are shown the mean courses and standard deviation of the stress-strain diagram for all sets of samples. For the UHPFRC samples is shown that the material exhibits high change in mechanical properties with increasing strain rate.

Yield stress σ_m is varying from $\sigma_{mquasi} = 103 \pm 17$ MPa for quasi-static experiments to $\sigma_{mlow} = 135 \pm 22$ MPa for low velocity experiments, and $\sigma_{mhigh} = 158 \pm 17$ MPa for the high velocity experiments respectively. This corresponds to 31 % and 54 % change in the yield stress with increasing strain rate of the experiment.

The identical trend is apparent for Young's mod-

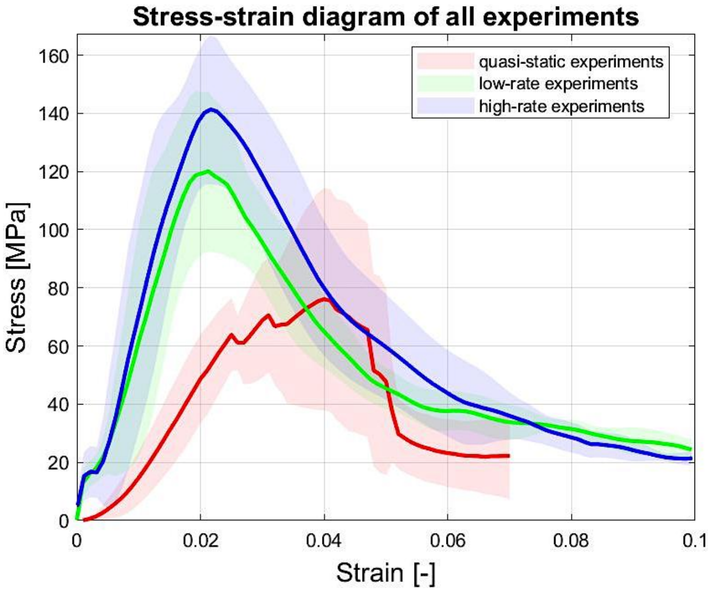


FIGURE 7. Stress-strain diagram with standard deviation of the results from quasi-static and dynamic experiments.

ulus. Young's modulus for the quasi-static experiments was $E_{quasi} = 4.1 \pm 0.7\,\mathrm{GPa}$, for the low velocity experiments Young's modulus was $E_{low} = 11.3 \pm 4.7\,\mathrm{GPa}$ and for the high velocity experiments $E_{high} = 13.9 \pm 5.1\,\mathrm{GPa}$. This is a 174 % and 237 % increase for low velocity and high velocity, respectively.

4. Conclusion

Mechanical properties in compression of the UHPFRC were investigated in quasi static mode and in elevated strain rate for three sets of samples. For each set were used 5 samples drilled from UHPFRC block. The material exhibit high increase of the mechanical properties in the dynamic measurement. The yield stress for the lower impact velocity increased by 31 % and for the higher impact velocity by 54 %. There is even higher increase in the Young's modulus where is the increase of 174 % for lower impact velocity and 237 % for higher impact velocity.

There occurred a problem because of the early failure of the specimen during ramp-in period of the strain pulse. Actual impact velocities during compression of the specimen were thus lower. Promising method how to overcome this phenomena is to arrange this measurement with a gap between the incident bar and the specimen to allow acceleration of the incident bar before the specimen impact.

Acknowledgements

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