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Behaviour of Different Types of Concrete under Impact and Quasi-staic Loading

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Abstract. Mixture formulation of High Performance Fibre Reinforced Concrete (HPFRC) with 2% of fibres by volume and its response to quasi-static and dynamic impact loading is described in this paper. This HPFRC mixture was prepared using locally available constituents and no special curing or mixing methods were used for its production. In addition, the mechanical parameters of three other types of concrete, i.e. normal strength concrete (NSC), fibre reinforced concrete (FRC) and high performance concrete (HPC) is compared. The main properties assessed throughout the experimental work are compressive, flexural and direct tensile strength as well as response of tested concretes to impact flexural loading. The impact loading is produced by a vertically falling weight of 24 kg from the height of 1 m on concrete prisms. The strain rate increase corresponds to low-velocity impacts such as vehicle crash or falling rocks. Compressive strength of HPFRC exceeded 130 MPa and its direct tensile strength was 10.3 MPa. This type of concrete also exhibited strain hardening both in flexure under quasistatic conditions and during impact. Based on the comparison of impact reaction curves, it was concluded that the resistance of HPFRC to impact loading is superior compared to the referent types of concretes (NSC, FRC, HPC).

Introduction

High rise buildings and other structures of strategic importance such as government buildings and television towers have become a symbol of developed cities worldwide. However, such structures are threatened by possible extreme-load events like earthquakes, gas explosions, car or plane impact and in recent years to terrorist attacks. New hi-tech materials such as ultra-high performance fibre reinforced concrete (UHPFRC) are ideal for applications where high compressive and tensile strength, small thickness and high energy absorption capacity are required. In addition, UHPFRC significantly improves blast resistance of cladding panels and walls while maintaining its standard thicknesses and appearance [1]. High performance fibre reinforced concrete can be characterized as a composite containing large volume of steel fibres, low water-binder ratio, high microsilica content and absence of coarse aggregate i.e. larger than 4 mm [2]. It has outstanding material characteristics such as self-consolidating workability, very high mechanical properties and low permeability which results in excellent environmental resistance and durability [3].Typical strengths are 150 to 200 MPa in compression and 7 to 15 MPa in uniaxial tension. Moreover, these materials exhibit strain hardening under tension [4,5] and high energy absorption capacity [6,7]. In addition, they show improved structural behaviour when compared to conventional concrete under both low and high velocity flexural impact loading [8]. For instance, Beckmann et al. [9] conclude that UHPFRC is able to resist perforation of a slab due to impact and that its performance is comparable to additionally fabric reinforced slab. Because UHPFRC is relatively new material, this paper describes both its mixture formulation and measurement of its mechanical properties. In addition, resistance of UHPFRC to impact loading was determined using a drop-tower based on the principle of falling weight. The loading strain rate was more than 100 000 times higher compared to quasi-static bending test. The performance of the newly developed material was compared to conventional concretes.

Composition of Tested Concretes

UHPFRC. During the mixing of UHPFRC, it is very important to achieve good workability, particle distribution and packing density. In comparison to normal strength concrete, UHPFRC contains more constituents, finer particles and short high-strength steel fibres. Usually it contains large amounts of cement. Steel high-strength (2800MPa) fibres with length of 13 mm and with an aspect ratio of 86 were used in the mixtures. The mixtures contained 2% of fibres by volume which corresponds to 160 kg/m3. The final mix design is presented in Table 1. According to the recommendation of several researchers [2,6] all fine dry particles were mixed first before water and high-range water reducer (HRWR) addition. This was because small particles tend to agglomerate and it was easier to break these chunks when the particles are dry. The shear action of fibres helped to destroy any remaining agglomerates in the fresh mixture. The total mixing time was 15 minutes for UHPC mixtures and 20 minutes for UHPFRC.

Reference Mixtures. For the comparison purposes two types of reference concrete were designed, normal strength concrete (NSC) and fibre reinforced concrete (FRC). The mixtures were designed, so that the target compressive strength after 28 days is more than 30 MPa, which corresponds to the strengths of most structural concretes used in Czech Republic. Due to the size of hardened samples the largest aggregates used in the mixtures were 8 mm in diameter. Hooked steel fibres with a length of 32 mm and an aspect ratio of 63 were utilized in the FRC mixtures. The tensile strength of the fibres was 1 345 MPa and they were added in the recommended amount by the manufacturer which is 50 kg/m3. The exact mix composition is presented in Table 1.

Table 1: Concrete composition

Component	NSC	FRC	UHPC	UHPFRC
	Mixture composition in kg/m^3			
Cement I 42.5 R	320	370	-	-
Cement I 52.5 R	-	-	800	800
Water	155	175	176	176
WR	1.45	3.5	-	-
HRWR	-	-	40	40
Aggregate 0/4 mm	850	1130	-	-
Aggregate 4/8 mm	800	750	-	-
Fine sand 0.1/0.6 mm	-	-	336	336
Fine sand 0.3/0.8 mm	-	-	800	640
Silica fume	-	-	200	200
Glass powder	-	-	200	200
Fibres (13×0.15 mm)	-	-	-	160
Fibres (32×0.55 mm)	-	50	-	-

Experimental programme

Quasi-static tests. Compressive strength and secant modulus of elasticity were measured on cylinders with 100 mm in diameter and height of 200 mm. Tops of the cylinders were cut off and grinded. Flexural strength in three-point bending configuration was measured on prisms with dimensions of 400×100×100 mm with a span of 300 mm. Under the assumption of linear elastic behaviour of the material, the loading strain rate was $d\varepsilon/dt = 2.2\times10^{-5}\ s^{-1}$ at mid-span on the bottom of the specimen. The deflection was measured by two linear variable differential transformers (LVDT) positioned in the middle of the span at the sides of the specimen. Direct tensile tests were carried out on dog-bone shaped specimens without a notch. The length of the specimens was 330 mm and the cross-section of the narrowed part was 30×30 mm. Because of the size of the moulds, only specimens with small aggregate, i.e. UHPC and UHPFRC were tested in direct tension. All quasi-static tests were performed in Experimental Centre at Czech Technical University in Prague.

High Strain Rate Bending Tests. An impact machine based on the principle of falling weight, so call drop-tower, was used to assess the response of studied concretes to high strain rate loading. The drop-tower facility is located in Otto-Mohr-Laboratory at TU Dresden, Germany and allows drop heights of up to 4.5 m and the maximal impactor weight is 50 kg. In this experimental work the falling weight had a mass of 24 kg and the impactor was mounted on its bottom. The complete test instrumentation and configuration used in this project are presented in Fig. 2. Throughout the experimental work constant drop-height of 1 m was used. For comparison purposes, the dimensions of the tested prisms were the same as for quasi-static bending. Neglecting friction and other losses the impact energy of the weight was 235 J and the velocity at the impact was calculated to be 4.47 m/s. The velocity value was also checked by using high-speed camera with a sampling rate of 100,000 fps. The measurement and determination of impact force is not very simple, because of the existence of large inertial forces that cannot be neglected. In this research the inertia was eliminated by measurement of the reaction forces. For this reason, a new type of supports instrumented with piezoelectric load cells was developed as shown in Fig. 2. The main advantage of this approach is that while the inertia is included in the impactor load readings it is not included in the reactions. The total impact load is then simply calculated as the sum of the reactions. This approach has also been adopted elsewhere [10]. In addition, impact load at the tup of the hammer was recorded by two load cells as presented in Fig 2. Two electrical resistance strain gauges were glued to the bottom of the specimen. The data acquisition rate for load cells was 1 MHz and for strain gauges 100 kHz because of the half-bridge limitations. Deflection of the specimen was not measured directly but was accomplished by analysis of the picture data from the high speed camera (100,000 fps).

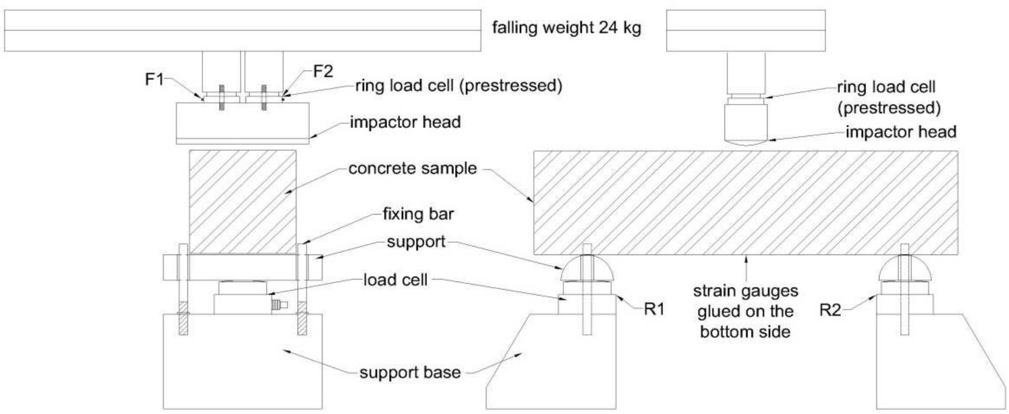

Figure 2: Sample position and instrumentation of the supports and impactor.

Results and Discussion

Quasi-static Mechanical Properties. The average results of mechanical properties are presented in Table 2. During the quasi-static three point bending tests specimens made of NSC showed small non-linear behaviour before reaching the peak load. UHPC samples behaved linearly elastically up to the brittle tensile-flexural failure. UHPFRC showed ductile behaviour. In the unloading phase of quasi-static bending, FRC samples exhibited tensile softening behaviour and UHPFRC exhibited tensile hardening before reaching the peak load which was followed by tensile softening region. Uniaxial tensile tests were performed only on mixtures with small aggregate and short fibres, i.e. UHPC and UHPFRC, because of the size of the dog bone specimens. The detailed measurement procedure is described elsewhere [11]. In case of UHPC the failure was sudden and brittle at the peak load. Samples made of UHPFRC exhibited strain hardening prior to reaching peak stress followed by strain softening behaviour during unloading phase. The average apparent strain for UHPFRC at the end of strain hardening region was 1105 µm/m at the stress level of 10.3 MPa.

Table 2: Mechanical properties

Property	Unit	NSC	FRC	UHPC	UHPFRC
Compressive strength	[MPa]	42.8	37.4	132.4	151.7
Secant modulus of elasticity	[GPa]	35.5	29.8	41.1	47.5
Flexural strength	[MPa] (kN)	6.2 (13.7)	7.1 (15.8)	13.9 (30.8)	29.7 (66.0)
Mid-point deflection at peak load for flexural tests	[mm]	0.16	0.29	0.31	1.36
Direct tensile strength	[MPa]	-	-	6.6	10.3
Maximal reaction impact force	[kN]	66.2	73.5	62.0	188.2

Bending Tests Under Impact Loading. From each concrete type 4 samples were tested in 3-point drop weight bending, giving the total of 16 tests. The average loading strain rate was in the range of $d\varepsilon/dt = 3.2\ s^{-1}$ and according to [12] is comparable with low velocity impacts such as vehicle crash or falling rocks. This value was measured experimentally by the strain gauges located at the bottom of the prisms. The measured strain rate is thus more than 100,000 times higher compared to quasi-static three point bending tests. The first three types of concrete (NSC, FRC and UHPC) showed brittle failure at the impact. Samples made of UHPFRC required up to 6 impacts to completely fail. The comparison of impact load and reactions in the first 4 ms after impact is shown in Figure 4 (a) and (b) respectively. From Figure 4 (a) it can be seen that there are no significant differences in the impact loads measured for all samples. The brittle concretes fail after the first peak which value is highly influenced by the inertia of the sample as mentioned before. The UHPFRC specimen did not break and the impactor started oscillating with the specimen at its eigen-frequency. After approximately 3 ms the impactor was deflected from the top surface of the specimen and started moving in the opposite direction. The analysis of high speed camera data supported this assumption. The reaction forces of the studied concretes are shown in Fig 4 (b). It can be seen that in case of UHPFRC all the impact force transfers to the supports, whereas for the broken specimens, only part of the impact force is transferred. This can be explained by the fact, that the influence of inertia in case of UHPFRC specimens is negligible, as there is nearly no movement of the specimen. On the other hand, in case of NSC, FRC and UHPC the specimen starts to move after the initial impact. It must also be noted, the construction of the supports did not restrain the vertical movement of the specimen, i.e. uplift and for this reason there can't be seen any negative reactions. This can potentially influence the results and will be eliminated in future work.

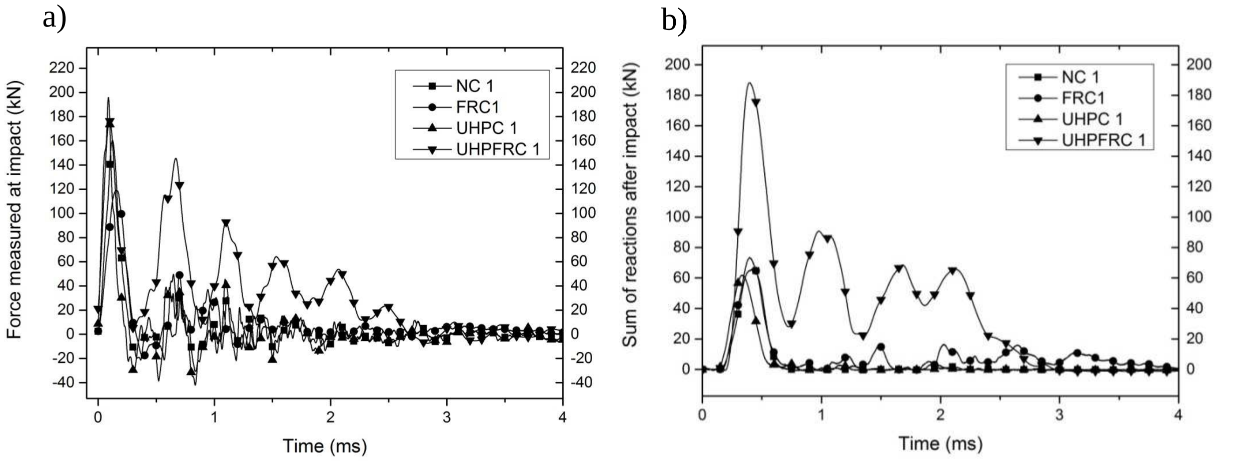

Figure 4. History of forces measured at the a) hammer tup and at the b) supports in first 4 ms after impact.

The difference between reactions of the first and last drop for UHPFRC specimen is shown in Figure 5. After the first impact there was a clear plastic deformation at the specimen which was recorded by the strain gauges located at the bottom side. After a detailed visual inspection a series of evenly spaced very fine cracks was observed at the underside of the prisms. No cracks were observed at the top surface. Usually after the second or third impact a macro crack started to form and propagate from the bottom of the specimen to the top surface. The complete failure of UHPFRC specimens required several more impacts. The mechanism of failure was by pullout of fibres and was very similar to quasi-static bending tests.

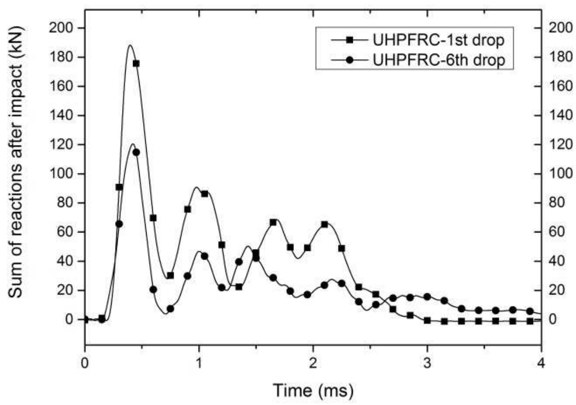

Figure 5. Reaction response of UHPFRC specimen, comparison between 1st and 6th hit.

Conclusions. The experimental work described herein showed the differences between the quasi-static and impact behaviour of four types of concrete. The UHPFRC performed the best and showed excellent energy absorption capacity. The main findings of our research are as follows:

- With an increase in target mechanical parameters, UHPC and UHPFRC become much more sensitive to quality of the components, the dispersion of the particles, mixing procedure, the specimen preparation and curing.
- A drop tower was used to produce a three point bending strain rate of 3.2 s^{-1}.
- To eliminate inertia, force at supports was measured and compared. It was found that the behaviour of NC, FRC and UHPC is very similar. The UHPFRC specimens required several weight-drops to break.
- Multiple evenly spaced cracking was observed at the bottom of specimens made of UHPFRC, which indicates strain hardening behaviour. The failure mode was by pull-out of the fibres which increases the capacity to absorb energy.
- It was verified that UHPFRC has much greater resistance to impact loading compared to traditional FRC. Thus, implementation of UHPFRC may result in highly resistant concrete elements such as cladding panels and walls in modern protective structures while maintaining its standard thicknesses and appearance.

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